Prepared for ESA/ESRIN

Application of Satellite Remote Sensing to Developing Countries

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Application Of Satellite Remote Sensing To Developing Countries

PRELIMINARY COPY

Note to the Reader

This booklet is a preliminary copy of the first set of viewgraphs being prepared by Satellite Observing Systems (SOS) for ESA to support Agency's activities for promoting the use of Earth observation data from space in various environmental disciplines and applications for developing countries.

The attached pictures are meant to show the material which is being prepared to illustrate marine applications. More material to demonstrate the use of ERS SAR data and its complementarity is in preparation.

The exercise is aimed at building viewgraph sets with specific characteristics oriented towards developing countries:

- user "language" is used, geared to parameters and phenomena familiar to the audience, particularly important in the case of decision makers
- emphasis is on applications and not on technology
- optical remote sensing is largely used in this initial set because it is historically more familiar to the target audience
- radar remote sensing is introduced with ERS-1 SAR images to initiate users to its uniqueness and its complementarity with other data
- particular attention is given to stressing the following benefits of satellite data:
  . monitoring at global scale with high local accuracy, in particular over areas with little or no conventional data
  . complementarity of optical and radar information
  . creation of long time series of coherent and calibrated data sets
  . contribution to research activities on the one hand and to operational forecasting models on the other hand.

The overall exercise is intended for the preparation of viewgraph sets like the attached one, as well as of brochures.

Frascati, 7 September 1994

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Applications of satellite remote sensing over coastal areas with particular reference to developing countries

SYNOPSIS

Observations of coastal zones by sensors carried on board earth orbiting satellites have been under development for a number of years. The performance of these instruments under different environmental conditions is now reasonably well-understood and space missions directed more specifically at marine activities are entering a more operational phase.

Since the launch of ERS-1 in July 1991, space programmes have become increasingly concerned with identifying the potential economic benefits from the comparatively large volumes of data generated from current and future satellites.

The value of the contribution that satellites will bring to environmental monitoring programmes designed to detect trends in global changes - whether brought about by natural causes or induced by human activities - is not in question and acts as a spur to technologically advanced nations to direct substantial sums in support of satellite missions.

But shorter-term economic applications of data derived from these spacecraft are now emerging and it is these which are addressed here. How can satellite-derived information be incorporated in existing coastal management programmes to the ultimate benefit of national or regional authorities?

In many situations one of the first obstacles to be overcome is rapid access to the data. Problems concerning data integration, processing, analysis and interpretation must also find solutions - but until information can be made available quickly to the relevant decision makers these problems remain of academic interest only.

Types of satellite-derived information.

Sensors for observing coasts and oceans are divided into three main categories - microwave, infra-red and optical.

Microwave or radar sensors such as those carried on ERS-1 offer the advantage of operating in all weathers, day and night. They have proved very sensitive to small changes in sea surface roughness and are therefore particularly useful for monitoring sea state (winds and waves) and detecting slicks, either man-made such as oil and effluent discharges, or natural slicks such as eddies, internal waves and ocean fronts. Imaging radar systems also have a fine enough resolution to detect medium size ships.

Infra-red devices such as the ERS-1 Along-Track Scanning Radiometer (ATSR) and NOAA's Advanced Very High Resolution Radiometer (AVHRR) are capable of

detecting temperature changes of less than a 1/2 degree over an area about 1km square.

Optical sensors operate in a number of discrete wavebands in order to distinguish and extract the ocean colour signal from changing conditions in the atmosphere between the satellite platform and the sea surface.

Satellite operations

Earth observing satellites generally fly at heights of around 800-1200 km completing a circuit of the globe in about 100 minutes. In this time the earth has spun 25^0 on its axis so that the next crossing of the equator by the satellite lies almost 3000 km to the west. By making small adjustments to the orbiting height of the satellite its ground track can be made to repeat exactly after a pre-determined number of days. Thus, the ERS-1 satellite has operated at three repeat orbit patterns of 3, 35 and 168 days. Topex/Poseidon repeats its tracks every 10 days while Seasat and Geosat followed a 17-day repeat orbit.

Selection of an orbit repeat pattern is often difficult since a compromise must be made between the frequency of observations and track separation. A 3-day repeat pattern equates to a track separation at the equator of little less than 1000 km. By contrast satellites designed to measure the shape of the earth have operated for 18 months without repeating, covering the globe with a dense network of intersecting ascending and descending tracks spaced no more than a few kilometres apart. ERS-2 will operate throughout its mission on a 35-day repeat orbit pattern providing a track separation of less than 100km at the equator.

It will be immediately evident that for monitoring surface features which may exhibit rapid changes - for example, sea state, slick patterns or ship traffic - the information derived from a single satellite must be integrated with information derived by more conventional means. In time, space agencies may follow the example of telecommunication satellites by launching a sufficient number of spacecraft dedicated to performing specific monitoring tasks. At present the state of a coastal environment may change too rapidly for a single monitoring satellite to make any significant impact where real-time intervention is needed.

Where satellites have proved invaluable is not so much in emergency 'fire-fighting' situations but in monitoring the pattern of events over longer time-frames. Seasonal or inter-annual variability along a coastline or across a continental shelf is best done from a satellite since no other system can combine wide spatial coverage with a long continuity of observations.

Reliable statistics lead to improved coastal management. The presence of a particularly violent storm, for example, may escape the notice of a single satellite if it is passing over the other side of the globe at the time - but statistics on the

probability of waves exceeding a certain height in any particular season or month may prove invaluable to an offshore operator planning the design of a rig. And these statistics can be extracted ***over any part of the globe.***

Likewise the passage of a particular ship may escape the notice of a satellite, but figures on the seasonal or annual density of ships crossing a region could prove more useful. A ship illegally discharging oil may think twice about the penalties if it is known that an orbiting satellite - capable of identifying both the offending slick and the ship - may be passing overhead.

Coastal applications

A combination of space sensors - radar, infra-red and optical - is capable of providing valuable data on sea surface roughness, temperature, colour and topography, and from these four basic parameters useful information can be derived on currents, winds, waves, slicks, effluent discharges and nutrient concentrations. and, as we have seen, ships can also be distinguished by high-resolution radars.

We shall examine each of these applications in turn and present examples of the sort of useful information that can be provided by satellites.

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REMOTE SENSING OF PLANET EARTH

REMOTE SENSING OF PLANET EARTH

The earth is unique within the planets of the solar system. It contains large quantities of water which allow life, as we know it, to survive.

In the last quarter of a century space technology has extended from placing men on the moon to monitoring the state of the surface of the earth. Sensors have increased in accuracy and resolution. It is now possible for a satellite to measure its own height above the sea surface to an accuracy that exceeds 5cm from a height of over 1000 km. Radar images can easily resolve individual waves within ocean swell. Very small changes in surface roughness caused by pollutants are immediately recognisable. Ships, their wakes and discharges, can be clearly distinguished.

Ocean colour changes reveal the presence of increased phytoplankton blooms (which might indicate richer fishing grounds) or of increased sediment load brought down by rivers - or effluent discharges into the sea. Long-term patterns of sea surface temperature changes may act as a precursor to a global climate change; so might diminishing ice caps, or increasing wind or surface wave patterns. All can be detected from satellites.

As indicated in slide (3) the range of spatial and temporal changes of the variability of earth processes is very large. Satellite monitoring is an ideal way to detect small changes over a long time interval while at the same time providing global coverage. Satellites are less suited to emergency, 'fire-fighting' operations where an immediate response may be required.

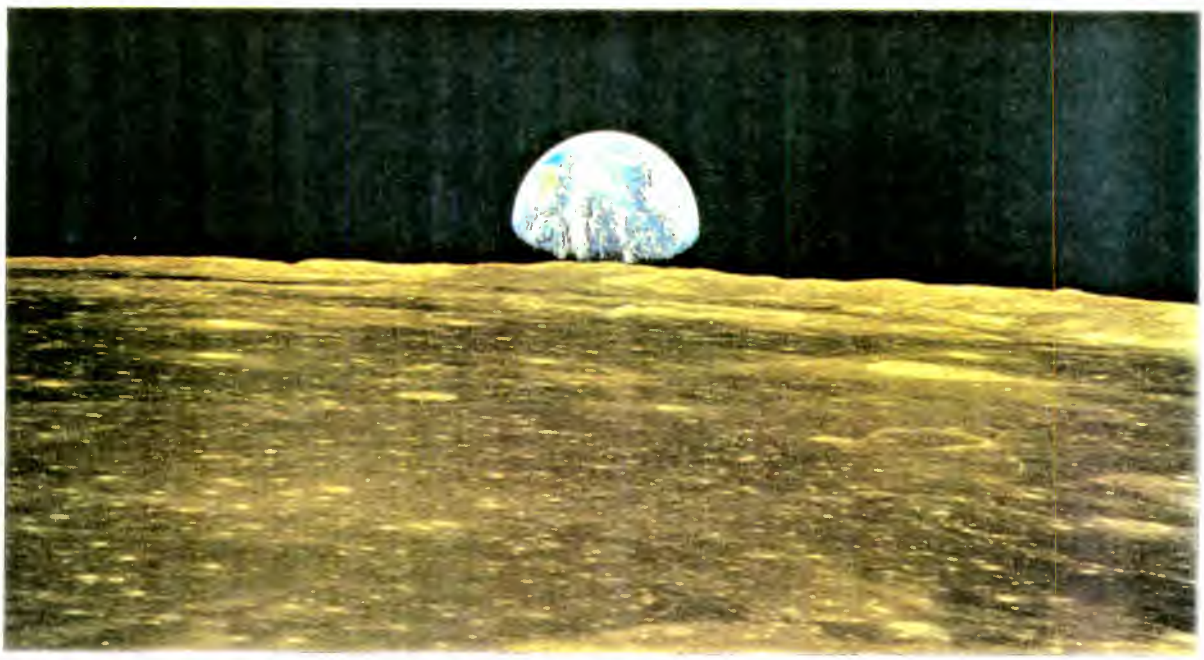
Many of the climate processes shown to make up the earth's climate system are amenable to satellite observation. But what of the shorter-term applications. Can satellites contribute to
- Improved management of fish stocks
- Pollution detection
- Flood warning systems
- Improved forecasting of offshore operating conditions
- Reduction of ship damage through improved routing
- Geophysical assessment of oil-bearing potential of offshore zones

The answer to all of these questions is a qualified 'yes'. A single orbiting earth observing satellite may be limited in the importance of its contribution but - as France, China, Canada, Japan and the European Space Agency all seek to follow the lead

given by NASA - it becomes increasingly likely that the next quarter of a century may herald the dawn of a new era.

The remainder of the illustrations in this first section are intended merely to illustrate the different view of ocean processes that may be obtained from space - in this case from a manned shuttle flight. Traditionally, ocean behaviour has been studied at the sea surface from buoys or research vessels. That is possibly the worst place from which to study large scale processes.

Earthrise as viewed from the moon



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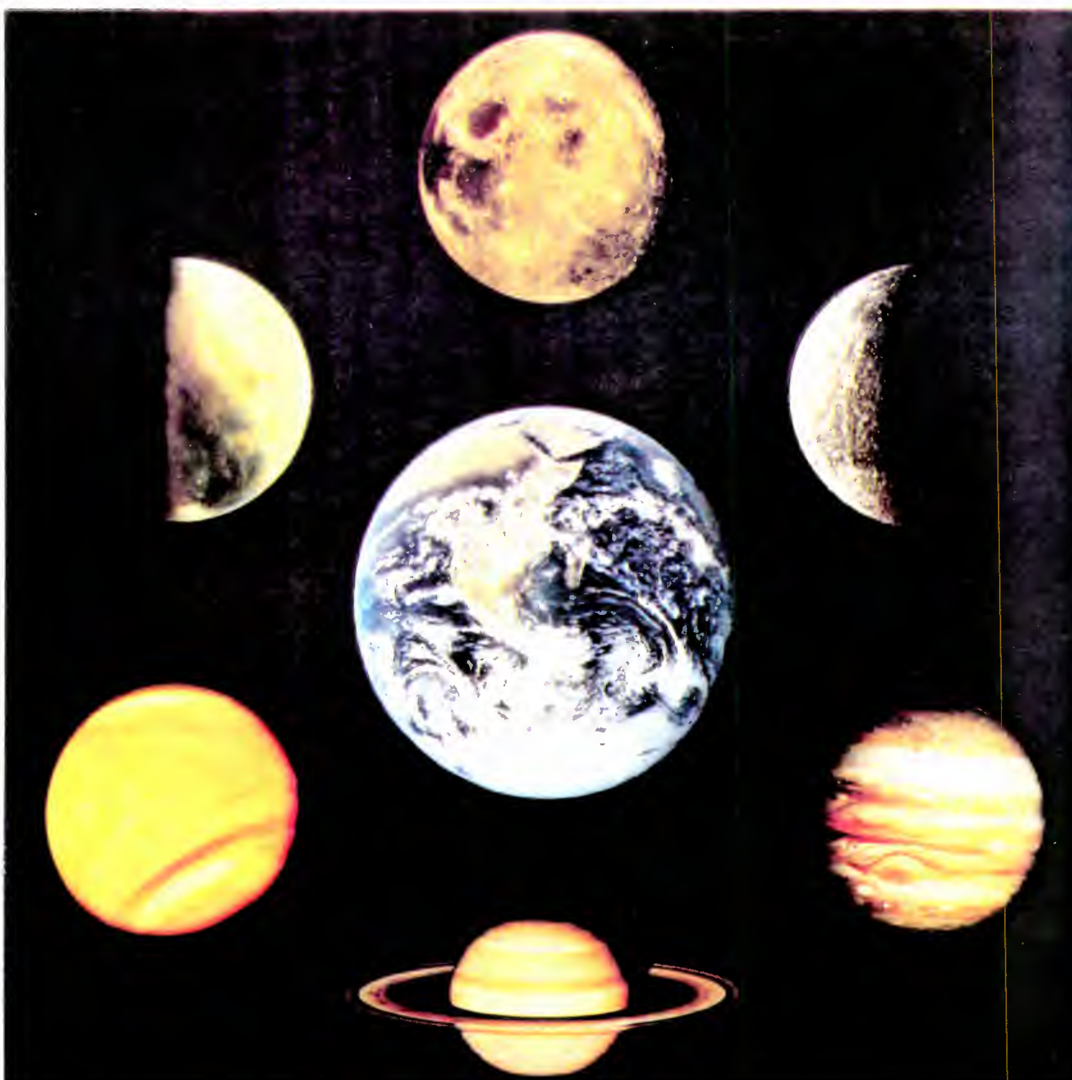
The 'blue' planet earth. Only earth has abundant liquid water to sustain life.



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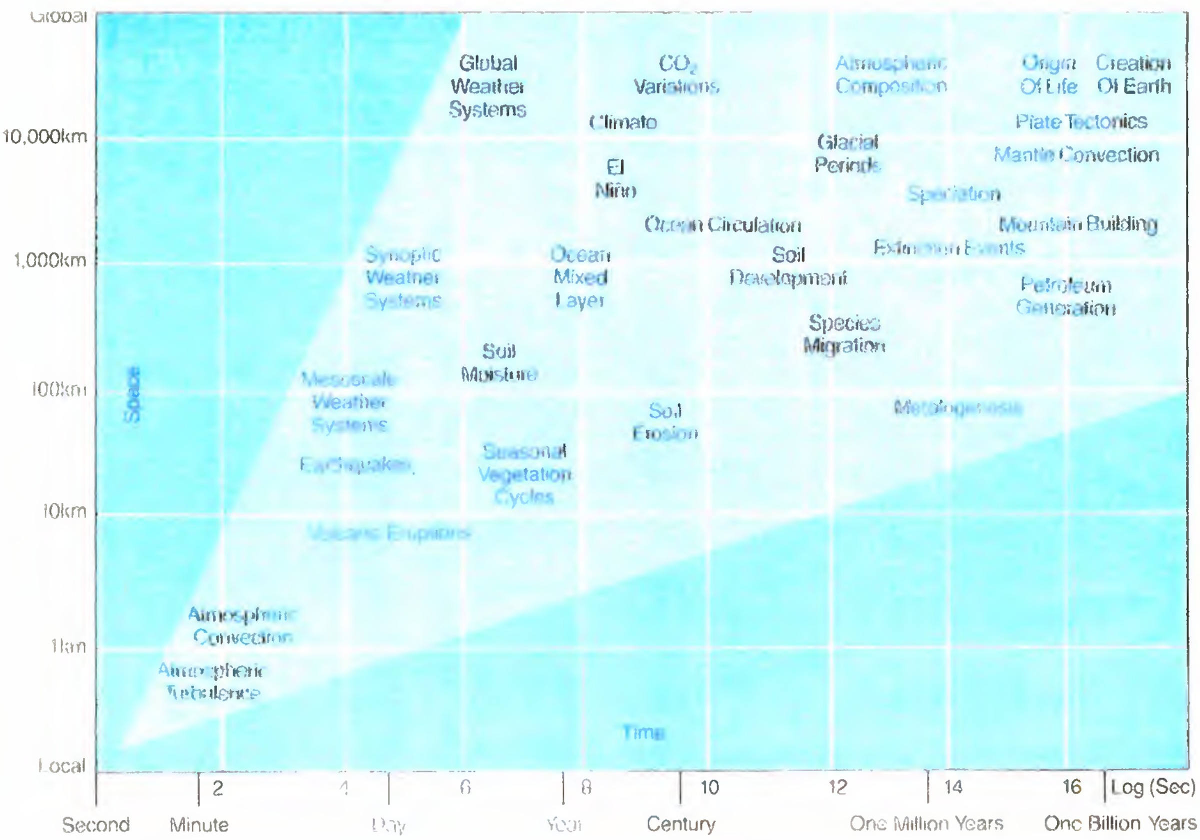
Characteristic space and time scales of earth system processes.



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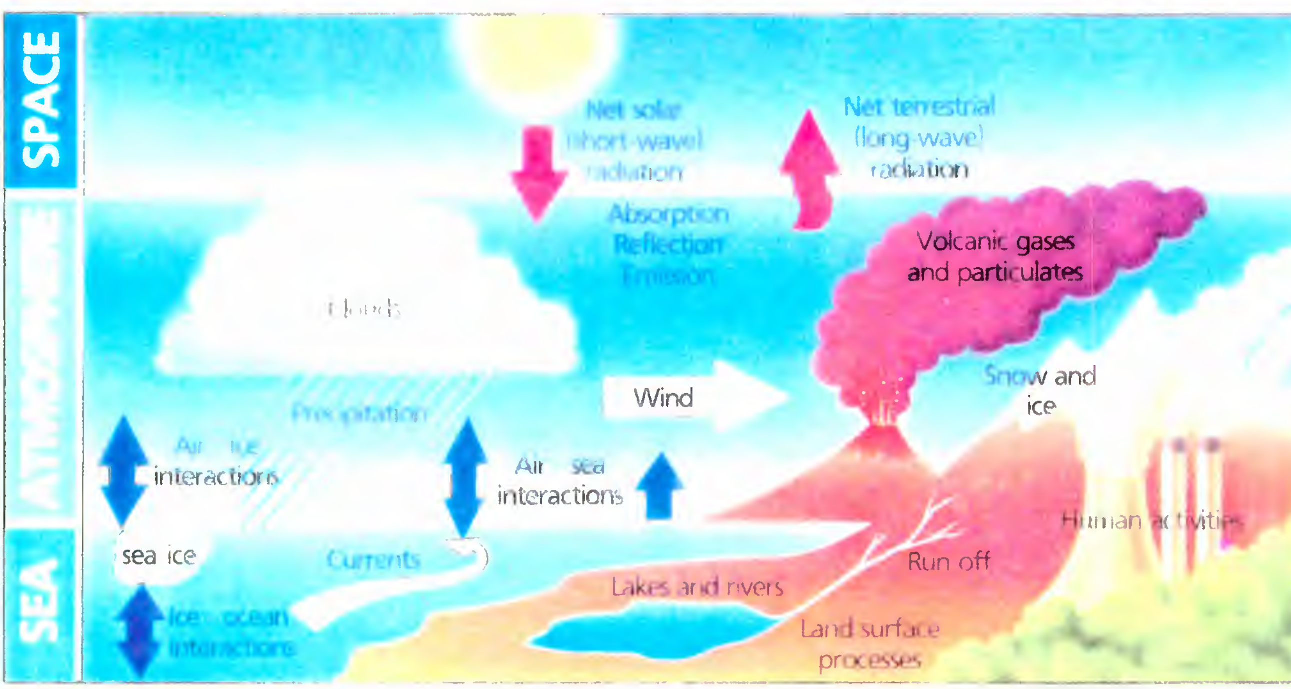
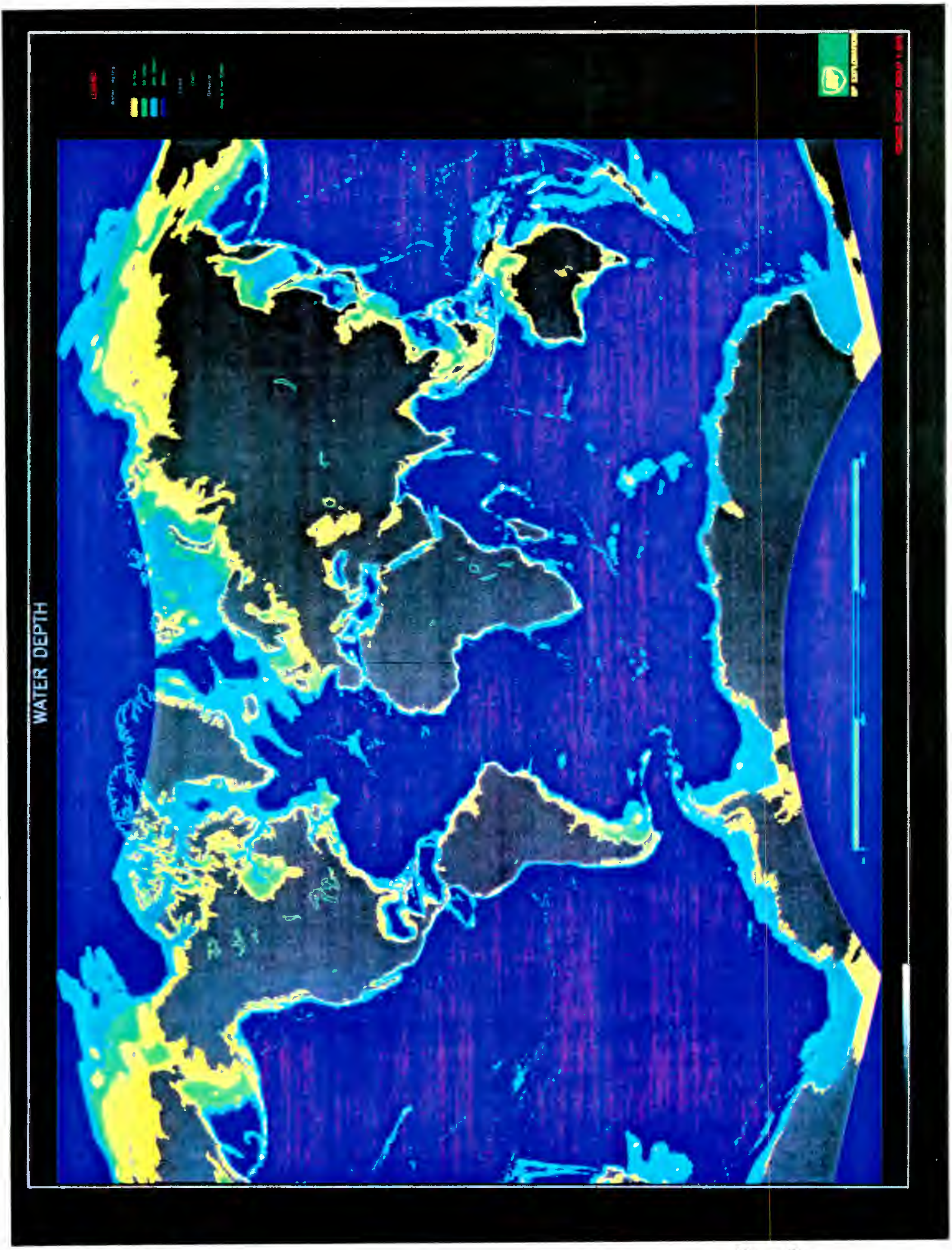
Cartoon illustrating the Climate System



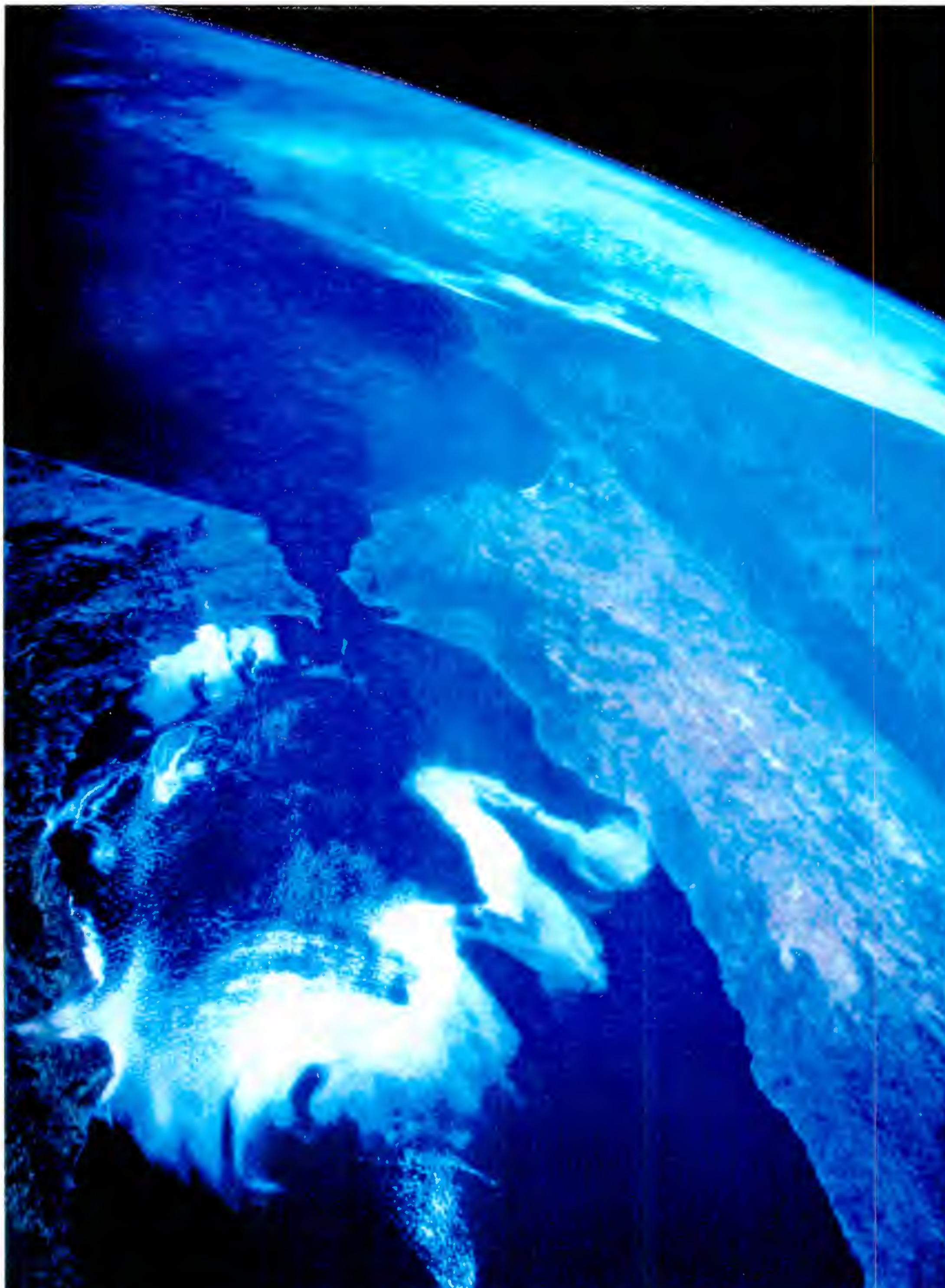
The boundary between vegetation and arid lane is strikingly apparent in this AVHRR image of N Africa (NOAA).

Global continental margins; light blue represents water depths less than 2000m; green represents depths less than 200m.



The Aegean Sea seen from Shuttle. Note the abundance of natural slicks and ship wakes.

The Atlantic, Strait of Gibraltar and the entrance to the Mediterranean taken from Shuttle.



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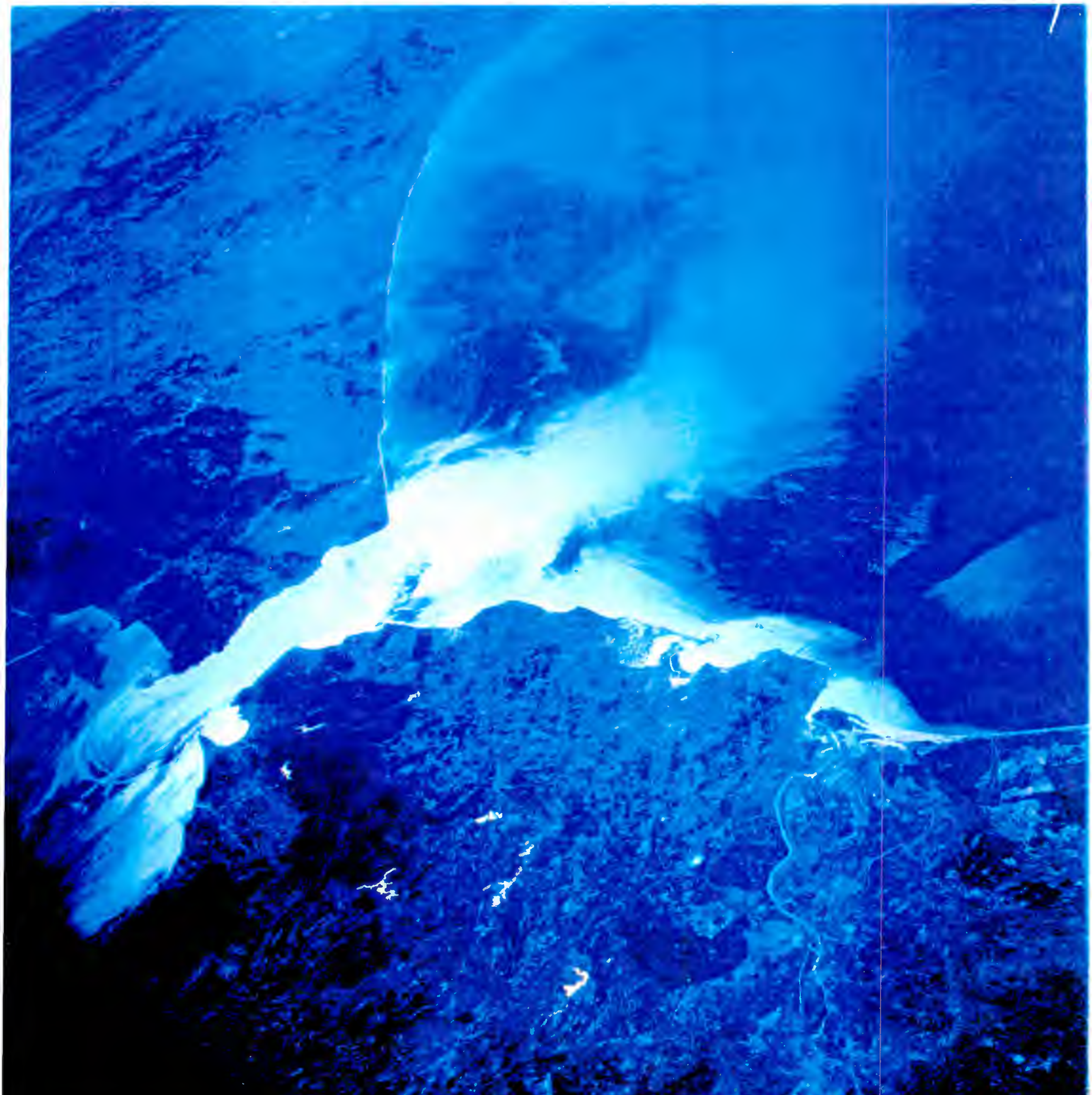
Internal wave trains pulsing through the Strait of Gibraltar.



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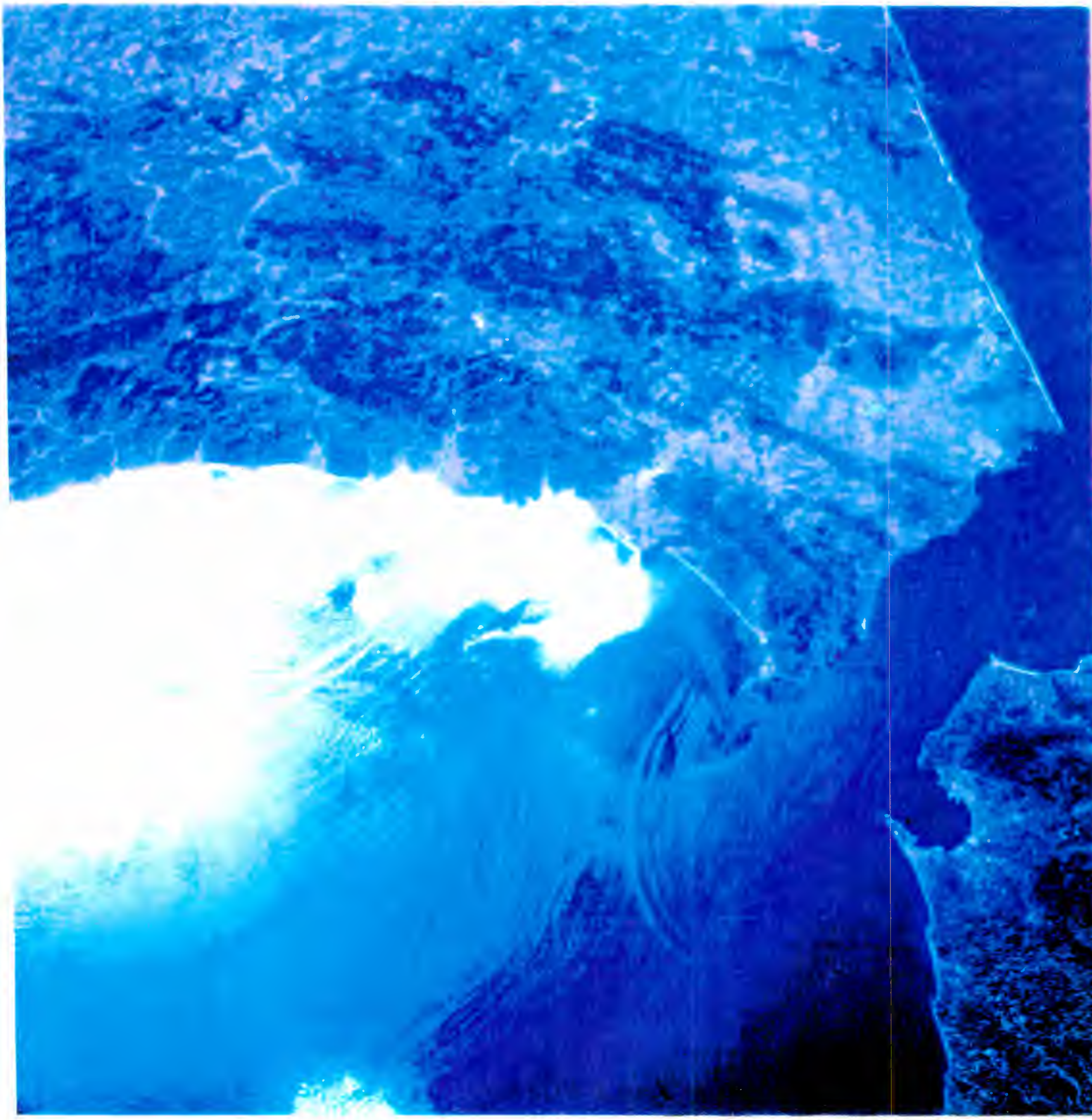
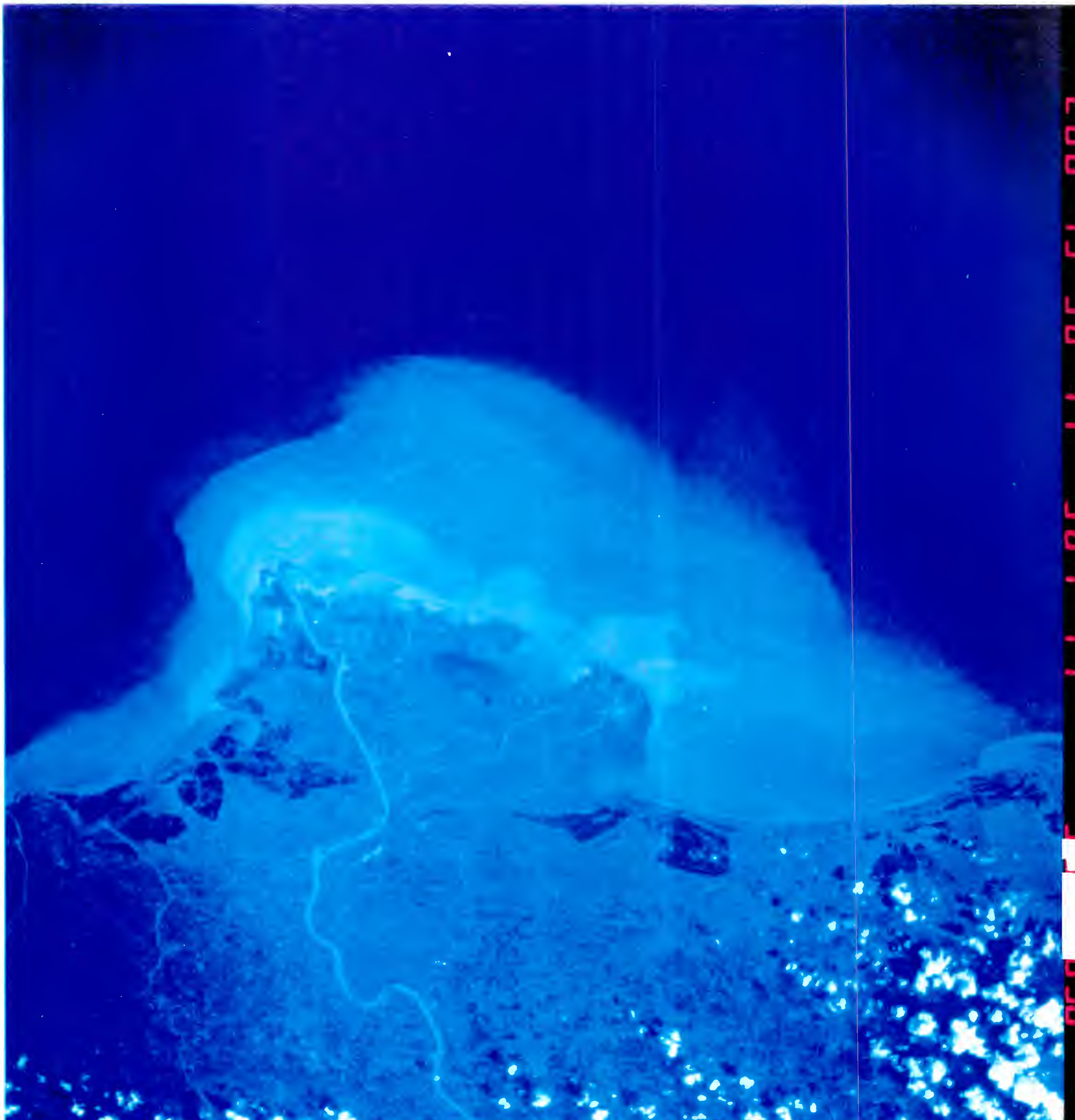
Closer view of internal waves in Strait of Gibraltar.



Discharges of river effluents into the Mediterranean as viewed by Shuttle.



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Natural slicks in the Mediterranean

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OCEAN COLOUR

OCEAN COLOUR

1978 was a vintage year for looking at the marine environment from space for in that year was launched:

SEASAT	the first ocean satellite to carry a suite of microwave sensors that could 'see' through cloud
NOAA	carrying the first Advanced Very High Resolution Radiometer (AVHRR) for the accurate measurement of sea surface temperature
Nimbus-7	carrying the Coastal Zone Colour Scanner (CZCS) for measuring changes in surface colour.

In this section we examine some of the records obtained by the CZCS. As colour image processing developed it became the custom to signify high chlorophyll-like pigments by yellow and red colours, lower concentrations by blue and purple.

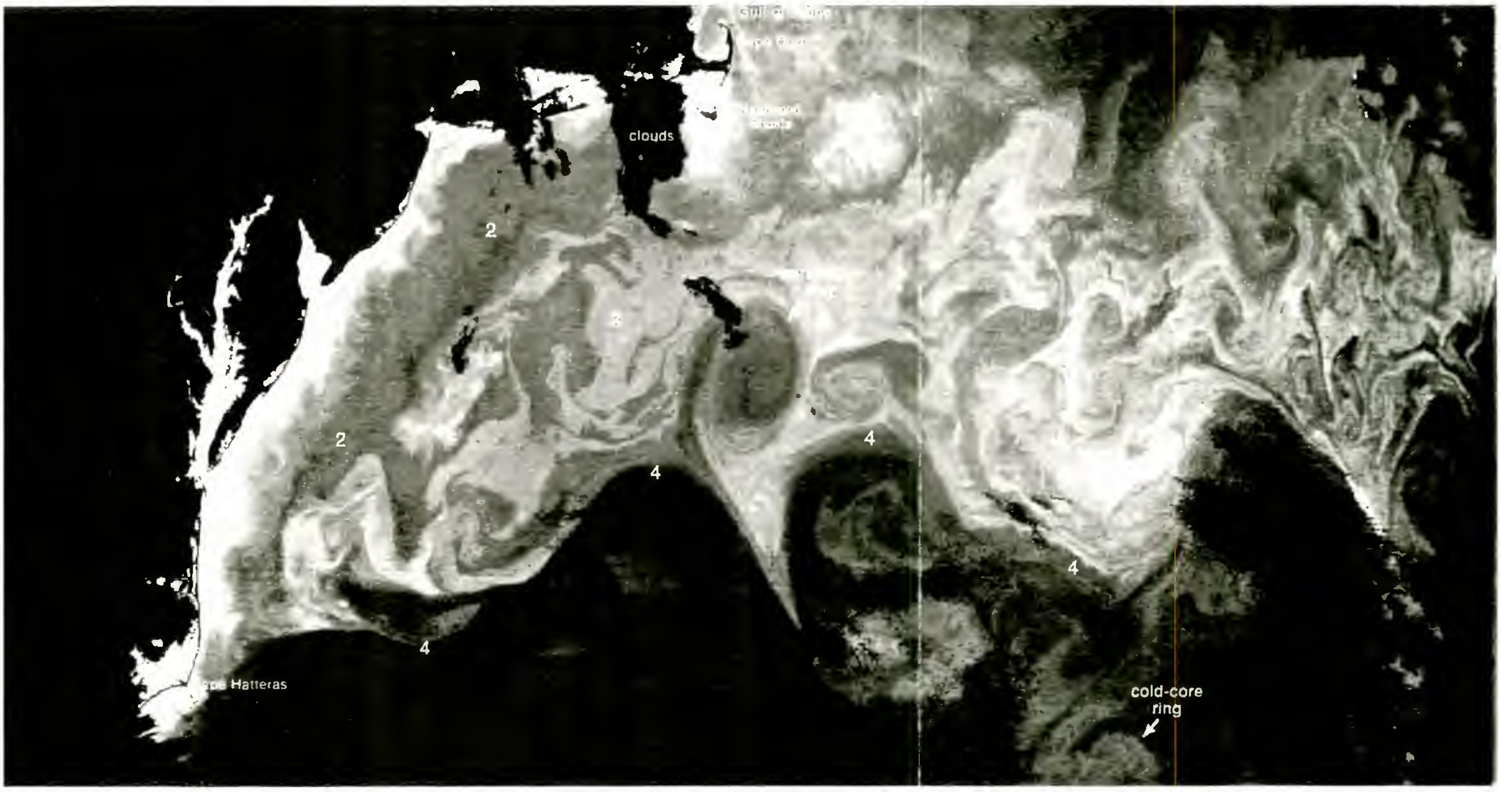
Once an annual pattern is established fish management control may become easier to implement. Examples are shown of the Black Sea, Adriatic, North-West African coast, North Atlantic and the coast of California where the changes in colour patterns are seen to be related to the fluctuations in sea surface temperature.

It is also interesting to note that the annual average of chlorophyll concentration in the Mediterranean shows a very low nutrient level (unlike the colder waters of the North Sea). In the month of May, however, an average of some 30 CZCS images demonstrates a high concentration of phytoplankton in and around the Gulf of Lyons area. The Black Sea is also seen to be productive at this time of year.

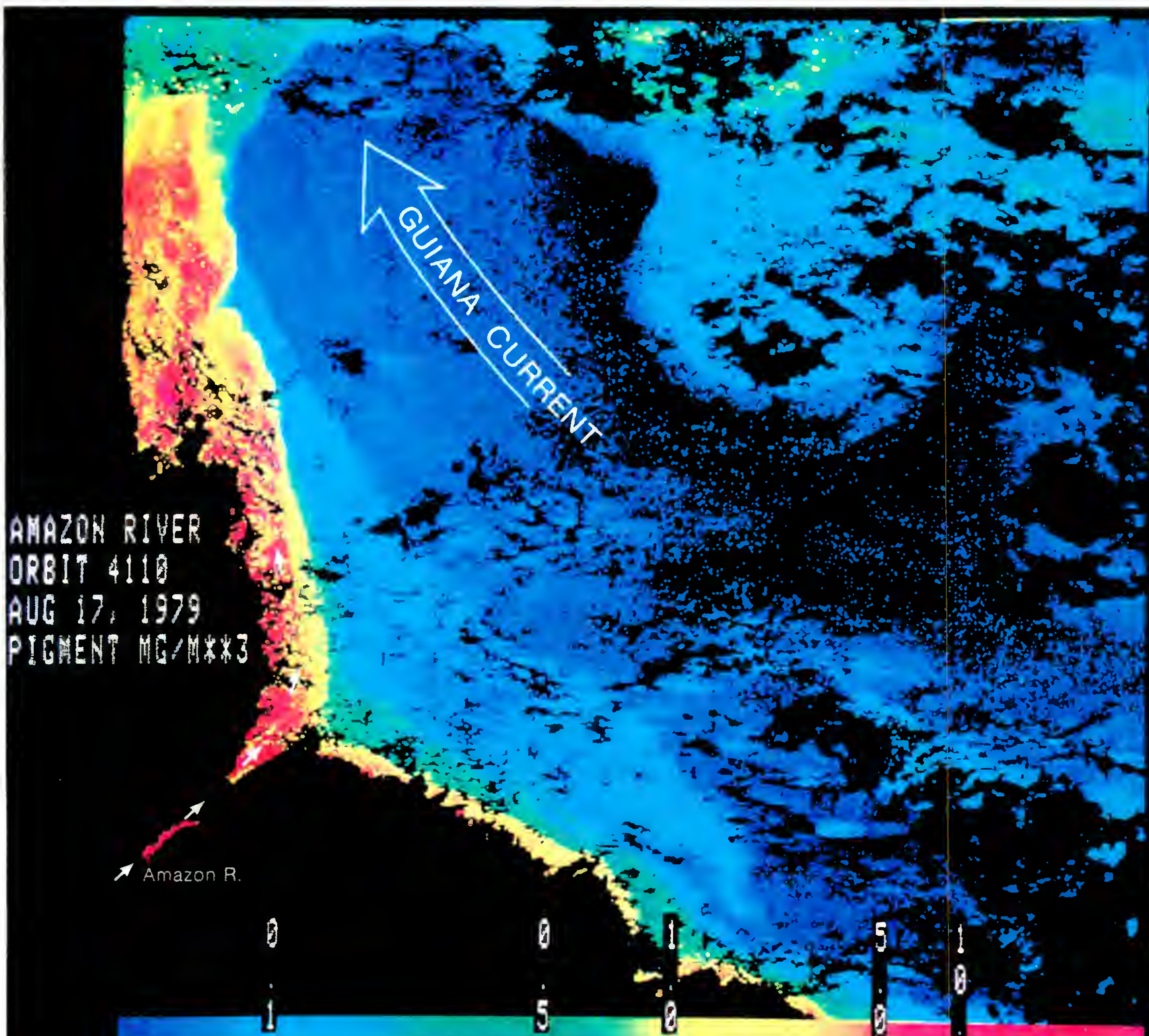
The last two examples in this section illustrate the usefulness of 'synergy' where information regarding surface conditions and their inter-relationships may be inferred from a combination of spaceborne sensors. The mean wave height and wind speed over the Indian Ocean were calculated and averaged for the months of January and July. Because of the onset of the monsoon, surface conditions are significantly rougher in July than in January.

In the next slide the top image represents low concentrations of chlorophyll over the same area in the month of May as measured by the CZCS. The situation has completely changed in the bottom image taken in September because of the high concentration of nutrients brought up to the surface by the upwelling of colder, deeper water caused by the monsoon.

Early black/white image of the N Atlantic taken by the Coastal Zone Colour Scanner.



CZCS image of the Amazon delta. Note the discharge carried northward by the Guiana current.



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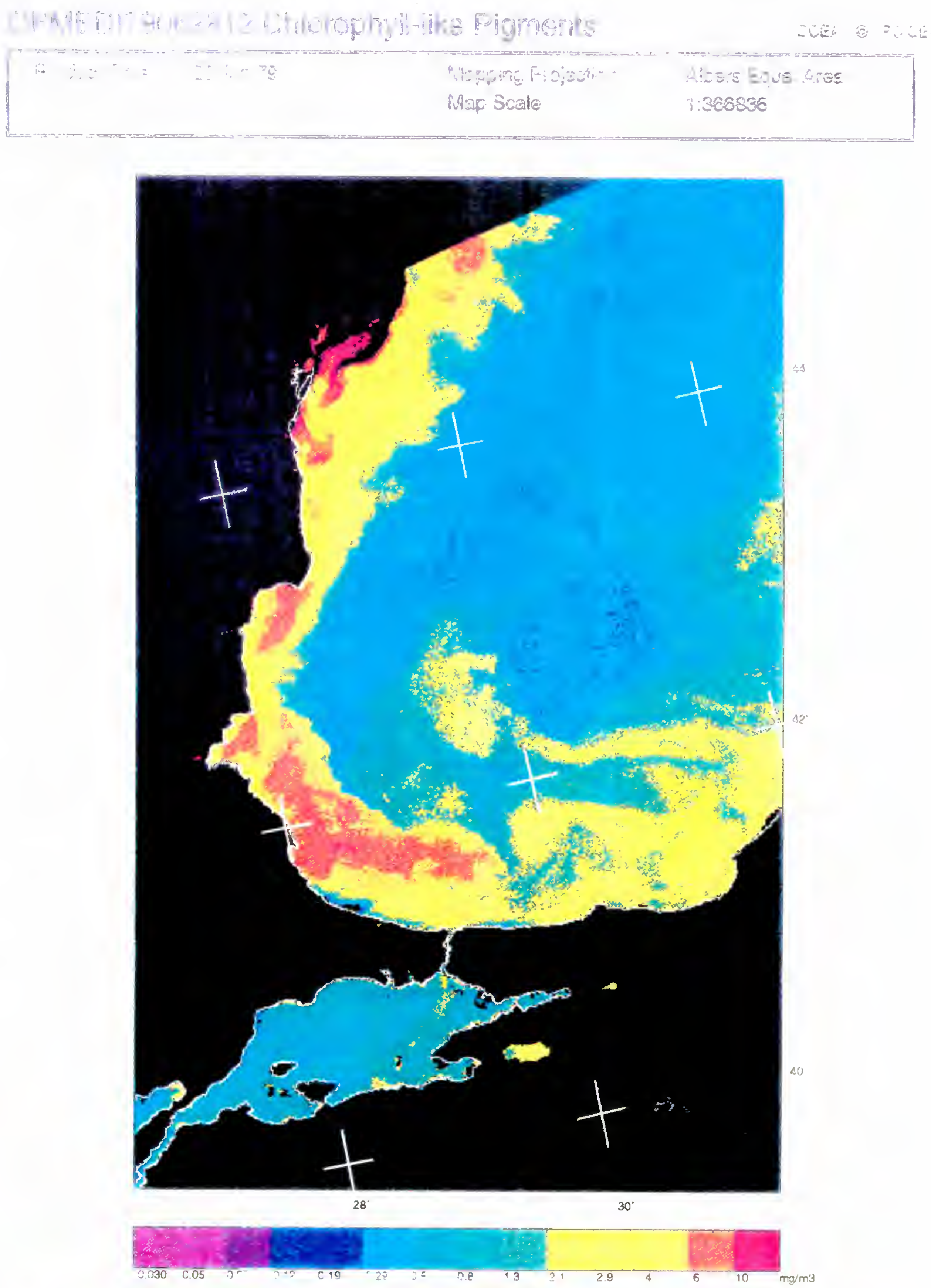
Chlorophyll pigments around the shore of the Black Sea



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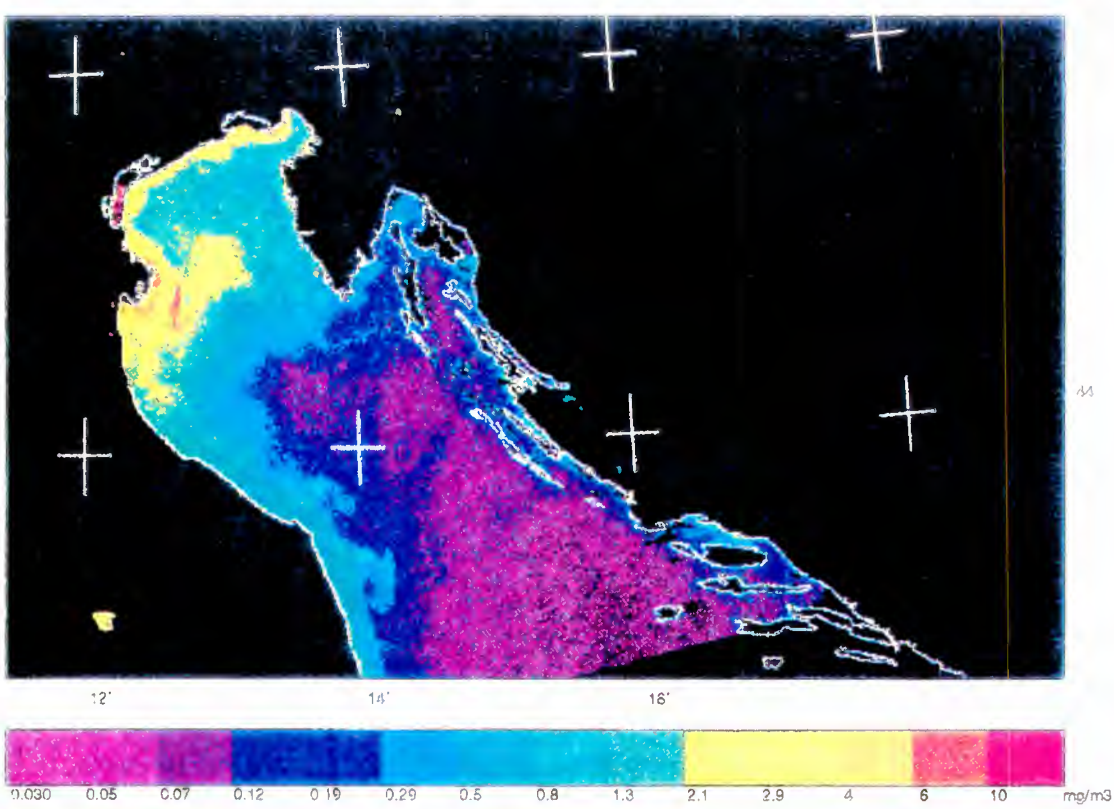
Nutrient concentration around the Po delta - 4 July 1980.

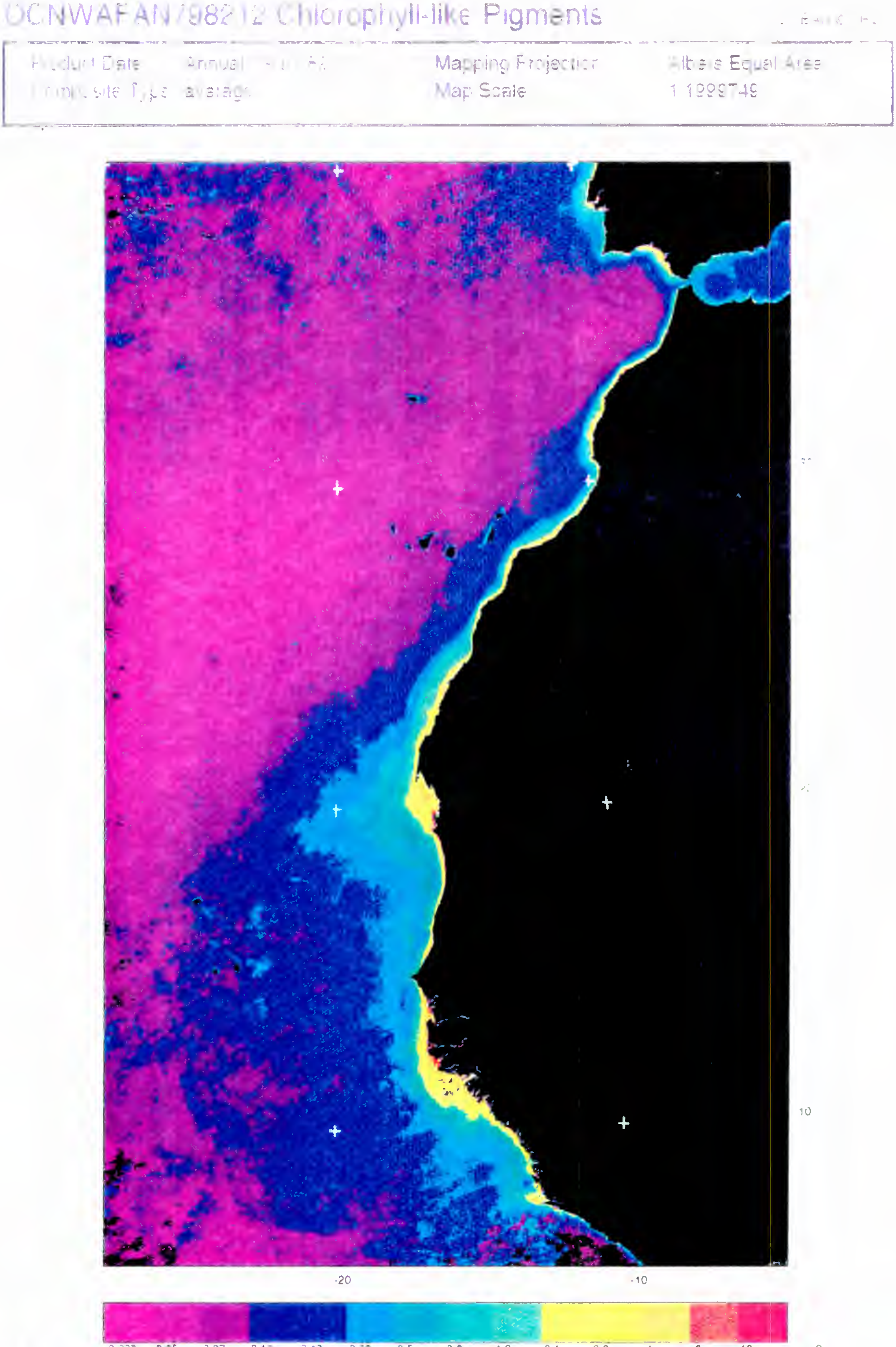
OPMEDI80070412:Chlorophyll-like Pigments

OCEAN © JRC/CEC

Product Date	04 Jul 80	Mapping Projection	Albers Equal Area
		Map Scale	1:440229



Average chlorophyll concentration along the West coast of Africa over a 4-year period (1979-83).



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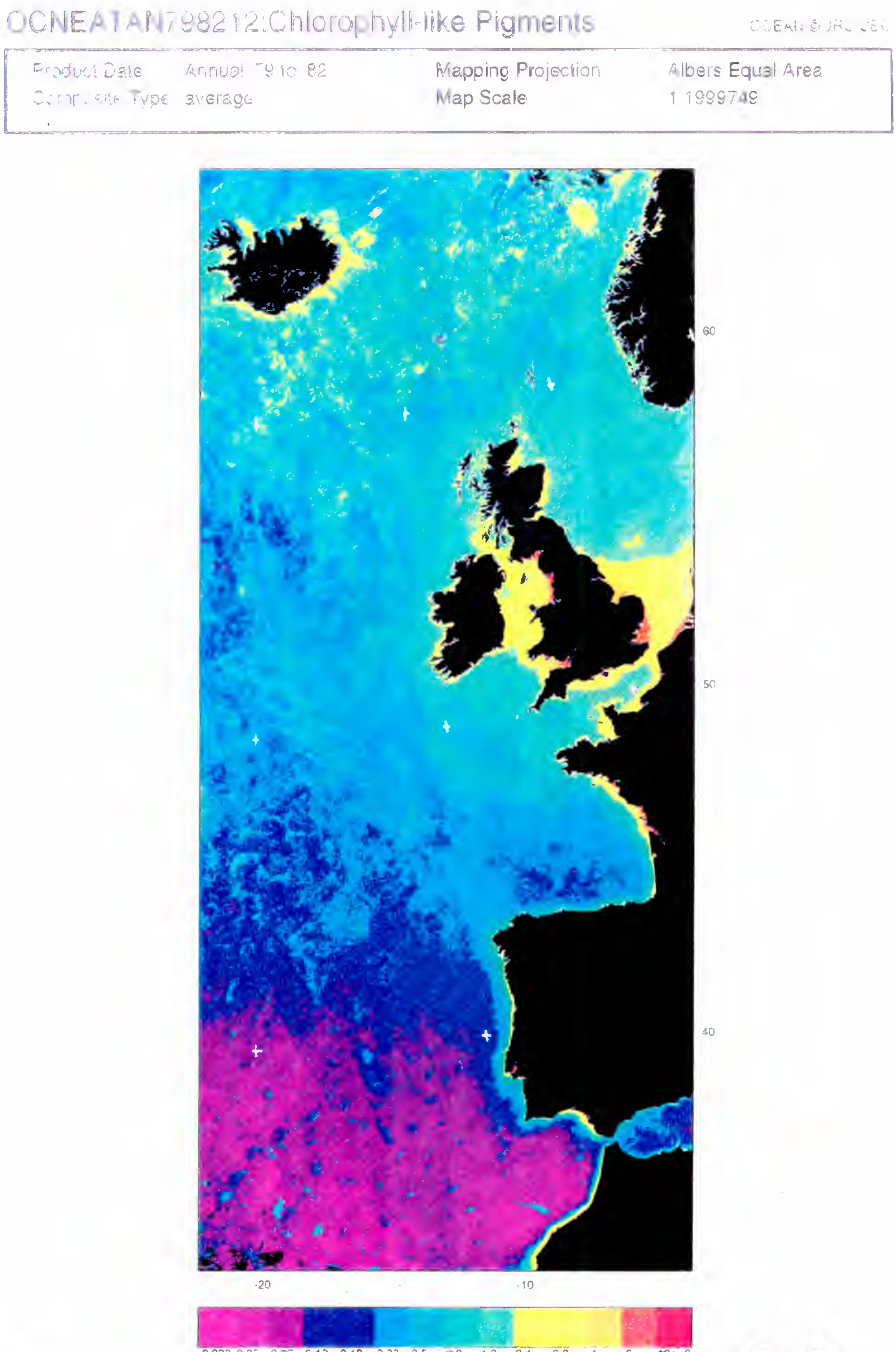
Average chlorophyll concentration in the North Atlantic over the 4-year period 1979-83.



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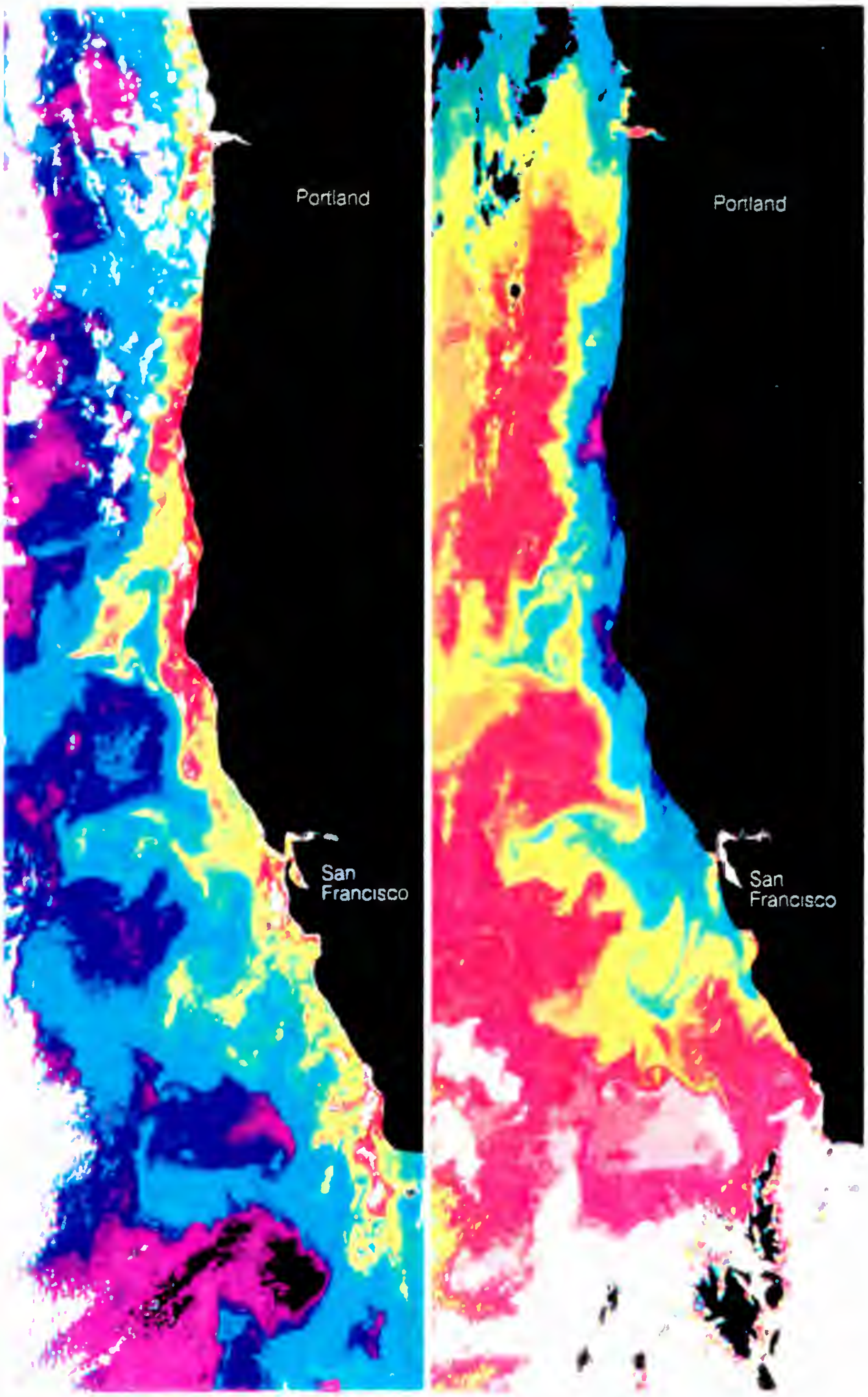
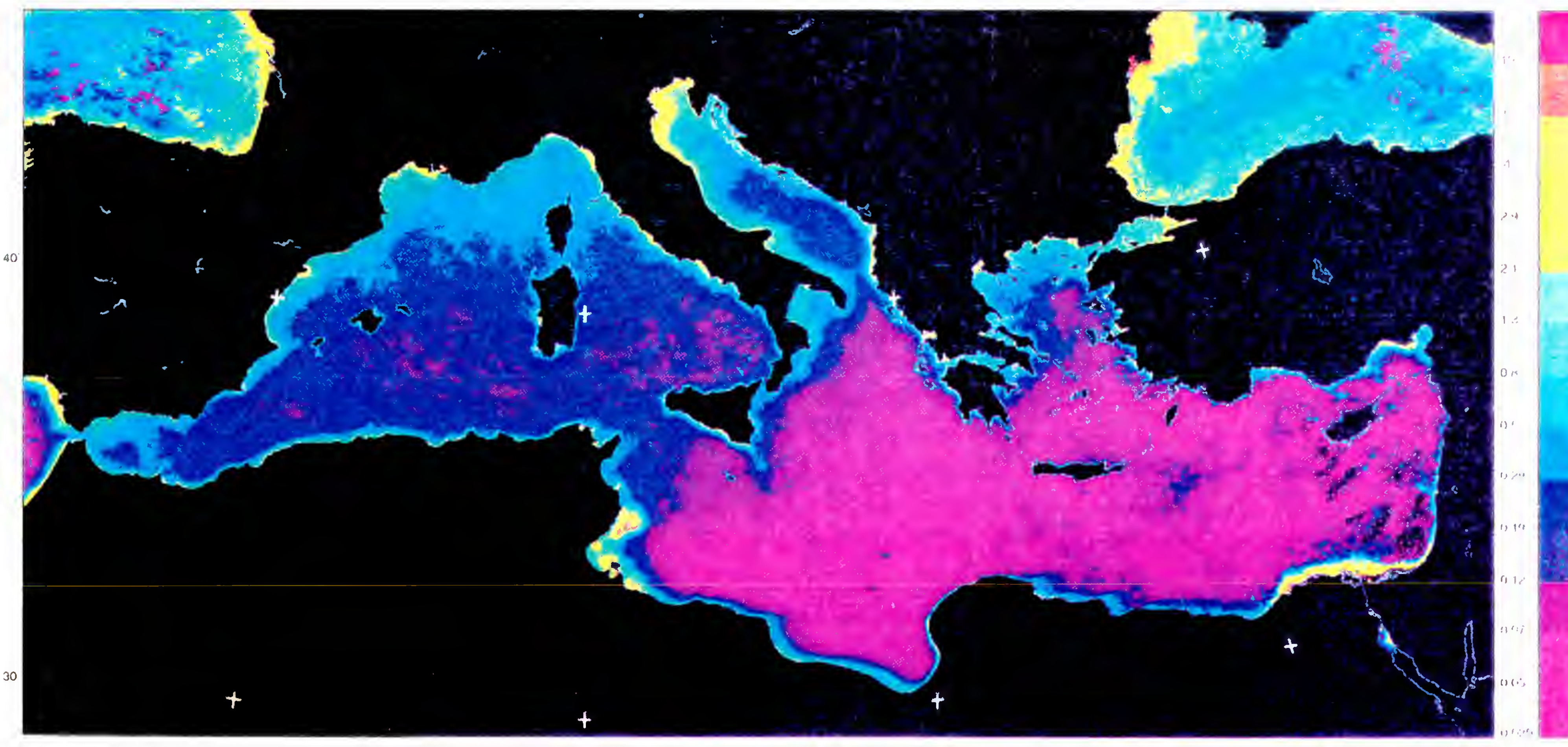
On the left - ocean colour (higher concentrations reds and yellows); on the right - surface temperature (cooler temperatures violet and blue). Note the correlation.



Average annual chlorophyll concentration in the Mediterranean for 1980

OCMEDIAN808012:Chlorophyll-like Pigments

Product Date	Annual '80	Mapping Projection	Albers Equal Area
Composite Type	average	Map Scale	1:1638523



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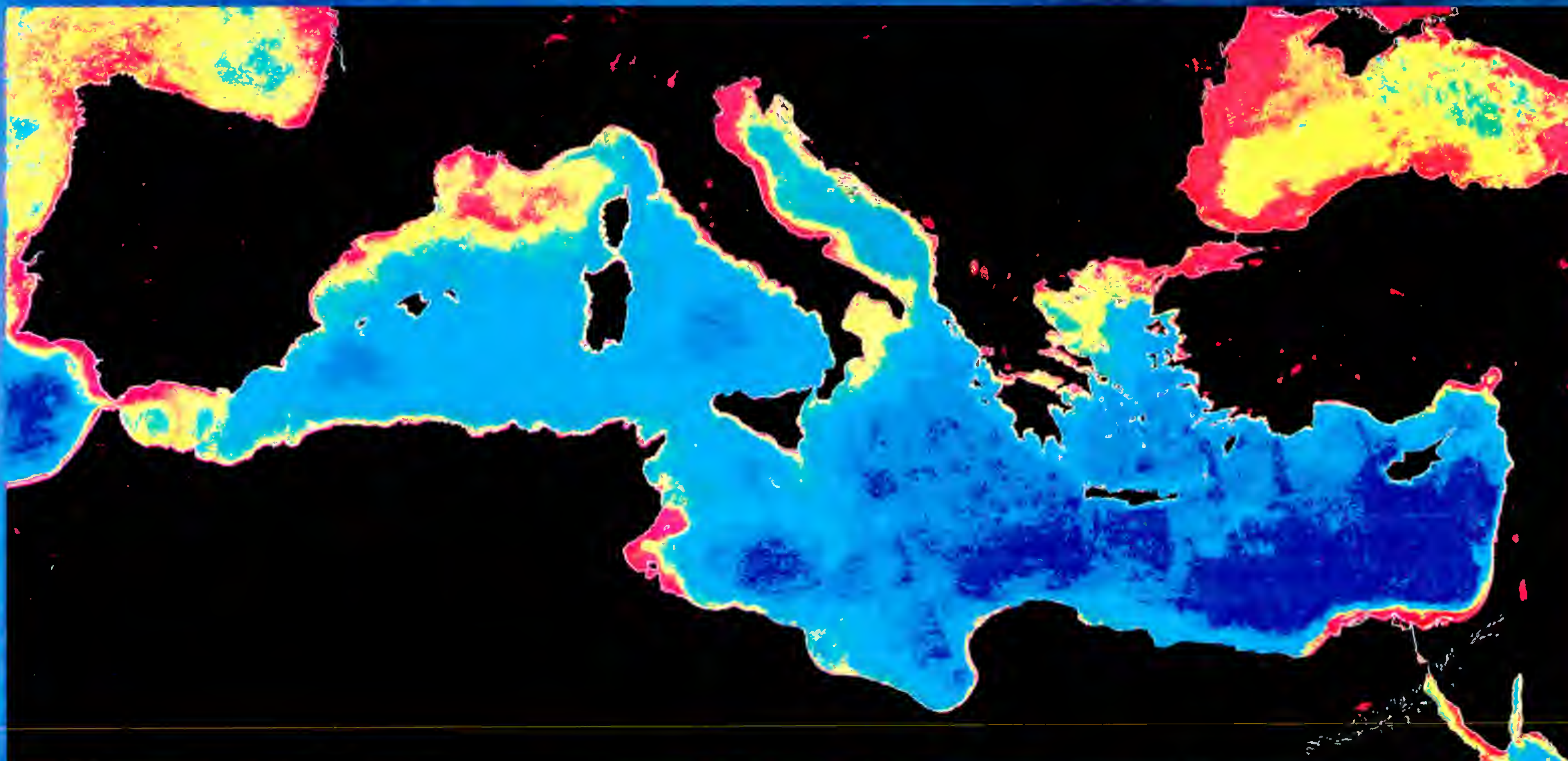
The high pigment concentration in the NW Mediterranean (Gulf of Lyon) averaged over 30 scenes acquired in May contrasts with the usual low annual levels shown previously.

Mediterranean

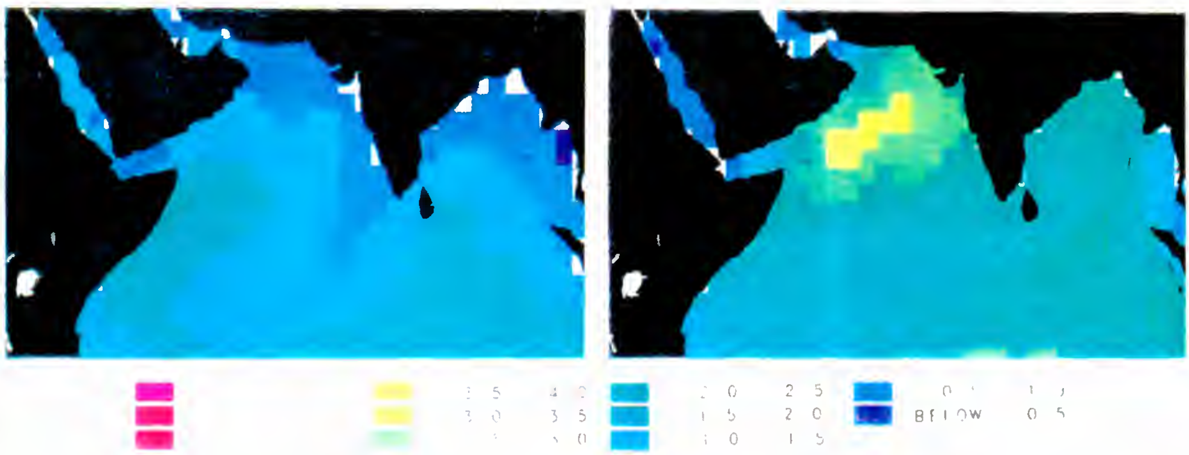


The relatively clear, pigment-poor waters of the Mediterranean contrast sharply with the plankton-rich Atlantic waters off northwest Spain (upper left). Clearly evident in this view of the Mediterranean is the well-known pigment front along southern France and Spain. The image is produced from 30 scenes acquired during May 1980. The gyre in the Alboran Sea near the Straits of Gibraltar is caused by complex circulation patterns resulting from water exchange between the Mediterranean and Atlantic Ocean. In some cases localized areas of high production are due to pollution from human activities.

Wave heights and wind speed are higher in the Indian Ocean in summer due to the Monsoon.

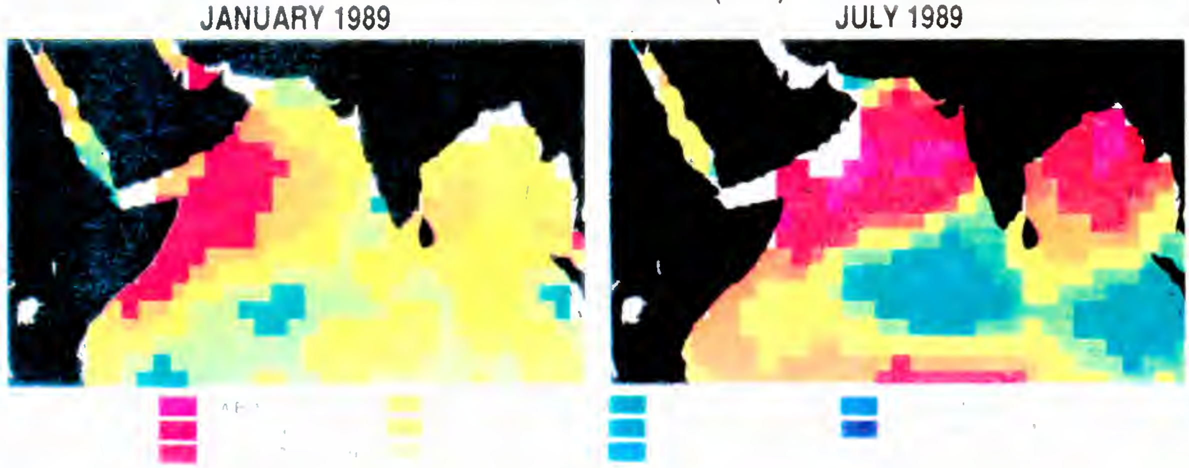
MEAN SIGNIFICANT WAVE HEIGHT (M)

JANUARY 1989 JULY 1989



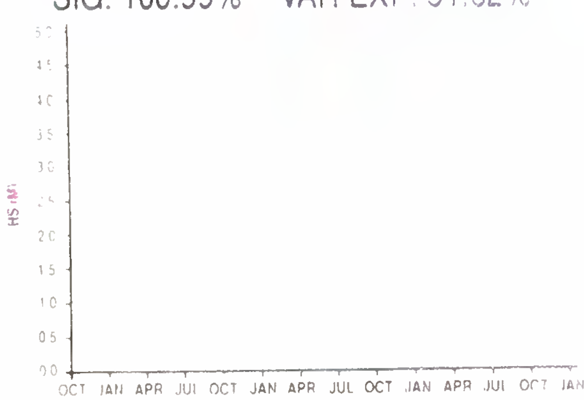
MEAN WIND SPEED (M/S)

JANUARY 1989 JULY 1989



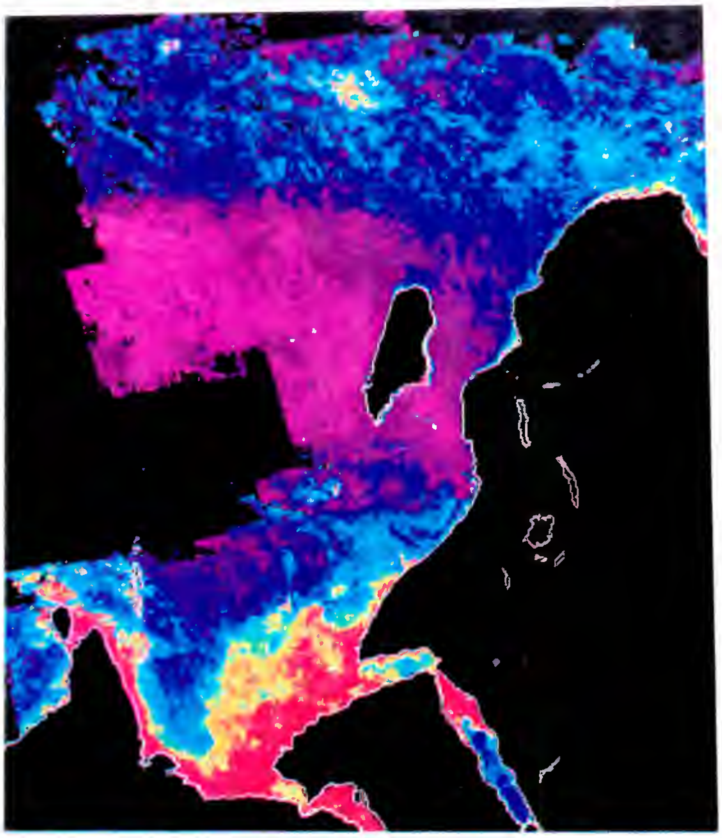
LAT: 15 LON: 65

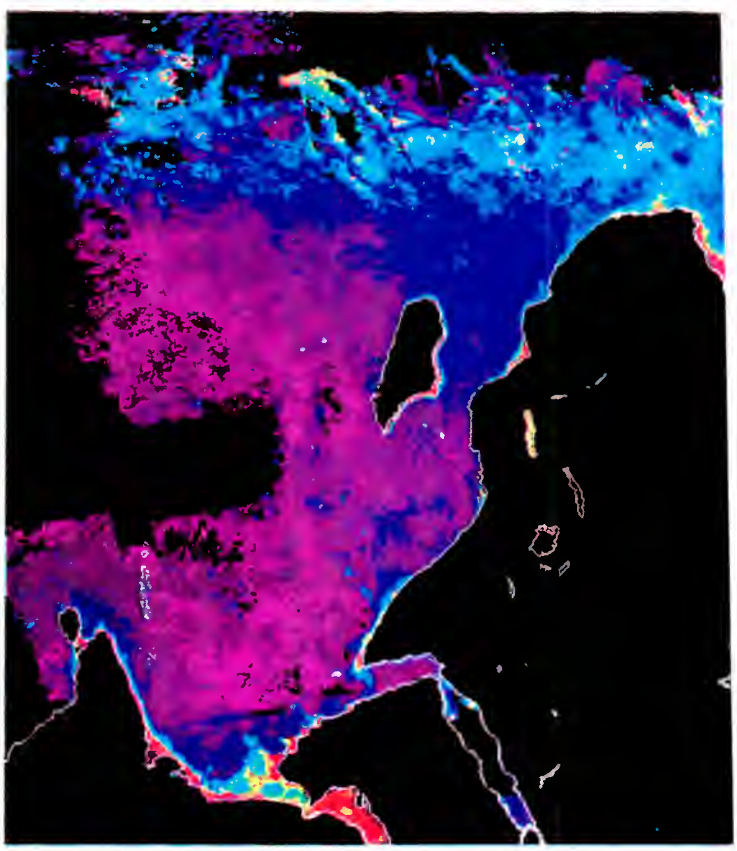
SIG: 100.99% VAR EXP: 51.32%



1985 - 1989

The same area imaged by the CZCS. The upper image shows how concentrations of chlorophyll before the onset of the SW monsoon. The lower image shows the high concentration in September brought about by upwelling following the onset of the monsoon.





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SURFACE TEMPERATURE

SURFACE TEMPERATURE

Changes in sea surface temperature are caused by a wide variety of surface features - currents, eddies (cold and warm rings as shown in the Gulf Stream), fronts, effluent discharges and changing weather patterns especially wind speed.

Temperature has been monitored continuously since 1978 by the NOAA series of satellites. It represents the longest record of any ocean parameter that can be measured to useful accuracies from satellites. (The others are colour, roughness and slope).

A temperature measuring device (the Along Track Scanning Radiometer) is also carried on ERS-1. These sensors operate in the infra-red and do suffer the disadvantage of being inhibited by cloud.

A number of attempts have been made to link patterns of sea surface temperature to certain marine applications. One such study carried out at the EC's Joint Research Centre at Ispra, and illustrated here, attempts to link seasonal variations in surface temperature along the coast of North West Africa with seasonal changes in surface wind speed.

Over a 10-year period 3400 individual SST images were generated from the NOAA AVHRR record to form a coherent cloud-free data set. From this set an SST 'upwelling index' was calculated as the difference in offshore temperature to a point 500 km to the west along the same latitude. In the slide this index is shown as a function of latitude and season. In certain latitude bands, particularly south of 20°N, upwelling is confined to the winter months. In other areas (20°N - 25°N) it is persistent throughout the year (blue and dark blue shades).

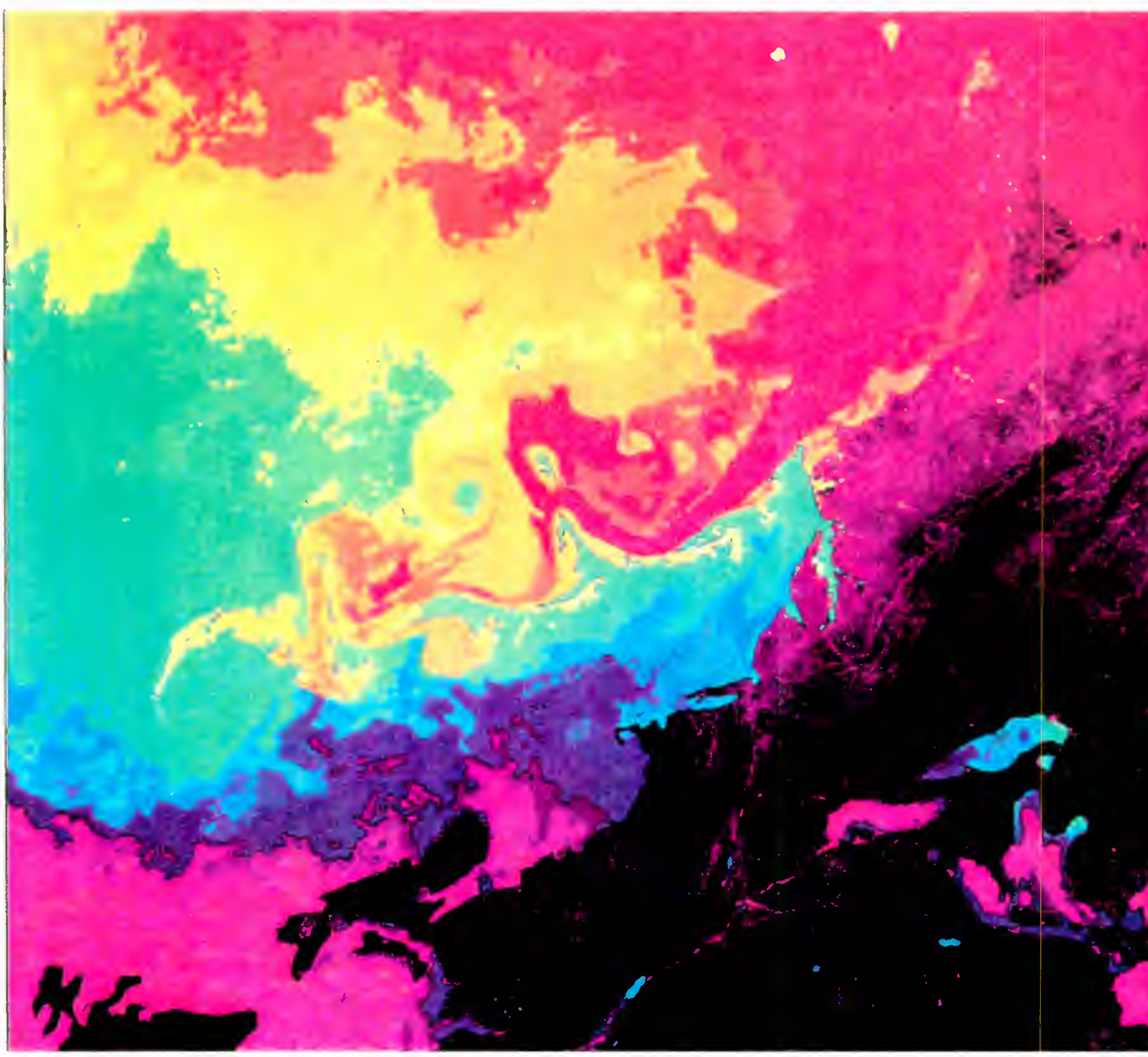
Coastal upwelling is commonly attributed to the force of the alongshore component of the wind (plus the rotation of the earth). From wind data supplied over the same 10-year period by ECMWF a similar upwelling index was calculated as the Ekman transport perpendicular to the shelf. This 'Ekman upwelling index' is quite independent from the index derived from the temperature records.

When the two records are compared there are local differences in the form of time lags between the maximum of the winds and the corresponding maximum of the SST index, but on the whole the two records are closely correlated. In fact when the cross-

correlation function is calculated the delay in one record relative to the other becomes more evident. The SST index always lags the Ekman index.

Through studies such as these in various parts of the world it is hoped to reach a better understanding of the physical processes involved in upwelling so that in future more reliable predictions of nutrient concentrations may be made.

Hot and cold eddies around the Gulf Stream as imaged by NOAA



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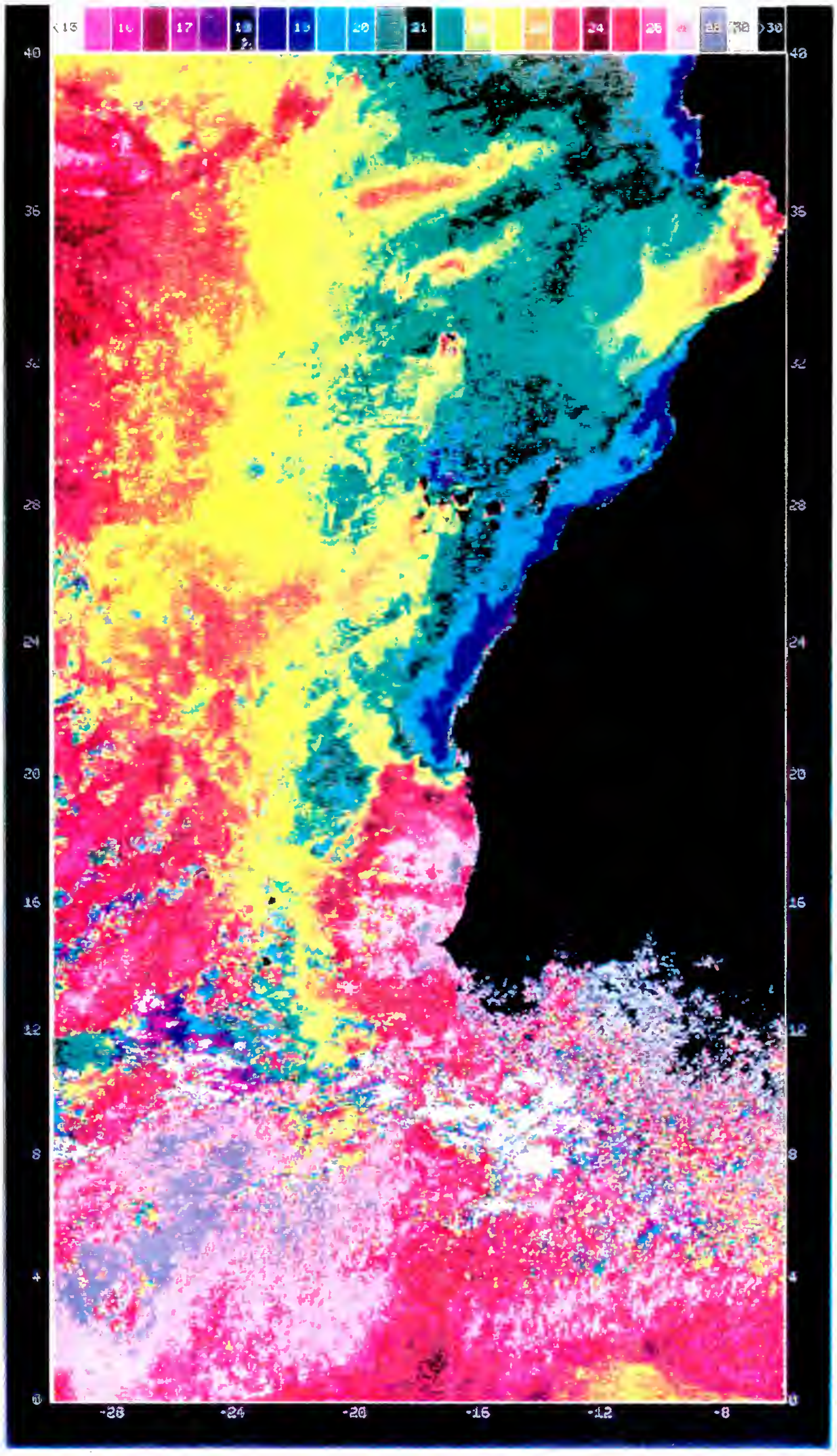
Sea surface temperature along the West Coast of Africa. Created from 12 images over a 10-day period (1-10 August 1985).



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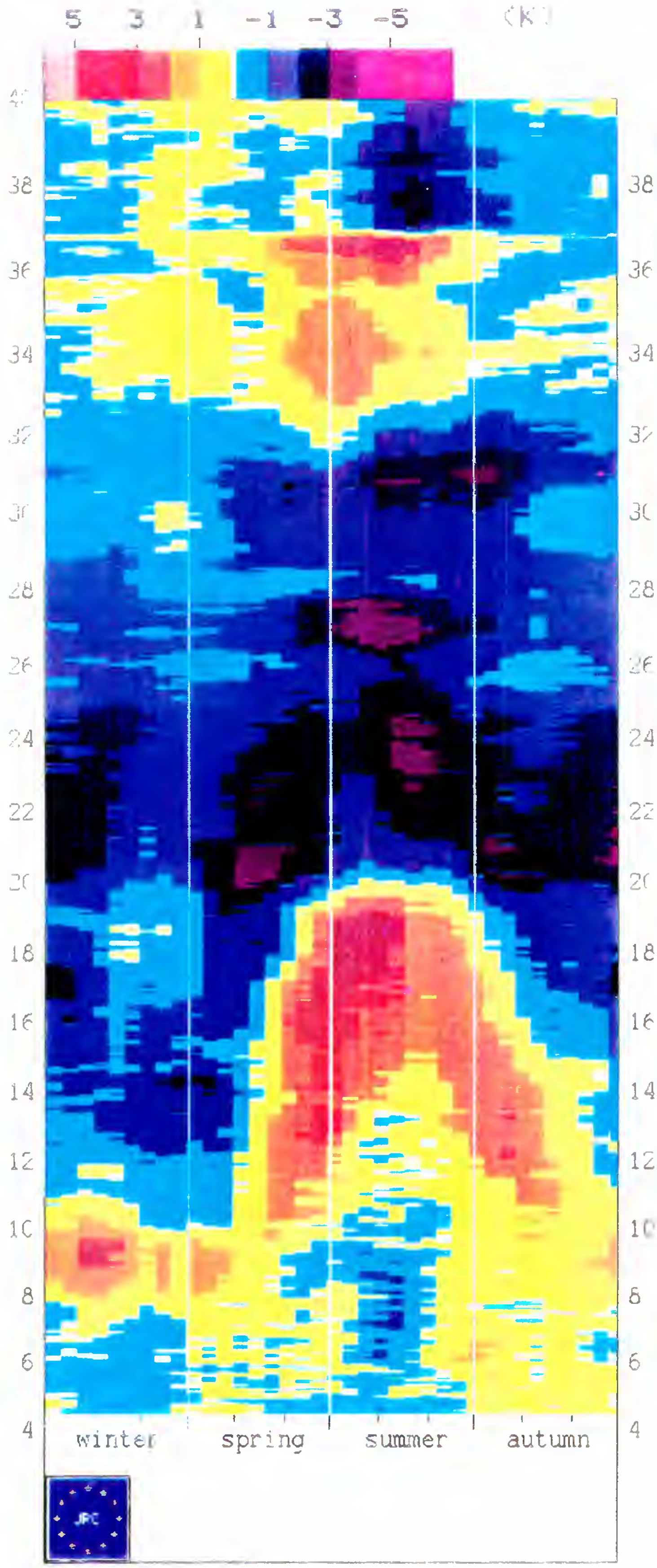
Seasonal cycle of SST upwelling index defined as the temperature difference between coastal water and water 500km offshore at the same latitude for the period July '81 - August '89.



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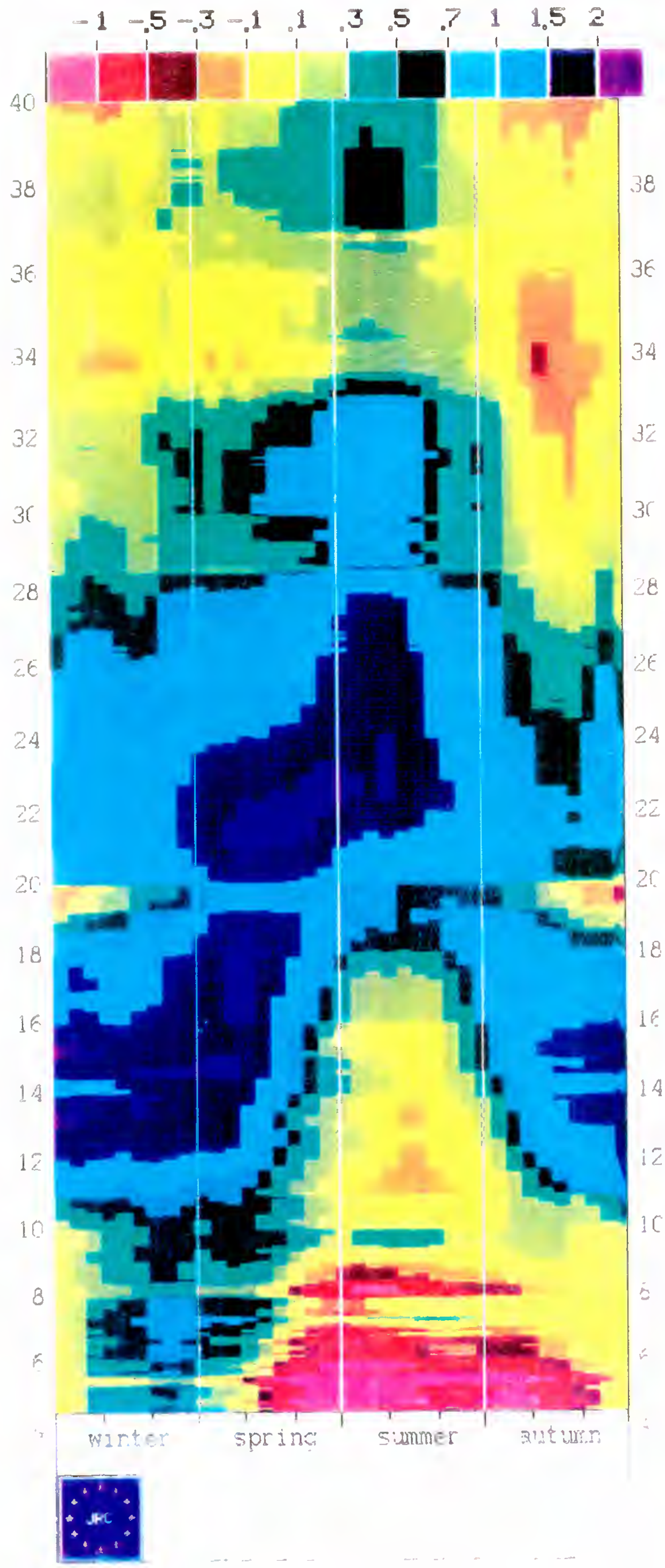
Upwelling index calculated from wind data (August '82 - June '91). This is independent of the temperature-derived index but clearly related to it.



ORBITS

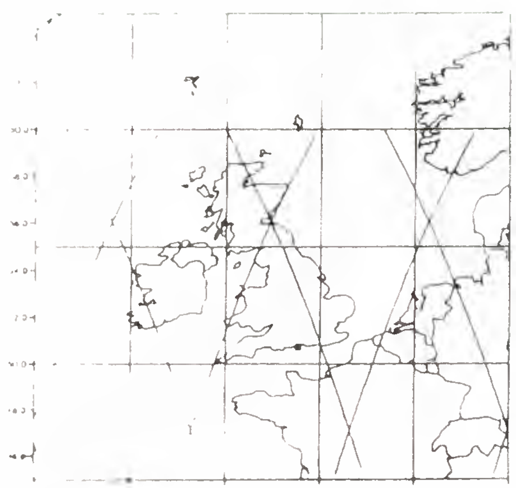
SATELLITE ORBITS

The height of a polar-orbiting satellite determines the pattern of its sub-orbital path over the globe. At a height of 800 km a satellite completes about 14 1/3 revolutions of the earth each day with a spacing at the equator between adjacent orbits of about 3000 km. If this pattern is made to repeat after (say) 3 days - the 44th track being laid down over the first - the relatively fast sampling allows monitoring of rapidly changing surface features but at the expense of large tracts between adjacent profiles that remain uncovered.

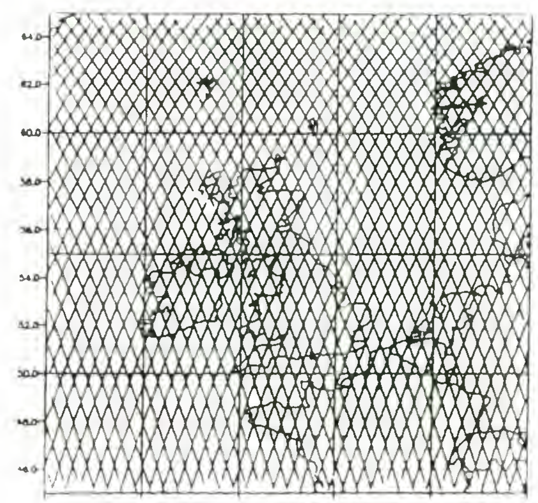
The slide demonstrates the ground patterns laid down by the 3 repeat orbits followed by ERS-1 - 3, 35 and 168 days. The latter pattern is used to map the shape of the earth - the geoid - which of course does not vary significantly with time but requires close spatial resolution to describe it in detail. An orbit repeat of 168 days is equivalent to about 17 km spacing between adjacent tracks at the equator.

The trade off between repeat sampling interval and track spacing is shown in the next slide. Note that to achieve faster sampling while maintaining the same profile separation would require more satellites to be in simultaneous operation.

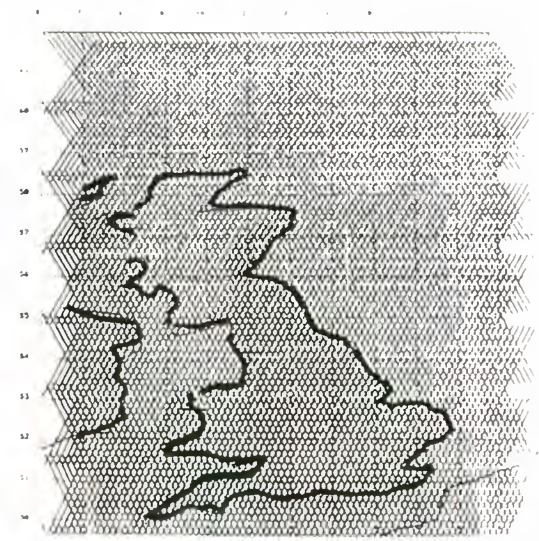
ERS-1 Orbit Patterns



3-day

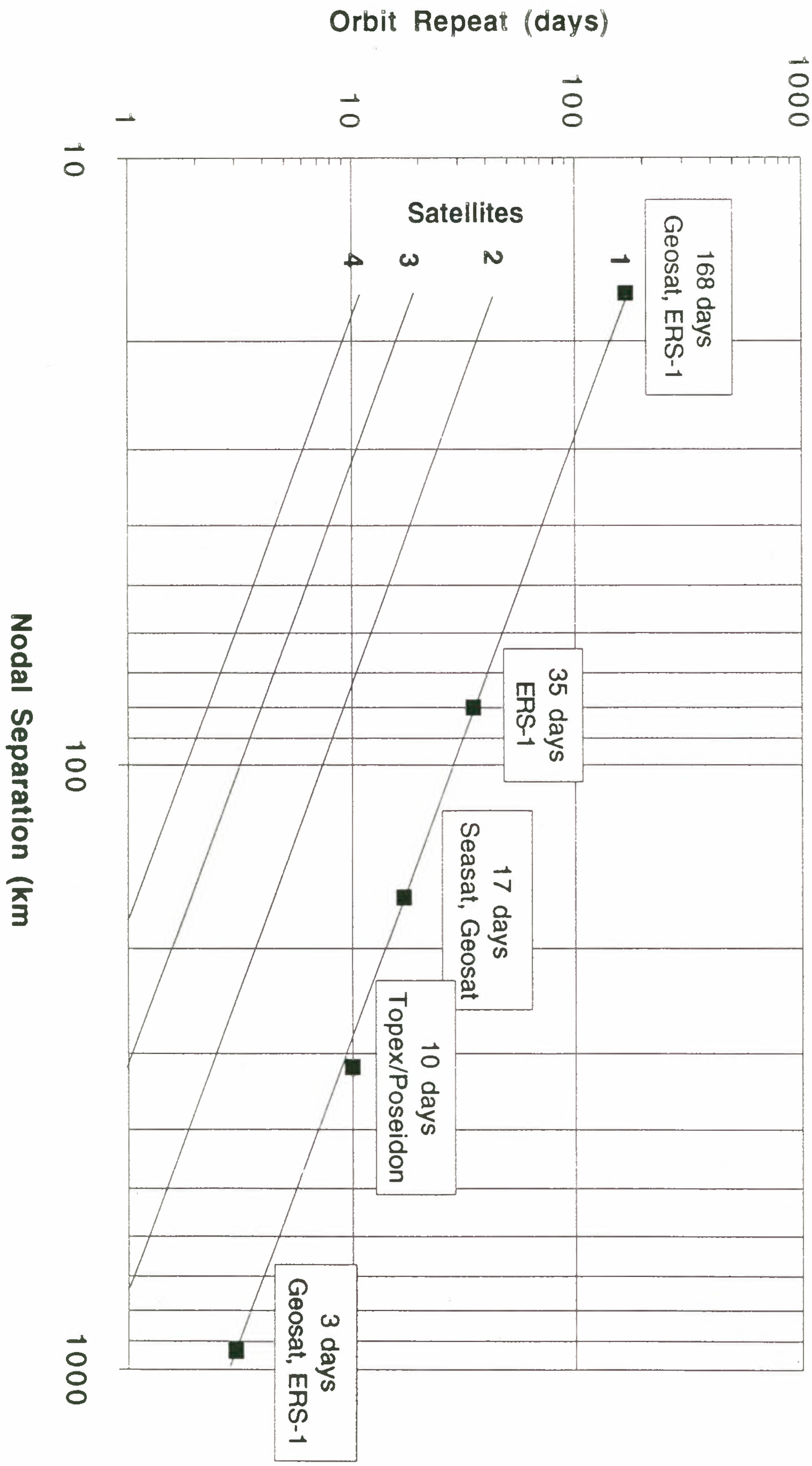


35-day



168-day

Orbit separation at the equator plotted against the repeat pattern in days.



GEOID
&
GRAVITY

GEOID AND GRAVITY

Until precise radar altimeters were flown in satellites it was not fully realised how comparatively small changes in the earth's gravity field would affect the shape of the sea surface. For, the sea surface is an equipotential gravity surface - that is gravity is everywhere acting at right angles to it. Change the gravity field and the surface tilts. It is this tilt which is detected by the altimeter.

The equipotential surface at sea level is referred to as the geoid. The shape of the geoid can be affected by a number of forces acting at different spatial scales - large convection cells within the earth's interior at scales of thousands of kilometres down to small changes reflecting an undulating sea floor bathymetry for example. The local geology can also have an affect and it is these structures offshore which are of interest in seeking out new oil and gas reservoirs.

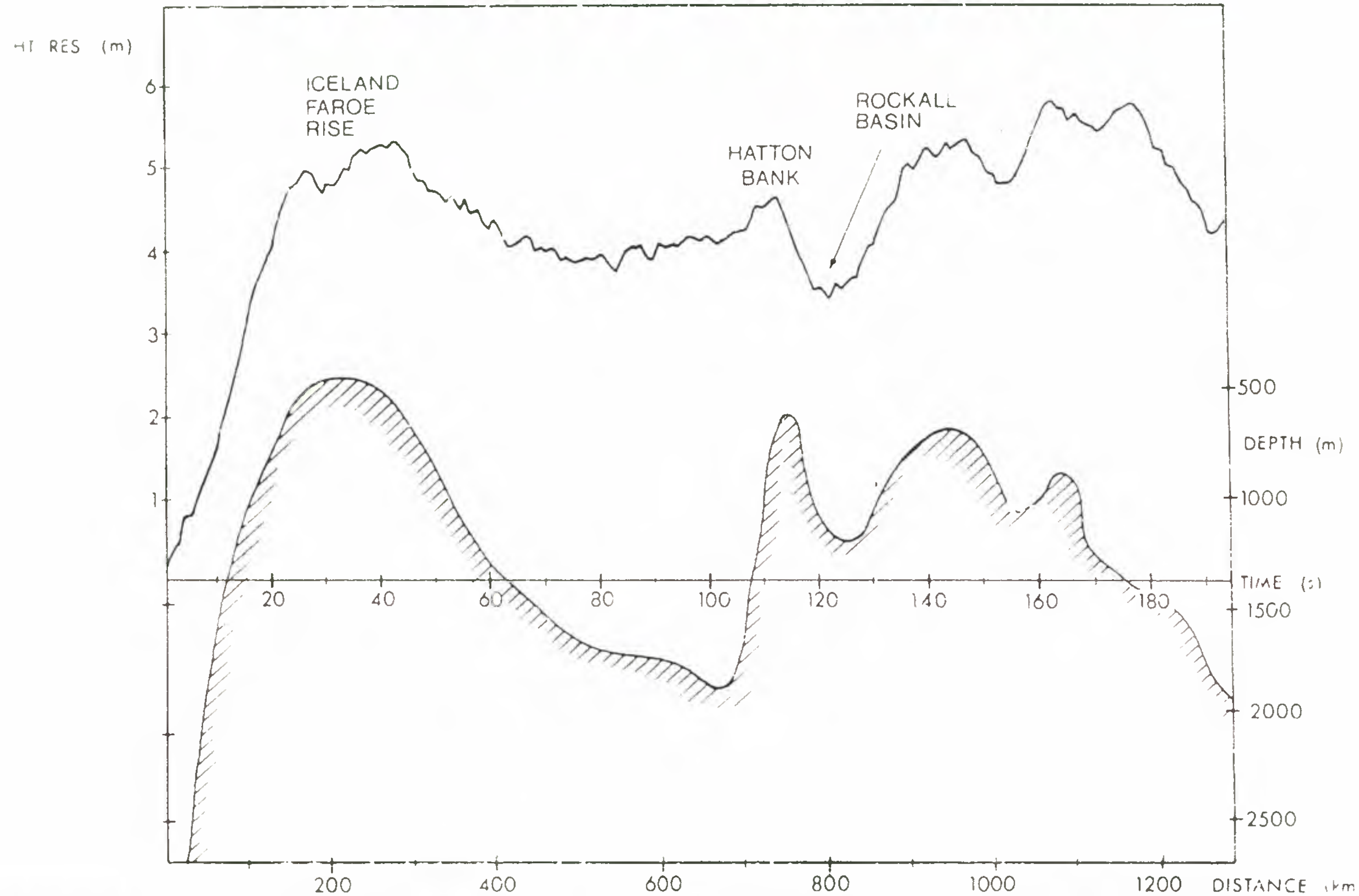
The slide shows one of the earliest examples of an altimeter trace of the height of the sea surface closely following the ups and downs of the sea floor topography. Also shown is a comparison of a negative gravity anomaly measured by a shipborne gravity meter in the Eastern Mediterranean and the same anomaly traced by the altimeter as a depression in sea surface level.

Over the surface of the earth the undulations of the geoid (with respect to a smooth ellipsoid) lie in the range $\pm$ 100m and since modern altimeters can resolve height differences of 2cm these sensors now represent a valuable surveillance tool. Care must be taken however to separate out the time-varying contributions to the signal from both atmosphere (water vapour, electron concentration) and at the sea surface (tides, eddies, currents, waves, barometric pressure etc).

Examples are shown of offshore gravity fields generated from the closely spaced altimeter profiles of the US Navy's Geosat mission. It is charts such as these which help individual countries and oil companies assess the potential oil bearing capacity of the offshore geological structures.

A slide of the gravity field over the globe estimated from data derived from radar altimeters is shown.

Sea Level Undulations



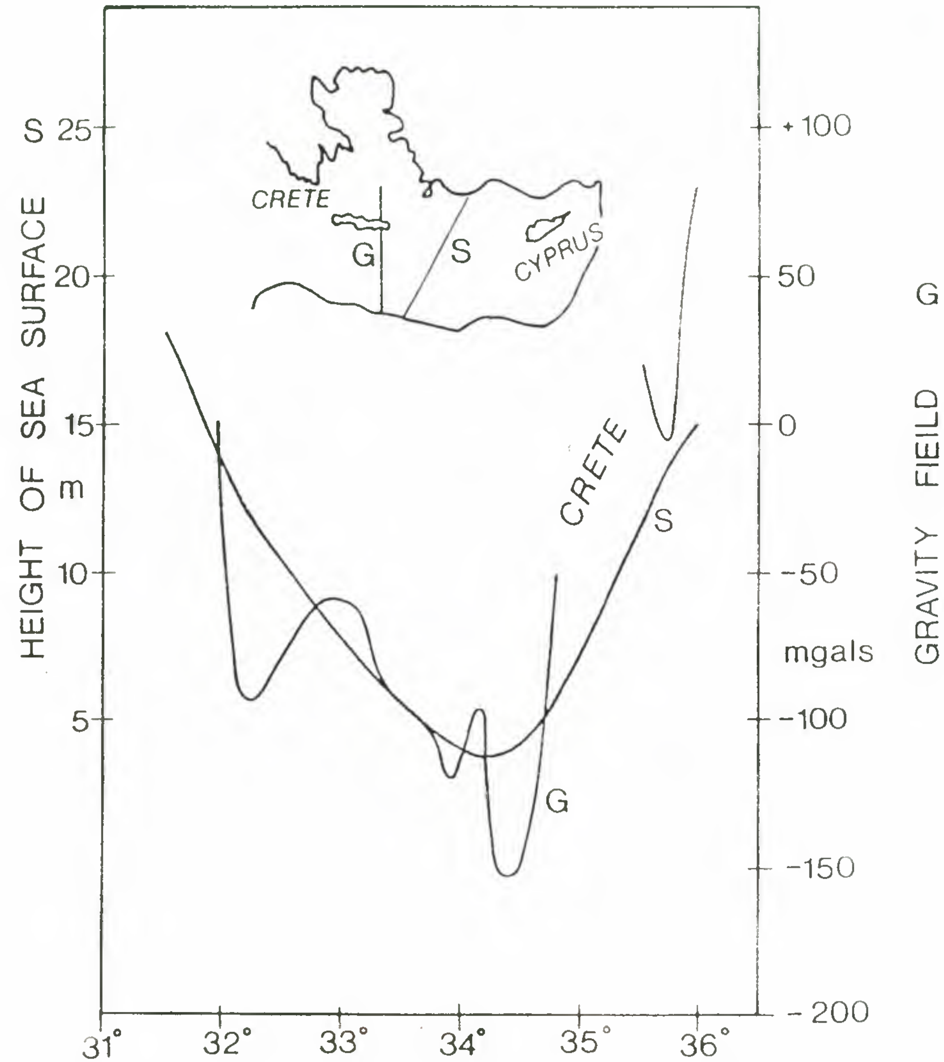
Early plot of Seasat altimeter trace reflecting sea level changes in harmony with underlying sea floor topography

Satellite Observing Systems

Early example of a radar altimeter reflecting large scale topography of the sea floor.

Sea Level and Gravity

Seasat plots dip in sea level in response to large negative gravity anomaly south of Crete



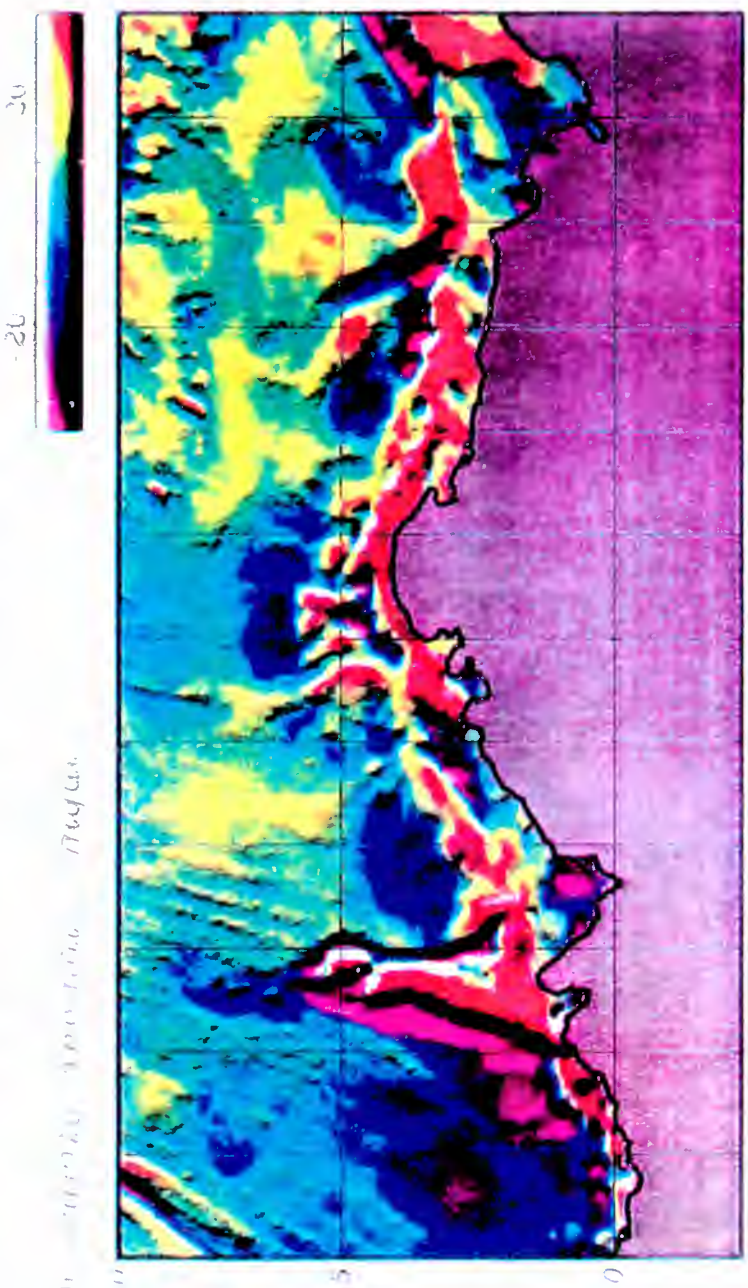
Negative gravity field south of Crete:-

i) measured by a ship in 1963

ii) measured by Seasat in 1978

Gravity anomaly off Antarctica calculated by Sandwell from Geosat altimeter data.

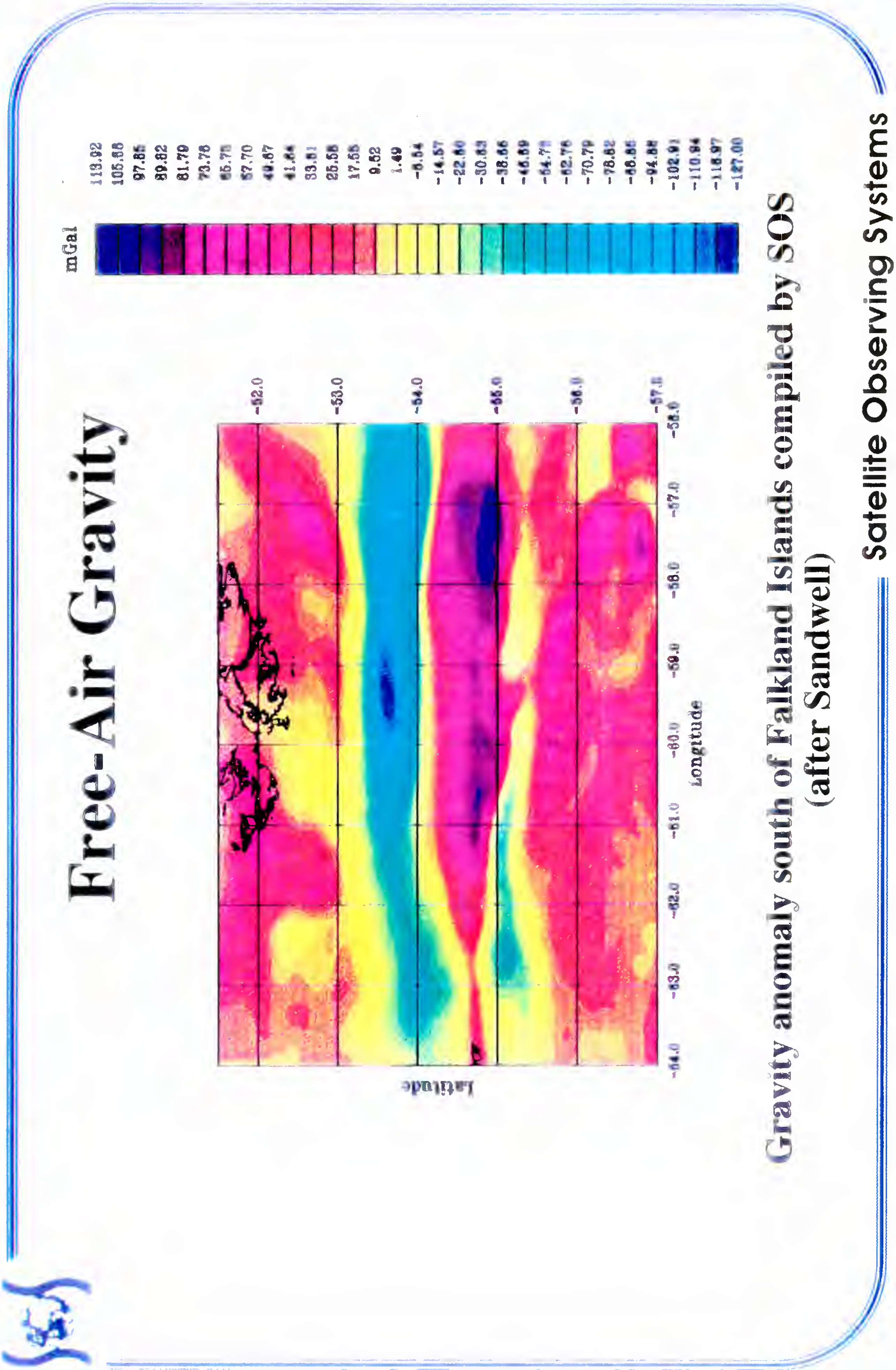
The Sandwell Approach



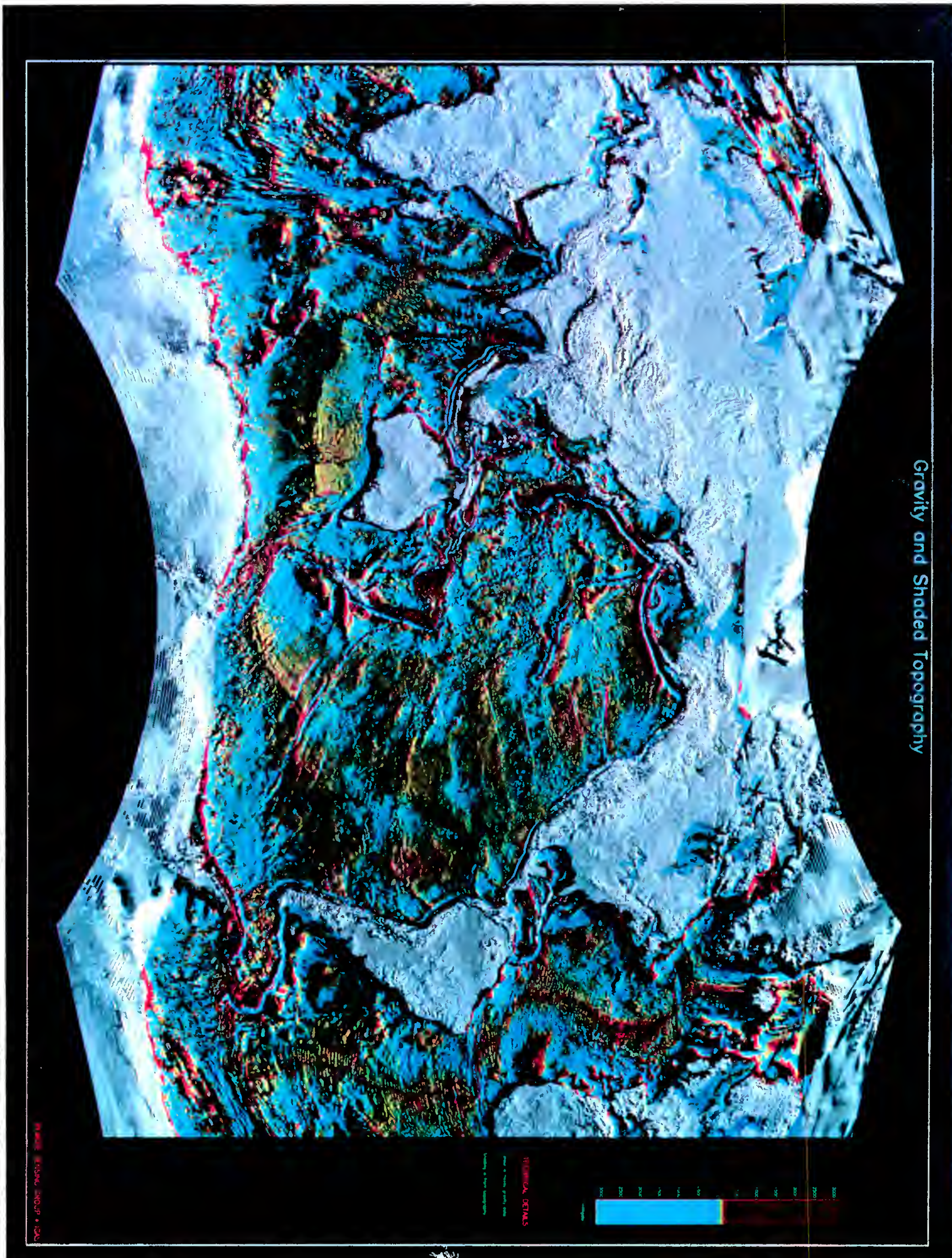
Gravity anomaly calculated by Sandwell from sea level gradient measured by Geosat

Satellite Observing Systems

Gravity anomaly south of the Malvinas (Falklands) plotted by SOS using the Sandwell method



Gravity and sea-floor topography of the globe derived from Geosat.



WAVE CLIMATE

WAVE CLIMATE

Extreme surface wave conditions during storms at sea can cause severe damage to ships and offshore structures. Each year many ships are sunk at sea and the destruction of a number of rigs - especially in the earlier days of offshore exploration - has led to the introduction of strict legislation on the design criteria of offshore platforms.

It is essential to accumulate the best available statistics on wave conditions so that more reliable predictions can be made. The only way to do this is by earth-orbiting radar altimeters which apart from measuring the height to the sea surface can also estimate the wave height through the shape of the return echo from a rough sea surface. The technique is illustrated in two slides.

If reliable statistics are to be built up it is important to check the accuracy of the altimeter's measurements against calibrated buoy measurements at sea. The slide shows the results of such calibrations for three satellites.

Once validated, the wave height estimates, which are recorded every second of flight by the ground stations, can be grouped into boxes of pre-determined size and statistics derived of (say) the monthly or seasonal mean. Likewise statistics on extreme conditions can be made available and it is these which are of interest to the rig designer who requires the best estimate possible of the height of the highest wave in a period of 50 or 100 years.

The slide shows, first, mean waveheight for the month of January for one area - the Mediterranean - derived from 7-years worth of data. Also shown is a calculation of the 50 year return waveheight in this case over a 2° x 2° square off the coast of New Zealand. This type of analysis can now be made routinely over any part of the global oceans. At the time of writing some 10 years worth of altimeter data have been archived. As it grows the accuracy of the statistics obviously improves.

Some other examples of the sort of statistics that can be derived in response to the requirements of the marine industries are shown in the slides.

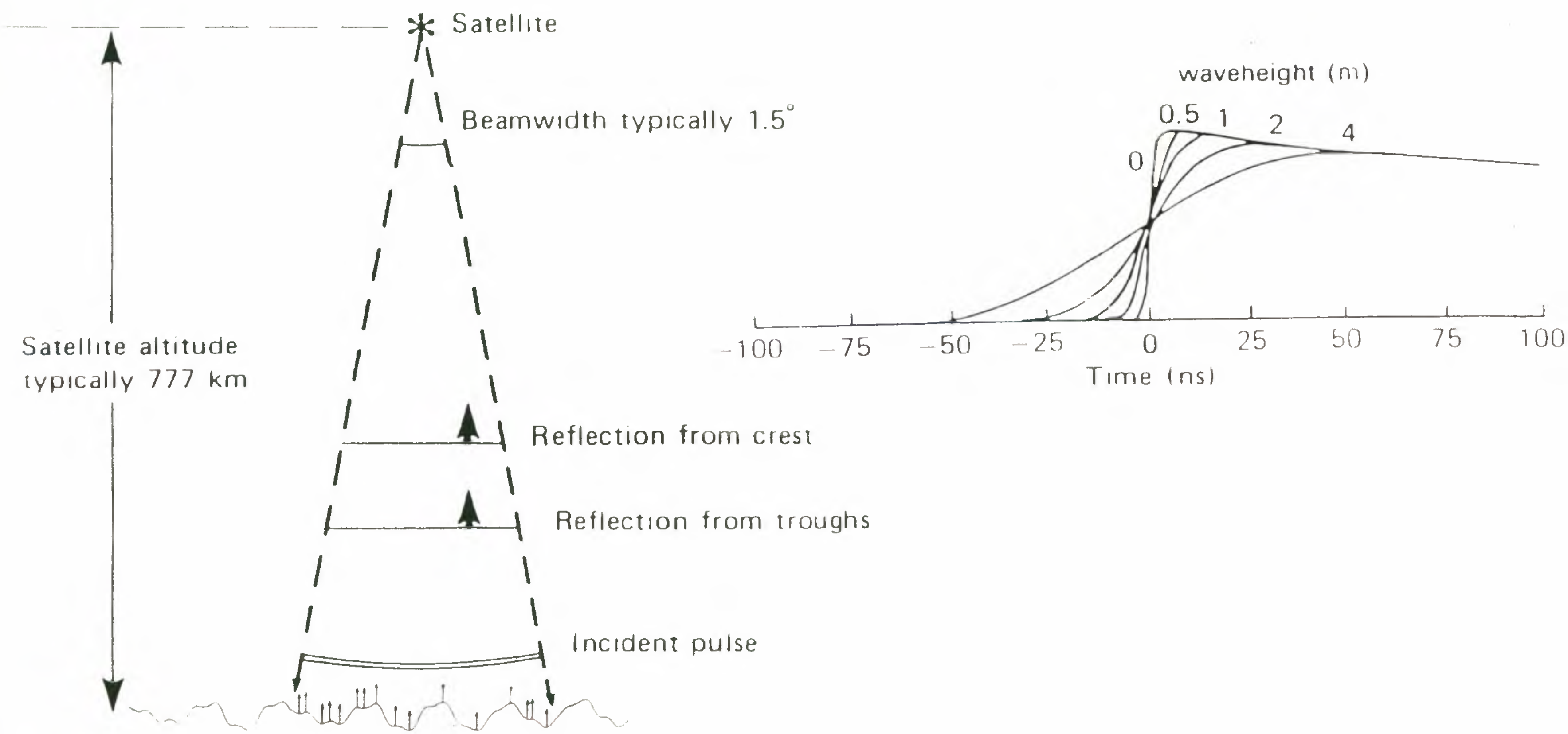
The final slide in this section illustrates the potential real-time use of the altimeter's wave height measurement. The trans-ocean

route of a ship is usually determined from meteorological observations. Waveheights are calculated from the forecast wind velocity by means of a wind/wave model. On the whole these produce accurate predictions and a route can be chosen to avoid the highest wave. During storm conditions - those which in fact are capable of inflicting the greatest harm - the extreme values over a small localised area may be suppressed by the grid size of the model.

On the slide the given figures represent the waveheight values measured by ERS-1. The red values are calculated from the model. At the point where ERS-1 measured 11.9m the model predicted 7.6m - that is, it underestimated the true value by more than 50%. It should be emphasised that these are exceptional circumstances. Models are usually more than adequate for ship routing purposes. But accidents occur in exceptional circumstances.

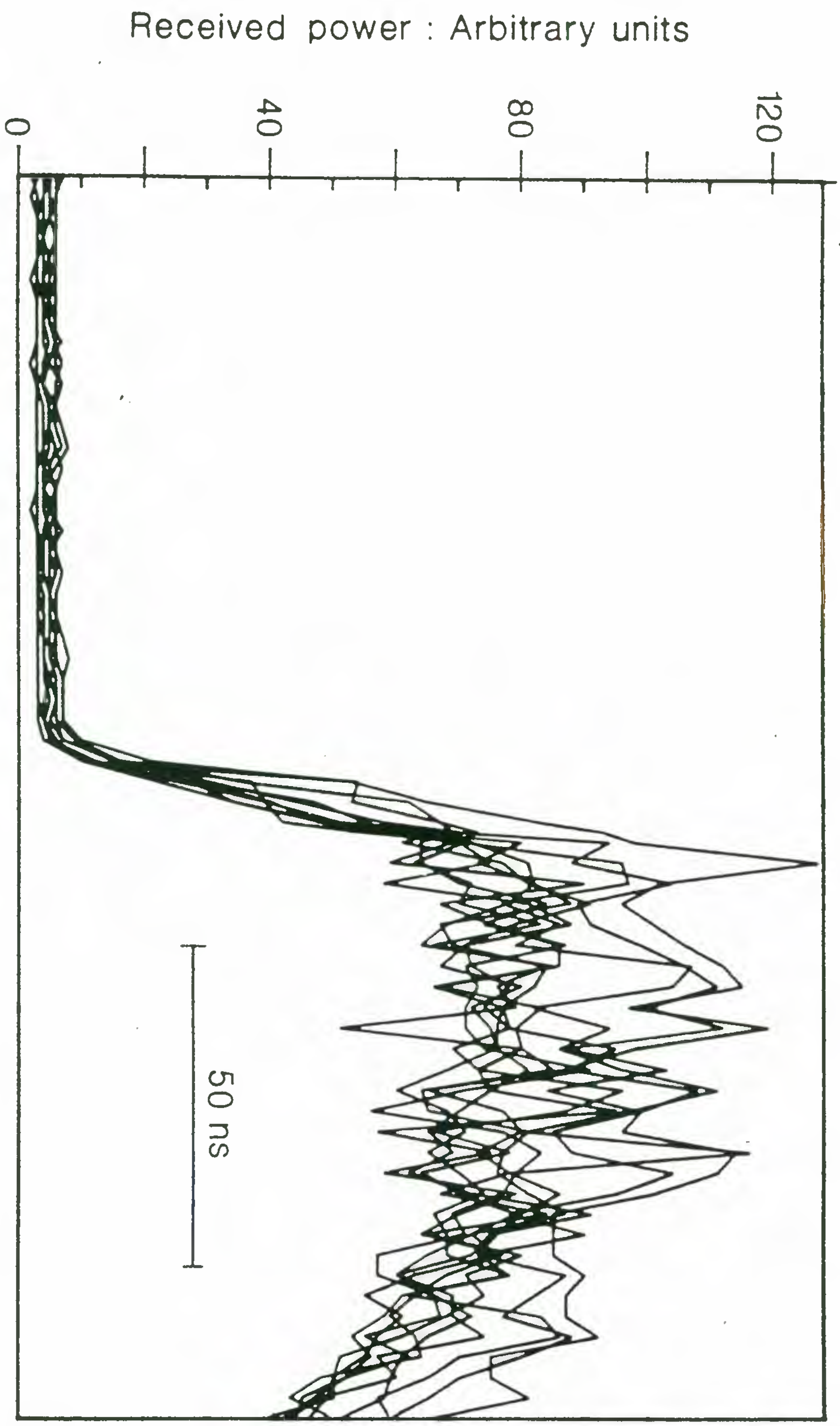
How a radar altimeter measures surface wave height.

Measurement of wave height by the radar altimeter



Satellite Observing Systems

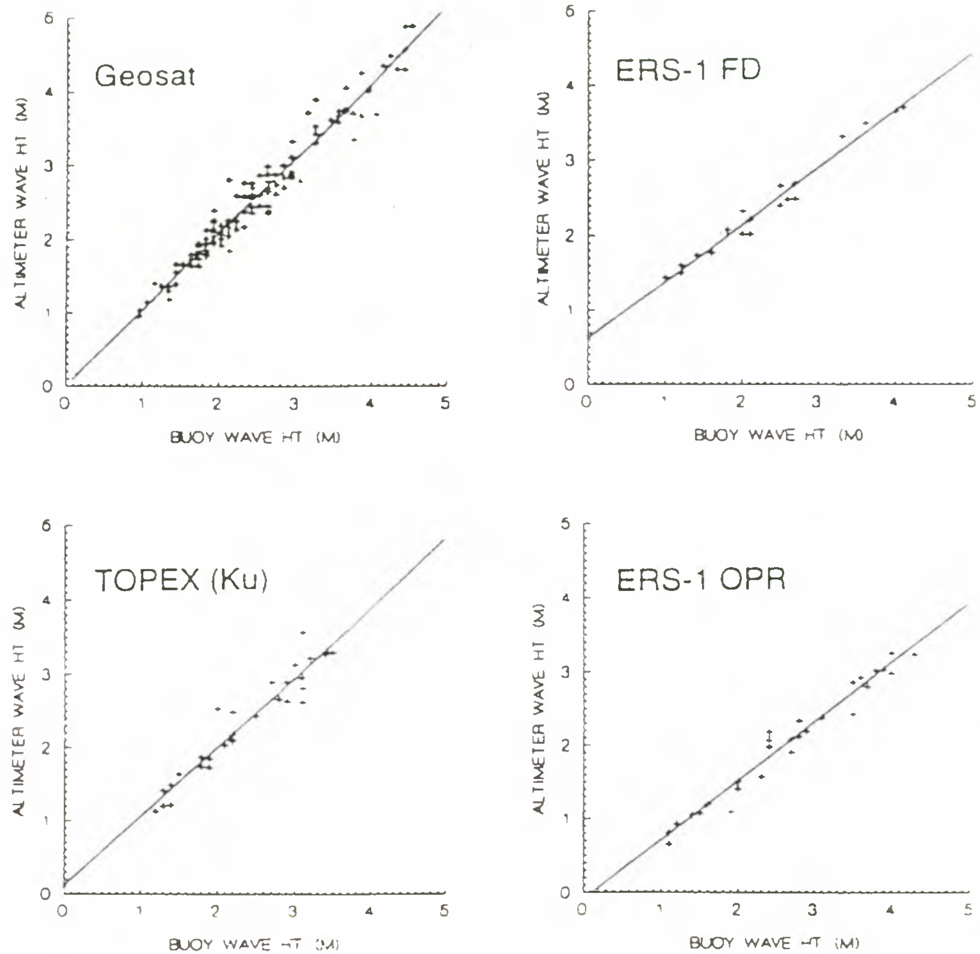
Plot of individual return pulses. Note the scatter. In practise an average of 1000 is taken to produce 1 value each second.



2. The radar altimeter. Each line is an average of the returns from 50 pulses, and the figure demonstrates the large variability still remaining.

Calibration

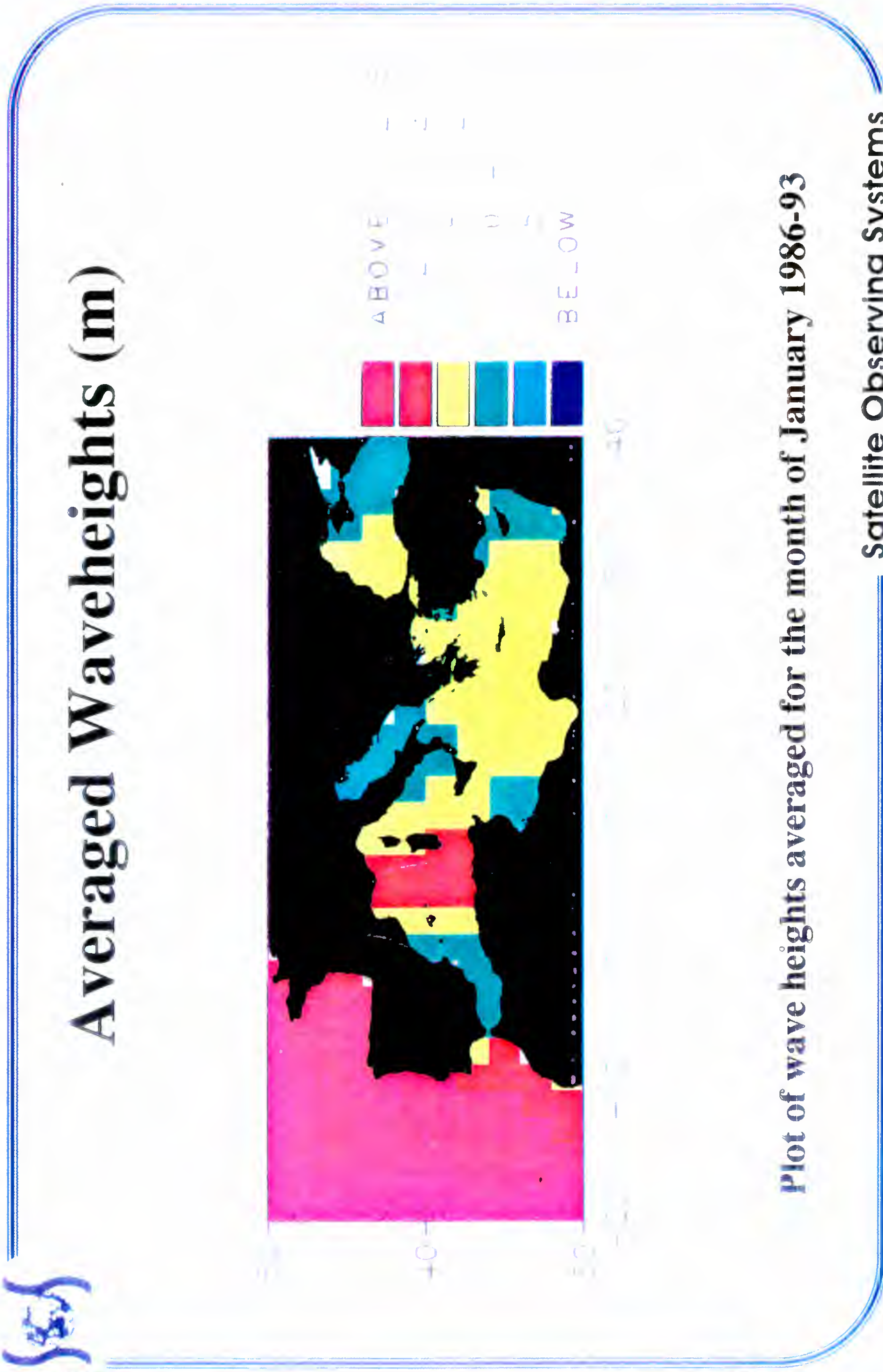
Comparisons of H_s measured by buoys and by radar altimeter



Satellite Observing Systems

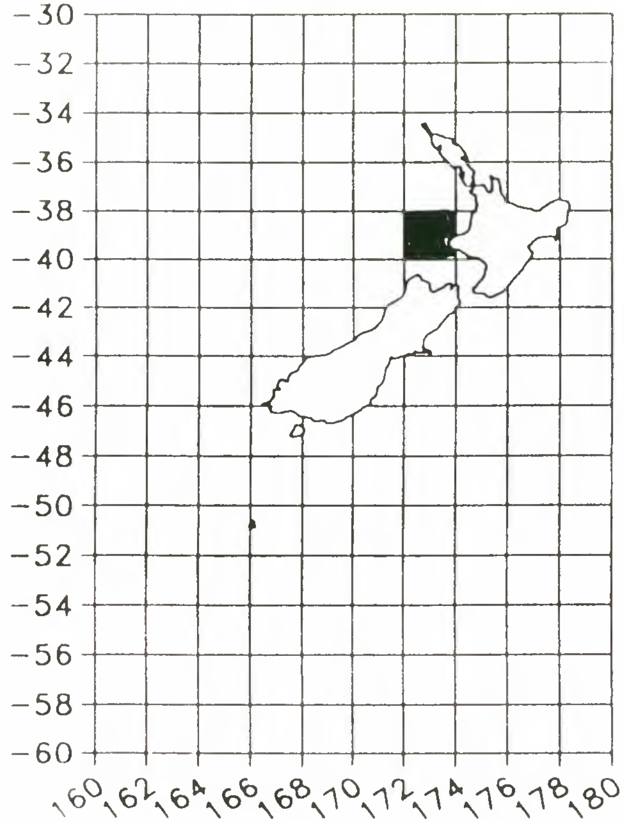
Calibrating satellite measurements of wave height against buoy measurements.

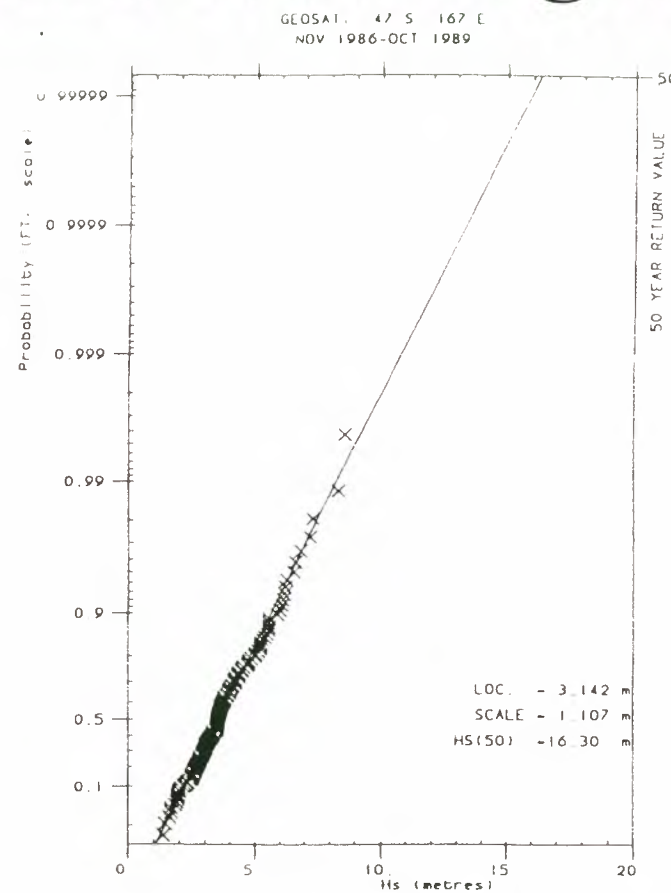
Wave heights over the Mediterranean from Geosat and ERS-1 data.



Calculated value of the 50-year return wave in a 2° x2° square off New Zealand.

50-Year Return Waveheight





Calculated value extrapolated from Geosat measurements at single location

Satellite Observing Systems

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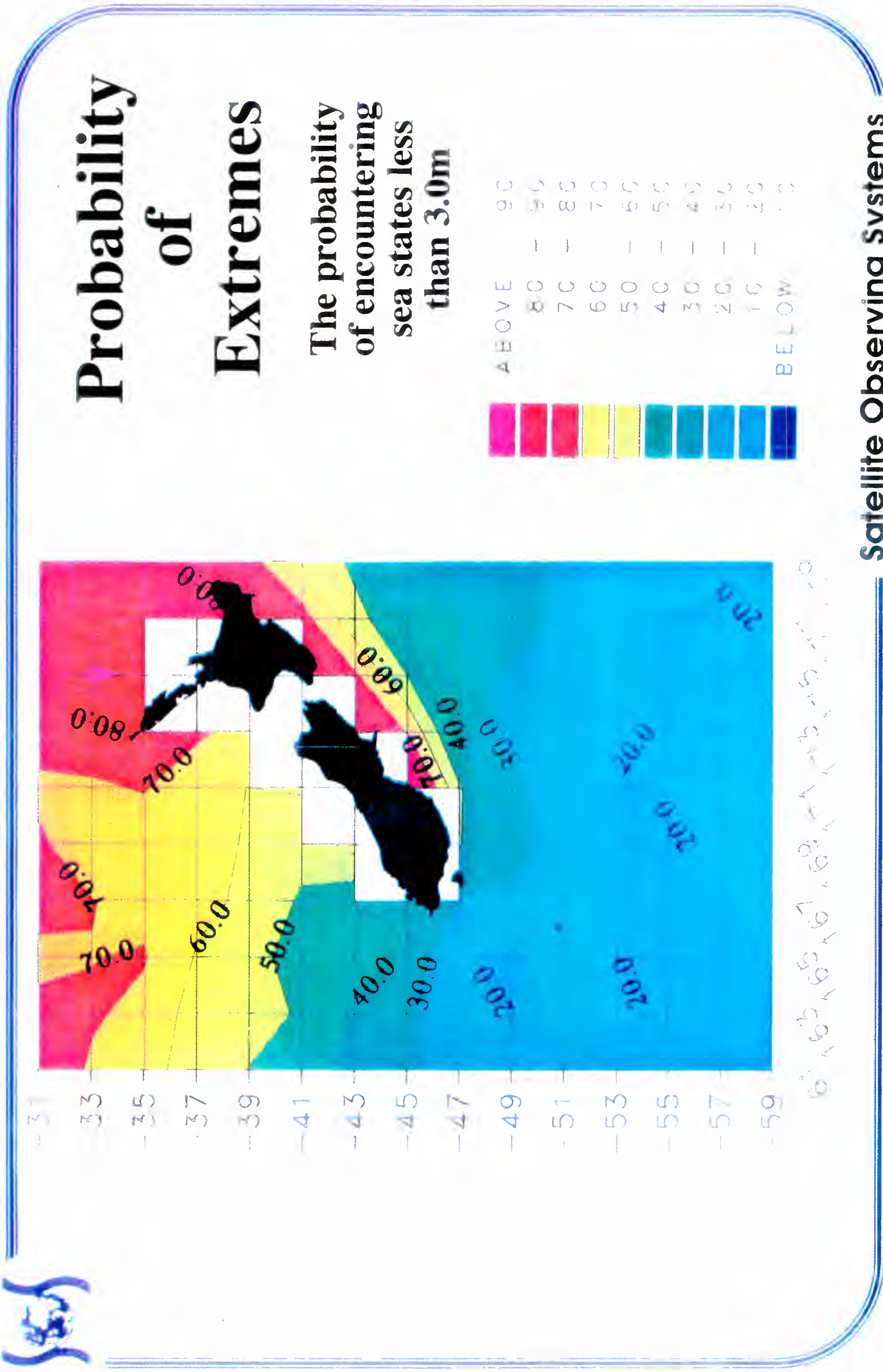
Probability of encountering sea states less than 3m off New Zealand.



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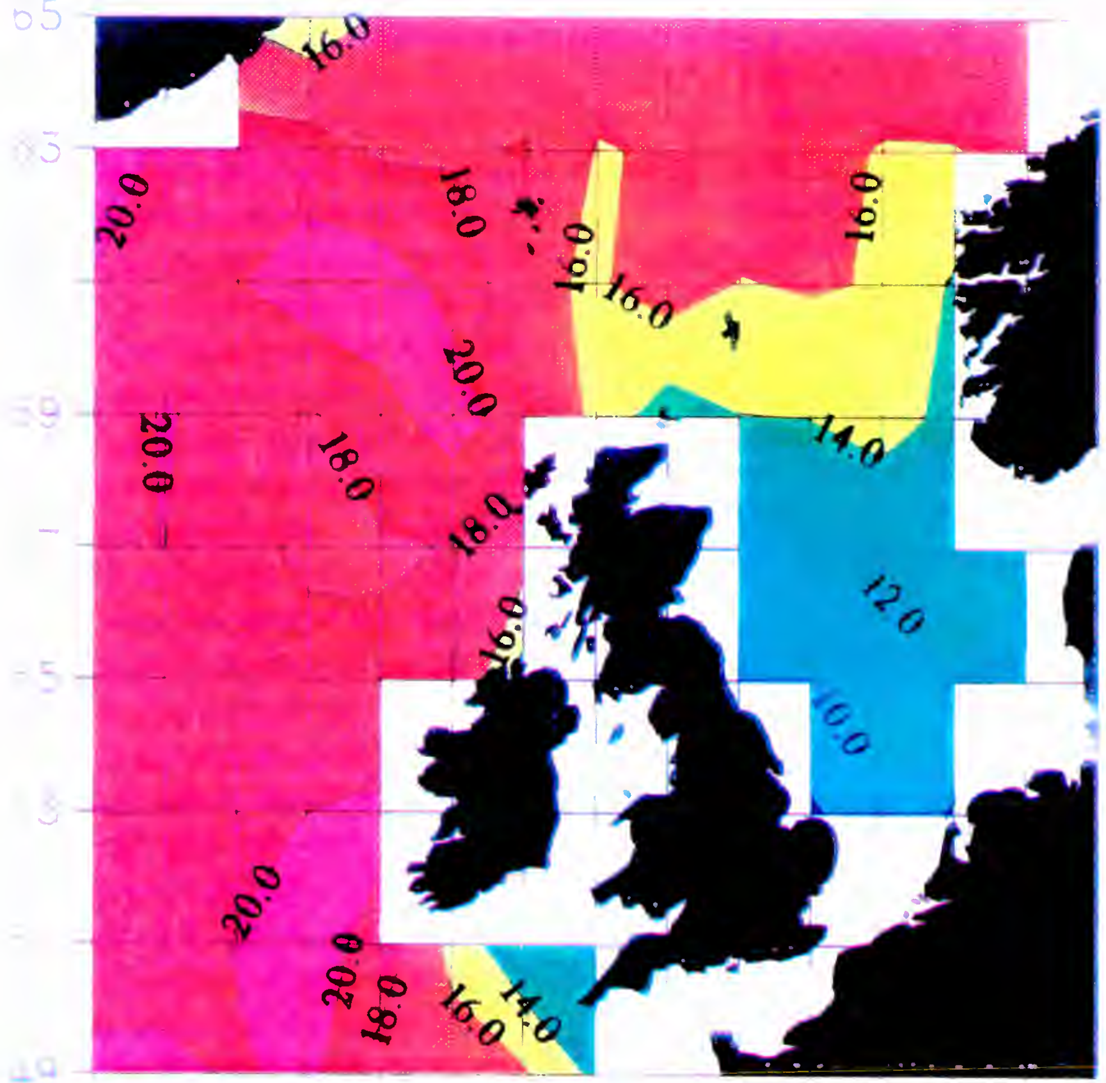
50-Year Return Wave Height (m)

based on Geosat observations



Contours of the height of the highest wave likely to occur over a 50-year period. Derived solely from satellite data and used in rig design.

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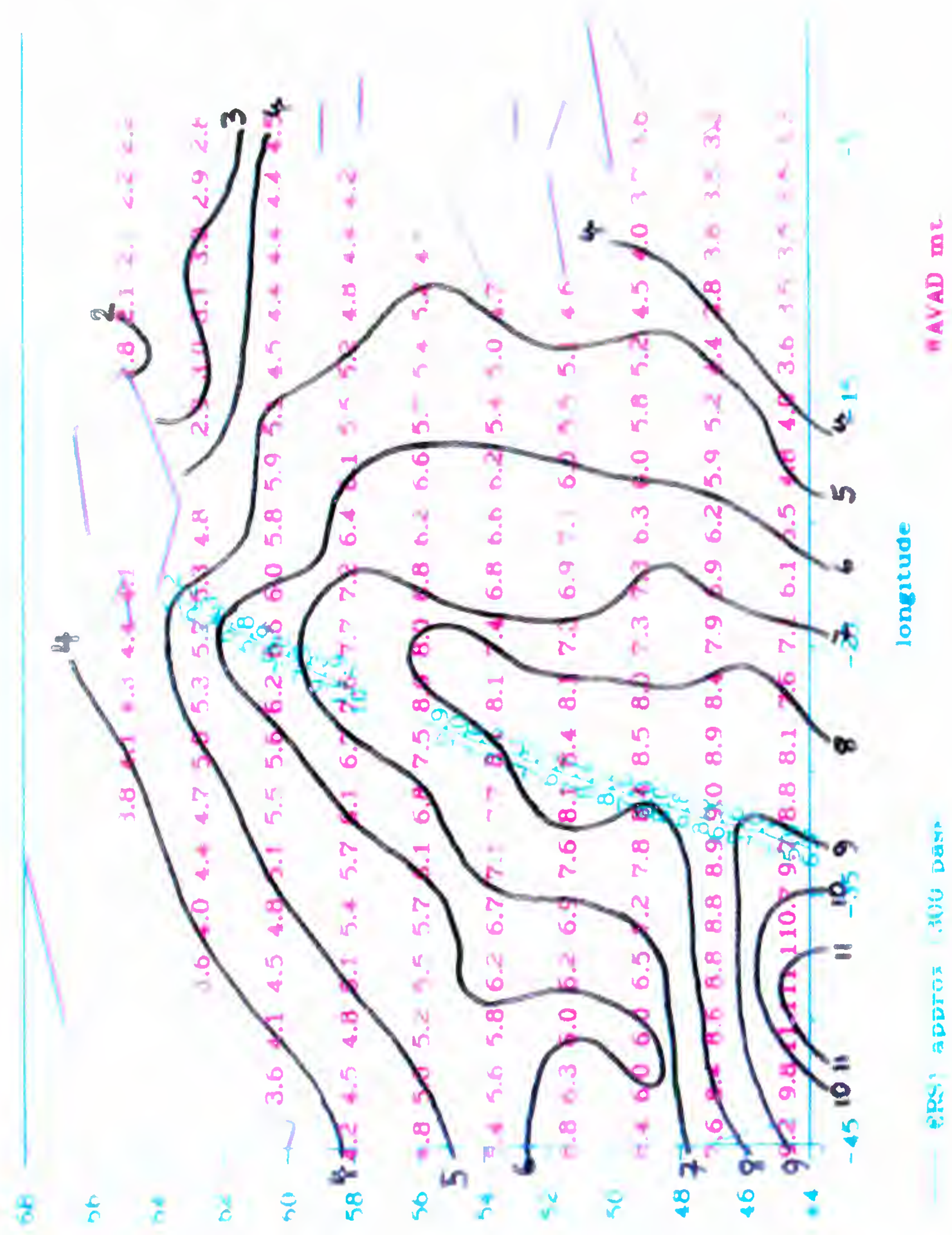
In a mid-Atlantic storm the wind/wave model used for forecasting predicted waves of around 7.6m high at a place where the altimeter measured 11.9 - i.e. the sea was underestimated by over 50%.

Comparison of the model and a descending altimeter track during a storm

3 March 1992, 1300GMT



Satellite Observing Systems

RADAR IMAGERY

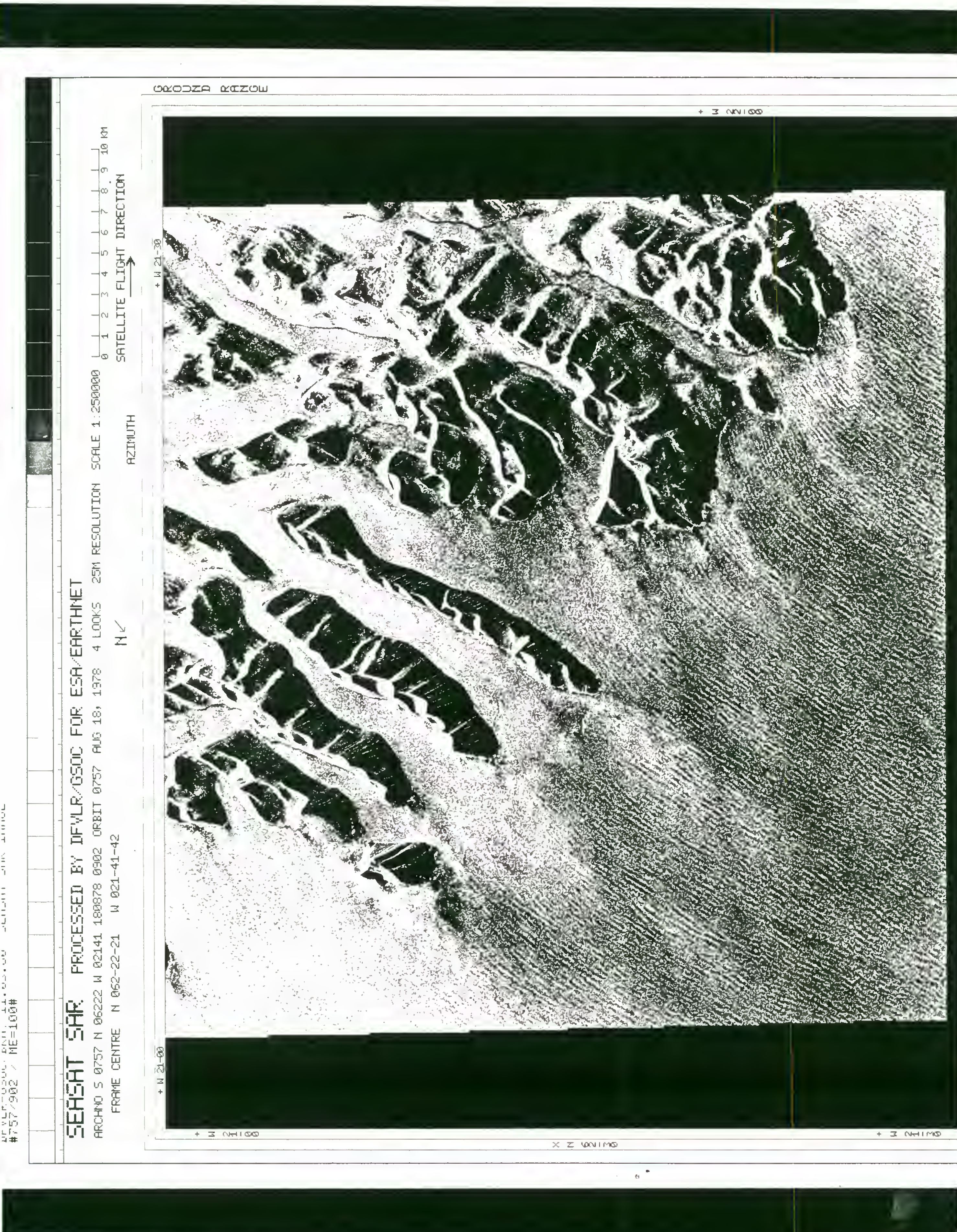
RADAR IMAGERY

Imaging radars mounted on satellites offer the advantage of operating through the cloud which inhibits the performance of optical and infra-red sensors. On the other hand they are limited in their operation to a single frequency and high resolution is achieved by such a high data rate (100 megabits/s) that storing the data on the satellite is not normally possible and dedicated ground stations are required to receive the imagery. Power consumption also restricts operation to about 10% of each orbit.

To achieve spatial resolution of the order of 25-30m using a real antenna would require an array some 15-20km long and since this is not practical on a satellite, high resolution is achieved by using the forward movement of the satellite to synthesise the operation of a real antenna. The phase history of the backscatter from each individual scatterer is recorded over a period of about 2 seconds in which time the satellite has moved some 15km. The instrument - referred to as the Synthetic Aperture Radar or more commonly, SAR - first flew on SEASAT in 1978. Two shuttle missions have carried SAR and one instrument has been operating on ERS-1 since 1991. The Canadians are about to launch a dedicated SAR mission - Radarsat - primarily for monitoring the movement of Arctic Ice.

SAR images of the sea surface have demonstrated the sensor's capability of detecting slicks - both natural and man-made (and it is often difficult to distinguish between them) - eddies, effluent discharges, ships and their wakes, shallow coastal bathymetry and, above all, surface waves. Just as the altimeter record is being used to build up more reliable statistics on wave heights so the SAR record is being used to derive the dominant period and direction of wave trains around the world. A few examples of ocean waves imaged by SAR and changing direction are shown in the slides. There is also an example of how the detail of a ship can be brought out by special image processing techniques. SAR could therefore become a useful tool in improving coastal management.

Atlantic swell passing the Faroes.



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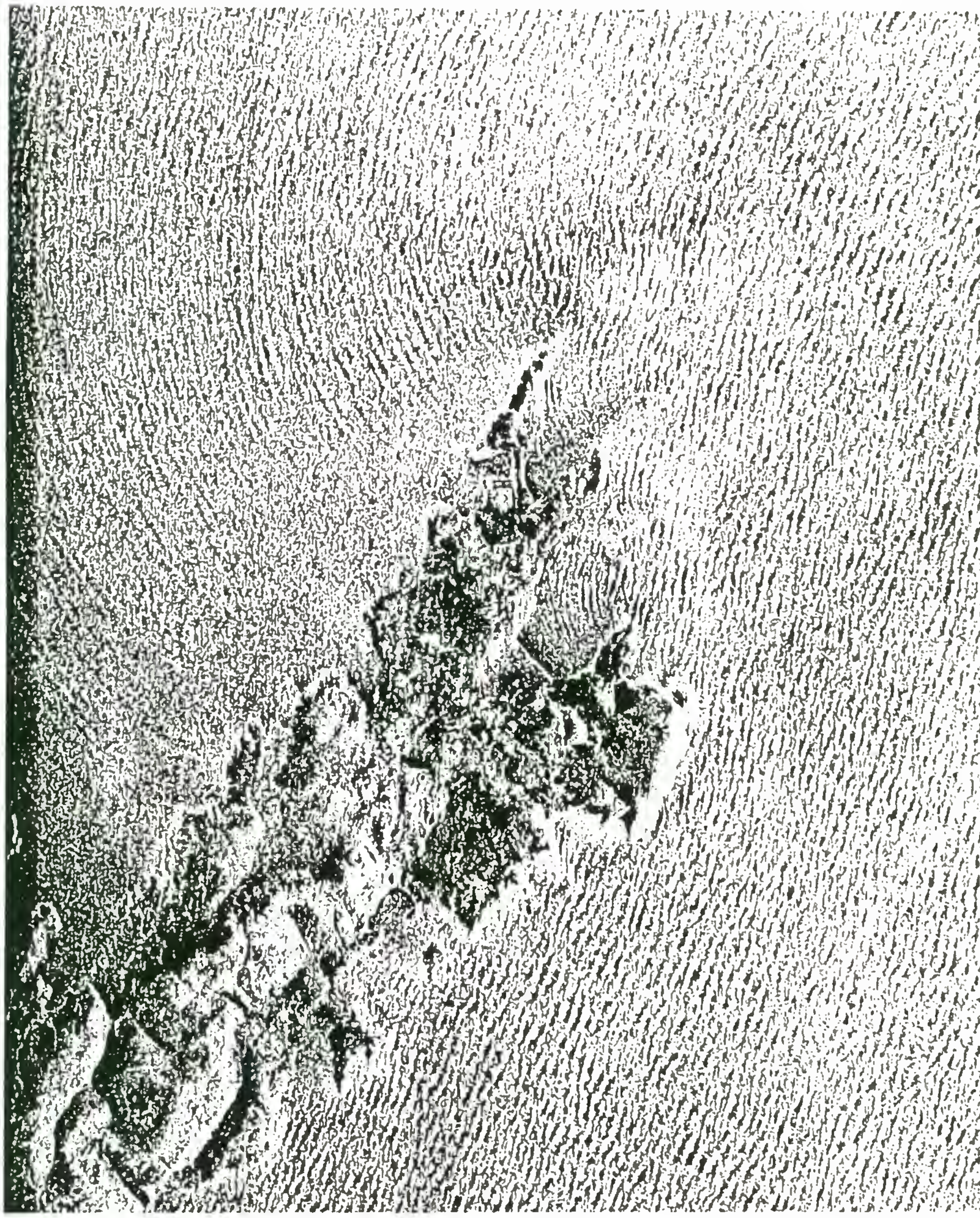
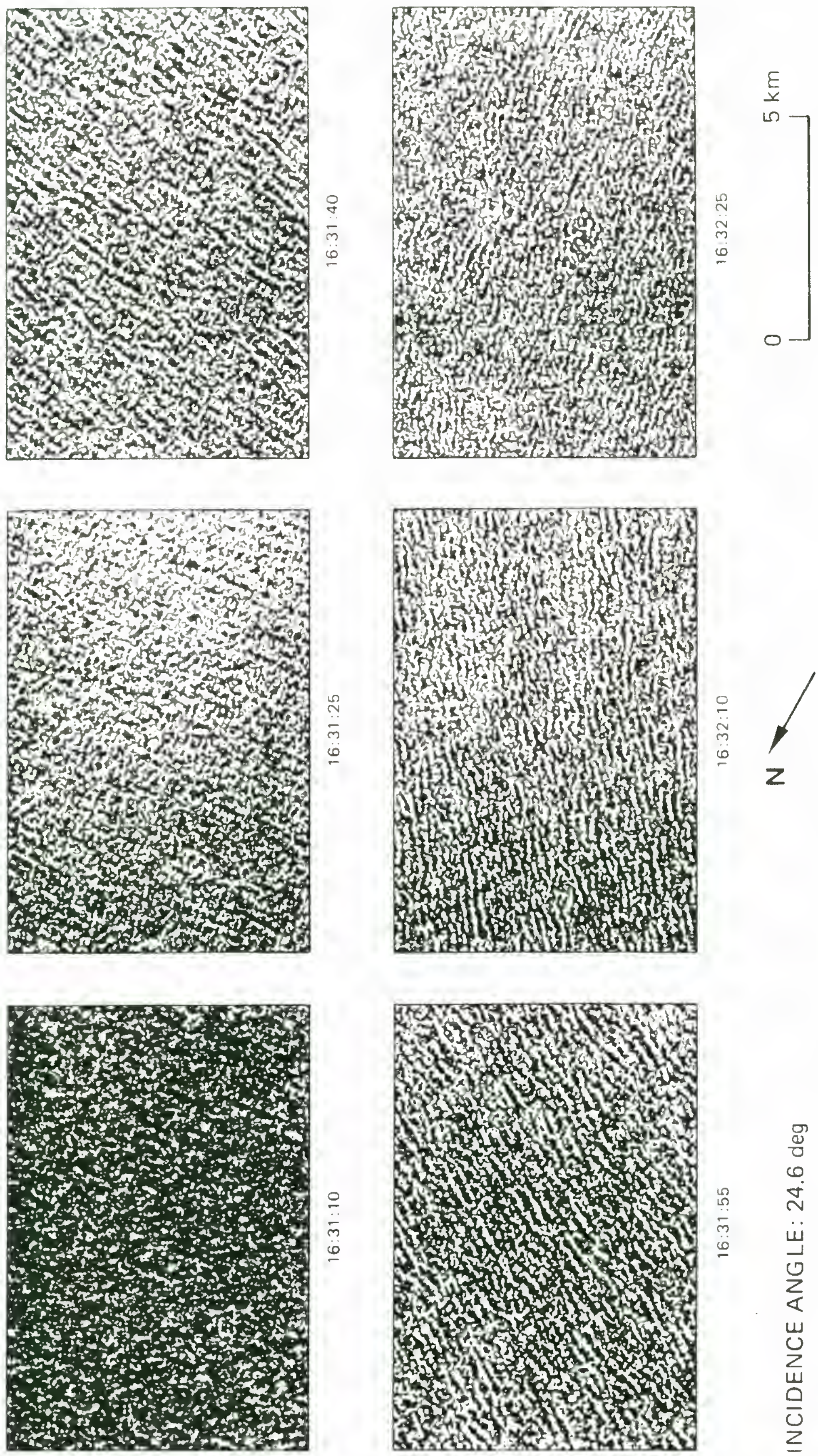
Diffraction of ocean swell passing a headland as imaged by SAR.



Shuttle passes over a hurricane in the N Atlantic. These radar images taken a few seconds apart illustrate the change of direction and wavelength in the pattern of surface waves.



A ship imaged by the Synthetic Aperture Radar from a height of 800km.

Image made by Remote Sensing Division, Farnborough.

Ship image obtained from Seasat data.

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SLICKS
-NATURAL & MAN-MADE

SLICKS - NATURAL AND MAN-MADE

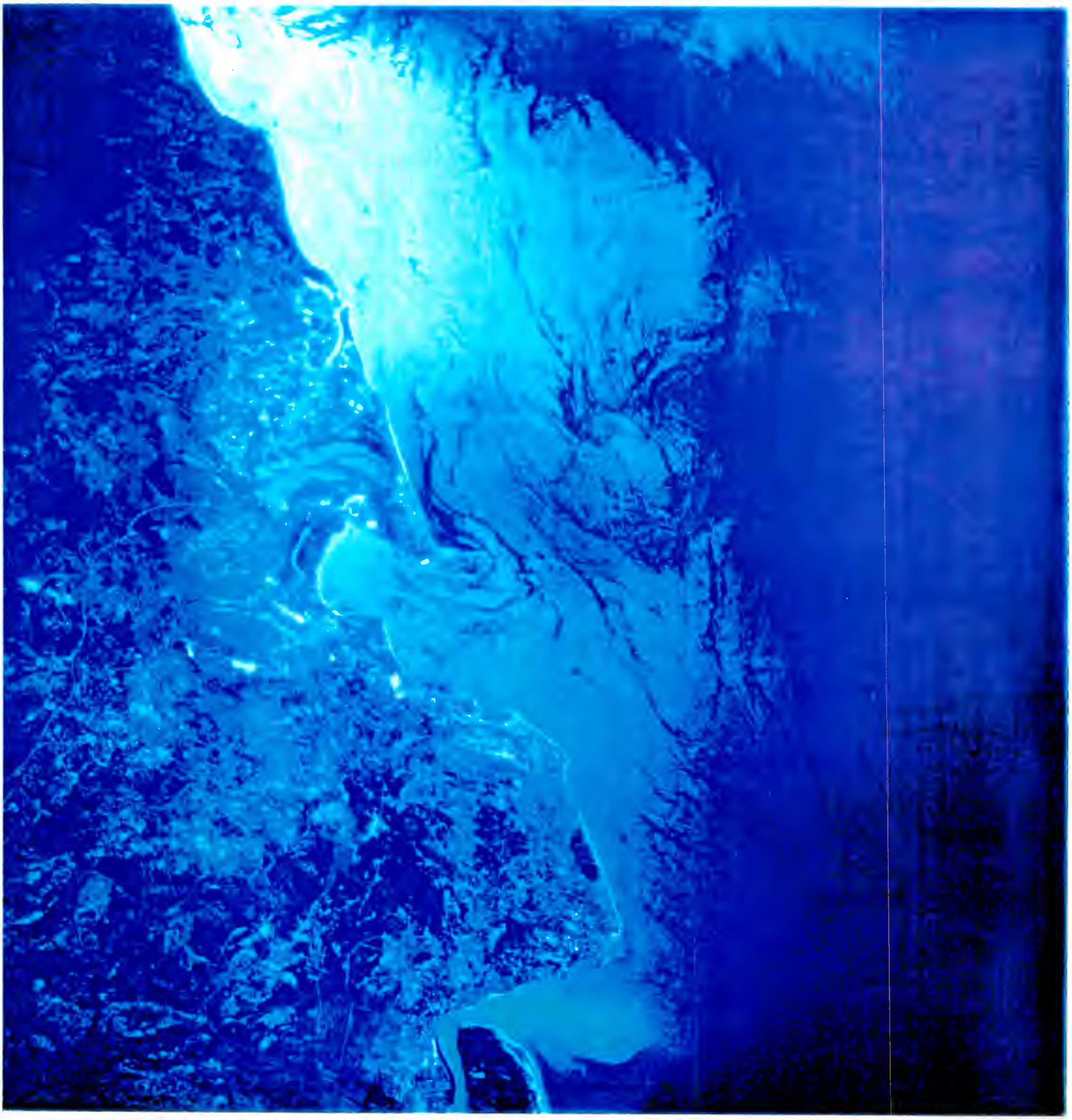
The ocean surface is subjected to change by a number of processes - the majority through natural forces but some through human activities. A change in the wind conditions will create a different pattern of surface roughness which can be detected by a SAR. Biological processes, internal waves, currents and other natural processes can also create changes in surface ripple patterns which we know as slicks and, as shown on the slides, these are common features of SAR images.

Other surface parameters are affected - especially colour and temperature. Thus multi-spectoral scanners and infra-red devices can be used to track the flow of effluents brought down to the sea by rivers. But these sensors, as we have seen, are inhibited by cloud which envelop some coastal zones more than half the time.

At present there is a move towards the synergistic use of satellite sensors whereby the individual characteristics of a feature - its colour, roughness and temperature - are brought together to help understand the nature of the ocean processes involved and the meteorological circumstances under which they recur. In this way it is hoped to build up and classify a library of images. Oil on the surface of the sea can be distinguished by satellite and some examples are shown in the slides. In some cases, as in the Arabian Gulf, these slicks are persistent and probably are indicative of oil seepage. As often as not however, the oil is the result of illegal discharges by ships, and nations are anxious to improve techniques for their detection. SAR has the potential to act as 'an eye in the sky' but more 'synergistic' research may be needed to distinguish the more prevalent natural slicks from the man-made variety.

Natural slicks off Majorca imaged by SAR.

Natural slicks in the Mediterranean



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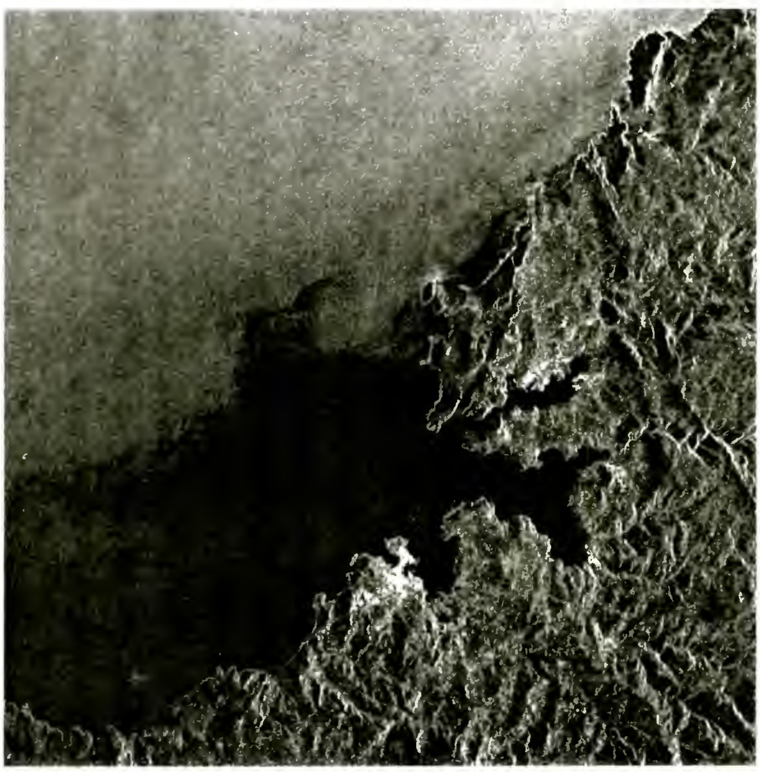
Prepared by Satellite Observing Systems

ERS-1 SAR image of an oil spill 10 days after an oil tanker ran aground near Corunna, Spain.



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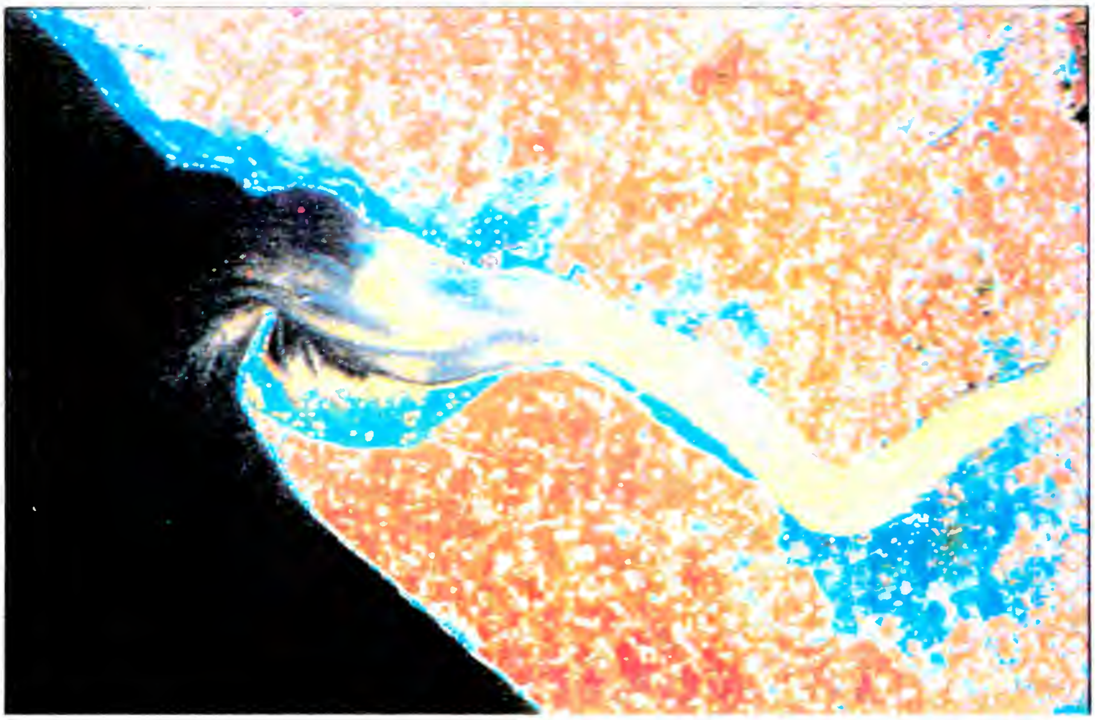
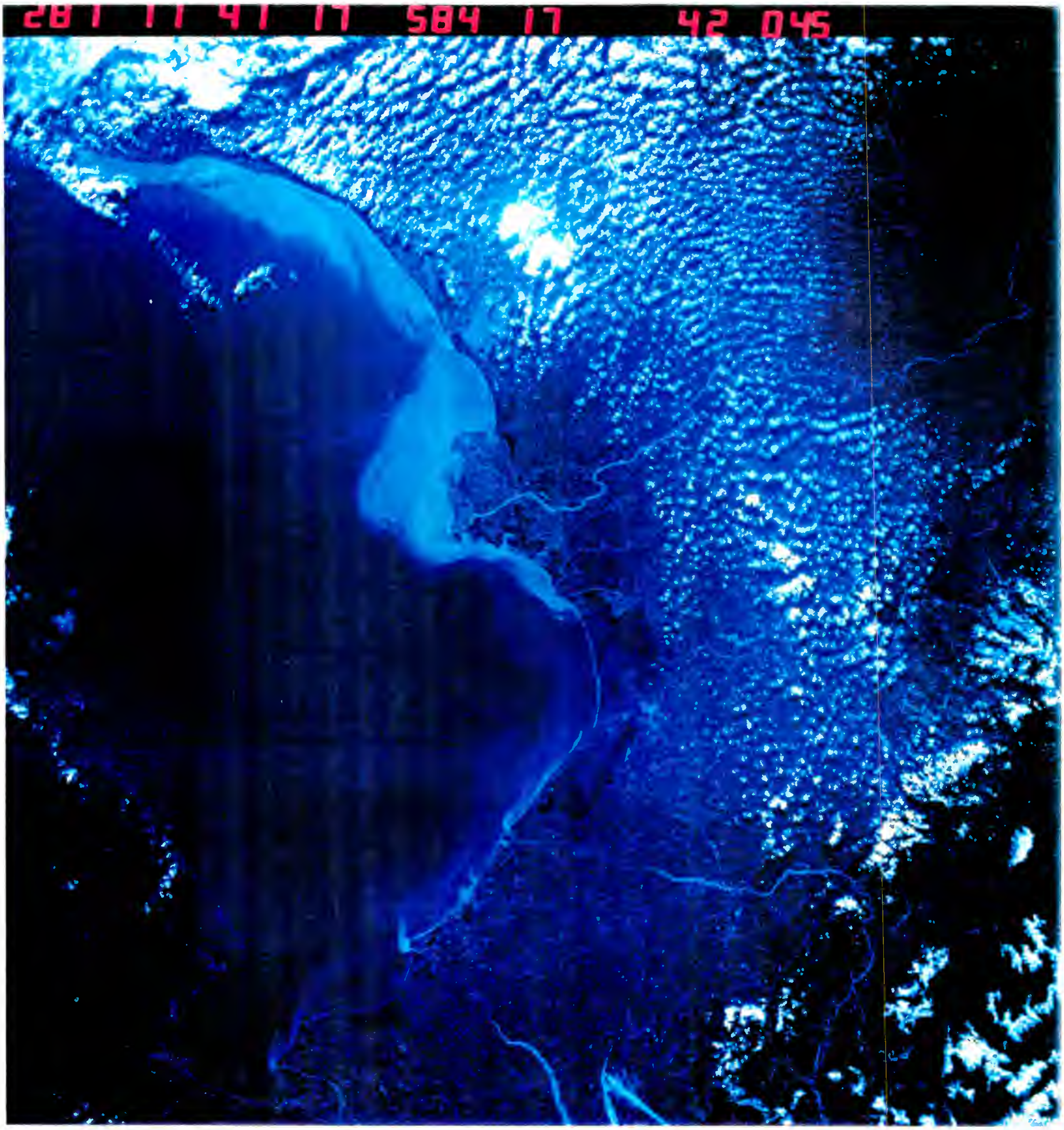
Prepared by Satellite Observing Systems

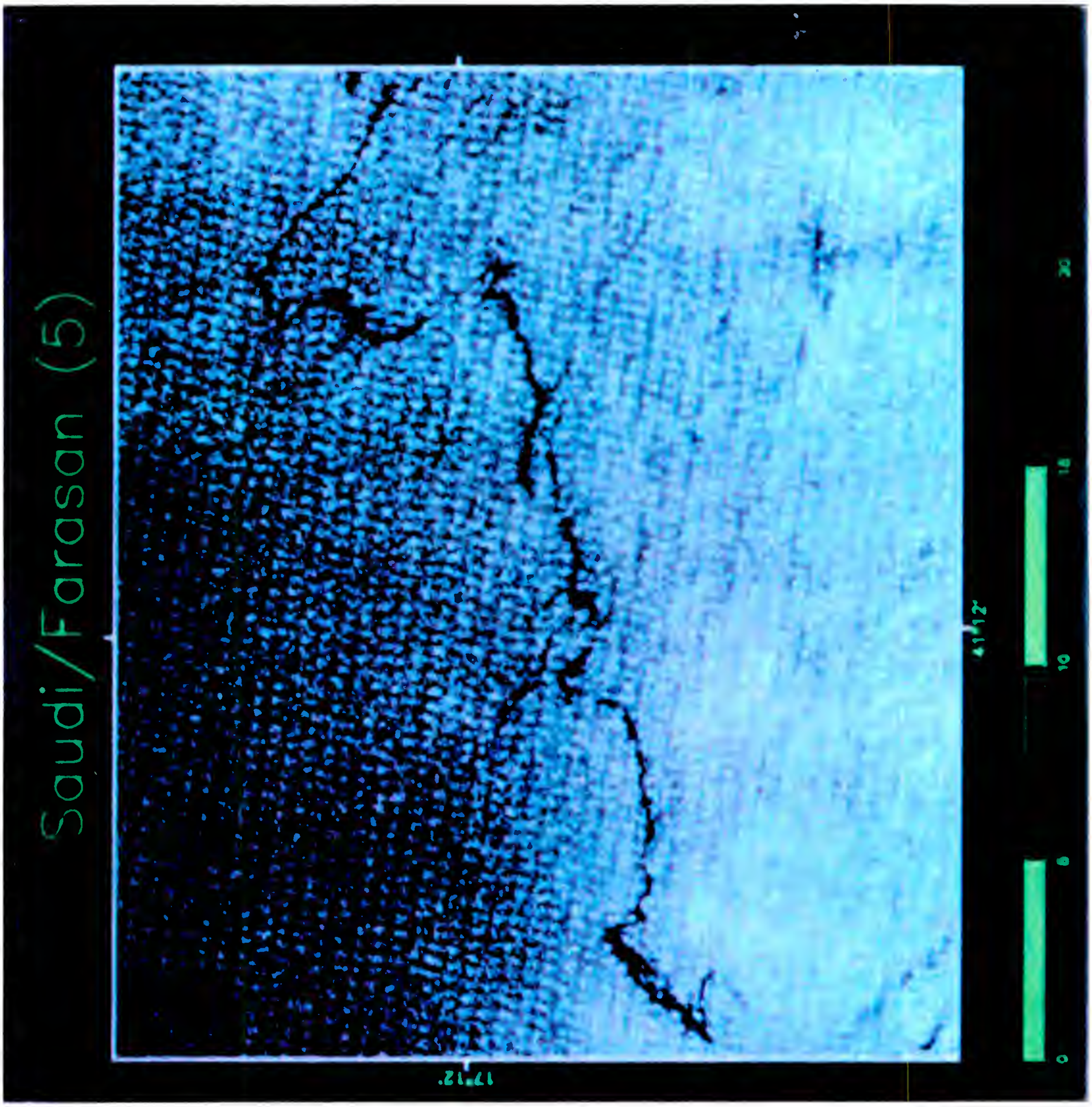
Landsat image illustrating sediment and effluent yields in the Humber estuary (UK)

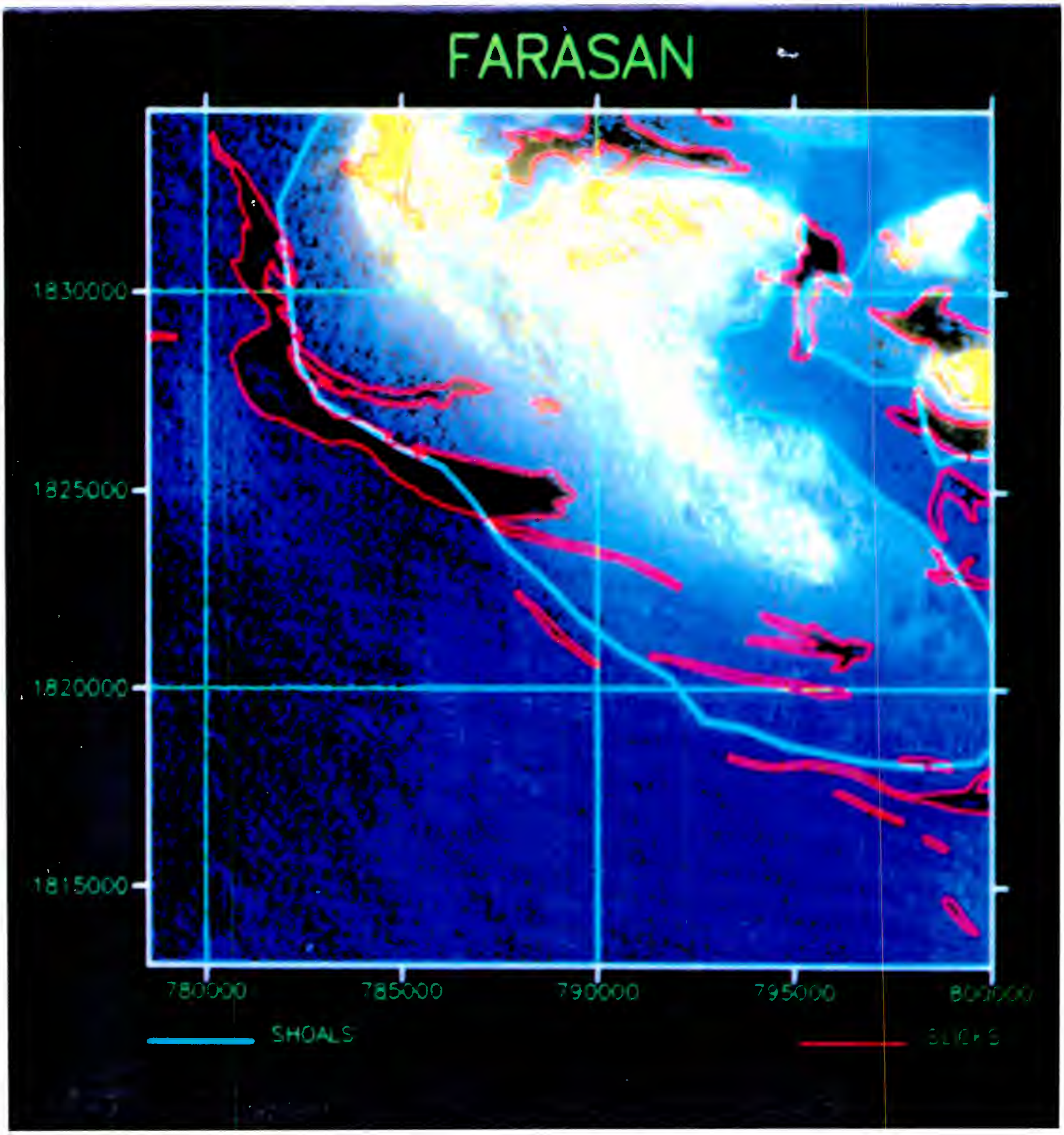


Discharges of river effluents into the Mediterranean as viewed by Shuttle.



Persistent oil seepage imaged by Landsat in the Arabian Gulf area (courtesy BP). The blue line indicates slicks.





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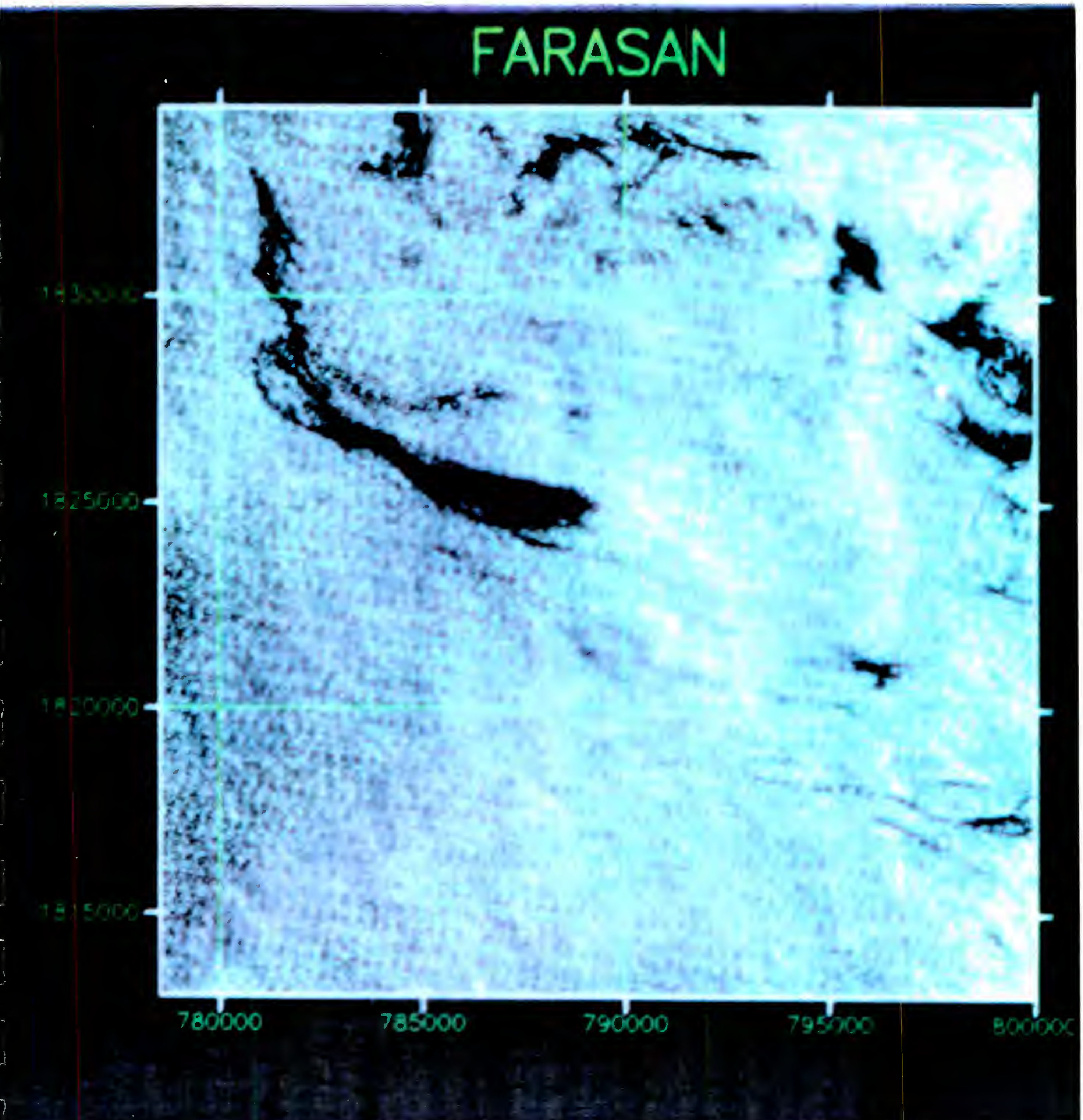
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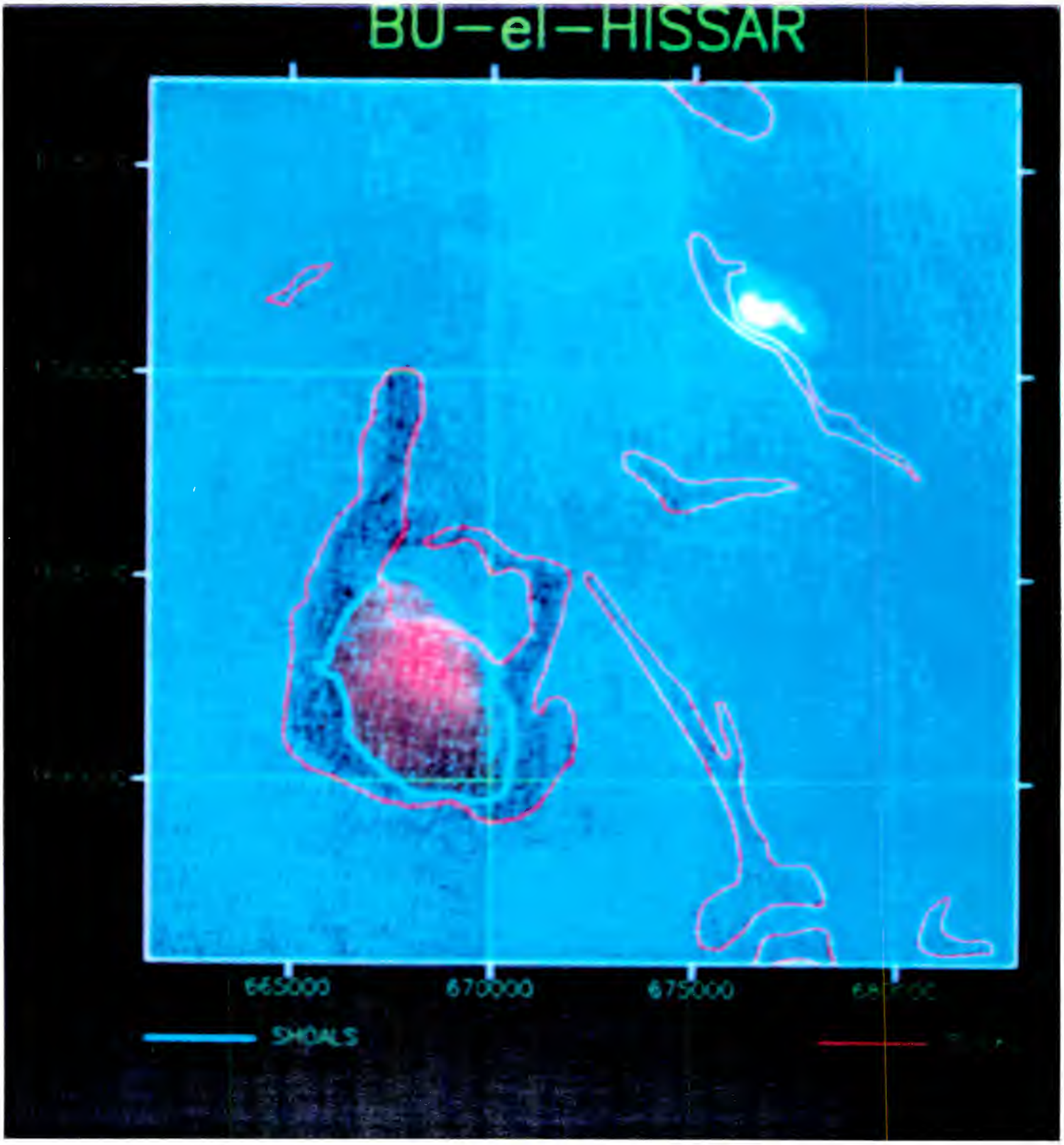
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APPENDIX

Application of Remote Sensing Techniques to Fisheries

Background

In many parts of the world the emphasis in the fishing industry is on conservation through improved management of stocks. There is therefore little or no incentive to encourage fishing fleets to increase their catches. Strict controls are introduced, and the main contribution of satellite remote sensing in those circumstances may be to assist fishery protection vessels detect foreign intruders.

But even if conservation were not the strong issue it is in waters of the North Atlantic and North Sea, there appears to be no direct link 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 can rarely be directly related to the presence of fish.

At certain times of the year, however, notably Spring, in areas of seasonal stratification the phytoplankton bloom is easily recognisable by the colour changes between the mixed and stratified regions. In these instances the newly-stratified water supports an often very intense phytoplankton bloom and, historically, fishermen have found shoals of fish associated with the front between the two water types.

Where the food chain is relatively short, as in sub-tropical upwelling areas, surface conditions of colour and temperature are more clearly related to fish catches than in more temperate sea areas with four or five trophic levels. The opportunities for using remote sensing in the tropics to increase catches (as practised by the French) is discussed later.

Concern about fish stocks is not new. In 1902 it led to the founding of the International Council for the Exploration of the Seas. ICES, the oldest marine commission in the world, now keeps a record of fish catches (on the basis of which the European Commission sets its annual limits on allowable catches), and these statistics can be compared with the observations of changing environmental parameters.

In the future, archives of remotely sensed imagery of ocean colour and temperature will assist in describing long-term changes in those

environmental conditions which may affect the migratory patterns of fish. Natural features such as oceanic fronts have been shown to move position over the years which may affect the whole marine eco-system.

It must also be borne in mind that over many temperate areas the skies are often cloud-covered which inhibits the operation of colour and infra-red sensors. (It has been estimated that there is less than a 5% chance of receiving two consecutive images with less than 30% cloud over Northern Europe).

Global perspective

Thus, information derived from microwave sensors which can operate through cloud - could prove particularly useful.

The total world catch is about 76 million tonnes of which 52 million tonnes 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%.

Some parts of tropical and sub-tropical areas are regarded as under-exploited. The Indian Ocean, for example, covers an area to 20% of the world's oceans yet provides only 5% of the total global catch. India lands 1.7 million tonnes a year but the sustainable yield over their EEZ (Exclusive Economic Zone) is estimated at 4.5 million tonnes. Ten years ago the catch of tuna fish by vessels operating out of the Seychelles was around 25,000 tonnes per year, today 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, 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 installed an AVHRR station on the island of Réunion 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 parameters - 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 10^0C, albacore tuna preferred water between 15^0 and 17^0C, while tropical tuna inhabited water of 27^0C.

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.

<u>Nutrients</u>

Along many coastlines - especially in the tropics - subsurface waters which ascend to the surface under the influence of trade winds have physical and chemical properties that are distinct from the usual surface waters. One important characteristic of potential economic importance is that these upwelled waters are colder and richer in nutrients than the surface water. They therefore attract fish.

Since the temperature differences can be as much as 6 - 8^0C, sea surface temperature acts as a good indicator of upwelling. This makes satellite observations particularly useful since temperature is a parameter easily measured by means of infra-red devices.

Before the advent of satellites, upwelling areas were inferred from the large scale wind field usually derived from the atmospheric pressure. Systematic use of 'in situ' data was next to impossible because of the dense network of stations required to describe adequately the extent of spatial and temporal variability. It is only now that sufficiently long time series of direct satellite

observations have been built up to allow the first steps to be taken towards developing predictions based on the recognition of reliable precursors.

Most, but not all, upwelling areas exhibit strong seasonal variability related to the onset of a seasonal wind field such as the monsoon. However, the pattern of a simple cause and effect mechanism may be disturbed locally by coastal orography and differential heating over land and sea.

To make a detailed study of the long-term relationship between wind field and temperature differences, the European Communities Research Centre in Ispra selected the northwest coast of Africa and accumulated satellite imagery and wind data over the 10-year period 1981-91. A total of 3400 satellite images were processed to generate charts of sea surface temperature variations. To make more quantitative comparisons with wind fields a 'coastal upwelling index' was defined as the temperature difference between coastal water and water further offshore at the same latitude. The actual positions of ends of the line over which the index was calculated were a point mid-shelf between the coastline and the 200m depth contour, and a position chosen arbitrarily 500km offshore from that point.

Wind data were made available by the European Centre for Medium Range Weather Forecasts in the UK. Spatial resolution is between 1^0 and 2^0 of both latitude and longitude.

Using an approach similar to the temperature data, an upwelling index based on the Ekman transport perpendicular to the mid-shelf line, was calculated for the wind.

There is a clear relationship between wind and upwelling. There also appears to be a time-lag of up to a month depending on latitude. This is the sort of study derived from satellite data, that must be carried out over other coastal areas in order to move towards reliable prediction models which should benefit the fishing industries of many nations in the tropics.

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 today can be dated from the beginning of the century when the American rainbow trout was imported and cultivated intensively in various parts of Europe.

Aquaculture as an industry is now growing considerably faster than traditional capture fisheries. There are few under-utilised fishery resources

available to the world today and as per the 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 million tonnes - 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 tonnes 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 exploration 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:

- 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 and human settlements

Almost all of the data required can be obtained from satellite observations and, in some cases, satellite data 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 of 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 the final site selection is made.

Potential Benefits of Information Derived from Satellites

Capture Fisheries: Temperate climate

Since there is usually no direct correlation between surface features in Northern Europe 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 to detect intruders, but this would require the force of international law to place identification transponders on every ship.

Capture fisheries: Tropical Zones

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 Climate

The industry has taken a firm hold in many parts of Europe 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. Neither can we 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 against which environmental trends may be detected. At the same time satellites may be able to warn against the onset of harmful algae blooms of the type which moved up the Norwegian Coast from the Scaggerak in 1988 threatening salmon stocks.

Aquaculture: Tropical Zones

It is not always appreciated that 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 UN Food and Agricultural Organisations (FAO), models based on Geographic Information Systems, incorporating the information listed above, 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.