



GUIDE TO SATELLITE REMOTE SENSING OF THE MARINE ENVIRONMENT

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IOC TRAINING PROGRAMME IN REMOTE SENSING

General

The Intergovernmental Oceanographic Commission (IOC) was founded in 1960 on the grounds that, as the oceans exert a profound influence upon all forms of life on the earth, they must be studied from many points of view and that many aspects of oceanic investigations present far too formidable a task to be undertaken by any one country or even a few countries. The Commission is established as a body with functional autonomy within UNESCO and numbers 118 Member States in March 1992.

The IOC is committed to providing the intergovernmental framework *"to promote marine scientific investigations and related ocean services, with a view to learning more about the nature and resources of the oceans"* (Statutes of the Commission, Article 1, paragraph 2). Such a duty is to be seen as unique within the overall United Nations system where the Commission is the competent organization to promote marine scientific investigations.

To discharge its duties, the Commission agreed to focus on four major themes, viz to:

- (i) develop, promote and facilitate international oceanographic research programmes to improve our understanding of critical and regional ocean processes and their relationship to the stewardship of ocean resources and their exploitation;
- (ii) ensure effective planning for the establishment, and subsequently the co-ordination, of an operational global ocean-observing system which will provide the information needed for oceanic and atmospheric forecasting, and for ocean management by coastal nations, and also serve the needs of international global environmental change research;
- (iii) provide international leadership for the development of education and training programmes and technical assistance essential to global ocean monitoring and associated oceanographic research; and
- (iv) ensure that ocean data and information obtained through research, observation and monitoring are efficiently husbanded and made widely available.

In particular, the commitment to Training, Education and Mutual Assistance in the marine sciences (TEMA) is intimately interwoven with other objectives of the Commission, including the fashioning of oceanographic research programme and the development of global and regional networks of ocean services.

Remote Sensing

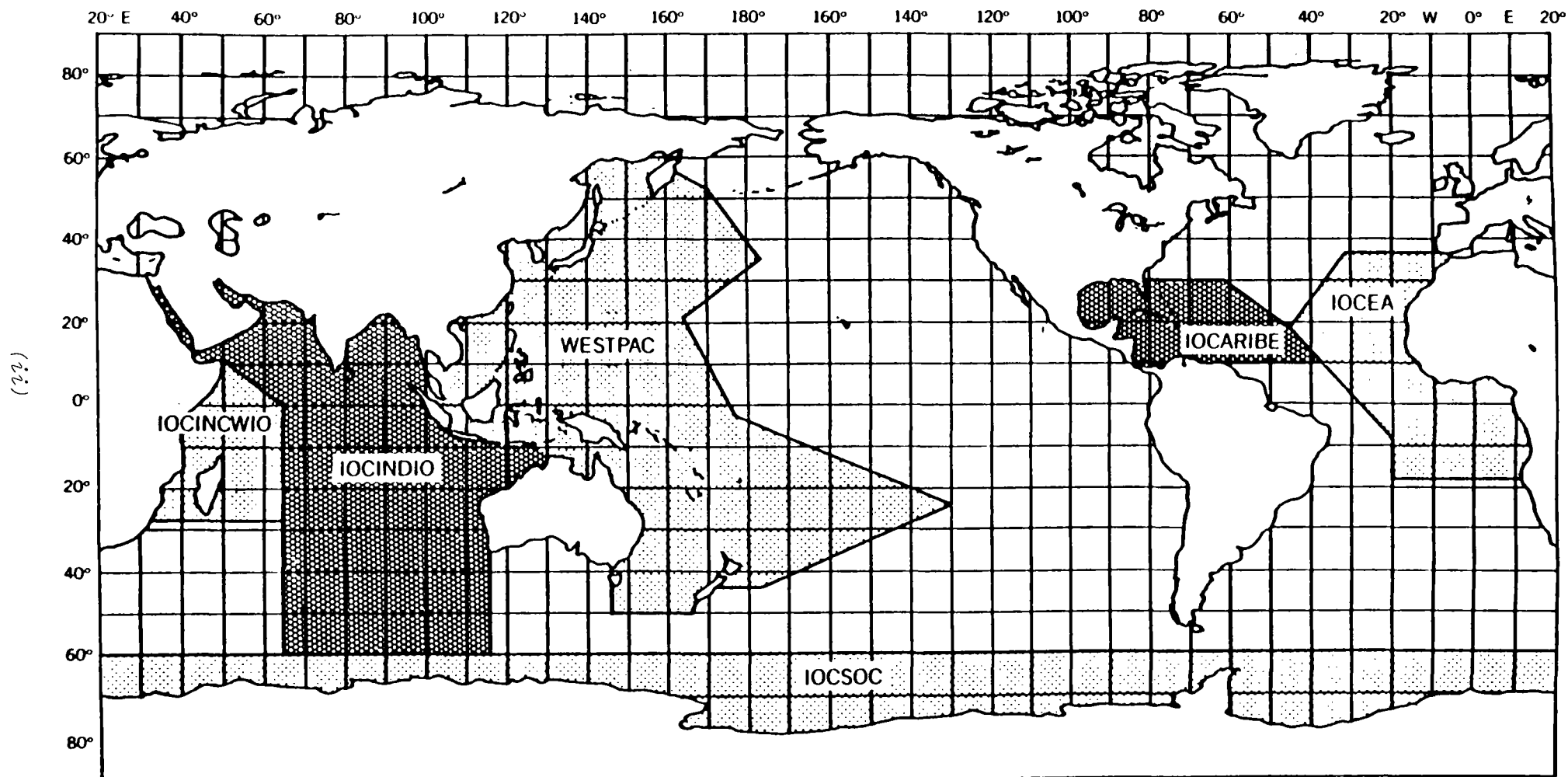
Oceanography has become increasingly a global activity requiring concerted and co-ordinated programmes to reach a clearer understanding of ocean processes. The World Ocean Circulation Experiment (WOCE) is a recognition of that fact.

After more than a decade of early promise, satellite remote sensing of the oceans has been significantly advanced with the launch of Europe's ERS-1. Satellites carrying precise sensors offer a global tool that is essential to match the global nature of many ocean processes. A fundamentally new approach is now required - quite different in its scope to the traditional methods that have been developed over the years for studying the ocean from research vessels.

Space sensors monitor the surface of all oceans equally several times a day, 365 days a year. If there are many ocean phenomena within the volume of the sea which remain unobserved from an orbiting satellite, the continuous monitoring of its surface accumulates vital information on the processes which in the shorter term most affect human habitations.

IOC has responded to the rapid development of this comparatively new technology by organizing training courses in developing countries through its regional centres. This Guide forms part of its new programme.

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PREFACE

Remote sensing of the earth's surface from orbiting satellites has revealed to mankind a distinctive panorama of his global environment. Never before has it been possible to observe in such detail the scale of interactions between atmosphere, oceans, ice and land surfaces which determine the earth's climate. And never before has mankind felt such concern about the possible environmental impact of his own activities.

Earth observation from satellites may not yet have reached the same stage of maturity as telecommunications or navigation, but it reveals great promise in many diverse fields; observations from polar-orbiting and geostationary satellites are now used routinely by meteorologists in preparing weather forecasts.

The uniformity of satellite coverage is one of its greatest advantages over conventional surface measurements: another is the facility of a spacecraft to build up a series of reliable, **repetitive** measurements to reveal changing patterns of behaviour.

A satellite's view may be restricted to the sea surface but many details of the underlying deep-sea topography, coastal bathymetry, circulation patterns, ocean productivity and heat transport have been detected from space. Besides, the changes in the marine environment which most affect human activities, tides, waves, storm surges, pollution and weather patterns, are to be observed at the surface.

Quite apart from the clearly-perceived long-term benefits of orbiting satellites in programmes such as global warming and the greenhouse effect, practical applications affecting day-to-day management are now emerging. Activities such as fisheries and the development of aquaculture, coastal management, ship traffic control, pollution control, offshore exploration, flood warning and daily weather forecasts are all now benefiting from satellite surveillance.

As the number of ocean satellites increase over the next decade so the information derived from their sensors will be seen to benefit a wide diversity of communities. It is the purpose of this guide to review the present state-of-the-art and point the way to future developments.

T.D. Allan

Acknowledgement

It is the pleasure of the IOC Secretariat, on behalf of the Commission and the world oceanographic community, to express its gratitude and congratulations to Dr. T.D. Allan for his invaluable contribution to the preparation of this Guide.

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1. REVIEW

1.1 EMERGENCE OF SATELLITES

Few technological developments have captured the imagination of the marine research community to the extent of satellite remote sensing of the oceans as demonstrated by the performance of precise active and passive instruments carried on recent satellites. For the first time it is possible to contemplate synoptic observations of geostrophic surface currents, wind stress and sea surface temperature over an ocean network approaching that now routinely available to meteorologists over land. These data when combined with subsurface density and current measurements should provide global information on the general circulation of the ocean and its primary driving forces.

But it is not only ocean dynamics which now lends itself to study by orbiting satellites. Analysis of the Seasat and Geosat altimeter records has revealed a strong correlation between the fine detail of ocean surface topography and the structure of the underlying sea floor. The maps produced from radar altimeter records bear a striking resemblance to physiographic maps showing tectonic patterns of the sea-floor, constructed from many years of ship surveys.

Whilst the oceans cover two-thirds of the earth's surface, ice sheets in Greenland and Antarctica constitute 10% of the land surface area of the earth, and their accumulated volume of ice comprises 90% of global fresh water reserves. Sea ice covers almost 12% of the world ocean surface. The investigation of ice masses is hampered by extreme cold, long periods of darkness and persistent cloud cover in some areas. Thus glaciologists have also come to appreciate the enormous potential of satellite microwave techniques for detecting changes in polar ice masses.

Ocean circulation patterns and long-term changes in polar ice represent two of the most fundamental processes in determining the earth's climate; until they can be accurately monitored over long time-scales reliable climate prediction will remain difficult if not impossible.

The global charts of ocean colour changes produced from the Coastal Zone Colour Scanner record reveal distinct seasonal patterns of change in chlorophyll concentrations which, in many tropical and sub-tropical coastal areas, reflect an increase in nutrients brought about by upwelling of deeper, colder water.

It is 30 years since the first man-launched satellite went into orbit around the earth. Initially, few environmental publications were complete without a 'bird's-eye' photograph taken from an orbiting satellite. But the 1970's saw a rapid development of much more useful high-resolution sensors culminating in 1978 with the launch of three highly successful spacecraft largely devoted to marine applications. The new generation of sensors comprised:

- * The suite of microwave (radar) sensors on Seasat.
- * The Coastal Zone Colour Scanner (CZCS) and Scanning Multichannel Microwave Radiometer deployed on Nimbus-7.
- * The Advanced Very High Resolution Radiometer (AVHRR) designed to measure sea-surface temperature to 0.5°K carried on the NOAA series of operational satellites.

In addition, the introduction of the French Argos system for tracking buoys - collecting and disseminating their observations - made possible global studies of ocean behaviour without having to leave the laboratory.

The fine-resolution multi-band radiometers of Landsat and SPOT were designed primarily for land applications but their images of coastlines, especially in the tropics and sub-tropics, provided information on shallow-water bathymetry that was to prove useful in coastal management.

Although ocean satellites to date have mostly been regarded as experimental, they have nevertheless contributed to an increasing awareness that the oceans, atmosphere and ice-covered regions are coupled in a way that determines short-term weather patterns as well as the longer-term climate changes.

It is their synoptic view which makes satellites such a potentially valuable oceanographic tool. In many respects the sea surface on which research vessels are constrained to operate is the worst place from which to study the ocean. The large-scale phenomena of regional and global behaviour revealed by satellites would not have been detected through conventional measurements.

This comparatively new awareness of the extent of global connections has persuaded marine scientists that we may have reached the dawn of a new era comparable to the geophysical revolution of 3 decades ago which revealed the tectonic pattern of the solid earth.

In years to come the 1980's will be viewed as a time of consolidation - a time of planning future systems based on experiences of the past; a decade of debate, deliberations and decision which saw NASA, ESA, Canada and Japan announce plans to launch dedicated marine satellite systems. The 1990's has been cast as the decade to fulfil the promise shown over the last 30 years.

1.2 WHAT CAN BE MEASURED?

Satellite sensors have been developed to operate either in the optical/infra-red part of the electromagnetic spectrum ($\lambda \sim 0.4\text{-}12\mu\text{m}$) or in the microwave part ($\lambda \sim 0.3 - 30 \text{ cm}$). Past experience with these sensors, either from an aircraft or satellite, has shown that four basic sea surface properties can be measured to useful accuracies.

These are:

- colour
- temperature
- slope/height
- roughness

At present all ocean features - physical, chemical, biological or geological - must produce a surface signature in one of those four parameters if they are to be monitored from space; that is, for example, chlorophyll concentrations must affect ocean colour (and possibly temperature), bottom topography must be reflected in sea surface shapes (and possibly roughness), surface waves must modulate small-scale surface roughness patterns, and so on. Only ocean colour cannot be detected by microwave sensors. The CZCS operated at 5 discrete wavebands in the visible, from blue to near infra-red.

1.3 WHAT ARE THE LIMITATIONS?

Despite the undoubted applications of satellite remote sensing techniques to the study of the sea, it is true to say that for a considerable time the concept of 'oceanography from space' remained more of a promise than a reality. It is not difficult to find reasons. In the earlier years it was hardly surprising that a satellite sensor orbiting the earth at a height of about 1,000 km, and travelling at a speed of about 7 km s^{-1} , could not match the accuracy and reliability of 'in situ' measurements from research vessels or buoys. (The usefulness of a satellite photograph lay mainly in its wide perspective which might allow large scale surface features to be detected.) Another serious limitation of satellites was that their view was restricted to the surface; they appeared to provide little or no information on processes within the volume of the sea.

The most serious constraint placed on the operation of the earlier satellites, however, was the inability of their sensors to penetrate cloud. There is a genus of marine studies which, for their solution, require measurements to be repeated at regular intervals. At a latitude of 50° N in Europe it has been estimated that there is no more than a 5% chance of obtaining two consecutive satellite images of one area containing less than 30% cloud. Thus, systematic studies of the sea from satellites proved difficult.

Let us list these three major obstacles to carrying out useful measurements of the marine environment from space, and examine how they have been largely overcome:

- ☐ Sensor accuracy
- ☐ Views only surface
- ☐ Cloud cover

(i) Sensor accuracy

In 1964, 150 oceanographers gathered at the Woods Hole Oceanographic Institute to attend a symposium called 'Oceanography from Space'. The title had an incongruous ring to it. It was but a few years since the launch of Sputnik and a community reared in the traditional methods of studying the sea from research ships was ready to display a healthy scepticism of what might be achieved from a satellite. At the conclusion of the meeting the participating scientists laid down accuracy specifications for future satellite sensors that at the time must have seemed almost impossible to achieve in the foreseeable future. Yet within 14 years the performance of Seasat with its suite of four microwave sensors not only surpassed some of the specifications laid down but, if the truth be told, caught the oceanographic community unawares. Oceanographers were simply not prepared to deal with the volumes of precise data and radar imagery that poured out of Seasat during its brief 3 months operation. The fact that Seasat remained unreplaced throughout the 1980's is the main reason that for so long the promise of satellite remote sensing remained greater than the reality.

(ii) Satellites view only the surface

Radio waves do not propagate through the ocean and the penetration of light is limited. It might seem then that satellites would reveal only a small part of ocean processes and would contribute next to nothing to our understanding of the physics, biology and chemistry within the ocean, and of the topography of the sea floor. This is only partly true, as we shall see, but, in any case, many of the changes in the marine environment which most affect human activity - such as tides,

waves, storm surges, ice floes, pollution and weather patterns - are to be observed at the sea surface. And, although the value of satellite measurements of the surface are undoubtedly enhanced by a coordinated programme of 'in situ' observations to provide a third dimension, the records of both the radar altimeter and the imaging radar carried on Seasat revealed astonishing detail of sea floor topography and, in the case of the altimeter, of crustal tectonic processes.

(iii) Cloud cover

The greatest drawback of the earlier satellite sensors was their inability to penetrate cloud which precluded the repetitive type of observations required by most oceanographers. The beautiful photographs one sees of land masses, looking as clear as a map, have always been the exception rather than the rule. It was not until the development of microwave sensors which culminated in 1978 with the launch of Seasat that 'oceanography from space' became a reality.

1.4 MICROWAVE SENSORS

The first experiments that gathered ocean surface data by means of microwave sensors were made by astronauts on board Skylab in 1974. Those experiments included a microwave scatterometer, a radiometer, and a low-resolution (~1m) altimeter. Geos-3 then demonstrated the potential of higher resolution microwave altimetry for sea-state and mean surface-level measurements while scanning microwave radiometers had been flown on Nimbus 5 and 6. In the meantime, synthetic aperture radars were being developed and flown on aircraft. Seasat brought them all together, providing the first satellite SAR, together with improved versions of the radar altimeter, scatterometer and scanning microwave multi-channel radiometer.

The principle of extracting useful information on the state of the sea surface by analysing the nature of the backscattered radiation is illustrated below. Scattering of e-m waves from the sea surface depends on:

Surface roughness <i>caused by</i>	and	Radar parameters <i>of which the most important are</i>
● Winds		● Power
● Waves		● Angle of incidence
● Currents		● Frequency
● Slicks		● Polarisation
		● Viewing angle

For years, extensive research programmes have been directed towards finding the optimum mix of the man-made radar parameters in order to extract the maximum information about the roughness of the sea (or ice) surface, and the forces causing it.

Microwave radar technology had been given a rapid impetus during World War II. As it happened, the original reason for studying the nature of radar echoes from a roughened sea surface was because 'clutter' interfered with the detection of military targets on or near the sea surface. After the war, work on the analysis of clutter proceeded in Europe, the USA and in the USSR, where much of the early theoretical work was made. Experiments made in the SW Approaches to the Channel in the early 1950's led to the conclusion that radio waves interacting

with the sea surface at an oblique angle were scattered according to Bragg's Law so that for backscatter at incidence angle θ (measured with respect to the normal to the surface), then $2L\sin\theta = n\lambda$ where L is the wavelength of ocean surface waves, λ the radar wavelength and n is an integer.

At HF frequencies the radar wavelengths match those of ocean gravity waves (say 50-300m) but at the centimetric wavelengths of microwave radars the backscatter is usually assumed to be the result of a two-scale rough surface whereby patches of Bragg scattering ripples are lifted and tilted by the larger dominant gravity waves - that is, the long waves modulate the shorter waves in a process known as 'straining'.

We provide here brief, summary descriptions of each of the microwave sensors that was successfully tried on Seasat, and are now operating successfully on Europe's ERS-1.

1.4.1 Scatterometer

The scatterometer is a radar designed to measure wind speed and direction at the sea surface. It transmits a fan beam of short pulses and measures the echo power backscattered (σ_0) from the surface at a variety of incidence angles. It is responding primarily to surface roughness but to a lesser extent will be influenced by foam and spray which places an upper limit on the accuracy of estimates of high wind speeds.

At incidence angles between 20° and 70° the backscatter is produced mainly by Bragg resonance and the magnitude of σ_0 is determined by the spectral density of the Bragg-resonant waves, by the polarisation of both the incident and backscattered radiation, the angle of incidence, and the azimuthal angle (which depends on the satellite's path with respect to the wind direction). The spectral density of the Bragg-resonant waves - hence σ_0 - can be related to the wind speed. The actual dependence has been largely derived empirically from pioneering work with airborne instruments, and from the earlier models flown on Skylab and Seasat.

The model can be expressed as $\sigma_0(\theta, \psi) = G(\theta, \psi) + H(\theta, \psi) \log W$, where θ is the incidence angle from the vertical, ψ is the azimuthal angle of the look direction with respect to wind direction, and W is the wind speed. It is the values of G and H which are derived empirically.

At nadir incidence the backscatter is due mainly to specular reflections and since higher wind speed makes the sea rougher leading to less specular reflection then σ_0 decreases with wind speed at nadir. At 10° incidence σ_0 is nearly independent of wind speed but at angles greater than about 20° σ_0 increases with wind speed according to the laws governing Bragg scatter. It is this regime in which scatterometers operate.

By viewing the ocean at different angles with multiple beams, solutions can be found which extract the wind speed plus the best estimate of wind direction - albeit, not without a certain ambiguity (Figure 1.1). Seasat looked in only two directions (45° forward and 45° astern of centre) with beams on either side of the spacecraft. To diminish the ambiguity ERS-1 is using three antennae but is restricted to measurements at one side only.

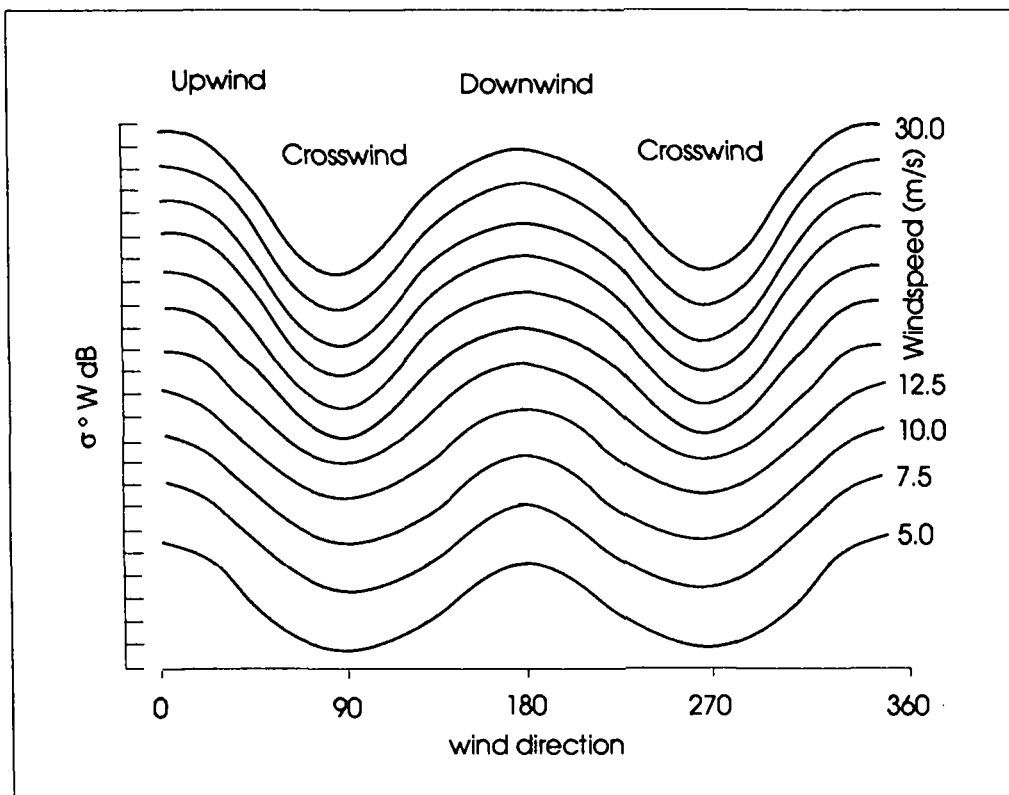


Figure 1.1 Relationship between wind direction, wind speed and σ_0

It is now clear that surface winds can be measured from satellites to as great an accuracy as from ships with the great advantage of providing even coverage over the global oceans. It is reported that more wind measurements were made during the 100 days of Seasat's operation than in the previous 100 years of conventional measurements from surface vessels.

The ERS-1 model was designed to measure wind speed to an accuracy of 2m/s in the range 4 m/s to 24 m/s; first analyses reveals a good performance also at higher wind speeds. Its swath width is 500 km and it provides wind vectors over a resolution cell of 50 km along and across track. The operation of the ERS-1 instruments is shown in Figure 1.2.

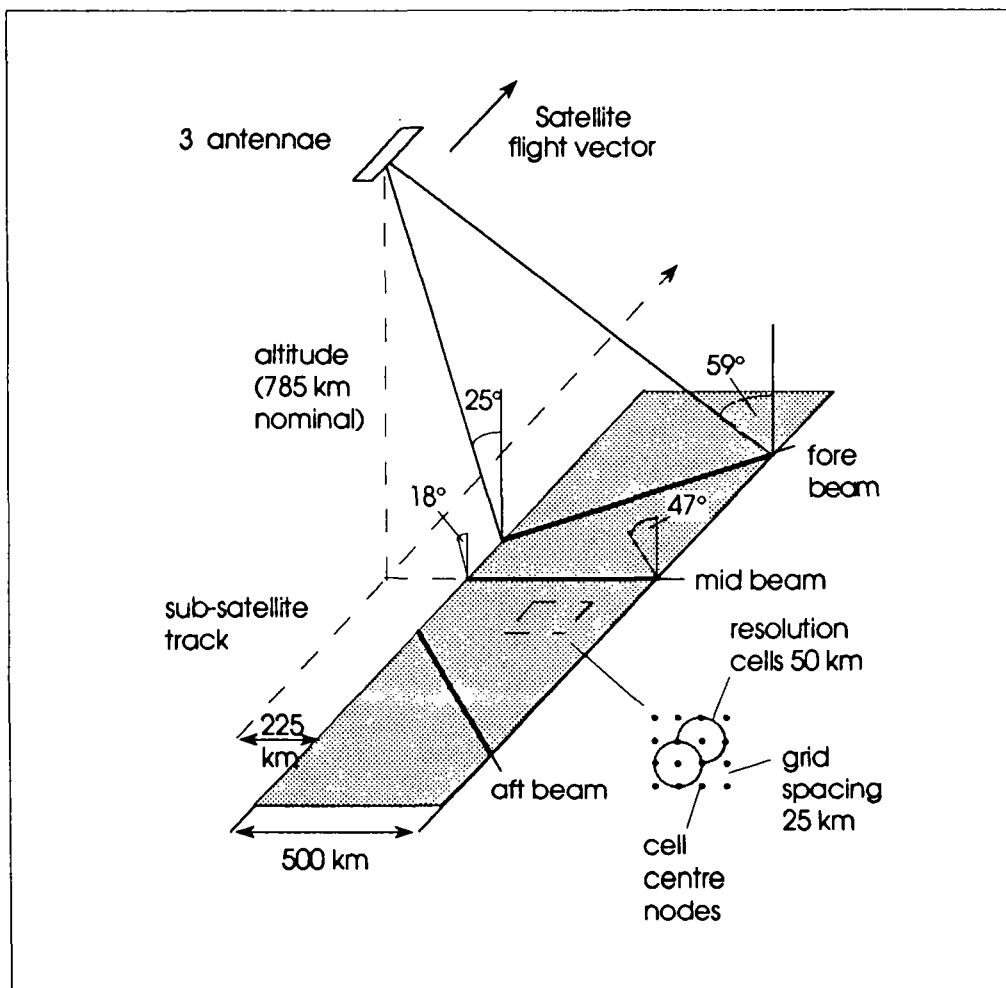


Figure 1.2 Wind scatterometer geometry

1.4.2 Altimeter

The altimeter is a nadir-looking radar that measures the precise altitude of the satellite above the sea surface by measuring the time interval between the transmission and reception of a stream of very short pulses. The present-day precision of around 5 cm is achieved through a mixture of sophisticated pulse-compression and sea-level tracking techniques.

Although the concept of precise altimetry and the present state of knowledge of its interaction with the sea surface is much less controversial than that of the scatterometer and SAR, radar altimetry was conceived and developed for use on a spacecraft much more recently than the concept of scatterometry. When in 1964 the marine science community which gathered at Woods Hole for the first 'Oceanography from Space' symposium, stipulated that they would require at least a 10 cm precision in order to monitor ocean currents and eddies, fulfilment seemed a long way off: yet it was achieved in less than a decade and a half.

The technique (illustrated in Figure 1.3) is basically simple if not always easy to execute. The orbit height - which is the radial height of the satellite above the geocentre - is measured and calculated through satellite tracking - usually a combination of lasers, transponders, GPS and on-board electronic systems such as DORIS or PRARE. The height of the sea surface can then be determined by subtracting the altimetric measurement from the orbit height. Variations of this surface are measured with respect to a reference ellipsoid which approximates the earth's surface and is defined by an internationally agreed formula.

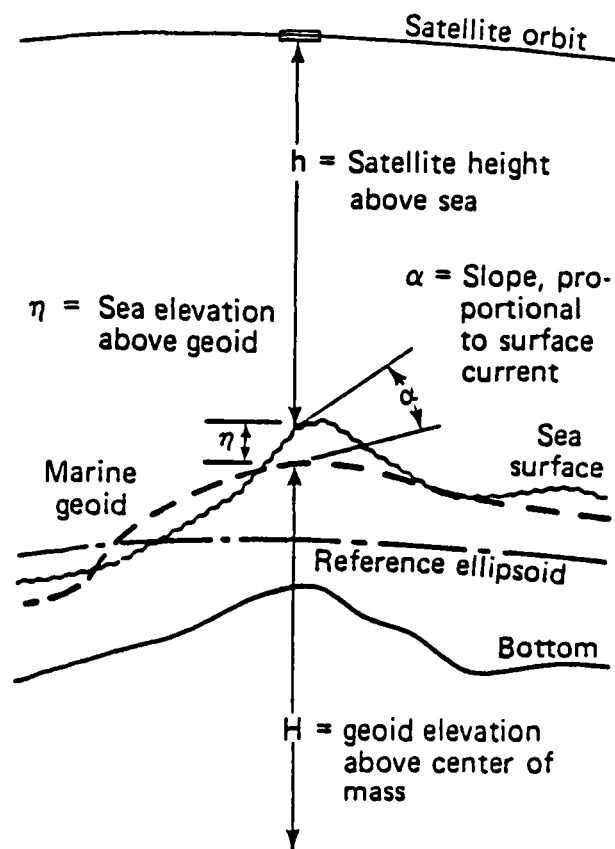


Figure 1.3 Measurement of sea surface elevation and sea surface slope from satellite altimeters. A precise knowledge of orbit and marine geoid are required.

Changes in sea level are mostly determined by the earth's gravity field. If the ocean were at rest, sea level would be a surface of constant gravity potential, referred to as the geoid. Across the surface of the globe the geoid varies by about 100m. By contrast the largest departures in sea level from the geoid brought about by tides, geostrophic currents and other dynamic processes (referred to as ocean topography) is of the order of 1m. The difficulty is that only in a few parts of the world's oceans is the geoid known to an accuracy sufficient to identify dynamic ocean changes. The altimeter has no way of differentiating gravity-induced from ocean-induced variability. But since the geoid can be considered invariant over the dominant time-scales of ocean dynamic processes, satellite altimeter tracks are made to repeat at reasonably frequent intervals (ERS-1 has a 3-day repeating phase, Topex/Poseidon 10-days).

There are three main sources of error - instrument, orbit, and environment (at the sea surface and within the atmosphere through which the altimeter transmits its pulses). The latter source of error can and must be minimised by measuring the constituents of the atmosphere - its water vapour and liquid water content as well as variations in the electron density within the ionosphere - while at the sea surface the effects of waves (wave troughs tend to reflect more energy back than wave crests causing a bias), tides (not always accurately known in the deep ocean), and atmospheric surface pressure (10 mbar is equivalent to 10 cm in sea level) must all be taken into account if the 5 cm precision of the instrument is to be fully exploited.

In the dedicated ocean topography mission of the joint US/French Topex/Poseidon satellite the altimeter will be dual-frequency instrument flying at the increased height of 1300 km and will aim at an accuracy of 2 cm. The ERS-1 altimeter is presently achieving a precision of about 5 cm.

Wind and wave height measurements

In addition to sea level measurements the altimeter's return signals can be used to measure surface wind speed and wave height. The measurement of wind speed is based on radar backscatter cross section at nadir. As the wind increases so the incident radiation is reflected away from a rougher sea surface, causing the backscatter cross section to decrease. The wave height measurement is based instead on the slope of the leading edge of the return pulse - the higher the waves the wider the return pulse (Figure 1.4 and 1.5).

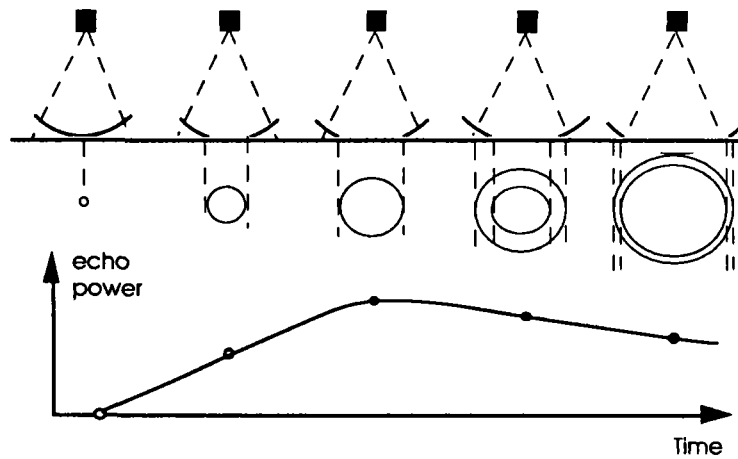


Figure 1.4 Intersections of an altimeter pulse with the sea surface

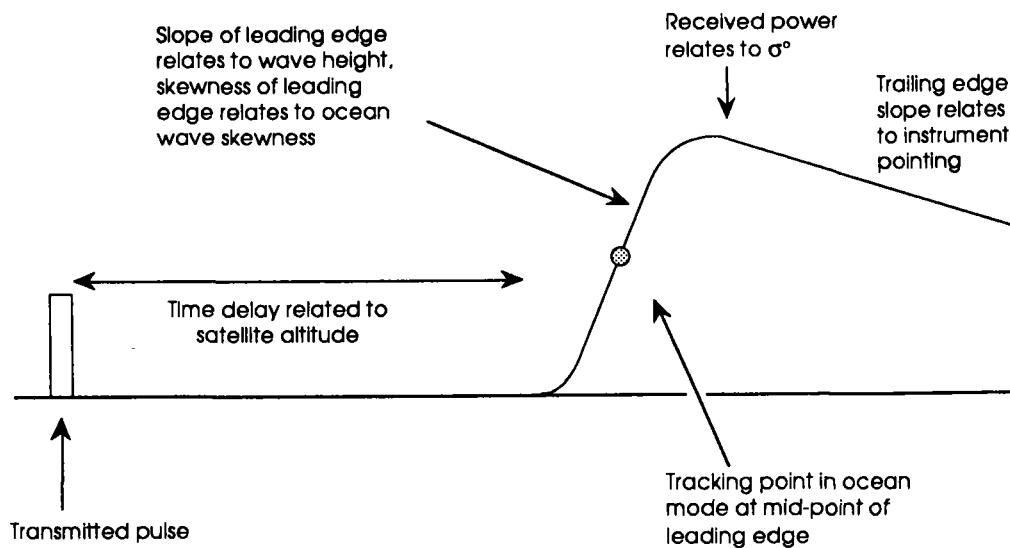


Figure 1.5 Wave-form of altimeter return pulse received at the sensor

The altimeter carried on ERS-1 is a Ku-band (13.8 GHZ) nadir-pointing instrument similar to that used on Seasat but with an increased capability of tracking over rough surfaces which allows it to monitor changing ice surfaces. It measures significant wave height to an accuracy of 0.5m or 10%, whichever is greater.

1.4.3 Synthetic aperture radar (SAR)

The synthetic aperture radar is an instrument for producing microwave images of the earth from space with a resolution comparable to optical systems. In the case of Seasat and ERS-1 - the only unmanned civilian satellites to have flown a SAR - this was about 25-30m. The method of aperture synthesis was first proposed in the 1950's; while normal temporal processing is employed in the range direction (that is, normal to the satellite's track) the azimuthal (along-track) resolution is achieved by retaining a target in the beam to obtain an unambiguous Doppler history as the satellite travels the length of a real aperture providing the same resolution. This length is of the order of 16 km. The geometry of the ERS-1 SAR is illustrated in Figure 1.6.

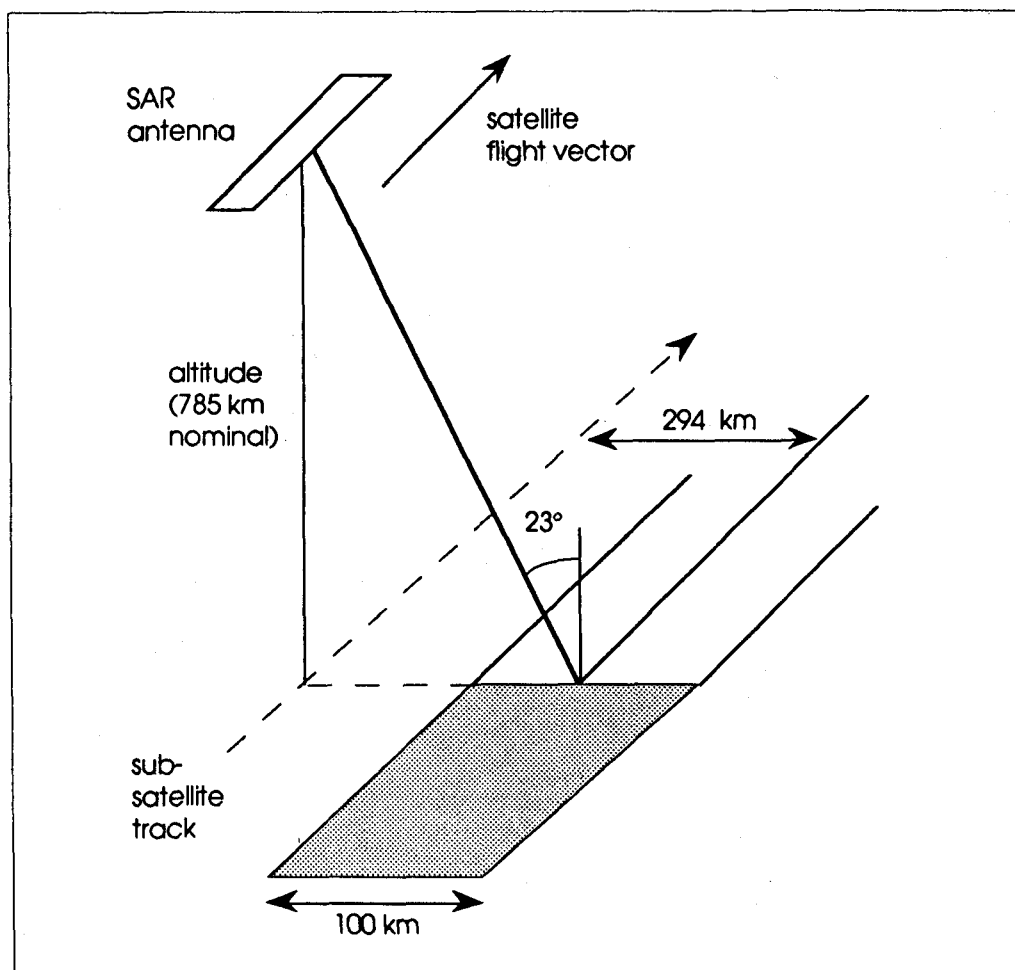


Figure 1.6 Geometry of the SAR carried on ERS-1

The return signal from each scatterer has its frequency modulated linearly and if the target is stationary the modulation constant is a function of known parameters, namely the radar wavelength, the velocity of the platform and its height. Broad beam antenna give better resolution than narrow beam, since resolution is inversely proportional to the total time the target remains in the field of view. In order to reduce speckle, processors will add 'multi-look' independent images of a target. Speckle being a type of random noise is thereby reduced but at the expense of resolution. A 4-look image would have an effective aperture length of 4 km.

Compared to land surfaces the ocean is relatively homogeneous with a low scattering cross-section and low contrast. Notwithstanding, imagery collected by Seasat, from the space shuttle (SIR-A & SIR-B), and now from ERS-1, have provided a wealth of information on surface features such as slicks, ships, currents, eddies, waves, and perhaps more surprisingly, on coastal bathymetry. Of greater concern than the low contrast is the wave motion for, unlike land targets, ocean scatterers do not remain stationary while retained in the radar beam. Indeed if Bragg scattering can be assumed to be the means by which the radar interacts with the sea surface (the larger ocean waves modulating and tilting the ripples with which the radar interacts) then for an L-band radar (1.4 GHz) the ripples would have a wavelength of around 30 cm while for the C-band (5 GHz) SAR of ERS-1 the interacting Bragg wavelength is around 6 cm. The form of such short wavelets will change considerably over a short time and may be expected to be smeared out on the image. Yet the larger gravity waves are clearly imaged by SAR.

Another related effect which has stimulated a lot of discussion leading to experimental work in wave tanks and in controlled experiments at sea is the extent of distortion that may be contained within an image due to the orbital movement of waves while being imaged. Because the SAR relies on measuring Doppler signals it misregisters scatterers with radial velocity components according to the relation

$$\Delta x = R/V \cdot v_r$$

where Δx is the azimuth displacement, R is the range from the platform to the scene scatterer, V is the velocity of the platform, and v_r is the radial component of the scatterer velocity. A typical R/V ratio for Seasat and ERS-1 is about 130 s and a typical rms scatterer velocity (orbital velocity) for swell waves might be 1 to 3 m/s. This could therefore lead to part of a wave being imaged some 150-450 m from its true position. The effect is known as 'velocity bunching' and suitable corrections must be made for waves with a component in the azimuth direction.

The ERS-1 SAR shares its electronics with the wind scatterometer. Because of its very high data rate (approaching 100 megabits/s) on-board recording is not possible and data must be transmitted in real-time to a ground station. There is, however, a wave mode built in to the ERS-1 model which, every 200 km along track, provides two-dimensional spectra derived from small imaggettes. This information can be stored on the spacecraft until transmitted to a convenient ground station. Thus statistics on global wave climate are being built up.

1.4.4 Passive microwave radiometer

The basic physics of thermal emission from flat surfaces has been understood since at least the turn of the century. Work in the 1950's established a significant connection between radar scattering and radiometric emission from rough surfaces. The theory was later extended to calculate the microwave brightness temperature of a rough wind-driven sea.

Spaceborne passive microwave sensors observe radiation emitted from the Earth in the range 1-300 GHz but most ocean-related parameters are retrieved from observations below 40 GHz. After a series of experiments at different microwave frequencies involving different polarisations and incidence angles, at different surface temperatures and wind speeds, a quasi-empirical set of relations was established. An electronically scanning radiometer (ESMR) was flown on Nimbus-5 while Seasat and Nimbus-7 carried almost identical scanning multi-channel microwave radiometers (SMMR's) which employed dual polarisation in each of 5 channels at 6.6, 10.7, 18.0, 21.0 and 37.0 GHz.

Sea surface temperature is observed at low frequencies generally in the range 5 to 10 GHz. The great advantage of microwave sensors for measuring SST over the more commonly used infra-red instruments is their ability to operate through cloud but this must be offset against their resolution of around 150 km which is too coarse to study mesoscale eddies. Higher resolution would require a much larger antenna than has been flown up to now. Another constraint is contamination by land masses and in general reliable measurements must be made in the open ocean more than 600 km from a coast. Thus, again, interesting ocean features such as boundary current and their associated eddies may not be capable of being studied with the microwave radiometer.

Ocean surface emissivity is affected by surface winds through the generation of waves and foam. Wind speeds have been retrieved from the Seasat and Nimbus radiometers but calibration and validation against reliable in situ observations has proved difficult and no information on wind direction is available.

Measurements of ocean parameters by microwave radiometers are affected by atmospheric water vapour, clouds and rainfall and most sensors are therefore backed up by frequencies sensitive to water in the atmosphere. This information is also of considerable importance where precise altimetry is required to measure very small changes in ocean topography. For this reason ERS-1 carries a dual-frequency (23.8 and 36.5 GHz) sounder pointing vertically down to sample along the sub-satellite path. From the two frequencies accurate estimates can be made of both the integrated water vapour content and the total liquid water content which can significantly affect the conversion of time delay measured by the altimeter into height to the sea surface.

1.5 OCEAN COLOUR AND INFRA-RED SENSORS

Satellite remote sensing of the ocean's surface in the visible and infrared part of the electromagnetic spectrum has a considerably longer heritage than microwave sensing. NOAA has been flying the Very High Resolution Radiometer for the measurement of sea surface temperature for many years and in 1978 this instrument was upgraded to the Advanced Very High Resolution Radiometer which has been operational on the NOAA series of satellites since 1978. Ocean colour was measured for close to 8 years by the Coastal Zone Colour Scanner - an instrument carried on Nimbus-7 which was planned to function for no more than 2 years.

1.5.1 Coastal zone colour scanner

The CZCS measured ocean colour in four discrete bands with a further low sensitivity band designed for coast and cloud identification. A further band in the infrared operated intermittently. The four colour bands were as follows:

Band	Wavelength (nm)	Properties
1	433-453	Blue radiance shows effect of chlorophyll absorption
2	510-530	Blue-green radiances are increased by particles in water. Some chlorophyll absorption
3	540-560	Green radiances increased due to particles in the water
4	660-680	Red radiances due almost entirely to scattering in the atmosphere for Case 1 waters

The spatial resolution was 800 m at nadir and the swath width 1650 km. Most of the data were collected in the first part of the mission with a significant drop post-1981. A signal from Nimbus-7 in 1984 indicated (falsely it transpired) that the scanner motor was not functioning properly. It was revived and operated intermittently until it was finally shut down in mid-1986.

In order to understand the link between the colour of the sea and the concentration of suspended matter within its surface layer, models of radiative transfer were constructed from a study of the spectral characteristics of a number of substances. Much of the approach was necessarily empirical. The total radiance observed at the sensor can effectively be divided into two components; i) 'water-leaving' radiance which is that part of the signal that has penetrated the sea surface and been reflected back, times the diffuse transmission between the sea surface and the sensor, and ii) radiance that has not penetrated the sea surface but has been reflected or scattered from other sources into the sensor. Whereas the effects of the ocean form part of the first, atmospheric effects dominate the second and make-up the unwanted noise. The basic task of processing the CZCS record is to identify and remove this noise and then, from the water-leaving part of the signal, to make the best estimate of phytoplankton pigment concentrations.

A very large effort has gone into the development of the best processing 'algorithms'. Although the CZCS included reference signals for calibration it became apparent at a comparatively early stage of the mission that the blue channel was losing sensitivity. For effects such as these various models have had to be devised. The largest effort has been directed to correcting for atmospheric effects which have two main components: radiance resulting from molecular scattering (Raleigh), and scattering due to aerosols (Mie scattering).

The Goddard Space Flight Centre has produced global and regional maps of processed CZCS imagery for different years and seasons. The Joint Research Centre of the European Communities is presently running a programme called OCEAN (for Ocean Colour European Archiving Network) to process all reliable CZCS data over European water.

At present there is no colour sensor in orbit and none is carried on ERS-1. NASA is planning to launch the Sea-Viewing Wide-Field-of-View Space Sensor (SeaWiFS) as a replacement to the CZCS, piggy-backing on another mission. At the time of writing there is uncertainty as to the launch date but 1993 looks a possibility.

1.5.2 Infra-red radiometers

The earliest repetitive set of sea surface observations taken from a satellite was of its temperature. The AVHRR first flew on TIROS-N in 1978 and has made a continuous series of measurements since that date. The platforms changed their name to NOAA satellites which now circle the earth in tandem. The sensors have alternated between 4-channel and 5-channel instruments with the latter having a $12\mu\text{m}$ channel in addition to a 3.7 and $11\mu\text{m}$ infrared channels.

The total radiance at the sensor is the sum of the radiance from the ocean surface, from the atmosphere, and from reflected solar radiation. The AVHRR uses the multi-channels to estimate and correct for atmospheric effects. Linear models are set up using a combination of observations at more than one wavelength and the coefficients are determined by regression with 'in situ' measurements. The type of algorithm produced is relatively simple and is referred to as the 'split window' technique. It forms the basis for the NOAA operational algorithm. The coefficients used in the split window technique are strongly dependent on atmospheric conditions. It also appears that they may vary regionally - between tropical and mid-latitudes for example. For good conditions rms errors of 0.5°K can be obtained although errors in absolute accuracy may be closer to 1°K in less than optimum conditions. The AVHRR has a wide swath (>2000 km) and a resolution cell of about 1 km.

The Along-Track Scanning Radiometer (ATSR) flying on ERS-1 also employs a near-infrared channel ($3.7\mu\text{m}$) and two infrared (10.8 and $12\mu\text{m}$) but seeks an increase in accuracy by viewing the surface at two angles - at nadir and at 47° - thus producing two independent measurements with different atmospheric path lengths. The ATSR aims at measuring SST with an absolute accuracy of better than 0.5°K with a spatial resolution of 50 km in conditions up to 80% cloud cover, and a relative accuracy of 0.1°K with a 1 km resolution over a 500 km swath. The geometry of the ATSR view of the sea surface is illustrated in Figures 1.7 and 1.8.

It should be noted that what the radiometer measures is the 'skin' temperature at the sea surface and this is not necessarily the same as the bulk or mixed layer temperature measured from ships and buoys. Differences of a few degrees have been recorded in areas of flat calm and high solar radiation so extreme care must be taken in calibrating the sensor against in situ observations. It is usually the bulk temperature which is required for oceanographic studies. Under most conditions the skin temperature is a good indicator of bulk temperature.

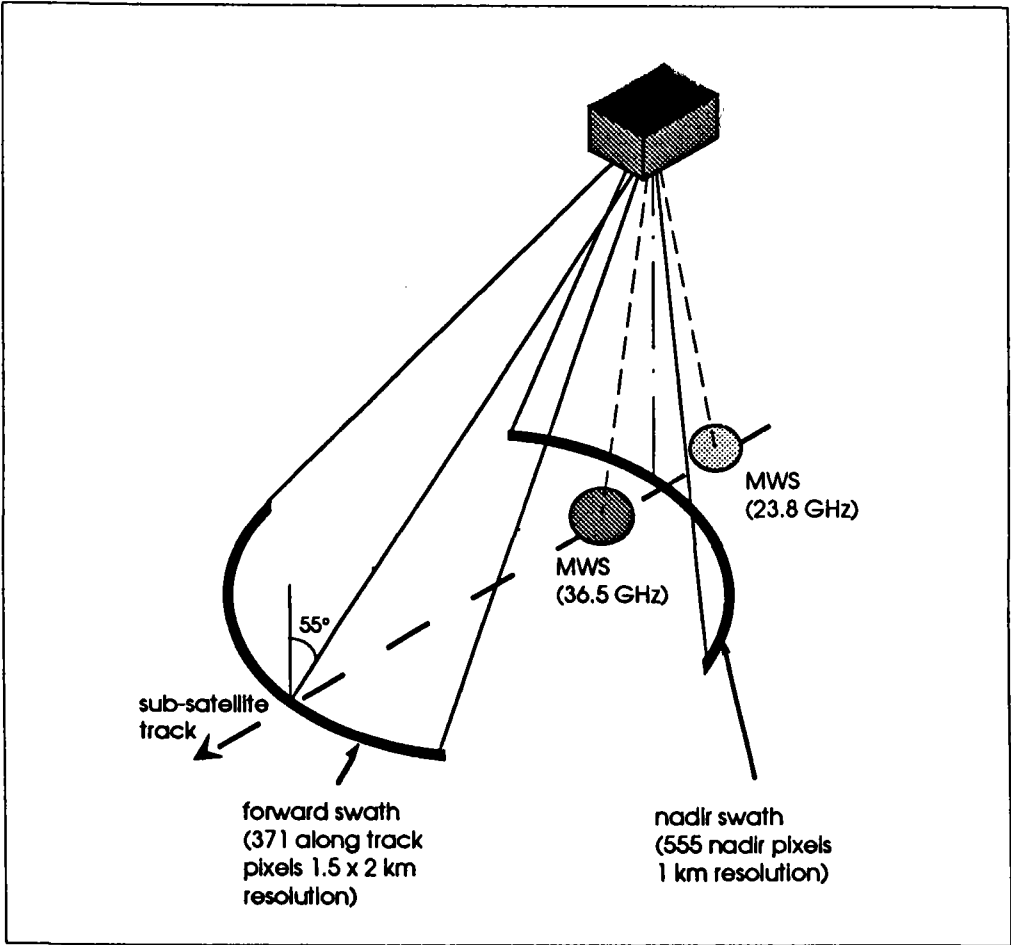


Figure 1.7 Viewing geometry of the Along-Track Scanning Radiometer

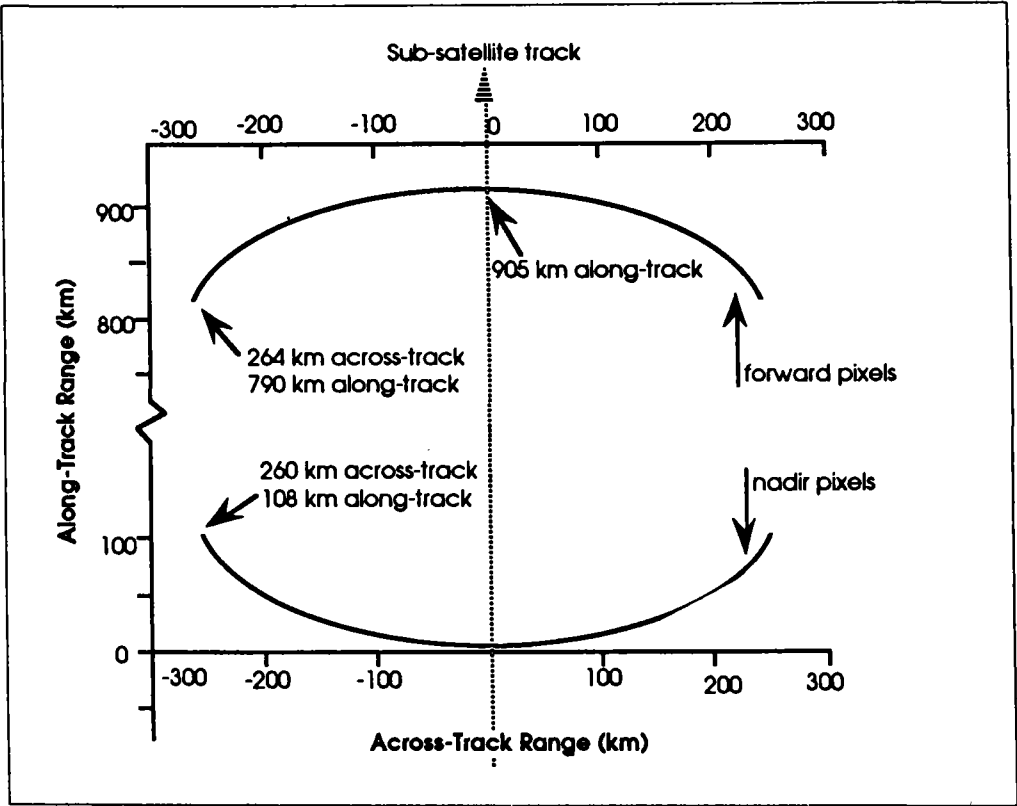


Figure 1.8 ATSR scans projected on to the earth's surface

2. MEASUREMENTS

2.1 SURFACE CURRENTS

The ocean is maintained in a state of continual motion through a combination of solar radiation and the earth's rotation.

Currents are produced as a result of the equilibrium established between a number of forces which include gravity, pressure gradients within the volume of the sea, the Coriolis force due to the earth's rotation, and frictional forces mostly due to wind. The pressure gradients within the water column are produced by differences in density at fixed depths brought about by different values of temperature and salinity.

Because the earth rotates from west to east an observer in the Northern Hemisphere would observe that a moving object was deflected to the right (that is, in a clockwise direction). In the Southern Hemisphere the deflection is to the left while at the equator there is no deflection. The strength of the horizontal component of the Coriolis force depends on the latitude and on the speed of a moving object such as a water particle.

If there were no Coriolis force acting (that is, if the earth were not in rotation) the pressure gradient would cause the water to move directly from high to low pressure. On a rotating earth the Coriolis force deflects the motion; the acceleration on the water will reduce to zero when the speed of the current at a given latitude is fast enough to produce a Coriolis force in exact balance with the horizontal pressure gradient. In the absence of frictional forces this balance, of course, is referred to as geostrophic flow.

At global scales the circulation of the upper layers of the oceans tends to divide into gyres that rotate mostly clockwise in the Northern Hemisphere and anti-clockwise in the Southern Hemisphere (winds and contours of coastlines may cause regional fluctuations).

The gyres tend to be elongated and in the northern hemisphere the poleward flow on the western side of the N Atlantic and N Pacific is fast, narrow and relatively deep. These are referred to as western boundary currents.

From the simple geostrophic relationship linking current speed and latitude to the earth's rate of rotation and to the acceleration due to gravity, the surface slope is easily calculated. Across the Gulf Stream slopes of up to 150 cm over 100 km were measured by radar altimeters on Seasat and Geosat. Normally, of course, deep ocean circulation patterns produce surface slopes at least an order of magnitude less. There is no method of measuring surface slopes directly at sea and until the advent of the satellite-borne radar altimeter they could only be inferred.

Surface slopes produced by currents are measured against a reference equipotential mean sea level referred to as the geoid. Over the surface of the earth variations in the gravity field cause the geoid itself to undulate with respect to a reference ellipsoid by about 200m. (The minimum is found in the Indian Ocean just south of Sri Lanka while the maximum is relatively close in the Eastern Pacific off Borneo).

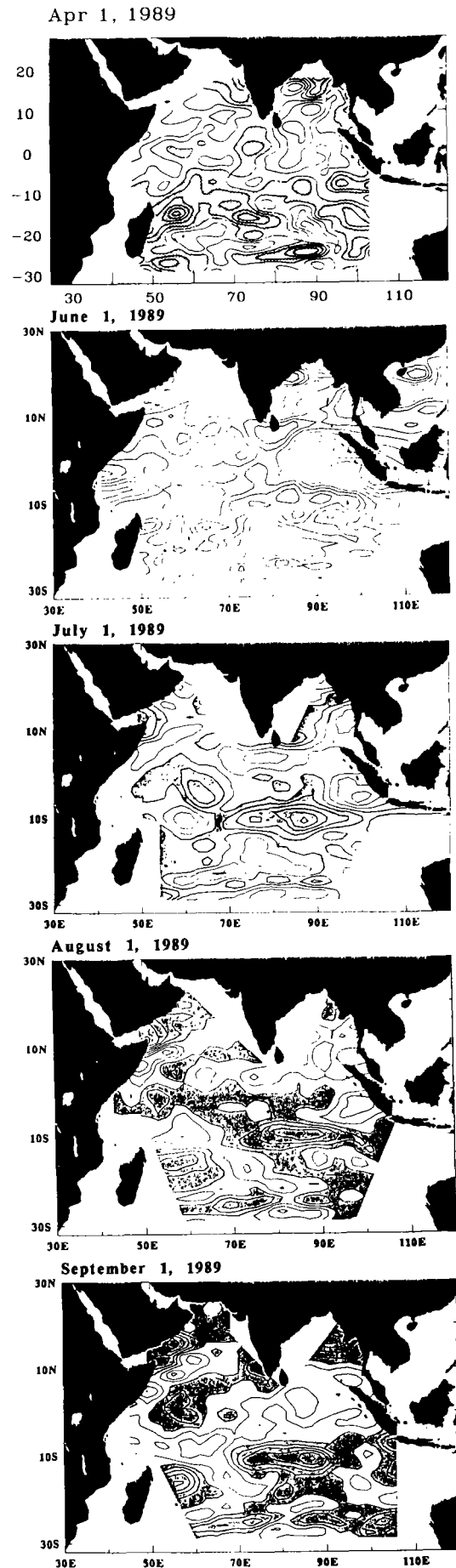
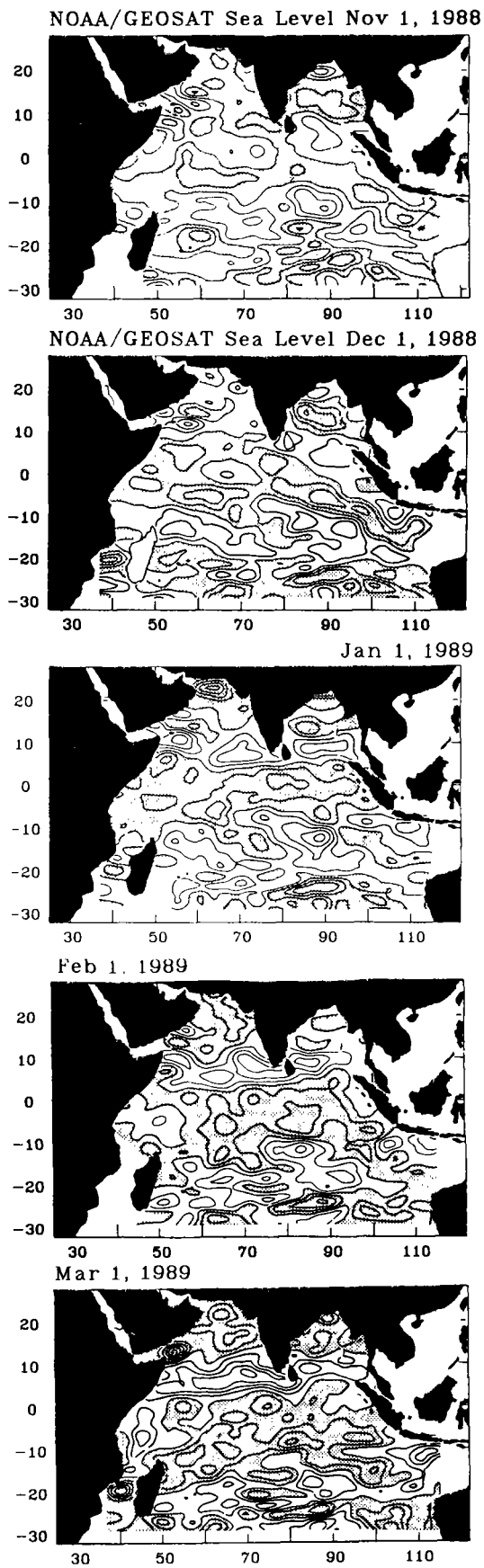
The altimeter which precisely measures its own height to the sea surface cannot easily differentiate between geoid fluctuations and slopes produced by currents but since the geoid unlike currents does not change with time, ocean variability may be mapped by comparing successive altimeter passes - a method successfully employed to map the major current systems.

Another method that has been used to compute patterns of sea level changes is to calculate a mean geoid over a selected area from (say) a year's altimeter's observations, subtract this out - and making corrections to the calculated height of the altimeter by minimising the differences at track intersections - record the differences.

The first method - employing frequent repeats to detect change - was used during the final 25 days of the Seasat mission when the repeat period was 3 days. The meandering of the Gulf Stream and the migration of its rings were graphically illustrated in the 8 repetitive passes. A similar approach is being used during the 3-day repeat periods of the ERS-1 mission.

At the conclusion of the US Navy's Geosat mission to map the earth's gravity field the satellite was placed in a recurring 17-day orbit (164 km between equator crossings), and given over to the oceanographic community. Using the second method of detecting variable ocean topography by computing a geoid from a long time series and subtracting this from the observations after minimising the track discordance NOAA was able to issue monthly charts of surface topography over all the world's oceans which were published in Climate Bulletin (see Figure 2.1). At middle and high latitudes the cross-track difference between the Geosat ground tracks was approximately 100 km making the altimeter observations useful for mapping the tracks of mesoscale eddies.

In areas of extremely high sea level variability the Geosat observations were used to compute a frequency-wave number spectrum of sea level variability which identified significant eddy energy at time scales longer than 34 days and spatial scales longer than 200 km.



The changing patterns of sea level recorded over a period of 12 months.
Contour interval 4 cm. Shaded areas negative.

Figure 2.1

2.2 SURFACE WIND AND WAVES

Ever since sailors first put to sea consistent efforts have been made to improve the forecasts of the conditions they may find there. Sudden storms still take their toll in terms of ships and men lost at sea. On 10 November 1988 a 65,000 ton British-owned oil tanker en route from Scotland to Canada split apart amidst 25-foot waves and 50-knot winds off the coast of Newfoundland. Twenty-seven crew members perished and a full load of crude oil formed a 30-square mile that began drifting back towards England. Each month sees two ships disappear without trace off the face of the globe. There are strong arguments therefore for improving the collection of reliable measurements of wind and wave conditions over the oceans.

One obviously successful area of international co-operation is the meteorological global network in which nations share their observations with each other. Routine measurements of surface pressure, humidity, precipitation, wind velocity, temperature and other parameters form the basis of the weather charts issued up to four times daily around the globe.

Ships, of course, play their own part in reporting conditions at sea. It remains true, however, that their observations are unevenly distributed over large tracts of open ocean especially in the southern hemisphere where comparatively few are reported.

Although wave forecasting has greatly improved from its empirical roots in the early 1950's major advances are still required. It is clear that satellites will play a primary role in helping to achieve its ultimate potential.

In general terms ocean waves are the result of winds blowing over the surface for a certain time (duration) and over a certain area (fetch). The primary elements of good forecasting are:

- * accurate wind estimates over the relevant duration and fetch
- * an understanding of how winds generate waves
- * an understanding of how waves are generated, propagated, transformed and dissipated along their route

Despite the significant advances made in the development of wind/wave models (aided by the increased power of modern computers) most models lack adequate validation in realistic open ocean conditions.

The reason why NASA's Seasat mission was judged such a success is that its new microwave sensors demonstrated a remarkable ability to make routine measurements of surface wind speed and direction over the oceans, as well as a global surveillance of surface wave conditions by means of its altimeter and synthetic aperture radar. The first global chart of significant wave-height was derived solely from 3 months of observations by Seasat's altimeter; and more observations of surface winds were made by the spacecraft's scatterometer in its 100 days of operation than over the previous 100 years of traditional measurements.

Before the advent of satellite microwave sensors, records of wave-height and period were measured at a number of discrete points at sea - usually by means of a wave-follower buoy. From these records - some covering periods of several years - average and extreme wave conditions could be evaluated which were of particular use in planning offshore operations. These records were inevitably too widely spaced, however, to allow scales of spatial variability to be studied.

During Seasat's brief life the SAR imagery was confined to the northern hemisphere since, as we have noted, its rate of data acquisition demands simultaneous transmission to a suitable receiving station; and the few that were commissioned at that time were located in the USA, Canada and the UK. The record provided striking imagery of the sea surface to a spatial resolution of 25m. Slicks, eddies, internal waves, ships, wakes, and oil spills were detected in the Atlantic and Mediterranean Sea. It was its ability to image surface swell waves that particularly attracted the interest of the oceanographic and meteorological communities - for it was recognised that synoptic views of surface waves could be obtained in no other way. (Figure 2.2).

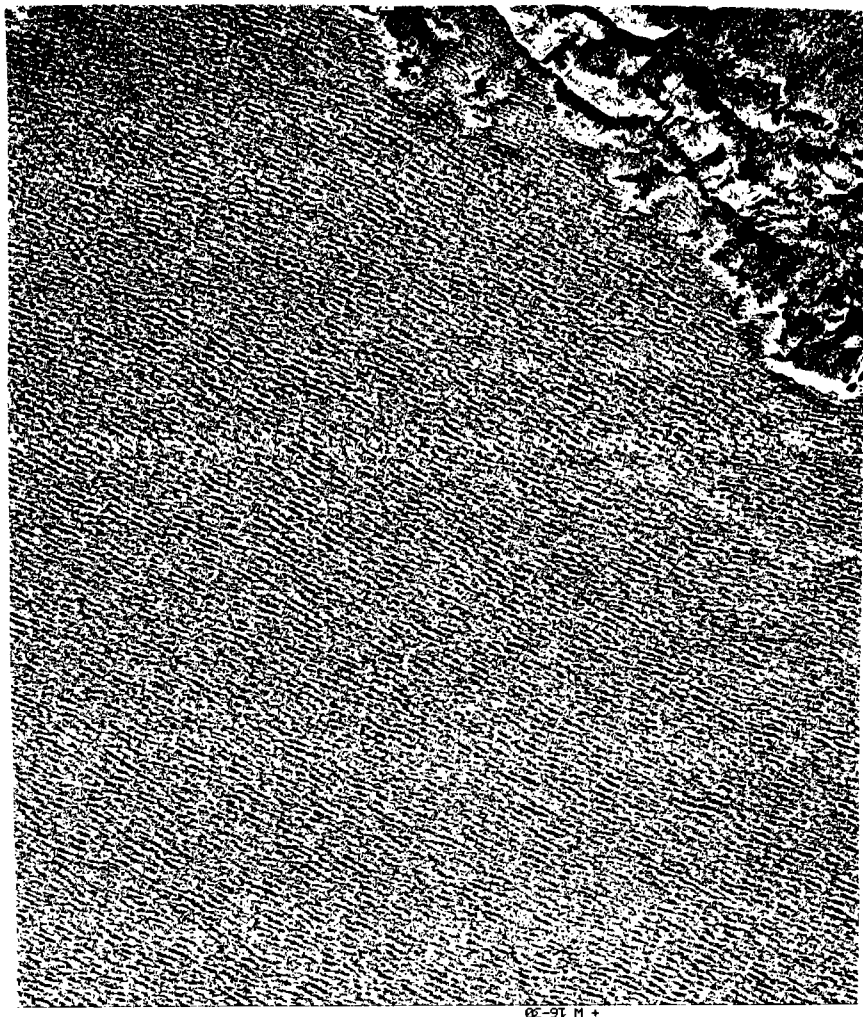


Figure 2.2 Swell waves imaged by SAR off the North Coast of Scotland

If a target moves during the time it remains in the SAR beam it will be incorrectly located on the image plane since the Doppler signal received at the satellite will have been shifted. In this way the speed of surface vessels can be estimated quite accurately by measuring the displacement from their wakes ($\Delta x = 130v_x$, where v_x is the component of speed in a direction parallel to the satellite's track).

If it is surface waves that are being imaged then some displacement of the position of the waves in the image may also take place - depending on the direction of propagation with respect to the satellite's viewing geometry, and suitable corrections must be applied.

On ERS-1 the SAR and scatterometer operate alternately (since they share the same electronics) but there are more ground stations in place than were operated for Seasat (16 at the time of writing) and coverage of all oceans (including the Antarctic) is now possible.

We have noted that the fine spatial resolution of SAR precludes on-board recording and data are normally beamed down to a convenient ground station. The ERS-1 SAR is operating a special 'wave mode' whereby 8 x 8 km 'snapshots' of the ocean surface are taken about every 200 km along the satellite's track. This amount of information can be stored on board and transmitted at an appropriate moment to a ground station. In this way useful global statistics on dominant wave directions and period are being accumulated.

A single orbiting satellite will be limited in the frequency with which it samples - and this may pose a problem for realtime operation especially where 'perishable' products such as winds and waves are concerned - but it will provide, nevertheless, a completely uniform coverage over every part of the global oceans enabling a reliable data bank to be created.

A detailed description of the measurement of wave height and wind speed from satellite radar altimeters is given by D Carter in Appendix A to this chapter.

2.3 SEA SURFACE TEMPERATURE

The ocean-atmosphere system is a heat engine powered by solar radiation. The average daily amount of incoming radiation decreases from the equator to the poles. Low latitudes receive relatively large amounts of radiation each year while winter darkness and the obliqueness of the sun's rays reduce the amount of radiation received at the higher latitudes.

The Earth also re-emits radiation from the sun at slightly longer wavelengths - most of which is absorbed by natural greenhouse gases in the atmosphere such as carbon dioxide, water vapour and cloud droplets. There is a net gain of radiation energy at low latitudes and a net loss at higher latitudes. But since there is no net gain of heat at low latitudes (or loss at higher latitudes) there must be a net transfer of heat to maintain a balance. This is brought about mainly through winds in the atmosphere and currents in the oceans.

In the tropics it is the oceans which contribute more to the poleward transfer of heat while the atmosphere contributes more at the higher latitudes. Across the equator the oceans provide the mechanism for a southward net transport from the northern to the southern hemisphere.

The two principal components of the ocean contribution are wind-driven surface currents and density-driven (thermohaline) deep circulation.

Of the total amount of energy received from the sun by the oceans about 41% is lost to the atmosphere as long-wave radiation and about 54% as latent heat by evaporation from the sea-surface. Temperature is a measure of the thermal energy possessed by the oceans and if the average temperature is to remain constant then the gains and losses must even out - that is, the heat budget must balance.

It is the role of the ocean in re-distributing heat by currents and mixing which ultimately will be one of the key factors in determining whether or not there will be a net warming over the globe due to a man-made increase in greenhouse gases.

Attempts to measure the oceanic heat transport directly by traditional observations have been less than successful in providing credible estimates. This is particularly true in the Southern Hemisphere where observations are so sparse that neither the magnitude nor even the direction of heat transport estimated directly agree with those inferred from the apparent global radiation budget.

What is urgently required are more accurate simultaneous measurements of the relevant atmospheric and oceanic parameters. In the atmosphere these are the temperature and wind profiles, while the most important ocean parameters are temperature and currents plus sea-ice coverage.

The capability to process and analyse large volumes of AVHRR data has become much more widespread and is no longer confined to large centres. Many individual research workers or small coastal management establishments operate AVHRR receivers and process their own data.

Patterns of surface temperature revealed by satellite have been used to study the flow of currents by following certain distinguishable features. Objective, maximum-correlation methods have been used successfully by a number of workers in the study of offshore current patterns. What is becoming increasingly common as more satellite ocean sensors come on line are studies linking temperature patterns to other parameters. Thus, major ocean phenomena such as El Nino is easily distinguishable as a temperature anomaly in the equatorial Pacific (Figure 2.3) but also provides a clear surface topography signal which was picked up by the Geosat altimeter.

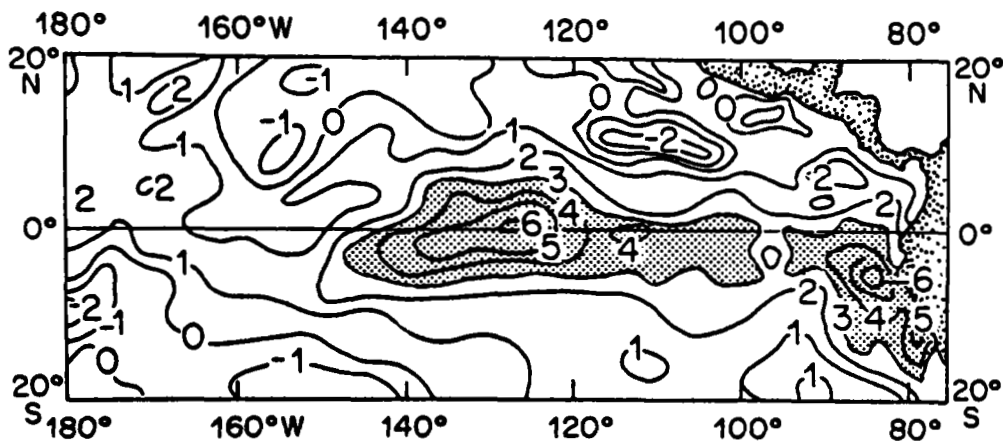


Figure 2.3 Anomalies of sea surface temperature in the eastern tropical Pacific at the 1982-83 maximum El Nino event

In a similar way sea surface temperature has been used to infer other variables in the upper ocean. Upwelling around the coasts of many tropical and sub-tropical countries carries a strong temperature signal which can be identified and studied from spaceborne infrared devices. By their very nature many such areas also exhibit a strong increase in phytoplankton as revealed in the record of the Coastal Zone Colour Scanner. Thus in some (but not all) areas sea surface temperature may be used as a useful tracer of nutrient concentrations.

Because of the longevity and general reliability of the AVHRR instrument several analyses have been carried out and published based on its record. In the monthly Gulf Stream bulletin, published by NOAA, AVHRR imagery is used to illustrate its meanders and the tracks of warm and cold rings. The French meteorological office publish regular charts of ocean fronts, internal wave trains and eddies in the Mediterranean Sea based on an interpretation of AVHRR.

The AVHRR has now been joined by the ATSR carried by ERS-1 and its successor ERS-2 is also scheduled to carry an ATSR (for Along Track Scanning Radiometer) which ensures that for several years to come more measurements will be made of SST than of any other ocean parameter.

2.4 OCEAN COLOUR

Measurements of ocean colour from space can provide quantitative maps of near-surface phytoplankton pigment concentration - as well as identifying pollutants spilled into the sea by effluent discharges. The Coastal Zone Colour Scanner launched in 1978 operated continuously for 7½ years producing a wealth of ocean data which has recently been processed to reveal for the first time cycles of phytoplankton blooms across the globe.

The spectral composition of the radiation above the sea (that is, its 'colour') is determined by the composition of solar irradiance plus the optical properties of the water column - in particular, the absorption, scattering, and to a lesser degree the fluorescence. The optical properties of the water column are, in turn, determined by those of pure sea water plus the concentrations of suspended and dissolved materials within its particulate organic matter (phytoplankton and its by-products), inorganic suspended particles, and dissolved organic decay products of mainly terrestrial origin ('yellow substance'). It is the unravelling of the disparate contributions to the signal which requires the development of processing algorithms that may differ from one ocean region to another.

An understanding of primary production and its role in the global carbon cycle is central to our ability to predict those processes responsible for the observed fluctuations. The only realistic approach to studying global patterns of temporal and spatial variability is by satellites. Only then can progress be made towards reaching an understanding of long-term trends.

However, in the shorter-term, fisheries research can be assisted enormously by a more precise knowledge of the elements in the food chain - larval recruitment, zooplankton production, and the patchiness of plankton. In this regard colour (and temperature) information derived from orbiting satellites is particularly useful in tropical and sub-tropical regions.

The requirement to monitor the spread of pollutants may be stronger in some areas than others. In closed or semi-enclosed seas such as the North Sea or Mediterranean the indiscriminate dumping of waste products into the sea has become a major source of concern and in many respects the ocean colour signal can be detected and traced from satellites. Colour imagery has also been successfully exploited in dynamical studies of the physics of shallow sea processes.

Upwelling

By considering the balance set up between frictional and Coriolis forces when the wind blows over the surface of the sea, the Swedish oceanographer Ekman deduced that the speed of the wind-driven current within the layers making up the water column would decrease exponentially with depth.

In the northern hemisphere the direction of movement of the resultant surface current is 45° in a clockwise direction (anti-clockwise in the southern hemisphere) from the wind direction. For the Ekman layer as a whole (that is, the depth over which friction is felt) the average motion is 90° to the direction of the wind. When the wind blows parallel to the coast the divergence of water away from the land leads to its replacement by upwelled sub-surface water and a lowering of sealevel towards the coast. As a result a geostrophic current is set up flowing at right angles to the pressure gradient - that is along the coast. The resultant water transport (wind-driven and geostrophic) therefore has an offshore component, and upwelling will continue as long as the wind blows.

This effect has been identified and clearly delineated by the CZCS in a number of upwelling areas; two of the most striking are the West Coast of Central and North Africa, and the Arabian Sea where the SW monsoon causes a strong upwelling of nutrient rich water in the late summer months (Figure 2.4).



May/June



September/October

Seasonal changes in chlorophyll concentration in the Indian Ocean. In the relatively calm period May-June there is little upwelling and phytoplankton is at a low level. Following the onset of the SW monsoon the wind-driven surface layer gives way to an upwelling of cold nutritious water reflected in the high concentrations of phytoplankton revealed by the CZCS imagery averaged over September/October.

Figure 2.4

Colour and temperature are usually related during the first stages of an upwelling event though the relationship becomes more complex during later developments when the surface water warms to match its surroundings while the chlorophyll content may remain comparatively high.

As we remarked in a previous section the processing of the CZCS record to extract information on chlorophyll concentrations has been a long and difficult task. Initially much of the analysis centred on local regions mostly around coasts where some independent 'in situ' observations had been taken. But as algorithms were developed, tested and applied to the substantial data set that had been acquired over the much extended life of the CZCS sensor, seasonal charts of chlorophyll concentrations at global scales were produced. The Goddard Space Flight Centre was particularly active in this work and has released a remarkably vivid set of charts which, notwithstanding the cloud cover that for much of the time hides many parts of the ocean from view, demonstrates for the first time the variations in productivity of the oceans across the globe.

As a replacement to the CZCS NASA plan to launch an enhanced colour sensor known as SeaWiFS (Sea-viewing Wide Field of view Sensor) which will have eight visible bands (centred at 412, 443, 490, 520, 565, 665, 765, and 865 nm). The channel selection will allow improved pigment retrieval in Case 2 waters (those with significant non-plankton materials) and improved atmospheric corrections.

A full treatment of the basic principles of ocean colour measurements is presented by S. Boxall in Appendix B to this chapter.

2.5 SAMPLING

A satellite moves in an elliptical path with the earth's centre at one of the foci. In a perfect polar orbit the spacecraft passes over both the north and south poles. In practice the plane of most polar-orbiting satellites is inclined. If i is the angle the orbital plane makes with the equator in an anti-clockwise direction then for $i < 90^\circ$ the orbit is referred to as prograde and its plane will precess to the west. Many polar orbits are planned to be sun-synchronous in which case $i > 90^\circ$, the orbit is referred to as retrograde, and precesses to the east. Expressions to describe the parameters of orbiting satellites are defined in Table 2.1.

Table 2.1

Expressions for orbital properties of satellites in terms of the earth's radius R (6378 km), the acceleration due to gravity at the earth's surface g (9.80 m/sec²) and the satellite's altitude H and inclination i .

Property	Expression	Value for H:		
		150km	800km	1500km
Satellite speed	$V = \sqrt{\frac{gR^2}{R+H}}$	7.81	7.45	7.11 km/sec
Satellite ground speed ⁺	$V_g = \frac{R}{R+H} V$	7.63	6.62	5.76 km/sec
Satellite period	$T = \frac{2\pi(R+H)^{3/2}}{R\sqrt{g}}$	1.28	1.41	1.56
Number of orbits/day	$N = \frac{24}{T}$	16.5	14.3	12.4
Separation of ascending tracks on equator	$D = \frac{2\pi R}{N}$	2434	2807	3227 km
Track separation if evenly distributed for M months	$\frac{D}{30.44 \times M}$	13.3	15.4	17.7 km in 6 months
Satellite precession rate [*]	$\Omega = -\frac{A \cos i}{(R+H)^{7/2}}$	3.14	2.26	1.63 °/day

* $A = 2.07 \times 10^{14}$ for $R+H$ in km and Ω in degrees/day.
Example values of Ω are for $i = 110^\circ$. Orbit is sun synchronous at a precession rate of 0.99° per day.

+ Velocity due to earth's rotation must be added to this.

The values selected for the height and inclination of an earth-observing satellite are normally the result of a compromise between a number of considerations chief of which are the following:

- Sampling period requested for the narrow swath sensors such as the radar altimeter. This must be set against density of spatial coverage as shown in Fig. 2.5
- Possible aliasing effects in the sampling (e.g. sun-synchronous orbits will cause the ocean tides to be aliased).
- Perturbations of the orbit due to uncertainties in the gravity field. The higher the satellite the less will be these effects.
- Available power of the sensors. For active radars the strength of the echo backscattered from the ocean and received at the sensor falls off to the 4th power of the distance.
- Position of the launch site. In the United States, for example, safety precautions demand that satellites in retrograde orbits be launched from the west coast out over the Pacific Ocean.

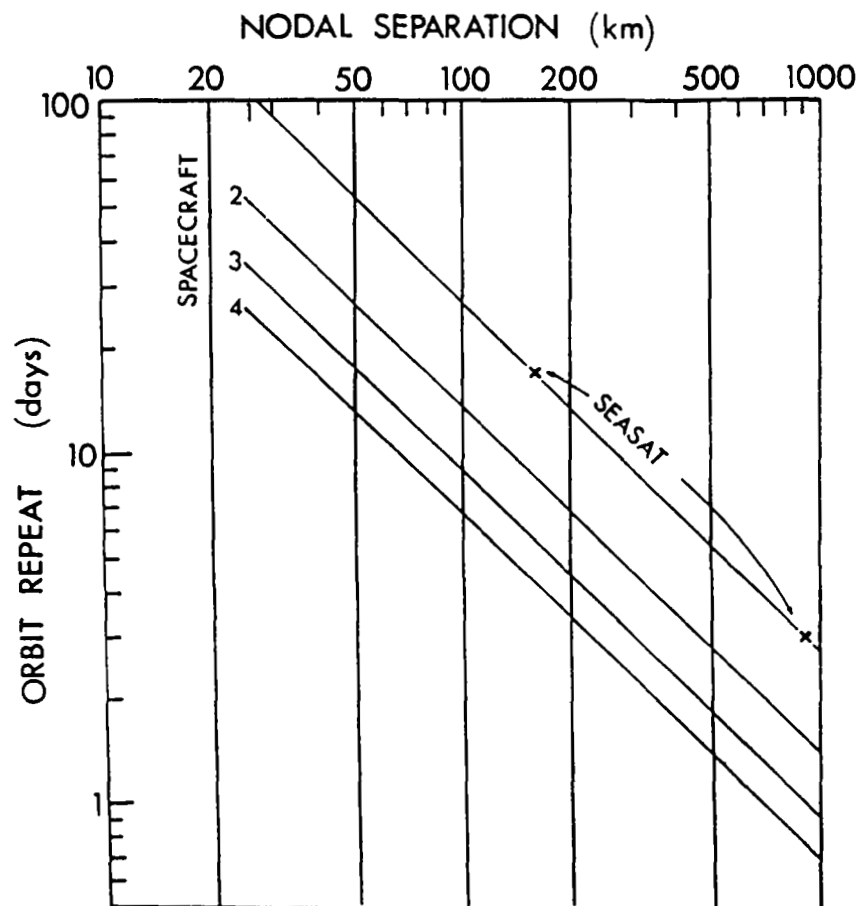


Figure 2.5 Plot of orbit repeat pattern in days v spacing between orbits at the equator for up to 4 satellites

Seasat operated at a height of 790 km and an inclination of 108° . For ERS-1 the values selected are $h = 770$ km and $i = 98^\circ$.

In such an orbit a satellite will complete about $14 \frac{1}{2}$ orbits per day; its ground pattern would repeat after 3 days with rev 44 lying over rev 1 and the distance between adjacent ground tracks would be 8.37° or about 930 km at the equator. The sub-orbital tracks of ERS-1 over 3 days is shown in Figure 2.6.

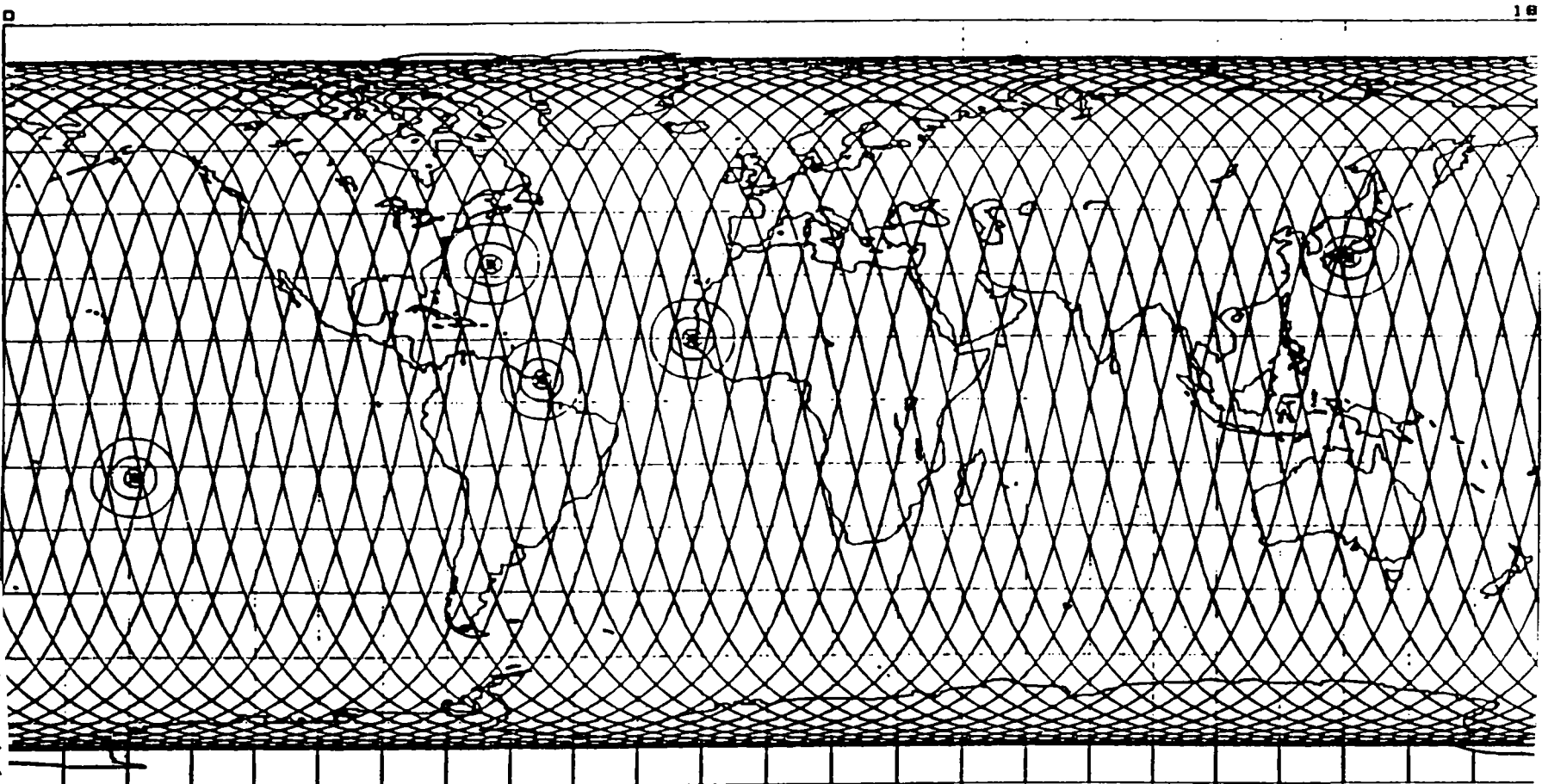


Figure 2.6 Sub-orbital tracks of ERS-1 over a 3-day period

As we have seen when discussing the use of satellite altimetry in measuring ocean surface currents the orbit of the satellite must be known with decimetre accuracy over global distances, and with centimetre precision over lesser distances - an accuracy and precision that are about an order of magnitude better than present capability.

Several forces combine to perturb the orbit of a satellite and the study of these may yield important information in their own right (e.g. the non-spherical shape of the earth's gravity field). It is usual to track the position of the satellite, calculate an orbital trajectory, and use this to predict past and future satellite positions. The orbital trajectory is re-evaluated each day, using the latest measurements of the satellite position, the frequency of the computation reflecting the accuracy with which the orbit must be known.

Satellite positions are measured by a number of different systems including radios which measure range and range rate, and lasers which measure the instantaneous range to satellites when skies are clear. The tracking stations can be fixed positions on Earth or on a higher satellite in an orbit less influenced by perturbations in the Earth's gravity field and atmosphere. Unfortunately the PRARE system on ERS-1, dedicated to precise tracking of the satellite, failed to operate.

The accuracy of tracking systems has improved dramatically during the past two decades. The latest generation of lasers can estimate ranges to better than 5 cm and the comparatively new Global Positioning System (GPS), using a constellation of 18 satellites in relatively high, precisely-known orbit, provides continuous determinations of a satellite's position to sub-metre, and normally sub-decimetre, precision.

It should be noted, of course, that for some applications of satellite remote sensing, precise orbit determination is not required to the same level as altimetry for ocean currents. Measurements of winds and waves do not require accurate orbit information, nor visible and infra-red observations.

Wave height and wind speed from satellite radar altimeters

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1 Introduction

The largest forces on any on offshore or coastal structure, from ships to offshore rigs to coastal defences, generally result from surface waves, which can cause destruction and devastation, in association with forces from winds, currents and sea level surges. Ships - even 100 000 ton carriers - routinely disappear in storms; offshore structures have been severely damaged (although very few have been destroyed: they have been designed to withstand the 50-year or 100-year storm, with considerable safety margins to allow for our ignorance of such storms and of the forces they impose upon complex structures); and millions of pounds of damage have been inflicted upon breakwaters in recent years. So a knowledge of ocean waves is essential for any activity connected with the seas.

Forecasts of wave conditions are required for operational planning, both at specified locations and across oceans for ship routeing. Estimates of wave climate, such as monthly average wave height or of the 50-year wave height, are needed for design purposes.

Forecasts are prepared using numerical wave models with forecast winds as input and using the physics of wave growth, transmission and decay developed in recent years, but forecasts are considerably improved if the models are initiated and updated with observations of wave height and period.

Our knowledge of wave climate is almost entirely based upon observations of waves, it is essentially a statistical exercise with very little physical input; so it is very dependent upon the quantity and quality of wave data. The difficulty of measuring ocean waves and the poor quality of visual estimates mean that we have a poor knowledge of wave climate, particularly in the southern hemisphere and of extreme conditions almost everywhere. Even in the NE Atlantic, a complete understanding of average conditions is lacking. The annual mean wave height here has shown an upward trend over the past thirty years, with very large variability from one year to the next. The reasons for this trend or for the inter-annual variability are not known. (Carter & Draper, 1988; Bacon & Carter, 1991; Barratt, 1991.)

A fundamental problem in studying ocean waves has been the difficulty of obtaining spatial data. Conventional instruments, such as the Waverider buoy, give a time series of surface elevation at a fixed point on the sea surface which provides temporal statistics, but does not answer the basic question of the area over which the results are valid. Measurements of waves from orbiting satellites provide data to answer this question on a global scale; and it is this provision of global data and consequently, hopefully, our increased understanding of spatial scales and interactions which will be the greatest benefit of satellite wave data. (Carter, Challenor & Srokosz, 1988)

This paper considers the estimates of ocean waves and of associated wind speeds which can be obtained from satellite radar altimeters. It briefly describes how the radar obtains these estimates and the spatial and temporal coverage they provide. The accuracy of individual estimates of wave height and wind speed and of the monthly mean values derived from them are discussed, using comparisons of results from one satellite: Geosat.

It then uses the estimates of monthly mean wave heights and wind speeds obtained from Geosat from 1985 to 1989 to illustrate the use of such data in studying global wave climate and its relationship to the wind climate.

2. Significant wave height and wind speed from the radar altimeter.

2.1 Definition of significant wave height and periods

Significant wave height, H_s , is a measure of the general sea state, an 'average' value of a prevailing wave height. It was originally defined, about fifty years ago when only visual observations could be obtained, as the mean height of the one-third highest waves, and was thought to give about the same value as an experienced seaman's estimate. With the development of instruments giving time series of sea surface elevation η , H_s was redefined in terms of the variance of the elevation as:

$$H_s = 4 \sqrt{\langle \eta^2 \rangle}$$

where $\langle \eta^2 \rangle$ is the surface variance. The '4' was introduced so that, for a narrow-band sea, the old and new definitions have the same value. It is sometimes expressed in terms of the spectrum of the time series:

$$H_s = 4 \sqrt{m_0} \quad (2.1)$$

where m_n is the n^{th} moment of the variance spectrum $S(f)$ in terms of the frequency f , given by

$$m_n = \int f^n S(f) df$$

Note that m_0 (or $\langle \eta^2 \rangle$) can be measured either over an area of the sea surface at any instant or over a period of time at a single position. Assuming stationarity in both space and time over the area and period of measurement, then the spatial and temporal definitions of m_0 are numerically identical. So this definition of H_s is equally applicable to the radar altimeter which takes a 'snap-shot' of the sea surface over several km^2 .

Wave periods can also be defined in terms of the spectral moments. See, for example, Tucker (1991). The average zero-upcross period, T_z , and the average period between successive crests, T_c , are given respectively by:

$$T_z = \sqrt{\{m_0/m_2\}} \quad (2.2)$$

and

$$T_c = \sqrt{\{m_2/m_4\}} \quad (2.3)$$

2.2 Various ways of measuring waves

It is very difficult to measure the height of ocean waves. Only during the past 40 years have instruments been developed which will measure them in deep water. Instruments have improved over the years since the deployment of the original experimental Shipborne Wave Recorder (SBWR) in the 1950's which gave only analogue estimates of sea surface elevation from a stationary or near-stationary ship. (Tucker, 1956). We can now regularly obtain digital data from improved SBWR's, from Waverider buoys and similar instruments from many sites around the world; although these sites are mainly quite close to the shore, with the notable exception of the network maintained by the NOAA's National Data Buoy Center. All of these measure vertical movement from which the variance spectrum $S(f)$, and hence H_s and T_z can be calculated; none of them gives satisfactory estimates of T_c because they do not measure sufficiently far into the high frequency tail of the spectrum to determine m_4 . Generally an accelerometer is used to measure the vertical movement, but a downward-looking laser has

been tried, and in shallow water a pressure sensor on the sea bed is sometimes employed. (The SBWR uses accelerometers and pressure sensors.)

Buoys which give some information on the direction in which components of the wave energy are travelling (that is, estimates of the directional spectrum $S(f, \theta)$), have been developed and operated routinely in recent years; but they are expensive to build and to maintain, and satisfactory routine analysis of the large quantities of data generated has proved difficult to run in near-real time.

Research has been carried out over several years into the development of a land-based HF radar to measure waves, using Bragg scattering. The Doppler shift in the return gives a good estimate of near-sea surface current towards the radar, and a system (OSCR: Ocean Surface Current Radar) with two radars is now used commercially to map current velocity within about 30 km of the shore. Extraction of wave information, which depends on second-order mechanisms, has proved more difficult; but recent research, also using two radars, has shown that directional wave spectral information can be retrieved (Wyatt, 1991). However, using sky wave returns to extend the range of the HF radar has not been successful.

A few attempts have been made to measure waves using stereo-photography. For example by Holthuijsen, 1983. It has proved difficult to obtain sufficiently well-synchronised photographs to eliminate the movement of the waves, but the major problem has been that of analysing the stereo-pairs, aligning the many hundreds of pairs to give the required detail. However, recent work to program automatic computer processing, for example in a joint venture by the James Rennell Centre of IOSDL and University College of London University, is looking hopeful. The unique advantage of stereo-photography is that it would provide data into the high frequency (or short wave length) end of the spectrum which is 'seen' by radar and will give useful independent estimates of m_4 .

Research into new methods of measuring waves using radar from aircraft and from satellites is continuing. For example a conically-scanning altimeter 'ROWS: Radar Ocean Wave Spectrometer (Jackson et al 1985); and a microwave Doppler radar for measuring wave spectra has recently been flown on an aircraft (Plant et al. 1987). However, the only two instruments currently in use to measure waves from satellites are the vertically mounted radar altimeter and the SAR: Synthetic Aperture Radar, both of which are operating from ERS-1, launched in July 1991. The latter gives some directional information but extracting it from the radar returns is a highly complex process because the synthetic aperture assumes that the surface which it is imaging is static and is inextricably confused by the movement of the sea surface. There is also the problem of handling 10^8 bits per second. However, further discussion of SAR is covered elsewhere; the remainder of this paper is devoted to the radar altimeter.

The 'proof of concept' of a satellite radar altimeter was established by an instrument carried on SKYLAB in 1973. Seasat, which was only operational for three months in 1978, was the first satellite with an altimeter to give global coverage, from 72°S to 72°N. (It also carried a SAR.) An earlier satellite, GEOS-3, carried an altimeter but it could not store the data on board so did not provide global coverage.

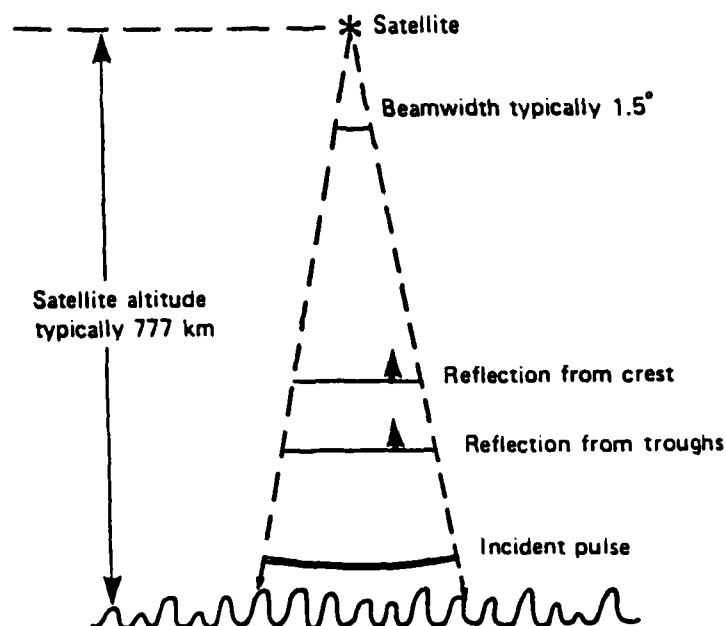
It was not until March 1985 that another satellite carrying an altimeter was launched: the US Navy's Geosat - with the same inclination as Seasat. As indicated by its name (GEOdetic SATellite), the satellite's primary purpose was to measure the marine gravity field with high precision. Because of the value of this information to the military, the first 18 months of observations were classified; but some data including wave height values have recently been released. The classified geodetic mission ended in September 1986, and during October the satellite's orbit was altered, placing it into a 17-day repeat pattern. The Geosat exact repeat mission started on 8 November 1976 and continued until the satellite failed in January 1990; but it began to malfunction early in 1989, and there was a significant decline in global coverage from about March 1989.

Thus Geosat has provided, for the first time, several years of near-global coverage of wave data. This unique data set has given us the opportunity to carry out long term validation of the altimeter data and provides a useful foundation for a global climatology and for investigations of climate variability.

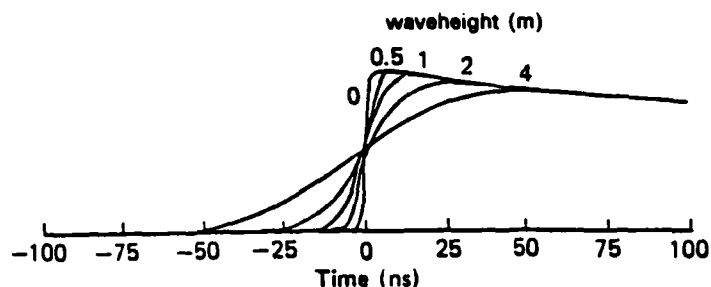
2.3 Estimating H_s from the radar altimeter

The slope of the leading edge of the return pulse from the downward-looking satellite's altimeter provides an estimate of the sea surface variance, $\langle \eta^2 \rangle$, and hence of significant wave height H_s ($4\sqrt{\langle \eta^2 \rangle}$). Essentially, the higher the waves over the footprint of the radar pulse (which is about 5-10 km in diameter, depending on the roughness of the sea), the more spread-out the time of arrival of the return pulse, whilst the 'height' of the return pulse is kept constant by the application of automatic gain control (AGC). The radar cross-section σ_0 (the strength of the vertical altimeter transmission) is obtained from the AGC value. See Fig.2.1, from Tucker (1991). Incidentally, it may be shown that σ_0 is related to the variance of the sea surface slope, and hence to the fourth spectral moment, m_4 - or more strictly to its spatial equivalent.

Fig.2.1 Estimating H_s from the shape of the return pulse from a vertical radar (from Tucker, 1991)



The satellite-borne precision altimeter used for measuring waveheight. The rise time of the reflected pulse is smeared by the different ranges to reflecting facets.



Precision altimeter: The average shape of the leading edge of the returned pulse for various waveheights.

The shape of the return pulse from a near-nadir radar is determined by specular reflection and depends upon the statistics of the reflecting surface. The physics of the process are well-understood. The shape of the leading edge is given, for example, by Lipa and Barrick (1981). The satellite processor assumes that the sea surface statistics are linear - and Gaussian, but even if assumed to be slightly non-linear then it makes very little difference to the estimate of H_s . See Srokosz 1986 and 1990 for a discussion of the non-linear effects. (The theory does not account for highly non-linear behaviour, such as breaking waves.) So the derivation of H_s is based upon sound physical principle, no empirical factor are involved, and estimates of H_s from satellite altimeters are widely considered to be satisfactory. However, there is some evidence that errors can be introduced by the data processing, and for example Geosat appears to have under-estimated H_s by about 13%. See Section 4 below.

The only problem expected from the theory is that individual returns from the sea surface are severely contaminated by noise. To reduce the effect of this, the pulses, which are transmitted at 1000 or 2000 Hz, are averaged to give one estimate of H_s each 0.1 s, and ten of these 0.1 s values are averaged again to give the 1 s values which are distributed as the Geophysical Data Records - either by NOAA or ESA. The satellites, in orbits with periods close to 90 minutes, travel at such a speed that the radar 'footprint' moves over the ocean at about 7 kilometres a second.

The standard deviation of the ten 0.1 Hz values comprising each 1 s value is also given in the the Geophysical Data Record, and provides a useful check on the validity of the H_s value.

2.4 Precision of estimates of H_s

The standard deviation (sd) of the ten 0.1 Hz values also provide a check on the precision of the estimates of H_s from the altimeter. An inspection of the Geosat data from the open North Atlantic indicates values of sd from less than 0.1 m for low H_s , rising to about 0.1 when H_s is 2.5 m and to about 0.2 when it is around 6 - 7 m. Now, the standard error in the estimate of the mean of N independent values is given by $sd/\sqrt{N}$. Successive 1 s (i.e. 7 km) estimates of H_s are not independent, but the auto-correlation structure suggests that the correlation falls off very rapidly, and that once any large scale correlation is removed, then there appears to be generally insignificant partial correlation between one value and that 2 s later (partial correlation removes the effect of the correlation with that 1 second ago which is correlated with that 2 seconds ago). So a rough measure of the standard error of the 1 s mean from 10 values is $sd/\sqrt{5}$. This would indicate a standard error in the Geosat altimeter 1 s estimates of roughly 1% - 2% of H_s .

However precision is only a measure of repeatability of the instrument (limited by noise and by sampling variability) and is not the same as absolute accuracy.

2.5 The accuracy of Significant Wave Heights from Geosat

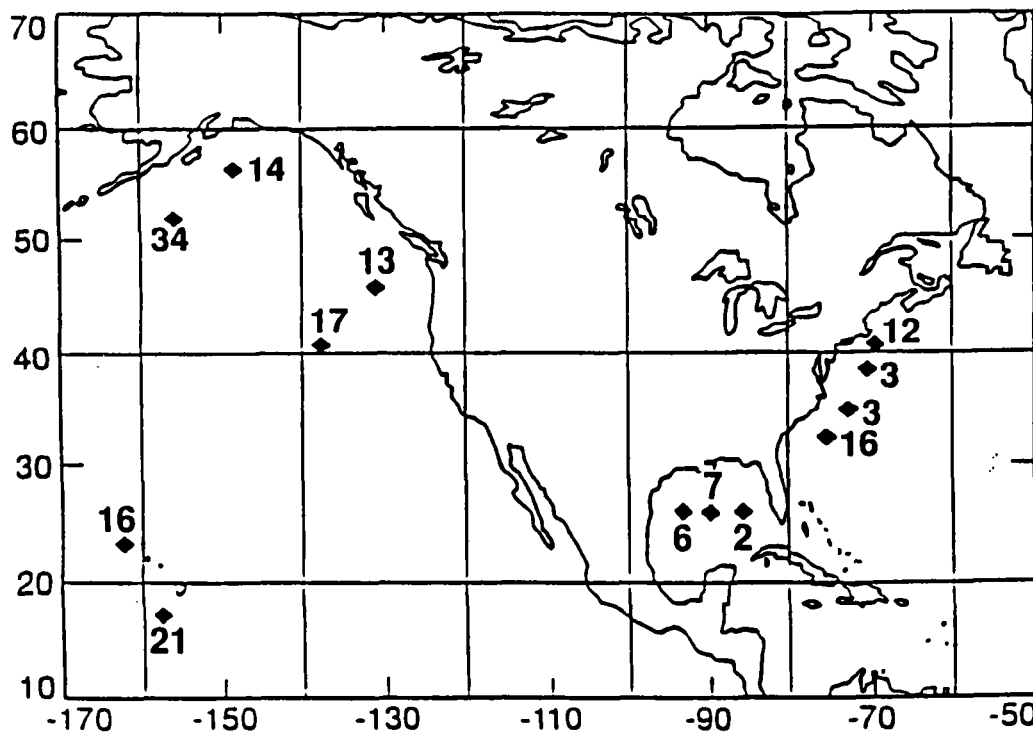
2.5.1 Comparisons with buoy data

The accuracy originally specified for Geosat's estimates of significant wave height, H_s , was the same as that for ERS-1: 0.5 m rms or 10% of H_s , whichever is higher. Dobson, et al., (1987) validated Geosat's estimates of H_s against values from buoys in NOAA's National Data Buoy Center network and concluded that the altimeter was performing within its measurement goal, but that on average the Geosat estimate was lower than the buoy's value by 0.4 m. Glazman and Pilorz (1990) report a similar bias of 0.4 m from a comparison of a larger set of buoy data and Geosat data from the exact repeat mission.

This larger data set of co-located buoy and Geosat measurements was recently established by Dr R E Glazman, who kindly provided us with a copy. The data set is fully described in Glazman & Pilorz (1990). Geosat parameter values, obtained between December 1986 and

November 1987, were extracted when the satellite's footprint was within a 1° box of 20 buoys of the US National Data Buoy Center of NOAA, and when the time difference between the satellite pass and the buoy measurements was less than one hour. Glazman and Pilorz derived a sub-set of these data by averaging the Geosat values obtained within $1/4^\circ$ of the buoy, and a detailed analysis of this subset which contains data from the vicinity of 13 buoys is reported by Carter, Srokosz & Challenor (in press). Fig. 2.2 (taken from that paper) shows the position of the buoys and number of records from each of them.

Fig.2.2 Position of The NOAA buoys used in the comparison of buoy and Geosat wave measurements. The number of observations are shown alongside.



A linear regression through the origin of the buoy H_s against the Geosat altimeter H_s gives

$$H_s \text{ buoy} = 1.1300 H_s \text{ alt}$$

where the standard error of the slope is 0.0067

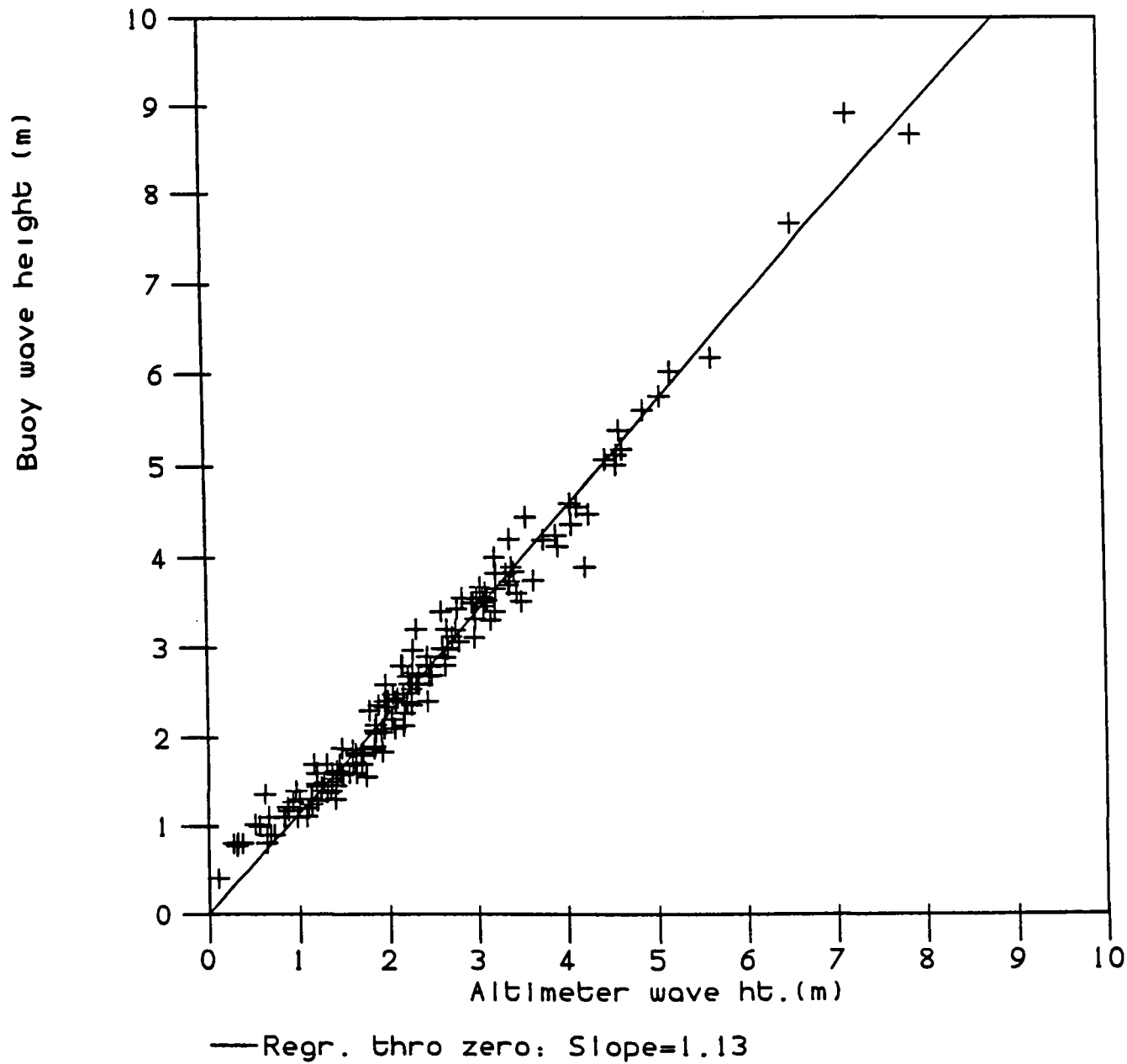
(The reduction in deviance from including a intercept in the regression was insignificant.)

The results of this analysis indicate that the buoy H_s values are on average about 13% greater than those estimated from the Geosat altimeter. A comparable figure seems to have been found in a preliminary comparison of US buoy data and Geosat geodetic mission altimeter values by Shuhy et al., (1987), as indicated in their Fig.6. However, they merely concluded that 'Overall agreement between GEOSAT and ground-truth data was excellent'.

Hayne and Hancock (1990) investigate the accuracy of the procedure used on board Geosat to derive H_s values - which are the values used in this paper - They compare the on-board values with those obtained by them using an improved waveform fitting procedure, and derive an empirical correction factor which is a third-order expression in H_s and mispointing angle. Table 2.1 gives the value of their factor for various values of uncorrected H_s and mispointing angle. Applying this correction factor to the Glazman and Pilorz Geosat H_s values, and

comparing the corrected values with the buoy data, Carter et al (in press) find that the excess of the buoy data over the Geosat values is reduced by about half, from 13% to 6%.

Fig.2.3 Comparison of NOAA buoy and Geosat altimeter estimates of significant wave height, with values from the data set of Glazman & Pilorz (1990).



2.5.2 A comparison with Seasat H_S

One way of checking the apparent 13% discrepancy with Geosat H_S values would seem to be to compare the average values from Geosat for the period 7 July to 10 October with those from Seasat for the same period published by Chelton, et al. (1981)*. Carter et al (in press) compare values of Geosat, averaged over $2^\circ \times 2^\circ$ bins, and find that the Seasat estimates are considerably higher, by about 0.4 m on average.

Increasing the Geosat H_S data by 13% to bring them into line with the NOAA buoy data, gives considerably better agreement between Geosat and Seasat, particularly in the North Atlantic and North Pacific, but these modified Geosat values remain lower than Seasat in large areas of the Southern Ocean and in the North Indian Ocean. However, there are two problems with the Seasat data : (i) there is some doubt concerning the accuracy of the Seasat H_S ; and (ii) the Seasat sampling in $2^\circ \times 2^\circ$ bins was not uniform throughout the period of its operation; during the latter part of its life Seasat was in a 3-day repeat orbit so did not cross some $2^\circ \times 2^\circ$ bins. See Carter et al (in press) for further details.

Finally, as noted above, this comparison between Seasat and Geosat assumes that there was not a global change in H_S of 13% from 1978 to 1987-88. It would have been extremely useful, for studies of climate change, to have been able to use data from the two satellites to investigate this assumption and to determine changes in H_S over various parts of the world. Clearly such an investigation is impossible unless the considerable doubts concerning the precise accuracy of both data sets can be resolved.

2.5.3 Comparison of Geosat and ERS-1 H_S with values from wave models

One way of investigating possible bias in altimeter estimates of H_S is to compare these estimates with values from wave models. Carter et al (in press) discuss a few attempts to check H_S values from Geosat by this method, including by Mognard & Magnusson (1988) and Romeiser (1990); but the results are inconclusive because of uncertainties concerning the accuracy of the models. However, models are known to be more accurate in some parts of the world such as the N Atlantic than in others such as the Southern Ocean (where there tend to be large errors in the estimates of the driving winds) whilst we would not expect the altimeter's accuracy to be a function of location (away from the ice edge - see below); so careful comparisons of the two data sets should contain useful information about short-comings in both the model and the altimeter.

Moreover, any large error in the altimeter should be revealed by the wave models. When ERS-1 was first launched in July 1991, there was some concern, based upon calibrations before launch, that H_S values might be too low by 20% (pers. comm. Dr R Francis). Comparisons of early data from ERS-1 with results from the third generation wave model run by the ECMWF show good agreement without this factor, and provide strong evidence that it is unnecessary.

* This assumes that the average value of H_S for July to October has not changed by 13% in 10 years - even though Bacon & Carter (1991) found a change of 28% over 25 years in the annual mean value of H_S in measurements from the Seven Stones Light Vessel, off Cornwall.

2.6 Spatial coverage of altimeter data.

As explained above, the satellite altimeter gives estimates of H_s (and of wind speed discussed later) every second, which corresponds to every 7 km along its track. Fig.2.4 illustrates some values obtained in the SW Approaches to the English Channel from 17 days of Geosat records. Clearly there is very good coverage along-track, revealing the finer structure of the distribution of H_s with a decrease in values as the track passes into the sheltered area East of the Isles of Scilly. But there are considerable distances with no data between the tracks. Moreover the time between the tracks may be several days. The distance between the tracks depends upon the satellite's orbit. If it is in an N-day repeat, then the distance between crossings of the equator is approximately $2700/N$ km, but with the tracks converging with latitude. So there is a 'trade-off' between spatial and temporal coverage. For example if $N=17$, then up-crossings of the equator are about 170 km apart, so a $2^\circ \times 2^\circ$ bin will probably have only 6-8 transects (combined 'up' and 'down') in a month, and might have fewer. If $N=3$ - which will be the case for ERS-1 for some months - a $2^\circ \times 2^\circ$ bin might have no transect through it. Fig.2.5 shows the ground track of ERS-1 in its 3-day repeat orbit planned for January-March 1992.

Fig.2.4 Geosat estimates of H_s (m) at 1 second (7 km) intervals, during 17 days.

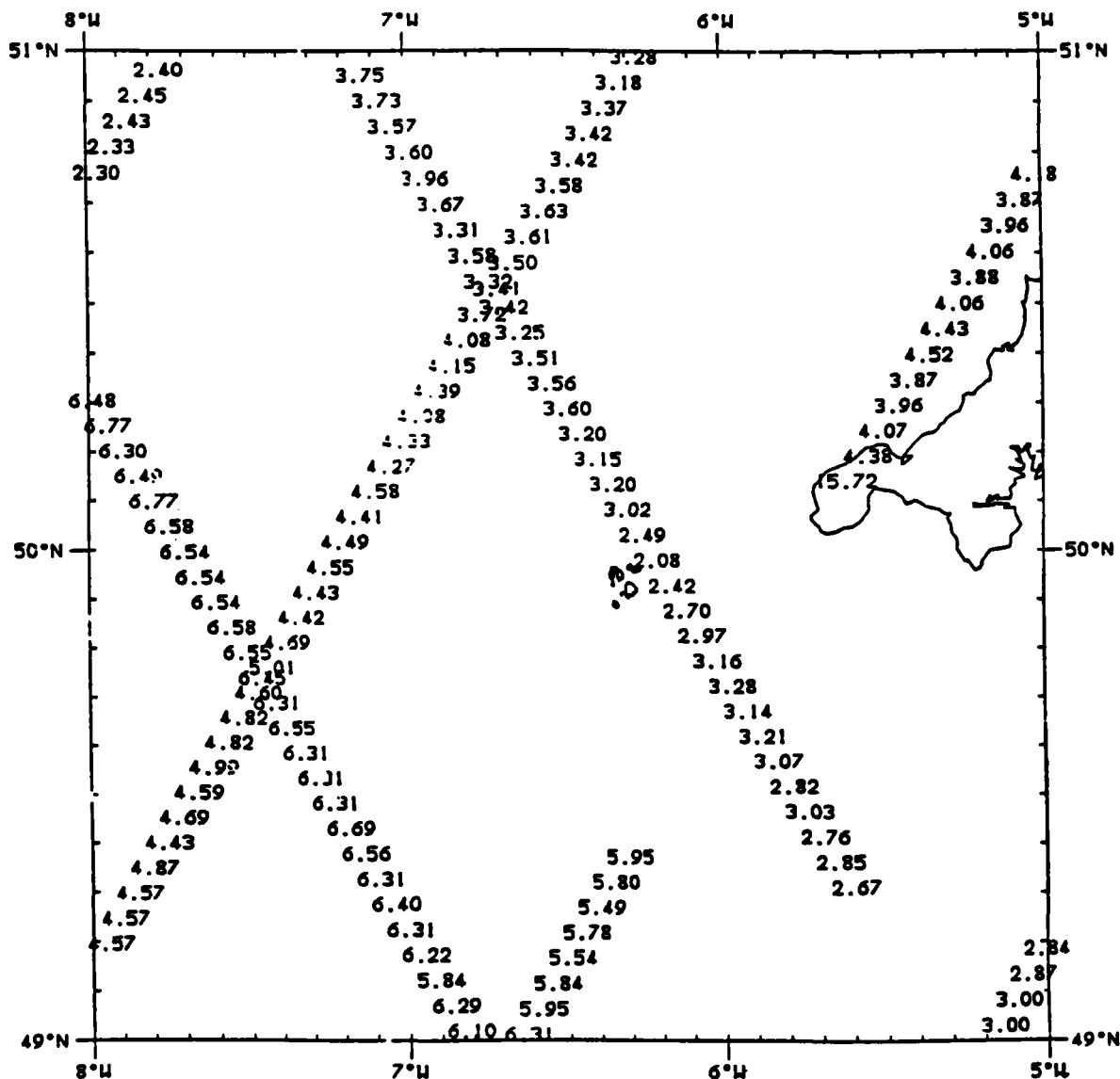


Fig.2.6 shows the proposed coverage for Topex/Poseidon in its 10-day repeat pattern.

Clearly the temporal or spatial coverage of a single altimeter provide insufficient data to analyse by themselves on a synoptic scale. For example, the satellite might miss a storm completely, at best it might get one or two 'slices' across it. So, at least until there are several satellites in orbit, for any detailed synoptic analysis, the data need to be used with other observations or incorporated into wave models; and for example the UK Meteorological Office is planning to use ERS-1 data in this way. (Francis & Stratton, 1990).

However, if only a very broad global view is required then this can be obtained from a few days of altimeter data - after-all, one altimeter produces as many estimates of H_s in a single day as a Waverider, making 3-hourly estimates, does in twenty years.

Fig.2.5 Planned ERS-1 3-day repeat tracks in UK waters.

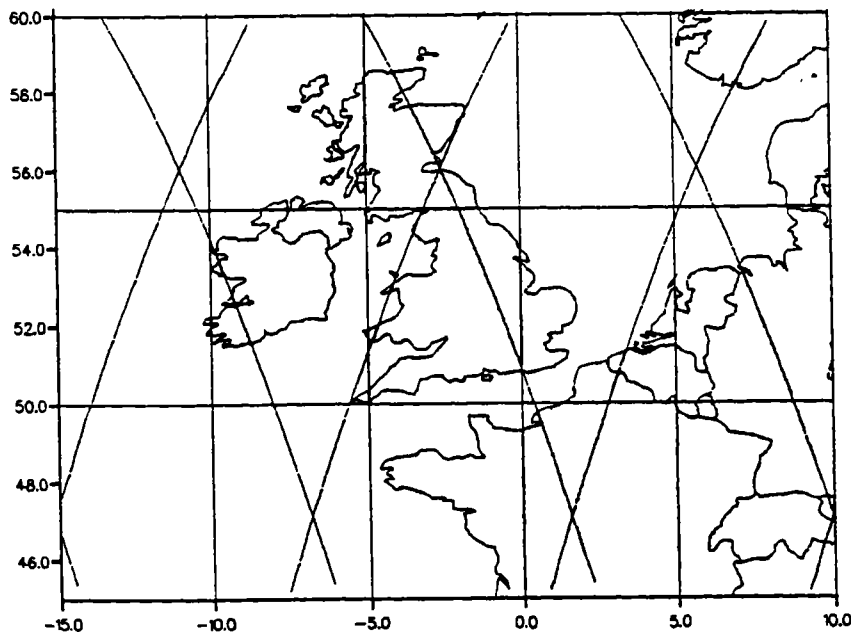
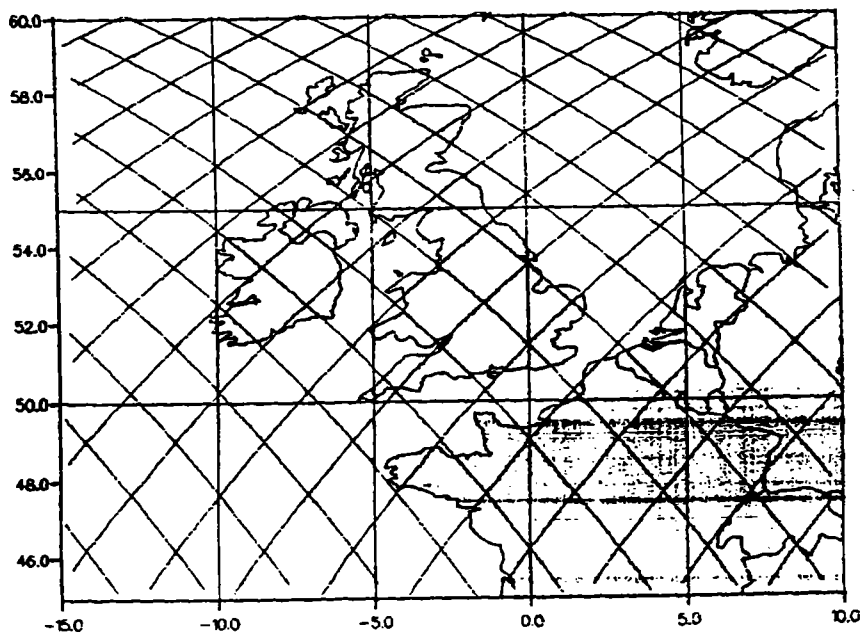


Fig.2.6 Planned Topex/Poseidon 10-day repeat tracks in UK waters.



2.7 Estimates of other wave parameters from the altimeter

The radar altimeter is processed to give two values each second, which are usually transformed into H_s (from the shape of the return) and wind speed (from the strength of the return). The latter is discussed in detail below. But what other wave data can be derived from these two values?

2.7.1 Wave energy

The most obvious is wave energy, since this is proportional to H_s^2 . In fact:

$$\text{Energy density} = \rho g m_0 = 630 H_s^2 \text{ joule/m}^2$$

where H_s is in metres. And the total energy in a $2^\circ \times 2^\circ$ bin is approximately:

$$\text{Energy} = 3.1 \cdot 10^{13} H_s^2 \cos \phi \text{ joule}$$

where ϕ is latitude.

So by calculating the global average value of H_s^2 from satellite data, we can get an estimate of the average wave energy. It works out, from Geosat (but increasing H_s by 13%), as approximately 5000 joule/m²; or a total global energy of $1.8 \cdot 10^{18}$ joule.

2.7.2 Wave power

To get estimates of wave power, we need an estimate of wave period (power is proportional to H^2T). We cannot obtain any of the usual definitions of period, but as Challenor has pointed out, (see Challenor & Srokosz, 1991), since H_s is related to m_0 and the strength of the return is related through the variance of the sea surface slope to m_4 , it is possible to obtain a wave period - or at least a value with the dimension of time - as:

$$T_{alt} = \{m_0/m_4\}^{0.25}$$

Note that, from equations 2.2 and 2.3, this is the geometric mean of T_z and T_c . Whether this wave period is of any practical use, either on its own or as an aid to estimate wave power is a matter for further research, which will depend partly upon being able to validate altimeter estimates of m_4 using stereo-photography.

2.7.3 Extreme wave height

Estimates of extreme waves, such as the 100-year return value of H_s , are required for the design of offshore structure, and are usually estimated from long series of site measurements, or calculated from estimates of the 100-year return value of wind speed. Using satellite data raises difficulties because of the wide spatial and limited temporal coverage; but Tournadre & Ezraty (1990) have investigated the problem using two years of Geosat data, and obtained reasonable estimates, compare with site estimates, for the northern North Sea. (Similar estimates of extreme wind speed were less successful.)

3 Estimating wind speed from altimeter radar

3.1 Introduction

Numerous attempts have been made during the past twenty years to relate the radar cross-section σ_0 (the strength of the return of the near-nadir altimeter transmission) to the wind speed near the sea surface. Physical arguments and comparisons between measurements of σ_0 from various satellites and wind speeds from buoys have both been used to develop algorithms. The first algorithm developed for use with satellite data was derived from GEOS-3 data by Brown et al. (1981). Goldhirsh and Dobson (1985) fitted a curve to the Brown algorithm to produce the widely-used smoothed-Brown algorithm, including often with Geosat data; for example by John Hopkins APL in the preparation of maps giving ten-day mean wind speeds of the central Pacific Ocean published in Climate Diagnostic Bulletin of the Climate Analysis Center.

A review of algorithm development and a description of various difficulties encountered are given by Chelton and McCabe (1985), who include a new algorithm which they obtained by comparing Seasat altimeter σ_0 values and scatterometer wind speeds. A slightly later paper by Guymer et al. (1985) also reviews the subject.

However, none of these algorithms appears to me to work satisfactorily with Geosat data. Carter et al (in press) obtain a simple two-stick fit of Geosat σ_0 to some NOAA buoy wind speeds, and produce another algorithm; but this raises problems because of the sharp change in slope at the junction of the sticks. Yet another recent algorithm, proposed by Witter & Chelton (1990), shows good agreement with the two-stick fit, except at low wind speed. (Witter & Chelton derived their relationship between Geosat σ_0 and wind speed using a completely different approach from Carter et al.. They start from the relationship between σ_0 and wind speed derived for Seasat by Chelton & Wentz (1986), then relate Geosat σ_0 to Seasat σ_0 by taking averages over large areas of the Southern Ocean and assume no climatic change in these averages.) Their algorithm - or rather a polynomial fitted to values tabulated by Witter & Chelton - is suggested by Carter et al. for use with Geosat data.

This fit is being used by ESA to generate fast delivery wind speeds from ERS-1 data, and preliminary validation results suggest it gives reasonable results, but few data particularly with high wind speed are yet available for comparison.

Figs 3.1 and 3.2, both taken from Carter et al (in press) show the two-stick fit to the Geosat σ_0 and buoy wind speeds, and some algorithms including the two-stick fit and the Witter & Chelton tabulated values.

The equations for the two-stick fit are:

$$u = \begin{cases} 44.73 - 3.424 \sigma_0 & \sigma_0 < 12.2 \\ 5.773 - 0.228 \sigma_0 & 25.3 > \sigma_0 > 12.2 \end{cases} \quad (3.1)$$

The value of u at $\sigma_0 = 12.2$ is 2.97 ms^{-1} . The rms deviation from this regression was 1.46 ms^{-1} .

The upper limit of 25.3 on σ_0 is included to prevent negative wind speeds. In practice, values of $\sigma_0 > 20.0$ are regarded as suspect, possibly due to sea ice, but there is some evidence that higher values might be obtained from glassy seas, with very light winds (see section 4.5).

The polynomial fit to Witter & Chelton is given in the following FORTRAN function:

```

      FUNCTION U10WCF(SS)
      *****
C
C
C TWO FIFTH ORDER POLYNOMIAL FIT TO WITTER & CHELTON (1990)
C WIND SPEED / SIGMA-0 (SS) TABLES.
C OBTAINED BY D J T Carter, 1991 USING
C DATA A UP TO SIGMA=14.0
C DATA B FROM SIGMA=14.6
C SUBROUTINE CHANGES CURVES AT 14.1
C BOTH GIVE THE SAME ANSWER AT SIGMA=14.1 (U10= 1.319, 1.315)
C
C IF SIGMA GT THAN ABOUT 19.5 THEN U<0.  FUNCTION RETURNS 0.
C
C IF SIGMA LT ABOUT 6 THEN U INCREASES RAPIDLY, BUT FUNCTION
C GIVES REASONABLE VALUES TILL ABOUT 5. HOWEVER,
C FOR SIGMA<7 A LINEAR RELATIONSHIP IS USED, (AS RECOMMENDED BY W&C)
C EXTRAPOLATING FROM FORMULA VALUE AT SIGMA=7 DB WHERE SLOPE=-3.120
C AND VALUE=20.1936
C I.E.      U(SS) = 42.03-3.12*SS
C
      DATA A0,A1,A2,A3,A4,A5/438.50,-215.82,44.578,-4.5509,0.22583,
&          -4.3522E-3/
      DATA B0,B1,B2,B3,B4,B5/1517.85,-437.88,50.509,-2.9084,8.3565E-2,
&          -9.5849E-4/
C
C
      IF(SS.LE.14.1) THEN
C
      IF(SS.LT.7.0) THEN
        U10=42.03-3.12*SS
      ELSE
        U10=A0+A1*SS+A2*SS**2+A3*SS**3+A4*SS**4+A5*SS**5
      ENDIF
C
      ELSE
C
        U10=B0+B1*SS+B2*SS**2+B3*SS**3+B4*SS**4+B5*SS**5
C
      ENDIF
C
      IF(U10.LT.0.0) U10=0.0
C
      U10WCF=U10
C
      RETURN
      END

```

Fig.3.1

Geosat σ_0 and wind speeds from the US NDBC network

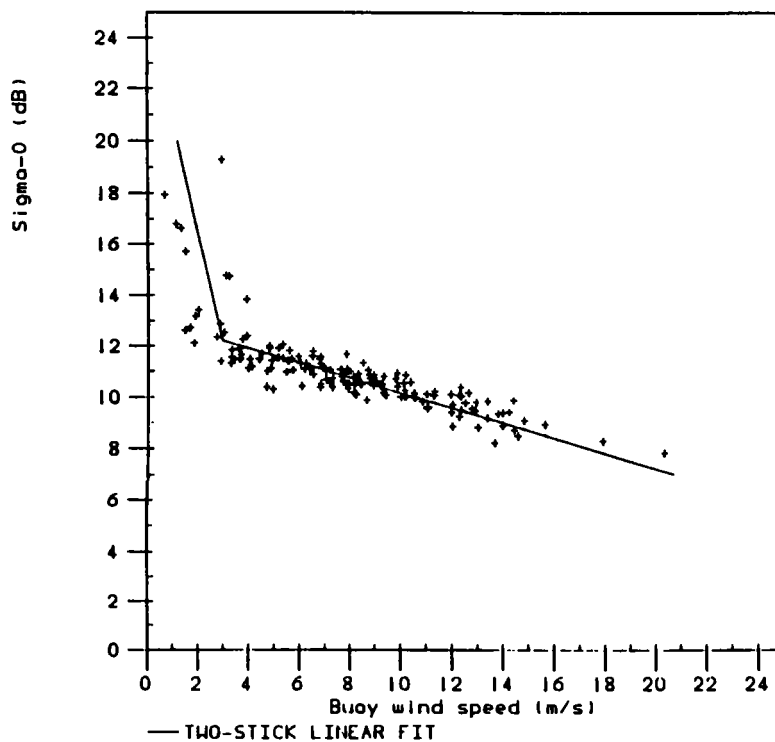
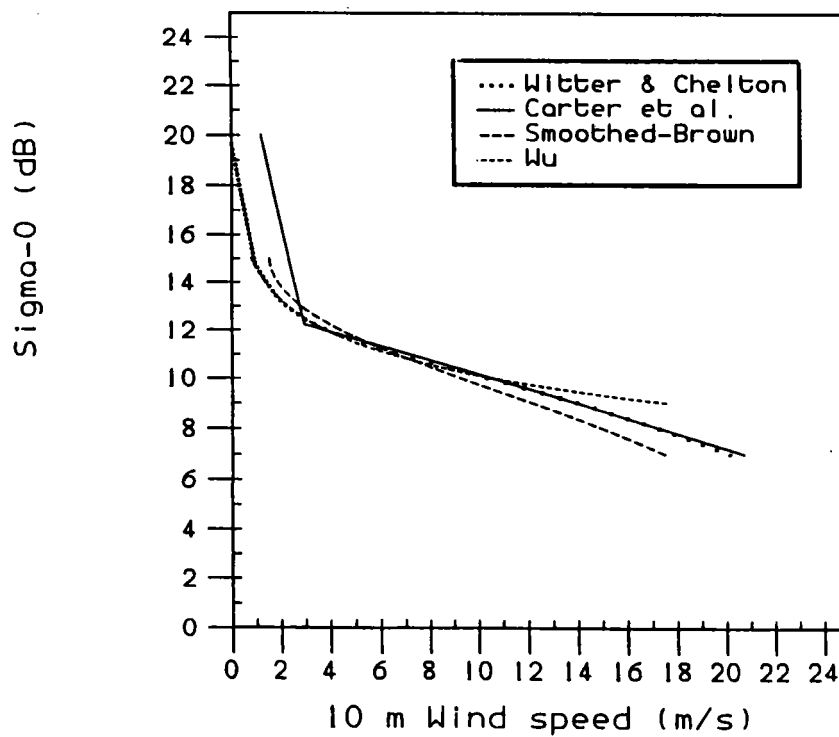


Fig.3.2

Some altimeter wind speed algorithms



3.2 Some general problems with estimating wind speed

There is no simple physical relationship between σ_0 and wind speed. From radar theory for specular point reflection, which is appropriate to near-nadir reflection, σ_0 is a function of the sea surface slope variance. But the precise relationship between slope variance and wind speed is not fully understood.

Recently, Glazman and Pilorz (1990) have pointed out that a simple one-to-one relationship between σ_0 and wind speed cannot hold. The sea surface spectrum, which determines the strength of the radar return pulse, depends not only upon the surface wind speed but also upon the state of development of the waves, or - using Glazman and Pilorz's term - upon the sea maturity. This age can be related to the significant wave height and the wind speed. Glazman and Pilorz are attempting to obtain an improved estimator of wind speed using both σ_0 and the altimeter's estimate of H_s .

A complication arises because the wave spectrum depends on the wind speed at the sea surface; but the wind speed required - and the value usually measured - is the speed at 10 m above the sea surface. The relationship between the surface wind and the wind at 10 m is not constant, but depends upon the stability of the atmosphere between the surface and 10 m. Sometimes a 'standard' height of 19.5 m is used!

A further problem arises because of mis-pointing of the radar. It may be shown that estimates of σ_0 are particularly sensitive to small changes in mis-pointing at low wind speeds. Geosat suffered badly from mis-pointing - sometimes by more than 1° - and it obtained no direct measurement of mis-pointing but could only estimate it from the shape of the trailing edge of the return pulse. However, preliminary attempts to estimate mis-pointing by ERS-1 have been unsuccessful, because it is so small, less than 0.1° .

Yet another problem occurs from the difficulty of calibrating σ_0 , because the strength of the return pulse from the altimeter is so weak, about 10^{-14} of the transmitted power. For example, comparisons of GEOS-3 and Seasat σ_0 data indicate that there are problems in calibrating σ_0 values to the very high precision required (Guymer et al., 1985).

Because of all these problems, the only practical course available at present seems to be to derive simple statistical relationships between wind speed and σ_0 , although this is clearly far from ideal.

4. Validation of radar altimeter geophysical data

4.1 Introduction

Deciding upon checks to test the validity of global altimeter data is a difficult problem. If only a few data values are of interest, then a careful scrutiny of the individual values and of the associated flags is possible; but this is not practical when analysing global data over many months. There is not a correct answer: a balance has to be struck between discarding a large number of good data and accepting some bad data. The following discussion is based upon consideration of Geosat data, taken -with minor amendments - from Carter (1990). Data are yet available from ERS-1, but no doubt many of the same problems will arise (although some will not: ERS-1 does not appear to suffer from mis-pointing and it should acquire lock quicker as it comes off land).

It would seem plausible to apply the same set of checks for the acceptance of both H_s and σ_0 : if one value is in error or missing then the other must be questionable. Moreover, a study of the correlation between wind and wave height should preferably be carried out using joint values. However, Geosat suffered frequently from mispointing. This has a smaller effect upon H_s than upon σ_0 , and it seems unnecessary to omit the rather large number of useful H_s values even though the associated σ_0 values have to be discarded because of mispointing. Moreover, values of σ_0 appear to be affected by moderate and heavy rain, whilst values of H_s are only affected by very heavy rain (>15 mm/hr) which distorts the return waveform (Srokosz & Guymier, 1988). Occasionally there appears to be a satisfactory σ_0 value but no H_s value. This seems to arise - at least sometimes - when the sea is glassy calm. The problem is discussed below, in Section 4.5.

4.2 General considerations

Very little appears to have been published on methods of checking altimeter data, but the following have considered the problem:

Carton (1989) analyses Geosat height data which he discards if the standard deviation of the 10 Hz values making up the 1 Hz average, $sd(H)$, exceeds 6 cm. Laxon (1990) investigates the distributions of $sd(H)$, H_s and AGC including their distribution south of 60°S. He decides to use $sd(H)$ as the primary indicator of sea ice, but settles on the following tests to identify ocean cells "unambiguously".

- (i) $sd(H) < 0.1$ m
- (ii) $H_s < 20$ m
- (iii) $AGC < 35$ dB

Unfortunately, the early Geosat data from the geodetic mission, prior to November 1986, does not contain standard deviation values of any of the parameters. This turns out to be a serious drawback to the quality control of these data.

Laxon is interested in the variation of Antarctic sea ice extent, and not concerned with the distribution of H_s , and his interest is reflected in his choice of an upper limit for H_s . We have no measurements of H_s exceeding 20 m, but the fifty-year return value in the N E Atlantic is around 20 m, so this limit would be unwise for wave studies. The relationship between AGC and σ_0 is well-hidden in the technical literature; it would seem that AGC is corrected for mis-pointing of the altimeter and for H_s , then a constant of around 15 dB is subtracted, so $AGC < 35$ dB corresponds roughly to $\sigma_0 < 20$ dB.

Romeiser (1990) carried out a detailed comparison of Geosat exact repeat mission values of H_s with estimates of H_s from the WAM third generation wave model. He decided that the Geosat H_s data should be discarded if the standard deviations of H_s , AGC or height are such that:

$sd(H_S) > 0.5$ m or $sd(H_S) > 0.5H_S$, $sd(AGC) > 0.3$, or $sd(H) > 0.3$ m. From an investigation, using data from the exact repeat mission, of the distribution of $sd(H_S)$, we found -in agreement with Romeiser - that its value increases with H_S , so that any check on its value has to include H_S . However we found that a more stringent test was needed than that proposed by Romeiser to eliminate spurious data in high latitudes, presumably caused by ice. It seemed necessary to discard data if $\{sd(H_S) \geq 0.1$ m and $sd(H_S) \geq 0.1 H_S\}$. The Geosat exact repeat data has a number of cases with $sd(H_S) = 0$, over the entire range of H_S values - see Romeiser (1990), figure 9. We decided to discard these values.

Challenor, Foale & Webb (1990) discuss, in some detail, methods of validating H_S from the 17-day exact repeat data. They decide upon the following checks on each 1-second value:

Omit the data if

- (a) flag indicates over land
- (b) H_S is not available (H_S is put to 327.67)
- (c) Within 6 s of leaving land
- (d) $\sigma_0 = 0$ or $\sigma_0 > 20$ dB (indicating possible sea ice)
- (e) $sd(\text{height}) > 0.1$ m (indicating possible rain cells).

Of course, (e) is not possible to apply to the geodetic mission data.

Following inspection of a large amount of data, Challenor et al. came to the conclusion that their checks were insufficient and they decided to carry out a further check, testing the relationship between each six consecutive values by (a) fitting a straight line (by least square) to the first five and comparing the sixth with the extrapolated value, and (b) fitting a straight line to the last five and comparing the extrapolated value back to the first with the previous extrapolated value for the sixth. Challenor et al. accept that these tests are stringent - removing about 16% of the data (with 11% failing the linearity tests) but argue it is better to discard good data rather than possibly including bad data. The algorithm they developed was quite complicated, because it had to cope with missing data, and took a considerable amount of computer time.

If the data are being checked prior to using them to estimate the average value of H_S and σ_0 , say during a transit of $2^\circ \times 2^\circ$ bin, then it seems reasonable to simplify the procedure if possible by applying checks only to individual values and to minimise the effect of an occasional bad value by taking the median value within each $2^\circ \times 2^\circ$ transit, rather than the mean which is less robust against outliers.

As Geosat came off the land, it often took several seconds to acquire lock. For example see Fig.2.4 in which Geosat loses lock crossing the Cornish peninsula (on a 'downward' track) and takes about 12 s (84 km) before re-acquiring lock. However once it acquired lock and the return was an ocean wave-form then we found that the values of H_S and σ_0 appear to be satisfactory within a few footprints, well before the 6 s in (c) above. But if the satellite track was at an oblique angle to the coastline, then one or two 1 s values were sometimes clearly in error.

Brooks et al (1990) investigate the effects upon Geosat's H_S , AGC and height measurements of land, studying data as Geosat passed over or close to small mid-ocean islands in the Tuamotu Archipelago in the southern Pacific Ocean. One transit of an atoll studied in detail found that the waveform from the 10 Hz data was first affected when the satellite ground track was 3.4 km from the island and continued to be affected until 5.3 km beyond the island. Brook et al. found that the pulse peakiness factor proposed by Laxon & Rapley (1987) - calculated from the individual wave form - generally clearly indicated returns affected by the island except when ocean-like returns were obtained from the interior lagoon - even though here the AGC values were still obviously wrong and the wave heights were given as higher than outside the atoll. They recommend an editing technique involving the pulse peakiness parameter and (unspecified) limits on H_S and AGC values. This can clearly not be carried out

with the Geosat data - either the geodetic mission data or the exact repeat mission data. (The ERS-1 geophysical data record will include the pulse peakiness parameter.)

4.3 The mispointing problem

The Geosat radar altimeter beam should point directly downwards, at nadir. However, the gravity gradient attitude stabilization system often allowed excursions from nadir by 1° , occasionally by 1.3° . The beam-width of the altimeter was only 2° , and off-pointing sometimes led to difficulties in reacquiring lock as the footprint passed from land or ice to water.

Even when the altimeter was able to track the return pulse, H_S and σ_O values had to be corrected for mispointing. These corrections, which depend upon the angle of tilt, the value of H_S , and upon the gate in the centre of the return pulse, were applied from look-up tables which had been calculated before launch. The tables (in terms of a voltage related to the angle of tilt, ξ) are given in Cole (1985). The procedure suffers from a drawback common to look-up tables: discontinuities in the distribution of the corrected values.

The corrections to H_S , which are proportional to ξ^2 , are generally not large, but have to be applied to obtain the specified accuracy for Geosat H_S of 10% or 0.5 m (whichever is larger).

The corrections to σ_O are more important. For example, with $\xi \approx 1^\circ$, an error in ξ of 0.1° gives an error in the σ_O correction of about 1.4 dB, which corresponds to about 4.8 ms^{-1} (for $H_S < 14.6 \text{ m}$).

The mispointing angle of Geosat's altimeter was estimated from the slope of the trailing edge of the return pulse, but the accuracy of this estimate appears not to have been determined.

Because of these problems, Dobson et al (1988) suggest that if ξ exceeds 1.1° then estimates of geophysical parameters from Geosat should only be used with considerable caution. Even though we are only interested in the average wind speed during a month or longer, this limit seems rather too high for σ_O values. It would appear safer to accept σ_O values only if $\xi < 1^\circ$, which is the limiting value used by Glazman & Pilorz (1990). But, for averaging purposes it seems preferable to use the H_S values for all ξ , accepting a possible error of around 20% in individual transects.

Sometimes the algorithm failed to estimate a value for ξ . In this case, the attitude is put to 0° ; and we decided to discard the σ_O values but to use the H_S values. (In the exact repeat mission data the 6th flag is then put to 1; the 5th and 7th flags when set to 1 indicate difficulties in determining ξ .)

4.4 Summary

From the considerations described above, Carter(1990) decided to use the following to check the validity of the Geosat 1 Hz values of H_S and σ_O . The checks marked with an asterisk (*) concern problems of mispointing and were not applied when checking H_S .

Discard the data if:-

1. Land flag set (i.e. Flag 1 = 0)
2. Measurement within 3 s (21 km) of leaving land
- 3.* Problems with estimating attitude, indicated by:
attitude=0.00 or attitude>1.0°
4. No H_S value calculated (i.e. $H_S=32767 \text{ cm}$)
5. $\sigma_O \leq 0$ or $\sigma_O \geq 20$

An inspection of the exact repeat mission data indicates that the following are also very useful checks on the validity of the data, but these are not available for the geodetic mission data:

6. $\{sd(H_S) \geq 0.1 \text{ m and } sd(H_S) \geq 0.1 H_S\} \text{ or } sd(H_S)=0$
7. $sd(AGC) \geq 0.1 \text{ dB or } sd(AGC) = 0$
8. $sd(H) > 0.1 \text{ m}$
- 9.* $\text{Flag 5} = 0, \text{Flag 6} = 0, \text{ or Flag 7} = 0$

The checks on the standard deviations are particularly useful in high latitudes for detecting returns from ice; so the geodetic mission data (with no standard deviations given) must be expected to include more dubious data than the checked exact repeat mission data.

4.5 A note on glassy seas

The relationship between the altimeter return and the characteristics of the sea surface are based upon assumption of specular point reflection from an isotropic Gaussian sea surface. Seasat occasionally gave an anomalous return over the open ocean, with a narrow high amplitude pulse giving a strong increase in σ_0 , similar to returns observed from sea ice resulting from near specular scattering. (Townsend, 1980; Laxon and Rapley, 1987.) These anomalous returns are possibly from areas of very smooth or glassy water associated with very light winds. An examination of the Geosat data reveals numerous occasions when high values of σ_0 are given (generally exceeding 11 dB, sometimes exceeding 20 or even 30 dB) with no value specified for H_S . These data have been found to prevail in the Mediterranean in summer. They also occurred extensively in the equatorial west Pacific (10°S - 10°N, 128°E - 150°E) during August and September 1988; RRS Charles Darwin was in the West Pacific during these months, her position never coincided precisely with these anomalous data, but winds were generally light throughout the the Darwin's cruise and the sea was often glassy calm (pers. comm. Dr D J Webb). In some cases the σ_0 values were rather low, suggesting a wind speed too high for a glassy sea. For example, $\sigma_0=11 \text{ dB}$ corresponding to 7 ms^{-1} . However, Wingham & Rapley (1987) show that saturation occurred during processing of narrow-peaked altimeter returns on board Seasat, which would have significantly reduced the measured σ_0 values. (They found narrow-peaked returns were from land, inland waters and sea ice, but they could also be expected from a mirror-like sea surface.) A similar saturation effect could have reduced these Geosat σ_0 values.

ERS-1 appears to have been similarly affected over the Mediterranean in September 1991. The seas were not flat, with some swell but no wind waves (pers. comm., Dr R Francis).

Further investigation of these anomalies is needed to prove that they are caused by glassy seas. Meanwhile it would appear safer to discard such records, because σ_0 is greater than 20 dB (which might indicate the presence of sea ice!) and because H_S is not specified. However, if they are related to very low wind speeds and to very low wave heights, then discarding them leads to over-estimating average wind speed and H_S - and hence to overestimating ocean/atmosphere fluxes.

5. Global averages of wave height and wind speed

5.1 Introduction

Estimates of the global climate of wave height and wind speed for each month of the year can be obtained from the altimeter Geophysical Data Records, such as the Geosat data, by averaging values in 2° latitude x 2° longitude bins. The method which has been used to calculate these 2° x 2° averages is described below. The results are compared with monthly mean values from buoy data, and some examples of the global climates are then presented.

5.2 Construction of Global Monthly Averages

There is no obvious choice of bin size. However, here the data are analysed in the same bin size - 2° x 2° - as used by Challenor, et al. (1990) and by Carter, et al., (1991) for their analyses of one year of the Geosat Exact Repeat Mission data. Of course, the actual area of the bin reduces with increasing latitude, but this is more than compensated for by the corresponding convergence of the satellite tracks. The smallest number of transects of a 2° x 2° bin during a month is at the equator, where - for the 17-day repeat mission - the tracks are separated by 160 km, or 1.4 degrees, and give a minimum of 4 transects a month (up-crossings and down-crossings in 34 days). So, at least in the tropics, some smoothing will probably be desirable. The Gaussian filter applied by Challenor, et al., (1990) will be used. (This smooths over 3×3 bins with weights $1 : 2 : 1, 2 : 4 : 2, 1 : 2 : 1$). Over large areas of the oceans, the wind and wave climate vary more rapidly with latitude than with longitude, so here it might be preferable to smooth more in the longitudinal direction - as for example Chelton et al. (1981) do, smoothing over 2.5° latitude x 7.5° longitude - particularly as the bins 'narrow' at higher latitude; but for global coverage the choice of Challenor et al. seems appropriate.

Porter and Cheney (1989) use a comparable amount of data to produce mean wind speeds over the tropical Pacific, constructing 10-day averages in 2° latitude x 8° longitude bins (using the smoothed-Brown algorithm). However, their figures suggest some further smoothing has been applied.

The average value of H_S in a 2° x 2° bin was obtained by taking the median of the 1 Hz values of H_S along each transect of the bin and then calculating their mean. The average value of wind speed was obtained by taking the median of the 1 Hz values of σ_o along each transect, calculating the wind speed corresponding to this median value using equation 3.1, and then calculating the mean of these wind speeds.

The median value is used for the transect average, as noted in Section 4, because it is more robust against outliers than the mean. Carter (1990) finds some skewness in the distribution of σ_o values across a 2° x 2° bin (but not in the distribution of H_S), with an average value for the median - mean of 0.6 dB. (So the median tends to under-estimate wind speed compared to the mean.) However, no allowance for this has been made in the wind speed values given in this report. Moreover, so that results given here might be compared with those from other analyses of Geosat H_S data, values of H_S in this report have not been increased by 13%, as suggested they should be in Section 2, except where specifically mentioned.

5.3 Comparison with monthly climate means from buoy data

The US Department of Commerce publish monthly the *Mariners Weather Log* (in association with NOAA, NESDIS and NODC). This contains the monthly mean values of wave height and wind speed obtained from (generally) hourly measurement from the NOAA's National Data Buoy Center's network. Data were extracted for 20 buoys, including the 13 with positions given in Fig.2.2, from October 1985 to December 1988, and compared with the corresponding estimates from the Geosat data. Geosat wave heights were increased by 13%.

Fig.5.1 a & b show the regressions of about 400 monthly means of H_s from Geosat against the values from the buoys. In 'a' the unsmoothed Geosat values are used and in 'b' those from applying the Gaussian smoothing function once. The regression slopes are not significantly different from 1.0, as would be expected since the factor was obtained from a comparison of individual buoy and Geosat data from 13 of the buoys (Section 2.5.1). The correlation improves considerably if the smoothed Geosat values are used, with the correlation coefficient increasing from 0.90 to 0.96.

Fig.5.2 a & b show the corresponding regressions for the monthly mean wind speeds. Again, the slope is not significantly different from 1.0, but to achieve this, the wind speeds had to be adjusted to a height above the sea surface of 19.5 m. Since the buoys measure the wind at a range of heights from 5.0 m to 13.8 m, clearly some adjustment has to be made. The more usual height is 10 m, but from these results it would appear that Glazman & Pilorz (1990) used 19.5 m; so that the two-stick wind speed algorithm (Equation 3.1), which is based upon their data, is also calibrated to 19.5 m. (The adjustments were made assuming that the atmosphere was neutrally stable, for which the 19.5 m wind speed is 6% greater than that at 10 m.) The wind speed regressions are clearly poorer fits, with correlation coefficients of only 0.54 and 0.66 for 'a' and 'b' respectively.

The differences between the estimates of monthly mean values from altimeter data and from buoy data could be due to several reasons. Spatial variation across the $2^\circ \times 2^\circ$ bin could occur, especially around the buoys closer to the shore, such as in the NW Atlantic. For the winds, there is also the introduction of possible error in correcting values to a standard height assuming the atmosphere is always in neutral stability. However, probably the largest source of the differences is the few transects used to calculate the altimeter values. For example, Fig.5.2 c shows the regression as in Fig.5.2.b but only for the 85 values when the $2^\circ \times 2^\circ$ bin had at least 6 transects with good wind speed data. The correlation coefficient is increased to 0.79. This raises the question of how many observations are required during a month to give a useful estimate of the monthly mean.

Fig.5.1 a & b

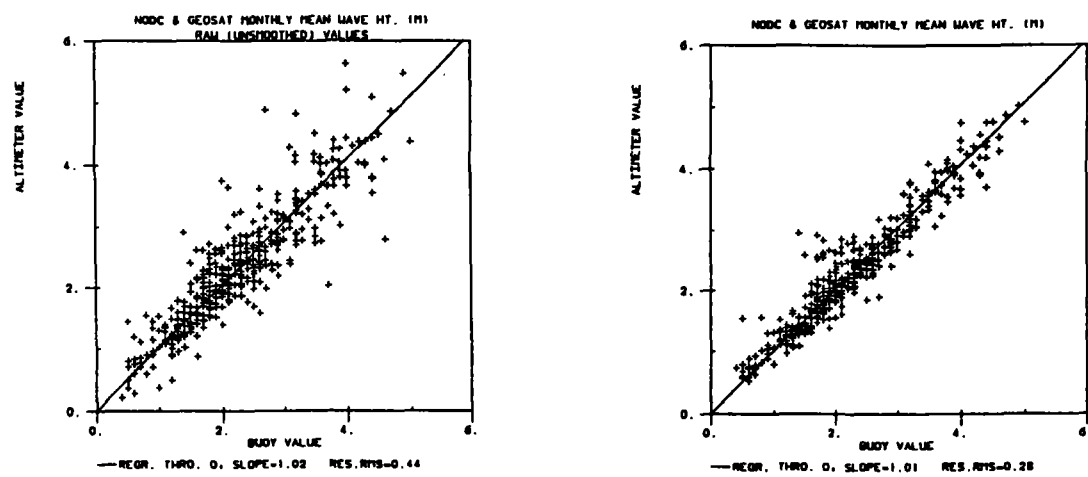


Fig.5.2 a & b

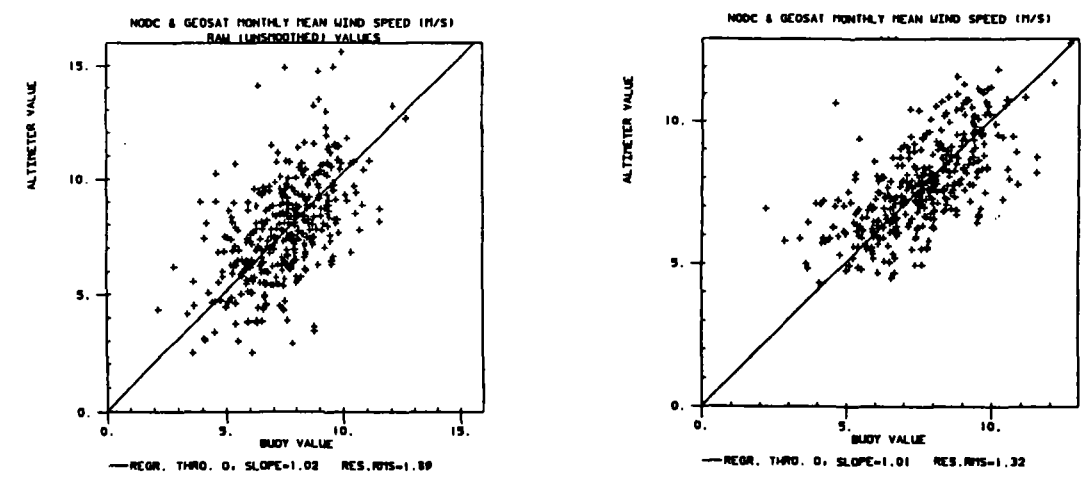
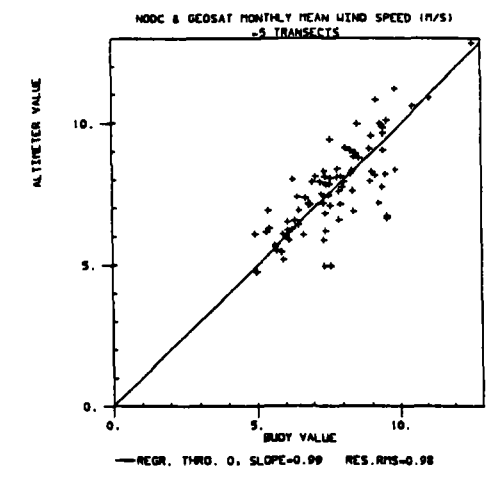


Fig.5.2 c



5.4 How many observations are required to estimate a monthly mean?

Fig.5.3 & 5.4 show the results (the residual rms and correlation coefficient) of fitting regressing altimeter monthly unsmoothed $2^\circ \times 2^\circ$ bin means on monthly buoy values, as in the above Section but as functions of the number of Geosat transects of the bin (each transect giving one value towards the altimeter monthly mean). From Fig.5.3 for wave height, ignoring the result for 9 transects calculated from only 6 events, the correlation coefficient rise with the number of transects N_t until $N_t=5$, it then remains nearly constant; the residual rms is around 0.5 m for $N_t < 5$ and roughly constant at 0.35 for higher N_t . This suggests that 5 transects of a $2^\circ \times 2^\circ$ bin give as much information as can be obtained from an altimeter, and that further transects do not improve the estimate of the monthly mean.

The results shown in Fig.5.4 suggest a different conclusion for wind speed: the residual rms is continuing to decrease with N_t up to 7 (ignoring $N_t=8$ with only 9 events) and the correlation coefficient remains around 0.6 until $N_t=7$. It would seem that more observations of wind speed are required to estimate a monthly mean than of wave height, with the consequently greater scatter in Fig.5.2 than in Fig.5.1.

Halpern (1988) investigated the number of observations required to estimate the monthly mean zonal and meridional components of wind speed at three buoy locations along the Equator in the Pacific. He found that about 9 random observations were need to obtain a 95% confidence limit of 1 m/s but there were significant differences between the three locations, with the number required being highly correlated with the monthly mean standard deviations. It would be interesting to investigate the results from Geosat as a function of location, but there are probably too few pairs of observations.

Fig.5.3 **Monthly mean wave height from Geosat & buoy data**
(Number of pairs in brackets)

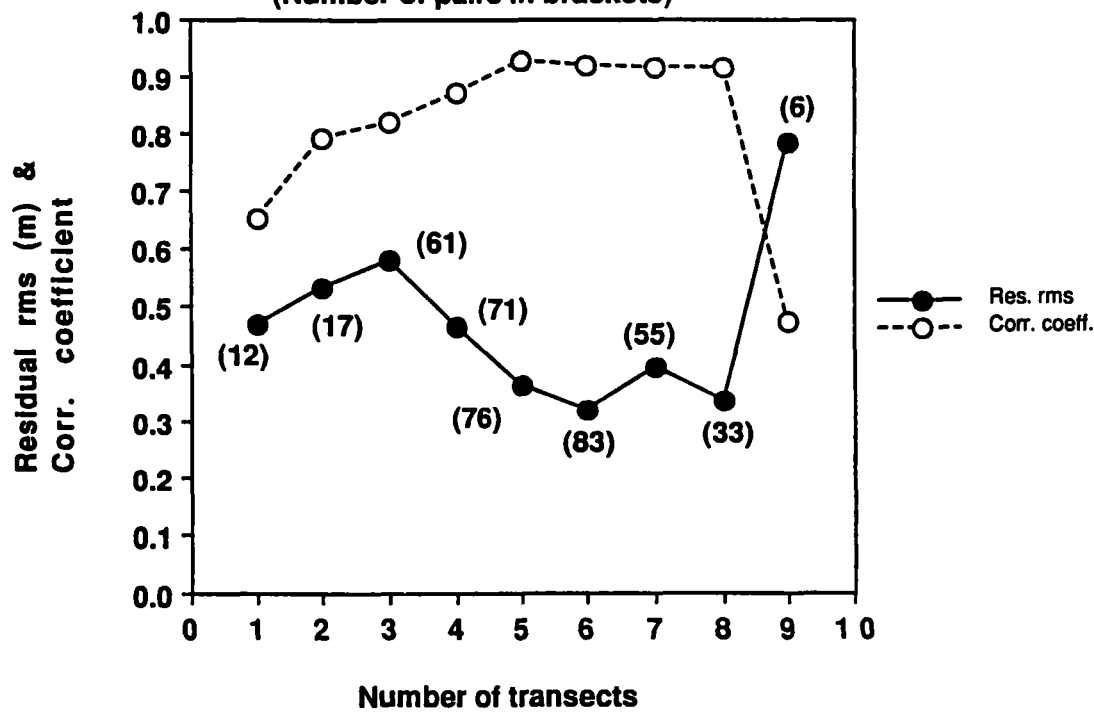
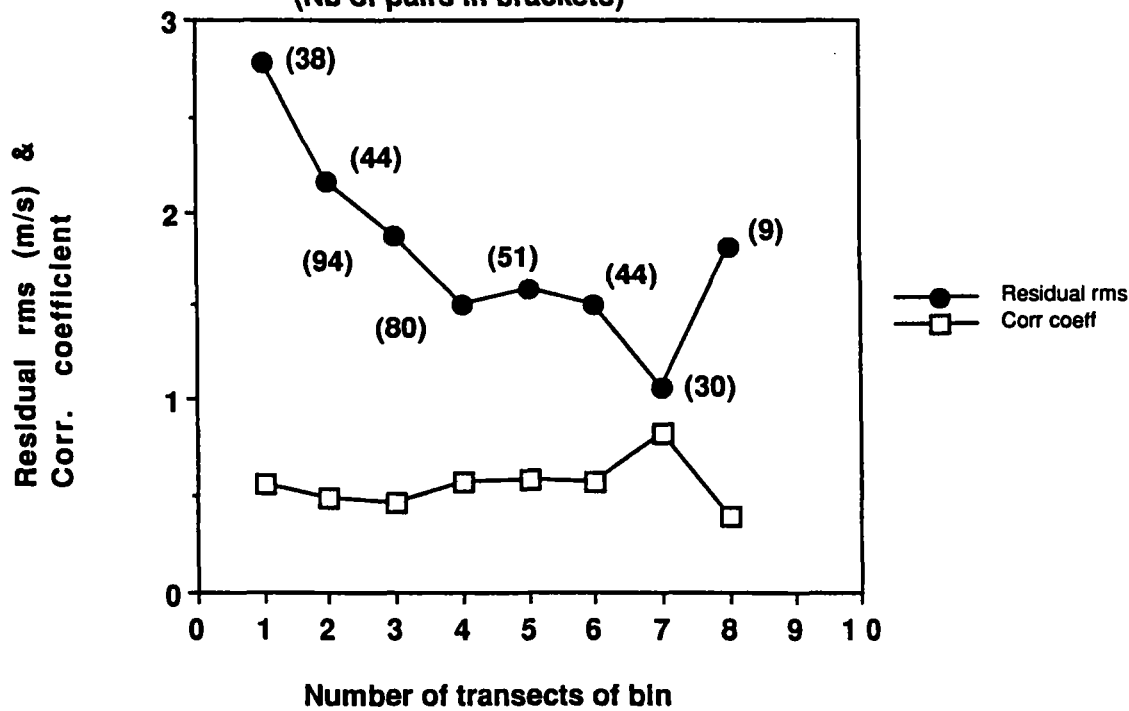


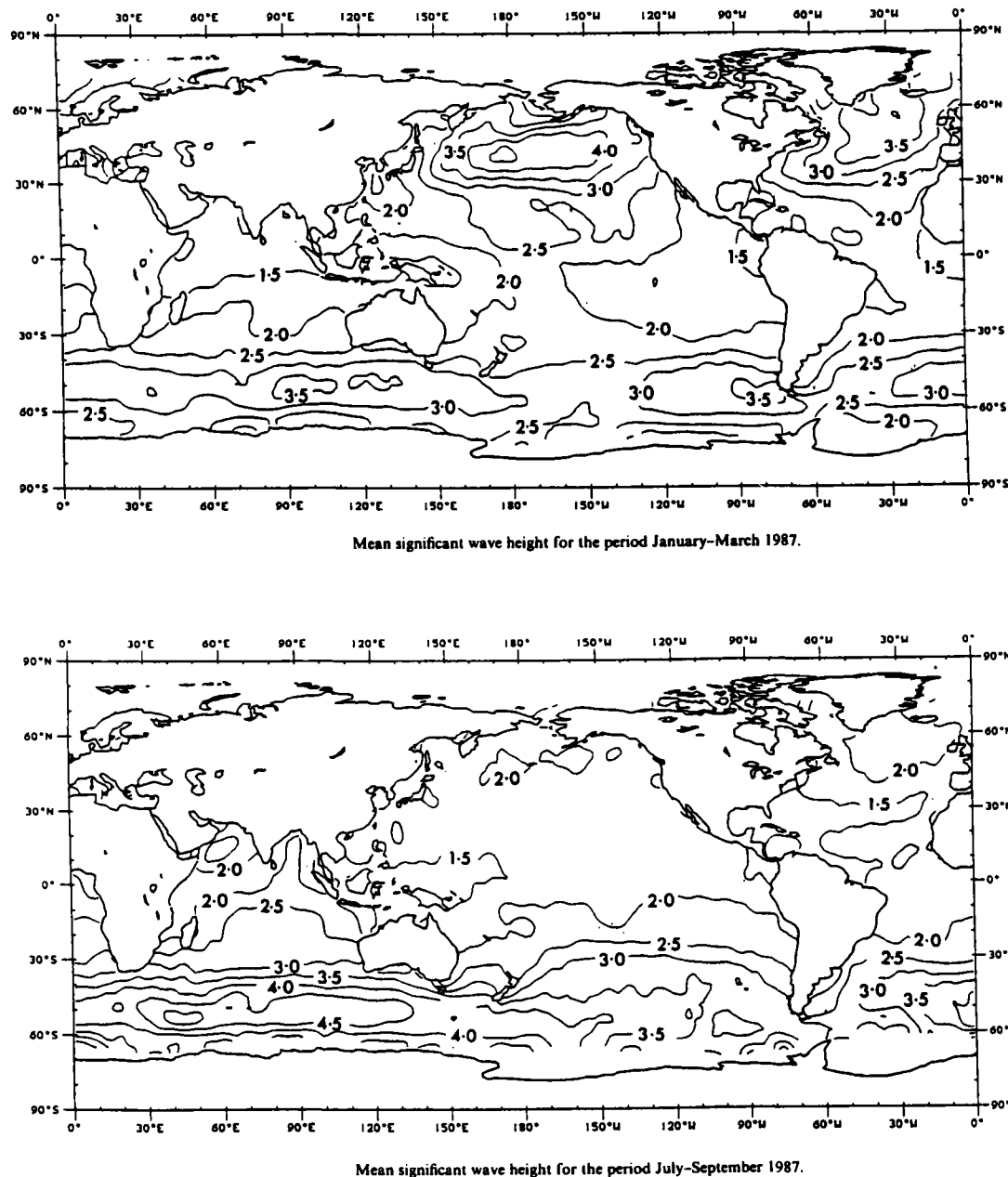
Fig.5.4 **Monthly mean wind speed from Geosat & buoy data**
(Nb of pairs in brackets)



5.5 Global wave height

The analysis of data in $2^\circ \times 2^\circ$ bins can be used to give an estimate of the global distribution of H_s , but for the reasons discussed above, some smoothing is desirable. Fig.5.5 shows the results from Challenor et al. (1990) from one year of Geosat data smoothed spatially and in time (over three months). The figure shows for example the relatively high waves in the southern ocean even during its summer month, and the high waves in the Arabian Sea during the northern hemisphere summer compared with the values there in January-March. These aspects will be discussed further in Section 6. Note that these Geosat values of H_s have not been increased by 13%.

Fig.5.5 Analyses of Geosat wave height data from Challenor et al (1990)



5.6 Inter-annual variability

The data from Geosat is particularly valuable because it enable us, really for the first time, to investigate between-year variability over the globe. Figs. 5.6 and 5.7 show the monthly mean wave heights and wind speeds for the NW Pacific and the North Atlantic for the four winters (December and January) from 1985/86 to 1988/89. The highest waves in the NE Atlantic were during the winter of 1988/89, and the lowest in that area were in 1986/87. The inverse appears to have occurred in the NE Pacific, with the highest average value in 1986/87 and the lowest in 1988/89. The wind speeds in the North Atlantic appear to have followed a similar variation as the wave height, with the highest mean value in the NE Atlantic in the winter of 1988/89; but in the NE Pacific, 1988/89 also had the highest wind speed - when the waves were their lowest. This illustrates the complex relationship between wave height and wind; involving not only the local mean wind speed but also its direction and persistence, as well as the wind over the entire ocean which can generate significant swell waves. It might also reflect the greater uncertainty in the monthly mean wind speeds.

Note that the strong gradients in wind speed at high latitudes for December 1985/January 1986 shown in Fig.5.7 result from errors in the data, which were obtained during Geosat's geodetic mission. The errors get into the analysis because the validation of the geodetic mission data is less satisfactory than the validation of data from the later exact repeat mission, because the earlier data do not include the standard deviations of the 10 Hz values, which were found to be good error indicators, particularly of returns from sea ice.

Figure 5.8 is a plot of the Southern Oscillation Index (SOI), taken from Kousky (1990). This shows the 1986-87 El Niño, with anomalously warm sea surface temperatures over the Eastern tropical Pacific, and the 1988/89 La Niña, with unusually cold surface waters. For a description of these terms, see for example Philander (1990). It may be of significance that the mean wave height for December and January in the NE Atlantic follow the Southern Oscillation Index, whilst those in the NE Pacific peak when the SOI is low in 1986/87. Niebauer (1988) finds a correlation between the SOI and the position and intensity of the average low pressure centre in the NE Pacific (the Aleutian low) during the winter, resulting in correlations between the SOI and the sea temperature, the air temperature and the ice cover of the Bering Sea - but a major exception was the very strong El Niño of 1982/83 which had little effect upon the Bering Sea. However, he found no significant correlation between the SOI and the wind speed on the Probilof Islands in the Bering Sea, which he explains by the apparent lack of a preferred site for the Aleutian low during an El Niño event - which might also explain why the major event of 1982/83 had little effect upon the Bering Sea. These variations in the pressure pattern over the NE Pacific could affect the pressure pattern in the NE Atlantic, and hence the wave heights there.

Bacon and Carter (1991) give monthly mean values of H_s from Shipborne Wave Recorder measurements at Ocean Weather Station Lima (57°N 20°W) from July 1975 to December 1988. The average for the two months of December and January for 1985/86, 1986/87 and 1987/88 were 5.6 m, 4.8 m and 6.0 m respectively, in agreement with the trend seen in Fig.5.6. However, the mean value from OWS Lima for December/January 1982/83 was 5.9 m, the third highest value in the Lima records; so if there is any justification in the suggestion from the Geosat data that low values in the SOI coincide with low winter wave heights in the NE Atlantic, then -as found by Niebauer (1988) - the major event of 1982/83 was an exception. Clearly the significance of any correlation between events in the tropical Pacific and wave heights in the North Atlantic require more years of data than are available yet from altimeters.

Fig.5.6

Average values of H_s during December & January from Geosat data.

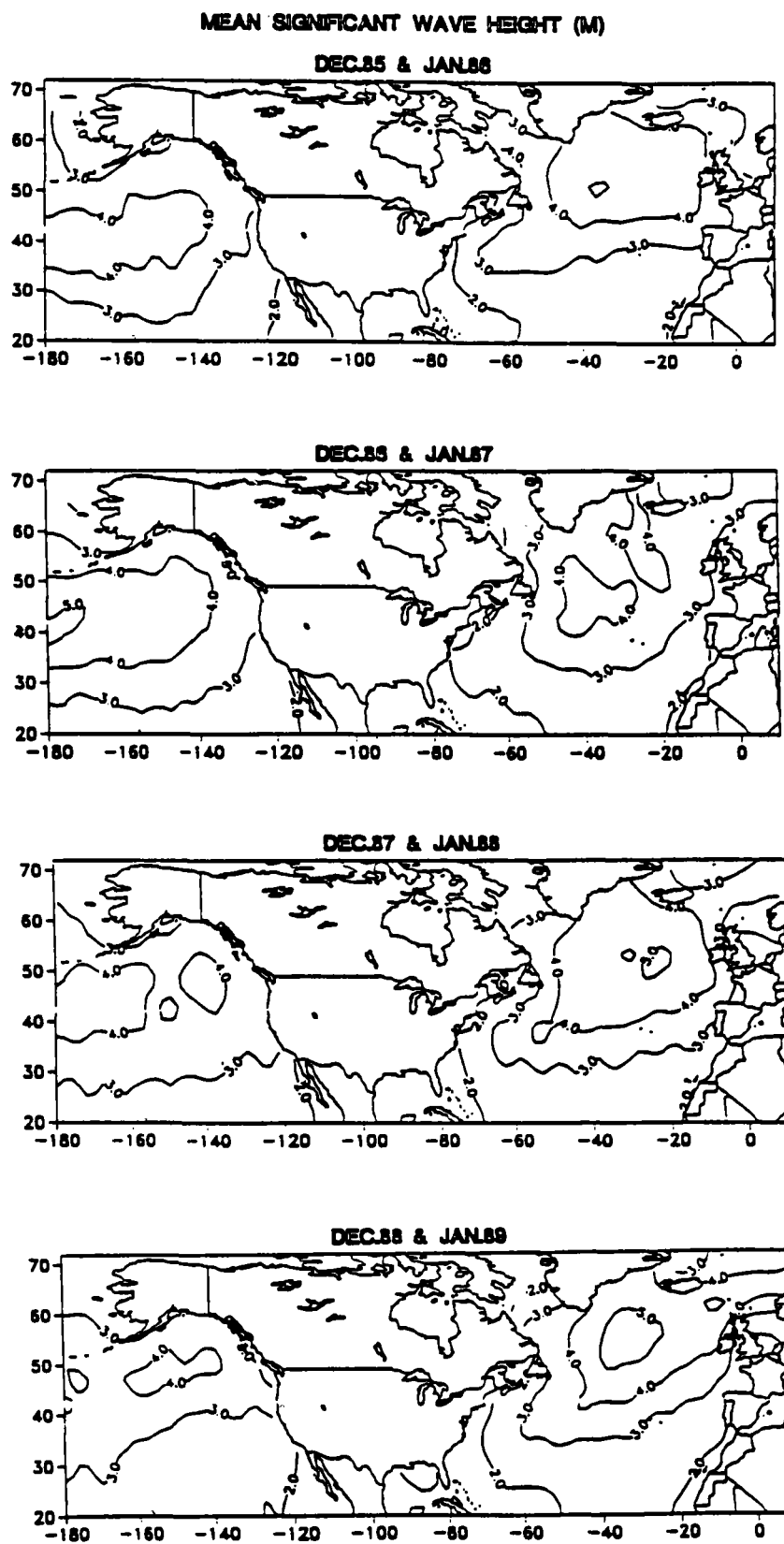
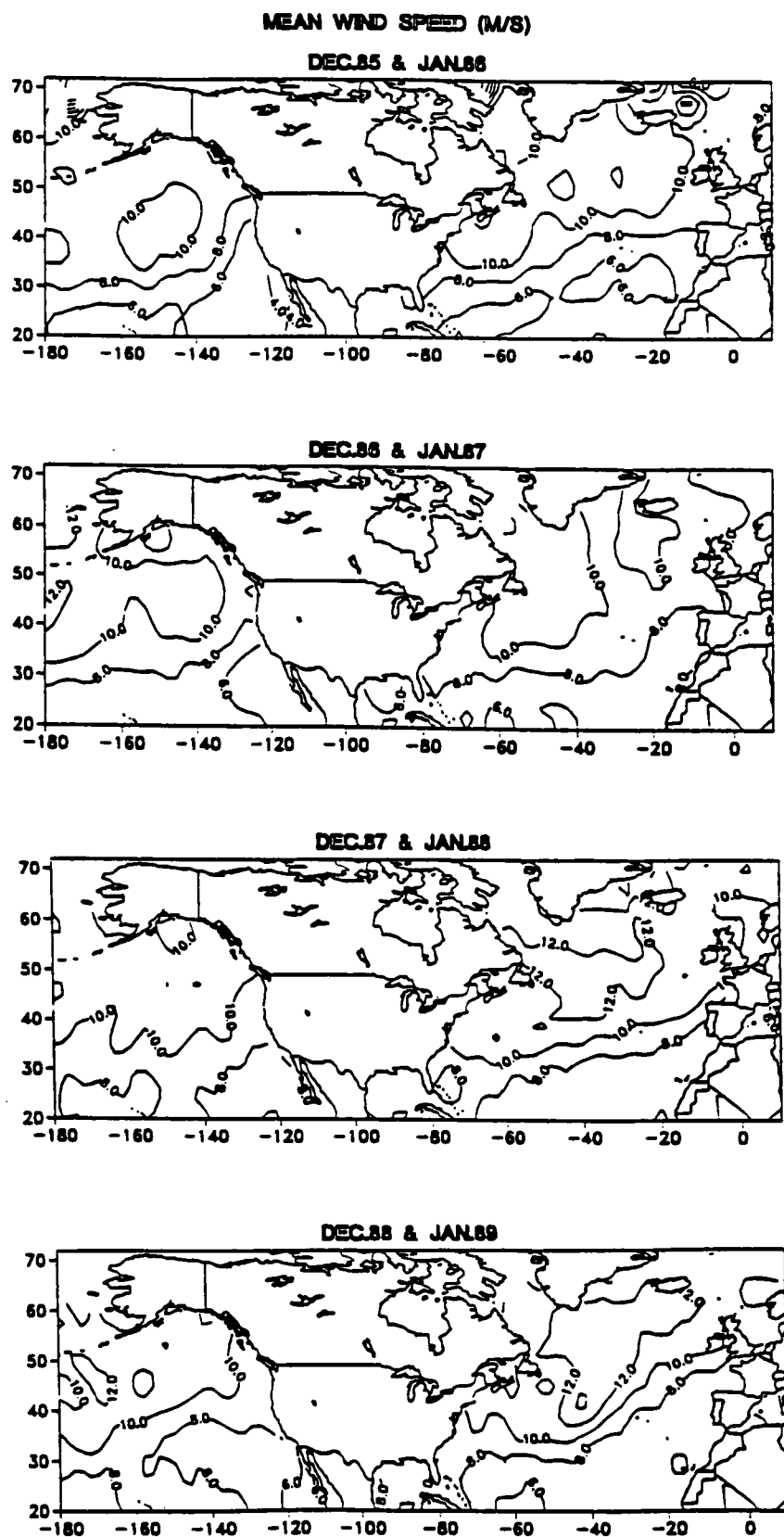


Fig.5.7 Average values of wind speed during December & January

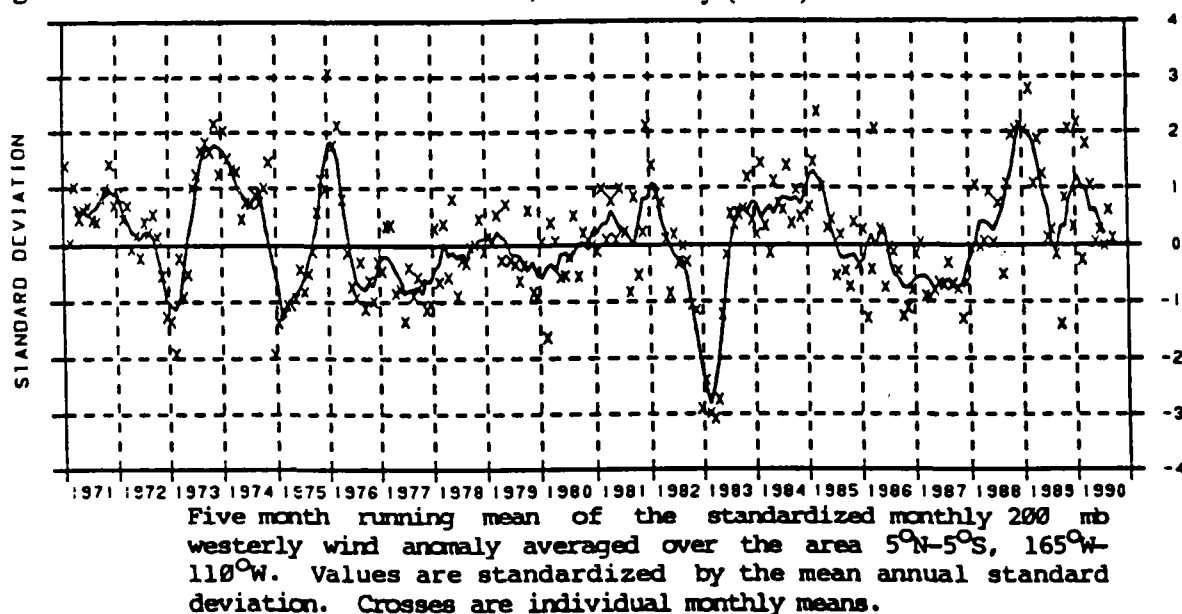


An analysis of the December/January SOI values and the average H_s values, from Bacon and Carter (op. cit.), for these months from a Shipborne Wave Recorder in the Seven Stones Light Vessel, sited between Cornwall and the Isles of Scilly, reveals no correlation. This result is not unexpected, the relationship between SOI and wave height in the NE Atlantic observed in Figs. 5.6 and 5.7 does not extend to the South West Approaches, where there were similar wave heights in the winters of 1986/87 and 1988/89.

A Tropical Ocean Global Atmosphere Program 'glossy' published by the Joint Climate Projects/Planning Office of the University Corporation for Atmospheric Research states that:

"Warm El Niño events appear to have some general consequences for the winter weather in North America...During a warm event,...storms are pushed to the north of their usual tracks, bringing above-normal temperatures to southeastern Alaska, western Canada, and the Pacific Northwest, and increased storminess to the Gulf Coast states.....La Niña can lead to short-term climate variations as dramatic as those associated with El Niño"

Fig.5.8 Southern Oscillation Index, from Kousky (1990).



5.7 Concluding remarks

The analyses of Geosat data carried out in this section, using average values by individual months and in 2° latitude x 2° longitude bins indicate that some smoothing in space or time is required to obtain a coherent and accurate picture. This results partly from data gaps caused by Geosat's mispointing problems, but even with a full data return, such as will hopefully be achieved by ERS-1, the coverage is insufficient for detailed, small-scale analysis, especially in the tropics.

The spatially smoothed data for a two month period have been used to illustrate the magnitude of inter-annual variability in global H_s values. It appears that the average wave heights in the NE Atlantic were correlated with the Southern Oscillation Index during December and January between December 1985 and January 1989, and were negatively correlated with wave heights in the NE Pacific. Clearly, satellite altimeter measurements are very useful for investigating such teleconnections, but considerably more years of data will be required to estimate the significance of these particular correlations.

6. Annual and semi-annual cycles

6.1 Introduction

Over much of the world's ocean, particularly in the northern hemisphere, there are large changes in the wave climate between summer and winter; this within-year cycle tends to dominate the climate. See for example Fig.5.5. In a few regions there is also a semi-annual cycle. The best known is probably the Arabian Sea where strong winds blow in the summer SW monsoon and in the winter NE monsoon, thus producing high seas twice each year, with quieter conditions between the monsoon periods. The semi-annual cycle is also of possible importance in some areas of the southern hemisphere, being found in meteorological data including meridional winds by van Loon and colleagues (1968, 1984).

In this Section, the global extent and significance of the annual and semi-annual cycles in monthly mean values of significant wave height, H_s , and wind speed are investigated by analysing the monthly means estimated from the Geosat radar altimeter.

6.2 Analytic procedure

Carter, Foale & Webb (1991) first looked at this problem, analysing one year of monthly mean H_s values from November 1986 to October 1987 in $2^\circ \times 2^\circ$ bins. They fitted the model:

$$H_{sm} = A + B\sin(2\pi m/12 + \theta) + C\sin(2\pi m/6 + \phi) + \epsilon_m \quad (6.1)$$

$(m = 1-12)$

where ϵ_m was assumed to be Gaussian noise.

Or

$$H_{sm} = X_0 + X_1\sin(\kappa m) + X_2\cos(\kappa m) + X_3\sin(2\kappa m) + X_4\cos(2\kappa m) + \epsilon_m \quad (6.2)$$

where $\kappa = 2\pi/12$

In Carter (1991) the model was extended to fit the 28 monthly mean H_s and wind speeds from November 1986 to February 1989. The fitting technique described below for any number of months is taken from that paper. It can also, of course, be applied to monthly wind speeds.

Clearly, equation 6.2 is a linear model applicable for any number of months, which may be expressed as:

$$H_{sm} = \underline{\alpha}_m \underline{X} + \epsilon_m \quad m = 1-M$$

where M is the total number of months (In Carter, Foale & Webb, $M=12$.)

The m^{th} row of $\underline{\alpha}$ is given by

$$\alpha_m = (1 \quad \sin(\kappa m) \quad \cos(\kappa m) \quad \sin(2\kappa m) \quad \cos(2\kappa m))$$

and

$$\underline{X} = \begin{pmatrix} X_0 \\ X_1 \\ X_2 \\ X_3 \\ X_4 \end{pmatrix}$$

Fitting this linear model is slightly more difficult than in Carter, Foale & Webb, (op. cit.). With $M = 12$ (that is over a complete cycle), the X_i are all orthogonal, and the order of fitting

the terms makes no difference to the estimate of X_i . With other values of M this may no longer be so. (Even if the data cover a year, any missing months will destroy the orthogonality, but Carter et al. found that if only one out of the twelve months were missing then the differences in the estimates were small. If two or more months were missing they did not attempt to fit the model.)

The procedure adopted here, for any M , and possibly with several missing values is:

- (a) Fit the annual cycle plus X_0 , and compute the significance of the annual cycle. (The IMSL routines RGIVN and RSTAT were used. These return the significance of the combined $\sin(\kappa m)$ and $\cos(\kappa m)$ terms, from the joint reduction in mean square deviation which has an F distribution.)
- (b) Fit the semi-annual cycle plus X_0 , and compute the significance of the semi-annual cycle.

and, finally, to obtain the results required,

- (c) Fit the more significant of the two cycles, then the other, then X_0 .

(Since the data might extend over say two winters and only one summer, X_0 cannot be fitted first.)

Whilst carrying out this procedure, the percentage reductions in variance from fitting the two cycles were also computed. Given N values (with $N = M$ if there are no missing values) then the total variance, i.e. the (mean square deviation)/($N-1$), is estimated by

$$V_T = \sum_{m=1}^N (H_{sm} - X_0)^2 / (N-1)$$

While the mean square deviation of the annual cycle model is

$$MSD_A = \sum (H_{sm} - X_0 - X_1 \sin \kappa m - X_2 \cos \kappa m)^2$$

which is obtained from analysis (a) above, the model residual variance is

$$V_A = MSD_A / (N-3)$$

(since a further 2 degrees of freedom have been used).

So the annual cycle model gives a reduction in variance of $100.(V_T - V_A)/V_T \%$

Similarly, from (b), the semi-annual cycle model gives a mean square deviation

$$MSD_S = \sum (H_{sm} - X_0 - X_3 \sin(2\kappa m) - X_4 \cos(2\kappa m))^2$$

and variance

$$V_S = MSD_S / (N-3)$$

So the semi-annual cycle model gives a reduction in variance of $100.(V_T - V_S)/V_T \%$

The mean square deviation of the joint model is given by

$$\begin{aligned} \text{MSD}_{(A+S)} &= \sum (Hs_m - X_0 - X_1 \sin(\kappa m) - X_2 \cos(\kappa m) - X_3 \sin(2\kappa m) - X_4 \cos(2\kappa m))^2 \\ &= \sum \epsilon_m^2 \end{aligned}$$

and the variance explained by the model is given by

$$V_{(A+S)} = \text{MSD}_{(A+S)} / (N-5)$$

The reduction in variance for the joint model is $100 \cdot (V_T - V_{(A+S)}) / V_T \%$

However, the reductions in variance given by each of the two cycles in the joint model are not uniquely defined. Using the expressions given above from fitting each component separately is not satisfactory because they do not add up to the reduction in variance from fitting them together. Even if the model components are orthogonal, the percentage reductions in variance of each component does not equal the reduction in variance of the joint model - only approaching it as N increases. It may be shown that if P_A and P_S are the percentage reduction in variance from fitting the annual and semi-annual cycles separately and $P_{(A+S)}$ is the reduction from the joint model, then if the two cycles are orthogonal:

$$P_A + P_S = P_{(A+S)} \{ 1 - 2/(N-3) \}$$

So given only twelve months of data, such as the wind climatology of Esbensen & Kushnir (1981), then $P_A + P_S = 0.78 \cdot P_{(A+S)}$

The procedure adopted here to define and calculate the percentage reductions in variance of the individual cycles in the joint model is as follows:

The reduction in variance of the more significant cycle is taken to be the value calculated above for the model with that cycle alone, and the reduction in variance for the less significant cycle as the reduction for the joint model minus that for the more significant cycle.

(It might have been preferable to calculate the percentage reduction in the sum of squares rather than the reduction in variance, but with N equal to say 28, - or larger - the differences are probably small.)

Occasionally the reduction in variance for the less significant cycle is negative. Clearly, the MSD of the joint model cannot be greater than the MSD of the individual cycle models, but its residual variance can be greater because of the reduction by 2 in the number of degrees of freedom.

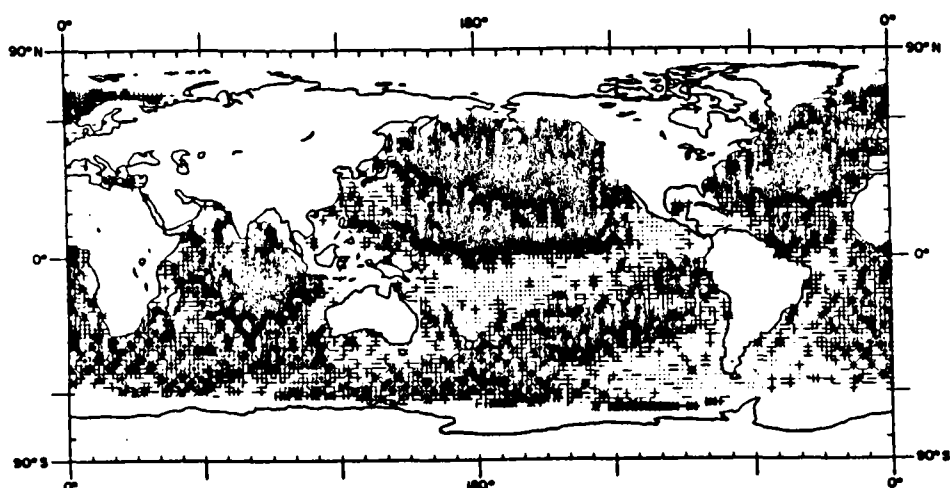
Note that in the examples shown below of model fits to individual $2^\circ \times 2^\circ$ bins, if the reduction of variance for one of the cycles is less than 10% that cycle is omitted from the reconstruction and the results from the other fit [(a) or b)] above is used. If neither cycle is significant, then the mean value is shown.

6.3 Results from Fitting the Model

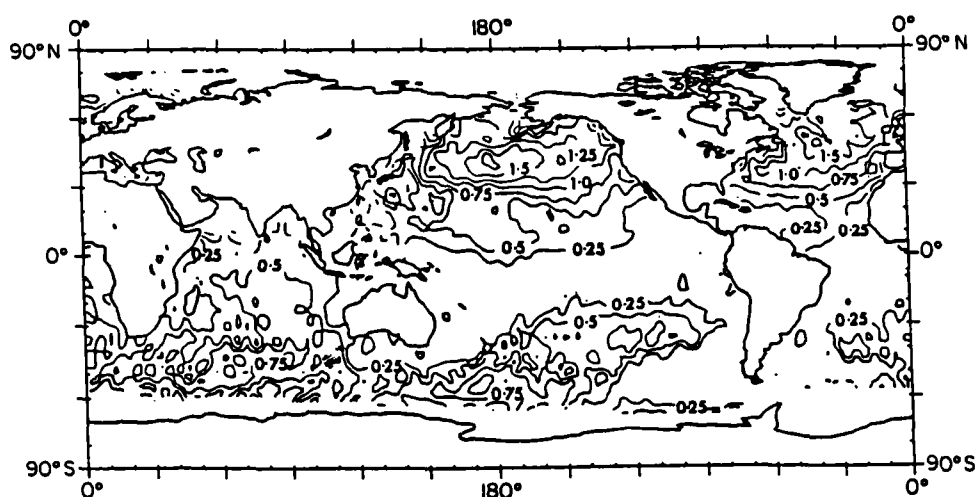
6.3.1 Significant wave height

The significance of the cycles estimated from $M=12$ by Carter, et al., (1991), are shown in Figs.6.1 and 6.2, taken from that paper, together with the estimated amplitude of the annual and semi-annual components where they are significant above the 90% level. Analyses with greater values of M give results which are generally similar to those obtained from analysing one year's data, except that the increased data reveals that the semi-annual cycle is no longer significant in the central N Pacific, but it is highly significant in the South China Sea. (In some areas there are still insufficient data; for example there is little evidence of any annual cycle in the Mediterranean, presumably because of the poor data return due to the difficulty Geosat had in acquiring lock when coming off land and the problem of glassy seas in the summer.) The mean value from November 1986 to February 1989 is shown in Fig.6.3; it has a maximum in the Southern Ocean, exceeding 4 m in places. The annual cycle is highly significant over large areas of the globe, especially in the northern hemisphere where the amplitude of this cycle is greatest. This difference between the hemispheres presumably results from the much greater proportion of land in the northern hemisphere which accentuates the difference in climate between summer and winter. The semi-annual cycle is only significant over a few areas, and its amplitude rarely exceeds 0.5 m.

Fig.6.1 Significance and amplitude (m) of the annual cycle in monthly mean Geosat H_s data from Nov.1986 to Oct.87. (From Carter et al., 1991)



Significance of the annual component: $\odot$ >99.9%; $\bullet$ 99.0-99.9%; + 95.0-99.0%; - 90.0-95.0%; $\cdot$ <90.0%.



Amplitude of the annual component of significant wave height (m).

Fig.6.2 Significance and amplitude (m) of the semi-annual cycle in monthly mean H_s data from Nov.1986 to Oct.87. (From Carter et al., 1991)

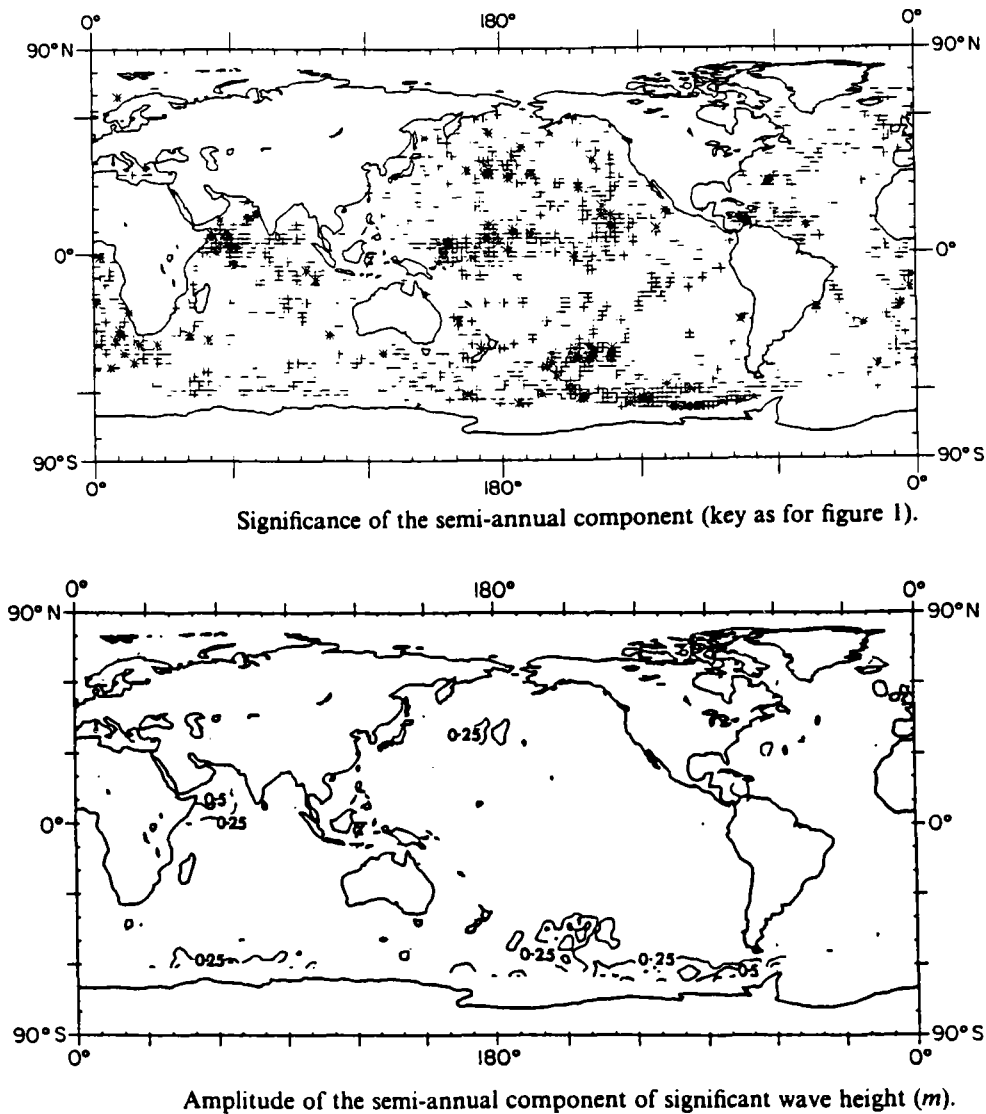
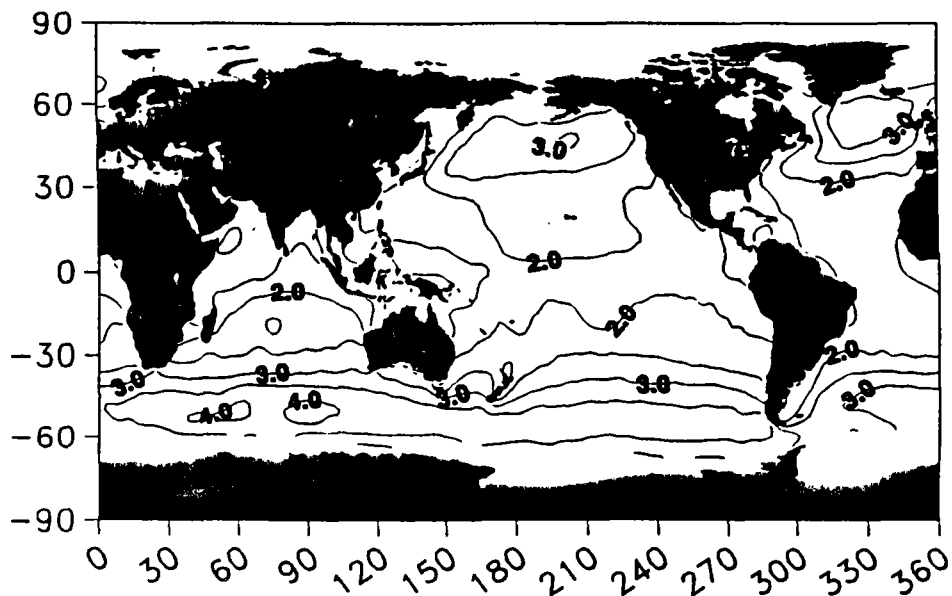
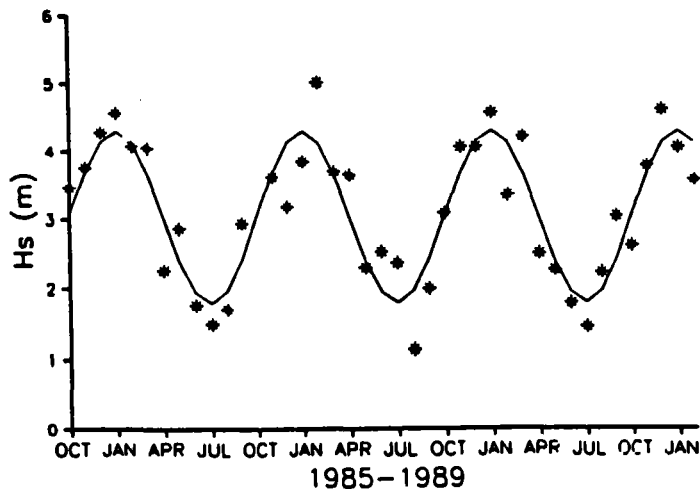


Fig.6.3 Fit to 12 monthly mean values of H_s from Geosat: mean value. (i.e. estimate of X_0 in Eq.6.2)



The variance explained by the model is about 60% - 80% over the open ocean in the northern hemisphere, mostly accounted for by the annual cycle. For example, Fig.6.4 shows the result of fitting this cycle to data around 57°N 47°W from October 1985 to February 1989, which explains 78% of the variance. (The semi-annual cycle is not significant. Its inclusion in the model leads to a *reduction* in the variance explained of 1%; this results from the decrease of 2 in the degrees of freedom.)

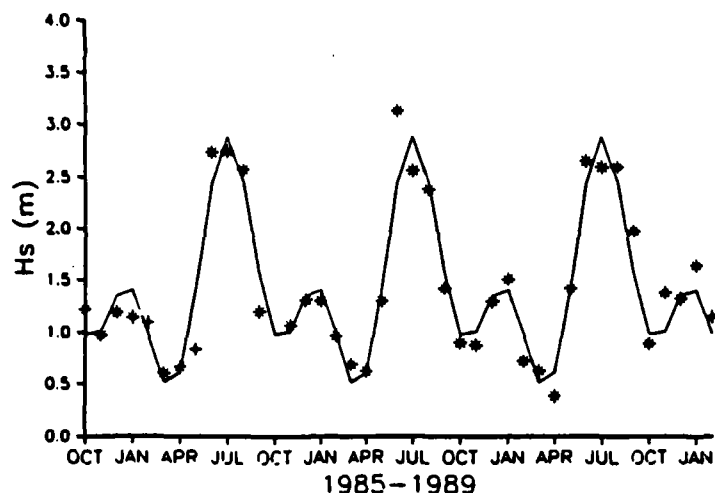
Fig.6.4 Monthly mean H_s from Geosat, Oct.1985 to Feb.1989, 56°-58°N 46°-48°W.



South of Japan, there is an area where the model is unsuccessful, explaining less than 20% of the variance. There are rather few transects of Geosat over this area which might explain the lack of success, but there are no fewer transects here than further north over the Sea of Japan where the model explains about 50% of the variance. As mentioned above, the lack of data probably explains the lack of fit in enclosed seas, such as the Mediterranean and Red Seas where a marked annual cycle might be expected. However, in general there seems to be little correlation between the number of transects and the variance explained. It might be that data from the area south of Japan are strongly 'contaminated' by high waves associated with typhoons which occasionally occur during most months of the year.

The model appears to be a particularly good fit in the Arabian Sea, explaining some 80%-90% of the variance. Fig.6.5 shows the results of fitting the model to the monthly mean values for the bin centred on 9°N 59°E. Both the annual and semi-annual cycles are highly significant at levels above 99.9%, reflecting the period of very high waves during the S.W. monsoon in July-August, and the moderately high waves during the N.E. monsoon in the winter months. The annual and semi-annual cycles explain 45% and 44% of the variance respectively.

Fig.6.5 Monthly mean H_s from Geosat, Oct.1985 to Feb.1989, 8° - 10° N 58° - 60° E.



The model is considerably less satisfactory in the southern hemisphere, where it generally explains only 40% - 60% of the variance, and in places less than 10%. Here the more interesting questions come from the apparent failure of the model. For example, there is a broad area from Central America across the Pacific to E. Australia where neither cycle is significant - as seen in Figs 6.1 and 6.2.. Here the monthly mean wave heights tend to be relatively low. The absence of either cycle over a large area west of Cape Horn is also intriguing, especially as this is an area of high wave heights. Fig.6.6 shows the data from 57° S 277° E; the monthly values of H_s appear to range from high to very high without any obvious cycles. Slightly further south, the semi-annual cycle is significant, as seen in Fig.6.2 and in Fig.6.7 for 61° S 277° E. Here both the annual and semi-annual cycles are highly significant (at >95%) even though they explain only 10% and 16% of the variance respectively.

Fig.6.6 Monthly mean H_s from Geosat, Oct.1985 to Feb.1989, 56° - 58° S 276° - 278° E.

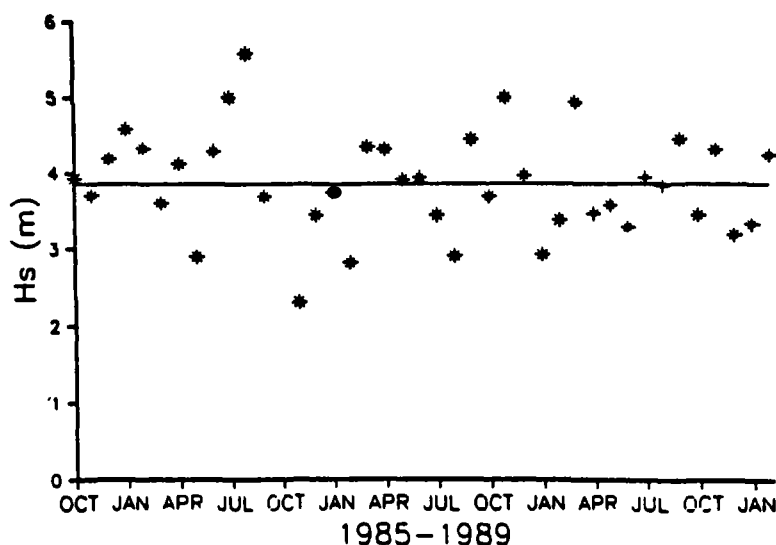
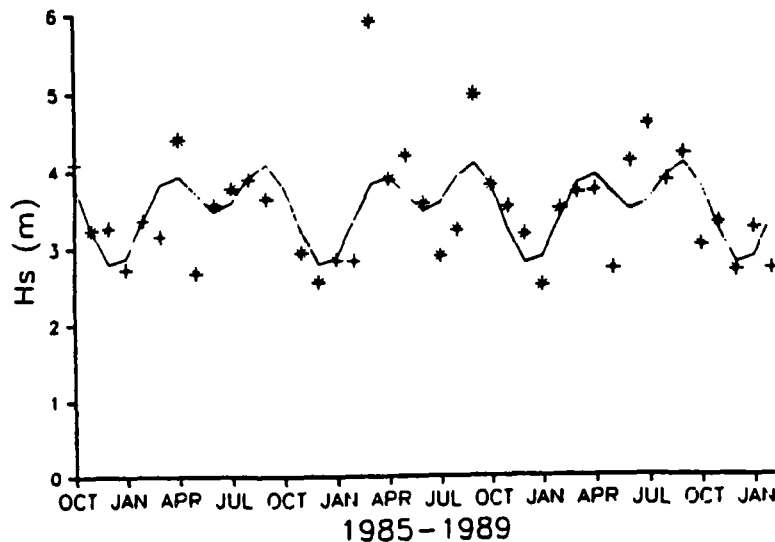


Fig.6.7

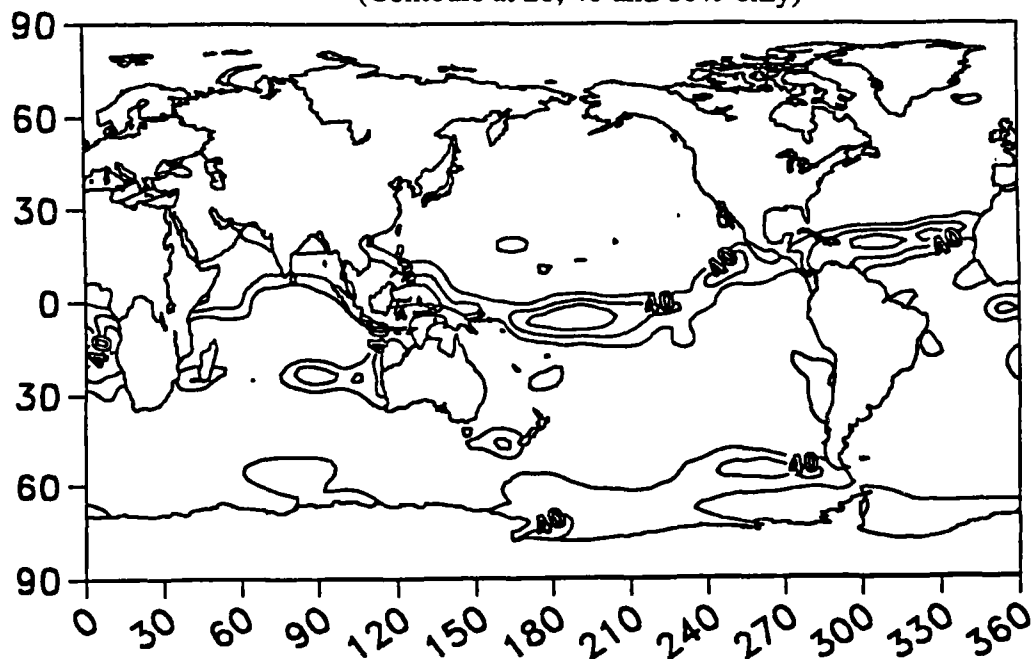
Monthly mean H_s from Geosat, Oct.1985 to Feb.1989, 60° - 62° S 276° - 278° E.

6.3.2 Wind Speed

Fitting the model to the monthly mean wind speeds gives pictures quite similar to those from the wave analysis - as might be expected - but in general the model is not such a good fit, rarely explaining 50% of the variance. This could be because Geosat provides fewer satisfactory estimates of wind speed than of H_s , or because H_s is less variable, being in some complex way an areal and temporal average of wind speed; probably both. Smoothing the monthly wind speeds with two passes of the 9-bin Gaussian filter, then fitting the model, results in a much improved fit, explaining generally 40% - 70% of the variance, but less than 20% in the region of the NE Trades in the Atlantic and Pacific (roughly 15° - 30° N). In the southern hemisphere, the model, even fitted to the smoothed data, rarely achieves a reduction in variance of 50%, and usually it is less than 30%. There is a general lack of fit along the swathe from Central America to E. Australia and west of Cape Horn, similar to the areas of lack of fit to H_s .

The model is a very good fit over much of the globe to the monthly mean wind speed climatology given in an atlas by Esbensen & Kushnir (1981), which is smoothed over $5^{\circ} \times 5^{\circ}$ bins, generally explaining more than 90% of the variance. There is no evidence of a poor fit from Central America to Australia, where in places the semi-annual cycle accounts for more than 40% of the variance - see Fig.6.8. The model is least satisfactory from about 45° S to 65° S, with large areas where neither the annual or semi-annual cycle is significant, but west of Cape Horn the semi-annual cycle explains 40% of the variance. This difference between the poor fit to the altimeter data and the good fit to the climatological atlas is probably due to the poor quality of the Geosat wind data and the small amount of such data - both to estimate monthly means and over so few years. But the ships' observations on which the atlas is based are notoriously inaccurate and in the southern hemisphere are few in number; and it may be that the heavy smoothing in the atlas obscures real features. So, it may be that the Esbensen and Kushnir winds are wrong, particularly in the southern hemisphere. Esbensen and Kushnir note a shortage of data south of 50° S, commenting on a 'deterioration' there in the comparison of the pressure gradient and wind speed fields.

Fig.6.8 Percentage of total variance in the monthly mean wind speed explained by the semi-annual cycle. (Data from Esbensen & Kushnir, 1981).
(Contours at 20, 40 and 60% only)



But measurements from Gough Island, in the south Atlantic around 40°S 10°W, indicate errors further north: Monthly mean wind speeds at Gough Island from 1968 to 1987, from South African Weather Bureau (1990), are given in Table 6.1. An analysis of these 12 monthly means shows that the annual cycle is not significant, but the semi-annual cycle is highly significant (at >99.9%) and accounts for 83% of the total annual variance.

Table 6.1 Monthly mean wind speeds (ms⁻¹) at Gough Island

Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Wind	7.5	6.8	6.5	6.9	7.0	7.6	7.6	7.2	6.8	6.6	7.0	7.5

Another reason for the relative lack of success in fitting the Geosat data compared to the fit of the Esbensen and Kushnir data, and that in Table 6.1 is that the monthly means have been averaged before fitting. This eliminates the between-year variation, so reduces the apparent total variance in the data. The comparison with estimates of the variance explained from the Geosat analysis is not strictly comparable. (Another example: van Loon and Rogers (1984) calculate that the semi-annual cycle accounts for 81% of the annual variance in the globally averaged sea level pressure between 50°S and 70°S. But their analysis was of twelve monthly means obtained from 12 or 13 years of data, eliminating the between-year variance.)

7 Wind Speed and Wave Height

7.1 Introduction

Waves in the open ocean are created by the wind, but the relationship between the two is complex. The radar altimeter gives concurrent estimates of wave height and wind speed, so provides useful data for the investigation of this relationship. Note that these estimates, from the shape and power of the return pulse respectively, are essentially independent. If the proposal by Glazman & Pilorz (1990) to improve the accuracy of the wind speed estimate from the altimeter by using the wave height information, is implemented, then this will no longer be so.

The sea state, the shape, speed of propagation, period and breaking of the waves, are determined by the strength of the wind and by the force of gravity; the only other factor of any significance is ocean currents which can occasionally have an effect. As the waves propagate into coastal waters, water depth becomes an important factor refracting the waves, causing breaking and the destruction of the waves. If the wind is blowing off the land then the waves at sites close to the shore are not fully developed but are 'fetch limited'. But in the open ocean, the only significant variable affecting waves is the wind. However, it is not only the wind presently blowing over the waves but also the wind hundreds of kilometres away blowing many hours ago, which put energy into the waves as they travelled towards their present location. Sometimes waves occur in the absence of any local wind; they have been created by distant storms and propagate into the area as 'swell'.

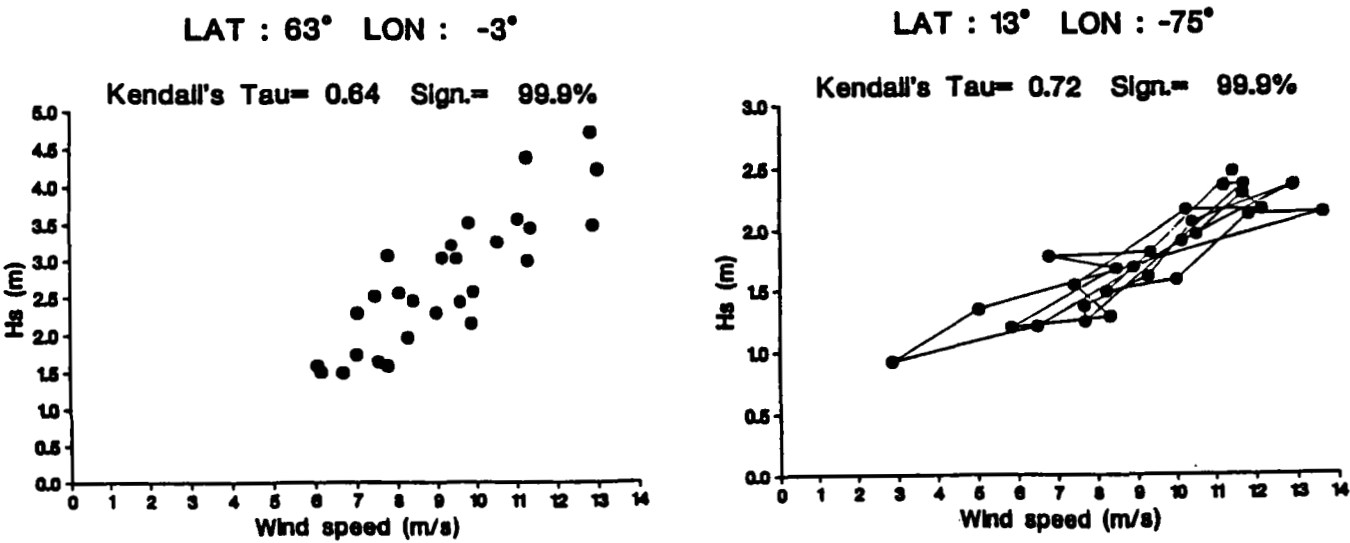
So, the significant wave height, H_s , at a location correlates with the wind speed and, for example, the Beaufort wind scale gives an estimate of wind speed based upon the appearance of the sea state. But the correlation can be poor. Partly because of the swell, but also because as the wind rises, it takes time for the seas to build up to their fully-developed height; until this occurs the waves are said to be 'duration limited'.

7.2 Relationship between monthly mean wave height and wind speed

As noted above, there is a complex connection between H_s and wind speed, and if instantaneous measurements from the open ocean of these parameters are made at the same time and plotted against each other, then the correlation is generally rather poor. However, as discussed in Section 6, the dominant component of monthly mean values over large areas of ocean of both parameters is the annual cycle. Moreover, these cycles tend to be in phase, with H_s and wind speed reaching their maxima at the same time of year. Consequently, where this occurs, the monthly mean H_s and monthly mean wind speeds are linearly correlated.

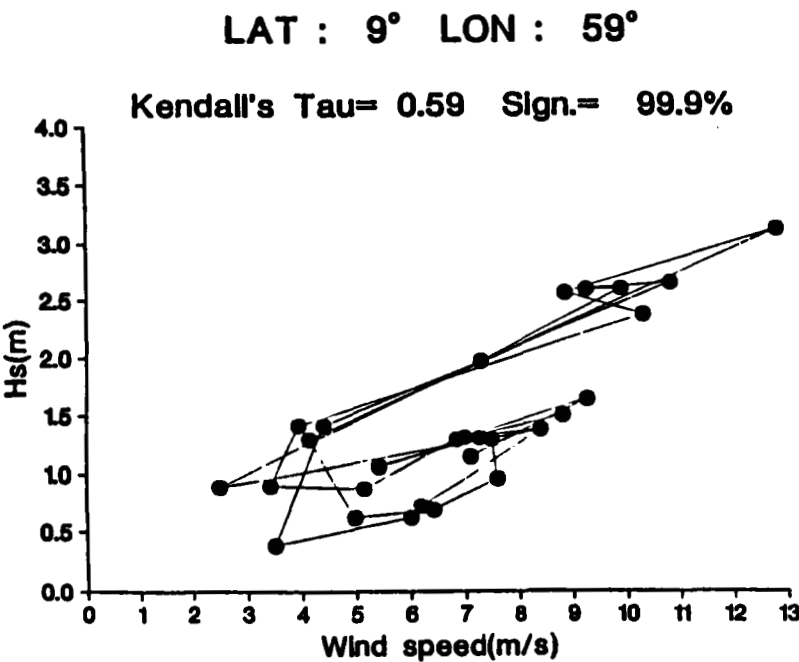
Fig.7.1 shows two examples, one from the Norwegian Sea, the other from the Caribbean. (Kendall's Tau value shown in these figures is a non-parametric test of correlation, the significance of which is also shown - 99.9% in both cases. The slope of the regression varies over the ocean, with H_s /wind speed tending to be highest in the northwest of the northern oceans - Atlantic and Pacific. Further research is needed to interpret these results.

Fig.7.1 Monthly mean H_s and wind speed values from Geosat data in the Norwegian Sea and the Caribbean.



The Arabian Sea is different (as usual). Fig.7.2 shows monthly mean H_s and wind speed from 9°N 59°E. Although the correlation is highly significant, clearly any attempt to estimate the monthly wave height climate to the monthly wind speed climate would not be very successful. The highest H_s occur in the SW monsoon, peaking in July; the secondary maximum with H_s around 1.0 - 1.5 m and wind speed around 9 m/s occurs during the NE monsoon during December - February. The higher waves occur during the SW monsoon partly because the winds tend to be higher then and partly because the fetch over which they blow tends to be longer, but the main reason seems to be the presence of larger swells from the south during that time.

Fig.7.2 Monthly mean H_s and wind speed values from Geosat data for part of the Arabian Sea



7.3 Wave development factor

Pierson and Moskowitz (1964) proposed a relationship between wind speed and the significant wave height of the corresponding fully developed sea, given by

$$H_s = \alpha U^2 \quad (7.1)$$

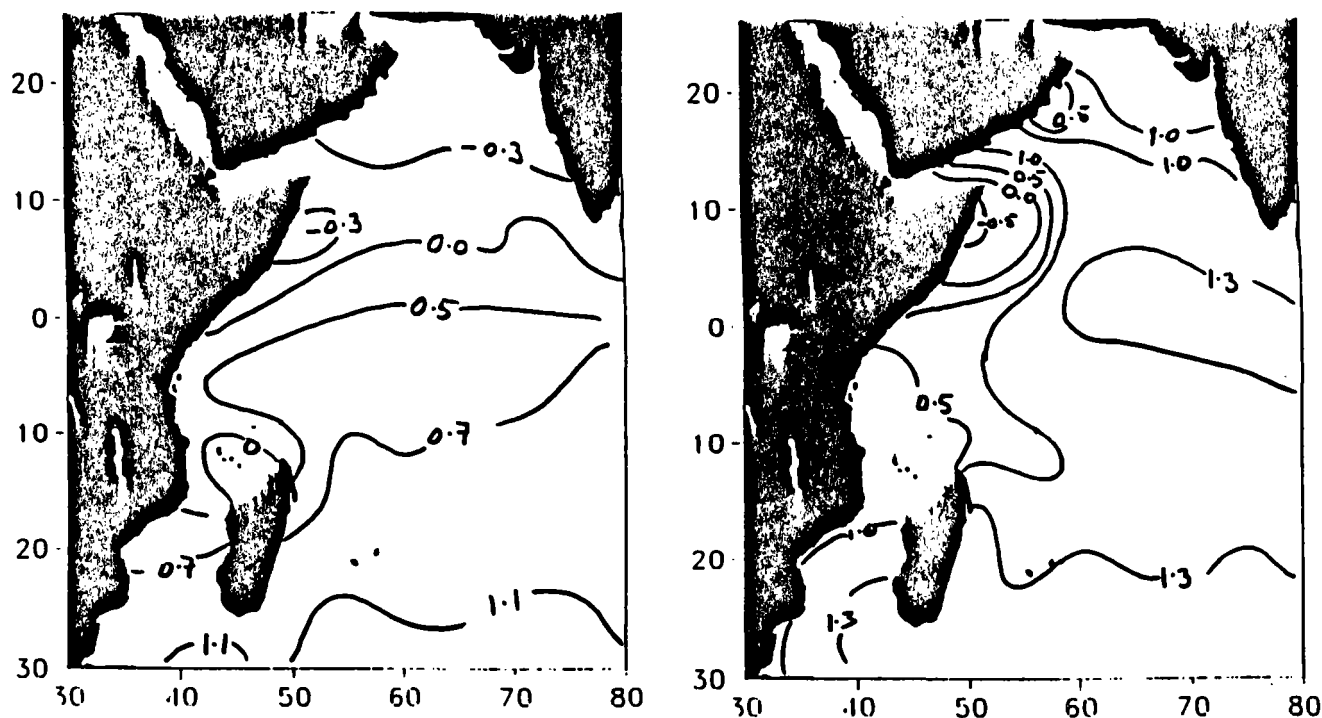
If H_s is in m, and U is the wind speed in ms^{-1} at 10 m above the sea surface then $\alpha = 0.02466$. (Pierson and Moskowitz's formula was originally for wind speed at 19.5m above the surface, the above value for α was obtained by Carter (1982) assuming $U_{10} = 0.93 U_{19.5}$).

If we calculate $X = H_s - \alpha U^2$ (using equation 7.1); then if X is negative, the wave field is not fully developed, and if X is positive, the waves are higher than the local wind could create so there must be some swell present. Even when $X < 0$, there could be a swell component, but X does give an indication of the development of the waves. The results of taking the monthly average value of X in the West Indian Ocean for January and July are shown in Fig. 7.3.

Fig.7.3 Minimum swell (given by monthly mean value of X - see text) (m)

JANUARY 1986-89

JULY 1986-88



In January, during the NE monsoon with winds coming off the Indian sub-continent, the waves in the Arabian Sea are not fully-developed and $X < 0$. Note also the small area to the northwest of Madagascar, where swell does not penetrate. But in July, with the SW monsoon at its peak and swell coming from the south, waves over the Arabian Sea are fully-developed except close to the Somali coast and in the Gulf of Aden where they are fetch-limited.

Note that Mognard (e.g.1983) has examined the distribution of 'minimum swell', which is related to X , but is numerically slightly different. Minimum swell is defined by assuming that the total wave energy (proportional to H_s^2) is made up of a swell term and a sea term.

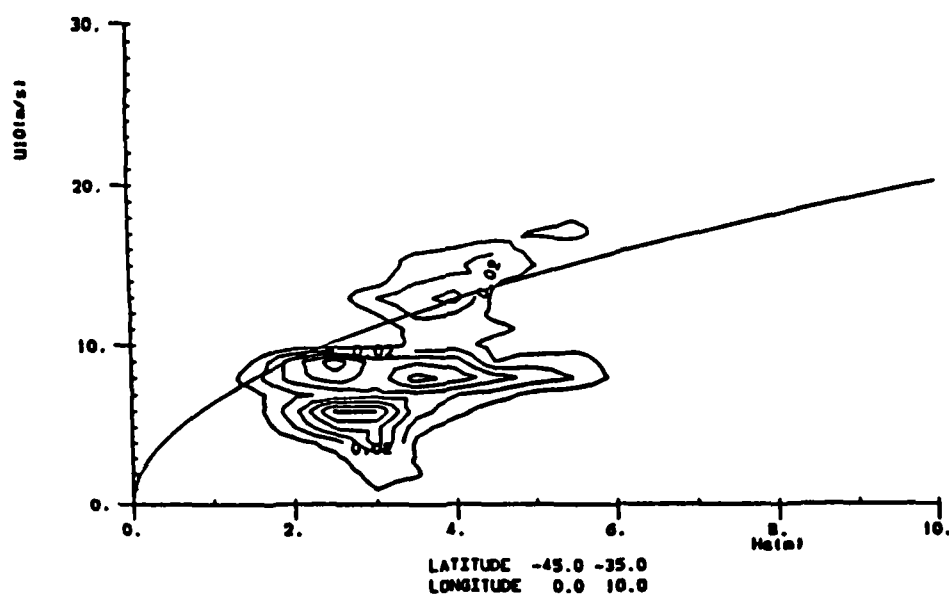
$$H_s^2 = H_{sea}^2 + H_{swell}^2$$

From (7.1) the maximum value of H_{sea} is αU^2 , so the minimum swell is given by:

$$H_{sw.min}^2 = \begin{cases} H_s^2 - \alpha^2 U^4 & \text{if } H_s^2 > \alpha^2 U^4 \\ 0 & \text{otherwise} \end{cases}$$

Challenor & Srokosz (1991) plot the two-dimensional histogram of H_s and U estimated from Seasat altimeter data, and use equation 7.1 to delineate between sea and swell conditions. Fig.7.4 shows their histogram for part of the South Atlantic, indicating a predominance of swell. They found similar results from other open ocean area - but the precise accuracy of the Seasat data is open to doubt.

Fig.7.4 Joint distribution of H_s and wind speed from Challenor & Srokosz (1991)



The contoured joint H_s - U_{10} pdf for the South Atlantic 10° square, estimated from Seasat data. The curve is the Pierson-Moskowitz relationship between H_s and U_{10} for a "fully developed sea".

8 Concluding remarks

The few months of global data from SEASAT obtained in 1978 showed clearly the importance of satellite radars for studying the oceans. Unfortunately, scientists had to wait until 1986 before any further data were available, from an altimeter on Geosat. These data have been extremely useful in advancing our understanding of such data, its limitations and strengths; and in helping to develop ways of analysing the data, and in particular in establishing the basis of a global wave climatology.

This report describes some of the research carried out into the uses of altimeter data for studying wind and waves, and gives references to much more.

I look forward to building upon this work with data from ERS-1, Topex/Poseidon and other satellites carrying a radar altimeter.

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Remote sensing of ocean colour

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Introduction

This set of notes summarizes two brief lectures on the remote sensing of ocean colour and temperature, their application, and a look at what the future holds. The first lecture covers the meaning of colour, its relevance in the ocean and the problems associated with detecting it from remote platforms such as space platforms and aircraft. Two current systems, the Coastal Zone Colour Scanner (CZCS) and Thematic Mapper are considered and their respective merits discussed. In the second focus is given to the applications of both colour and thermal remotely sensed data, in oceanic as well as coastal environments. Finally an introduction is given to the new generation of imaging spectrometers and results from some preliminary experiments carried out at Southampton with such devices will be presented.

What is Ocean Colour?

Colour (light) covers the visible part of the electromagnetic spectrum between 0.4 and 0.8 μm (or 400-800nm). At 400nm we have violet-blue light. As we go to longer wave lengths we pass through green-yellow and onto orange-red at the 700/800nm end. Below this range, 0.1-0.4 μm , is ultra violet radiation (most of which is absorbed by the ozone layer), whilst above are near infra-red (0.8-8.0 μm) and thermal infra-red (8.0-13.0 μm) radiation.

To understand more about the electromagnetic spectrum it is useful to consider two important governing equations.

The first, *Stefan's Law*, states that all bodies radiate energy at a rate proportional to T^4 (temperature, T , in $^{\circ}\text{K}$). This energy is in the form of electromagnetic energy with a spectrum of wavelengths (λ).

The second, *Wien's Law*, states that there is a peak of energy at λ_{max} for each body of temperature T ($^{\circ}\text{K}$) such that $\lambda_{\text{max}}T = 2897 \mu\text{m}^{\circ}\text{K}$ (ie constant). So hot bodies radiate short wave energy whilst cool bodies radiate long wave energy.

The implication is that, for the Sun: $T \sim 6000^{\circ}\text{K}$

$$\lambda_{\text{max}} \sim 0.5 \mu\text{m} (500\text{nm})$$

whilst for the sea surface: $T \sim 293^{\circ}\text{K} (20^{\circ}\text{C})$

$$\lambda_{\text{max}} \sim 11 \mu\text{m}$$

Over 50% of the energy from the sun is in the visible part of the spectrum and is referred to as short wave energy, the peak at 500nm. being blue light. That emitted (rather than reflected) from the ocean is referred to as long wave radiation or energy and is focused in the thermal infra-red part of the e.m. spectrum.

It is of interest to note that for both the incoming sunlight and outgoing thermal energy from the sea surface transmission windows occur in the atmospheric gases (sketch 1).

What actually determines the colour of an object, or why is a red ball red and a blue ball blue? The colour of an object or material depends not only on the light reflected from its surface but also on that which is absorbed. If we assume that the light striking an object is white, ie is composed of the full spectrum of colours, then the blue ball is blue because the blue light is reflected and the red light is absorbed - visa versa for the red ball. Similarly the oceans colour is determined by the absorption and reflection of light differentially at differing wavelengths.

So what happens to light when it reaches the sea surface? The incoming skylight (sketch 2) is assumed to have a fairly flat spectrum (white) although a combination of Wien's law and atmospheric particles gives a bias to the blue end of the spectrum. At the surface some of this light (about 5%, depending on sun angle) is reflected back to the atmosphere without modification. The rest enters the sea and is absorbed and scattered by: the sea water itself, organic particles (phytoplankton for example), inorganic particles (sediments), and dissolved constituents in the seawater. Often a stream of photons of light will undergo a number of scattering and absorption events, with some eventually upwelling to the surface. This upwelled light is *modified* in wavelength and intensity and, after some further reflection at the air-sea interface is re-emitted back to the atmosphere. It is this that determines the oceans colour. That energy which is absorbed by the water and particles contained therein warms up the ocean and is eventually emitted as long wave thermal infrared energy.

We now consider how each of the oceans constituents effect light. First we consider pure seawater. Sketch 3 shows the plot of absorption coefficient (K) against wavelength (λ μm). The attenuation of light in the sea is wavelength dependent, with energy penetration being given by:

$$I_z = I_0 e^{-Kz}$$

where I_z is the remaining radiation at depth z (Wm^{-1}), I_0 is the incident radiation, K is the absorption or vertical attenuation coefficient and z is depth. Note that I and K are wavelength dependent. The Y-axis of sketch 3 is also annotated with approximate depth equivalents for K values (ie the depth at which all energy is absorbed). Note that in the ultra-violet and infra-red regions seawater absorbs energy very efficiently - for thermal infra-red ($\sim 12\mu\text{m}$) energy is absorbed in the first few μm . There is a very convenient *hole* in the system in the visible range of $0.4\text{-}0.8\mu\text{m}$. In fact the least attenuation is at $0.5\mu\text{m}$, corresponding to λ_{max} for the incoming radiation. This blue light will penetrate to 100m in pure seawater. At increased wavelengths in the visible, towards red, light is absorbed more readily. Most red light is absorbed in the first few metres.

This all explains why the deep open ocean appears blue (though some sky reflection is also involved) and why many undersea photos also have a blue/green bias. Blue light is all that remains after a short depth to be reflected. Sketch 5 shows both the absorption (a) and scattering (b) of pure seawater, the scattering also being greater in the blue rather than the red.

Sketch 4 illustrates what happens to the light in the presence of chlorophyll, the main pigment of phytoplankton. The phytoplankton absorb blue light in order to photosynthesize, explaining the strong absorption peak at 440nm. In addition they fluoresce at about 685nm. The backscatter is fairly flat, but because most of the blue light has been absorbed then a high concentration of phytoplankton (chlorophyll) appears green. Sketch 6 shows the

reflectance spectra (effect of absorption and reflectance) for low to high concentrations of chlorophyll laden waters. The other annotations on the sketch will be covered later.

Sketch 7 illustrates what happens to reflectances in sediment laden waters, whereby absorption tends to be more evenly spread across the spectrum. Note that for sediments, as will be seen in the final section, the colour will vary dramatically depending on the mineralogy of the materials. Sketch 8 illustrates the effects of yellow substances or dissolved organics (Gelbstoff). In this case blue and green are absorbed by the gelbstoff, red by the water, leaving green-yellow; hence the name.

In typical coastal waters, where we get a combination of all of these factors then the picture is very complex. However, in open ocean waters, where sediments and gelbstoff are in very low concentrations and seawater and plankton dominate, the problem is more straightforward. This has led to a number of optical classification schemes being set up to describe water types. Jerlov described 3 ocean and 9 coastal water types (sketch 9), with ocean I being *pure* seawater, ocean III being water with strong bioactivity, coastal 1 being shelf-break water with low sediments and coastal 9 being the murkiest estuarine water. Generally, in remote sensing we tend to classify these to two simpler categories: **CASE 1** open ocean waters which can be assessed reasonably well by their colour and **CASE 2** waters which contain more than just water and bioproductivity and are a more complex problem.

How do we measure Ocean Colour?

The standard method for recording colour is by photographic techniques, using chemical processes. However these are qualitative, not very reproducible and getting the film back from a satellite is not particularly easy! Although it is a technique that has a place in airborne remote sensing and aboard manned spacecraft it is not really a scientifically viable media.

For remote sensing electronic scanners are used. These provide quantitative, reproducible (in a well calibrated system) data that can be stored and transmitted to a receiving station on the ground. In simple terms light from a target is passed through a filter or series of filters onto an electromagnetic sensitive sensor. This creates a voltage which is digitized and the data stored or transmitted. An integrated measure of the colour at discrete wavebands determined by the filter(s) within the field of view or footprint of the scanner is produced.

If the device is then moved to a new part of the target then an integrated view of that area is produced and successive pixel or footprints build up a complete image of the entire target. The instruments, or radiometers, fall into two categories; *scanning and push-broom* radiometers. Sketch 10 illustrates both. In the case of the scanning radiometer a rotating mirror focuses a part of the scene below through a series of optics onto an array of detectors, each with its own filter measuring a part of the light spectrum (ie red, green, yellow, blue etc.). The data is logged and then the mirror scans the next part of the scene or swath. Eventually a complete scan line is made. The platform, whether it be a satellite or aircraft, is moving over the ground/sea as this occurs so that when the mirror finally returns to its original starting point it is now viewing a new piece of the area further along the ground track. In this way an image is built up of the underlying scene.

In the case of the push-broom radiometer a line array of sensors *views* the underlying scene. Each sensor element is focused on a part on the scene below and so the *scan line* is viewed simultaneously. Multi channel (or colour) information is obtained by a two dimensional array of sensors, one dimension covering the spatial swath, the other the spectral information (see CASI later).

The push-broom has the major advantage of no moving parts, but the disadvantage of more complex electronics, though with recent advances in CCD array technology this is becoming less of a problem.

These numbers can then be reconstructed as images, or pictures, for analysis back on the ground. There are a number of immediate problems with the data, which apply equally to colour and thermal sensors.

The first is **GEOMETRIC DISTORTION**. The footprint of the sensor directly beneath the sensor (at Nadir) will be smaller than that at the edge of the swath. However when the data is reconstructed as an image it is initially assumed that all of the pixels represent the same area, making the image look compressed at the edges. This can be corrected using either the geometry of the system or using known *ground control points*, landmarks on the image, the positions of which are known. This is simple for most land applications and fairly straight forward for coastal areas, but there are few landmarks in the open ocean. Further distortions are introduced by the curvature of the planets surface, the non-uniformity of the sensors motion such as yaw, pitch and roll (particularly major problem on airborne sensors) and the non-linearity of the sensors optics. Again, if these factors are recorded or known then we can mathematically correct for them.

The second is **CALIBRATION**. The sensor itself distorts the radiance reaching it and there will also be sensor noise and drift to account for. These can be corrected using either on-board calibration lamps and sources on board the space craft, or by laboratory calibration for aircraft sensors and predeployment space sensors.

The third is **SENSOR RESPONSE**. Satellite radiometers are designed to measure radiant flux, Φ , in restricted wavelength ranges λ_1 to λ_2 say. Ideally:

$$\Phi(\lambda_1\text{-}\lambda_2) = \int_{\lambda_1, \lambda_2} \Phi_{\lambda} d\lambda$$

This basically produces a square response with no signal either side of the $\lambda_{1,2}$ range. In reality the sensor has a spectral response (ie: does not have an equal response to all λ_1 to λ_2) and does not have a clean *cut off* at $\lambda_{1,2}$. The sensor has a response dependant on wavelength, $R(\lambda)$, such that the output signal in volts from the sensor is:

$$S_{\text{volts}} = \int_{0, \infty} R(\lambda) \Phi_{\lambda} d\lambda$$

The stated bandwidth will be:

$$(\lambda_2 - \lambda_1) R_{\text{peak}} = \int_{0, \infty} R(\lambda) d\lambda$$

which implies that:

$$\Phi(\lambda_1 \text{ to } \lambda_2) = S/R_{\text{peak}}.$$

The final, and major problem, is that of atmospheric interference (for both colour and thermal remote sensing). Gaseous components and atmospheric particulate materials effect intensity and spectral distribution of energy leaving the ocean and reaching a sensor in the air or in space. Problems of *absorption* and *scattering* are encountered.

It was seen earlier that absorption bands (opaque atmosphere) and atmospheric windows (transparent atmosphere) occur due to the component gases of the atmosphere. This absorption by the gas molecules raises the energy level of the atmosphere and this excess energy is re-emitted as thermal infra-red energy. In addition the signals from the sea surface are absorbed.

Scattering of energy, or reflection, also takes place due to particles such as molecules, dust and water droplets in the atmosphere. These can be considered in three classifications:

- (i) Rayleigh scattering, where the particle sizes are much smaller than λ ,
- (ii) Mie scattering, where the particle sizes are of a similar size to λ , and
- (iii) Non-selective scattering, where the particle sizes are much larger than λ .

Rayleigh scattering can be reasonably well modelled for the various regions of the world and given some background meteorological information. However, Mie and non-selective scattering are highly variable over small time and space scales and as such are unpredictable. Scattering by particles reflects energy into the optical path of the sensor which adds to target reflection from outside the target area, as well as leading to a loss of energy from the target itself. In trying to correct for this we are effectively trying to solve the equation:

$$L_s = L_a + L_R + T'L_w$$

where L_s is the signal arriving at the sensor, L_a the overall effects of aerosol particle scattering (mie and non-selective), L_R the effects of Rayleigh scattering, T' the diffuse transmittance (similar to beam transmittance in oceanography) and L_w is the water leaving radiance (The Objective!). The table below shows the relative contributions of each component to the signal reaching the instrument. $T'L_{refl}$ represents surface reflections.

Wavelength (nm)	Contribution to signal (%)					
	Clear water			Turbid Water		
	$T'L_w$	$L_R + L_a$	$T'L_{refl}$	$T'L_w$	$L_R + L_a$	$T'L_{refl}$
440	14.4	84.4	1.2	18.1	80.8	1.1
520	17.5	81.2	1.3	32.3	66.6	1.1
550	14.5	84.2	1.3	34.9	64.1	1.0
670	2.2	96.3	1.5	16.4	82.4	1.2
750	1.1	97.0	1.9	1.1	97.4	1.5

As can be seen in general 80% of the signal reaching the sensor is actually atmospheric noise which needs to be corrected before the data can be used in quantitative applications. In many equations and algorithms developed to solve the problems L_{ss} is used as opposed to L_w . L_{ss} is the *subsurface* radiance rather than the water leaving radiance L_w , whereby:

$$L_{\text{ss}} = n^2 L_w (1-\rho(\theta'))^{-1} ,$$

where n is the refractive index of the air/water interface and ρ is the surface reflectivity, both are dependent on wavelength and ρ is very dependent on θ' , the view angle.

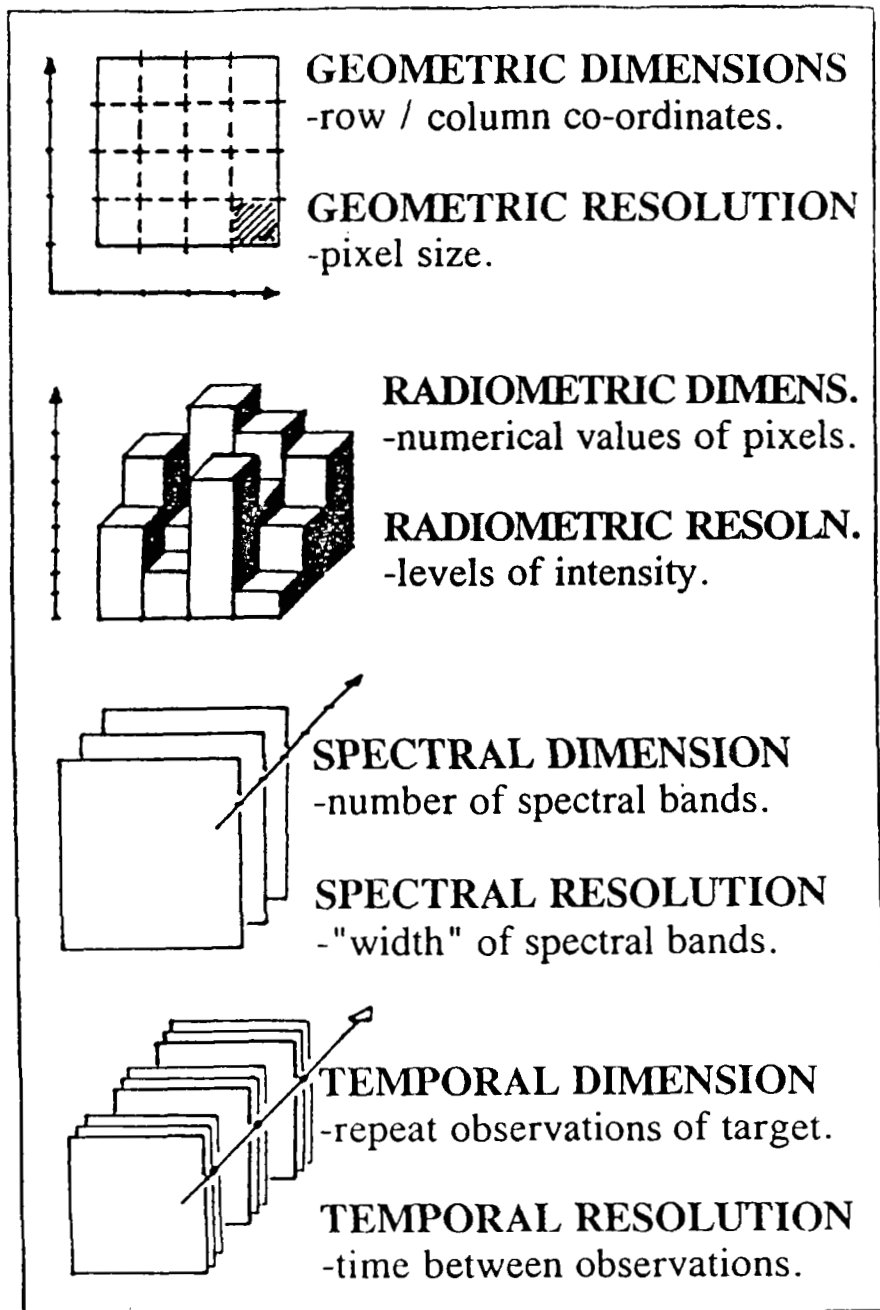
In the open ocean it is assumed that the L_{ss} in the near infra-red part of the spectrum is zero; the sea neither emits nor reflects much energy at these wavelengths. Thus any signal in this part of the e.m. spectrum is tacitly from the atmosphere, enabling a correction to other wavebands where one may expect sea signals. This approach was used in the CZCS (see next section) with a waveband at about 700nm. Whilst it proved sufficient for corrections in case 1 waters, it failed in case 2 waters where strong sediment concentrations gave signal returns at these wavelengths. The approach has been to take a *darkest pixel* approximation whereby it is assumed that somewhere within an image there is no return at the red end from the sea. Assuming a locally homogeneous atmosphere, this would give the lowest signal return in the image for that channel, ie it would be the darkest pixel. This pixel would then be used to correct the rest of the image. The system assumes much and its success is varied. However the only viable alternative is for synoptic measurements to be taken at sea of atmospheric turbidity and of L_{ss} in order to effectively atmospherically calibrate the image.

Existing Ocean Colour Systems

When considering design criteria of sensors for both colour and temperature measurement there are four important *Dimensions*. These are illustrated over the page.

The Geometric dimensions determine the row/column co-ordinates, the latitude and longitude of the systems view. The geometric resolution determines the pixel size - the minimum spatial resolution of the system. There is often a balance between resolution and overall dimension. Most instruments have a limit to the number of pixels that can be obtained in a single swath, so a high resolution (small pixel size) also means a limited area of coverage. Thus, on the one hand if one is studying mesoscale eddies in the open ocean, a wide swath of say 500 - 1000km, with 1 km. resolution would be more suitable than a 60km swath with 10m resolution. Equally if one was studying the fate of a sewer outfall off a coastline the spatial resolution of the later specification would be essential.

The Radiometric dimensions determine the numerical values of the pixel, the intensity of radiation (irrespective of wavelength). The differences of intensity across the marine environment tend to be quite small. However, many sensors are shared with the land remote sensing community where intensity variations from a light building to a dark road, or a snow capped hill to a deep lake are large. A sensor set up for ideal radiometric range and resolution for the ocean would saturate over land quite readily and so often a compromise has to be reached. Improvements are being introduced by using 12/16 bit instruments rather than 8 bit systems.



The Spectral dimensions determine the number and coverage of the spectral bands; is the system measuring just one wavelength or a spectrum of bands? The resolution is determined by the width of the bands. The importance of these will become clearer when we consider two widely used systems, CZCS and TM.

The temporal dimension determines the repeat observations of a target and the resolution the time between successive observations. For land applications high frequency sampling is either not required or can be readily achieved on the ground without recourse to remote sensing techniques. However, the ocean varies on time scales of seconds - minutes - hours - days, all of which can be measured from a point source but the spatial/temporal perspective can only be obtained using remote sensing. Again, a large scale ocean feature may only require sampling every few days, whereas a coastal feature in tidally dominated waters requires sampling intervals in minutes/hours.

Two spaceborne scanners have been widely used by the marine science community for some years now: The *Coastal Zone Colour Scanner (CZCS)* and the *Thematic Mapper (TM)* flown aboard Nimbus 7 and the Landsat series of satellites respectively.

The first of these, the CZCS, was designed specifically for marine applications and its specifications are given in sketch 11. It was launched in 1978 and continued to collect and transmit data until June 1986. It had a wide swath width with a resolution of 0.825km. (at nadir). The wide swath meant that on a polar orbit each point on the Earth's surface could be sampled twice a day (though one of these were at night - of limited use for colour, but useful for thermal infra-red), if the CZCS was on and clouds willing. It made it an ideal open ocean and offshore instrument. It had six bands: 4 visible, one near infra-red and one thermal infra-red (though this gave poor sea resolution and failed early on in the mission). The wavebands were relatively narrow (~20nm) and the radiometric resolution and range were well set up for the marine environment, even though it was only an 8-bit system.

The bandsets on the CZCS were chosen to specifically measure chlorophyll, and as can be seen by referring back to sketch 6 (spectra for differing chlorophyll concentrations) by ratioing the bands (which are marked on the curves) it should be possible in case 1 waters to measure chlorophyll. Assuming accurate atmospheric correction (ie $L_w \approx 0$ at 670nm - channel 4) then two channels are required to determine chlorophyll concentration. NASA use:

$$C \text{ (chlorophyll in } \mu\text{g/l)} = 1.13(L_{ss}(443)/L_{ss}(550))^{-1.71} \quad \text{for } C \leq 1.5\mu\text{g/l}$$

$$3.326(L_{ss}(520)/L_{ss}(550))^{-2.439} \quad \text{for } C \geq 1.5\mu\text{g/l}.$$

The second system, the TM, was designed for more general applications - mostly land based. This requires high spatial resolution (good for near shore studies) but has poor swath coverage as a result. A number of systems have been operational over the years and in addition a French system, SPOT, is also available. The TM specifications are given in sketch 12. Again it is an 8-bit system, but the sensors have to cover a much higher dynamic range and so the radiometric detail measured over the sea is very poor - over open sea no variability is usually observed. The bandsets (7 in total) cover a wider part of the e.m. spectrum, with only bands 1-3 and 6 being of any use in the marine environment. In addition the bands are quite broad, making any determination of the complex sea spectra difficult. The greatest drawback is the repeat time for an overpass at a particular point on the Earth's surface - 12 to 18 days! In European waters, in a typical year of cloud cover, only 3 images are obtainable for a particular target.

Regional and Global Applications

This final section provides a brief overview of the wide range of applications of remotely sensed ocean colour and temperature.

The use of CZCS data to measure chlorophyll and hence phytoplankton concentrations worldwide is perhaps the most important Global application. The technique is timely with current uncertainties on *Global Warming* and both archive CZCS data and future colour scanner missions provide a timely data set for programmes such as WOCE and JGOFS. It has been shown that chlorophyll concentrations can be determined by band ratioing. There are a number of uncertainties in transferring a measure of the integrated near-surface chlorophyll concentrations to an overall depth integrated measure of phytoplankton (eg; effects of other pigments, consistency of a direct chlorophyll/phytoplankton relationship, and the relationship of near surface concentrations to other depths) but in comparisons with in-situ depth integrated measurements values compare to better than 20%. Given the uncertainties in chlorophyll measurement in-situ, this figure is encouraging. The algorithms break down in the transition between case 1 and case 2 waters but 82.5% of the total productivity of the global marine environment is thought to occur in case 1 waters. The ability to provide long term seasonal maps of global productivity, and to monitor interannual variability over decades will be essential in understanding the global carbon cycle.

The limitations of direct water quality assessment using CZCS/TM in case 2 waters does not preclude applications in the coastal zones. The spatial patterns of suspended materials have been used to study shelf sea dynamics by a number of researchers. An example of a study made of the Channel utilizing CZCS data in conjunction with models and current measurement demonstrates the importance of the remotely sensed data in providing an otherwise unobtainable spatial and temporal perspective.

The importance of using both thermal and colour data in studying a region is demonstrated with data obtained using an airborne Thematic Mapper off the south coast of England. The advantage of the aircraft platform is not only improved spatial, and controllable temporal resolution, but the fact that synoptic sea-truth data becomes easier to co-ordinate and obtain. Examples of improved algorithms for both sediment and chlorophyll concentrations are possible if quasi-synoptic data are available, and examples are shown. However, detailed water quality assessment, the ultimate aim for the technique of remote sensing, is still not possible with the limited broadband sensor technology.

The new generation of sensors, imaging spectrometers, are discussed and examples of data off both the UK and France are presented. Imaging spectrometers are push-broom sensors that have very high spectral and radiometric resolution. Typically they may have 200-300 channels in the visible range with bandwidths of 2-3nm. The data has a much higher dynamic range (12 or 16 bits) and the hardware/software combinations provide a potent tool for the oceanographer in all disciplines of the subject. The problem for the user community now is how to interpret the data. Libraries of spectra for single scatterer populations can be built up for cross referencing with sea data. However, few areas of case 2 waters are dominated by only one or two scatterers. Some unique features, such as the fluorescence emission of chlorophyll, can be detected above the background signal from the sea and success has been achieved in obtaining reliable algorithms for chlorophyll in case 2 waters with such devices.

As such there are a limited number of such systems available. The Moniteq FLI was one of the first which has now been superseded by the ITRES CASI (Canadian). Within Europe a number of companies and institutes have begun development of such systems, with two (Corsair - a line scanner, and Caesar - a true imager) now operational in The Netherlands.

Plans for the deployment of spaceborne imaging spectrometers are advancing with instruments such as the MERIS planned for deployment later in the 1990's. However, one of the many problems of transferring the technology to space platforms is the volume of data produced by such systems. With only 6 channels CZCS has produced vast quantities of data most of which has yet to be studied. With up to 50 times as many channels the problem of data transfer to ground stations and of data archiving becomes important.

One final problem still exists for both thermal and colour measurement from space. It is assumed that sea-truth measurements are just that - true. The remotely sensed data is then compared to this and any discrepancies are attributed to the remote data. In the case of temperature the data from a vessel is subtly different to that from above the surface because of the skin layer effect. The relationship between the surface skin temperature and the underlying bulk temperature still requires further detailed study. In addition, in studying the air-sea boundary layer questions arise as to which is the more relevant measurement. In the case of colour there are as many discrepancies between differing *established* techniques of in-situ measurement as there are between the in-situ data and the remotely sensed data products. Which is correct?

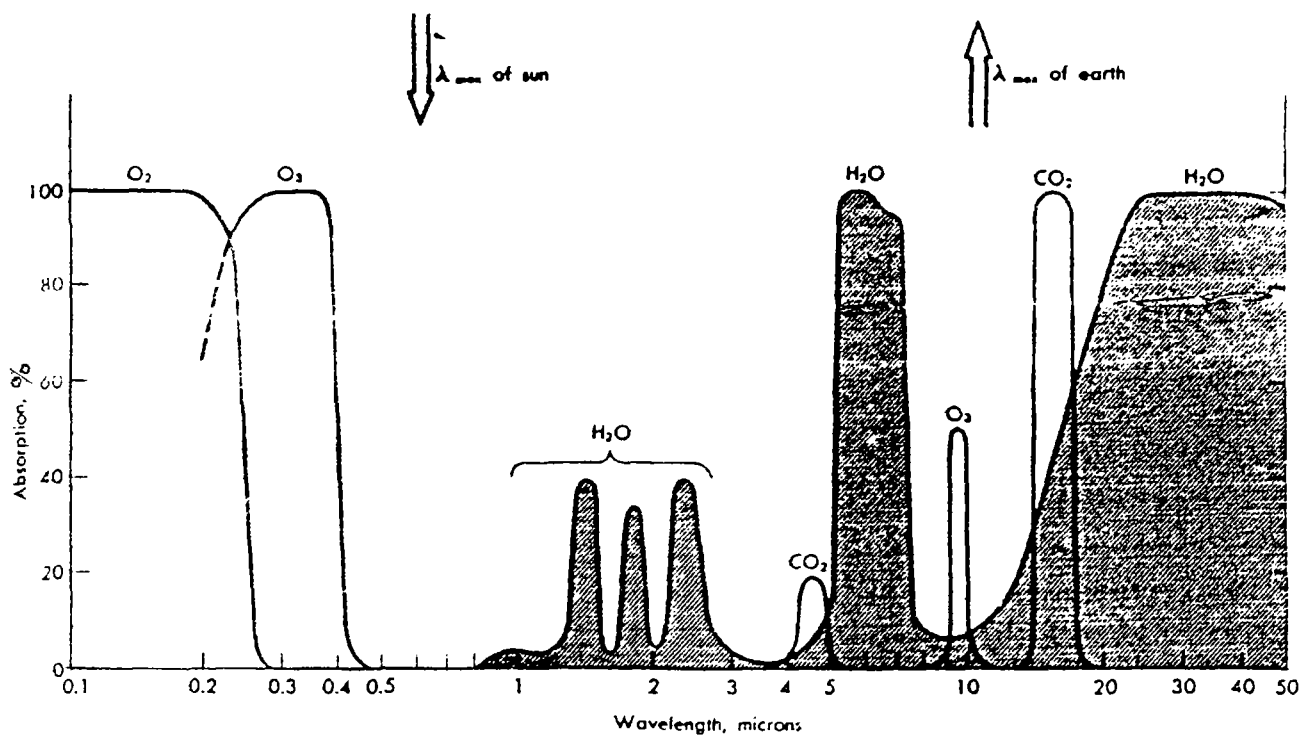


Figure 1

Schematic diagram of the absorptivity of water vapour and other atmospheric gases

What happens to light when it reaches the sea surface?

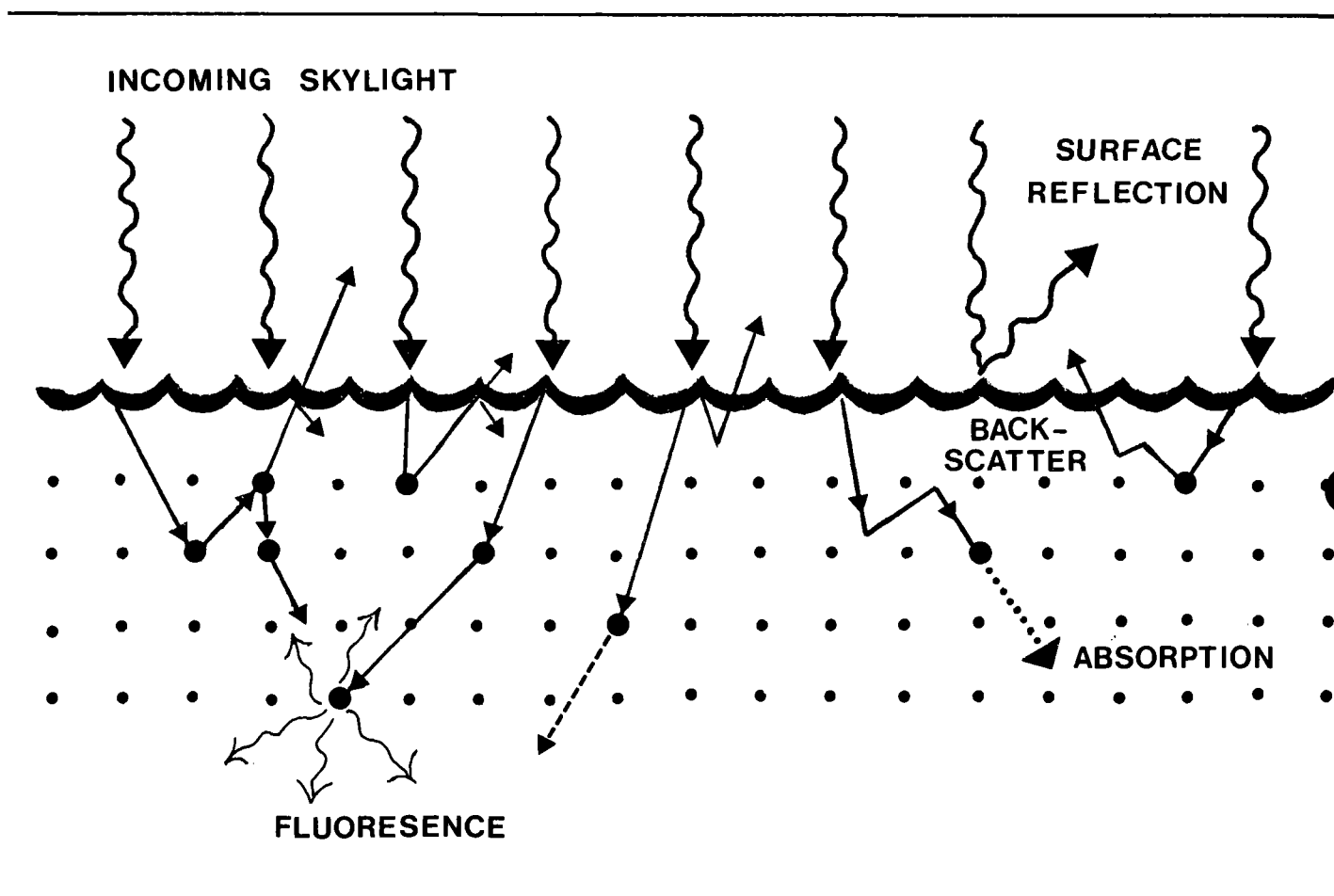


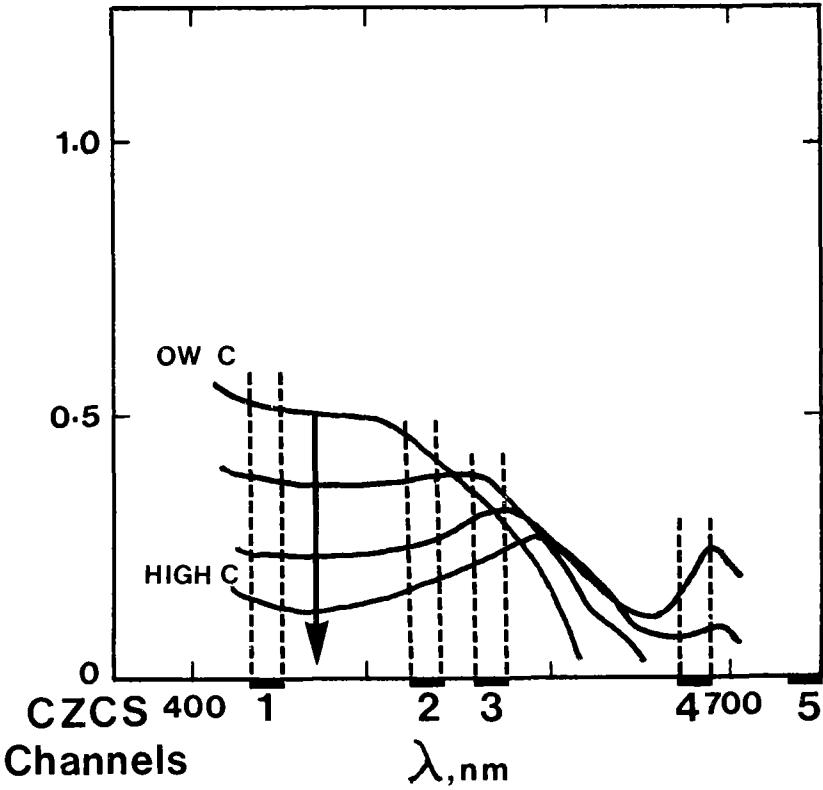
Figure 2

Absorption and scattering by sea-water

Absorption and scattering by suspended material (organic and inorganic)

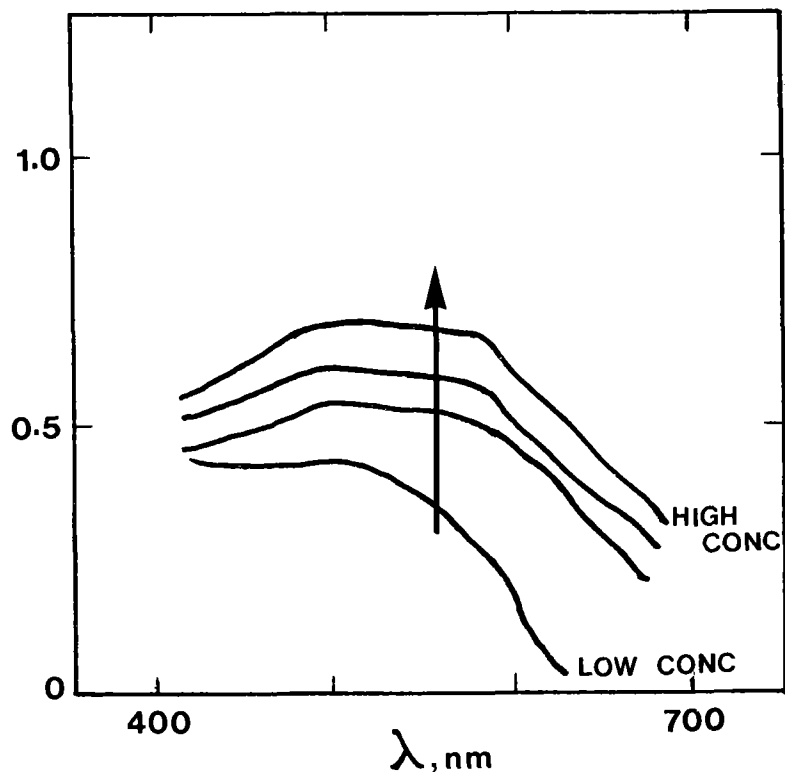
Light scattered back to the surface (upwelling light) is modified in wavelength and this determines the ocean's colour

Figure 6



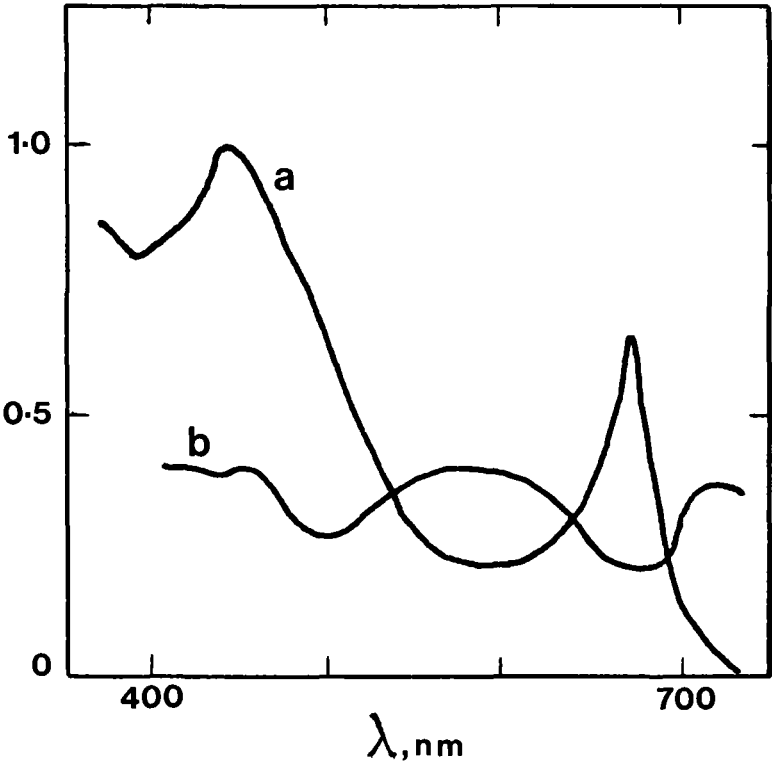
REFLECTANCE SPECTRA FOR
CHLOROPHYLL-LADEN WATER.

Figure 7



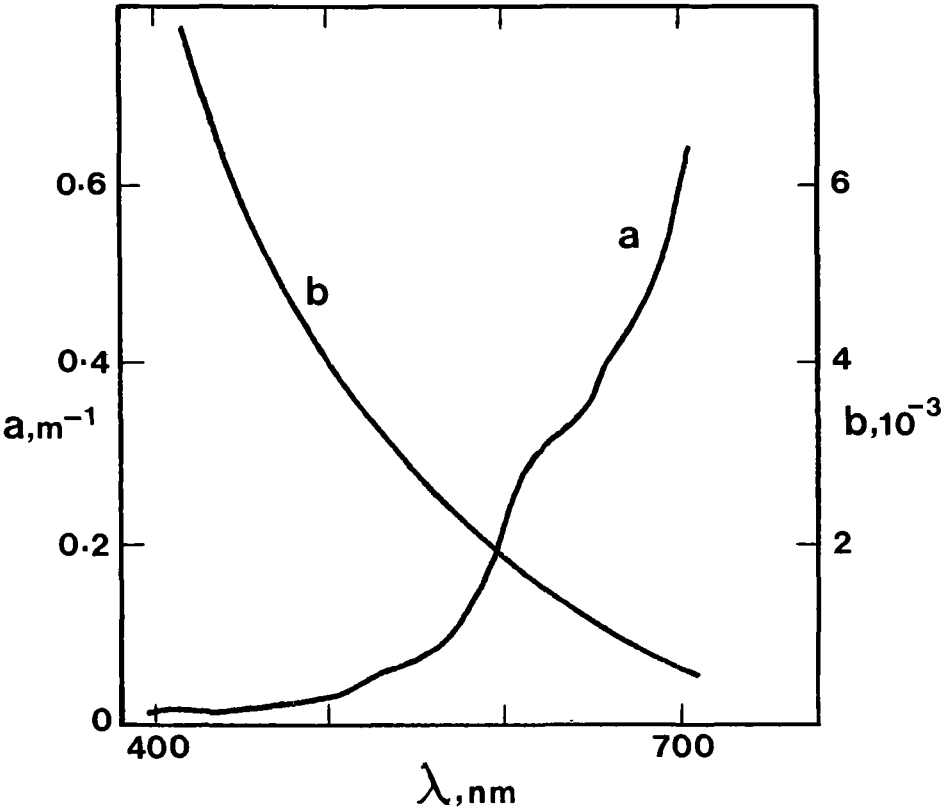
REFLECTANCE SPECTRA FOR
SEDIMENT-LADEN WATER.

Figure 4



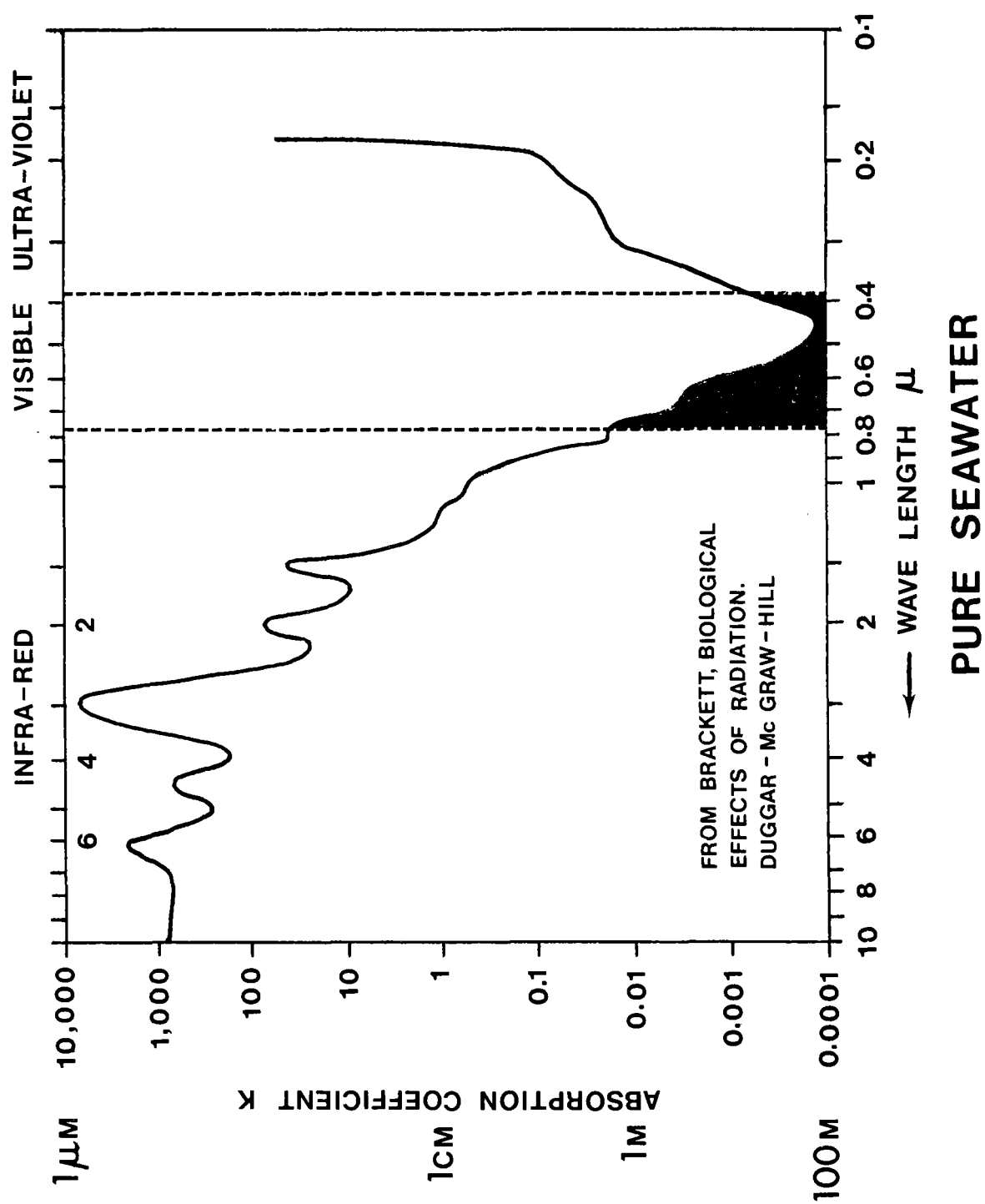
Typical spectral variation of (a) absorption due to chlorophyll, normalised at 440 nm and (b) specific backscatter coefficient. Values of (a) at 440 nm vary between 0.01 and $0.1 \text{ m}^{-1} (\text{mg m}^{-3})^{-1}$, depending on the age and species of phytoplankton. Units of (b) are typically of the order of $10^{-3} \text{ m}^{-1} (\text{mg m}^{-3})$.

Figure 5



Absorption (a) and scattering (b) of pure sea-water.

Figure 3



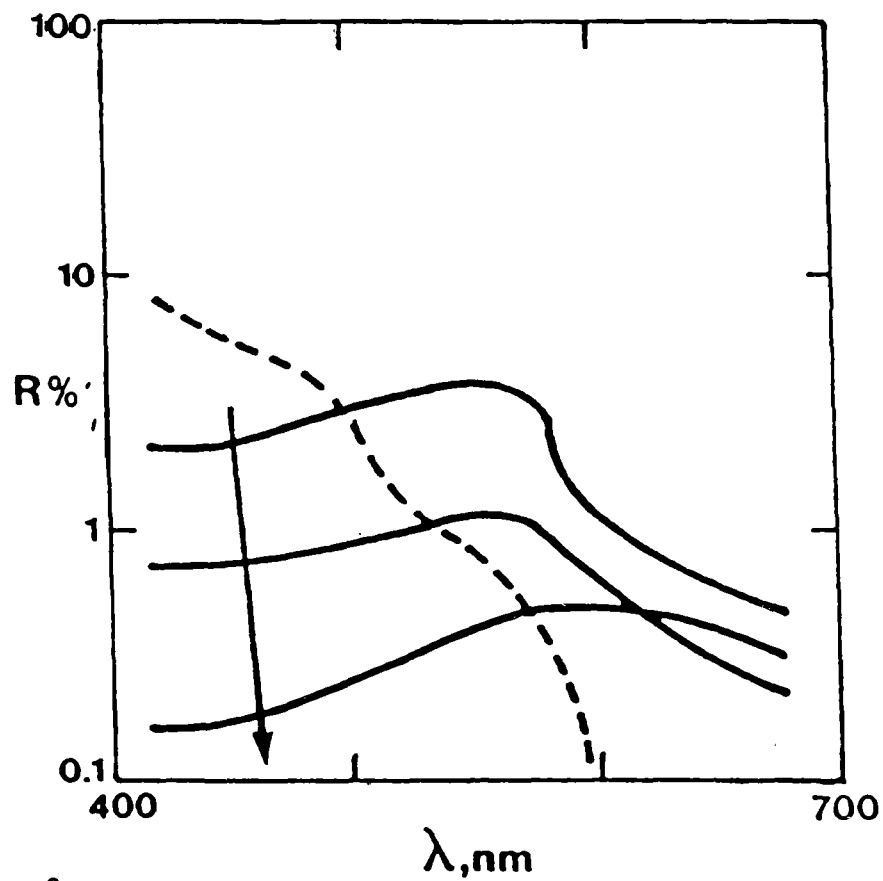


Figure 8

Typical reflectance spectra for yellow-substance dominated case 2 water. The arrow indicates increasing concentration. The dashed line is the clear-water spectrum.

JERLOV WATER TYPE	EXAMPLES OF TYPE	DEPTH FOR ATTENUATION OF 90% OF INCIDENT SOLAR RADIATION	DEPTH FOR ATTENUATION OF 99% OF INCIDENT SOLAR RADIATION	GENERAL WATER TYPE
OCEAN 1	SARGASSO SEA (NO BIOACTIVITY)	33	85	CASE 1
OCEAN 2	N.E. ATLANTIC	14	45	
OCEAN 3	EQUATORIAL E. PACIFIC (UPWELLING, STRONG BIOACTIVITY)	8	25	
COASTAL 1	CONTINENTAL SHELF BREAK	7	20	CASE 2
COASTAL 9	BALTIC SEA	2	5	

Figure 9

SCANNING

AND

PUSH BROOM

RADIOMETERS

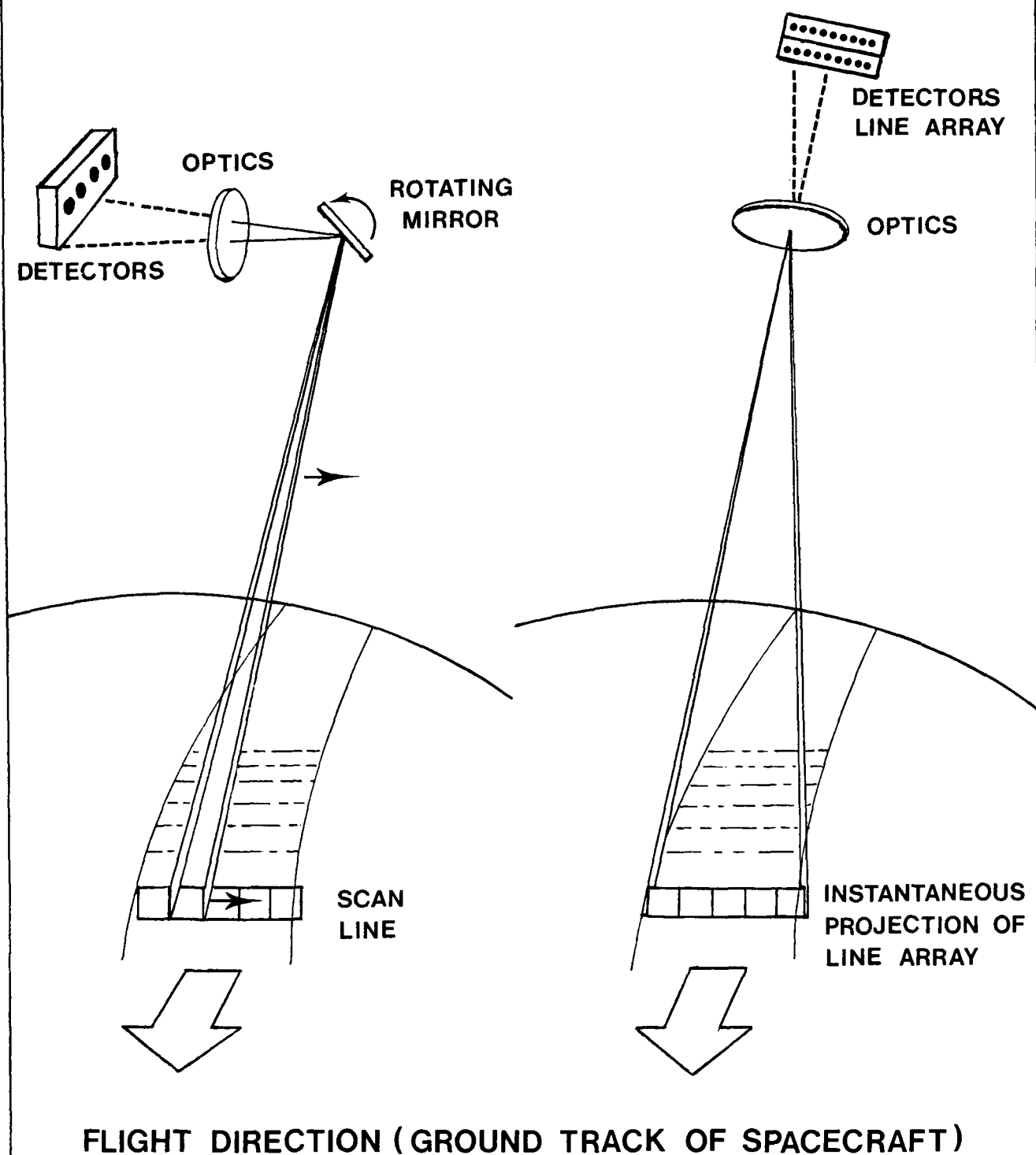


Figure 10

Figure 11

Characteristics of the Coastal Zone Colour Scanner (CZCS)

Band No.		1	2	3	4	5	6
Wavebands, nm		443 ± 10	520 ± 10	550 ± 10	670 ± 10	700 → 800	10.5 → 12.5 μm
Saturation radiance							
	max. gain	5.41	3.50	2.86	1.34	23.9	
	(mW cm ⁻² μ ⁻¹ sr ⁻¹)						
	min. gain	11.46	7.64	6.21	2.88	23.9	
No. of digitisation levels				256			
Angular field of view				0.825 m rad			
Ground IFOV at nadir				825 m × 825 m			
Max. scan angle from nadir				± 39°			
No. of samples per scan line				1968			
Swath width							
(when not tilted in track direction)				1636 km			

Notes: Channel 6 gave poor sea resolution and failed eventually.

Channel 5; land/cloud determination, no sea return except in very turbid waters.

Figure 12

Characteristics of the Landsat Thematic Mapper (TM)

Band No.	1	2	3	4	5	7	6
Nominal wavebands μm	0.45–0.52	0.52–0.60	0.63–0.69	0.76–0.90	1.55–1.75	2.08–2.35	10.4–12.50
No. of digitisation levels	256	256	256	256	256	256	256
Radiometric sensitivity							
(noise equivalent reflectance %)	0.8	0.5	0.5	0.5	1.0	2.4	
(noise equivalent temperature deg. K)						2.0	0.5
Ground IFOV at nadir			30 m × 30 m				120 m × 120 m
Maximum scan angle from nadir			± 7.5°				
Length of scan line (swath width)			185 km				
No. of samples in scan line (approx.)			6200				1550
Pixel size at sub-point			30 m × 30 m				120 m × 120 m
Data rate			83 × 10 ⁶ bps				

3. APPLICATIONS

3.1 OVERVIEW

The major areas of marine application which can benefit from satellite-derived information are listed in Table 3.1. With the possible exception of marine meteorology, satellite remote sensing promises more benefits than it has delivered in the past. There have been no operational satellites dedicated exclusively to marine applications, but the entry on to the stage of the European Space Agency, France, Japan, Canada, and possibly other national agencies, will provide a variety of space platforms and sensors which should lead eventually to more fully operational systems.

The oceans offer mankind a hidden pool of natural resources - fisheries, oil and gas reserves, and minerals - which require to be managed efficiently, fairly and safely. Some nations have greatly benefited from the discovery of oil and gas reserves under the sea. Others are engaged in exploration of their own continental shelves. The greatest contribution of satellites probably lies in the area of improved weather forecasts though, in the longer term, satellite altimetry over the deep ocean, and radar imagery of coastal regions, may provide valuable geological and geophysical background information.

A general overview of potential marine applications is given below; a more detailed treatment of each is given in the succeeding sections of this chapter.

The potential contribution of satellites to marine applications

Table 3.1

Application	Relevant satellite products
Marine resources	
Offshore oil and gas	Wind and waves (real time and archive)
Fisheries and mariculture	Temperature, colour
Renewable energy	Wind and waves, tides
Marine transportation	
Ship traffic control	Fine resolution imagery (radar and visible)
Optimum ship routing	Wind and waves, currents
Marine pollution	
Spillage at sea	Radar imagery, currents, colour
River effluents	Radar imagery, colour, temperature
Marine meteorology	
Improved weather forecasts	Winds and waves
Long term trends	Statistics on winds, waves, currents
Marine science	
Physical, biological, chemical and geological	All products - temperature, colour, waves, winds, radar imagery
Global warming	Sea level, temperature and other products

Much of the weather we experience is to a large extent spawned over the oceans through complex air-sea transfer processes. Meteorological forecasts of wind and sea-state are presently based largely on spot observations of barometric pressure by ships of opportunity. In some parts of the ocean where ship traffic is relatively dense these may be considered to provide an adequate amount of information, but in other parts, especially in the southern hemisphere, reports are very sparse. The table below (Table 3.2) was compiled by the US Fleet Numerical Weather Centre; it compares the number of ship reports received to the number of equivalent observations made by Seasat. At the time of writing the volume of data generated by ERS-1 is already many times larger than that of Seasat.

Table 3

OCEAN BASIN	SURFACE WINDS		WAVEHEIGHTS	
	FNOC	SEASAT	FNOC	SEASAT
N. Atlantic	982	3365	718	5960
S. Atlantic	60	3890	52	6655
S. Pacific	96	8360	85	14768

Number of Seasat observations of winds and waves over different ocean basins compiled by US Fleet Numerical Weather Centre. (N.B. Seasat data concentrated along satellite track.)

As we have noted, however, meteorologists normally deal with surface pressure fields which are transformed into forecasted wind speed and direction, and further converted into wave heights through a wind/wave model. Satellite microwave sensors provide estimates of wind speed and direction, and significant wave height directly through the scatterometer and altimeter with support from the SAR if information on dominant wave periods and wave direction is required. One of the problems to be solved by forecasting centres in the 1990's is how to assimilate these satellite estimates into traditional forecasting techniques. For despite the global coverage of satellite systems and the high rate at which they generate data, it remains true that 'perishable' products such as wind and waves cannot be sampled frequently enough by a single polar-orbiting spacecraft. One sampling option - and it was implemented during the last 25 days of the Seasat mission - is to repeat the orbit pattern every 3 days. But this still falls far short of the sampling frequency required for monitoring waves - and leaves a gap of 900 km at the equator between adjacent ground-tracks. If enough satellites to monitor sea-state (say 4-6) could be simultaneously deployed then forecasting centres could probably dispense with their present network and rely entirely on satellites. Until that day their main task is to learn how to integrate satellite-derived and 'in-situ' data into forecasting models. Significant progress along these lines is being made by the European Centre for Medium Range Weather Forecasts.

Another important application of global measurements of wind and waves is the creation of an archive which, in future, will allow more accurate predictions to be made of the statistics of extreme conditions. These, in turn, will prove useful in the design and operation of off-shore platforms. Satellites have the advantage of providing uniform coverage over the global oceans whereas *in situ* observations are usually very sparse over the more remote corners of the seas in which major offshore exploration may be planned.

The routing of ships to save possible damage and valuable sailing time is another commercial activity which must ultimately benefit from the measurement of sea-state from satellites.

The advent of sensors for detecting changes in surface colour opens the way to synoptic studies of the oceans' fertility. Photosynthesis is characterized by the uptake of simple inorganic substances converted to complex organic compounds. It is the affinity of these compounds for oxygen which provides the energy for the rest of life in the sea. Monitoring the growth, fate and transport of phytoplankton is now possible globally through satellites; and by no other means.

The French have been particularly active in exploiting sea surface temperature imagery derived from the AVHRR to detect ocean conditions in tropical regions favourable to the presence of tuna and other economic species. And for several years now the European Communities, through the JRC, have been carrying out studies on the detection of upwelling of cold, nutrient-rich water off the coast of West Africa as an aid to improved fish management in the area.

Pollution is another area where the application of remote sensing techniques will have a significant impact. It can be argued that the ocean should be regarded as a resource shared by all nations, a common heritage which should not be contaminated by industrialized states discharging their wastes into it. But, in practical terms, economic forces come into play and the oceans do receive part of the world's waste. All international conventions on the subject have accepted this so long as the risk of damage is acceptable. And that, of course, is the crux of the matter. Reliable monitoring systems are required and satellite surveillance becomes important not so much for local surveys but for detecting the evolution of significant changes over extensive geographical areas.

The pollution of Europe's inland seas has become a sensitive issue leading to the Commission of the European Communities issuing a number of directives to control it. Effluents discharged into the North Sea and Mediterranean by industry now pose a threat not just to marine life but also to the health and cleanliness of beaches to which many millions of holiday-makers would normally be attracted. It is also clear that as developing countries seek the economic benefits of industrialisation they too will wish to minimise costs by directing waste products into the sea. Some form of internationally-agreed control will become necessary - especially in semi-enclosed seas. Satellite imagery could be used to monitor levels of pollution and presage the onset of potentially dangerous levels.

It is true to say, however, that the greatest interest in remote sensing of the sea surface presently derives from the scientific community. Scientists have provided the drive towards oceanographic satellites largely through a recognition of the limitations placed on surface vessels and buoys in reaching an understanding of global ocean processes.

More recently, concern over future climate trends and the uncertainty surrounding the possible impact of human activities has heightened awareness of the need to gather reliable and repetitive measurements at global scales. Clearly the oceans play a key role in regulating the rate of any change in the world's climate and, for that reason alone, dedicated ocean satellites are now required.

3.2 NON-OCEAN APPLICATIONS OF 'OCEAN' SENSORS

3.2.1 Ice

Ice sheets in Greenland and Antarctica constitute 10% of the land surface area of the earth while sea ice covers a maximum global surface area of 24 million km² during the northern summer which represents about 7% of the world's ocean surface. These ice masses are coupled closely to other aspects of the natural environment through complex exchanges of energy and mass. An understanding of their dynamics and thermodynamics is fundamental to global modelling of climatic oceanographic and lithospheric processes.

Satellite microwave remote sensing has already demonstrated its ability to provide much more accurate and extensive information than present day *in situ* methods. The altimeter for tracking the height of the ice sheets, the SAR for delineating the patterns, floes, polynyas, glaciers and so on, and, perhaps the most impressive of all up to the present, the microwave radiometer (SMMR) for month-by-month and year-by-year representation of sea ice cover - showing, incidentally, that the annual variations in the position of the ice edge has remained remarkably constant over the last decade (Nimbus 7).

Although Seasat only reached to latitude $\pm 72^\circ$, and although its altimeter was not designed to track over ice, analysis of the record confirms that altimetry can potentially provide more accurate and extensive information on changes in ice sheet volume than present surface observations allow. The European satellite ERS-1 was designed to include ice surveillance as part of its mission. Its orbit takes it 10° beyond the Seasat orbit and its altimeter has been adapted to hold lock more easily over ice masses. A change in ice thickness could be an important precursor of impending climate change.

3.2.2 Solid Earth

The greatest variation in the height of the sea surface measured by an earth-orbiting radar altimeter is caused by undulations in the shape of the geoid which is defined as the gravity equipotential surface of the oceans after removing the effects of all external forces such as those due to tides, currents, storm surges, wind and atmospheric disturbances. If the ocean and atmosphere were motionless the geoid would coincide with mean sea level.

Attempts to describe the shape of the earth as exactly as possible represents one of man's earliest scientific endeavours. Over the past 30 years geodesy has been greatly advanced by calculating the harmonic components of the earth's gravity field through monitoring the drift of many polar-orbiting satellites. However, as first Seasat and latterly Geosat have demonstrated, a precise altimeter is capable of delineating much finer scale geoidal fluctuations by monitoring changes in sea level from an orbit which remains stable and reactively unaffected by short wavelength changes in gravity.

Earth and ocean tides, the refraction of electromagnetic waves in the atmosphere, the internal structure of the earth, the change in sea level due to barometric pressure fluctuations, and the location of ice caps are areas of research intimately involved in the interpretation of the radar altimeter's record. It means that in interpreting an altimeter's signal geodesy has become inextricably linked with other components of the earth system such as oceanography, atmospheric physics, geology and glaciology.

In the interpretation of altimetry in terms of the contribution to the signal of the dynamic ocean it is essential, for example, to be able to identify the much greater contribution from the time invariant geoid. As an example, a current of (say) $\frac{1}{4}$ knot (12 cm s^{-1}) might produce a change of slope in mid-Atlantic of about 1m over 1,000 km. By contrast, the geoid drops by 110m from a point west of Ireland to a point off Florida. To detect and identify the individual contributions to a radar altimeter's signal represents one of the greatest challenges to future altimeter missions.

Not only have radar altimeters provided a good representation of the high wavenumber part of the spectrum of geoidal variations but also, because of their disturbance of the local gravity field, sea floor topographic features - ridges, seamounts and trenches - produced significant changes in sea level which were easily measurable by the altimeter.

3.3 LONG-TERM SCIENTIFIC RESEARCH

3.3.1 Physical Oceanography

Background

Since 1950 the number of people who regard themselves across the globe as specialists in marine science has been doubling roughly every seven years: in 1988 they numbered 18,000. The number of research vessels has increased less rapidly but developments in instruments and methods have made them much more efficient in the sense that many more data are collected much more rapidly. From the early days, when observations were written in laboratory notebooks and plotted by hand, there has been a gradual evolution through punched tape, punched cards, magnetic tape, diskettes and optical disks so that large data-sets can now be computer-processed quickly, often while the ship is still at sea. Large amounts of data can be compactly stored in computer-compatible form rather than in bulky filing cabinets or the traditional laundry boxes in which some oceanographers used to keep their unanalysed (sometimes never to be analysed) observations.

There remains, however, a need for skilled and persistent personal attention if the observations are to be of sufficiently high quality. Many of the important marine parameters vary over a relatively small range so that high accuracy in their determination is essential. Temperature, to take a common example, is needed to a few millidegrees, salinity to about a part per million. Only after the quality of the data has been fully established can they be confidently used by the scientist who collected them and, even more important, confidently contributed to the common pool of marine observations. Progress in marine science does not depend only on the ability of an individual oceanographer to collect, process and interpret his own observations but even more on the extent to which reliable data can be obtained in a timely manner from measurements made by scientists from other vessels and other laboratories all over the world.

Computer based data management has become an essential component of all the disciplines of modern marine science. There are complicated interactions between the physio-chemical characteristics of the ocean and the creatures that live in it, and between the ocean and its boundaries, which require data to be accessible to a multi-disciplinary research community. The design and maintenance of an efficient data-handling, processing and banking system that will allow quick and easy access to reliable marine data presents a major challenge.

Data Exchange for Marine Science

Traditionally data has been exchanged on a personal basis and this continues. But increasingly marine research is carried out as part of a larger national or international project and this leads to the observations made on the several research vessel cruises being pooled for common use by those taking part. It is an obvious extension that such a databank should later become accessible to other scientists and this has led to the creation of national and international data centres whose mission is to collect and to archive marine data and to make appropriate sets of them available to users.

Most countries that are active in marine research now have data centres (there are now more than 40) and they seem likely to assume an increasingly important role as marine science continues to develop.

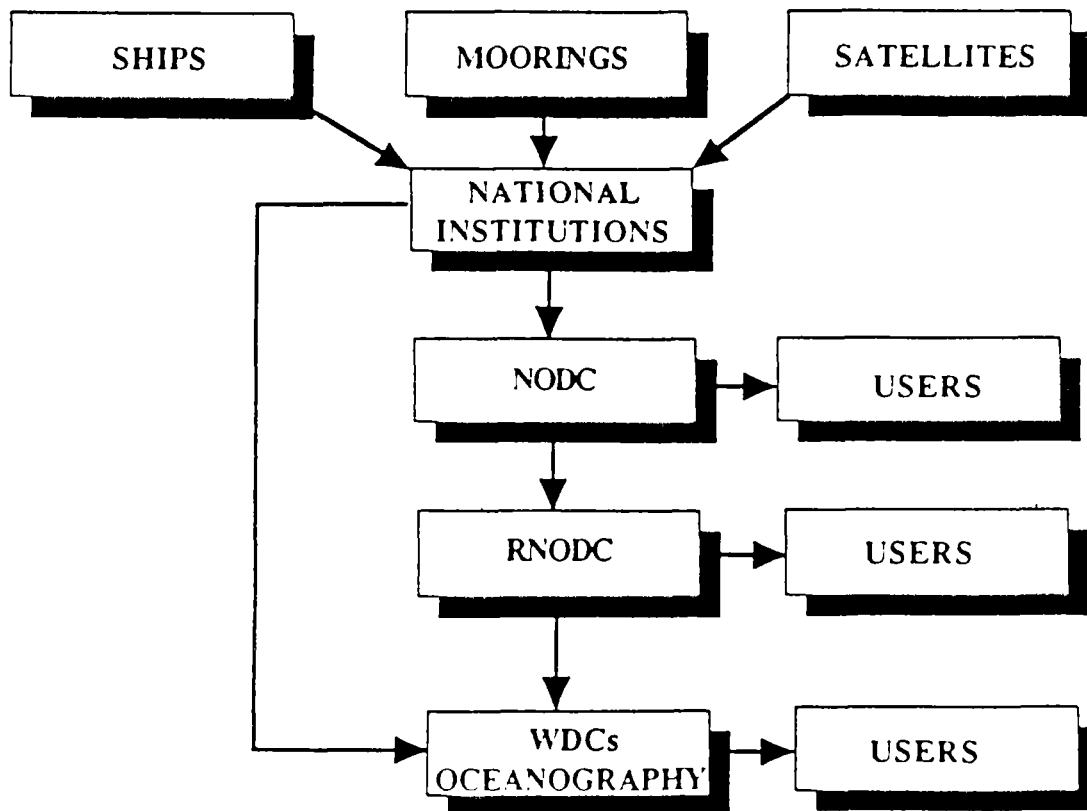


Figure 3.1 The International Oceanographic Data Exchange Organisation

The International Oceanographic Data Exchange (IODE) is a programme of the Intergovernmental Oceanographic Commission that maintains procedures and formats to facilitate the exchange of oceanic data internationally through a network of national data centres, Responsible National Oceanographic Data Centres, and the World Data Centres (WDC) for Oceanography. The WDC for Oceanography are part of the WDC system of the International Council of Scientific Unions. As indicated in Figure 3.1 they receive data and inventories from NODC, RNODC, marine science organisations and individual scientists; they freely exchange data and inventories among themselves and provide copies to NODC, RNODC and to international cooperative programmes.

A list of National and International Ocean Data Centres is in Annex 3.3.1

Data Exchange in Meteorology

Although a large and growing amount of information is held in the various oceanographic data centres a great deal more is dealt with by meteorological agencies that are members of the World Meteorological Organisation (WMO). The WMO is a specialised agency of the United Nations (as distinct from the Intergovernmental Oceanographic Commission which is a quasi-autonomous body within UNESCO). The basic programme of the WMO is the World Weather Watch (WWW) started in 1961 from an existing world-wide network of meteorological observing stations owned and operated by individual countries. The WWW is the only *operational* system and it collects meteorological data and distributes it in real-time in connection with weather forecasting and other activities of meteorological agencies.

The Global Observing System of WWW is made up of regional synoptic networks and a fleet of Voluntary Observing Ships. At present there are about 9,500 land stations, 7,000 ships, 220 fixed or drifting buoys, 600 radar stations and 3,000 aircraft. There are also two Ocean Weather Ships (at 59-N 20 W (UK) and at 66-N 02-E (Norway)) that make surface and upper air meteorological observations and sub-surface oceanographic (hydrological) measurements. These are the only components of the WWW that make observations beneath the sea surface: the future of these Ocean Weather Ships is uncertain.

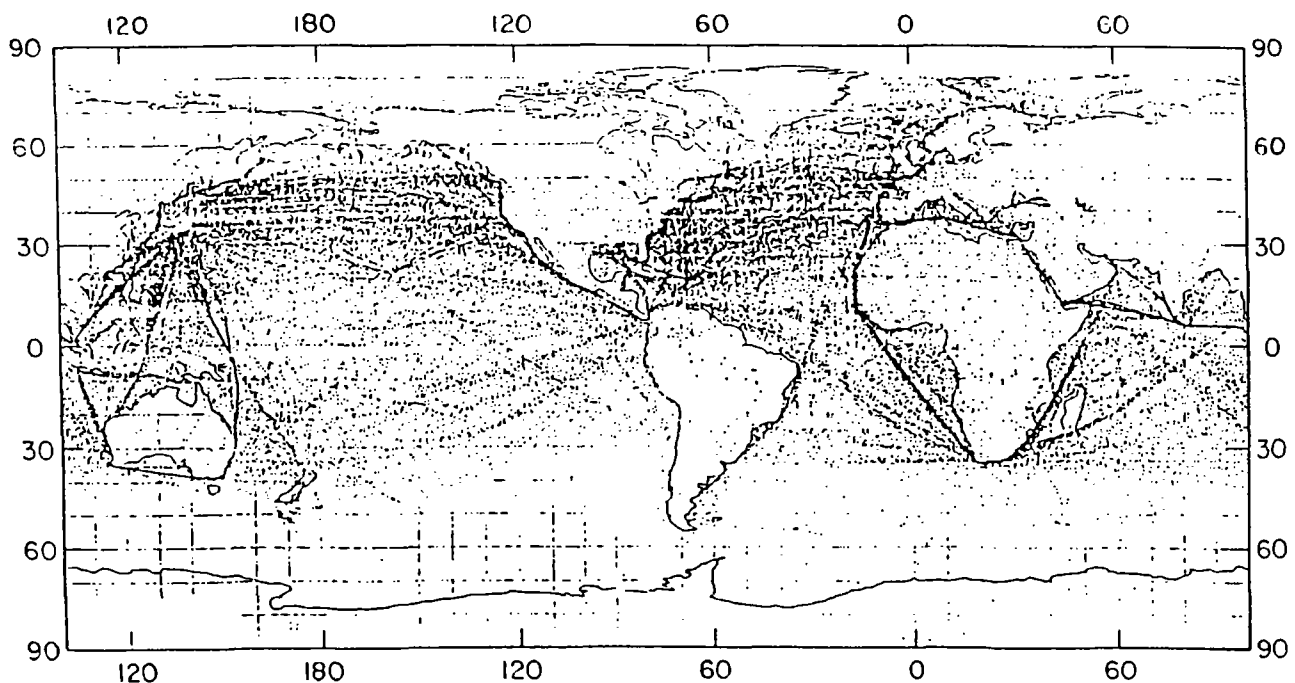


Figure 3.2 Distribution of weather observations from ships of opportunity during the Seasat mission. The dots correspond to the location of each ship report received in real-time by forecasting centres. Note the significant numbers of ship positions reported over land masses - casting doubts on the integrity of some observations.

The distribution of the land surface observing sections is uneven and the voluntary observing ships are concentrated on shipping lanes (see Figure 3.2) so the WWW includes a space-based (satellite) subsystem with both near-polar-orbiting and geostationary meteorological satellites (see Figure 3.3). The geostationary satellites carry sensors for sea surface (or cloud) temperature and transmit images (cloud-pictures) in the visible and infra-red bands as well as having a capacity for data relay of surface observations. The polar orbiting satellites carry various sensors, the long-established (30 years) NOAA series includes automatic picture transmission. Infra-red sounder and other equipment.

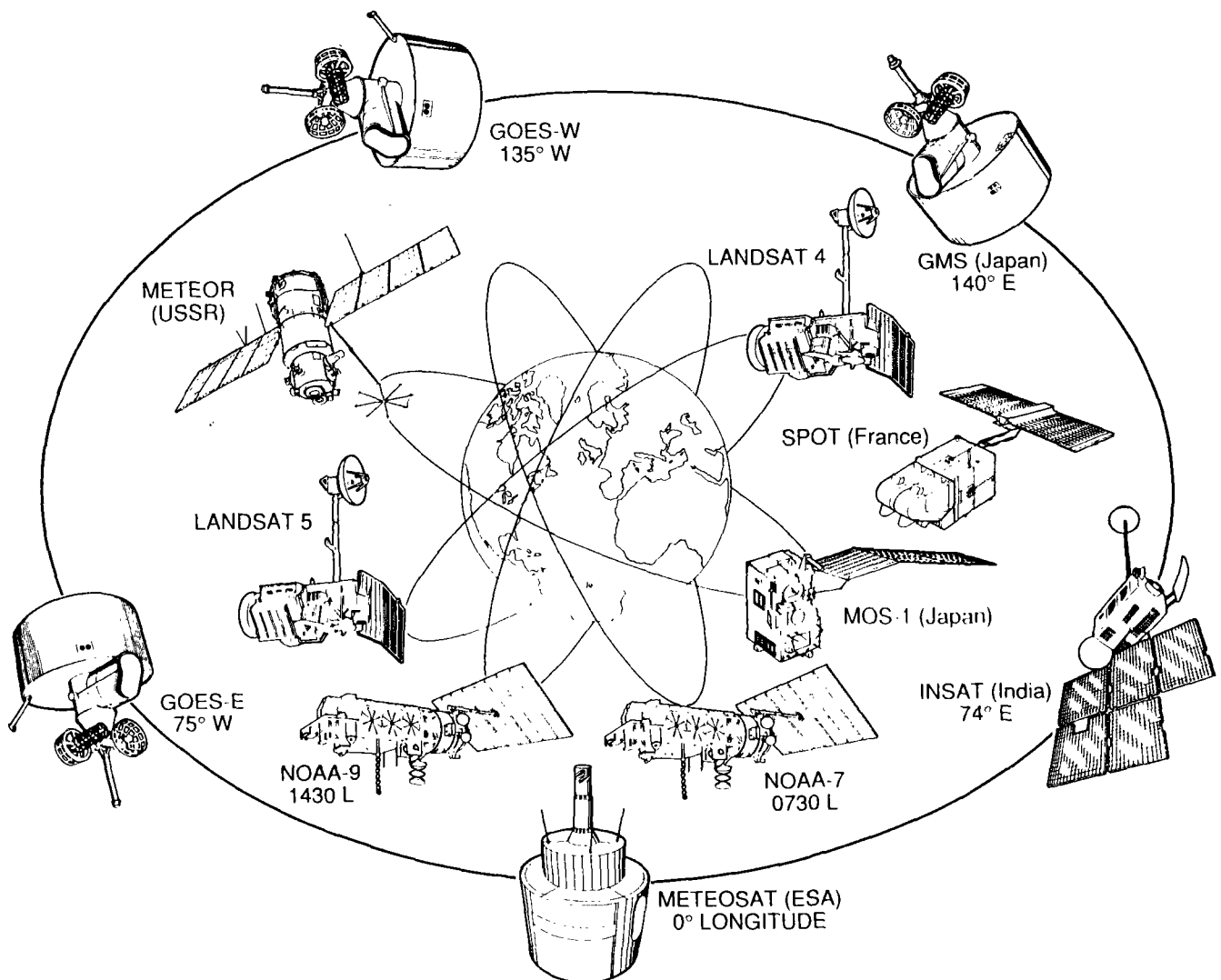


Figure 3.3 Operational meteorological satellites

As well as the Global Observing System the WWW includes the Global Telecommunications System, a largely automated network of telecommunication services for rapid dissemination of observational data and of processed information such as forecasts. The capacity of the main telecommunication network of the global Telecommunications System will probably meet the needs for the global exchange of conventional oceanographic data for the rest of this century. There is also a Global Data Processing System which consists, in an analogous way to IODE, of World Regional/Specialised and National Meteorological Centres that provide processed data, analyses and other products. Among other WWW support functions are WWW Data Management to manage data flow, WWW System Support Activity to give guidance, information and training to those developing WWW activity and to initiate, coordinate and evaluate various WWW activity.

The WWW is a large and expensive system estimated to cost some £1000M/year, which has evolved to fill what is essentially an economic need: it provides information to the data-processing centres that nowadays compute weather forecasts using the largest and fastest computers available. It happens that short-term weather forecasts (for up to five days say) do not require oceanographic observation: all they need to know about the ocean is the sea surface temperature and that they can take to be constant over the forecast period. Had there been an equivalent socio-economic demand for forecasts that involved deeper layers of the ocean perhaps a parallel operational system would have developed for marine observation; but there are great technical difficulties. Satellite remote sensing is a powerful tool but the interior of the ocean is not accessible to electromagnetic radiation. Measurements *in situ* have traditionally been made by lowering instruments from a stationary research vessel. But there is so much ocean and ships are so expensive that a close global network of them would probably be impossible to justify.

Climate programmes

Scientists have known about the greenhouse effect for about two hundred years and been concerned about the possible effect of increasing atmospheric CO₂ for about one hundred. Politicians became aware of the (anthropogenic) greenhouse effect only two or three years ago, leading to a great deal of publicity on the subject of man-made climatic change and to the First Assessment Report of the WMO/UNEP Intergovernmental Panel on Climate Change. Concern about global warming has served to direct attention (and funds) to the climate problem but in doing so has tended to obscure the importance of climate research already in process.

The reasons why the Earth's climate is as it is are not well understood. Natural changes have so far exceeded those thought to be due to man's activity. Present day science and technology has reached a stage where a better understanding of climate and its natural variability is possible and it may be that useful predictions of climatic change can be made, with great socio-economic benefit, particularly to poorer countries. The importance and fascination of climate studies is such that they should be fostered even if the man-made global warming were to prove negligible. This was the reason why in 1985, the International Council of Scientific Unions (ICSU), together with the World Meteorological Organisation, proposed the World Climate Research Programme with the overall aim of understanding climate variability and its causes, whether from natural or human origin.

It was clear at the outset that the ocean was a critical component of the climate system, since its thermal inertia and relatively slow motion were relevant to variation on the time-scale from months, through decades, to centuries, so steps were taken to set up two large international programmes - TOGA and WOCE. This was done through a Committee on Climatic Change and the Ocean jointly sponsored by the ICSU Scientific Committee on Ocean Research and the

TOGA, the Tropical Ocean Global Atmosphere Project, is studying the El Nino-Southern Oscillation phenomena that every few years modify the current and thermal structure of the tropical Pacific Ocean, with devastating effects on the economy of some South America countries and significant modification of weather patterns worldwide. The TOGA Project has led to a large increase in the amount and the quality of data collected from the low latitude oceans (see Table 3.3).

	Existing permanent	TOGA (at peak)	WOCE (at peak)	GOOS (routine)
XBT/month	6,000	2,000	3,000	25,000
CTD/month	(Variable quality)	50	2,000	25,000
Sea level sites	150	200	65	300
Subsurface floats	0	0	1,000	1,000
Surface drifters	150	250	1,000	1,000
Moorings	15	65	70	100
Satellite missions	0	0	3	8

Table 3.3 The Global Ocean Observing System

WOCE, the World Ocean Circulation Experiment, is a large project that is just getting under way. It seeks to collect oceanographic observations to design and test computer models for simulating climate change. WOCE scientists are expected to collect, during the ten years of the project, more data than have been assembled in data centres until now. WOCE is relying on the availability of data from orbiting satellites with a capability for observing the variability of near-surface currents from radar altimetry.

Both TOGA and WOCE are research programmes and a recent development is a proposal, at the Second World Climate Conference of 1990, for an *operational* system, the Global Climate Observing System (GCOS), to monitor climate, detect changes and assess responses. The GCOS is to be based on an improved World Weather Watch together with a newly established Global Ocean Observing System (GOOS), which will evolve from present national and international observing systems and experimental programmes. It will be based on:

- the Global Sea-Level Observing System (GLOSS) and ships of opportunity supplying data through the Integrated Global Ocean Services System of IOC and WMO
- systematic deep hydrography as in WOCE and upper ocean sampling as in TOGA, supported by moored and drifting instruments
- a suite of operational satellite sensors including altimeter, scatterometer, imaging radiometers in the visible, infra-red and microwave bands, and precision surface temperature radiometers
- new technologies such as acoustic and optical remote sensing, autonomous submersibles, automated data retrieval systems for moored and drifting instruments, and acoustic current profilers.

GOOS will also include worldwide ocean data centres designed to generate the products needed to meet GOOS objectives (see Figure 3.4). It seems likely that GOOS will generate very large amount of oceanographic data (see Table 3.3). Remote sensing will be a vital component: GOOS will require continuity of satellite missions for ocean observation. The transition from essentially sporadic research projects to a continuing operational ocean observing system will take at least a decade: it will lead to unprecedented demands on data processing for remotely sensed and in situ data, and for their combination, through new methods of data assimilation into the coupled atmosphere - ocean computer models that it is hoped will provide useful and timely forecasts of climatic change. A very rough preliminary estimate is that a GOOS would cost about £1000M/year together with about £200M/year for data processing.

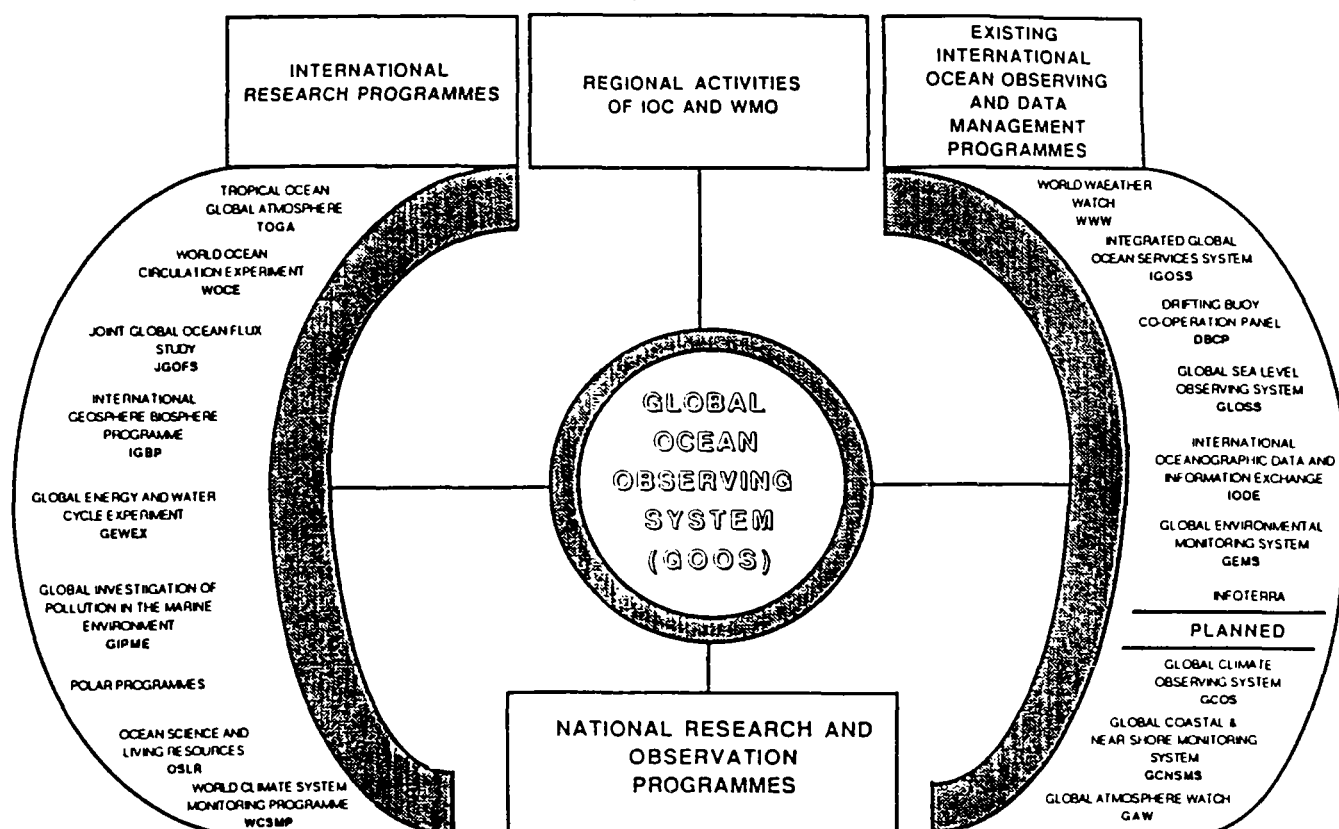


Figure 3.4 Relationship of Global Ocean Observing systems (GOOS) to other programmes

Remote Sensing for Process Studies

An operational system for continuously observing the Earth's environment will provide the initial and the boundary conditions for computer models and will test their performance. There is also a need for observations to map characteristics that vary on so long a scale that they can be taken as constant over the period, of order of centuries, for which climate forecasts are needed. The topography of the Earth's solid surface is an obvious example, and another is the geoid, a knowledge of which would expand the scope for the interpretation of sea-surface topography measured by satellite altimetry. It is hoped that space agencies will commit themselves to providing gravity field mapping missions to provide an improved geoid reference surface: the ESA ARISTOTELES mission is an obvious example.

As well as mapping the slowly varying background features observations both from space and in situ are needed to help design parametrisations for processes that are on space scales too small to be resolved in climate models even on the most powerful computers that may become available. Such processes are active in clouds, in atmospheric and oceanic fronts and especially in the atmospheric boundary layer overland and the coupled air/sea boundary layer at the ocean surface.

The processes by which sea ice interacts with the atmosphere and ocean need to be better understood. Visual and infra-red sensors are useful in cloud free zones and can be supplemented by observations in the microwave. Studies of sea and ice dynamics can be helped by the detailed images obtained using SAR.

Ocean waves are of economic importance: the time may be approaching when ships become subject to the same kind of traffic control that is now used for aircraft and any such system will need accurate information in real time about waves and tides as well as near-surface ocean currents. From a scientific viewpoint waves are important because they may affect the relation between the wind above the sea surface and the currents it produces. Global mapping of wind and waves by satellite scatterometer and altimeter can be reinforced by more detailed studies from SAR.

It also seems likely that the living material in the upper layers of the ocean can affect climatic development by a complicated biological feedback through the transfer of carbon dioxide. Impressive results have been obtained from the Nimbus 7 Coastal Zone Colour Scanner (CZCS) that maps the surface abundance of chlorophyll, the main phytoplankton pigment. CZCS images show novel features that can be related to physical factors. Future challenges are to derive basin-wide estimates of water column productivity (taking account of components that cannot be observed from space) and to get information on the composition of phytoplankton blooms, distinguishing species (and perhaps their growth system) by subtle variation in their pigment signatures. Simultaneous modelling of the biological organisms and their biological environment may be crucial to our understanding of the rate of any global warming.

The most significant small-scale transfers of heat, water and momentum take place in the atmospheric boundary layer over land and, even more important, in the **coupled air-sea boundary layer**. Even the climatology of such transfers is not well established, particularly south of 40° S (see Figure 3.2). The global mapping from space of sea surface temperature and of the drag of the wind on the sea (from scatterometer) provides some guidance but there is a great need for more information, for instance of the near-surface air temperature (for heat transfer) and especially the near-surface humidity (for the rate of evaporation). Correspondingly, **rainfall** is almost impossible to measure in a ship and its distribution badly known: a method of

measuring rainfall from space would be very useful and would help to interpret satellite cloud images in relation to atmospheric models. Further advances may come from the use of backscatter radar, which might monitor the topography of the top of the atmospheric boundary layer so as to improve our understanding of boundary layer dynamics and our boundary layer models.

International Programmes

There is a bewildering array of international research programmes and of international ocean observing and data-management programmes, all interacting with the proposed Global Ocean Observing System (see Figure 3.4). All the research programmes are multi-disciplinary and inter-related. They also have in common the fact that they need both satellite remote sensing and *in situ* observations together with reliable and recoverable data analysis and archiving. The longest lead time is in the provision of Earth observation satellites which must provide long term, global observations. If plans for the Global Ocean Observing System come to fruition there will be a need for eight polar-orbiting satellites instrumented for ocean observation. Dealing with data from such satellites and making it compatible with that from augmented *in situ* collection, in the context of computer modelling, will present a major opportunity for marine scientists and engineers worldwide.

1. International Oceanographic Data

1.1 World Data Centres for Oceanography

WDC-A	(Oceanography)	USA (Washington)
WDC-B	(Oceanography)	Russian Federation (Obninsk)
WDC-D	(Oceanography)	People's Republic of China (Tianjin)
WDC-A	(Marine Geology & Geophysics)	USA (Boulder)
WDC-B	(Marine Geology & Geophysics)	Russian Federation (Gelendzhik)

1.2 Responsible National Oceanographic Data Centres (RNODC)

-	RNODC Drifting Buoy Data	Canada
-	RNODC's IGOSS	Japan, USA, USSR, (NODCs)
-	RNODC's for Marine Pollution Monitoring	Japan, USA (NODCs)
-	RNODC for instrumented and remotely sensed wave data	UK
-	RNODC for Development of Acoustic Doppler Current profiling (ship-mounted) Data Management	Japan
-	RNODC for the IOC WESTPAC	Japan
-	RNODC for the Southern Ocean	Argentina
-	RNODC - Formats	ICES
-	RNODC for MEDALPEX	Russian Federation

2. Integrated Global Ocean Services System

2.1 World Oceanographic Centres (IGOSS)

Russian Federation (Moscow)
USA (Washington)

2.2 Specialised Oceanographic Centres (SOCs)

-	SOC South Atlantic (South of 20°S)	NODC, Argentina
-	SOC Indian Ocean and Pacific Ocean (South of 20°N)	NODC, Australia Bureau of Australian Meteorology
-	SOC for drifting Buoy Data	Service Central d'Exploitation de la Meteorologie, Paris, France
-	SOC for the Pacific Ocean	JMA, Japan
-	SOC for the IGOSS Sea Level Programme in the Pacific	University of Hawaii, Honolulu, Hawaii, USA

3. National IODE and IGOSS Centres (National Oceanographic Data Centres (NODCs)/designated National Agencies contribute to IODE; National Oceanographic Centres (NODCs) or National Meteorological Centres with Corresponding Functions contribute to IGOSS)

	IODE NODCs/DNAs	IGOSS NOCs
Argentina	NODC	NOC
Australia	NODC	NOC
Brazil	NODC	NOC
Bulgaria	NODC	
Canada	NODC	NOC
Chile	NODC	NOC
China	NODC	
Colombia	NODC	
Democratic People's Republic of Korea		NOC
Ecuador	NODC	NOC
Egypt	NODC	
Finland	DNA	NOC
France	NODC	NOC
Germany	NODC	NOC
Ghana	DNA	
Greece	NODC	
Guatemala	NODC	NOC
Iceland	NODC	
India	NODC	
Italy	NODC	
Japan	NODC	NOC
Kenya		NOC
Mexico	NODC	
Morocco	NODC	
Netherlands	NODC	
Norway	NODC	
Pakistan	NODC	
Peru	NODC	NOC
Philippines	NODC	
Poland	NODC	
Portugal	DNA	
Republic of Korea	NODC	
Romania	DNA	
Russian Federation	NODC	NOC
Spain	NODC	
Sweden	DNA	NOC
Tanzania	DNA	
Trinidad and Tobago	DNA	
Turkey	DNA	
United Kingdom	NODC	
United States of America	NODC	NOC
Uruguay	NODC	
Venezuela	NODC	
Vietnam	NODC	

4. **Permanent Service of Mean Sea Level (PSMSL)** Proudman Oceanographic Laboratory, Bidston UK

5. **Oceanographic Data Centres of the TOGA Programme**
 - Global Sea Surface Temperature Washington DC (USA)
 - TOGA Sub-Surface Data Centre Brest (France)
 - Tropical Sea Level Data Centre Honolulu, Hawaii, (USA)
 - TOGA Marine Climatology Data Centre Bracknell (UK)

6. **Oceanographic Data Centres of the WOCE Programme**
 - 6.1 **Drifter Data Centres**
 - NOAA, Miami, Florida, (USA)
 - Scripps Institute of Oceanography, La Jolla, California (USA)
 - MEDS, Canada

 - 6.2 **Upper Ocean Thermal Data Assembly Centres**

NODC, Brest (France)

 - 6.2.1 **Global Supporting National Centres**
 - NODC, USA
 - NODC, Australia

 - 6.2.2 **Regional**
 - Scripps Institute of Oceanography, USA
 - NOAA, Miami, Florida, USA
 - CSIRO, Hobart, Australia

 - 6.3 **Sea Level Data Assembly Centres**
 - University of Honolulu, Hawaii, USA
 - Bidston Observatory, UK

 - 6.4 **Data Information Unit**
 - University of Delaware, Lewes, Delaware, USA

3.3.2 Ocean Colour

Despite the lack of satellite ocean colour data in recent years the science community has continued to make progress in the field of ocean colour, using archived satellite data, aircraft data and *in situ* data. In many cases, this has been working towards the development of algorithms for future systems.

With several ocean colour sensors scheduled for launch on future satellites there are plans within most of the large community projects to make use of the ocean colour measurements when they become available. It is apparent that these measurements could provide valuable data for global science.

Introduction

Though the possible applications of ocean colour are many and somewhat diverse, to date there have been few which actually use satellite measurements of ocean colour. Much of our present knowledge of ocean colour has been related to deriving algorithms to map chlorophyll concentrations, which give a measure of primary production in the oceans. Advanced algorithms have been formed which have allowed atmospheric correction of the satellite data and, in so called 'Case 1' waters where the water colour is a function of the biological material present, have permitted maps of primary production to be derived. This has been possible in some 'Case 2' waters, where water colour is also a function of suspended sediment and other non-biological parameters, but not in all 'Case 2' waters. These waters, of which the UK coastal waters are an example, tend to require specific localised algorithms.

Most of this work has been based on the (CZCS) data archive. This sensor was launched in 1978 and operated well until 1981/2 when decay factors started to reduce its sensitivity and coverage. It died completely in 1986.

Ocean colour measurements have thus been very limited in recent years, and to a large extent work in the science community has relied on aircraft remote sensing and *in situ* (i.e. ship-board) ocean colour work. As a result of the lack of satellite ocean colour data much of the work being done at present using ocean colour is based on either past data from the CZCS archive or from aircraft data, or is validation work aimed at future satellite sensors.

One aspect of ocean colour work which is also being studied at present is the development of algorithms for ocean colour based on in-situ measurements. This involves ship-time commitments and in-water radiometers to stimulate the satellite sensors, as well as all the in-water measurements for chlorophyll, suspended sediment, yellow substance etc. This work is, of course, vital for future ocean colour studies as it will help scientists to decide which wavelengths and bandwidths are the best for the derivation of different in-water parameters. With many narrow bands it is hoped that work as detailed as speciation of phytoplankton or sediment typing may be possible.

Future Ocean Colour Work

Future Ocean Colour Sensors

The future of satellite ocean colour work throughout the world is dependent on the launch of new sensors. At present there are a few colour sensors available on Landsat, AVHRR, SPOT, MOS-I, etc., but the number of available channels, their wavelengths and bandwidths are not suitable for ocean colour research. Several similar sensors are also planned for the future e.g. the Along

Track Scanning Radiometer (ATSR) on ERS-2. Looking to the future, hopes are pinned on the launch of SeaWiFS, the Sea-Viewing Wide-Field-of-view Sensor, which should be launched in late 1993, as part of the Earth Probes Mission. This will have five visible channels of 20 nm bandwidth as well as infra-red ones, and will be very similar to the CZCS. The addition of an extra channel nearer 400 nm is important to enable some distinction to be made between yellow substances and chlorophyll.

Following this the Japanese plan to launch ADEOS, the Advanced Earth Observing Satellite, in 1994. ADEOS is to carry an Ocean and land Colour Temperature Scanner (OCTS). The OCTS should have six visible channels of 20 nm bandwidths, with six infra-red channels. It will have a resolution of 0.7 km.

It is hoped that ADEOS will overlap SeaWiFS and also provide some continuity of measurements until 1997/1998 when the European (ESA) and American (NASA) Polar Platforms should be launched.

The European Polar Platform will have on-board MERIS, the Medium Resolution Imaging Spectrometer, which will cover a range from 400 to 1050 nm with 288 channels 2.5 nm apart. The resolution is to be 1 km over the ocean and 0.24 km over the land and coast. It is planned to give continuous data as part of the Meteorological Ocean Climate Mission. It will not be able to transmit 288 values and so will be programmed after launch to transmit those bands which are deemed the most necessary for its varied scientific applications.

The NASA Polar Platform will carry MODIS, the Marine Observation Data Information System. This is very similar to MERIS, though will have about 60 fixed channels.

3.4 FISHERIES

3.4.1 Preamble

The emphasis in the fishing industry in Northern European waters, its conservation and strict legislation, national and European, is in place to curb overfishing. There is therefore little or no incentive to encourage fleets to increase their catches; on the contrary the Total Allowable Catches (TAC's) laid down by the European Commission are easily attainable and many trawlers in Europe spend much of their time tied up in harbour.

With the exception of a handful of local fishing communities, few people doubt the importance of conserving fish stocks. The herring all but disappeared from the North Atlantic a decade ago. Overfishing can also have a profound knock-on effect by upsetting the balance of the food chain. Populations of seabirds and marine mammals have been affected in the past. A migration of seals a few years ago from the Barents Sea, following overfishing of the capelin on which they feed, had a drastic effect on coastal fishing communities in northern Norway

In many areas of the world satellite remote sensing is more likely to make a greater contribution in assisting surface units detect foreign fishing vessels than in directing the fleet to richer fishing grounds.

Even if conservation were not a strong issue there is, in any case, no direct link in temperate waters between the presence of fish and surface features detectable from a satellite. The patchiness of plankton and the random nature of processes that stem from it through various trophic levels inhibit the creation of an orderly pattern that might be reflected in sea surface properties. The changing colour of the ocean and its temperature patterns provide indicators of marine processes physical, chemical and biological - but, at present, these cannot be directly related to the presence of fish.

Where the food chain is relatively short as in sub-tropical upwelling areas, surface conditions of colour and temperature are more likely to be related to fish catches than in the more temperate sea areas with 4 or 5 levels. The opportunities for using remote sensing in the tropics to increase catches (as prosecuted by the French) is discussed below.

3.4.2 Development of Fisheries Globally

The total world catch is about 76 mtonnes of which 52 mtonnes are consumed directly by humans. While catches in developed countries remained static or declined over the last decade, developing countries such as India, Peru, Chile and China have increased their share of the market by 25-50%.

In contrast to the seas around Europe some parts of tropical and sub-tropical oceans are regarded as under-exploited. The Indian Ocean, for example, covers an area equal to 20% of the world's oceans yet provides only 5% of the total global catch. India lands 1.7 mtonnes a year but the sustainable yield over their EEZ is estimated at 4.5 mtonnes. Ten years ago the catch of tuna fish by vessels operating out of the Seychelles was around 25,000 tonnes per year; to-day it has reached 250,000 tonnes representing a \$250m industry. None of this catch is taken by the locals; the fishing fleets of France, Spain and Japan pay a licence to the island and share the market.

The phenomenon known as upwelling - an intrusion of deeper, colder, nutrient-rich water to replace surface waters driven offshore (usually) by winds - occurs along the eastern margins of the major tropical oceans; that is, Chile and Peru, the West African coast states, India and Sri Lanka, Indonesia, and Australia - and several smaller states. Productivity is estimated to be over 10 times greater within those comparatively narrow strips. In fact although they represent less than 0.2% of the total area of the world's oceans, over 50% of the world's fish is caught within them.

Tuna fish are frequently to be found on the warm side of an ocean 'front' where sharp temperature gradients occur. The French recently commissioned the University of Dundee to install an AVHRR station on the island of Reunion to help detect fronts in the central Indian Ocean.

Colour is another important tracer in upwelling zones since it reflects the level of chlorophyll and other suspended matter. The two - temperature and colour - are often related in the early stages of upwelling though the relationship becomes more complex during later developments when the surface water warms to match its surroundings while the chlorophyll content may remain comparatively high.

A fishery demonstration programme conducted by NASA appeared to confirm that certain species of fish have different optimal temperature requirements. Thus, salmon were usually caught in water below 10 C, albacore tuna preferred water between 15 and 17°C, while tropical tuna inhabited water of 27°C.

The Japanese, now one of the biggest fishing nations in the world, are also significantly among the biggest users of remote sensing; their fishing industry has been one of the prime motivators in the development of their Marine Observing Satellites (MOS) programme. The merging of two major current systems - the Kurishio and the Oyashio - generates a complex front which supports a high density of fish.

Fishing resources for many of the smaller developing countries - especially tropical islands - represent an important part of their economy. Although long-term management of stocks will remain a key element in any fisheries strategy there is not the same requirement to suppress fishing by limiting catches as in Europe.

3.4.3 Aquaculture

There is reason to believe that fish farming started in Ancient Egypt; certainly, in one form or another, it has existed for many centuries particularly in South-East Asia. In Europe carp farming has a long history. The industry as we know it to-day can be dated from the beginning of the century when the American rainbow trout was imported and cultivated intensely in various parts of Europe.

Salmon farming started in the 1960's with experiments in Norway and Scotland. By 1978 most of the technical problems had been overcome and the prospects of a good return encouraged several companies to invest.

A recent study commissioned by the Nature Conservancy Council of Scotland identified the following actions as part of responsible aquaculture management.

- * maintain water quality
- * alleviate effects on sediment and benthos
- * safeguard bird and mammalian predators
- * safeguard natural fish population, including wild salmon
- * prevent adverse impact on the intertidal and nearby land

Aquaculture as an industry is now growing considerably faster than traditional capture fisheries. There are few under-utilised fishery resources available to the world to-day and as the per capita consumption of fish increases in developed countries, the shortfall is being largely met by a burgeoning aquaculture industry.

By the year 2000 it is estimated that production of fish through aquaculture will surpass 20 mtonnes - about a quarter of predicted total world production.

Although, within the last decade, Norway has increased its reared production of salmon by more than a factor of 10, the greatest increases have occurred in the developing countries, especially Asia, which now accounts for 85% of all aquaculture production. Some 300 species of fish - finfish, molluscs and crustaceans - are being reared in different parts of the world. Some of the most prominent finfish are bream, carp, salmon, sea bass and turbot; the majority of molluscs are clams, mussels or oysters while of the crustaceans, shrimps and prawns are now being produced on a massive scale in countries such as Taiwan, India and the Philippines.

The European Commission is lending support to the development of aquaculture in Spain - both along the Atlantic shoreline and the Mediterranean. At present the 20,000 ha under cultivation produce 300,000 tons of fish annually. The goal is to triple that amount over the next 5-6 years. The Norwegians in particular are investing in a variety of joint aquaculture development projects in Spain. At present a careful appraisal of several different types of site is being made - and this is an area where satellite observations can prove particularly useful.

As a comparatively new field in the exploitation of renewable natural resources, aquaculture does not enjoy the same level of practical, scientific knowledge that accompanies activities in agriculture and forestry; in many respects aquaculture must be considered a 'high-risk' operation.

One of the most important requirements for information when making an economic assessment is the suitability of the proposed site. The type of environmental data required includes is listed in Table 3.4.

In almost all of these areas satellite observations are capable of making an important contribution and, in some cases, may represent the only feasible means of monitoring longer-term variability. Most of the damage suffered by aquaculture sites to date has been brought about by unforeseen environmental changes.

Stocks must be reared over a period up to several years in locations which are protected from extreme conditions. A reliable inventory is therefore required of both average conditions and the scales of variability before final selection of a site is made.

Table 3.4 Environmental data required for economic assessment of aquaculture site

- * Regional and detailed local surveys to establish proximity to tidal channels, lakes or estuaries.
- * Surface cover type and density - delineation of aquatic vegetation.
- * Water quality and variability
- * Water quantity - rainfall (annual and monthly averages) - hydrology (currents, tides, river flow) - evaporation rates
- * Soil parameters (pH, permeability, compaction)
- * Topography - land/water area, elevation, slopes, water depths, protection against strong winds
- * Meteorology - prevalence of severe conditions (storms, floods, high waves)
- * Water conditions and range of variability (for species selection) - temperature, salinity, climate
- * Type of pollution: water effluents - industrial, sewage thermal pollution - warm effluents deforestation, mining, logging prevalence of harmful algae
- * Infrastructure - proximity to roads & human settlements

3.4.4 Potential applications of remote sensing from satellites

We have reviewed the present state of traditional capture fisheries and the rapid development of aquaculture and have attempted to identify those areas where we consider satellite remote sensing will be able to make a significant contribution. These can be summarised as follows:

Capture fisheries - temperate seas

Since there is no direct correlation between surface features in Northern European waters and the detection of fish there is no obvious 'real time' mode in which satellite imagery could be used to direct fleets to fishing grounds. Even if this were not the case national and European legislation imposes strict limits on annual catches.

Satellites will of course contribute to the on-going programme of traditional hydrographic and biological measurements in support of fisheries research leading in the longer-term to improved management of fish stocks.

Satellites could play an important role as an 'eye-in-the-sky', assisting the authorities detect intruders but this would require the force of international law to place identification transponders on every ship.

Capture fisheries - tropical seas

The picture changes in tropical and sub-tropical zones where the upwelling and oceanic fronts which attract commercial fish such as tuna can be identified and tracked by satellite. The Japanese have used AVHRR imagery as an aid to their fishing fleet over their own national fishing grounds while the French - largely through the ORSTOM organisation - have installed satellite stations to monitor conditions in the ocean areas around developing countries.

Aquaculture - temperate seas

The industry has taken a firm hold along many European coastlines with no assistance from remote sensing to date. Much of the development is local and at too small a scale for sensor information with a spatial resolution of a kilometre to be practical.

We cannot see the higher resolution radar sensors of ERS-1 and its successors being of great direct benefit to the industry.

However, while local 'in situ' monitoring is proceeding to guard against unwelcome pollution effects that may emerge over a period of time, archived colour and temperature imagery will provide a valuable backcloth against which environmental trends may be detected. At the same time satellites may be able to warn against the onset of harmful algal blooms of the type which moved up the Norwegian coast from the Skagerrak in 1988 threatening salmon stocks.

Aquaculture - global development

The greatest growth in aquaculture has been in third world countries - especially in the cultivation of tropical shrimps and prawns in mangrove swamps.

The tendency now is towards larger stockades making them more efficient but also more vulnerable to changing environmental conditions. Site selection is thus assuming a greater importance as many of the projected areas are remote and inaccessible. High-resolution SPOT imagery has been used by the French to assist in the selection of aquaculture sites in SE Asia.

With the encouragement of the FAO, models based on Geographic Information Systems, incorporating the information listed in Table 3.4, are now being developed for the selection of optimal sites and in their subsequent management. Satellite-derived information on prevailing winds, waves, currents and temperature as well as colour will serve as useful inputs to these models.

3.5 OFFSHORE EXPLORATION & PRODUCTION

3.5.1 Preamble

Early years

The requirement of the oil companies for marine environmental information started with the first exploratory offshore investigations made in the Gulf of Mexico some four decades ago and has continued more or less uninterrupted ever since. When exploration and production moved into the harsher environment of the North Sea the industry had to overcome more difficult technical problems. Almost overnight - as the extent of North Sea reserves were revealed - an urgent need was created for:

- i) historical data, especially of wind and wave fields to assist in the design of platforms built to withstand the worst conditions that would be encountered
- ii) reliable forecasts in the short-term to assist in day-to-day operations

To satisfy the first of these demands all available observations were assembled - the great majority visual estimates of wind strength (Beaufort scales and waveheight).

Partly to improve future forecasts, partly to create an archive for the future, individual companies then initiated their own measurement programmes or, individually or in concert, commissioned service industries to carry out a programme of regular environmental monitoring.

Budgets

It is reported that the oil & gas industry spends some £90m on marine research and development in the UK alone.

There is continuing pressure on oil companies to find new fields. In the case of BP their two major fields - Alaska and Forties - have passed their peak. Attention is turning towards other potential marine areas - off Russia, Norway, in the Gulf of Mexico and in SE Asia.

The trend now is to move into deeper water. Although the increased size of drilling ships and rigs allows them to continue working in heavier seas than before, currents in the deeper water off Scotland may now present the more serious impediment to uninterrupted operation where long drilling risers are required.

3.5.2 Requirements for information

The requirements for metocean data in terms of their quantity and quality increase as a field is developed - with safety playing a key role.

The sequence of individual activities involved in the progressive development of an offshore field - from preliminary exploration through economic assessment to production - make different demands on the type of environmental information required.. A brief summary is presented below.

Seismic exploration

The hydrocarbon-bearing potential of a sedimentary basin is determined largely through seismic surveys. Here, the type of operational data required is generally in the category of estimating the percentage of time that the significant waveheight (H_s) is likely to be above certain operational thresholds for different months (as shown in Fig 3.5).

Information is also required on predominant wave and current directions for optimising the direction in which seismic lines should be run.

At this stage the primary source of information is generally global atlases but these suffer from two main drawbacks:

- i) Statistics usually cover a large area and may not be representative of the smaller area of the survey.
- ii) The temporal resolution of the atlas may be seasonal whereas the survey will usually require monthly estimates.

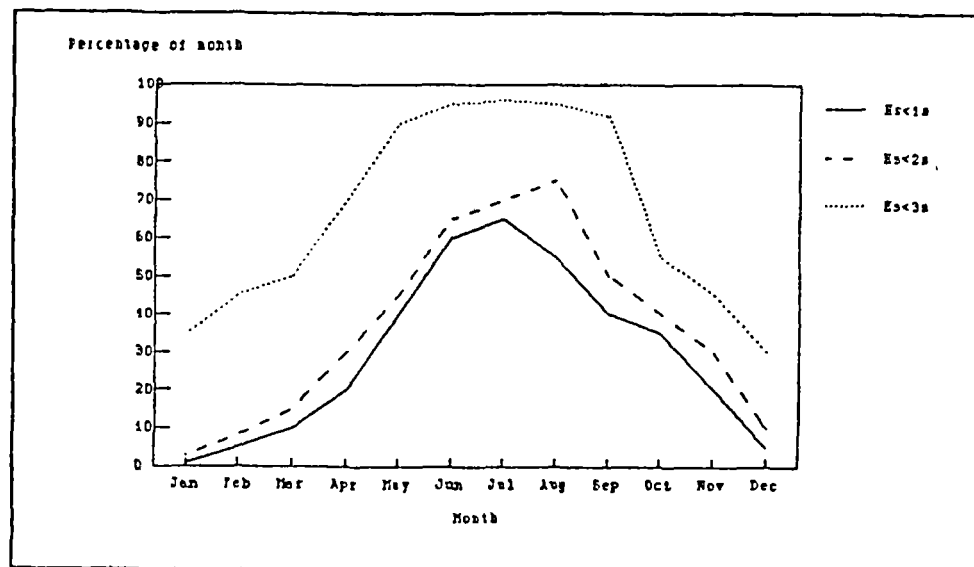


Figure 3.5 Monthly percentage exceedance statistics for operations planning

Economic assessment

If the seismic results look encouraging the next stage is to make an assessment of various development scenarios. Approximate costs must be prepared for platform/pipeline constructions (plus pipelaying) and an important part of this assessment will be the assumptions made on the environmental conditions to be encountered. These are usually known imprecisely but companies aim to produce oceanographic criteria for their engineers which are accurate to at least 30%.

Once the limiting environmental conditions (mostly wave behaviour) are estimated it is reasonably straightforward to calculate 'down-time' during different months. The parameter most commonly required is the extreme maximum storm waveheight with an average return period of 100 years. The main objective at this stage is to provide a rapid estimate based on a limited data set which when tested against a more accurate estimate derived from a fuller, site-specific series of measurements will be right to 30%.

The estimate will err on the conservative side (i.e it will not be lower than the more accurate estimate ultimately produced). That these differences can be significant and can thereby lead to serious miscalculations of downtime is illustrated in Fig 3.6.

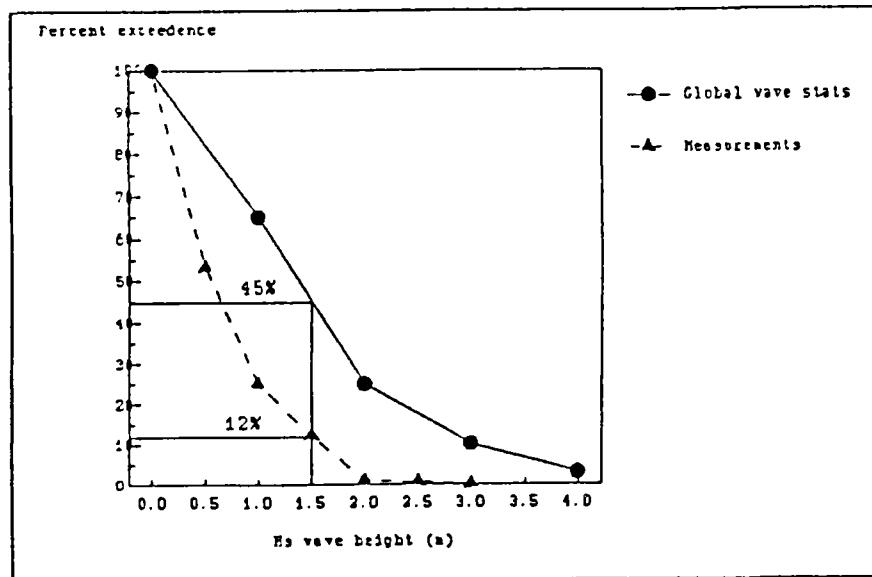


Figure 3.6 Comparison of downtime estimates from a wave atlas and from measurements

Experience to date demonstrates the limitations of existing data. First, atlas statistics are frequently based on an uneven distribution of observations; secondly, although the number of visual observations, built up over the years, may partly compensate for their relatively poor accuracy, it is also true that the greatest errors are likely to have been made in the very stormy conditions which are particularly important to the estimation of extreme values. Tests have shown these estimates to be too high - which is on the right side of safety but will also increase construction costs.

As mentioned previously, large-area statistics may not be entirely applicable to a small zone within that area; and this is particularly true close to shore where water depths are much shallower than those in which the majority of the observations were made.

Exploration drilling

In most areas investigations will not proceed beyond the analysis of the seismic results. But if these should prove promising, the preliminary economic assessment encouraging, and lease applications are granted, then the company would normally proceed to the next phase which is exploration drilling to estimate the size of the reservoir.

The exploration rig must now be designed according to certain assumptions made on extreme conditions - extrapolated from the best quality information available. Not just waveheight but, where possible, wave spectra are required to determine the dynamic response of the rig. A summary of the principal metocean variables used in structure design is given in Table 3.5.

Table 3.5 Principal metocean variables used in structures design

WAVE	Maximum wave/crest height (Peak) wave period Wave Direction Spectral width Directional spread
CURRENTS	Surface speed/direction Profile with depth
WINDS	Speed/direction at 10m a s l Profile with height
SEA-LEVEL	Surge height Tidal height
METEOROLOGICAL	Sea Ice Temperatures Rainfall Visibility Salinity

For planning purposes two different categories of information must be derived at this stage:

- i) the design storm values required by the engineers,
- ii) an estimate of the number of wells which must be deployed to reach the target depth in an operating season given the expected downtime.

The accuracy of the information required is now higher than in previous stages. As stated before, the industry (and the responsible government agencies) will err on the conservative side - yet serious overestimates can be costly.

If good quality field information is important so too is the time spent in finding and analysing it. Very often, as was initially the case in the North Sea, the data base on which crucial decisions must be made is very limited.

Forecasting Sea State

Once drilling is underway the emphasis for environmental information shifts towards reliable forecasts to assist in day-to-day operations. Models are used increasingly to predict the response of a drilling vessel to certain sea states so that an accurate forecast may allow a drilling riser (say) to be disconnected from the well-head before vessel motion causes serious damage.

Clearly, more reliable forecasts over longer time intervals would allow operational programmes to be planned with a greater degree of confidence. A number of offshore companies now seek specific forecasts (provided by national meteorological offices and local service organisations) for their particular operational area. Oil companies also participate in efforts to improve forecasts by comparing predictions with actual platform observations.

Production

Throughout the later stages of developing and bringing an offshore field to full production an increasing emphasis is placed on the generation and subsequent validation of forecast models. As in scientific research so in commercial applications the ultimate aim is to understand a phenomenon well enough to be able to predict its development accurately from an initial set of observations. To this end models must be validated and re-tuned where necessary. Hindcasting of severe storm conditions is one method commonly used in testing models.

It must be emphasised, however, that no matter how good the model, its predictive performance will depend finally on the quality of the input data.

Waves remain the most important single parameter to be accurately forecast. Their behaviour is crucial to the performance of operating platforms and to long-distance tows where fatigue damage must be minimised.

Wave prediction is also important to both the design and laying of pipelines. Here the priorities may be different to platform operation in that the greatest emphasis will be on the shallow water regions where the pipeline approaches the shore.

Pipelines are particularly sensitive to wave direction so that good estimates are required of the wave spectral peak period. The angle between the pipeline and the dominant wave direction will also be required at several locations along the intended route since savings may be made by selecting the most favourable path.

3.5.3 The role of remote sensing

The launch of ERS-1 sees the start of a continuing programme for monitoring the behaviour of ocean waves over the surface of the globe. Waveheight is being measured by the radar altimeter; wave period and direction by means of the synthetic aperture radar. Unlike Seasat, on which ERS-1 is modelled, the ERS SAR operates a wave mode which allows 5 x 5 km 'snaps' to be recorded on board the satellite every 200-300 km. Surface windspeed and direction will also be measured though not without some restriction. The scatterometer, for example, cannot function simultaneously with the SAR and is limited in the top of its measurement range to wind speeds of 24 m/s though higher speeds appear to have been accurately measured.

The ability of these microwave sensors to measure the extent of sea surface roughness was amply demonstrated in 1978 by Seasat; more recently some 2-years of altimeter wave data measured by Geosat's altimeter have been analysed. In the first instance records such as these will prove invaluable in testing the validity of models by hindcasting wave conditions from meteorological inputs (see D.J. Carter in this Guide).

The long sampling interval of a single orbiting satellite is considered by the industry to provide too coarse a resolution in both space and time to be of direct benefit. In terms of real-time operations this may be true - though satellite derived information over a location some considerable distance from a platform may provide a useful input towards a more accurate weather forecast for the following day.

What can be demonstrated, however, is the power of a global archive of wave data which will allow much more reliable predictions to be made of monthly average and extreme wave (and current) conditions than those presently available based as they are on sparse and unevenly distributed observations. Satellites will produce a much more ordered data set against which standard analysis techniques can be developed for detecting trends.

As exploration moves into deeper water it will also become increasingly important to forecast variations in patterns of currents or eddies. The potential contribution of a radar altimeter (aided by SAR), deployed from a single earth orbiting satellite such as ERS-1, needs to be demonstrated over selected pilot areas.

The principal applications of metocean data to the offshore industry are summarised in the Table 3.6. Satellite observations will make valuable contributions to all of these; but in the interim period between experimental (or pre-operational) ocean satellites and a fully operational marine monitoring system, the greatest value is likely to lie in creating a uniform grid of reliable, repetitive measurements increasing in value with time as a global archive is built up. An operational, multi-platform system would make a real contribution to the monitoring of day-to-day operations by increasing the accuracy of short-term forecasts.

Table 3.6 Principal applications of metocean data

APPLICATIONS
Drilling campaigns Exploration surveys
Environmental impact studies
Tow routing
Liability claims
Platform design Pipeline design
Selection of floating units Scheduling supply or crew boats/helicopters Loading at terminals Diving operations
Design of on-shore sites Flooding studies

3.6 SHIP TRAFFIC

3.6.1 Preamble

The applications of satellites to maritime operations have, in the past, lain mostly in the area of communications, navigation and improved safety at sea. The introduction of systems such as INMARSAT which makes use of geostationary satellites has revolutionised ship communications. Likewise, the US Global Positioning System (GPS) employs 18 satellites to provide ships routinely with positions accurate to a few tens of metres. The world-wide Safety & Rescue service relies on satellites to pick up signals transmitted by ships in distress.

By contrast remote sensing from satellites has made little or no impact on ship operations. Although the fine resolution sensors carried by the French satellite SPOT have provided clear images of ships in coastal regions, its operation is limited to clear skies during the hours of daylight.

The sensor which has demonstrated that it could image ships in all weathers and function also at night is the synthetic aperture radar (SAR) which in 1978 operated for a brief 3-month period on Seasat. Apart from two brief trials on the NASA shuttle (SIR-A & SIR-B) SAR did not fly again until the launch of ERS-1 in July 1991.

If satellite programmes are carried out as presently planned, imaging radars will be orbiting the earth for many years to come. ERS-1 is to be followed by ERS-2 while the Canadians are to launch Radarsat, the Japanese J-ERS and another advanced SAR is scheduled for the polar platform post-1997.

Could operational SAR's make a contribution to maritime operations comparable to the earlier communication satellites? One significant difference is that the surveillance of shipping made possible by an orbiting 'eye-in-the-sky' may not be universally welcomed in some quarters.

'Freedom of the Seas' is a tradition jealously guarded not only by shipowners but also by the majority of national navies who are reluctant to have the whereabouts of their forces made known to the world at large. There is no mandatory 'black box' carried on ships as there are on all passenger aircraft which would reconstruct the ship's track - as well as record the weather encountered en route, the distribution of stress throughout the ship, unscheduled stops, and other parameters. A transponder could be included which would identify the vessel when interrogated by surveillance aircraft or satellite.

But, while the idea of ship traffic control would be resisted by part of the industry, individual nations go to considerable lengths to protect their coastlines.

There are two major areas of concern:

- i) Illegal discharges of oil residues from ships bilges in coastal waters.
- ii) Illegal fishing by foreign vessels not authorised to fish in national territorial waters.

Five aircraft are presently employed in the surveillance of UK coastal waters. Several other countries (France, Norway, Netherlands, Sweden etc) also deploy patrol aircraft so that the total number engaged in protecting European coastlines is probably in the range 8-10.

Thus it is fairly clear that given the capability of SAR to detect ships - and possibly the wastes they discharge - ERS-I and its successors could make a useful contribution to coastal ship traffic control if required to do so (see figure 3.7).

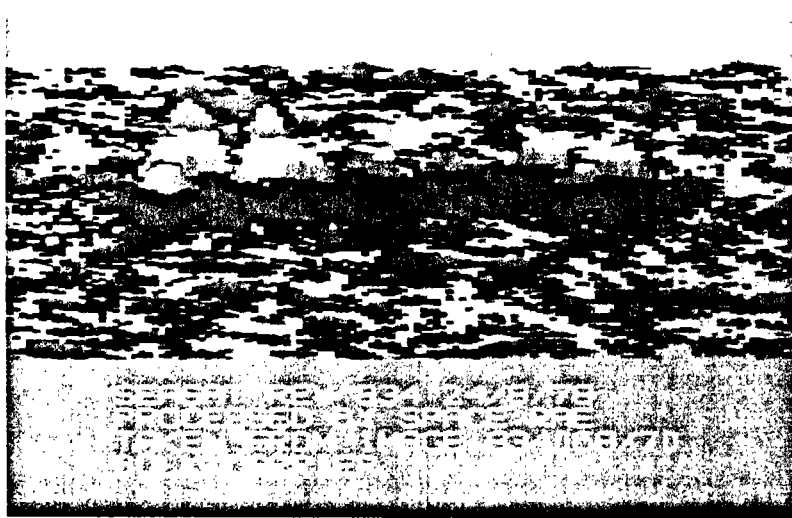


Figure 3.7 Seasat SAR image processed to reveal the superstructure of a ship

A second, potentially important application to shipping lies in the area of monitoring sea state and relaying the information to ships - either through broadcasts via satellites direct to the ships or through the inclusion of satellite observations in meteorological forecasts.

A ship's captain could take evasive action if satellite observations could be relayed in near-real time to warn (for instance) of a severe storm ahead of him. Alternatively an agency providing information on a trans-ocean passage could update their meteorological forecasts with fresh data supplied by the satellite.

There are also occasions when an independent assessment of sea state might be useful. This could involve litigation between a ship owner and the charter party. Or a ship may be claiming damages from an insurance company in circumstances where the reported sea state is called into question. Again, in a special one-off situation - towing a large platform across the Gulf of Mexico for instance - the insurer may wish to know, using the most reliable statistical information available, what the chances are of a hurricane in (say) October.

The three ways then in which satellite-derived information on sea state may be useful are - in real-time forecasting, in hindcasting, and in building up a reliable statistical data base.

In summary, remote sensing from satellites could be used either to provide information on the marine environment of direct interest to the shipping industry, or it could be used by national (and international) authorities to detect and deter unwanted pollution by ships. These different potential applications are examined more closely below.

Safety at Sea

The International Maritime Organisation was founded to improve the safety of ships at sea and this remains its prime concern though as we shall see it has become involved in other areas of ship operations. The first SOLAS Convention (Safety of Lives at Sea) was held shortly after the sinking of the Titanic; it comes as something of a surprise to learn that many smaller ships today still rely on a radio operator tapping out morse. IMO hopes next year to introduce the Global Maritime Distress and Safety System universally which will rely on INMARSAT communication links.

Equally, most but not all ships now obtain accurate positions through the US Global Positioning System (GPS) which employs 18 satellites; smaller vessels still use the older traditional methods of navigation.

Black boxes (called Vessel Event Recorders) are now being installed on some freighters to monitor the distribution of stresses felt by a ship. It would be a short step to add sea state and wind velocity to the record; and a transponder could be another addition which would allow the ship to be identified by a passing aircraft or satellite.

In view of the strength of the opposition to the notion of keeping a track of ships at sea it seems very unlikely that in the near future satellites will be used in that role. Satellites already play an important role in improving safety at sea - but in the area of communications rather than remote sensing.

Detection of Ships by Satellite Radar

Many ships were imaged by the synthetic aperture radar during its first satellite deployment on Seasat in 1978. Also a shift in the Doppler frequency of the signal received at the satellite from the moving ship causes the ship's image to be displaced with respect to its wake and affords a way of estimating its speed through the water.

Ships can also be seen on SPOT images but here detection is limited to daytime operation with clear skies - and the speed of the ship cannot be estimated as with SAR.

Any oil (as well as other substances) discharged from the ship will usually alter the surface roughness to an extent that will also cause the slick to be detected in the radar's image. It would therefore be possible in principle to conceive a system of operational control that detected potential pollutants discharged from a ship and identified the suspected offender by calling up its transponder.

The strength of satellite surveillance may be its deterrent effect though a determined ship's captain may also find it comparatively easy to discover the schedule of overhead passes and plan his actions accordingly.

Satellite radar surveillance could also be extended to the detection of illegal fishing vessels - but again an identification of the ship would be required through an automatic communication link.

3.6.2 Monitoring Sea State

a. Forecasts

Regular and accurate forecasts of sea and wind conditions is clearly of paramount importance to shipping, and meteorological offices direct considerable effort to providing them. ERS-1 data are being sent directly to the European Centre for Medium Range Weather Forecasts and will be progressively introduced as one of several elements that contribute to a forecast.

Likewise ship routing operations should benefit from assimilating satellite-derived information in their forecasts. To date remote sensing satellites have had little impact on these activities but direct observations of both winds and waves by ERS-1 could prove useful. An important consideration will be an assessment of costs vis-a-vis potential savings in ship time.

With technology available to-day information on sea-state gathered by an orbiting satellite could be broadcast directly to ships at sea. Seasat sensors detected the storm at sea in 1978 which subsequently caused some damage to the QE2. Advance warning transmitted directly from the satellite to the ship may have allowed the captain to have taken action to avoid the worst of the storm.

b. Hindcasts

There are occasions where there is a need to assess the sea conditions that surrounded a certain event at sea. This might be the case in a dispute over a marine insurance claim or, more commonly, a disagreement between the charterer and ship owner over the sea conditions encountered by the vessel on a particular passage where, for instance, a certain time had been stipulated at (say) average Beaufort scale 4 conditions.

c. Archives

In the long run the continued operation over a number of years of satellites measuring sea conditions will create a much more reliable archive of information than any that exists at present. This should prove particularly useful in assessing risks. We have already discussed the potential benefits to the offshore oil industry in planning their operations. Insurance companies might also be expected to benefit if more information were available to them - especially over the more isolated parts of the oceans.

In the longer term a more accurate perception of both average conditions and the likely occurrence of more extreme events will surely allow a better overall risk assessment to the ultimate benefit of the industry.

Lloyds Register of Shipping is conscious of the benefits that an improved archive could bring. Since they are responsible for granting certificates of seaworthiness it is important for them to be fully aware of the worst conditions in which a ship may find itself. Waveheight of swell waves in the Pacific (say) might be similar to that in the Atlantic but the period of the waves could be significantly different.

3.7 COASTAL MANAGEMENT

For many countries around the world adequate management of their own Exclusive Economic Zone (EEZ) has assumed a much greater importance than before. The aim of most governments is to find an acceptable balance between sound market principles applied to economic growth, and good management to ensure adequate protection of their environment. In the recent past a succession of natural and man-made disasters involving on the one hand severe flooding and on the other serious pollution, has drawn world attention to the vulnerability of many coastal areas.

The sea has traditionally been used as a sink for the disposal of sewage and other waste products and until a more economic alternative is found this practice will continue. Many countries are also engaged in the search for offshore gas and oil reserves. Drilling rigs are becoming a familiar sight around many coasts - and these carry their own threat to the state of the environment through accidental spillage and the disposal of associated waste products such as drilling muds (Figure 3.8).

The control of fishing and the conservation of stocks is also becoming increasingly important to a number of countries and greater effort than ever before is now directed to the introduction of more effective controls. But control to be effective must rely on observations.

What sort of contribution may remote sensing technology make to those national authorities charged with protecting their coastline and offshore area? It has been demonstrated that satellites can detect surface pollutants through the use of radar imagery and, in some cases, through colour and infrared scanners. Ships can also be clearly seen in the record of the synthetic aperture radar which is presently being carried on ERS-1. Satellites may therefore prove their usefulness to coastal managers in a reconnaissance role but their comparatively long re-visit cycle - perhaps as long as 35 days - places a severe limit on their contribution to day-to-day operations.

In a typical 'fire-fighting' situation where a fast response and probably continuous monitoring are required then aircraft fitted with such devices as side-scan radar (SLAR) and infrared and ultra-violet scanners can prove much more effective. The strength of satellites lies in their ability to build up an archive of coastal conditions - revealing slowly changing patterns of temperature, colour and/or surface roughness which in turn may indicate changing levels of effluents being carried out to sea, or an increase in the level of oil spillage or seepage. Satellites may also provide first indications of gradual changes in (say) coastal erosion or shifting sandbanks on the sea floor allowing timely 'in situ' intervention.

A satellite's radar will provide recurrent 'snapshots' of the number of ships on passage or stationary offshore which could prove useful to fishing control authorities though until such time as it becomes mandatory for owners to place identification transponders on their ships there is little chance of successfully identifying any transgressor.

We have dealt in a separate section with the type of information required by the offshore industry which could be generated routinely from satellite observations.

Perhaps the greatest longer-term application for satellite reconnaissance of coastal areas lies in monitoring the combination of weather and sea conditions which may produce severe flooding. Information on surface winds, sea level and current systems may prove a valuable complement to ground-based systems already in operation in a number of vulnerable areas.



Figure 3.8 Slicks imaged by SAR in the Mediterranean. The top image (off Majorca) is probably of natural slicks; the bottom image (Strait of Sicily) is more likely an oil spill.

3.8 ENERGY FROM THE SEA

3.8.1 Preamble

Man has studied the feasibility of extracting energy from the sea for as long as his ever-increasing requirements first took shape, but with so many non-renewable, relatively cheap sources of energy easily available there has never been a very pressing need to devote substantial resources to developing alternatives such as wave or tides.

The situation may be changing, however. Concern over the Greenhouse Effect - or, more specifically the extent of man's contribution to it through increased emissions of CO₂ and other gases - plus a comparable concern over both the long-term consequences and potential short-term hazards of nuclear power plants (in the wake of Chernobyl), and the recent demonstration of political instability in oil-rich regions such as the Middle East have combined to re-engage the interest of governments in the feasibility of meeting at least a part of their total energy demands through the use of renewable, comparatively clean energy extracted from the sea.

Let us examine briefly the two main systems in contention for the extraction of energy from the sea.

3.8.2 Waves

In the early 70's the UK Department of Energy instigated a comprehensive investigation into different methods for extracting energy from waves. Attention was directed to the Atlantic rollers off the west coast of Scotland. An intensive research & development programme was pursued for the best part of a decade but was then allowed to run down. More recently it has been revised and new studies are underway on the potential economic return of certain devices for extracting wave energy.

As long as the increasing need for energy is met by consuming non-renewable resources (oil, gas and coal), there is every reason to believe that governments will keep a watching brief on the practicability of exploiting renewable wave power.

Several advanced studies have been carried out and models of several devices built and tested. The Norwegians were the first to install an operational wave energy device in Europe on a cliff near Bergen - but it fell into the sea during a severe storm. At present a modest pilot study of an oscillating water column is being carried out on the island of Islay in the Inner Hebrides.

Economic factors have been central in the past in inhibiting governments from proceeding beyond paper studies. Although it is calculated that the waves off Scotland contain 70KwH/m of power dropping off to 10KwH/m in the shallower inshore water where waves break and lose energy, both the installation and the maintenance of such a system would prove so expensive that it could take many years of operation to begin to show any return. Present cost estimates per KwH are 2-3 times greater than energy generated by more conventional means.

Proponents of wave energy argue, however, that it must ultimately be cheaper since the 'fuel' is free. Uncertainty surrounds estimates of the expected life of an array or tower; and the vulnerability of the devices to damage in high seas allow a wide divergence of estimates of probable cost.

Islands states such as Hawaii, Seychelles and Mauritius have at one time or another shown an interest in wave energy devices and the Norwegians have surveyed the potential world market. It may also be true that the increasing emphasis on 'green' issues could bring pressure to bear on governments to develop pilot models of wave devices to replace ultimately polluting coal/oil and potentially unsafe nuclear power stations.

The high development and running costs of wave energy devices might be reduced if benefits were shared with other activities and in this regard consideration is being given to combining with fish farming (where the onshore waters behind the wave device would be much smoother), with recreational activities (diving, windsurfing etc), and with coastal protection measures in areas where erosion is taking place.

3.8.3 Tidal

Power can be generated by letting the head of water built up on an incoming tide pass through turbines before washing out to sea on a low tide. For electricity generation to be economic it is estimated that the tidal range must exceed 5m. There are several places in the world where tides exceed this figure but, of course, account must be taken of other factors environmental as well as economic. The French operate a modest tidal generated power station at Rance.

3.8.4 Requirements for satellite data

For any conceivable wave energy installation information derived from satellites such as ERS-1 would become vital since its altimeter provides information on the distribution of wave heights throughout the year, and from its imaging radar, statistics on the dominant swell directions and periods may be built up.

In the light of economic factors coupled to increasing concern over the use of other more 'conventional' sources of energy, if the decision were ever taken to proceed with coastal constructions for extracting energy from the sea, then there would be the most pressing need to analyse as long a time series as possible to derive reliable wave statistics.

A tidal barrage would not obviously require equivalent information from a satellite since the most important measurements can be made on the ground.

4. FUTURE TRENDS

4.1 INTERNATIONAL PROGRAMMES

The promise of a series of satellites in the 1990's carrying microwave sensors of comparable accuracy and resolution to ERS-1 - and probably better - has generated a great interest in studying the Earth as an entire Global System in which interactions take place between the physical, chemical, biological and geological processes occurring within the atmosphere, oceans and solid earth.

The great majority of human beings today enjoy greater abundance from the Earth than at any time in our history. Further advances in weather prediction, fish management, navigation, mineral and energy resources should accompany an increased understanding of Earth processes.

Now that the inhabitants of the earth are perceived to be contributing to what were previously natural processes of global change, our habitat could be significantly altered within a few generations. In some cases, such as the depletion of the Earth's energy and mineral resources, the effects of human activity are obvious and may be irreversible. In other cases, such as the alterations of atmospheric chemical composition, changes may be more difficult to document and their consequences in the long-term harder to predict. The time scales of human-induced changes may not be matched to the scale of their effect.

What is required is a set of Earth observations that allow us to distinguish the different interactions among the Earth's components and to document these effects over different time periods. It is the realisation that only satellites equipped with the right sensors are capable of providing continuous monitoring of the globe over sufficiently long time periods, which has spurred the various space agencies to plan their own polar-orbiting missions - ESA, NASA, France, Japan and Canada to name a few.

The community of environmental scientists has not been slow to respond to the initiative of the space agencies by planning ambitious multi-national programmes of research collecting 'in situ' observations across the surface of the Earth to complement the satellite programmes. In the field of marine science there have been a number of major initiatives including:

(i) Global Ocean Flux Study (GOFS)

GOFS is aimed at improving our understanding of the bio-geochemical processes influencing the dynamics of elemental cycling, particularly of carbon, in the oceans. Four major components - air-sea exchange, primary production, particle production and benthic fluxes - will be underpinned by a range of activities including modelling, and organic and inorganic geochemistry. Remote sensing, including the monitoring of ocean colour, will play an indispensable role.

(ii) The World Ocean Circulation Experiment (WOCE)

WOCE is a major element of the World Climate Research Programme (WCRP) of the World Meteorological Organisation. The planning of WOCE has continued for a number of years and an international WOCE Office is now established at the Institute of Oceanographic Sciences in the UK. Ships, buoys and other platforms from many nations will be devoted to observational campaigns in the 1990's to coincide with ESA's ERS-1 mission and the TOPEX/Poseidon (US/France) precise altimetry mission.

(iii) Tropical Ocean and Global Atmosphere (TOGA)

This international programme is still going on. Although its reliance on satellites is confined to the operational series of NOAA satellites, which provide sea-surface temperature readings through the AVHRR, Nimbus 7 and SSM/I, (and, more recently, altimeter measurements from Geosat) it should not be overlooked that satellite observations in the past played an important part in confirming one of the most important of recent discoveries of ocean-atmosphere interaction - the association between the El Nino sea surface temperature anomaly in the Pacific Ocean off the South American coast, with the Southern Oscillation atmospheric pressure phenomenon.

It should be noted here that the provision of the Along-Track Scanning Radiometer (ATSR) on ERS-1 provides sea surface temperature measurements of a higher accuracy than the AVHRR. These together with measurements of surface wind, and possible precipitation, provide most (but not all) of the parameters required to measure global surface fluxes between atmosphere and ocean.

(iv) Ocean Modelling

The ultimate goal of large-scale global ocean studies is the development of reliable predictive models. The progress made in all scientific investigations - and particularly true of environmental studies - is through good quality observations leading to a theory, usually tested by further observations, leading to a predictive model which is then 'tuned' or improved through further observations taken under a variety of conditions. The major obstacles in the past to producing ocean models have been, first the limitations on the speed and capacity of digital computers and, secondly the difficulty in obtaining a representative sample of evenly distributed ocean observations to validate the models. The present and future generation of computers will overcome the first obstacle but only satellite observations can realistically surmount the second.

(v) Mediterranean Research Programmes

(a) POEM (Physical Oceanography of the Eastern Mediterranean) is a campaign which has been in the planning stages for a number of years and has attracted the participation of oceanographers from the USA, Greece, Turkey, Israel, Italy and Yugoslavia.

(b) Western Mediterranean Circulation Programme

This campaign has been underway since 1986 and is now completed, though it may be revived during the life of ERS-1. It concentrated on a series of measurements using research buoys, ships and aircraft in the Strait of Gibraltar and Alboran Sea, along the North African coast, the Strait of Sicily, and the Tyrrhenian Sea. It involves the USA, Spain, Italy and France.

vi) Global Ocean Observing System

At the second World Climate Conference in 1990 it was proposed that an operational system, the Global Climate Observing System (GCOS), be implemented to monitor climate, detect changes and assess responses. The GCOS is to be based on an improved World Weather Watch together with a newly established Global Ocean Observing System (GOOS) and will be based on present national and international observing systems and experimental programmes. It is proposed that part of the system will comprise a suite of operational satellite sensors including altimeter, scatterometer, imaging radiometers in the visible, infra-red and microwave bands, and precision surface temperature radiometers.

4.2 DISTRIBUTION OF SATELLITE DATA

There are at least two major aspects of satellite data which set them apart from more traditional measurements.

- i) Even set against the high costs of running research vessels, satellite missions are expensive. The ERS-1 programme will cost over \$600m.
- ii) The proprietorial rights of satellite data are not the same as for measurements taken at sea to which claim can usually be made by individual scientists or groups of scientists.

The effects of the higher costs of satellites is, in many cases, to make space agencies reluctant to 'give away' their observations to anyone who has an interest in them. The tendency in the last few years has been towards a commercialisation of space where 'realistic' prices are to be charged for data. This has been evident in recent Earth Observation programmes through the creation of Eosat to market Landsat data, the launching of SPOT Image, and the statements made by the administrators of some of the countries supporting the ESA programmes to the effect that space must ultimately respond to market forces and that the foundations for this policy should be laid now.

At the same time the majority of users of satellite remote sensing data - especially over the ocean - are drawn from the scientific community who, from the start, lent strong support to the space agencies in establishing ocean observing programmes, and who later made important contributions to the calibration and validation of sensors, and to the interpretation of their output. Thus, the scientific community has built up a lot of credit with the space agencies - a fact not always appreciated by those who would now charge them 'realistic' market prices.

For their experimental, pre-operational missions space agencies appoint a number of 'principal investigators' selected on the basis of research proposals solicited through an 'Announcement of Opportunity'. In this way European oceanographers gained access to data from NASA's Seasat and several others now sit on the Topex/Poseidon Science team. Likewise the 200 PI's selected by ESA to participate in the ERS-1 mission (of whom the vast majority are scientists) include investigators from several non-European countries. At present - and this issue is still being discussed in ESA - only PI's will enjoy free access to data - and the quantity is limited to what is deemed sufficient to satisfy the aims of the experiments selected.

As we have noted, one way to increase the dissemination of satellite-derived ocean products should be through international collaboration in recognised global experiments such as WOCE. It is already implied in the WOCE planning document that designed Special Analysis Centres will assume responsibility for generating 'merged' level 3 products. The ESA plan is to make ERS-1 data available at level 2 which will be produced in Processing and Archiving Facilities (PAF's) appointed and supported by the Agency to carry out different tasks.

France is responsible for over-ocean low-bit rate data from the altimeter and scatterometer required to meet the WOCE goals.

If participation in international research programmes is one way to gain access to satellite data, there is, nonetheless, within individual countries a wide interest in obtaining regional offshore data. To many nations, whose resources in terms of research vessels or moored buoys are limited, satellites offer the only realistic means of providing regular monitoring of storm surges, potential pollutants, plankton blooms, anomalous temperatures, fronts, and ship traffic within

their economic zone. In this regard the synthetic aperture radar, infra-red sounder and coastal zone colour scanner are more likely to head their priority list of sensors. It may be in the processing and interpretation of these data rather than in the analysis of global ocean altimeter data that training is more urgently required.

At present the ERS-1 SAR operates on a 10% duty cycle - that is, it can function for up to 10 minutes on each 100 minute orbit. The UK has responsibility for processing SAR Imagery over Western Europe and the Atlantic.

SAR imagery is not addressed in the WOCE plan since it does not sit easily within the stated objectives of the experiment. Nevertheless there is likely to be considerable demand for it if appropriate ground stations are installed - for the SAR data rate in its full imaging mode precludes on-board recording so that dedicated ground stations are essential. (It was for this reason that no Seasat SAR imagery was taken over the southern hemisphere).

4.3 EDUCATION & TRAINING

Earth observation from space has continued more or less uninterrupted for over 20 years and many remote sensing training schemes have been developed around it. Several textbooks on the fundamental principles of remote sensing have been produced but the major thrust has always been towards land applications. Too many remote sensing symposia, conferences or workshops have been organised around the technique itself as if it could be applied equally to all earth disciplines. This is not the case. The specific ocean applications of remote sensing need to be treated separately. Most remote sensing centres concentrate on image processing, but although this may play an important role in some areas of marine sciences it is not the dominant technique in every marine application. A more rewarding approach in the future is likely to be the merging and interpretation of signals from several sensors operating from the same platform - the symbiotic approach.

The impact of dedicated ocean satellites in the next decade and beyond should be so great that all future oceanographers will need to be educated in this area. No longer will it be regarded as an optional extra. In particular, it is important to avoid creating a small core of 'satellite oceanographers', set apart from their colleagues, and whose numbers would be too limited to tackle the global data sets of the future. Ultimately it is the availability of trained personnel which will limit the full exploitation of the technique.

We have seen that programmes such as WOCE - and others on the horizon - were planned around the satellite programmes proposed for the 90's. They now form part of the fundamental strategy. Yet the plans to merge satellite observations over the oceans with other data sets as inputs to ocean predictive models almost certainly requires more people skilled in remote sensing than are presently available.

This comparative shortage of skilled people is not confined to the scientific aspects of the problem. There is probably a greater dearth of adequately trained staff in the commercial sector of marine applications - an area which for obvious reasons the space agencies would like to see developed. Future training programmes should not lose sight of their requirements.

It is true that remote sensing is a technique rather than a scientific subject in its own right; but it remains a complex technique providing unique global perspectives. It requires a quite different approach to those of the traditional methods of hydrographic casts, current profiles and surface drifters.

To date little formal training in satellite remote sensing has been available to oceanographers. The initiatives in training have mostly come from a few academic institutions such as the University of Dundee who have mounted summer schools and short courses. Far too often young oceanographers must look for what marine pickings they can find in the larger assemblies called to examine 'remote sensing'.

There is now surely a strong case for space agencies to combine with international organisations such as IOC in promoting training programmes in satellite oceanography.

CONCLUSIONS

The past quarter of a century has been one of the most exciting and rewarding in the history of the study of the earth and its environment. Our view of the solid earth, for example, was totally transformed in the 1960's by the notion of sea-floor spreading and plate tectonics. Predictive models of the atmosphere and oceans can now be created and expanded largely due to the rapid growth in computer power. At the same time we have witnessed a remarkable improvement in the performance of earth observing satellites. Today's sensors are capable of providing precise information on small but significant changes in the earth's surface features.

Environmental research covers many different disciplines including studies of ocean behaviour; the evolution of plate tectonics; the nature of the Earth's atmosphere; the dynamics of polar ice caps; and the interdependence of terrestrial eco-systems and their relation to hydrological cycles. Although each field demands its own tools and method of investigation, it is becoming increasingly clear that the continents, oceans, atmosphere and biosphere are components of a complex and dynamic earth system.

If the advances in our understanding of the fluid earth have been less dramatic and revealing than our understanding of solid earth processes, it is recognised, nevertheless, that the oceans, atmosphere and ice-covered regions are coupled in a way that determines short-term weather patterns and long-term climate trends. In this area, satellites have played a major role. Synoptic observations of global temperature, moisture and cloud cover have led to considerably more accurate predictions of the general circulation of the atmosphere.

It is this new awareness of a pattern of global connections plus the impressive advances in satellite and computer technology that persuade many environmental scientists that we may have reached the dawn of a new era of scientific discovery. With almost daily reminders of the effect of natural disasters on human life - earthquakes, volcanoes, drought, flooding and storms - and with man demonstrably increasing the carbon dioxide content of the atmosphere, satellites may provide a much needed lifeline.

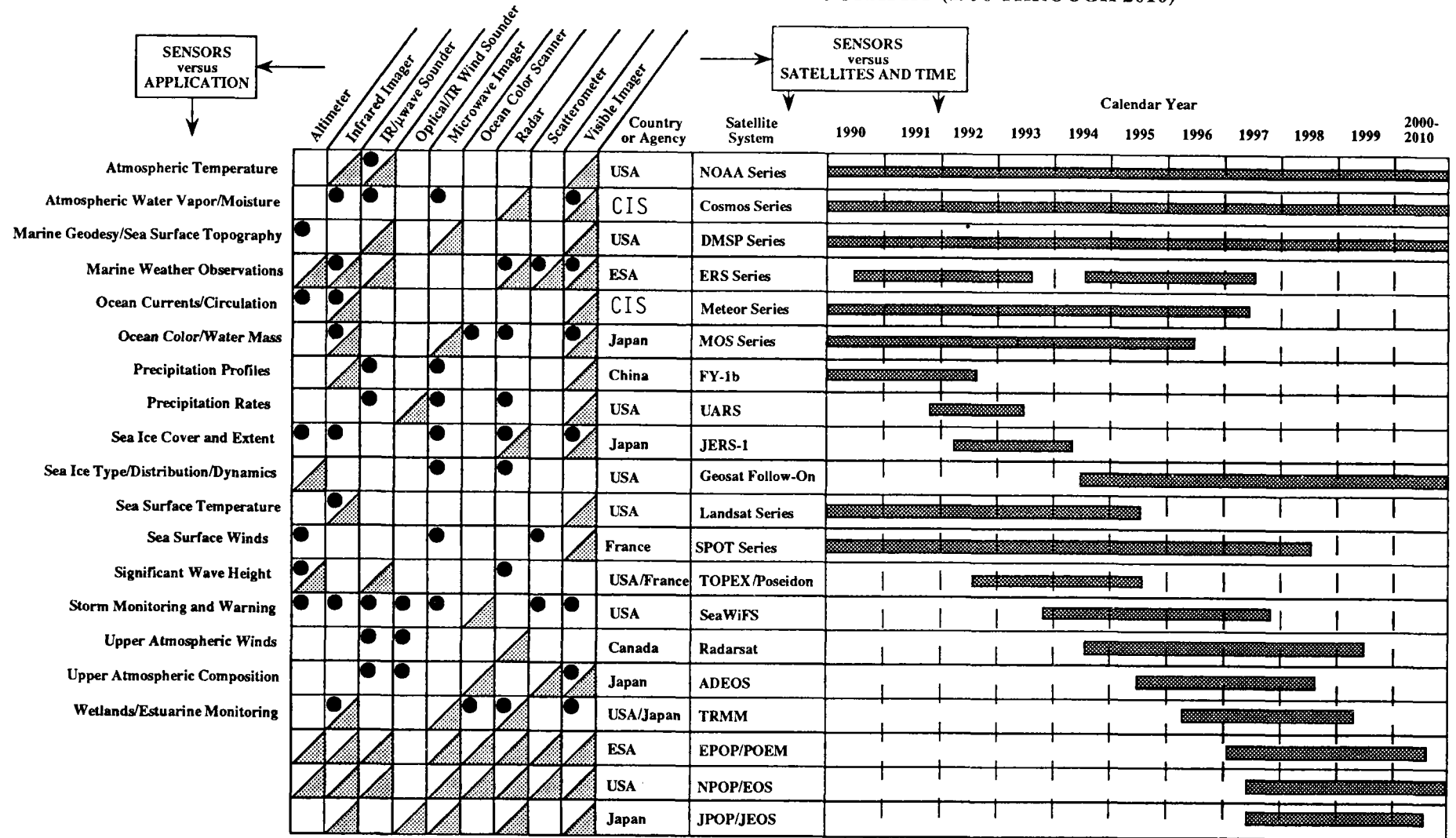
More short-term, practical marine applications of remote sensing are also emerging. Offshore exploration, fisheries, aquaculture, coastal management and energy from the sea programmes have all been shown to be potential beneficiaries of a programme of regular monitoring of satellites.

An urgent problem to which a solution is required quickly if the new generation of marine satellites is to be fully explored is how best to transfer the information cheaply and rapidly to the point of use in a format that can be employed immediately without the need for complex data receiving centres. Satellite data must be aimed at the PC's of local or regional marine environmental centres.

ANNEX

List of the individual current or planned oceanographic satellites and their main characteristics. The first table summarises the sensors to be deployed and their applications

**TABLE 1. CURRENT AND PLANNED SATELLITE SYSTEMS IN SUPPORT OF
MARINE METEOROLOGY AND PHYSICAL OCEANOGRAPHY (1990 THROUGH 2010)**



Legend for Support to Marine Meteorology and Physical Oceanography:

▲ = Sensor Manifested on Satellite (Use right hand Portion of Table)

→

● = Sensor Application to Marine Meteorology and Physical Oceanography (Use left-hand Portion of Table)

←

Name: Defence Meteorological Satellite Program (DMSP)

Type: polar

Operating period: continuing program

Sensors:

Operational Linescan System (OLS):

3 bands in 0.4-0.95 μm , 0.4-1.1 μm and 10.2-12.8 μm

Smallest ground detail: 0.62 km

Ground coverage: 2963 km

Sensor System Microwave Imager (SSM/1

7 bands in 19.3 - 85.5 GHz

Smallest ground detail: 25/50 km

Ground coverage: 1290 km

Operating agency: NOAA, National Environmental Satellite Data, and
Information Service (NESDIS) Satellite Data Services
Division
Room 100
World Weather Building
Washington, D.C. 20233, USA
Tel: +1-301-763 8111

Name: Meteosat 1-4
Type: geostationary 0° longitude
Operating period: from 1977 onwards

Sensors:

Visible and Infrared Radiometer:

3 bands in 0.4-1.1 μm , 5.7-7.1 μm and 10.5-12.5 μm

Smallest ground detail: 2.5 or 5 km (visible)

5 km (infrared)

Ground coverage: full earth disc

Operating agency: ESA-ESOC
Robert Bosch Strasse 5
D 6100 Darmstadt
Germany

Name: Meteor series
Type: polar
Operating period: continuing program from 1977

Sensors:

Scanning Telephotometer (for direct imaging):

1 band in 0.5 - 0.7 μm
Smallest ground detail: 2 km
Ground coverage: 2100 km

Scanning Telephotometer (for global coverage):

1 band in 0.5 - 0.7 μm
Smallest ground detail: 1 km
Ground coverage: 2400 km

Scanning IR Radiometer (for global coverage):

1 band in 8 - 12 μm
Smallest ground detail: 2 km
Ground coverage: 2600 km

Scanning IR Spectrometer:

8 bands in 11 - 18 μm
Smallest ground detail: 30 km
Ground coverage: 1000 km

Operating agency: Hydrometeorological Research Centre of the Russian Federation
9-13 Bolshhevistskaya Street
Moscow 123376
USSR
Tel. +7-095 3186251
Fax. +7-095 2539484

Name: NIMBUS-7
Type: polar
Operating period: 1978-1986

Sensors:

Coastal Zone Color Scanner (CZCS):

six bands 0.4-12.5 μm
Smallest detail: 800 m
Ground coverage: 1600 km

Operating agency: NASA
National Space Science Data Centre
Code 630.2
Goddard Space Flight Center
Greenbelt, Maryland 20771, USA
Tel: +1-301-286 7354

Name: SEASAT-A

Type: polar

Operating period: 1978

Sensors:

Scatterometer (SASS): 14.5 GHz

Smallest detail: 50 km

Ground coverage: 900 km

Scanning Multispectral Microwave Radiometer (SMMR):

5 bands 6.6 - 37 GHz

Smallest detail: 37-150 km

Ground coverage: 600 km

Synthetic Aperture Radar (SAR):

Smallest detail: 25 m

Ground coverage: 100 km

Operating agency: NASA

National Space Science Data Centre

Code 630.2

Goddard Space Flight Center

Greenbelt, Maryland 20771, USA

Tel: +1-301-286 7354

Name: TIROS-N
Type: polar
Operating period: 1978-1980

Sensors:

Advanced Very-High Resolution Radiometer (AVHRR)

five bands 0.58-12.5 μm
Smallest detail: 1.1 km
Ground coverage: 2240 km

Operating agency: NASA
National Space Science Data Centre
Code 630.2
Goddard Space Flight Center
Greenbelt, Maryland 20771, USA
Tel: +1-301-286-7354

Name: STS - Space Shuttle
Type: polar, about 250 km altitude
Operating period: regular missions since 1984

Sensors:

For each mission a specific package is selected usually containing several photographic cameras, TV-like and digital scanning instruments. On-line referral database accessible via SPAN, INTERNET or direct on-line.

Operating agency: NOAA, National Environmental Satellite Data and Information Service (NESDIS) Satellite Data Services Division
Room 100
World Weather Building
Washington, D.C. 20233, USA
Tel: +1-301-763 8111

Name: GOES D - G
Type: geostationary at East and West longitudes
Operating period: from 1985/87

Sensors:

Visible and Infrared Spin Scan Radiometer (VAS):
5 bands in 0.55 - 0.7 μm and 3.90 - 14.7 μm
Smallest ground detail: 1 km (visible)
8 km (infrared)
Ground coverage: full earth disc

Atmospheric Sounder (VISSR):
12 bands in 3.90 - 14.7 μm
Smallest ground detail: 7-14 km
Ground coverage: full earth disc

Operating agency: NOAA, National Environmental Satellite Data, and
Information Service (NESDIS) Satellite Data Services
Division
Room 100
World Weather Building
Washington, D.C. 20233, USA
Tel: +1-301-763 8111

Name: MIR Space Station
Type: polar, about 300 km altitude
Operating period: since 1986

Sensors:

During the lifetime different sensors have been operated including several types of photographic cameras, TV-like systems and digital scanner instruments.

Source for data: Soyuzkarta
45, Volgogradskij Pr.
Moscow 109125
Russian Federation
Tel: +7-095 1774050
Tlx: 411942 REN SU

Name: SPOT-1
Type: polar, 830 km, coverage cycle: 26 days
Operating: 1986-1990

Sensors:

HRV-1 and HRV-2

-P(anchromatic)mode

1 band 0.51-0.73 μ m

Smallest detail 10 m

-XS (multispectral) mode

3 bands 0.5-0.89 μ m

Smallest detail 20 m

Both: ground coverage: 60-80 km

Operating agency: SPOT IMAGE
16 bis, Av. Edouard Belin
F 31030 Toulouse Cedex
France
Tel: +33-61-539976
Fax: +33-61-281859
Tlx: 532079F

Name: MOS-1A (Marine Observation Satellite)
Type: polar, 990 km, 103 minutes
Operating since: 1987

Sensors:

MESSR: Multispectral Electronic Self-Scanning Radiometer

2 bands visible, 2 bands near-infrared

Smallest ground detail: 50 m

Ground coverage: 100 km

VTIR: Visible and Thermal Infrared Radiometer

1 band visible, 3 bands thermal infrared

Smallest ground detail: 900 m (visible)

2700 m (thermal infrared)

Ground coverage: 1500 km

MSR: Microwave Scanning Radiometer 23/31 GHz

Smallest ground detail: 32 km (23 GHz)

23 km (31 GHz)

Ground coverage: 320 km

Operating agency: NASDA

National Space Development Agency of Japan

2-4-1, Hamamatsu-cho

Minato-Ku

Tokyo 105

Japan

Tel: +81-3-5470 4111

Fax: +81-3-433 0796

Tlx: 28424 (AAB: NASDA J28424)

Name: MOS-1B (Marine Observation Satellite)
Type: polar, 900 km altitude, 103 minutes
Operating period: > 1989

Sensors:

MESSR: Multispectral Electronic Self-Scanning Radiometer

2 bands visible, 2 bands near-infrared

Smallest ground detail: 50 m

Ground coverage: 100 km

VTIR: Visible and Thermal Infrared Radiometer

1 band visible, 3 bands thermal infrared

Smallest ground detail: 900 m (visible)

2700 m (thermal infrared)

Ground coverage: 1500 km

MSR: Microwave Scanning Radiometer 23/31 GHz

Smallest ground detail: 32 km (23 GHz)

23 km (31 GHz)

Ground coverage: 320 km

Operating agency: NASDA

National Space Development Agency of Japan

2-4-1, Hamamatsu-cho

Minato-Ku

Tokyo 105

Japan

Tel: +81-3-5470 4111

Fax: +81-3-433 0796

Tlx: 28424 (AAB: NASDA J28424)

Name: GMS-4 (Geostationary Meteorological Satellite-4)
Orbit: geostationary, 140° E
Operating period: from 1989

Sensors:

VISSR: Visible and Infrared Spin Scan Radiometer
0.50-0.75 μm in 4 channels
Smallest ground detail: 1.25 km
Ground coverage: full earth disk

Operating agency: NASDA
National Space Development Agency of Japan
2-4-1, Hamamatsu-cho
Minato-Ku
Tokyo 105
Japan
Tel: +81-3-5470 4111
Fax: +81-3-433 0796
Tlx: 28424 (AAB: NASDA J28424)

Name: SPOT-2
Type: polar, 830 km, coverage cycle: 26 days
Operating: from beginning 1990

Sensors:

HRV-1 and HRV-2

-P(anchromatic)mode

1 band 0.51-0.73 μ m

Smallest detail 10 m

-XS (multispectral) mode

3 bands 0.5-0.89 μ m

Smallest detail 20 m

Both: ground coverage: 60-80 km

Operating agency: SPOT IMAGE
16 bis, Av. Edouard Belin
F 31030 Toulouse Cedex
France
Tel: +33-61-539976
Fax: +33-61-281859
Tlx: 532079F

Name: FY-1b
Type: polar, 900 km altitude, 102.86 minutes
Operating period: since September 1990

Sensors:

VHRR: 5 bands from 0.58 - 12.5 μm
Smallest ground detail: 1.1 km
Ground coverage: 1500 km

Operating agency: Satellite Meteorology Center
State Meteorological Administration
Beijing
Peoples Republic of China

Name: ERS-1
Type: polar, 785 km altitude, 100.485 minutes
Operating period: from 1991

Sensors:

Active Microwave Instrument (AMI): 5.3 GHz

Smallest ground detail: 30 m (SAR image mode)
Ground coverage: up to 100 km (SAR image mode)
Ground coverage: 9.6 - 12 km every 200 km (wave mode)
Smallest detail: 50 km (wind mode)
Ground coverage: 500 km (wind mode)

Radar Altimeter: 13.8 GHz

Accuracy better than 10 cm

Along Track Scanning Radiometer/ Microwave Sounder (ATSR/M):

4 bands on 1.6, 3.7, 10.8 and 12.0 μm
Smallest ground detail: 50 km (0.5 K absolute)
1 km (0.1 K relative)
Ground coverage: 500 km
2 bands on 23.8 GHz and 36.5 GHz, footprint: 22 km

Operating agency: ESA Earthnet
Via Galileo Galilei
00044 Frascati
Italy
Tel. +39-6 941801
Fax. +39-6 94180361

Name: GOES I - M
Type: geostationary at East and West longitudes
Operating period: from 1991/2000

Sensors:

Imager:

5 bands in 0.55 - 12.5 μm
Smallest ground detail: 1 km (visible)
4 or 8 km (infrared)
Ground coverage: selectable areas

Atmospheric Sounder (VISSR):

19 bands in 3.7 - 14.7 μm
Smallest ground detail: 8 km
Ground coverage: selectable areas

Operating agency: NOAA, National Environmental Satellite Data, and
Information Service (NESDIS) Satellite Data Services
Division
Room 100
World Weather Building
Washington, D.C. 20233, USA
Tel: +1-301-763 8111

Name: Pritoda-1
Type: Space station
Operating period: > 1992

Sensors:

Imaging spectrometer, details unknown yet

Operating agency: Hydrometeorological Research Centre of the Russian Federation
9-13 Boishhevistskaya Street
Moscow 123376
USSR
Tel: +7-095-3186251
Fax: +7-095-2539484

Name: JERS-1 (Japan Earth Resources Satellite)
Orbit type: Polar, 568 km, coverage cycle: 44 days
Operating period: 2 years after February 1992

Sensors:

Synthetic Aperture Radar (SAR): 1275 MHz

Smallest ground detail: 18 m

Ground coverage: 75 km

Optical Sensor (OPS):

8 bands 0.56 - 2.33 μm (one stereo)

Smallest ground detail: 18-24 m

Ground coverage: 75 km

Operating agency: NASDA
National Space Development Agency of Japan
2-4-1, Hamamatsu-cho
Minato-Ku
Tokyo 105
Japan
Tel: +81-3-5470 4111
Fax: +81-3-433 0796
Tlx: 28424 (AAB: NASDA J28424)

Name: GEOSAT Follow-On (GFO)
Type: polar, 800 km altitude
Operating period: 1994 (GFO-1), 1997 (GFO-2)

Sensors:

Altimeter 13.5 GHz

Operating agency: NOAA, National Environmental Satellite Data, and
Information Service (NESDIS) Satellite Data Services
Division
Room 100
World Weather Building
Washington, D.C. 20233, USA
Tel: +1-301-763 8111

Name: Radarsat
Type: polar, 1000 km altitude, 105 minutes
Operating period: from mid 1994

Sensors:

Synthetic Aperture Radar (SAR) 5.3 GHz
Smallest ground detail: 28 m
Ground coverage: 500 km (in 130 km subparts)

Operating agency: Canadian Centre of Remote Sensing
1547 Maryville Road
K1A 0Y7 Ottawa, Ontario
Canada
Tel. +1-613 9520500
Fax. +1-613 9527353

Name: GMS-5 (Geostationary Meteorological Satellite-5)
Orbit: geostationary, 140° E
Operating from 1994

Sensors:

VISSR: Visible and Infrared Spin Scan Radiometer
0.50-0.70 μm in 4 channels
Smallest ground detail: 1.25 km
Ground coverage: full earth disk

Operating agency: NASDA

National Space Development Agency of Japan
2-4-1, Hamamatsu-cho
Minato-Ku
Tokyo 105
Japan
Tel: +81-3-5470 4111
Fax: +81-3-433 0796
Tlx: 28424 (AAB: NASDA J28424)

Name: TOPEX/POSEIDON
Type: polar, 1334 km altitude
Operating period: 1994 (GFO-1), 1997 (GFO-2)

Sensors:

Altimeter 1: two bands 13.6 + 5.3 GHz

Altimeter 2: 13.65 GHz

Operating agencies: NOAA, National Environmental Satellite Data and
Information Service (NESDIS) Satellite Data Services
Division
Room 100
World Weather Building
Washington, D.C. 20233, USA
Tel: +1-301-763 8111
and
CNES
18 Avenue Edouard Belin
31055 Toulouse Cedex
Tel. +33-61 273131
Fax. +33-61 273179
Tlx. 531081

Name: ADEOS
Type: polar
Operating period: >1995

Sensors:

Ocean Colour and Temperature Scanner (OCTS):

12 bands from visible to thermal infrared

Smallest ground detail: 700 km

Ground coverage: 1400 km

Advanced Visible and Near Infrared Radiometer (AVNIR):

5 bands from visible to near infrared

Smallest ground detail: 8/16 m

Ground coverage: 80 km

Operating agency: NASDA
National Space Development Agency of Japan
2-4-1, Hamamatsu-cho
Minato-Ku
Tokyo 105
Japan
Tel: +81-3-5470 4111
Fax: +81-3-433 0796
Tlx: 28424 (AAB: NASDA J28424)

Name: ATMOS
Type: polar
Operating period: > 1995

Sensors:

ROSIS (Reflective Optics System Imaging Spectrometer)
0.390-1.050 μm in 15 channels
Smallest ground detail: 250 m
Ground coverage: 1400 km

Operating agency: Bundesministerium für Forschung und Technologie
Heinemannstrasse 2
Bonn Bad Godesberg
Germany
Tel. +49-228 593250
Fax. +49-228 593601

Name: TRMM (Tropical Rain Mapping Mission)
Type: polar, 350 km height
Operating period: three years after 1996

Sensors:

Precipitation radar: 14 GHz
Smallest ground detail: 5 x 4.5 km
Ground coverage: 220 km

AVHRR: 0.65-12.0 μ m
Smallest ground detail: 2x3 km
Ground coverage: 700 km

SSM/I: 19.35/22.235/37/85.5 GHz
Smallest ground detail: 16x23 km (19 GHz)
Ground coverage: 580 km

ESMR: 19.35 GHz
Smallest ground detail: 12x24 km (15°)
Ground coverage: 700 km

Operating agency: NASDA
National Space Development Agency of Japan
2-4-1, Hamamatsu-cho
Minato-Ku
Tokyo 105
Japan
Tel: +81-3-5470 4111
Fax: +81-3-433 0796
Tlx: 28424 (AAB: NASDA J28424)

Name: SeaWiFS
Type: polar, 705 km
Operating period: > 1995

Sensors:
8 bands 0.43-12.5 μm
Smallest detail: 1.13 km

Operating agency: NOAA
National Environmental Satellite,
Data, and Information Service (NESDIS)
Satellite Data Services Division
Room 100
World Weather Building
Washington, D.C. 20233, USA
Tel: +1-301-763-8111

Name: Earth Observing System (EOS)-A
Type: polar
Operating period: from 1997

Sensors:

High Resolution Microwave Spectrometer Sounder (HIMSS):

several bands in 6.6 - 90 GHz

Smallest ground detail: 5 - 50 km

High Resolution Imaging Spectrometer (HIRIS):

200 bands in 0.40 - 2.5 μm

Smallest ground detail: 30 m

Ground coverage: 30 km

Multi-Angle Imaging Spectro-Radiometer (MISR):

4 bands in 0.40 - 0.86 μm

Smallest ground detail: 0.216 - 1.73 km

Moderate Resolution Imaging Radiometer Nadir (MODIS-N):

40 bands in 0.40 - 1.50 μm

Smallest ground detail: 200 - 800 m

Moderate Resolution Imaging Radiometer Tilt (MODIS-T):

64 bands in 0.40 - 1.04 μm

Smallest ground detail: 1 km

Ground coverage: 1500 km

Operating agency: NOAA, National Environmental Satellite Data and
Information Service (NESDIS) Satellite Data Services
Division
Room 100
World Weather Building
Washington, D.C. 20233, USA
Tel: +1-301-763 8111

Name: Earth Observing System (EOS)-B
Type: polar
Operating period: from 1997

Sensors:

Altimeter (ALT) 5.3 and 13.6 GHz

Smallest ground detail: 2 - 10 km
altitude accuracy 2 cm

Stick Scatterometer (STIKSCAT) 5.3 GHz

Smallest ground detail: 25 km
windspeed accuracy 2 m/s and 20 degrees

Operating agency: NOAA, National Environmental Satellite Data and
Information Service (NESDIS) Satellite Data Services
Division
Room 100
World Weather Building
Washington, D.C. 20233, USA
Tel: +1-301-763 8111

Name: European Polar-Orbiting Platform (EPOP)/Columbus
Type: polar, 824 km altitude
Operating period: from 1997

Sensors: (final package still under discussion)

Radar Altimeter (ALT-2): 13.8 GHz

Active Microwave Instrumentation (AMI)

Medium Resolution Imaging Spectrometer (MERIS):

9 bands in 0.39 - 1.05 μm

Smallest ground detail: 500 m

Ground coverage: 1500 km

Multiband Imaging Microwave Radiometer (MIMR):

7 bands in 1.4 - 36.5 GHz

Ground coverage: 1400 km

Synthetic Aperture Radar C band (SAR-C): 5.3 GHz

Smallest ground detail: 10 m

Ground coverage: 100 - 800 km

Wind Scatterometer (SCATT-2): 5.3 GHz

Smallest ground detail: 25 m

Ground coverage: 120 - 700 km

Operating agency: ESA

8-10, Rue Mario Nikis

75738 Paris-Cedex 15

France

Tel. +33-1 42737654

Fax. +33-1 42737560