APPLICATIONS OF SATELLITE REMOTE SENSING OVER THE MEDITERRANEAN SEA

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Foreword

For many centuries the Mediterranean Sea has played a significant role in the affairs of Europe, but at no time has attention been focused more strongly than at present. The shorelines of two founder members of the Community, France and Italy, encompass much of the western basin while Spain, the third of this triumvirate, is a more recent recruit as is Greece, which stands sentinel over part of the eastern basin.

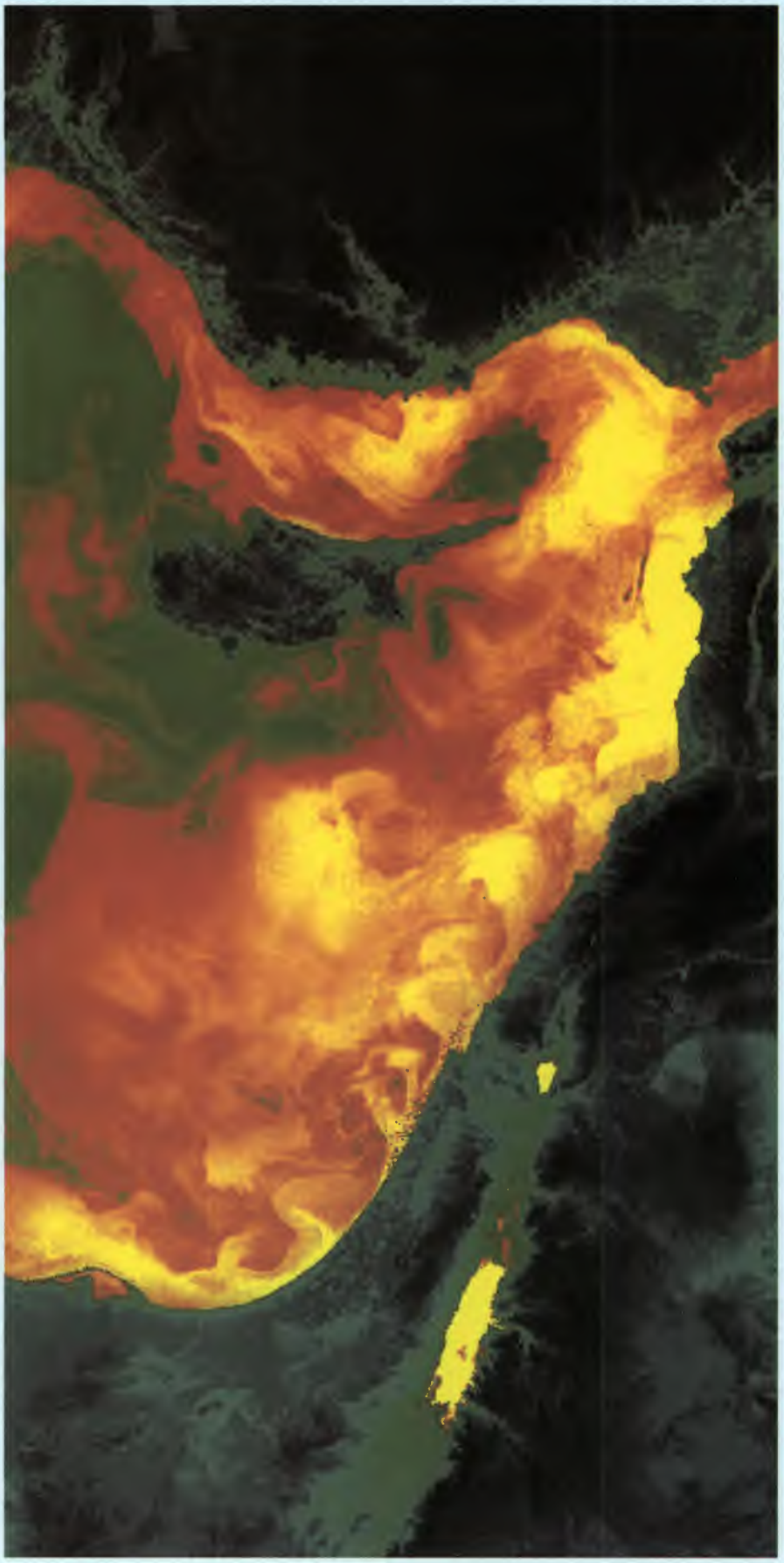
A natural beauty and warm climate combine to attract more and more people to its shores each year placing a considerable strain on an eco-system already in the balance. For human activities profoundly affect the health of the sea. Cities grow larger, traffic increases – in the air, on the roads, and at sea. Fisheries are strained beyond levels that can be sustained and some species are in danger of disappearing altogether. The search for offshore resources continues. And we need no reminding that recently the area has seen more than its share of human conflict.

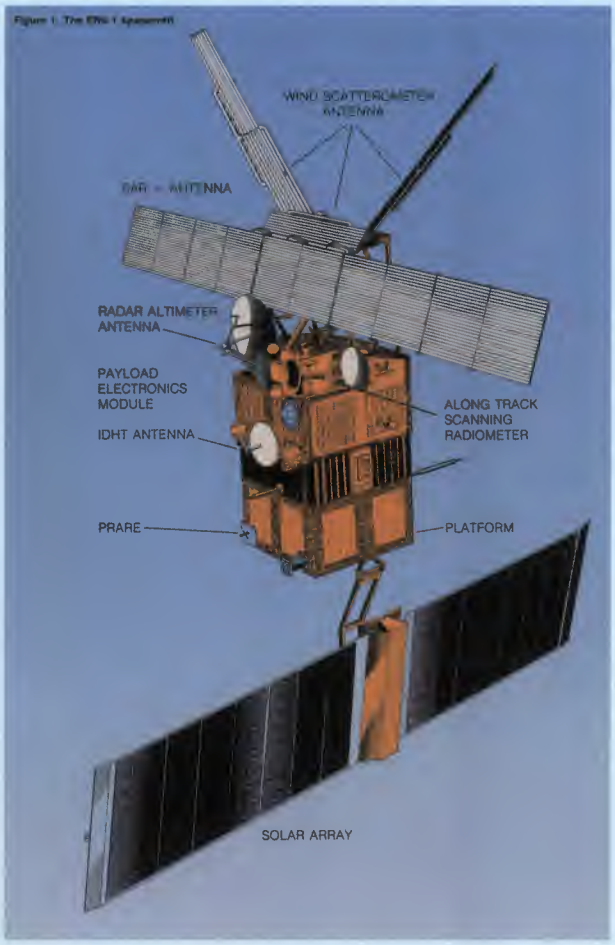
More than ever, a watchful eye is required. National agencies maintain a careful guard over there own coastlines – but a more global perspective has been difficult to achieve. Is the level of pollution within individual Mediterranean basins increasing? Or, are the agreements drawn up between most of the bordering countries under the auspices of UNEP's Mediterranean Action Plan acting as a deterrent to potential polluters? There is no unequivocal answer.

One powerful tool now at the disposal of the Mediterranean community is remote sensing from global orbiting satellites. The European Space Agency has already launched two major spacecraft designed primarily to monitor the state of the sea surface. Others from America, France, Canada, Japan, India and Russia are also in orbit around the earth or about to be launched. What can they tell us about the Mediterranean marine environment? At a time when the European Commission is increasing its own role in satellite programmes by funding co-operative investigations into the development of applications, and setting up a Centre for Earth Observation based on a network of European data bases – and now that the European Space Agency is moving closer to designing satellites to monitor the coastal environment, this booklet sets out to examine that question.

E Cresson
Commissioner of the Science & Technology Directorate

INTRODUCING SATELLITES





The ERS-2 Spacecraft.

The Emergence Of Earth Observation

Earth observing satellites have been circling the globe for over three decades. The early spacecraft were designed to generate high-resolution imagery of land surfaces, and today the US Landsat, the French SPOT, and the Japanese MOS satellites continue to provide information that finds many useful applications around the globe. Resolution is down to about 10 metres and programmes underway aim to develop a sensor with a 1m resolution.

Satellites designed specifically for ocean use took longer to emerge. Rapid progress was made throughout the 1970's, however, culminating in 1978 - a vintage year for ocean surveillance satellites. For in that year were launched:

Seasat - equipped with a suite of microwave sensors designed to measure sea state day and night, whatever the cloud cover

Coastal Zone Colour Scanner of Nimbus-7 - which continued to provide global images of changes in ocean colour for over 7 years

NOAA's Advanced Very High Resolution Radiometer (AVHRR) - a system still operational today providing images of sea surface temperature accurate to about 0.5°C.

Fucino Space Centre, Italy.

The 1980's was a time of consolidation - a time of planning future systems based on the experience of the past - a decade of decision which saw NASA, ESA, France, Canada and Japan announce plans to launch dedicated marine satellite systems.

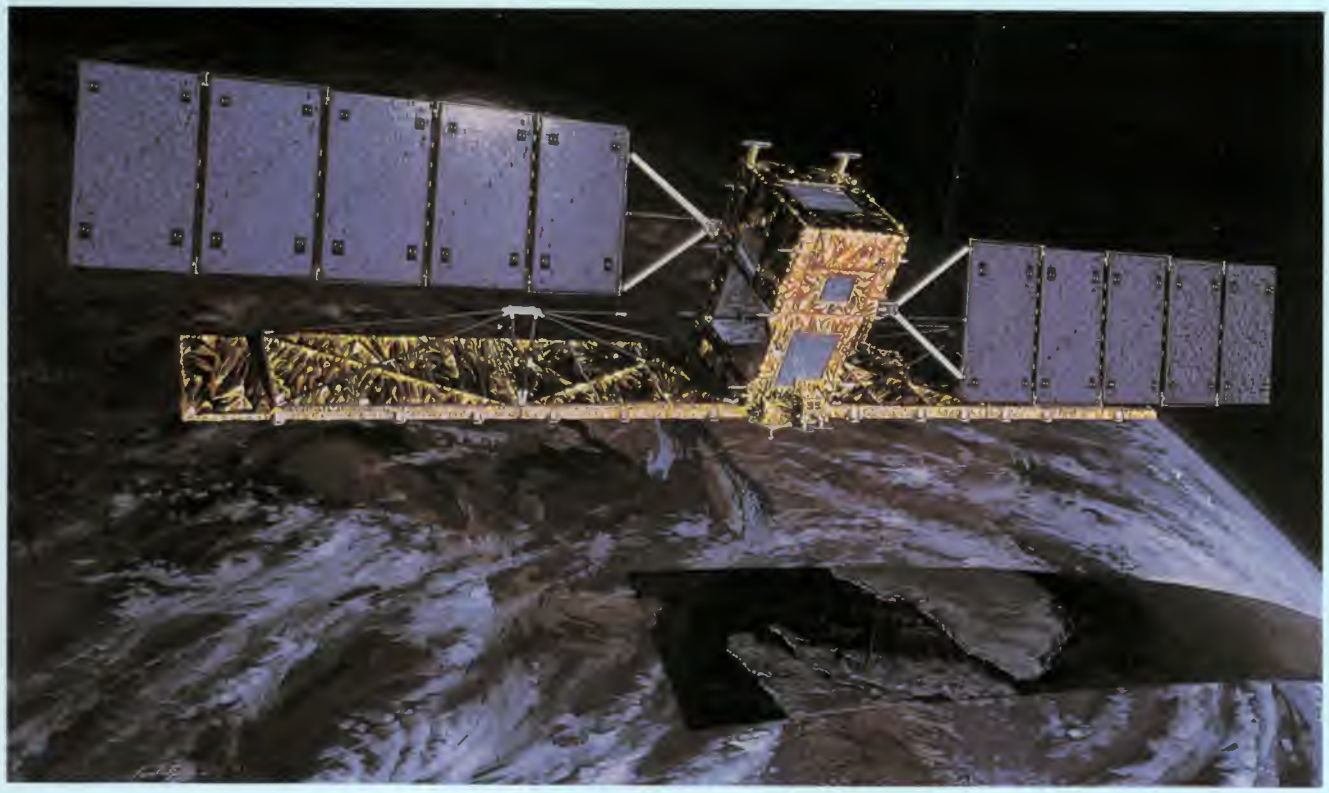
In addition, the introduction of the French Argos system for tracking buoys - collecting and disseminating their observations - made global studies of ocean behaviour possible without having to leave the laboratory. Satellite data collection systems based on the geostationary Meteosat, GOES and GMS are also used to collect and disseminate data from moored buoys and fixed coastal stations.

The fine resolution multi-band radiometers of Landsat and SPOT were designed primarily for land applications but their imagery 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.

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 30 years ago which revealed the tectonic patterns of the solid earth.

Artist's view of Radarsat, a Canadian remote sensing satellite.



Laser tracking station at Matera.

The CNR Oceanographic Research Platform off the Italian coast, near Venice. This platform was the main reference for sea-level determination during the calibration/validation phase for the ERS-1 altimeter.

The View From A Satellite

In many respects the sea surface on which research vessels are constrained to operate is not ideal for studying ocean processes. Conventional measurements often fail to reveal the large-scale phenomena of regional and global behaviour demonstrated in the synoptic view from a satellite. What makes satellites so valuable is this perspective coupled to their phenomenal global coverage. Polar-orbiting satellites complete an orbit of the earth in about 100 minutes depending on their operating altitude. At a height of 800km they travel at speeds of about 7km/s and complete 14 1/3 orbits per day. Once launched they can stay up for many years. The first satellite of the European Space Agency, ERS-1, was designed for a 3-year operation but when its successor, ERS-2, was launched from Kourou in French Guiana on April 21 1995, ERS-1 continued to work well.

If the great strength of satellite surveillance of the oceans is their unsurpassed coverage of all parts of the globe, their limitations must also be recognised.

Satellite sensors are designed to measure surface colour, temperature, roughness and slope; any ocean feature to be monitored from an orbiting satellite must produce a signature in one of those four basic parameters. Thus, wind, waves and surface slicks will change the pattern of small-scale roughness to which radars are particularly sensitive; patches of phytoplankton produce detectable changes in ocean colour; the surface slope over a geostrophic current can be accurately measured by a precise radar altimeter; and shifting temperature patterns are revealed by scanning infra-red devices.

These measurements can make a significant contribution towards a clearer understanding of physical, biological and geological processes that occur within the sea. When the first satellites were being designed, space engineers were well aware of the limitations that had to be overcome. Sensor accuracy, it was believed, could not compete seriously with 'in situ' observations. Satellites viewed only the surface of the sea and saw little of the deeper processes. Cloud covers much of the earth for much of the time preventing sensors operating in the visible or infra-red part of the spectrum from viewing the sea surface. And, of course, rapid sampling cannot be made from a solitary, earth-orbiting satellite.

These limitations exist today but since the launch of the first ocean satellite it has emerged that they can also be overcome or, at least, reduced. As we shall see one of the earliest revelations in the satellite record was that processes in the volume of the sea could produce a signal at the surface detectable from space. In shallow

The ERS-1 solar array.

A night-time launch of Ariane.

coastal zones imaging radars revealed details of bottom topography. Over the deep ocean the level of the sea surface was also revealed to rise or fall according to the depth of water. Thus submarine ridges, canyons and the like showed up clearly on the record of the satellite's precise radar altimeter.

Indeed, the precision of satellite sensors now surpasses that achieved by conventional 'in situ' methods. The altimeter on Topex/Poseidon measures its own height above the sea surface to better than 5cm. The synthetic aperture radar has achieved a spatial resolution of about 25m. Changes in sea-surface temperature of a few tenths of a degree are detectable with the Along Track Scanning Radiometer flown on ESA's twin spacecraft. And surface wind velocities over the sea can be measured over 50km cells to an accuracy of about 2m/s in speed and 20° in direction.

The height, direction, and period of waves can be monitored more reliably from satellites than through the sporadic, uncalibrated estimates made by human observers at sea. And the very small slopes produced by ocean currents on a rotating earth, which cannot be measured directly at sea, were tracked by a precise radar altimeter designed for that purpose.

Changes in chlorophyll concentration can be detected by satellite-borne colour sensors and - especially where these are brought on suddenly by an upwelling of nutrient-rich deeper water around the coast - the imagery has proved useful in directing fleets to fishing grounds. High-resolution radars have provided images of river plumes, effluents, oil spills and ships.

The changing patterns of sea surface temperature can be mapped routinely from orbiting satellites to reveal details of ocean dynamics and heat transport mechanisms which will aid climate studies.

When radars are not deployed the greatest constraint to achieving regular coverage remains cloud cover. Although some progress has been made in looking obliquely in more than one direction to find gaps in the clouds, their presence is still extensive enough over many parts of the globe to preclude adequate cover by satellite-borne infra-red and colour sensors. Fortunately, the Mediterranean skies are clearer than some and, as shown on those pages, useful repeat measurements can be built up. There is, however, a genus of marine studies which absolutely require for their solution that measurements be repeated at regular intervals. Only radars can give this guarantee.

The number of dedicated marine monitoring satellites has increased considerably since the launch of NASA's pioneer spacecraft, Seasat in 1978. Canada, the USA, the European Space Agency, France, Japan, Russia, India and others have all launched satellites designed to look down at the sea surface. More are promised. If the large volumes of information generated by so many satellites are to be put to the best use, both in improving our scientific understanding of marine processes and in providing the greatest benefits to on-going activities in the public and private sector, it is important that all potential applications are visited and an assessment made of the present state-of-the-art.

This booklet is an attempt to do that for one of the most important of Europe's seas and certainly one of the busiest - the Mediterranean. Over this land-locked basin we have made a conscious effort to illustrate one of the great strengths of polar-orbiting satellites - their unique ability to repeat observations at regular intervals so that changes from month to month or year to year may be detected.

THE MEDITERRANEAN - A BRIEF REVIEW

Multitemporal ERS-1 SAR image off the Northern Adriatic with Venice and the Po delta. Three images taken on different days have been combined to produce this colour product. Changes in surface roughness produce differing image intensity for the different dates, which show up as colour in this composite image. Areas corresponding to no change appear as shades of grey.

High tide in Venice produces floods in St Mark's Square.

Seasonal average of planktonic pigments measured by the Coastal Colour Scanner. This image portrays Autumn 1985. The reader can follow the evolution from season to season and year to year by flicking through the brochure from page 58 which starts with Spring 1980 (courtesy Joint Research Centre, Ispra).

Boxing fresco, one of the many buried under a thick layer of pumice after the 1500 BC eruption on

Salt drying at Lanzarote, Spain. Sea salt is produced by flooding the salt pans and leaving the water to evaporate.

Mare Nostrum

The Mediterranean - centre of the earth, cradle of civilisation - holds a unique place in our collective consciousness. Although it occupies an area no more than 7% of the total area of oceans in the world, its influence on human behaviour and world events belies its modest size. The name is applied not only to the sea but to the area around it, its people, vegetation, climate, countries - and way of life.

Its 2.5 million square kilometres encompass a number of separate basins which, though they cannot match the depths of its larger neighbours - the Atlantic and Indian Oceans - are still considerably deeper than the shallow, shelf seas encircling other parts of Europe. Apart from the Gulf of Lyons its continental shelves are comparatively narrow accounting for less than 20% of the total area and 1.5% of its volume of water.

Its maximum length from Gibraltar to Syria is 3,800km and its maximum width from France to Algeria no more than 900km. The Mediterranean is connected to the Atlantic via the Strait of Gibraltar which is 15km across and 290m deep. Its only other connections with neighbouring water masses is via the Dardanelles/Sea of Marmara/Bosphorous to the Black Sea, and through the Suez Canal (120m wide, 12m deep) to the Red Sea.

The Mediterranean is dotted with islands - especially in the Eastern basin. One is never more than 370km from the coast, 50% of the time less than 100km.

The Sea is divided into 2 major basins - Western and Eastern - separated by the Strait of Sicily which is 35km wide. Each basin is sub-divided into a number of provinces. In the west, the Alboran Sea acts like a funnel, through which the surface Atlantic water flows. The Algero-Provençal (or Balearic) Sea lies to the west of Corsica and Sardinia connected in the north to the Ligurian Sea and in the south to the Tyrrhenian Sea via the wide channel between Sardinia and Sicily. The deepest part of the Tyrrhenian lies at 3500m; the other basins reach depths of 2500m.

The Eastern Mediterranean is more complicated. Here the four main sub-regions are the Adriatic, Aegean, Ionian and Levantine. The Ionian averages 3500 - 4000m in depth with the deepest part reaching over 5000m (measured to reasonable accuracy by the Ancient Greeks).

The Mediterranean Sea.

The Adriatic is connected to the Ionian by the Strait of Otranto with a width of 75km and sill depth of 800m. To the north lies an extended continental shelf.

The pattern of water circulation in the Mediterranean, and its overall water budget, are markedly different from most of the major oceans, maintaining a delicate balance and constantly varying response to inflow from the surrounding river systems, evaporation to the atmosphere, seasonal swings in winds blowing over the sea and a complex bottom topography.

The Sea loses by evaporation almost three times as much water as it receives through rainfall and runoff and this potential imbalance is compensated by a constant flow of water from the Atlantic. As the main flow travels eastwards from the Strait of Gibraltar it loses momentum and is warmed by the sun. Evaporation causes salinity to increase and the constant increase in density carries the water to greater depth. In winter, cold winds from the north may cool the surface waters sufficiently to cause additional sinking to greater depth. The denser water of the deeper layers then flows steadily back towards the Strait of Gibraltar where it eventually spills out over the sill into the Atlantic. It is now, of course, considerably more saline than the eastern Atlantic water and can be traced northwards for a long way.

As we shall demonstrate in what follows the surface of the Mediterranean displays a rich canvas of sharply contrasting features. The patterns of eddies, ocean fronts, gyres and slicks revealed by the sensors carried on the first satellites to look down on the earth were more striking over the Mediterranean than over most other sea surfaces across the globe. The scientific community that had studied the sea for centuries and devised theories to explain its basic behaviour was forced to the inevitable conclusion that the processes at work were more complex than had been believed.

Summer 1985

Brief History

The fossil record shows the Mediterranean to have undergone substantial upheavals in the past. The Strait of Sicily acted as a land bridge and the remains of mastodons and other prehistoric creatures have been identified on the island of Malta. The Strait of Gibraltar regularly closed and opened again.

The historical record of civilisations around the borders of the Sea indicate that significant changes in sea level have occurred. The ancient port city of Carthage is now far removed from harbour facilities. Along the Versilia coast in Tuscany the towns of Carrara, Pietrasanta and Massa required marinas to be built to keep them trading. By contrast on the eastern seaboard of Italy, Venice is known to be sinking. The eustatic changes throughout the Mediterranean in the last 2,000 years are thus still in evidence today - and this has little to do with sea level changes brought on by global warming.

A diver brings a first-century BC Greek amphora to the surface near the island of Corfu, Greece.

The mild climate of the Mediterranean region encouraged human settlement and a succession of cultures grew up on its shores. The calm waters and steady winds (over most of the year) made seafaring relatively easy and the indented coastline and many islands provided natural harbours and ports.

The Egyptians were the first important influence in the region around 3100 BC, whilst the Minoan civilisation on Crete, which followed shortly after, grew to be the most advanced in Europe. The Helladic civilisation on the Greek mainland, often referred to in later stages as the Mycenaean civilisation, after one of the Helladic cities, had widespread influence: by 1450 BC Mycenaean ships controlled the Mediterranean, trading with cities in present-day Lebanon and Syria.

The Phoenicians then came to prominence from 1200 BC, sailing from their homes on the eastern shore to all parts of the sea, even through the Strait of Gibraltar to the Atlantic. Legend has it that they learned to dip their sails into the outflow of Mediterranean water in the Strait to assist their passage, thus establishing an early knowledge of the counter current.

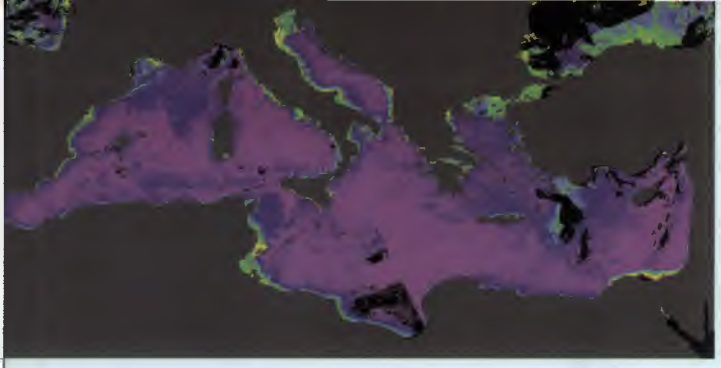
Today, there are 20 countries bordering the Mediterranean: Spain, France, Monaco, Italy, Croatia, Bosnia, Serbia, Albania, Greece, Turkey, Cyprus, Syria, Lebanon, Israel, Egypt, Libya, Tunisia, Malta, Algeria and Morocco. The importance to them of their Mediterranean coasts varies considerably. All use the Sea as an important resource (chemicals, oil/gas, fishing, tourism), for transport, as a site for urban and industrial development, and as a dumping ground for waste materials.

Natural Processes

The natural forces that act on the Mediterranean Sea, and on the land masses that contain it - geological, climatological, oceanographic and biological - combine to produce an area of many contrasts. The hot, arid climate of African shores is markedly different to the climate over much of Italy, Spain and the South of France. The Mediterranean area is geologically young and tectonically active causing rugged mountain ranges to form a shield around most of the Mediterranean rim. In several coastal resorts in France and Italy the ski-slopes are within an hour's drive. This topography plays a key role in the local meteorology, channelling the winds blowing over the sea into a number of pre-set directions.

The area represents a meeting of continents, its structures trapped in the vice of an African plate closing inexorably on Europe. The several volcanoes - some active, others now passive, and the many earthquakes throughout Italy, Greece and Turkey bear testimony to the tectonic instability of the area.

Shuttle image of the Aegean Sea.



Spring 1985

Much of the floor of the Western Mediterranean is underlain by a stratum of evaporites - mostly rock salt - which, in places, reaches a thickness of almost 1km. The floor of the Balearic basin is pitted with knolls, which closer examination has revealed to be salt domes similar to those discovered in the Gulf of Mexico. Such a layer of salt was formed by evaporation when the water depth was considerably shallower than present-day levels.

The circulation of the Sea is a result of the fine balance maintained between a number of factors - Atlantic water flowing in through Gibraltar like an ever-open tap, run-off into the sea from an intricate drainage network linking the rugged terrain to the coast, evaporation from the surface, and the return flow of Mediterranean water into the Atlantic after a sojourn of about 80 years.

Shuttle image of the Strait of Gibraltar.

In more ways than one the Mediterranean character undergoes violent swings. Its water, for example, can reach 25°C in the summer and cool to 12°C in the winter. By contrast, the Caribbean, of comparable size but lying further to the south, maintains an almost even surface temperature throughout the year. No parcel of water in the Mediterranean - from the surface to several kilometres deep - is colder than 12°C so that in the winter the cold winds blowing off the Maritime Alps can cool the surface water to an extent that the delicate balance of density is upset, the surface waters become marginally heavier than the rest of the supporting column of water, and a dramatic overturning can occur.

The Sea lacks the nutrient concentrations found in the waters of the neighbouring Atlantic. To an extent, the more nutrient-rich deeper water of the Mediterranean which passes out to the open Atlantic represents a gain for the ocean at the expense of the sea. Periodically, due to a combination of meteorological and oceanographic events, the more nutrient-rich deeper water is brought to the surface through upwelling - an event which can so increase the surface concentration of chlorophyll that its extent can be clearly delineated by satellite-borne colour scanners as shown in the illustration of the Gulf of Lyons.

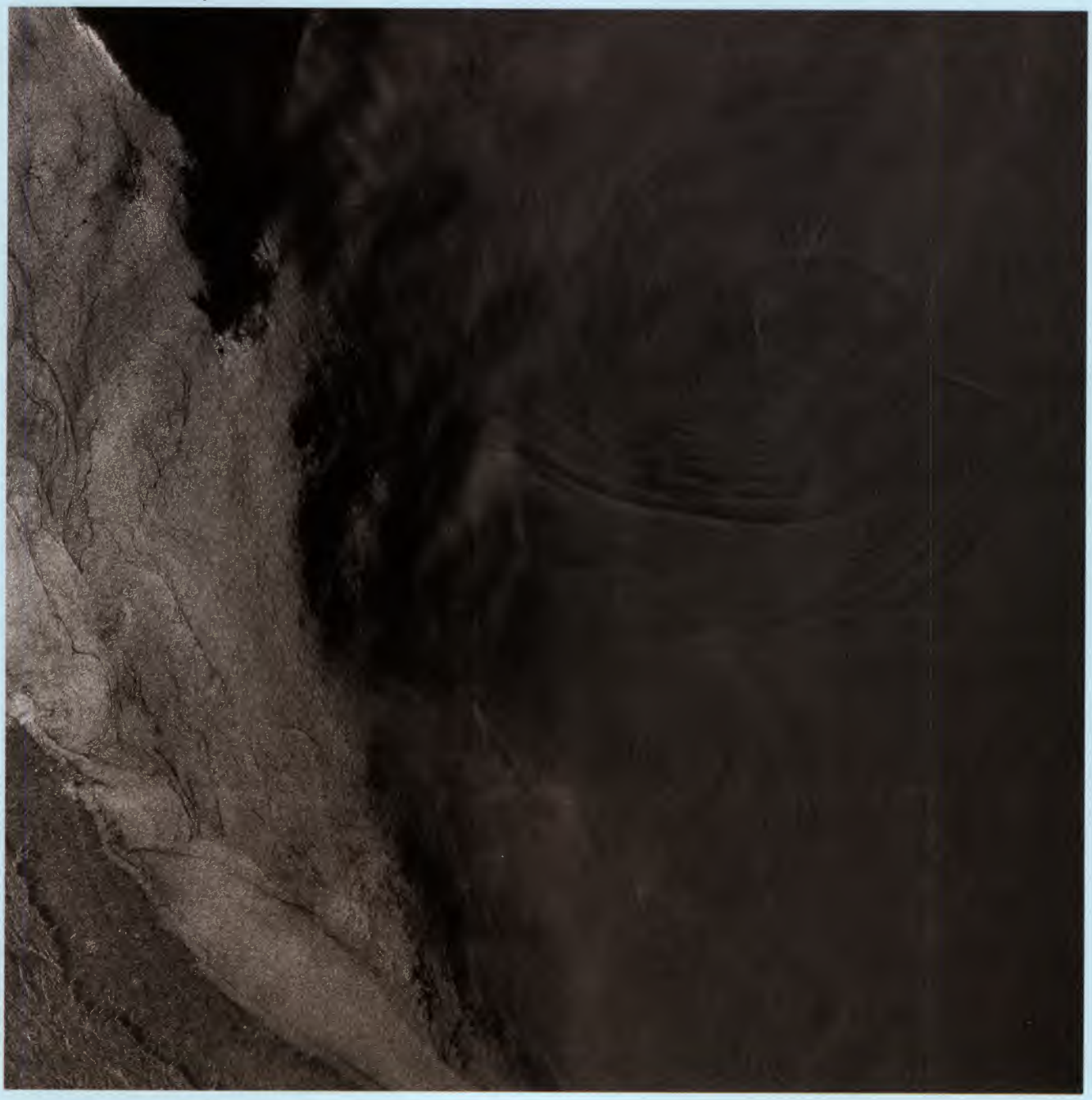
The vegetation to be found around the Mediterranean is a product of its unique climate. It is the rapid drop in rainfall and rise in temperature from north to south that transforms the comparatively fertile lands of eastern Italy to the barren deserts of North Africa in less than a thousand kilometres.

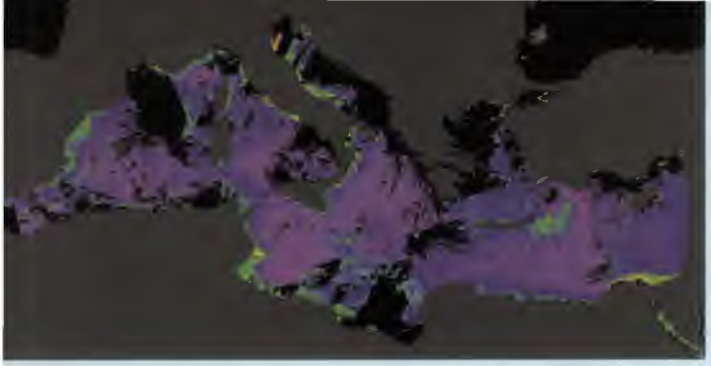
The small trees and shrubs to be found throughout France, Italy and Spain (and known respectively as *maquis, macchia* and *mattoral*) make best use of the seasonal rainfall and form the natural vegetation of the Mediterranean - or, at least, the European part.

The surface of the Mediterranean Sea displays a rich diversity of features the true extent of which was not fully appreciated until the advent of satellite remote sensing. The sea represents a tapestry of natural slicks produced by eddies, by 'internal' wave trains or by biological/physical interactions. These intricate patterns can often be spotted by the naked eye from the comfort of an aircraft seat at 10,000m. But it was left to satellite sensors to reveal their true extent.

If the natural processes acting on the sea are more than a little complex, the activities of the 400 million people living in the area introduce their own effects - many of which are potentially harmful to the environment, and for many years now international consortia of the countries that ring the Mediterranean have sought agreements on how to legislate to reduce the damage.

ERS-1 SAR image of internal waves in the Adriatic Sea on 14 July 1993.





Winter 1985

Human Influence

The environmental pressures exerted over many parts of the earth as a result of human exploitation are felt particularly keenly in the Mediterranean region. While the natural processes that shape the area's unique environment are capable of violent extremes that create their own hardship, it is the balance between the exploitation of natural resources and unacceptable damage to the environment that causes increasing concern. Can such a small, semi-enclosed basin support all that humans throw at it?

Most of the Mediterranean is over-fished and stocks in some parts are dangerously depleted. While, again, this is a problem of almost universal concern, Mediterranean waters are already depleted in nutrients compared to other seas. Little over 1% of the world's total catch of fish is taken from the Mediterranean. Yet the demand increases each year due in large part to the steady increase in the number of tourists. This demand so much exceeds supply that in terms of value, Mediterranean fisheries account for as much as 5% of the world's market. High prices increase the pressure to catch more fish from stocks already depleted.

Effluents from the river Po are clearly seen in this Shuttle image.

Tourism is a major source of revenue to the countries surrounding the Mediterranean.

Aquaculture is growing. Although some of the very earliest records of fish farming refer to ancient Egypt and subsequently to Roman times, the industry was revived recently following the lead given by Northern Europe. It is still fairly modest, however. One of the problems is finding suitable space along coastlines already crammed with holiday resorts and marine leisure centres.

The commercial trading of 20 countries is reflected in the Mediterranean ship traffic. Some 200 vessels pass through the Strait of Gibraltar every day. The region supports about 200 ports in all, although fewer than 10% of those account for 90% of the total transport of goods.

Dense ship traffic leads inevitably to accidents and spillage incidents. Lacking the flushing tides of the great oceans, the Mediterranean is particularly vulnerable to the effects of spills, and many marine ecosystems are placed at risk. Estimates of how much oil finds its way into the sea vary considerably since few ships admit to deliberate dumping. Of the 200 million tonnes carried through the Mediterranean each year, a modest estimate puts the amount spilled at 300,000 tonnes. Certainly, since the introduction a few years ago of more regular surveys of the area by the radars carried on ERS-1 and ERS-2, the images reveal a sea surface frequently streaked with oil.

Pollution is not confined to oil. Large scale outflows from both domestic and industrial sources are seriously affecting the coastal environment of the western Mediterranean. The introduction of toxic materials, together with organic pollutants contained in domestic sewage, can poison coastal aquatic life and starve it of oxygen. Much of the sewage entering the Mediterranean is untreated.

Pollution was recognised as a potentially serious problem in the 1970's. In 1976 a treaty was signed by most nations bordering the Mediterranean aimed at reducing the levels of pollution. Other treaties and action plans have followed, mostly sponsored by the United Nations (UNEP), with the European Union playing an increasingly important role.

Oil washed up on a beach.

The UN-sponsored Mediterranean Action Plan led to a treaty signed by all but one country in 1980 with the primary aim of eliminating chemical discharges and fostering a greater hope of co-operation in cleaning up tanker spills.

Despite the will of those countries to reduce hazards, pollution remains a major threat. Some 30% of all tourists in the world head for the Mediterranean. Each year 150 million take up temporary residence - the great majority in coastal resorts. The number is rising rapidly and many coastlines, along the South of France and the

Autumn 1984

Costa Brava for example, are already fully developed. There is no room left. Such an influx clearly has an enormous impact on water consumption, sewage, and directly or indirectly, on coastal eco-systems.

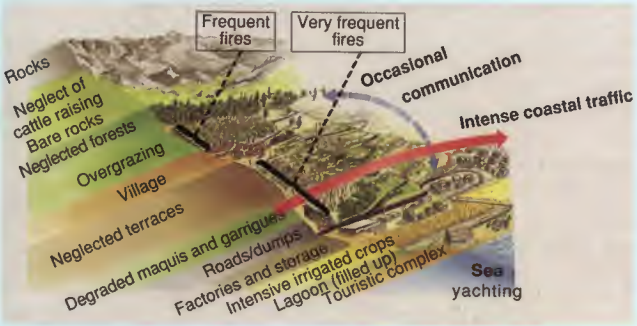
Islands are particularly vulnerable. For many, tourism has become the main industry. Hotels, marinas, restaurants, bars, and airport expansion schemes have developed very rapidly and are placing an extra strain on an environment with no room to expand. In many resorts the sewage system is barely adequate for the local population, let alone the huge influx of tourists. In Malta it is estimated there is one vehicle for every 9 metres of road!

Of a total population of 400 million in Mediterranean countries, 150 million (38%) live in the coastal area. Witness the rate of growth in the post-war era of such cities as Alexandria, Algiers, Athens, Barcelona, Beirut, Genoa, Izmir, Marseille, Naples, Rome and Tunis. The greatest increases are in the south. Cairo has a population of 12 million.

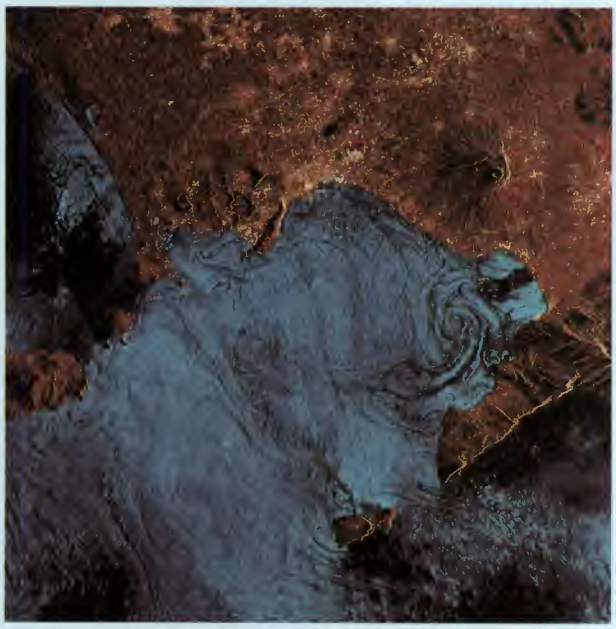
Some years ago Sarah Arenson, author of *'The Encircled Sea'*, wrote:

> *"The civilisations which have evolved on its shores shaped the history of mankind. Since pre-historic time the relationship between man and the sea has been stronger around the Mediterranean than anywhere else. For this reason the Mediterranean may serve as a living laboratory, in which new ways of understanding and furthering that relationship can be developed"*

The emphasis today is on tempering economic growth with environmental responsibility. Coastal management is more vital than ever before, and modern spacecraft can make an important contribution. A new era may be about to dawn.



The changing use of the Mediterranean coastal zone (upper). The traditional Mediterranean slope of today (lower).



Multi-temporal SAR image of the Bay of Naples. See caption Page 11 for explanation of tints.

Physical Description

Vegetation

Mediterranean agriculture is characterised by multi-faceted crops but, increasingly, irrigation is required in the south to maintain or increase crop production. Coastal regions tend to have little agricultural land but, what there is, is often of high quality, particularly around deltas.

In the north more efficient farming and growing urbanisation is leading to increased abandonment of farmland with a corresponding advance of forests. This is in contrast to the south and east where marginal areas are being cleared for grain production. Lack of rain and the lack of continually flowing rivers has restricted the use of irrigation, however, and one result has been increased desertification in North Africa and the Near East.

The Mediterranean climate has favoured the development of unique forms of vegetation. Small trees and shrubs with small thin leaves, deep root systems and thick bark make best use of seasonal rainfall and are protected from the high temperatures and drought in summer. It is the cultivation of the larger trees - especially the olive - which has led to calls for high-resolution monitoring from satellites to act as a control to the EC's agricultural policy.

Geomorphology

Until the 1960's when the theory of plate tectonics was used to explain the formation of the Mediterranean (and much else besides) it was considered to be a remnant of the ancient Tethys Sea but studies since the 70's suggest that the sea floor is not old enough to be part of Tethys.

Because the Mediterranean is geologically young, there is a close interpenetration of mountains and sea. It boasts few large plains, good agricultural land is comparatively sparse (it is not self-sufficient in food), and many ports and harbours are tightly hemmed-in between sea and rock.

Except for the Egyptian and Libyan coasts the whole of the Mediterranean is almost entirely surrounded by mountains. In the north we find the Pyrenees, Alps and Apennines, with the Balkan and Anatolian mountains in the north-east. In the south west the Atlas mountains form a barrier. The coast along the south-eastern shore is desert, however, with no barrier to affect the air flow. This imbalance in the geomorphology is an important factor in determining the ecology of the Mediterranean region.

Summer 1984

Negative gravity anomaly in the Eastern Mediterranean.

The main rivers are the Ebro, Rhone, Po in the north while the Nile is the only comparable river in the south, but since the building of the Aswan Dam, its outflow to the sea is very much diminished. They are responsible for draining geological terrains far from the present coastlines and account for the transport of 50 million tons of sediment annually. There is also a large number of shorter, often torrential rivers along the mountainous coasts which drain small areas, usually on a seasonal basis.

In the 1960's and 70's several ships - including American and Russian research vessels - embarked upon geophysical investigations of the Mediterranean. The measurements of gravity which revealed the large negative anomaly over the area separating Crete from North Africa were made in conjunction with measurements of magnetic field and sea floor topography. They employed fairly large, stable ships to minimise accelerations and good navigation was required to calculate the effect of the ship's motion on the gravity reading. Surveys over a limited area with a reasonably close spacing between adjacent tracks could take months to complete.

Thirty years on, satellites equipped with precise altimeters to detect very small changes in sea surface level were covering the length and breadth of the Mediterranean at ground speeds of some 7km per second. In less than 6 months in 1994-95 the satellite ERS-1 of the European Space Agency surveyed the whole of the Sea - not to mention the rest of the world's oceans - at a spacing between adjacent tracks of around 10km. Accuracy and spatial resolution between satellite and ship surveys were comparable.

Main rivers draining into the Mediterranean Sea.

Autumn view of the Apuan Alps, Italy.

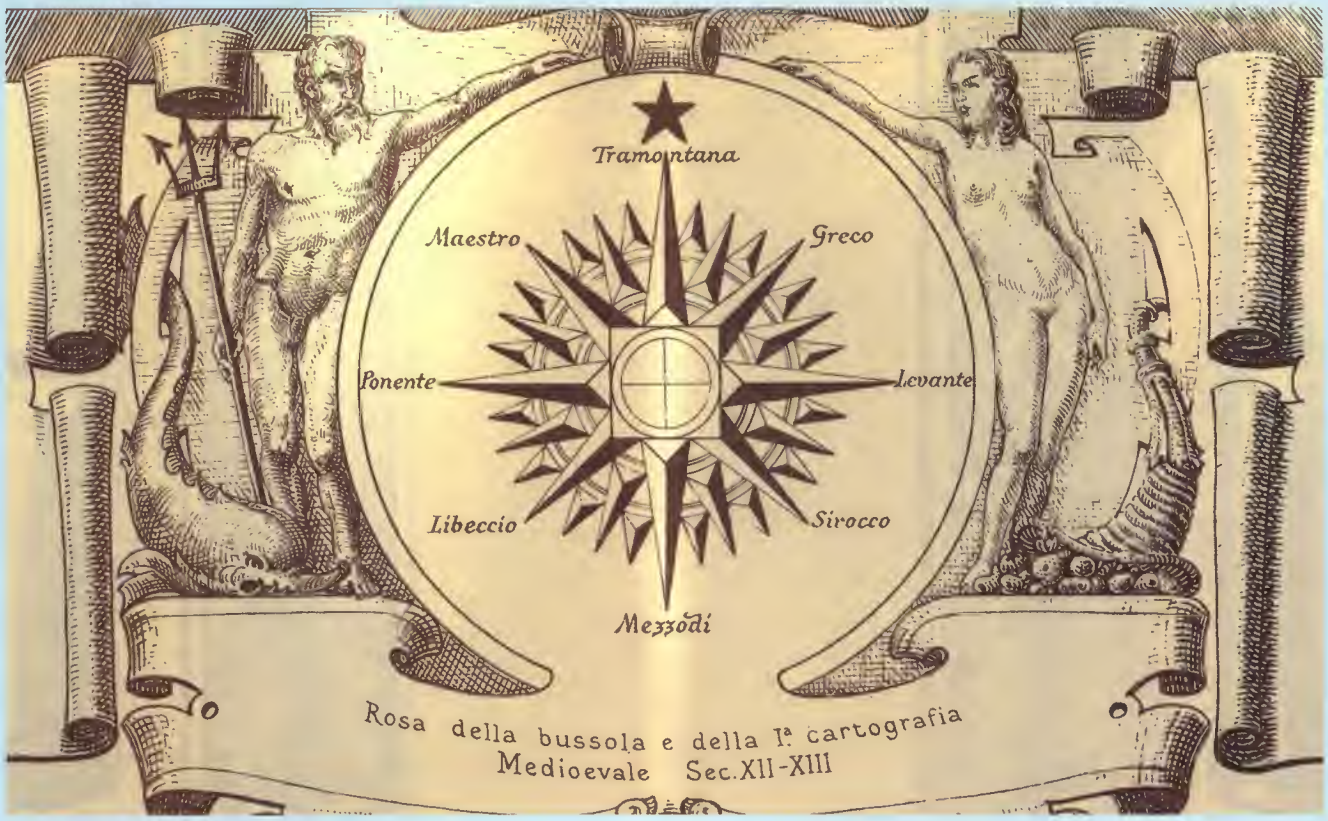
Earthquakes occur frequently throughout the region particularly in Greece and western Turkey. Several of the many islands are of volcanic origin and some volcanoes are still active including Stromboli, Etna and Vesuvius. The damage and casualties caused by each destructive earthquake in the region reinforce the resolve of scientists and politicians to seek ways of increasing our understanding of these natural forces to the point one day of possibly predicting their occurrence. That day may still be a long way off but the recent ability of satellites to detect very small movements of the earth's crust through interferometric patterns generated by juxtapositioning radar imagery of the same site is opening up a very promising line of research.

Climate

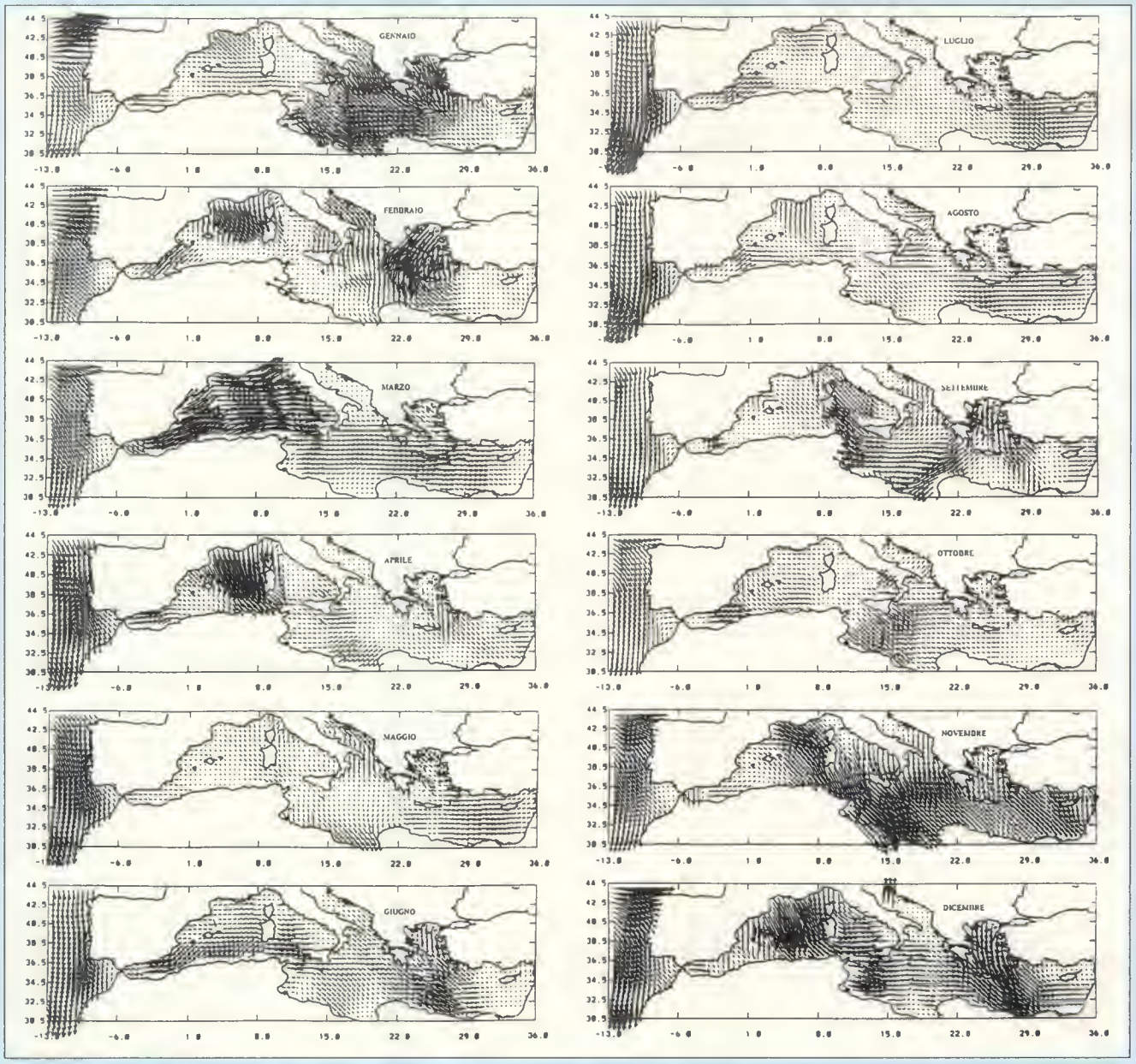
Since the Mediterranean area attracts more tourists to it than any other area in the world the climate - as well as the food and the wine - must count as one of its attractions. But what do we mean by a 'Mediterranean climate'? A scientific definition is simply an area in which winter rainfall is more than three times summer rainfall.

Most of the Mediterranean satisfies this definition. In fact, over much of the region the summer rainfall is practically zero. The Mediterranean is also a transitional area climatically with the temperate, damp climate of the north in marked contrast to the arid conditions of the south. The disparity in the amounts and occurrences of precipitation is influenced by the topography of the land and the climatic conditions of the area.

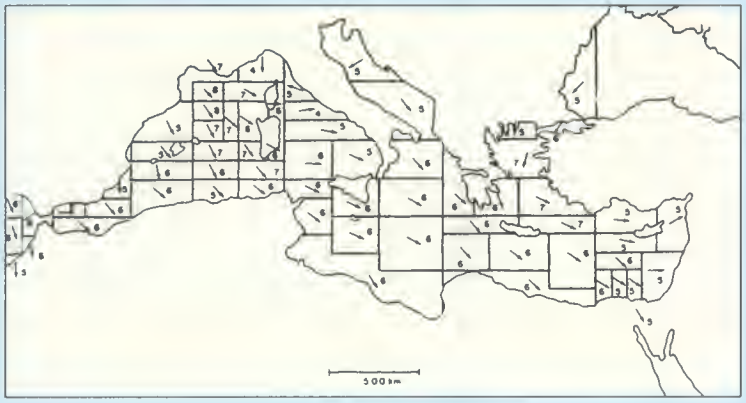
Mediaeval compass rose showing regional wind directions.



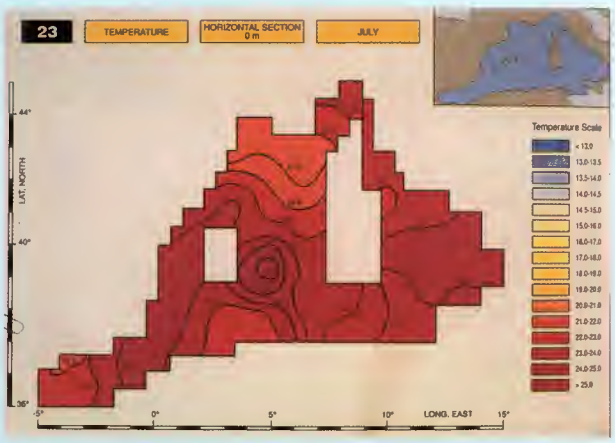
Spring 1984



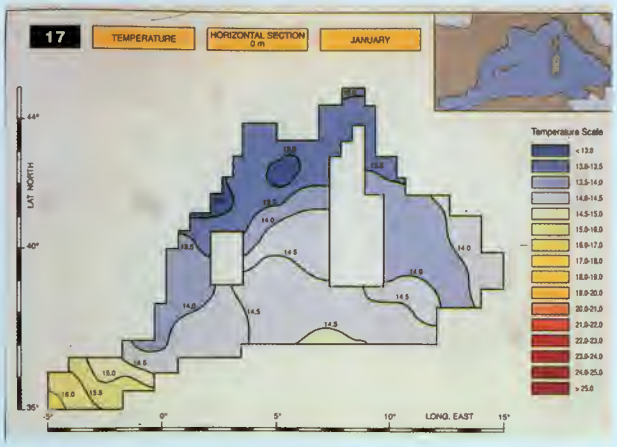
Mean monthly surface winds in the Mediterranean as calculated from satellite scatterometer data.



Annual observed mean surface winds (ms^{-1}) for the Mediterranean (1941-1972) determined from surface marine observations.



Summer sea-surface temperatures in the Western Mediterranean as measured by 'in situ' instruments.



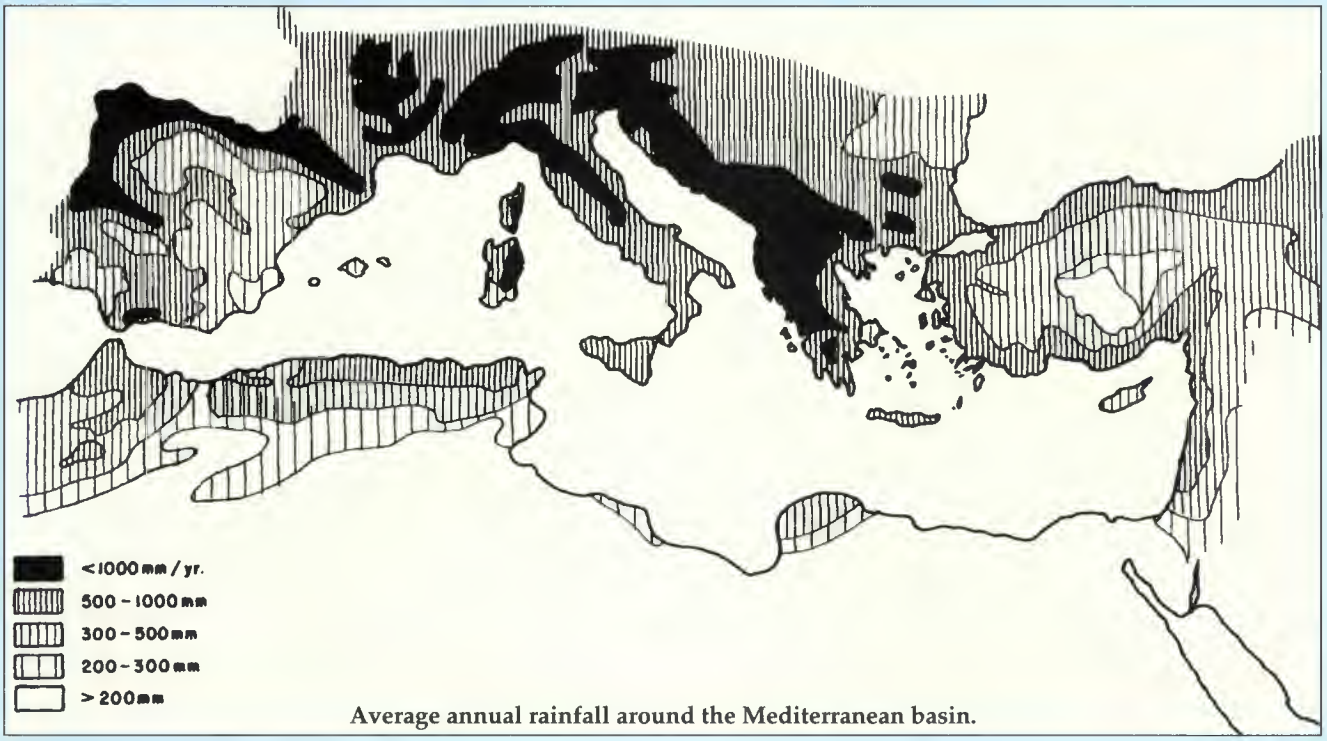
Winter sea-surface temperatures in the Western Mediterranean as measured by 'in situ' instruments.

A strong influence in determining rates of evaporation, and the transport of heat and moisture to the atmosphere, is the annual mean wind which as shown in the diagram is generally from the north and west.

The average surface air in contact with the sea surface is normally dry since it has to descend from the mountains. The combination of dry winds and sunny days which occurs as often as 250 times a year produces a strong evaporating influence over the entire surface of the Mediterranean that counteracts the effects of precipitation and run-off.

Greenhouse gas changes may affect the large-scale characteristics but in the Mediterranean the precise pattern of future climatic changes will be controlled by geography. At the present time it is estimated that the impact of human-related activities - rapid population growth in the south, migration to urban areas, major economic changes, and the steadily increasing influx of tourists each year - will be as great as any 'natural' climate change.

Satellites can make only a limited contribution to regional Mediterranean climate studies. Their strength lies in detecting global changes and providing the data required to model the larger-scale processes from which regional effects may be inferred. Already a dense meteorological network is in place around the Mediterranean. Satellite observations of sea-surface winds are difficult because of the number of islands but inter-annual variation in sea surface temperature monitored by satellite-borne infra-red devices may yet signal an early warning of longer-term climate variations.



Average annual rainfall around the Mediterranean basin.

Winter 1984

Water balance

More water is lost by evaporation from the surface of the sea than is gained through precipitation and river run-off. The difference is about 1m which is largely balanced by the inflow of Atlantic water through the Strait of Gibraltar.

When surface water temperature is simply plotted on a map, areas of warm water can assume an exaggerated importance; in reality they may be little more than extensive shallow pools of relatively warm water lying in and above an enormous volume of much colder water. Thus, while in other oceans and seas the natural distinguishing parameter is temperature, in the Mediterranean it is more instructive to use salinity as an identifier of water provenance.

Estimates of the different terms in the water balance equation are (in million m^3s^{-1}):

	Loss	Gain
Evaporation	92,000	
Precipitation		33,000
River run-off		14,000
Black Sea		6,500
Gibraltar net inflow (126,500 in; 88,000 out)		38,500
		92,000

A schematic of the vertical distribution and directions of the different flows from west to east is shown opposite.

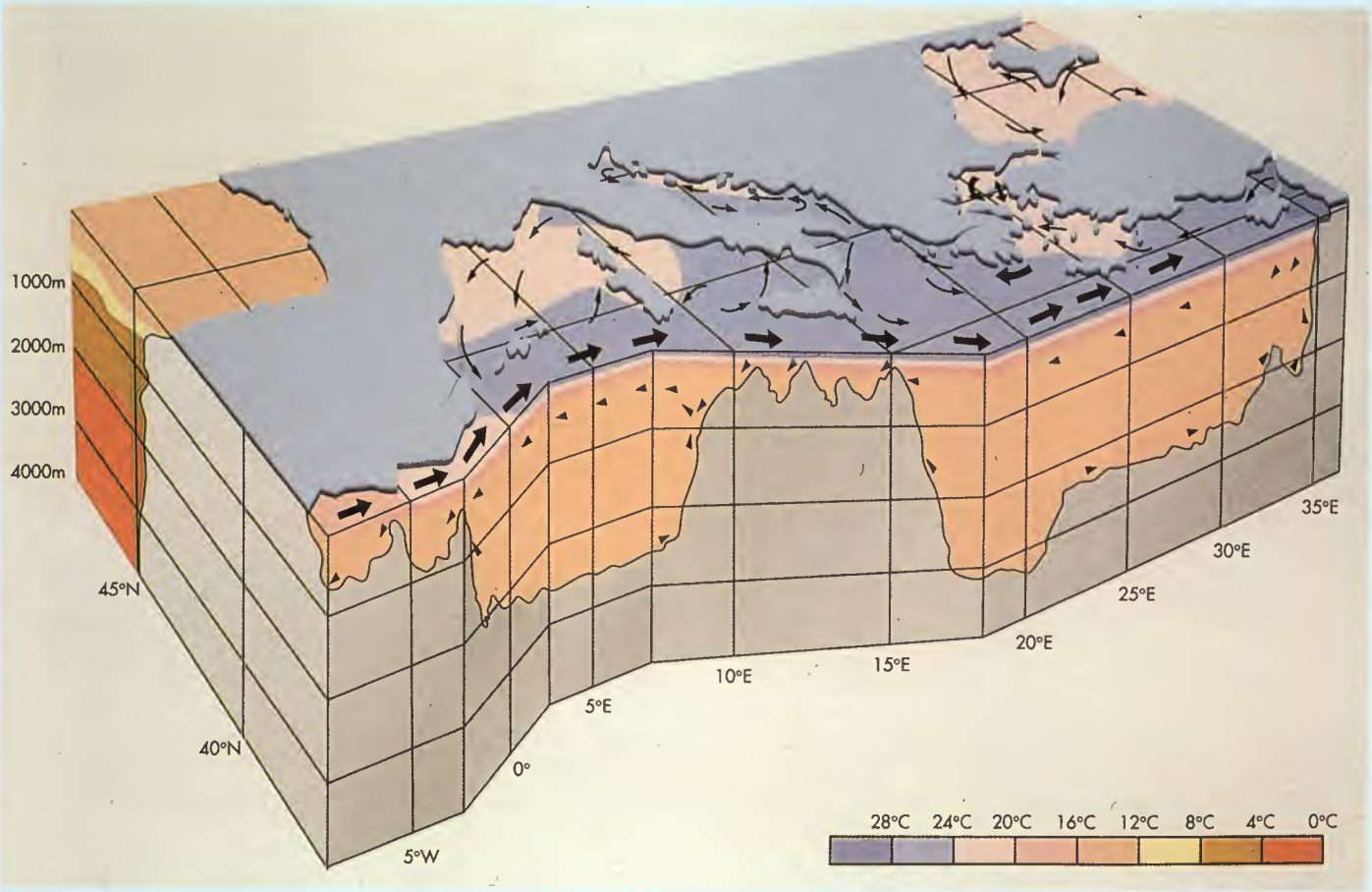
Circulation

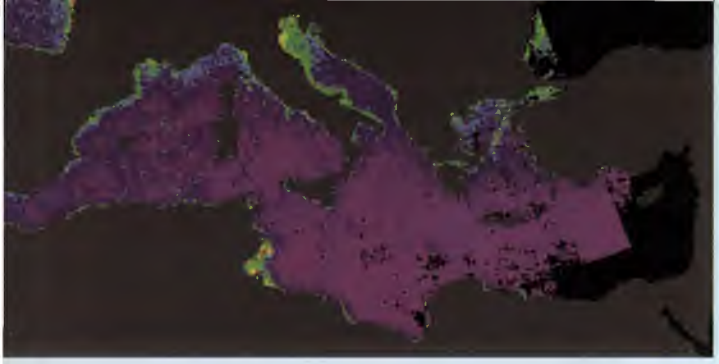
The ways in which water moves around the Mediterranean basins - changing character, forming new bottom water, flowing between the major channels, exiting into the deep Atlantic across the Strait of Gibraltar while depending on replenishment from Atlantic surface water pumped in on the tide - these processes have been observed over the last 20 years or so and are now generally well understood.

A column of water in the Mediterranean can be characterised by three distinct water masses. The top layer down to a 100m or more is referred to as Modified Atlantic Water. The layer below this, distinguished by its increased saltiness and reaching down to about 500m, is referred to as Levantine Intermediate Water. Below this layer is the Mediterranean deep water derived in certain areas from winter cooling of surface waters causing an increase in density which can lead to the water column becoming unstable and overturning.

Within the Mediterranean the Strait of Sicily is the major channel separating the Eastern from the Western Mediterranean. This and other channels largely determine the oceanographic characteristics of the individual basins. The width of the channels and the bathymetry of the sea floor impose their own constraints on a flow which must be two-way in order to maintain conservation of mass.

The Mediterranean is composed of basins which are separated from the Atlantic by a sill at the Strait of Gibraltar. The warm, dry Mediterranean climate means that the amount of water lost through evaporation exceeds the amount entering the sea from precipitation and run-off. Water flows in from the Atlantic through the Strait of Gibraltar to compensate for this loss. This sectional view shows both the surface inflow and the return flow at depth.





Autumn 1983

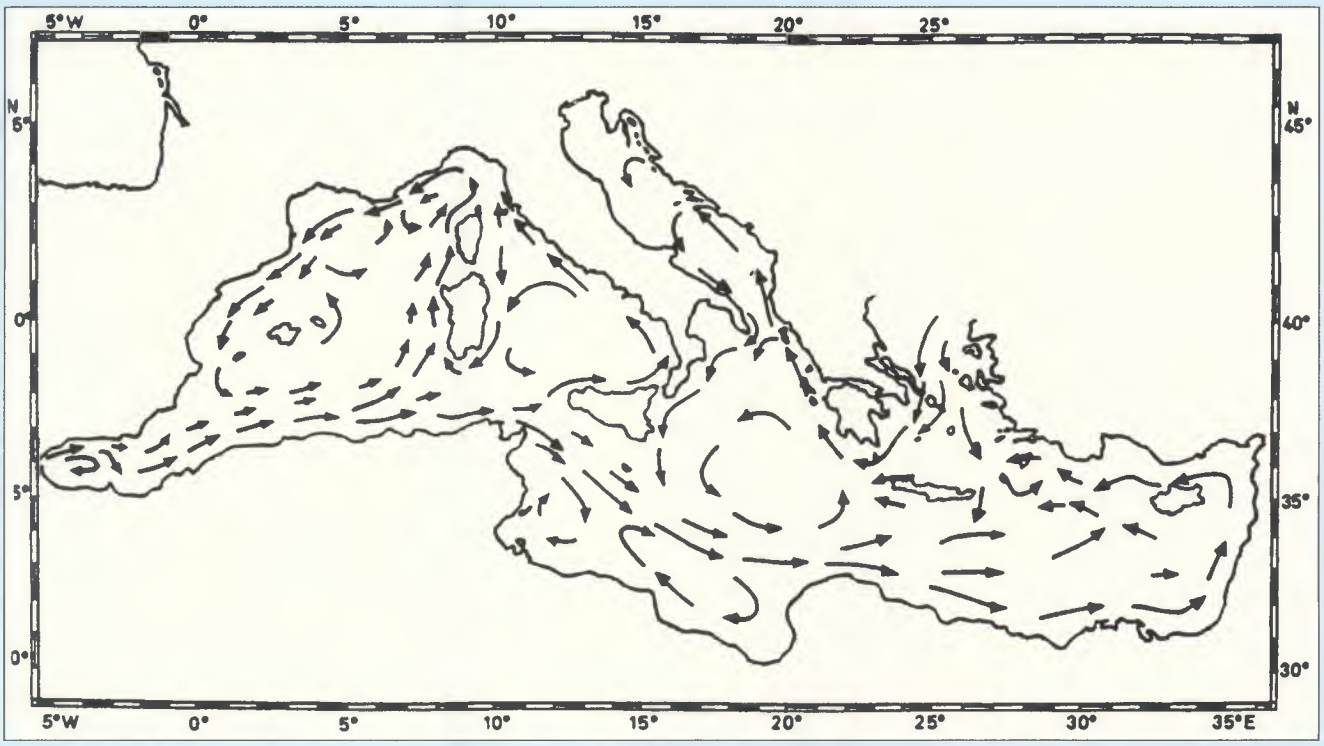
To start at the beginning, surface currents are largely driven by the influx of Atlantic water through the Gibraltar straits moving eastwards with spin-off eddies and characterised by a salinity of a little over 36 parts per thousand (36‰). The annual thermal changes are large and control the density of surface waters and the annual biocycle. There is no surface return system from east to west. Return is mostly by way of the Levantine Intermediate Water (LIW), and the Mediterranean deep water flowing from east to west until it spills over the sill of Gibraltar into the deep Atlantic where it can be traced for a very long way.

We show here the chart of Mediterranean surface currents in summer published in 1971.

It is not surprising that as more and more observations have been made, and as sensors became more accurate, the pictures that emerge are proving more complex than the original models suggested. In this regard satellites have played an important role.

The record of sea surface temperature from satellite measurements stretches back almost two decades. The complexity of patterns revealed by temperature gradients is now supported by radar imagery over the whole of the Mediterranean routinely obtained by ERS-1 and 2 since 1991.

Surface currents in the Mediterranean Sea in summer.



Current meters moored from the French Navy B.S.R. La Gazelle.

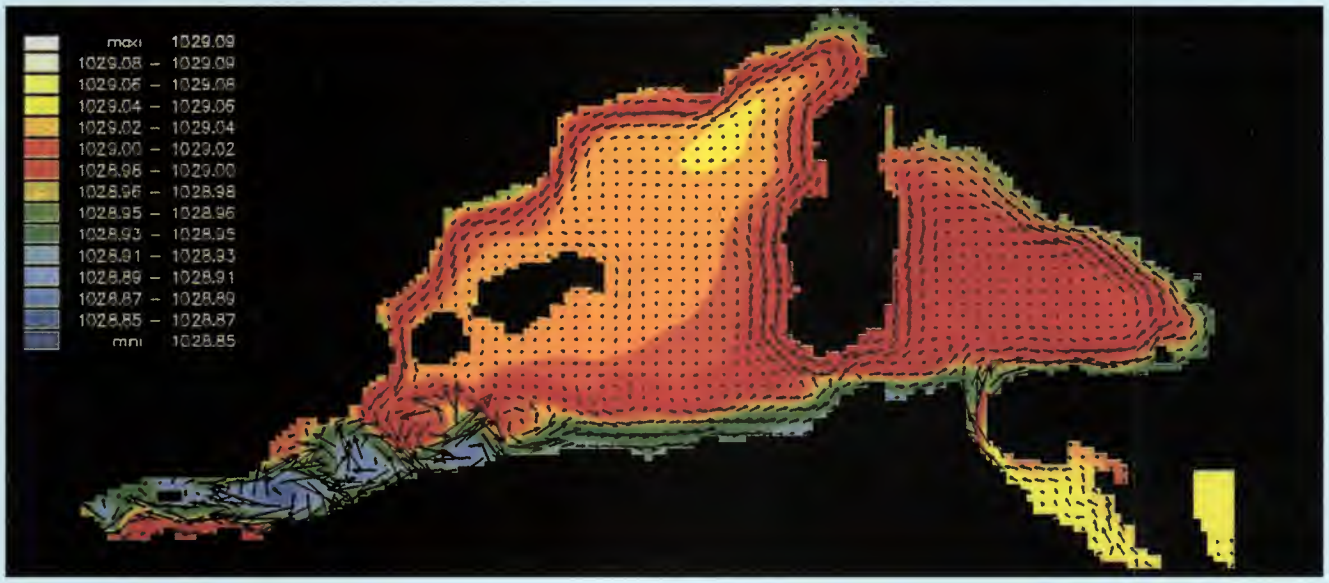
Predictive models

The Mediterranean is one of the most extensively studied basins in the world. One can trace recorded scientific investigations back to the Ancient Greeks. It was on the shores of the Mediterranean that Aristothenes first calculated the circumference of the earth to reasonable accuracy by measuring noon-time sun angles at 2 locations and measuring the distance by camel.

The comparatively complex circulation of the area has generated a number of investigations since the research vessel *Thor* entered the Mediterranean more than 80 years ago. Very careful, and extensive hydrographic surveys were made by *R/V Atlantis* in the winters of 1961 and 1962. Those observations of temperature and salinity from surface to bottom became the data base from which theories of the dynamics of Mediterranean circulation were derived. Until fairly recently individual investigations tended to be unco-ordinated but two major initiatives - the Western Mediterranean Circulation Experiment (WMCE) and POEM (for Physical Oceanography of the Eastern Mediterranean) - brought together the resources (ships, buoys, satellite imagery, models and instruments) of a number of research institutes. Today, co-ordinated research programmes, many of them supported by the European Union, are well-established.

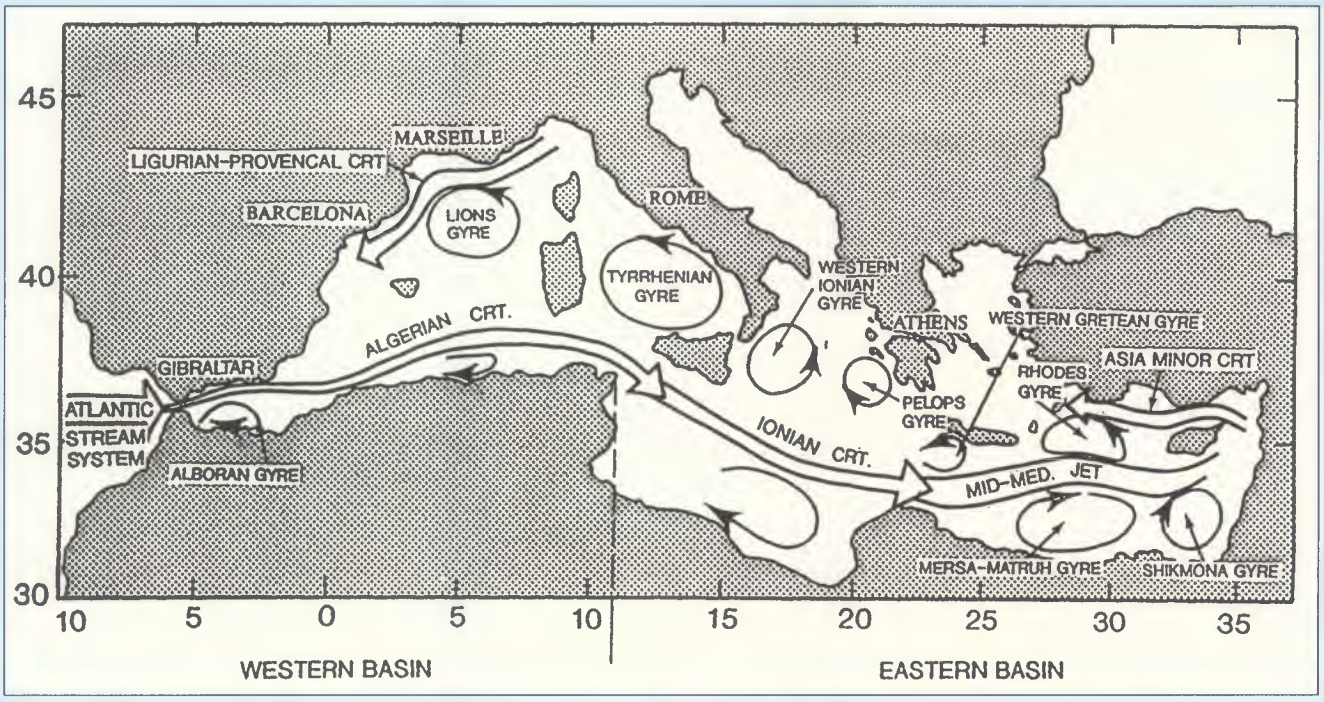
As in all environmental research the purpose of systematic investigations is to gain sufficient understanding of the processes at work to enable reliable predictions to be made. There are two approaches - deductive and inductive. Modellers use the deductive approach - that is, they apply physical and mathematical laws not to the real ocean but to conceptual models. They seek to suggest generalisations about how the ocean behaves.

A simulation of Levantine Intermediate water circulation in the Western Mediterranean Sea.



More commonly, an inductive approach is used. Observations are made, the structure and behaviour of the whole and its parts are described and attempts made to relate them in a consistent way.

Obviously the two approaches are complementary. Historically, the chief source of ideas comes from new observations. Theories derive from them and this has certainly been true of the Mediterranean. It is also true that the Mediterranean is a relatively complex structure to model. There are an almost infinite number of interactions between variables. The inter-connecting basins are far from evenly shaped and the depth of water varies from 0 to 5,000m.



Main features of the circulation in the upper layer of the Mediterranean, showing inflow of Atlantic water at the Strait of Gibraltar. Note the many semi-permanent gyres.

But real progress has been made in the last decade and models begin to simulate real behaviour at quite small scales. There are discrepancies, of course, but the model is tuned and run again until prediction and 'reality' start to converge.

Partly this is made possible by the increasing power of modern computers. Millions of complex calculations can now be made in a fraction of a second.

One of the most recent models uses a horizontal resolution of 0.25° with up to 16 levels in the vertical. The model is initialised with annual average values describing the vertical density structure. Wind forcing consists of monthly mean climatological stresses. The results show that the circulation has a multiple time-scale character with seasonal excursions comparable to steady state amplitudes. Sub-basin scale gyres amplify seasonally and exhibit partial or total reversal of currents in many subpartitions of the basin.

The Mediterranean monk seal now numbers only a few hundred individuals, and has been classified as endangered since 1966.

There is still some way to go before models and observations agree given the level of complexity of the surface features revealed on the satellite image. Gyres, eddies, filaments and fronts separating water masses with different characteristics, sometimes appear, disappear and reappear at a rate which would be hard to reproduce in a model. But if the surface detail revealed on a satellite image may be difficult to replicate, considerable progress is being made in reproducing the major features of Mediterranean circulation patterns including some of the more persistent sub-basin gyres.

One thing remains reasonably clear. Although satellite data by themselves are insufficient to explain the dynamical behaviour of the entire water column, models must ultimately pass the test of replicating the complexity revealed by the satellite.

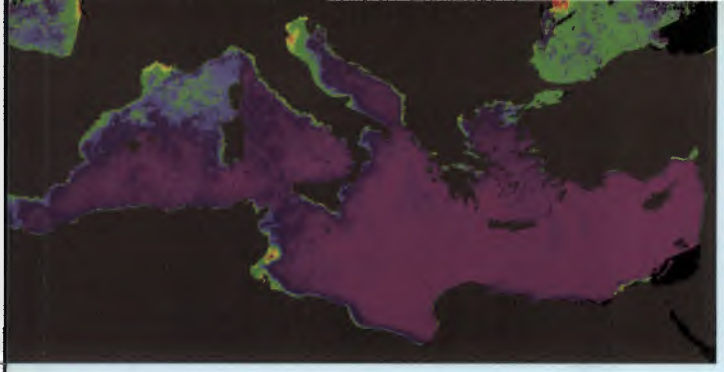
Biology

Sea grasses trap and stabilise sediment, providing a habitat for rich detritore and herbivore food chains.

A fundamental characteristic of Mediterranean water is its impoverished nutrient concentration. None of the deep nutrient-rich Atlantic waters take part in the Mediterranean circulation. Since only the upper 150m or so of Atlantic water provide replenishment for the Mediterranean Sea, any increase of concentration of nutrients in excess of the amounts contained within the surface layers of the neighbouring Atlantic are probably due to local phenomena. Nutrients enter the Mediterranean in the run-off of rivers, with their land-derived salts, sediments and pollutant materials. Here again there is a marked difference between north and south with river run-off concentrated in the north. Only the Nile effluents count in the south and these were substantially reduced by the construction of the Aswan Dam.

The more nutrient-rich deep water of the Mediterranean passes out to the Atlantic at depth, so there is a net gain to the Atlantic at the expense of the Mediterranean. The Mediterranean may be poor in the quality of organisms it produces but not, however, in variety. About 12,000 species of marine biota have been identified.

Conventional plankton studies have revealed that zooplankton species characteristic of the Aegean Sea are spreading into Black Sea communities; and Mediterranean plankton communities have themselves been altered by the entry of Red Sea species through the Suez Canal. It has been suggested that the removal of a seasonal lower salinity barrier caused by the reduction in Nile outflow together with higher water temperatures in the Levant area have facilitated colonisation of the eastern Mediterranean by species adapted to higher salinities. By now over 500 species entering from the Red Sea and Indian Ocean have been identified.

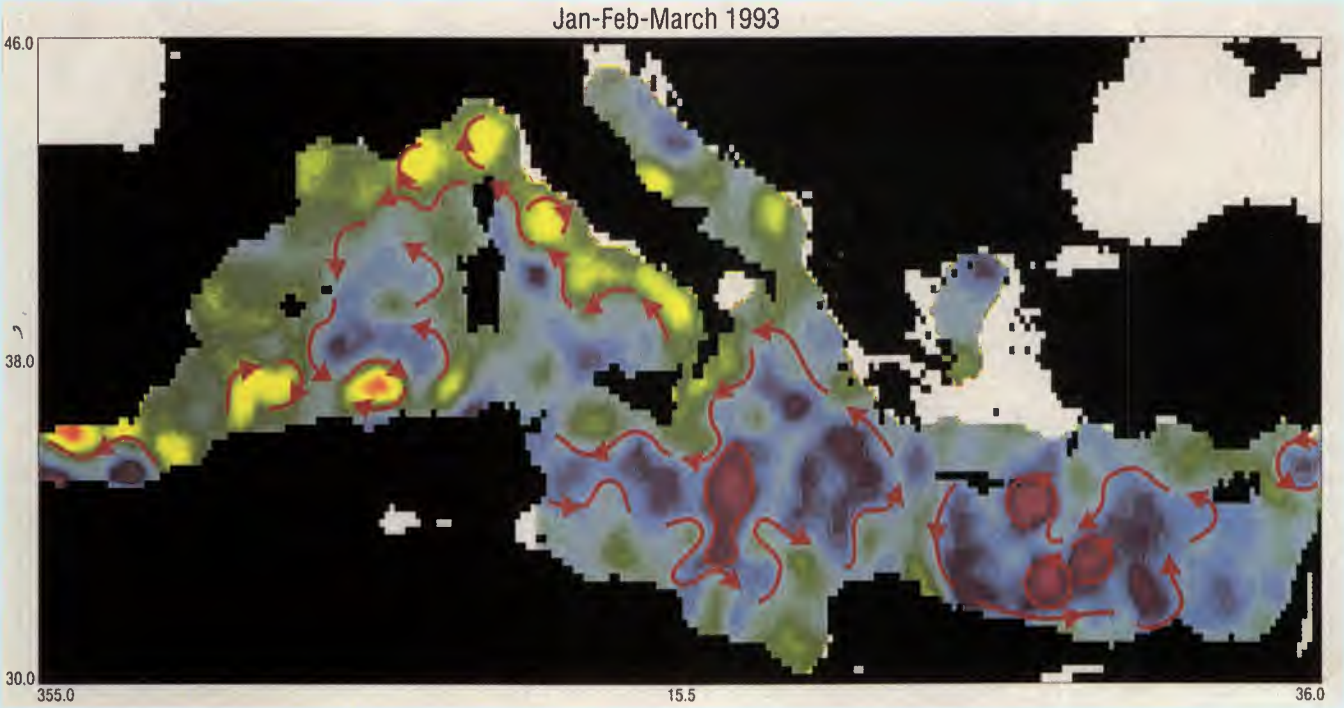


Spring 1983

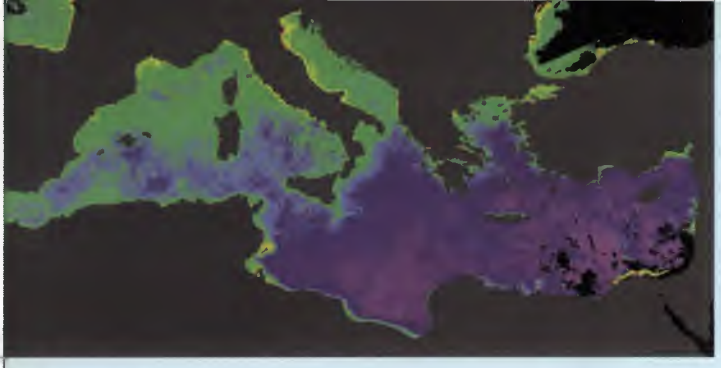
The proportion of the nutrient-enriched production that is translated into enhanced fisheries yield has not been quantified. What appears true is that nutrient discharges have a deleterious impact on the diversity of fauna and flora close to the points of discharge.

Local nutrient enrichment cannot be divorced from pollution. Although there have been considerable improvements over the last decade through UNEP's Mediterranean Action Plan, it remains true that few of the 56 Mediterranean coastal cities with populations over 100,000 have adequate sewage treatment facilities. Has nutrient enrichment increased the amount of Mediterranean fish landings? There is tenuous evidence that a moderate level of enrichment can relax the nutrient limitation that has applied historically in the Mediterranean ecosystem and that some fisheries yield may increase. At the same time, considering the Mediterranean as the world centre of tourism, the loss in revenue that could occur as a result of cultural eutrophication of coastal waters is considered by experts to far outweigh any marginal increase in fish caught.

Primary production can be unusually high at the mouths of rivers and along coasts in winter time. Mixing in the Gulf of Lyons can also generate higher productivity than average. Upwelling regions are often associated with fronts, eddies and gyres. In the northern Mediterranean the nutrient levels and biomass can occasionally reach values more commonly associated with the Atlantic.



Sea level anomaly for January - March 1993 in the Mediterranean as measured by the ERS-1 and Topex/Poseidon altimeters. Sea level fluctuations due to changes in density brought about by shifts in water temperature can now be detected using satellite data.



Winter 1983

Satellites, Sensors & Synergy

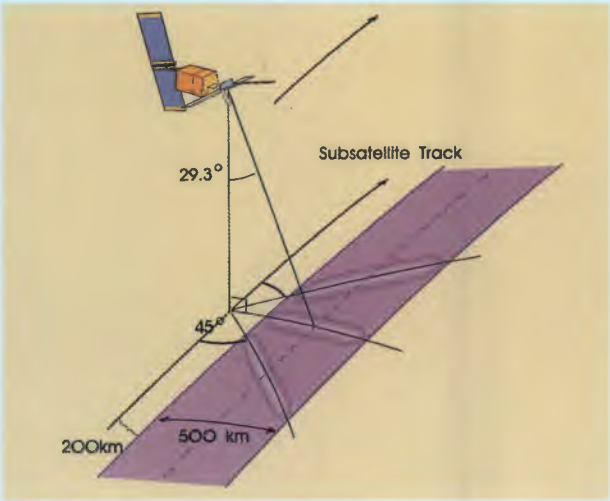
The number of spacecraft designed to monitor the state of the sea surface increases each year. By the end of the century there should be around a dozen in orbit. At the time of writing the European Space Agency's pair, ERS-1 and 2, are operating in tandem the one chasing the other 30 minutes behind on the same orbit. The precise radar altimeter on Topex/Poseidon continues to reveal details of surface currents and eddies. A follow-on version is being planned and the US Navy plans a successor to Geosat. ESA's Envisat is on schedule for a launch towards the end of the decade while the Japanese ADEOS will carry an advanced wind scatterometer plus an ocean colour scanner to complement SeaWiFs should it eventually fly. The NOAA satellites continue to monitor global changes in sea surface temperature and extra visible channels are planned to be added to a new AVHRR. Canada's Radarsat offers a SAR with a selection of operating modes in which swath width can be traded against spatial resolution.

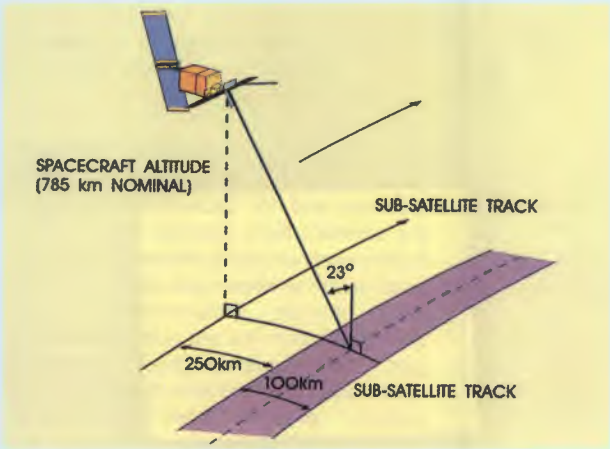
As we have seen the payload of these ocean satellites is a mix of sensors designed to detect small changes in one of only four surface parameters - temperature, colour, roughness and slope.

The **synthetic aperture radar** detects small modulations of surface ripple patterns caused by winds, waves, eddies, slicks, effluents or other surfactants. A moving surface feature will be shifted in the image plane due to its contribution to the Doppler signal used by the SAR processor to locate a particular target. This can have the effect of introducing non-linear distortions into the image of surface waves so care must be taken in deriving wave spectra from the image.

The main purpose of the **radar altimeter** is to detect the changes in sea surface height brought about either by anomalies in the earth's gravity field, or by geostrophic currents, surges or tides. The height of surface waves can also be monitored, however, through measuring the slope of the leading edge of the return pulse, and information contained in each pulse on the scattering cross section of the sea surface provides an estimate of surface wind speed.

The **wind scatterometer** is a radar designed to measure the backscattering cross-section along rows of cells on the sea surface and convert the observation into estimates of wind speed. The swath width is wider than that of SAR (500km as opposed to 100km in the case of the ERS satellites). Wind direction is inferred by deploying more than one sideways-looking antenna.





ERS-1 and 2 modes of operation. On this page are shown the SAR wind mode and image mode.

Features which produce a change in surface temperature or colour may be more difficult to track in temperate, cloud-covered latitudes, but the record of the **Advanced Very High Resolution Radiometer (AVHRR)** now spans almost two decades. This NOAA sensor was supplemented in 1991 by the launch of the Along-Track Scanning Radiometer on ERS-1, enabling features such as ocean fronts, eddies, currents and other dynamic features to be detected and tracked, while the 7.5-year record of the **Coastal Zone Colour Scanner** delineated areas of coastal upwelling rich in nutrients and other large, seasonal blooms.

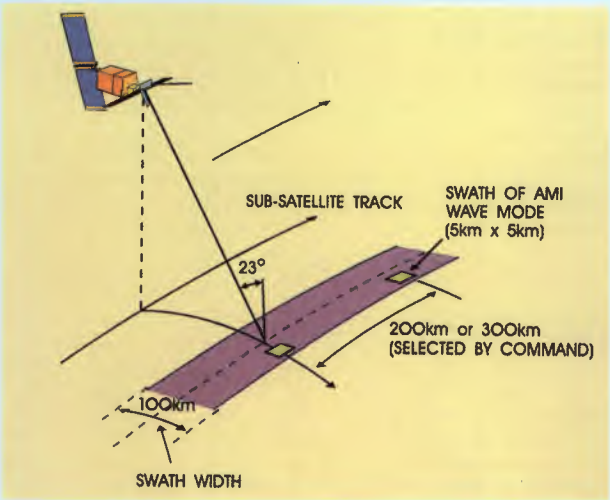
What is becoming clear in recent records is that many surface features produce an anomalous surface signal in more than one parameter. Thus an eddy can exhibit a surface roughness signature detectable by SAR. The same eddy may also be warmer or cooler than the surrounding water mass and therefore detectable by an infra-red sensor. A change in colour may be evident in the same eddy and, if it is a dynamic feature, then a change in slope across it can be measured by a radar altimeter. In fact the inter-relationships that exist between the biology of the sea and the physical processes acting on it were more clearly illustrated from satellite imagery than from preceding 'in-situ' observations.

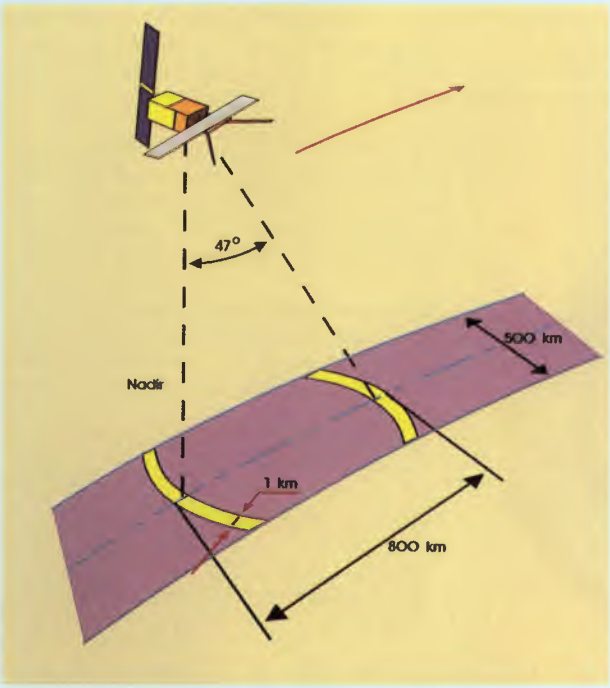
The identification and tracking of a number of prominent ocean or coastal features could, therefore, be made more feasible by interpreting the signals from not one but several sensors that operate in different parts of the electromagnetic spectrum.

This synergistic approach, whereby the outputs from different sensors combine to provide a higher information content than the individual parts, is one that is gaining ground, but demands a detailed systematic analysis of the meteorological and oceanographic surface conditions that produce – or fail to produce – detectable signals.

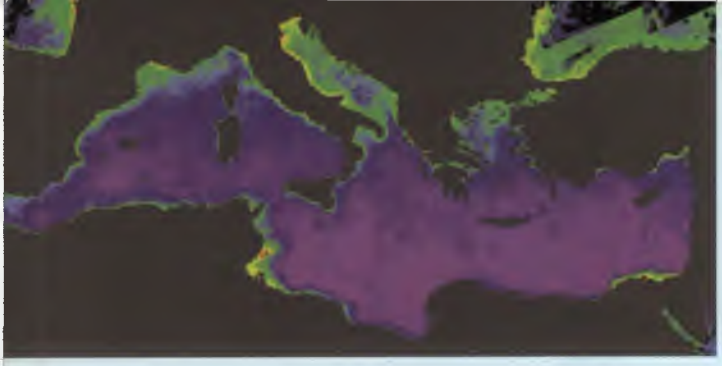
Satellite sensor records are at their most useful when they represent repeated measurements over the same track or scene. It is mostly the *changes* which are of interest. The usefulness of the radar altimeter was first appreciated through its ability to distinguish dynamic features - eddies and currents - along repeat tracks from the unchanging signal produced by the geoid.

SAR imagery of the same scene taken at different times has been shown to change dramatically - sensitive to surface wind conditions and, possibly, air-sea temperature differences. Greater understanding of the interactions between the sensors and meteorological and oceanographic conditions can only be brought about by repeat measurements over the same sites. If and when a sensor's records are shown to be different, two basic questions can be asked:





Here we see the SAR wave mode and ATSR.

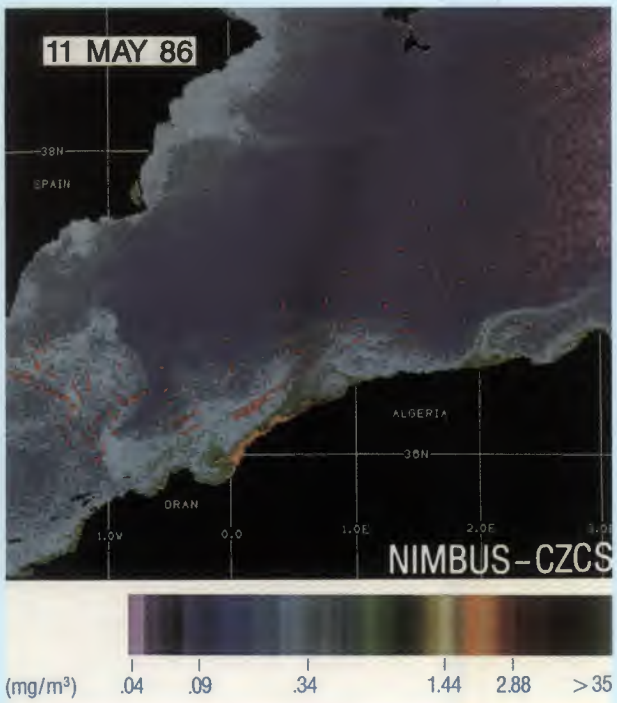


Autumn 1982

i) What change in surface conditions could have caused the difference ?

ii) Are corresponding changes observed in the other sensor records ?

At the time of writing, programmes to study conditions conducive to producing a degree of synergy between the different sensor records are being planned over the Mediterranean. The Mediterranean represents an ideal 'natural' laboratory in which the logistics of organising the collection of reliable 'in-situ' data are considerably easier than for the open ocean — more than 50% of its surface area is within 100 km of land, and no point is further than 370 km. Its surface also exhibits a wide variety of features – slicks, eddies, fronts, internal wave trains – and it is unique in the extent of its large swings in surface temperature from summer to winter. It is also true that the monitoring and management of the Mediterranean is of major concern to the nations that compose its margins.



Satellite images of the Almeira-Oran Front and the beginning of the Algerian Current, obtained during the Western Mediterranean Circulation Experiment. Superimposed on the thermal (upper) and chlorophyll (lower) images are 10-m current vectors. The larger vectors indicate speeds greater than 0.8ms-1.

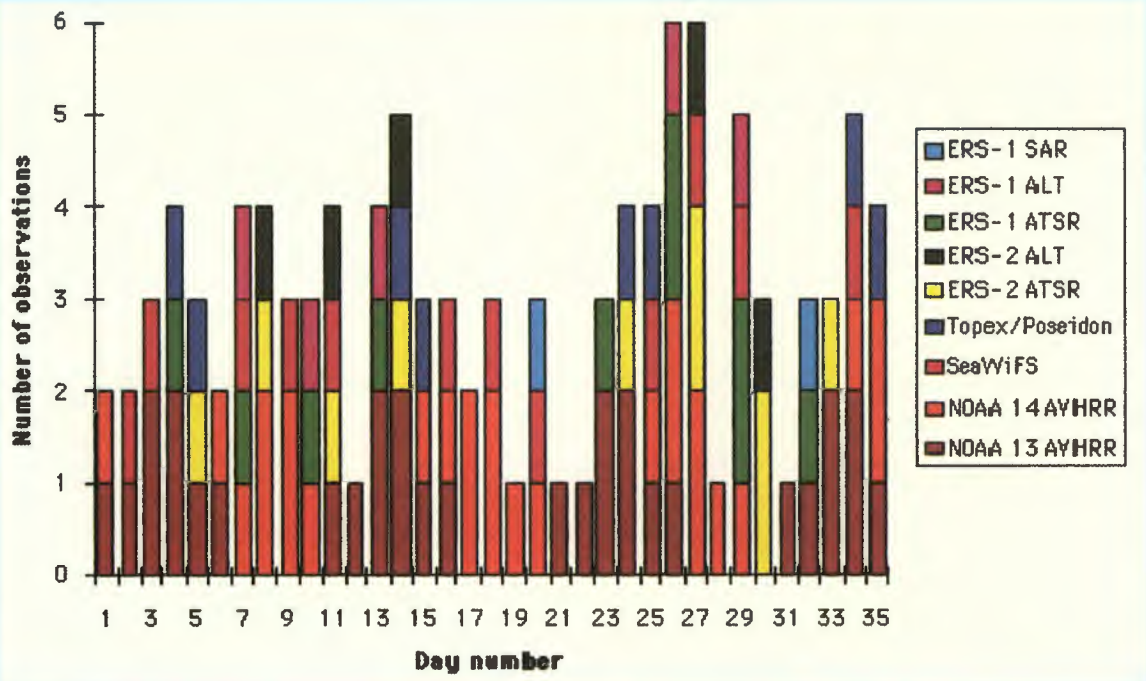
Sampling

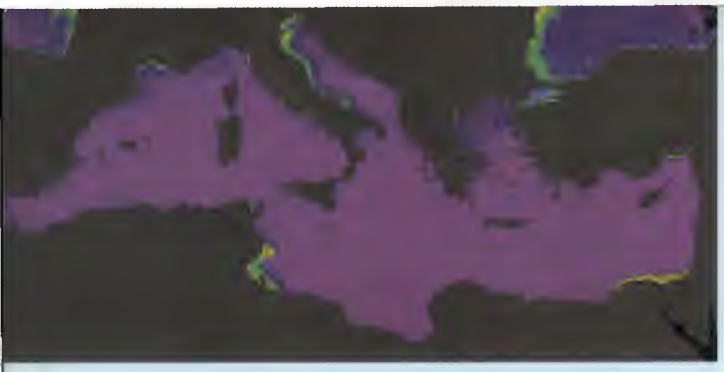
Many earth-observing satellites orbit at a height of around 800km, completing 14 1/3 orbits each day at a ground speed of around 7km/s. The number of days between exact repeat orbit patterns depends on the satellite's height. If it completes exactly 14 1/3 orbits per day the pattern will repeat after 3 days - orbit 44 being laid down over the first orbit. A very small change in orbit height could change the pattern from 14 1/3 per day to (say) 14 12/35 orbits per day - a pattern which would then repeat every 35 days. These repeat intervals vary from satellite to satellite according to mission objectives and, of course, are designed to match the scales of spatial and temporal variability of the features under study. Some satellites have employed different repeat patterns during their lifetime. ERS-1 used 3, 35 and 168-day repeats - the latter to determine the earth's gravity field. Topex/Poseidon is in a fixed 10-day repeat pattern, Seasat was 3 and 17 days, Geosat 17 and 168 days, and so on. With wide swath sensors such as the AVHRR, CZCS or Windscat the repeat pattern is of no great consequence but with the altimeter and SAR a careful choice must be made.

The figure overleaf demonstrates the sub-satellite tracks for repeat patterns of 10, 35 and 168-days.

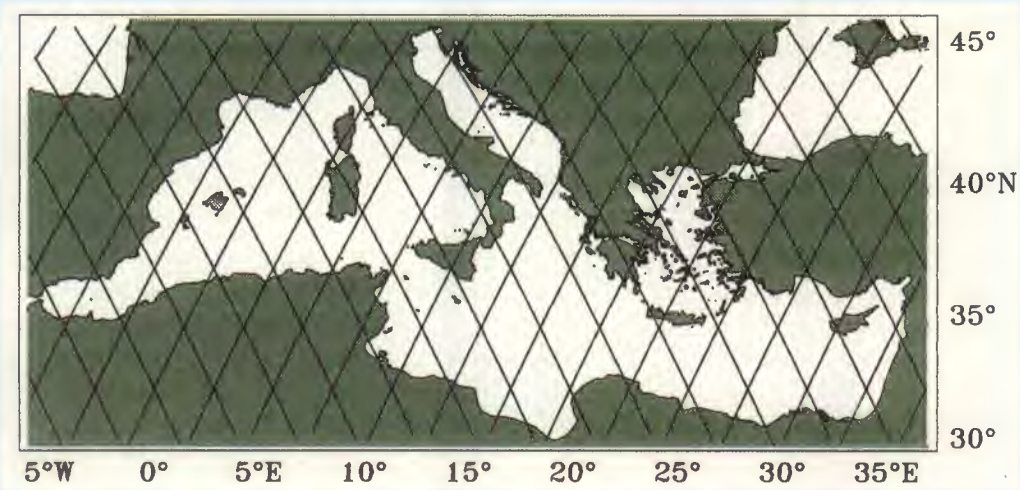
Over any particular area one can draw up a 'timetable' of passes showing, from those satellites presently in orbit or planned to be launched soon, a day-by-day chronicle of the different type of measurements to be made. In the example shown we have chosen the Strait of Sicily and assumed that a colour scanner (such as SeaWiFs or the Japanese OCTS) will fly soon. The diagram shows how satellites ERS-1 and 2, Topex/Poseidon, NOAA and a colour scanner will provide information on colour, temperature, slope and roughness over the site.

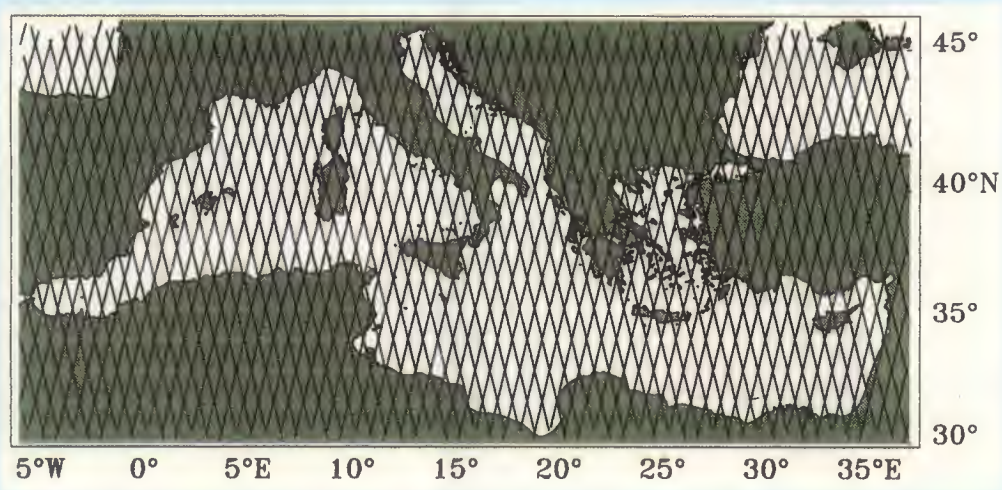
Theoretical frequency of observations over the Strait of Sicily. The chart shows the type of different measurements that could be made each per day for the sensors on board the 9 ocean observing satellites presently in orbit, or planned to be launched soon. Some satellites carry more than one sensor, but not all sensors on the same satellite can be operated simultaneously.

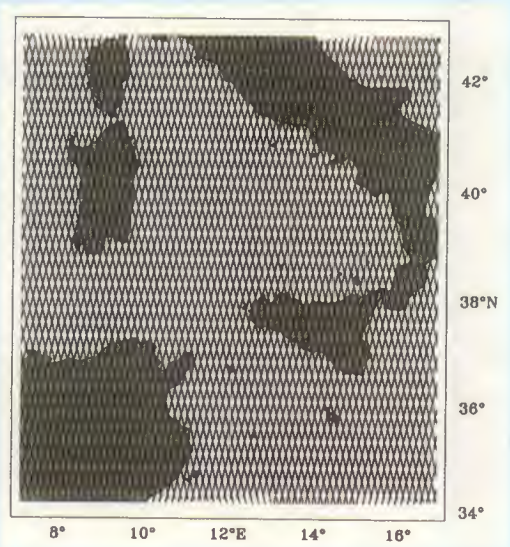




Summer 1982

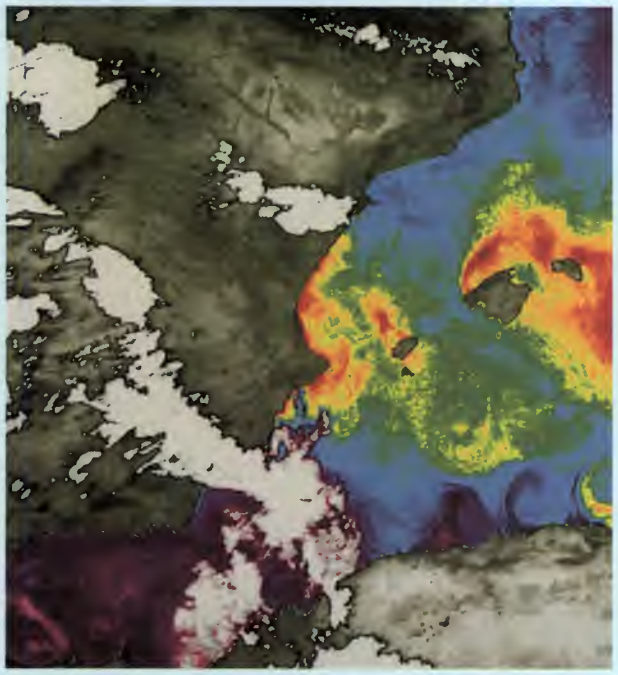






Coverage of altimetry missions. The top diagram shows the ground coverage of Topex/Poseidom with a 10-day repeating pattern. The lower two show ERS-1 (and ERS-2) in a 35-day repeat pattern, and, over the Tyrrhenian Sea and Strait of Sicily, the 168-day repeat executed over 2 cycles by ERS-1. (Only one cycle is shown).

Surface Temperature

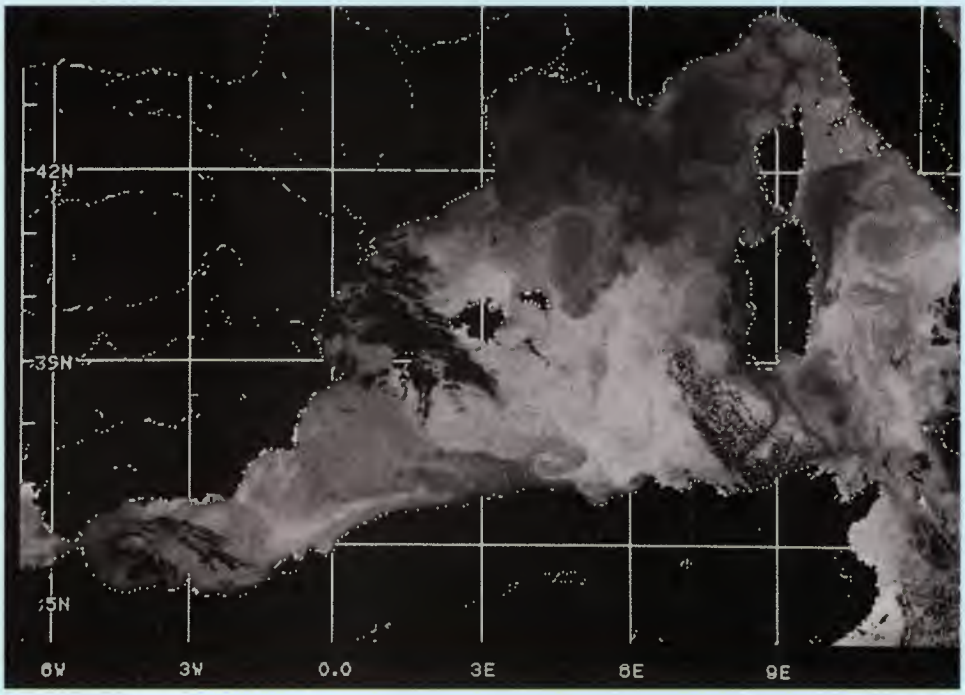


Thermal image of the Alboran Sea, Western Mediterranean, acquired by the AVHRR sensor on NOAA-9 showing the Almeira-Oran front.

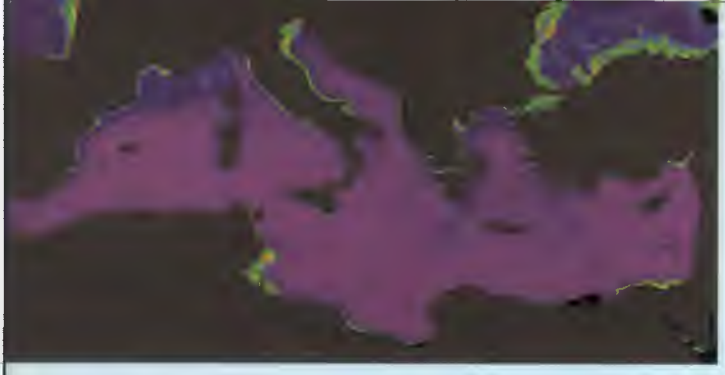
The nearest to a continuous set of satellite measurements to be taken over the Mediterranean is that of sea surface temperature derived from the Advanced Very High Resolution Radiometer (AVHRR) of the NOAA satellites supplemented more recently by the Along-Track Scanning Radiometer (ATSR) of ERS-1. Accuracies lie in the range of 0.3 - 0.5°C and spatial resolution is about 1km.

Some of the most striking SST imagery is that of the surface of the Mediterranean. The prevalence of mesoscale eddies gyrating both clockwise and counter-clockwise - some, semi-permanent features which appear, disappear and re-appear in roughly the same location, some which are clearly seasonal, and other features which appear to migrate across basins - was one of the first revelations of ocean satellites. It was clear that Mediterranean dynamics was more complex than had been imagined since the energy associated with such mesoscale activity can be shown to be an appreciable fraction of the total transport energy.

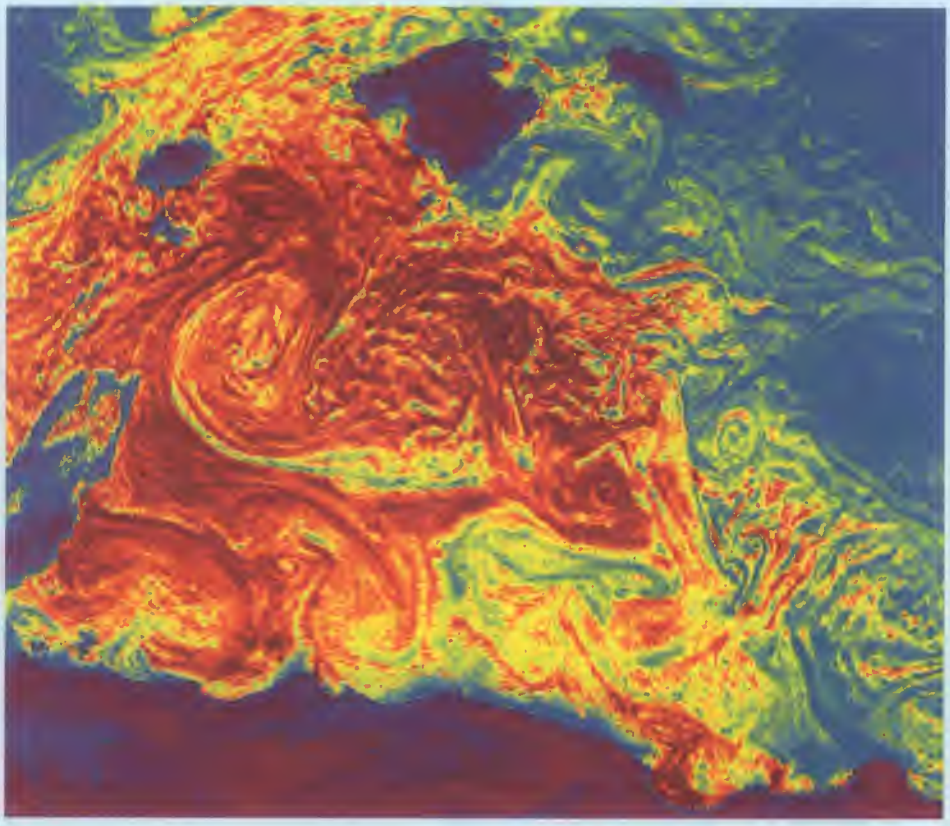
Several research vessels are now equipped with AVHRR receivers or at the very least are in continuous communication by fax with their base. It is now common practice to use the infra-red imagery as a guide in selecting the position of hydrographic stations. An example is shown across the Almeria-Oran front in the eastern Alboran Sea. This is a NOAA image taken on 9 November 1985. The marked positions are the locations of hydrographic stations located across the axis of the front. Another complex pattern of eddies taken during the same campaign is shown over the entire basin of the Western Mediterranean.



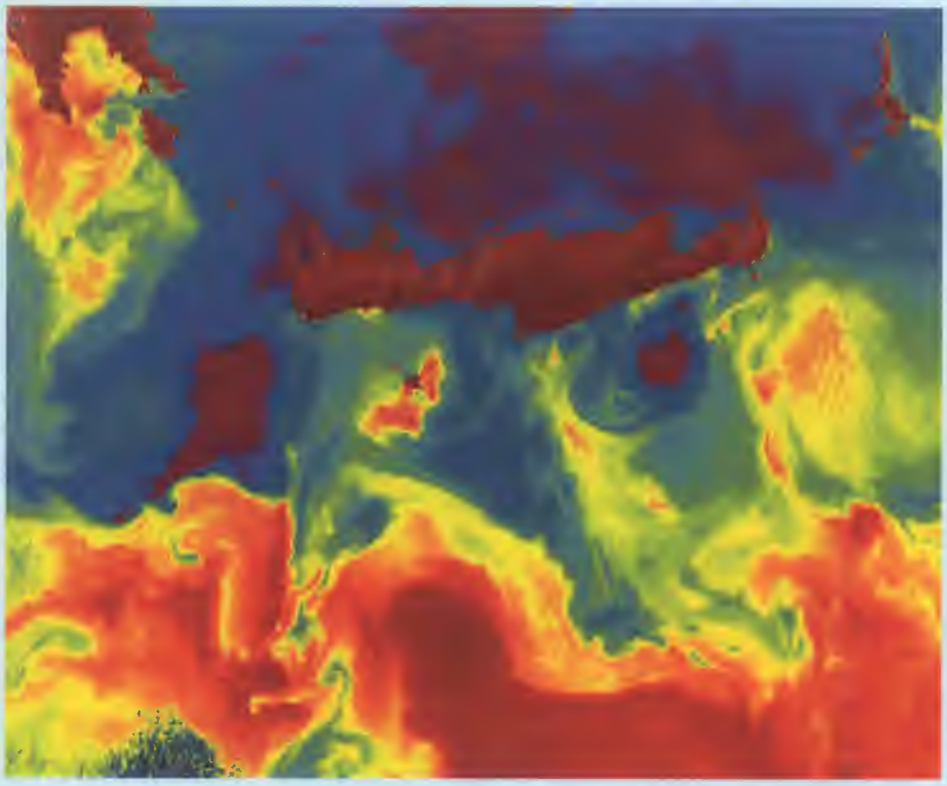
Complex eddy pattern in the Western Mediterranean, as shown in a thermal image acquired by the AVHRR sensor on NOAA-9.



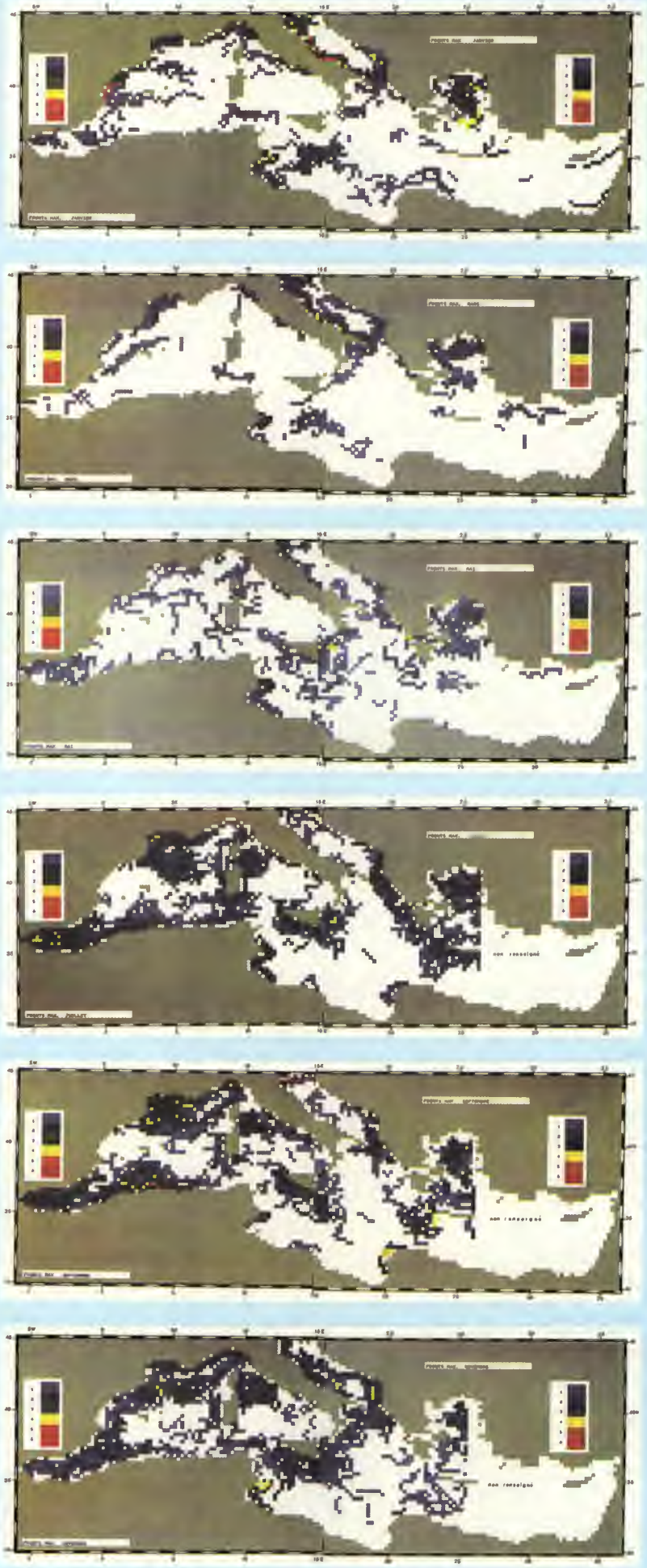
Spring 1982



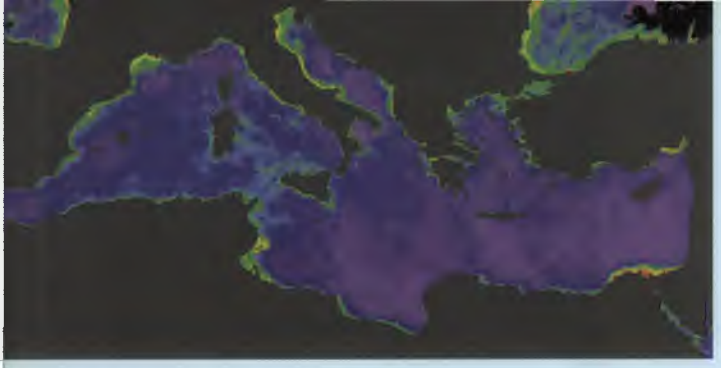
ATSR sea-surface temperature image of the Balearic Islands. In this night-time image, the coldest areas – which include all the land – are shown in purple and blue, whilst yellow and orange are used to represent successively warmer temperatures over a total range of 278-293K. The most striking feature of this image is the intricate pattern apparent in the Mediterranean Sea temperature. Eddy structures ranging in size from less than 10km to nearly 100km decorate the entire sea area.



A similar ATSR image of the Eastern Mediterranean south of Crete.



Sequence of charts at 2-monthly intervals showing the maximum values of thermal gradients derived from the AVHRR record in the period 1980-86. They are displayed in units of °C/5km on a scale 0-6.



Winter 1982

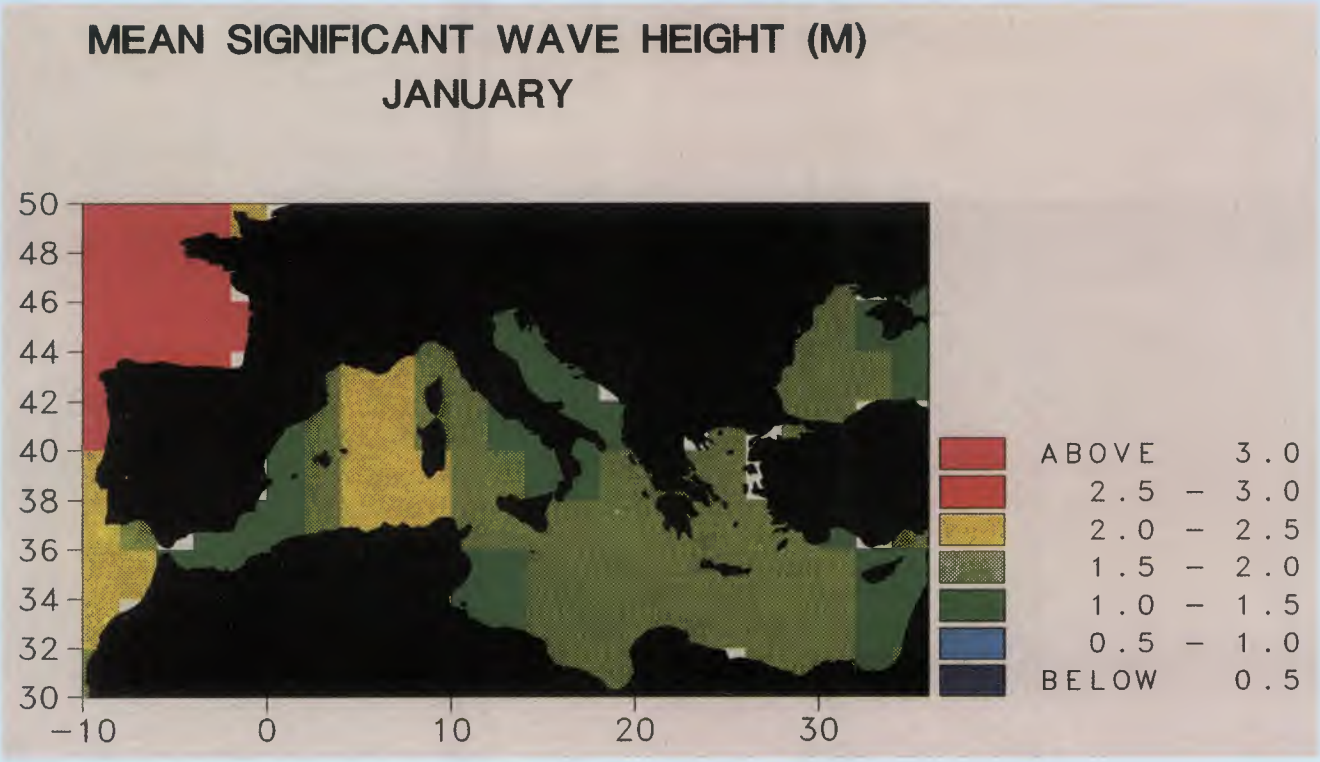
Surface Roughness

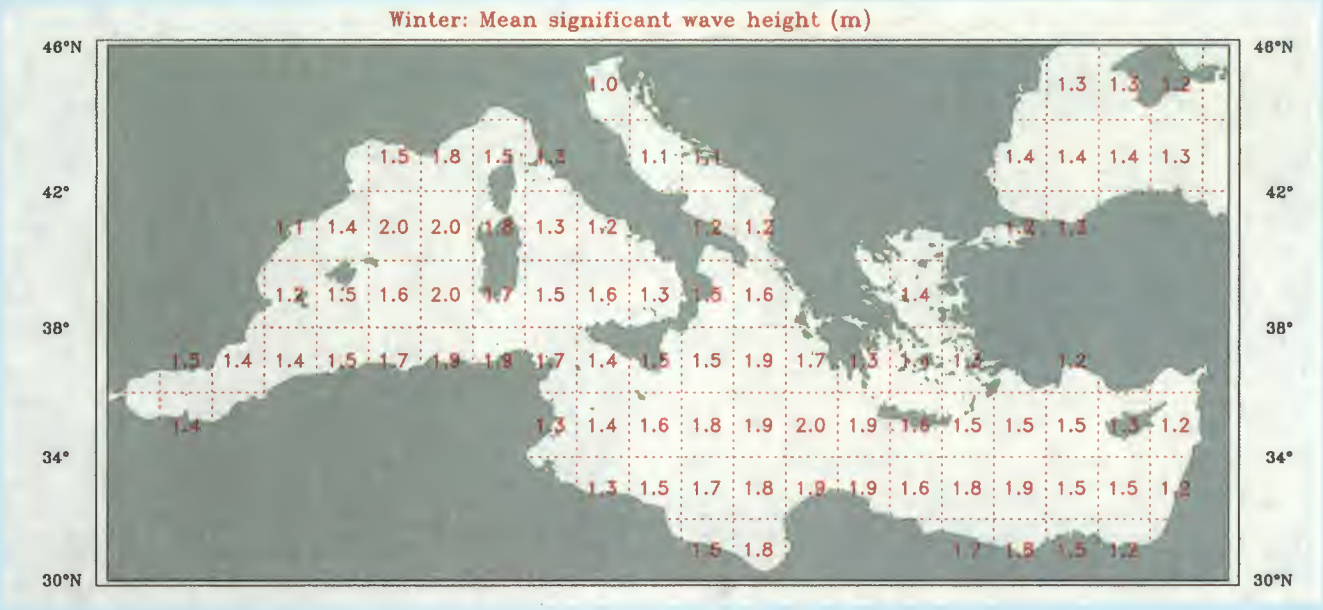
Waves and wind

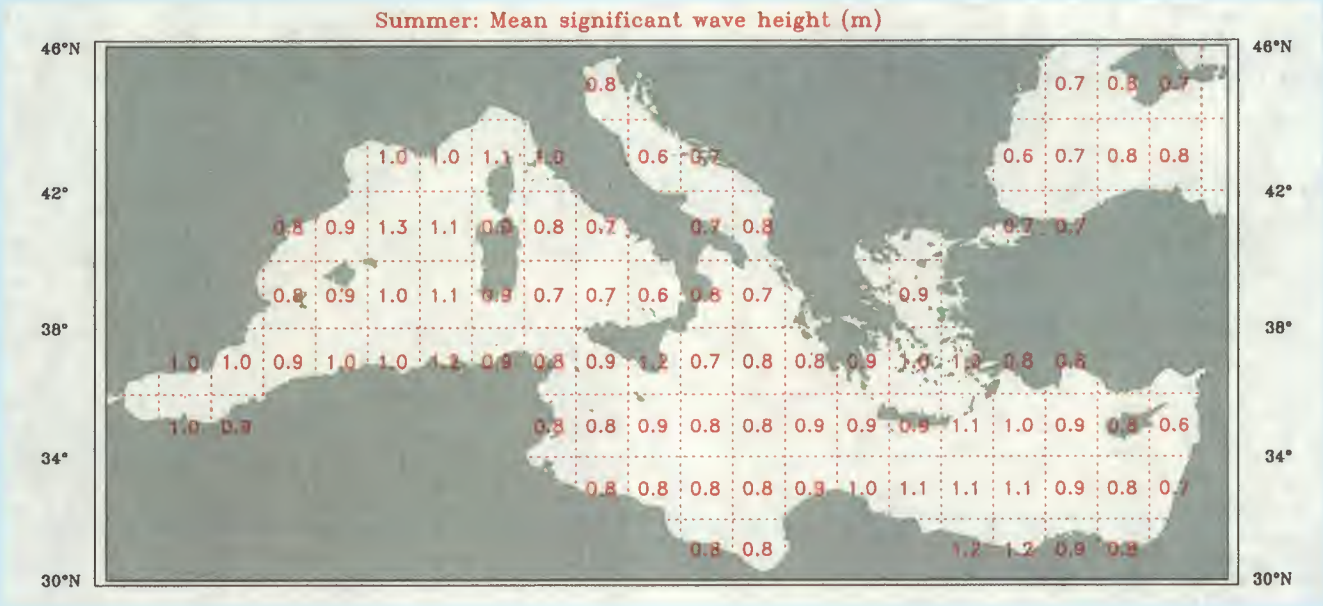
SAR imagery of the ocean's surface provides useful information on the period (or wavelength) and direction of surface wave trains. The minimum wavelengths that can be imaged by SAR appear to be limited to about 100m, however, which means that few waves have been imaged in the Mediterranean. Because of the short fetch over all Mediterranean basins most wave periods are below the 8 seconds which correspond to 100m wavelength.

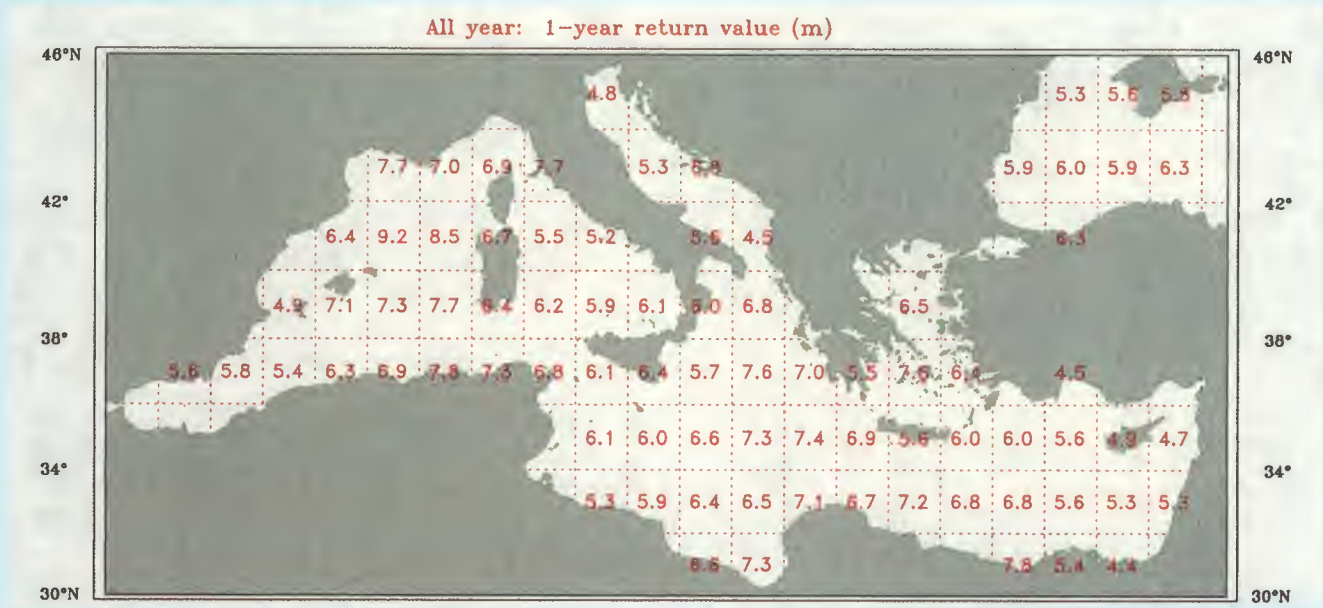
As we have seen, however, the radar altimeter is capable of measuring wave height to good accuracy. Readings are taken every second along the satellite's track corresponding to a spacing of about 7km. Altimeters have been in operation since 1985 and there are currently three orbiting the earth (ERS-1 and 2 and Topex/Poseidon). From this archive of data the statistics of the surface wave conditions can be calculated with acceptable accuracy. Monthly mean values together with the probability of meeting waves within a prescribed range (2-3m, 3-4m 4-5m etc) may be calculated. Mediterranean surface waves are more subdued than waves in the North Atlantic. We show here a plot of January wave heights averaged over 7 years. Also shown one below the other are plots of the 2° x 2° values in winter and summer together with a plot of the highest waveheight which will be met within 1 year.

Mean significant wave height in the Mediterranean for January, derived from 8 years of altimeter data (1986-93).



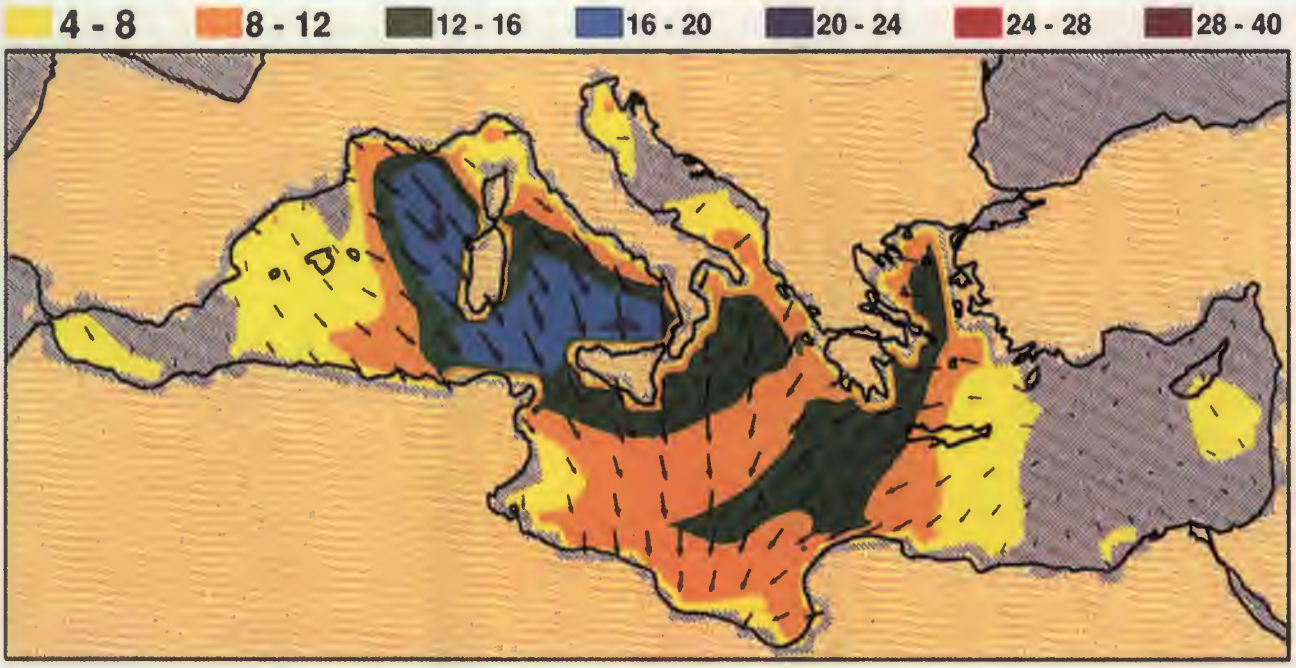






Altimeter wave data: Mean significant wave height, winter (top) and summer (middle). 1-year return value (lower).

Autumn 1981



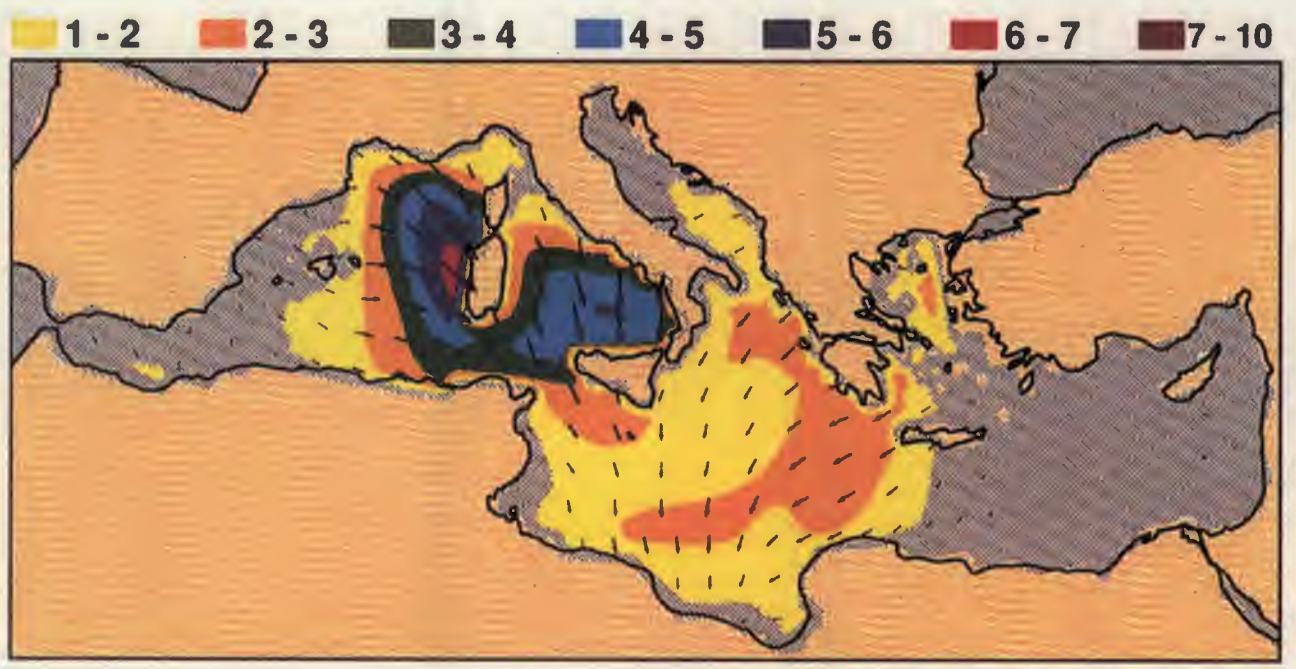
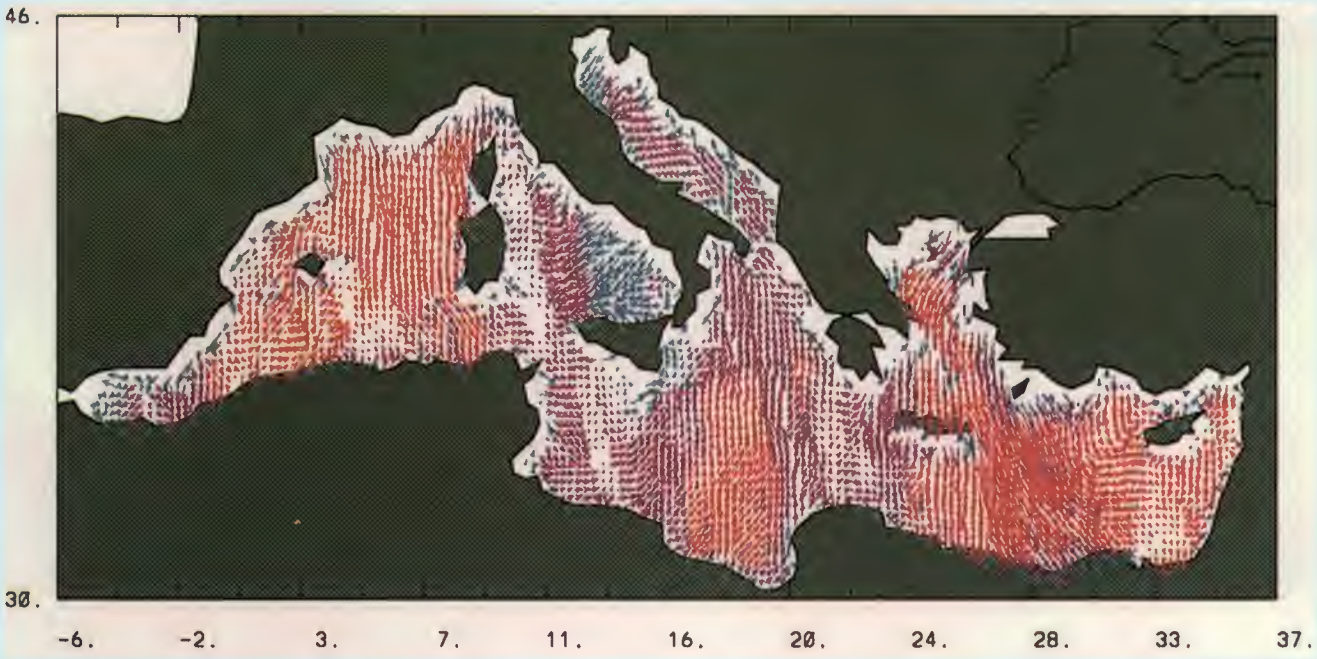


Illustration of wave heights calculated from conventional derived wind field by means of a wind/wave model (WAM).

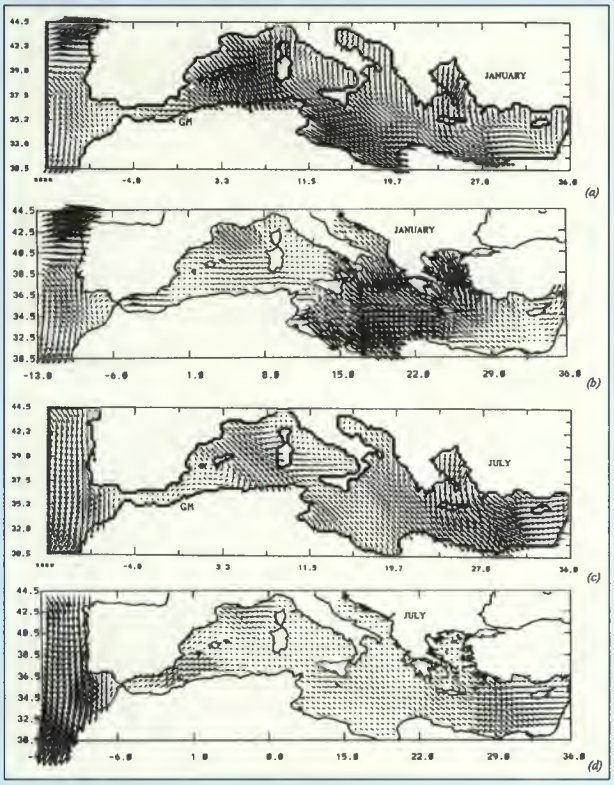


Wind field derived over 3 days from the ERS-1 scatterometer.

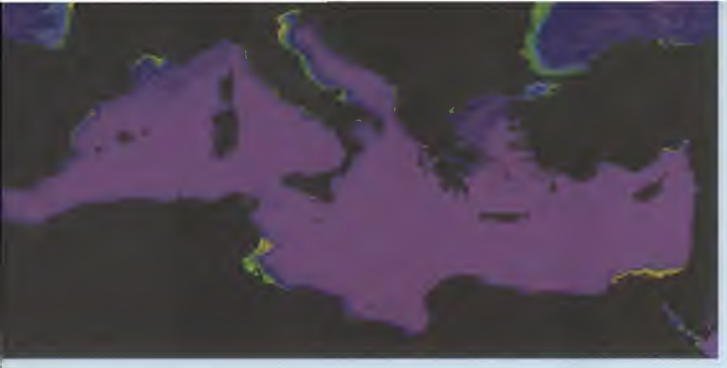
The speed and direction of the surface wind is estimated from a measurement of the surface backscatter made by another active microwave instrument carried on ERS-1 - the wind scatterometer. Although the speed is directly related to the strength of the backscatter, an estimate of wind direction requires the same spot on the surface to be viewed from different directions in order to resolve ambiguities. In the case of the ERS satellites three antennae are deployed - one looking 45° in the forward direction, one abeam and the third at 45° to the rear. In the open ocean these three measurements are normally sufficient to determine wind direction.

With so many islands and coastlines in the Mediterranean, there is a serious problem in obtaining 3 unobstructed views to allow the wind vector to be calculated. The ESA/Italian processing and archiving facility (PAF) has devised a method to extract the direction using only two of the antennae. Even so, deriving scatterometer winds over the Mediterranean sea surface is much more difficult than over the open ocean.

Work in this area has been carried forward by Italian marine research organisations. The results that emerge are used not in preparing day-to-day weather forecasts but as inputs to numerical circulation models. An example of such an analysis is shown.



Comparison between surface wind fields calculated using ERS-1 scatterometer values and those output from numerical models, for January and July. The scatterometer winds are shown in the upper box in each case.



Summer 1981

Slicks and spills

The Synthetic Aperture Radar (SAR) is sensitive to small changes in the pattern of ripples at the sea surface, and the SAR record is replete with slicks - some produced by natural physical and/or biological processes such as fronts or internal waves; others such as the example shown here are the result of the deliberate dumping of oil at sea. This image of an area off the southern Italian peninsula was acquired by the ERS-1 SAR in August 1994.

Experience with the SAR of ERS-1 reveals that the identification of surface slicks depends on the surface wind speed lying in the range 2 - 12m/s. In the Mediterranean many oil spills have been revealed on the SAR record but no positive identification has yet been made. Until the carrying of transponders by all ships is made mandatory under international law, the identification of offenders will remain a major difficulty.

ERS-1 SAR image of the Ionian Sea and the southern part of the Italian peninsula. The image covers an area 100km x 75km and was acquired on 31 August 1994. The two dark streaks off the east coast are very likely to be oil spills released by a ship.

Seasat SAR image taken in August 1978 of the area around Majorca. The slicks seen off the coast are most probably of natural origin.

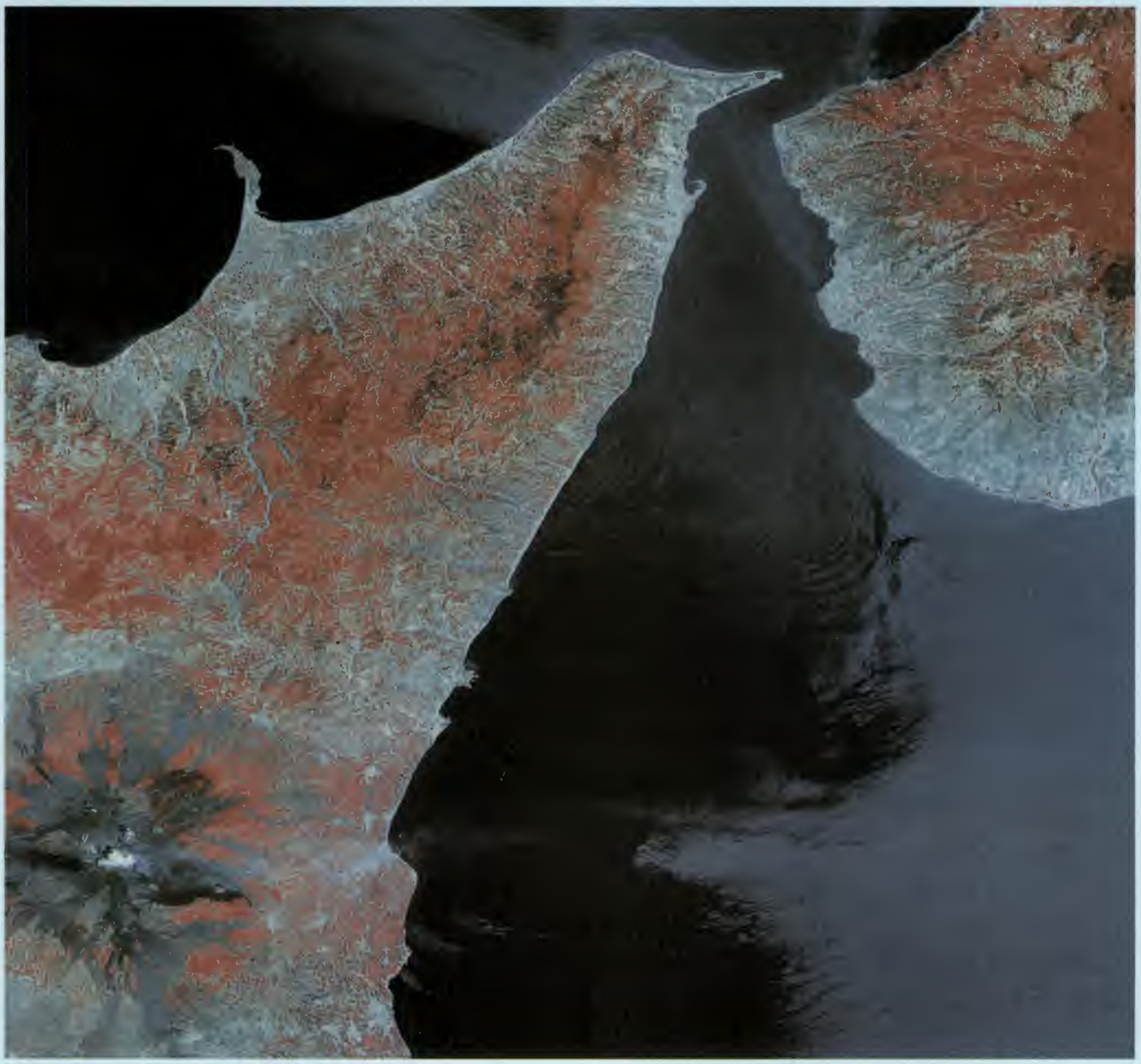
Internal waves are often generated at the interface of two water masses through a forcing mechanism such as tides or currents encountering a bottom feature such as a sill. That is the case in the Strait of Gibraltar where dense Mediterranean water flows out into the Eastern Atlantic and encounters warmer, less saline water flowing in across a sill. Those internal waves can have amplitudes of up to 100m as shown in the record of a buoy, equipped with a vertical chain of temperature measuring devices, moored in the Strait. As the waves pass into the Mediterranean their slow oscillations carry micro-organisms to the surface which dampen the small-scale surface ripples. This effect is captured by the SAR as shown. Other less striking patterns of internal waves are observed passing through the Strait of Messina. The

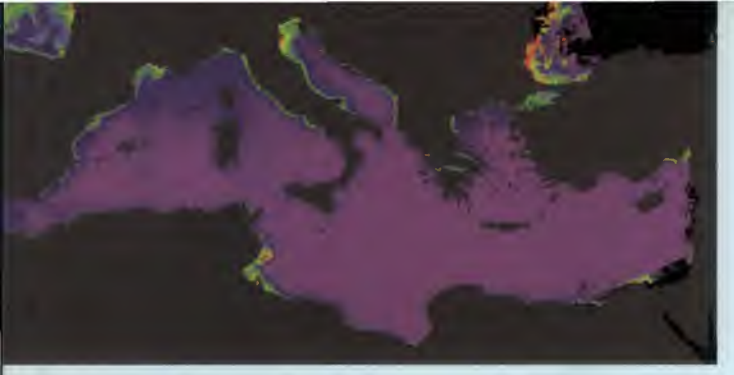
example shown is an image of the Japanese JERS satellite acquired at the Fucino ground station. The Mount Etna volcano is clearly seen in the image.

Slicks which are probably of biological origin are also a common feature on many SAR images of the Mediterranean surface. These resemble the same meandering patterns sometimes observed from aircraft on a sunny day reflecting sun-glint patterns. An example off the coast of Majorca imaged as long ago as 1978 by the Seasat SAR is shown in the example.

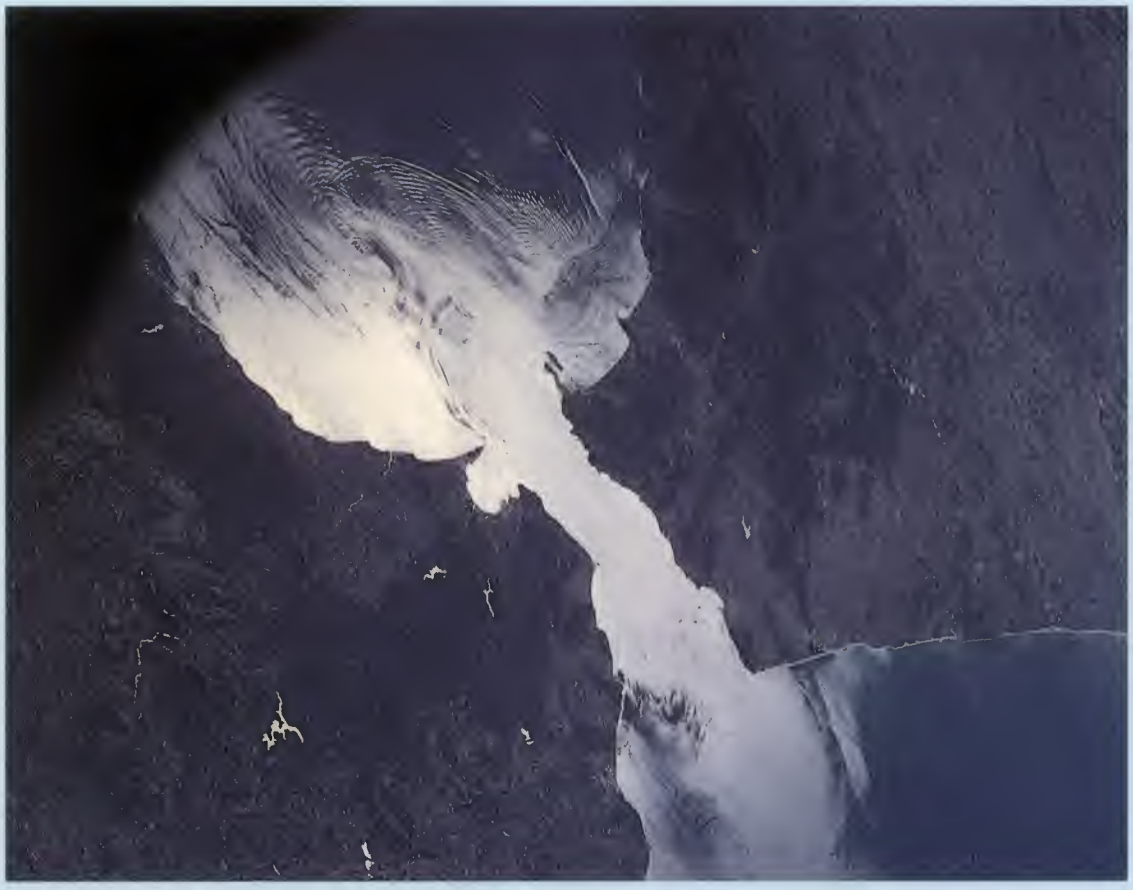
It is sometimes difficult to distinguish these natural slicks from oil spills though the spill tends to present a straighter feature. Investigations are presently underway to identify from the ERS-1 SAR record areas of persistent slicks which are believed to be related to oil seepage. This can provide a useful piece of information when combined with the results of detailed gravity and seismic surveys.

Sunglint image of internal waves in the Straits of Messina. This JERS-1 image was acquired at the Fucino Ground Station on 22 June 1992 and processed by ESA/ESRIN, Frascati.

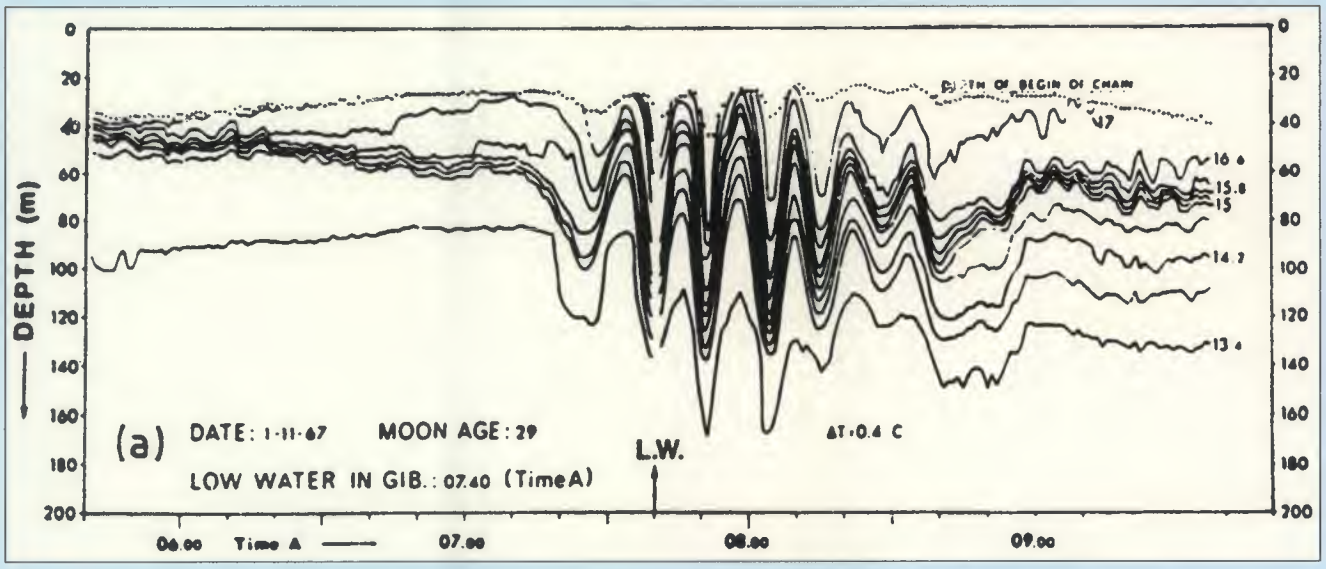




Spring 1981



Internal waves in the Strait of Gibraltar: a SAR image.



Internal wave signature, east of Gibraltar, as measured using moored thermistor chains. The temperature contours are shown at 0.4°C intervals. The oscillations during the passage of the wave reach up to 100m.

Winter

Spring

Summer

Autumn

Coastal Zone Colour Scanner (CZCS) on Nimbus-7. From the top: 7-year seasonal averages of chlorophyll pigment obtained from CZCS imagery in the period 1978-85.

Colour

In common with infra-red radiometers for measuring sea-surface temperature, colour scanners cover wide tracts of ocean on any one pass.

The Coastal Zone Colour Scanner (CZCS) which operated on Nimbus-7 in the period 1978 - 1986 had a swath width of 1636km which ensured that successive orbits overlapped, providing at least one daytime pass per day over every point on the earth. This gives them a distinct advantage over narrow swath instruments such as SAR or the radar altimeter but, of course, neither colour nor infra-red devices can penetrate cloud.

The CZCS carried 5 visible wavebands and one infra-red. The bandwidths were selected to respond to the known properties of chlorophyll absorption. These were narrower than the bands of the Landsat Thematic Mapper and the detectors were made more sensitive to respond to the relatively low radiances of sea surfaces.

Although the CZCS was deployed as an experimental rather than an operational sensor - so there was no commitment to a continuous archive of global data - its longer-than-anticipated lifetime provided an impressive archive which remains today the only global perspective of the variability from place to place and season to season of ocean colour.

At the time of writing there are at least three ocean colour sensors planned for launch. The uncertainties that dogged previous plans to launch a replacement colour sensor call for a note of caution to be introduced in forecasting future developments, but it seems likely that within a short time ocean colour data may again become available after a decade's gap in the record.

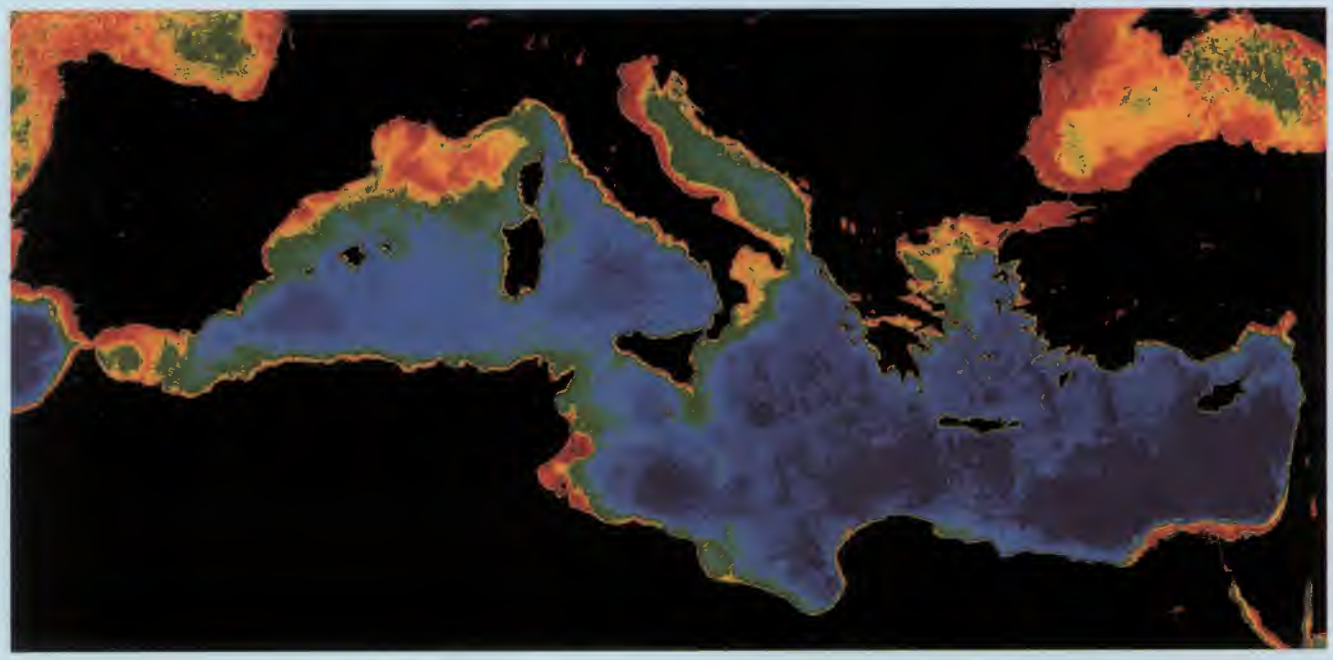
Data from the Landsat Thematic Mapper and other visible sensors have in fact been used for ocean colour studies, in the absence of a dedicated ocean colour instrument. Their better spatial resolution may in some cases compensate for poorer spectral resolution.

Phytoplankton and sedimentation

The spectral properties of pure sea water are known. For observations of ocean colour to be interpreted in terms of water-quality parameters it is clearly necessary to know how these parameters may affect the optical properties of the water.

Water containing phytoplankton has complex spectral characteristics. The living cells of the plant organisms and algae contain chlorophyll used for photosynthesis and since this requires solar power as its energy source it is to be expected that chlorophyll absorbs sunlight

Winter 1981

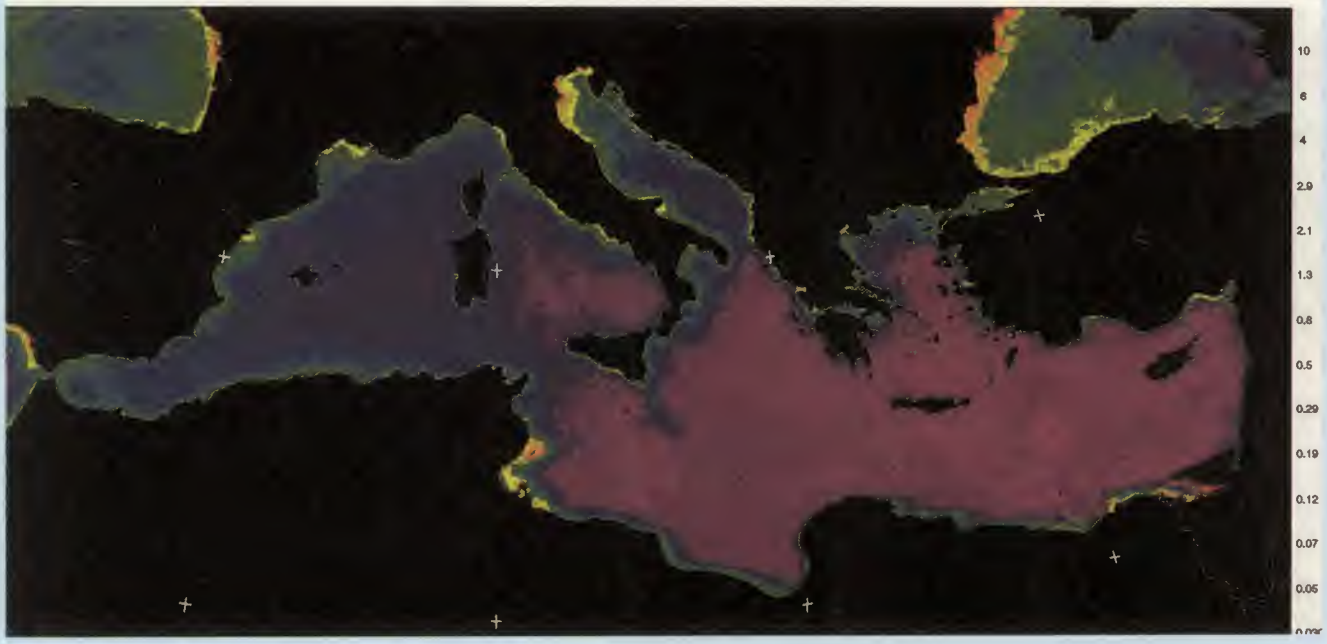


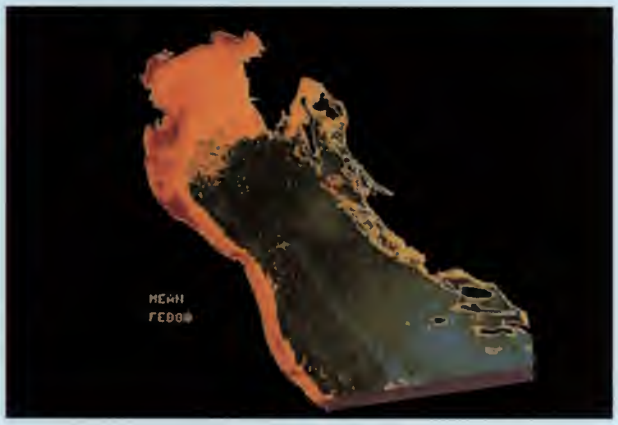
Chlorophyll-like pigments in the Mediterranean, as derived from CZCS imagery. The relatively clear, pigment-poor waters of the Mediterranean contrast sharply with the plankton-rich Atlantic waters off north-west Spain as illustrated in the lower image which is the actual mean concentration for 1980. The upper image was produced from thirty scenes acquired during May 1980. Significant pigment concentrations are seen along southern France and Spain. Localised areas of high production are in some cases due to pollution from human activities.

OCMEDIAN797912:Chlorophyll-like Pigments

OCEAN © JRC/CEC

Product Date	Annual '79	Mapping Projection	Albers Equal Area
Composite Type	average	Map Scale	1:1638523





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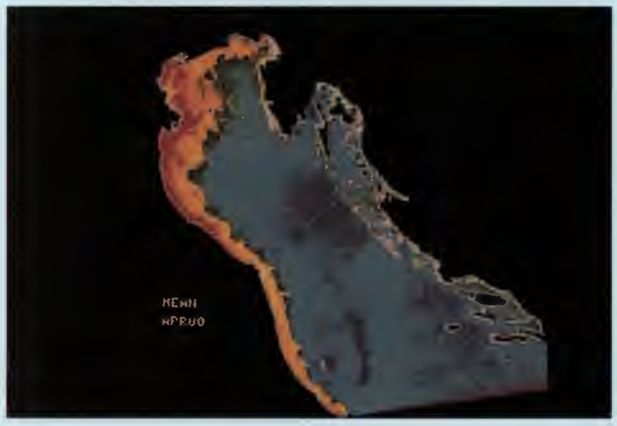

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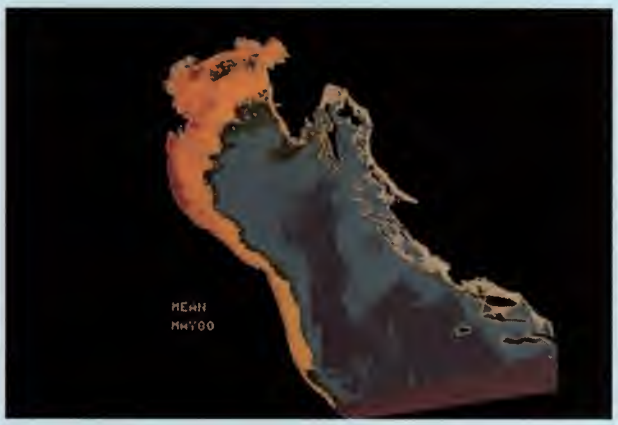

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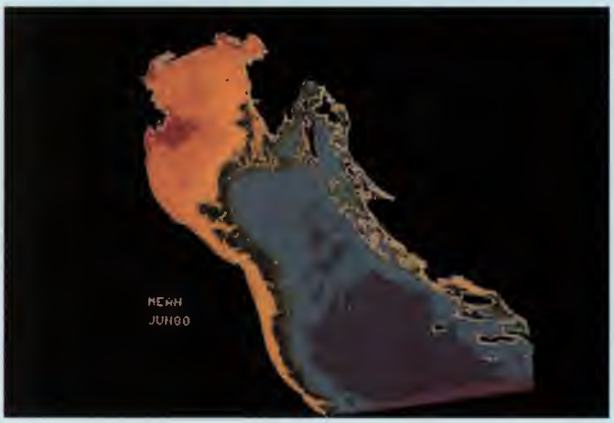

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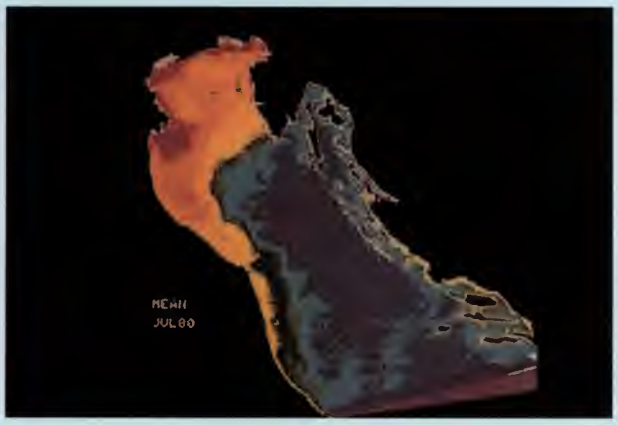

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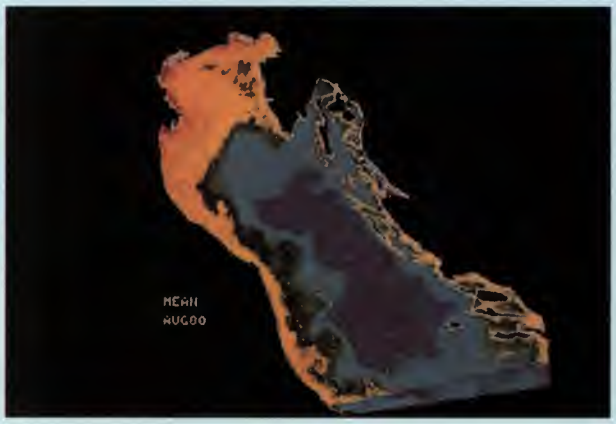

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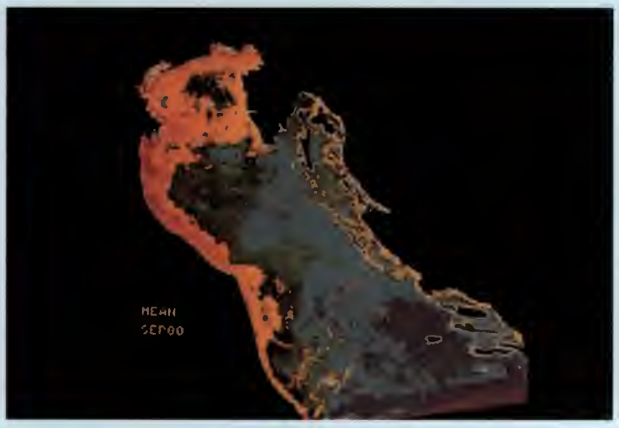


g

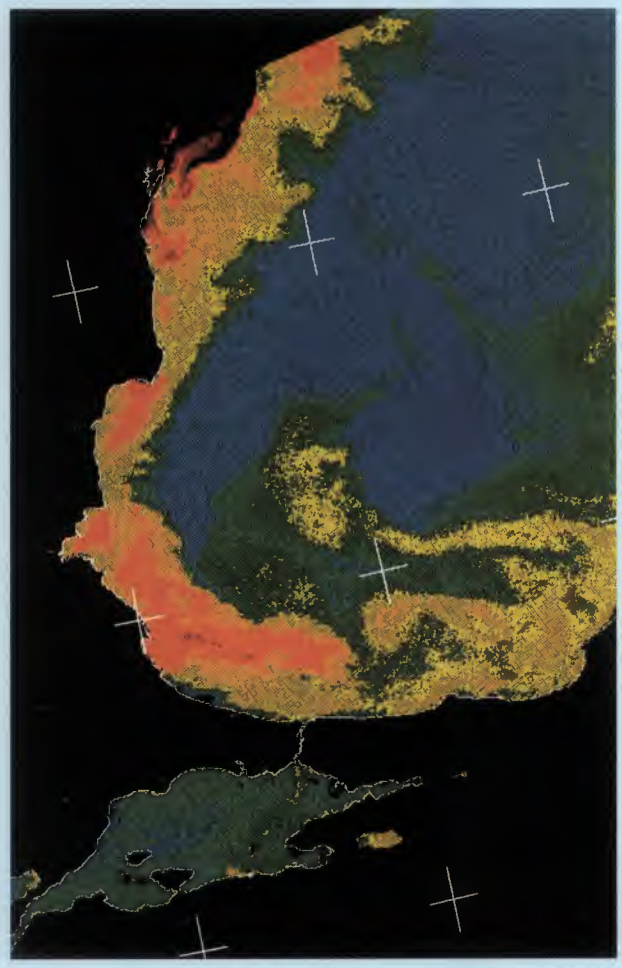
Monthly mean images of chlorophyll-like (phtyoplankton) pigments in the northern Adriatic, for February and April - September 1980, as derived from CZCZ data. This is one of the most productive areas of the Mediterranean, with significant nutrient input from the Po river.

Autumn 1980

strongly in certain parts of the spectrum. The process is not simple. The detritus of dead organisms contributes to both the scattering and absorption of light. The presence of decayed vegetation (yellow substance) and sediment further complicates the problems of interpretation and many scientific papers and text-books have been devoted to the subject.

Some of the most important European research in developing the best techniques for extracting the required information from the multi-band signals has been carried out at the Joint Research Centre of the European Commission at Ispra. Through a joint JRC/ESA OCEAN programme (for Ocean Colour European Archiving Network) all available CZCS data over the Mediterranean Sea have been processed. This analysis has allowed seasonal and inter-annual variability to be studied.

The other major contribution to ocean colour is the presence of suspended particulate material which may be due to bottom sediment, riverborne sediment, eroded coastal and beach material or to the dumping of sewage-sludge waste or dredging spoil. Research carried out on the 7+ years of CZCS imagery has been directed to distinguishing the different contributing factors within contrasting water masses of the global oceans and inland seas.



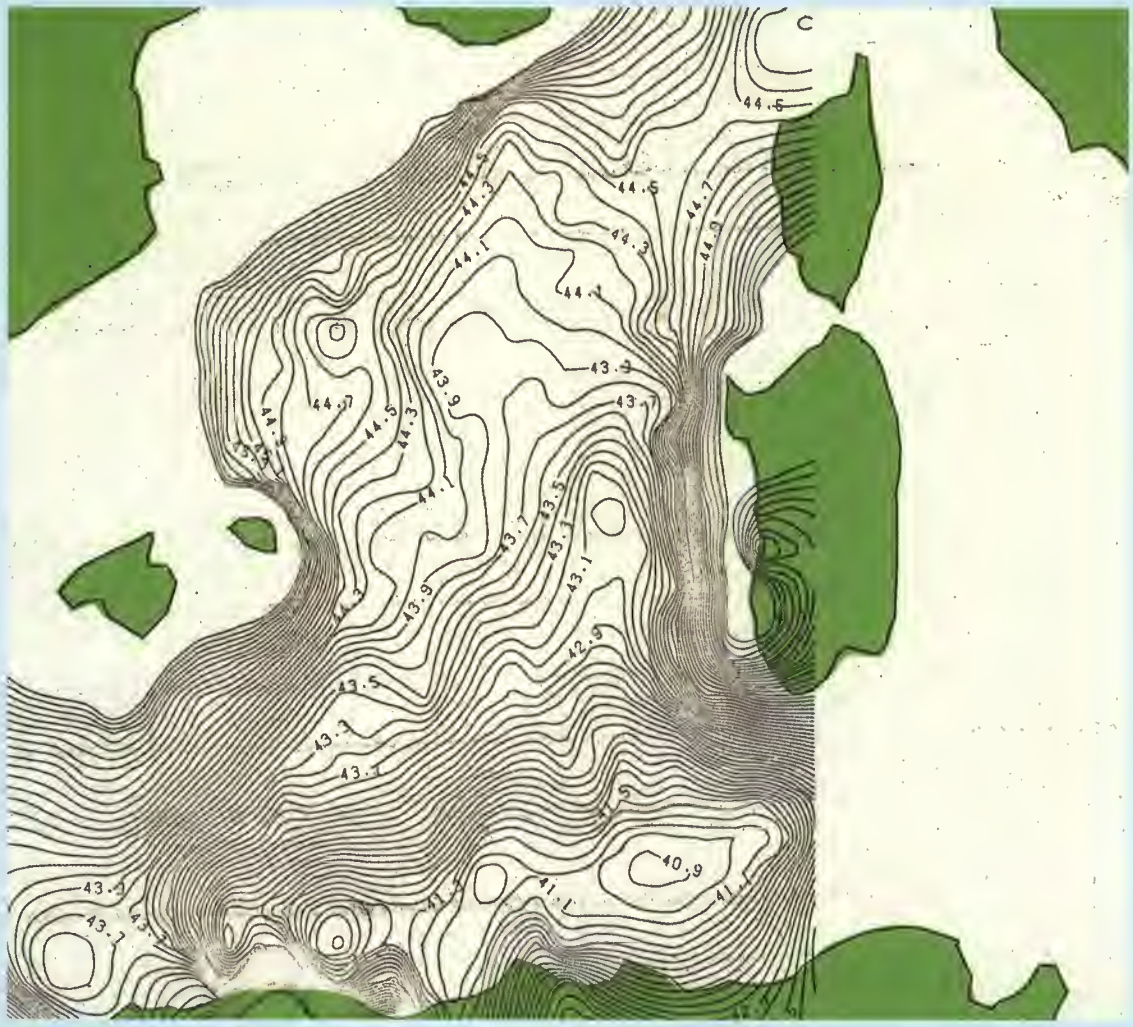
Chlorophyll-like pigments in the Black Sea, from CZCS imagery. Pigment concentration there is much higher than in the Mediterranean.

Surface Height And Gravity

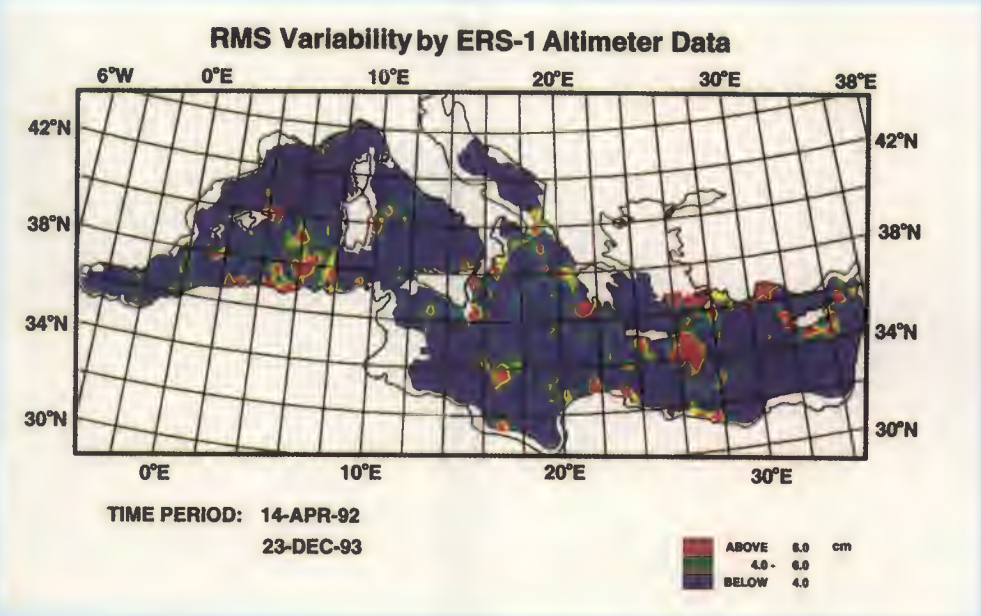
We have seen that a radar altimeter is capable of measuring its own height above the sea surface to a precision better than 10cm, and since there are presently three instruments in orbit around the earth which between them have clocked up over 10 years worth of 1-second recordings, it can be appreciated that estimates of sea surface level and its variability over the Mediterranean have become increasingly accurate. This has required the support of a global network of tracking stations, for the precision of the altimeter can only be used effectively if the height of the satellites is determined independently. Examples are shown of the earliest attempts (with Seasat data) up to the present day where Topex/Poseidon can identify the change in level from one season to another.

Gravity field can now be estimated from the gradient of the altimeter height measurements. Until ERS-1 was placed into an orbit pattern which took 168 days to repeat, the spacing between adjacent satellite tracks had been too wide to allow contouring to be carried out with confidence. Even the 35-day repeat cycle now followed by ERS-1 and 2 leaves a gap of 80km between tracks at the equator.

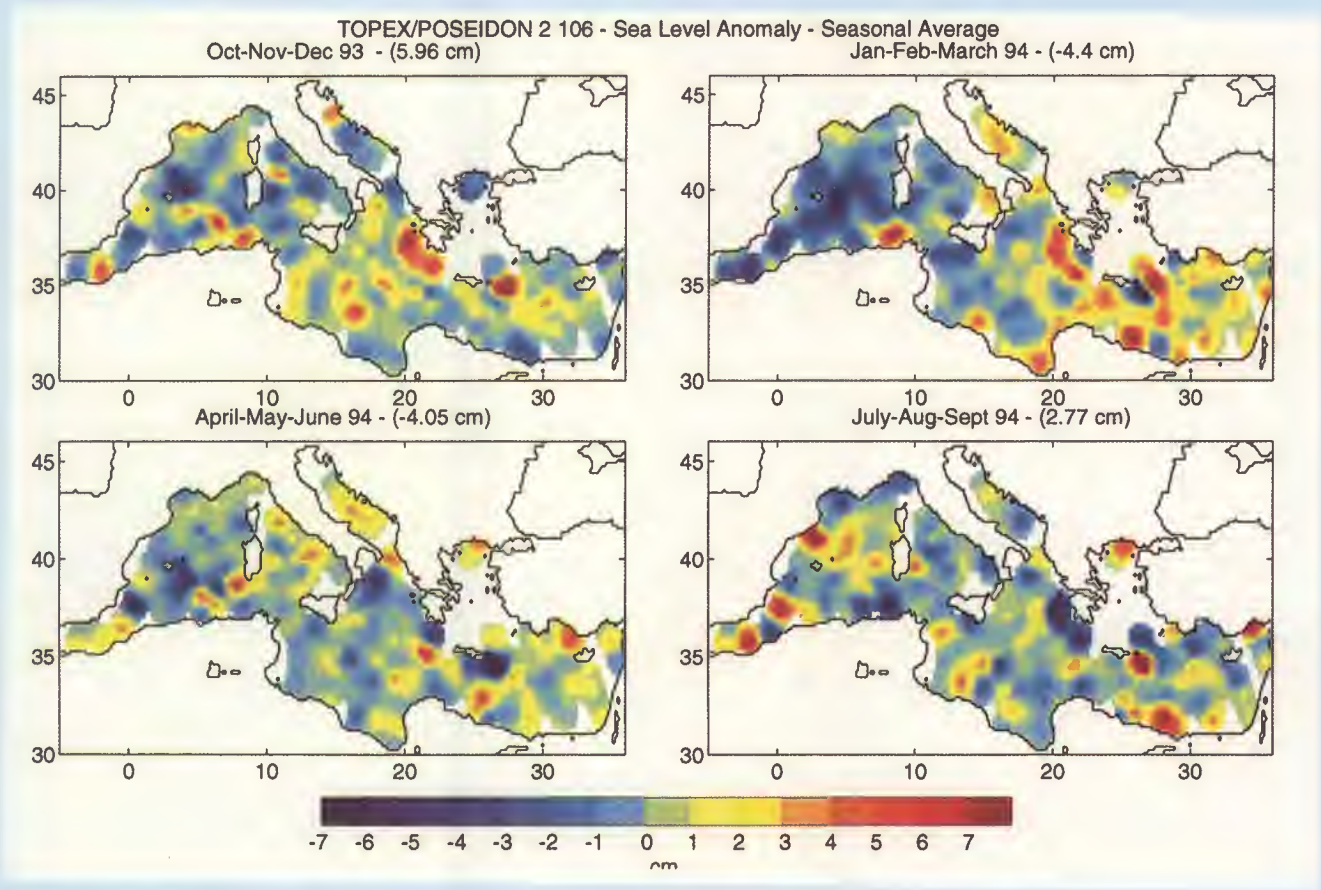
Sea surface height (above a reference geoid), as calculated from Seasat altimeter data for part of the Western Mediterranean. Contour interval is 10cm.



Summer 1980



Root mean square variability in sea surface height for the Mediterranean, as calculated using 20 months of ERS-1 data. High values of rms variability may indicate non-permanent features such as eddies, seasonal currents and upwelling.



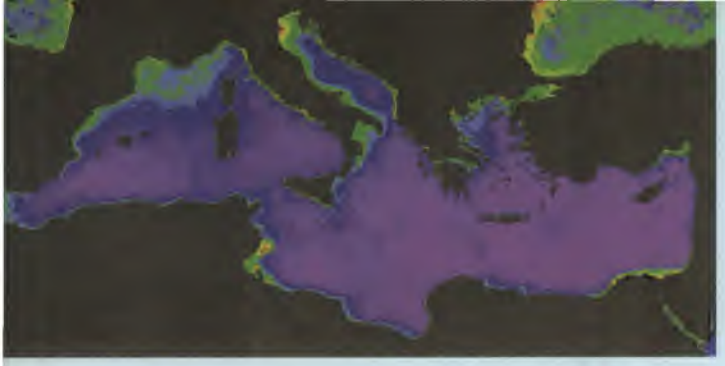
Seasonal sea level anomaly in the Mediterranean as measured by the Topex/Poseidon altimeter. Differences in sea level of a few centimetres can be explained in terms of the different water temperatures (and therefore water density) in Spring and Autumn.

Gravity anomaly field for Strait of Sicily, derived from ship-borne survey.

The 168-day repeat pattern followed by ERS-1 during the last few months of its projected life cycle reduced this to 16km at the equator and to 10-12km at mid-latitudes. Thus the cross-track spacing became comparable to the 7km spacing along track.

A comparison is shown between the gravity anomaly field derived from a ship-borne survey carried out over the Strait of Sicily in the 1960's and the estimates derived from the ERS-1 altimeter. It can be seen that the strike of the main features line up reasonably well.

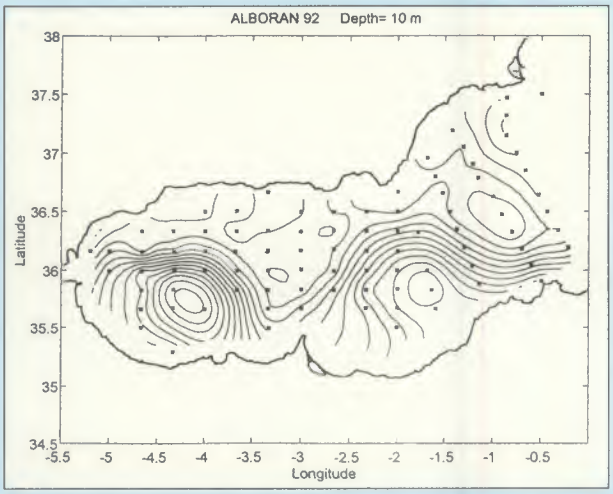
Gravity anomaly field of same area as derived from ERS-1 altimeter data.



Spring 1980

A Case History - the Alboran Gyres

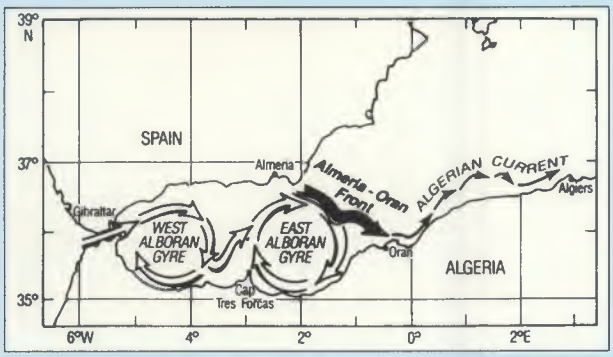
The Alboran Sea is the first check-point the eastward surging Atlantic flow encounters on its Mediterranean journey. It forms a comparatively narrow funnel which for most (but not all) of the time supports at the surface two anti-cyclonic gyres, stretching from Spain to Morocco. Although, in fact, salinity differences dominate, it is the distinct temperature signatures which were picked up so clearly by the earliest of the infra-red sensors carried by polar-orbiting satellites. The counter-flow of this new Atlantic water entering while the 80-year old Mediterranean water slips out quietly underneath to rejoin the ocean has for decades attracted many scientific investigations. The appearance and re-appearance of the two gyres over a matter of weeks or days means that even the most intensive of 'in situ' studies may fail to provide a true picture of the dynamics of the area. The positions of the gyres are clearly reflected in the plot of surface heights calculated from a series of closely-spaced hydrographic stations (measuring salinity and temperature against depth). But the monthly series of AVHRR imagery demonstrated how the most easterly of the gyres changes shape and position, sometimes disappearing altogether.



The surface dynamic topography in the Alboran Sea derived from 134 CTD profiles in 1992, showing the two anticyclonic gyres.

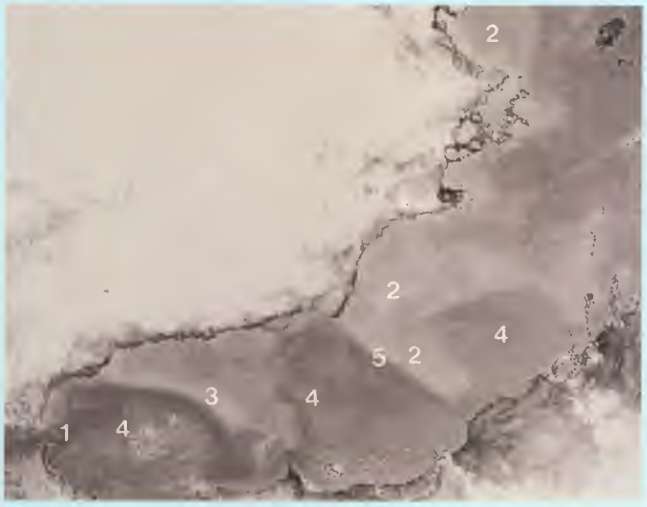
It was largely this satellite imagery that demonstrated, perhaps not surprisingly, that the more generalised models that had been previously used to describe the behaviour of the exchange of water between the Atlantic and Mediterranean - and the subsequent flow along the North African coast - failed to reflect the full range of complexity. In particular the imagery illustrated more graphically than was possible from the detailed but time consuming 'in situ' surveys, that circulation is composed of a series of interconnected mesoscale patterns modified by bathymetry, seasonal changes, meteorology and tides. As that distinguished oceanographer Walter Munk remarked:

> *'It is a fortunate accident that the resolution required for observing mesoscale processes (determined by ocean dynamics) matches the resolution available from satellite orbits (determined by celestial dynamics)".*



Schematic diagram of the surface flow field in the Alboran Sea and along the coast of Algeria.

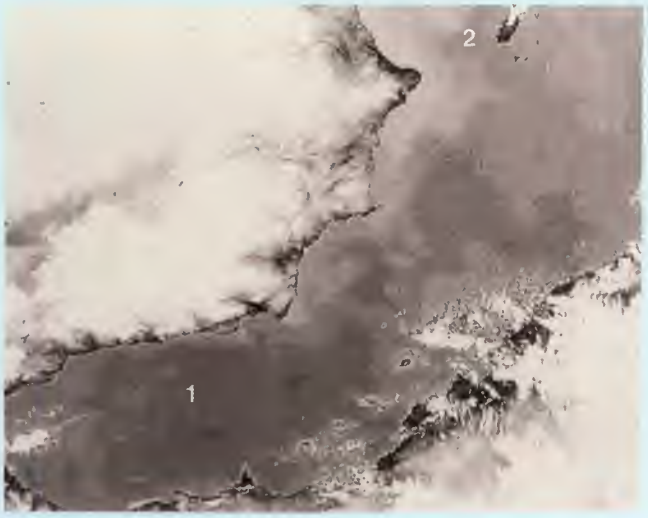
The discovery of such mesoscale features here and in many other parts of the global oceans was important not only in modelling and forecasting the general circulation but also in delineating areas of sharp gradients which may be associated with upwelling of nutrients of importance to fisheries, or with discontinuities in the sound velocity profile which through its marked effect on the performance of sonar equipment attracts the interest of naval forces.



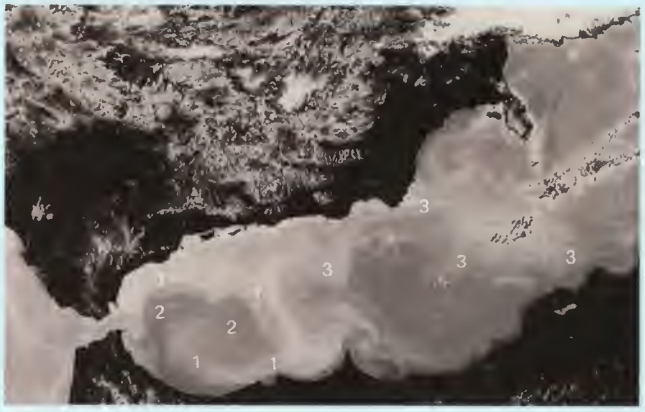
January

February

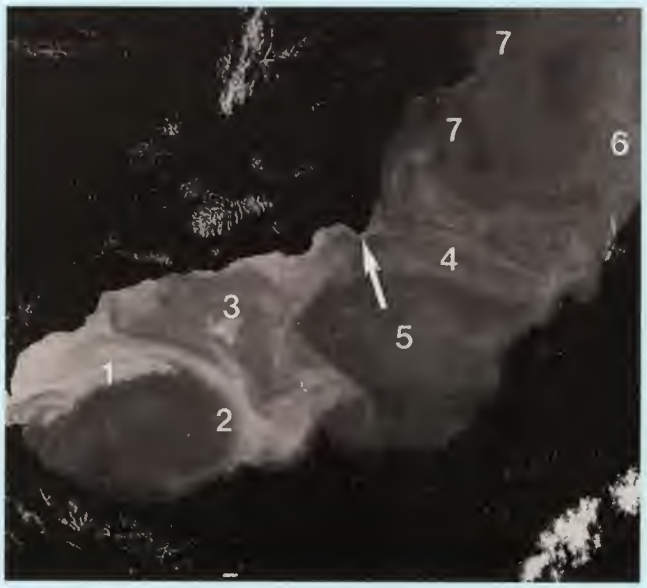
March



April

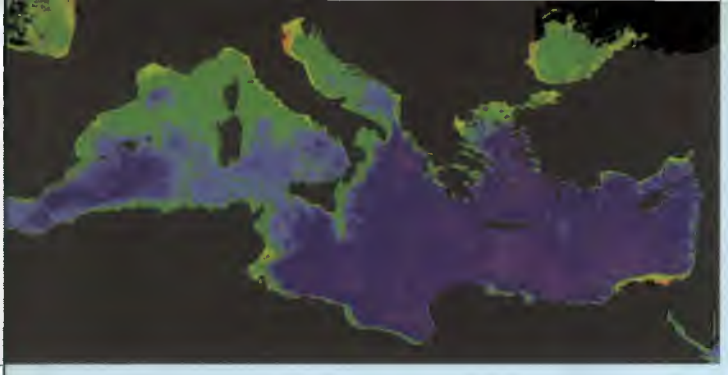


May



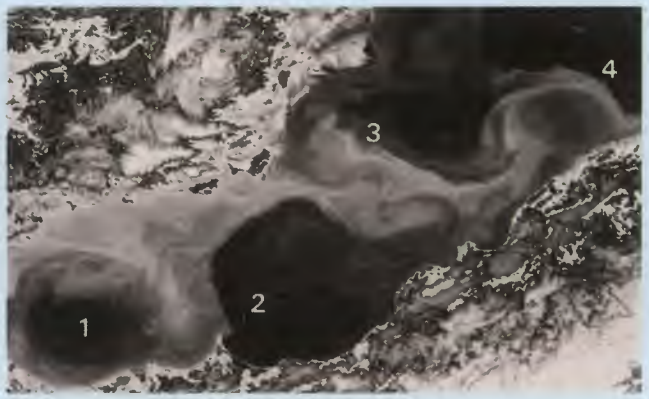
June

A time series of satellite thermal images of the Alboran Sea showing appearance, disappearance and reappearance of the two Alboran gyres.
This page: January to June. Next page: July to December.

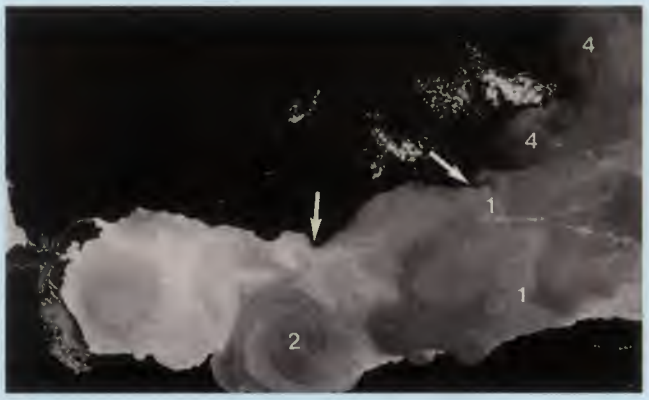


Winter 1980

July

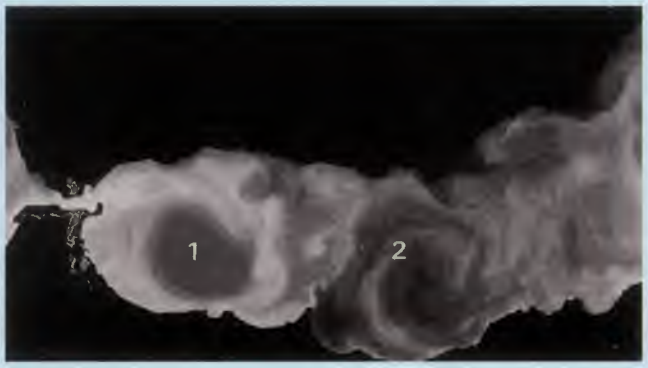


October



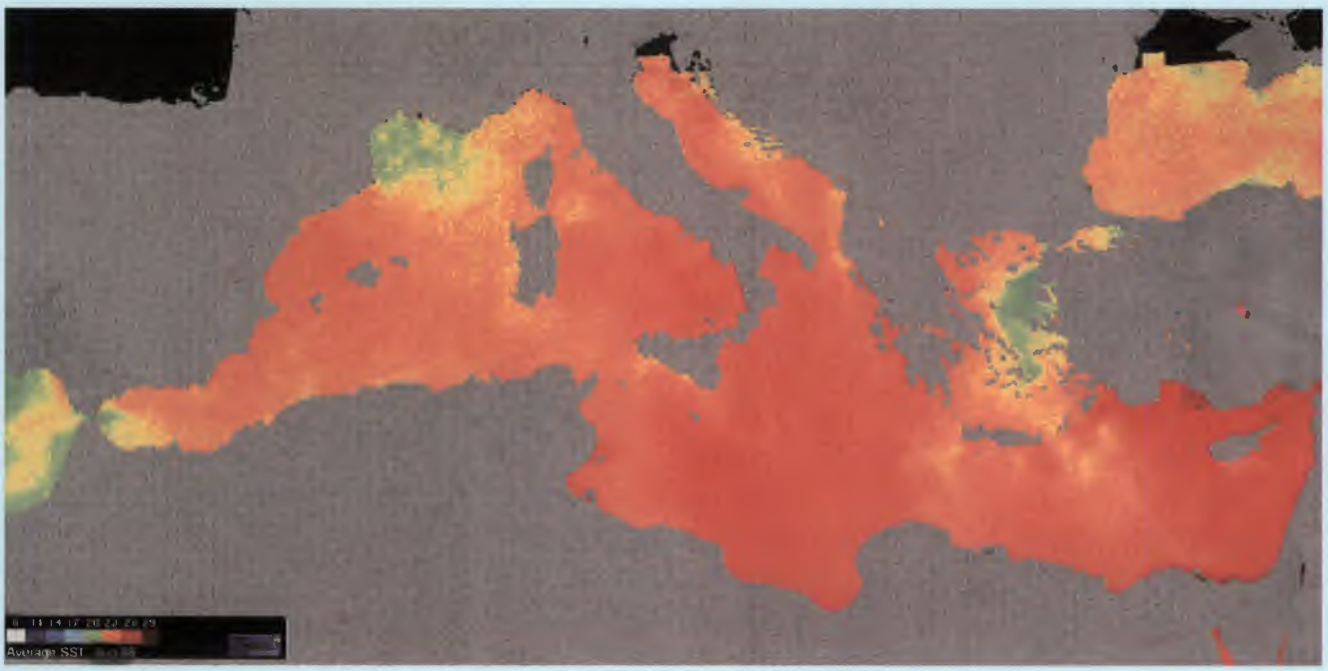
August

November



September

December



The European Commission's Joint Research Centre at Ispra (Italy) has recently added an extensive archive of infra-red imagery (CORSA), based on 15 years of AVHRR imagery, to its OCEAN archive, derived from 7 years of Coastal Zone Colour Scanner imagery over European waters examples of which have been prominently displayed throughout this booklet.

Here we see an example from this latest archive. It portrays the Mediterranean in August 1988 when surface temperature ranged from about 19°–27°C.

Both of these archives can now be accessed routinely through Internet.

WHO MIGHT BENEFIT?

Commercial Activities

Fisheries

Fishing nets hung up to dry.

Fishing activities in the Mediterranean have been going on for centuries, adapting themselves to the local conditions in such a way that a very high catch/primary production ratio exists despite the low biological productivity.

Main commercial fish are hake, flounder, sole, turbot, sardine, anchovy, bluefin tuna, bonito and mackerel. Corals, sponges and seaweed are also harvested.

Exploitation is very intensive in some areas and most are over-fished. Better fish management is being introduced in some areas. In Cyprus production practically doubled by introducing measures to protect stocks. But much of Mediterranean fishing appears to be small scale and legislation is slow to implement.

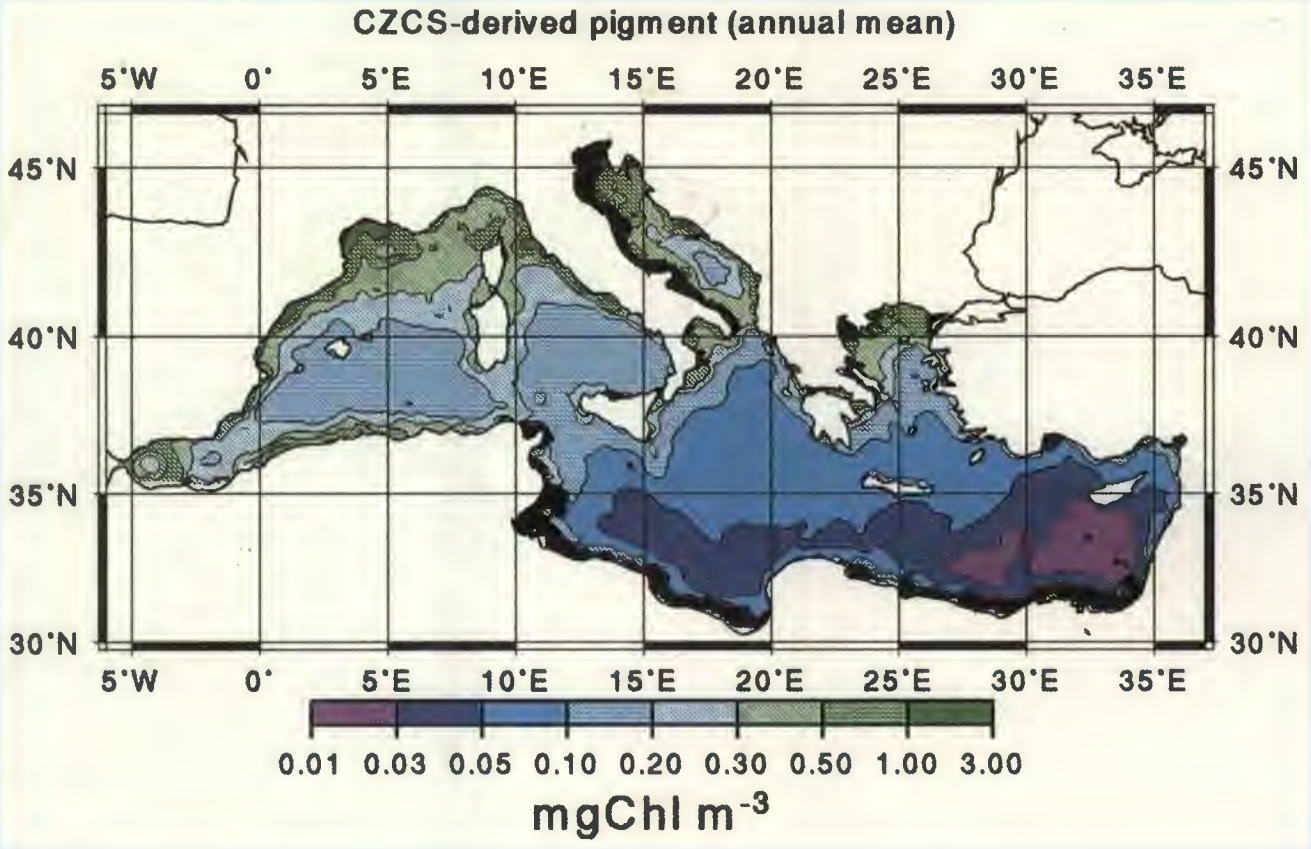
Although the amount of fish caught in the Mediterranean has not altered appreciably over the last decade, distinct differences in catch structure have been noted. In the more developed northern countries, there has been a significant decrease in the catch of average-quality fish such as sardines and mackerel and an increase in the quantity of higher-quality fish such as mullet, perch, dorade. In other countries no real change has been noted in the amount of poor-quality fish caught. While regionally individual fish species may be caught in amounts significantly lower than those that would endanger their survival, some species in some areas are clearly over-fished. Mackerel have now all but disappeared from the Adriatic.

Growing populations and the associated growth of industrial, agricultural and tourist industries are affecting, and will continue to affect, the fishery sector - together with the well-recognised impact over the last decade or so of a largely uncontrolled increase in effective fishing effort.

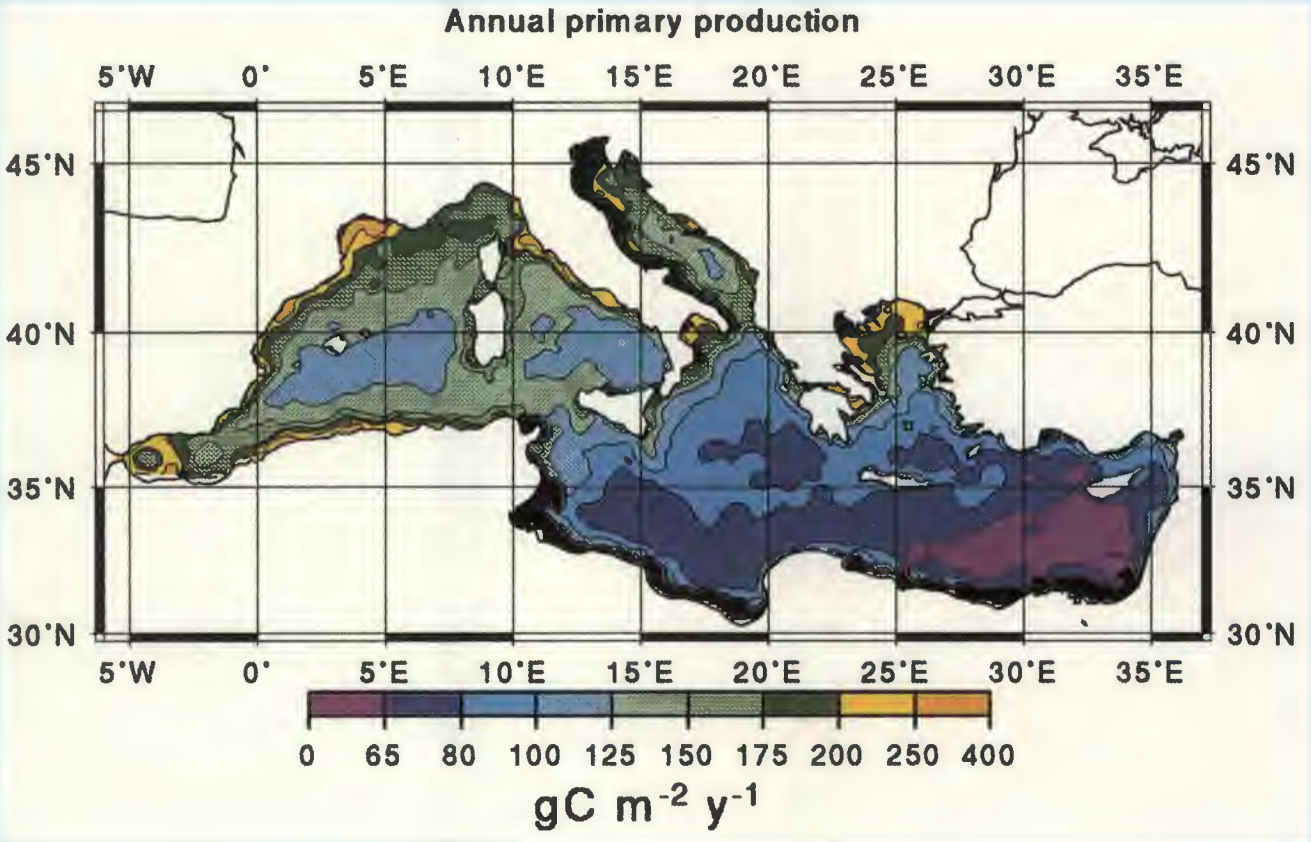
Fishery experts have pointed to three separate types of impact:

i) Discharge of toxic chemicals into river systems. Given the hydrographic conditions and low flushing rates of the Mediterranean these chemicals will tend to accumulate. The main risk actor today is probably mercury where several species tested exceed the levels permitted by some countries.

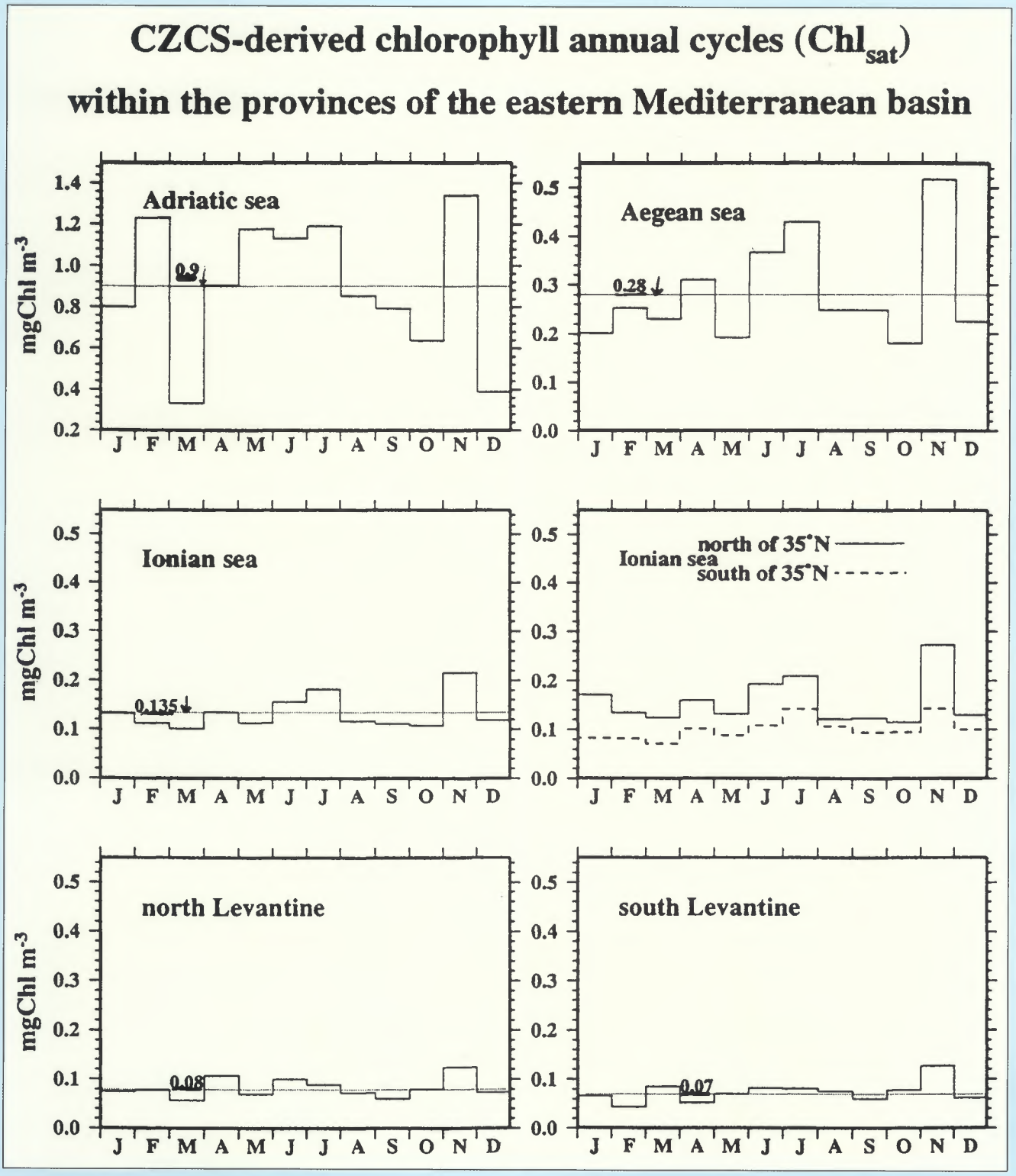
ii) The discharge of biodegradable organics and nutrients increases primary production and changes the ecosystem - first in coastal areas, lagoons and estuaries, ultimately in offshore areas.



Annual mean chlorophyll pigment concentration, as derived from satellite ocean colour images for the years 1979-81.



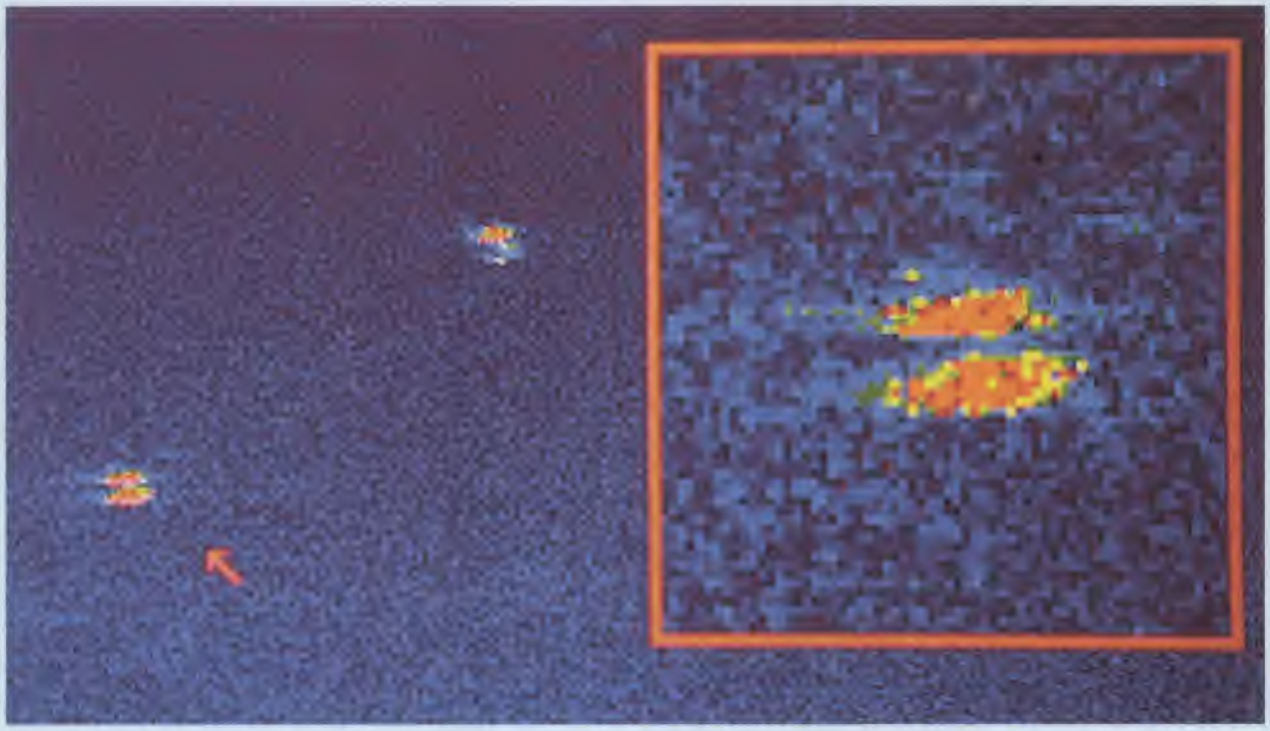
Primary productivity, calculated using the pigment concentration shown top as input to a spectral light-photosynthesis model.



CZCS-derived chlorophyll monthly concentrations for the provinces of the Eastern Mediterranean basin. The Adriatic and Aegean have significant nutrient inputs from rivers, and in the case of the Aegean, the Black Sea. These inputs vary with season. Seasonal upwelling also contributes to the variation in chlorophyll concentrations throughout the basin.

SAR image of pair of whales. Airborne. The whales appear to occupy an area 60m by 20m.

A photograph of a similar whale, showing the perturbation to the sea surface.



Radar image of the pair of whales, after using the processing developed for detecting tuna.

In moderation these influences may not all be harmful for fisheries; in the early stages, production of certain species may be increased, but their ultimate effects on marine recreational activities are likely to prove serious.

iii) The increasing population - especially the huge influx of summer tourists - creates a high demand, hence high prices for the higher quality fish which without adequate controls are then over-fished. This is undoubtedly the trend today. The main commercial fish stocks are considered to have been at maximum sustainable yield levels for the last decade.

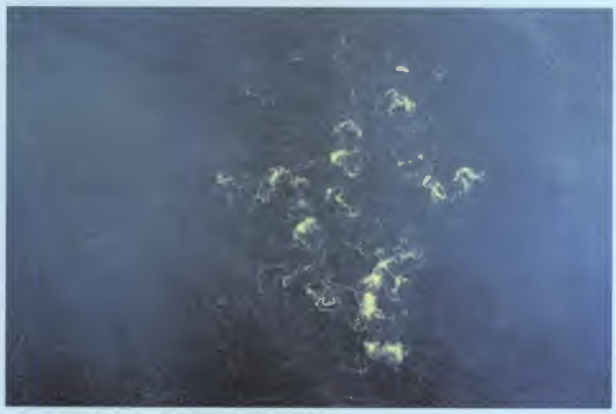
Experts conclude that environmentally induced effects may play a major role and that, ultimately, these could be more serious, and irreversible in the long run than over-exploitation.

Fish shoaling

It has been suggested that in certain parts of the Mediterranean when schools of tunny fish inhabit the surface layers, and occasionally break surface, the resultant patterns of foam and ripples might be located and identified from a satellite. Trials were carried out in an area to the south of the Gulf of Lyons by the French organisation ORSTOM employing a radar-equipped aircraft of the German Space Agency (DLR). Aerial photographs of different-sized tunny are shown to illustrate the extent of surface disturbance.

Although on this occasion no SAR images of tunny schools were made, the example shows the disturbance made by a whale at the surface and the radar image of two such whales.

To date, there is no unequivocal evidence of shoals of large fish in the Mediterranean being imaged by a satellite's SAR.



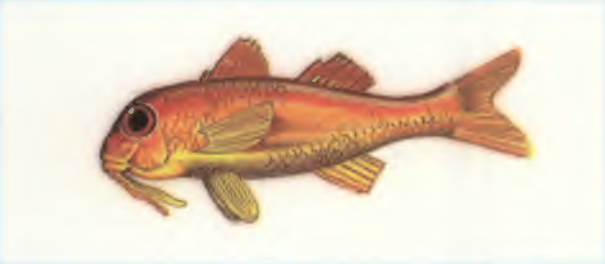
Surface roughness caused by tuna shoals jumping and moving rapidly, resulting in rough, white water. (middle) Surface perturbation caused by subsurface shoal, with ripples at surface. (bottom) Surface perturbation caused by small number of tuna just breaking surface, with localised white patches.

Aquaculture

The techniques in use today in the artificial rearing of fish are not so different from those used in Roman times and, before that, in ancient Egypt. Although the industry is increasing there is competition for space along the already crowded coastline, and at present the number of fish reared in captivity is less than 5% of the total Mediterranean catch. Most aquaculture sites are located in lagoons where water depth is little more than 0.5m.

The most popular species remains the mussel but there has been a small increase in the rearing of sea bream and bass after overcoming initial problems of larvae.

An increasing population and the tourist industry may create a greater demand for fish, but the social problems in the form of increased sewage and less available space are in direct conflict with the need to expand the industry. For example, it is estimated that on average there are today 0.4 tourists for every metre of coastline. The coastline cannot increase but the number of tourists will, so that by the year 2000 the figure will rise to 0.6 tourists per metre.



The effect on aquaculture development is obvious. The cost of land, and hence of coastal installations, is raised and there are obvious conflicts with leisure activities, water sports etc. There are also increasing health hazards from polluted shellfish if untreated sewage is placed close to aquaculture sites.

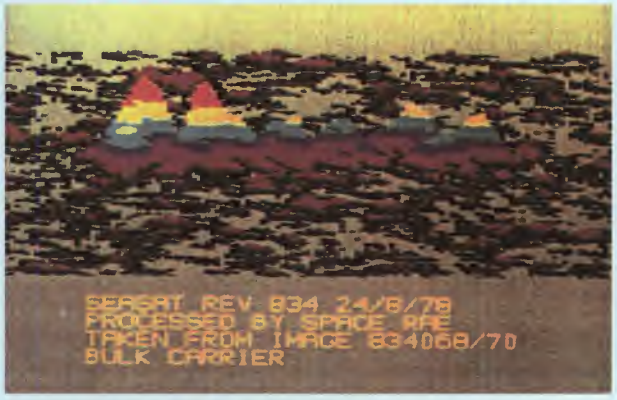
Some countries are expanding in this area faster than others. France, Italy and Spain remain the larger aquaculture producers. Others are trying to attract foreign technology and capital but in such a way that local capital will not lose control of the sector.

But just as the total fish catch in the Mediterranean is very modest by world standards, so the growth of aquaculture remains modest compared to other areas of the world such as Southeast Asia or Northwest Europe. The former has seen a massive increase in prawns, while the majority of salmon and trout on sale in Europe were reared in aquaculture sites - but these would not survive the high temperatures of Mediterranean sea water in the summer months.

There is some concern at the introduction of 'exotic' species suitable for aquaculture rearing since their accidental escape into estuaries may upset established ecological balances. Already the migration of Red Sea fish through the Suez Canal is affecting the biota of the Eastern Mediterranean. The spread of a rapidly growing sea weed which was accidentally leaked to the sea from the Marine Station at Monaco and is reported to be spreading rapidly across the floor of the Ligurian Sea is causing some alarm.

Shipping

Ships passing through Suez Canal.



Seasat SAR image of a single ship.

Seaports are not evenly distributed around the world and the same is true in the Mediterranean. The concentration of ports around the Western Mediterranean reflects industrial concentration and the hinterlands which they must serve. The developments of the last few decades of a comprehensive and efficient inland transport network have resulted in more intense inter-port competition for the European trade with its concentrated population. There have been significant changes over the years as the importance of one seaport declines while another grows.

The Mediterranean was the greatest water route in the world from ancient times until the 16th century. In the Middle Ages cities such as Barcelona, Constantinople, Genoa and Venice were trading centres linking Europe and Asia, their ships bringing goods from India and China via a land-sea route. However, the opening up of the all-water route round Africa to the East by Vasco da Gama in 1497/8 dealt a blow to the Mediterranean routes, and their importance declined until the opening of the Suez Canal in 1869.

The pattern of ship traffic in the Mediterranean has been strongly linked to the history of the Canal. Its opening had an immediate effect on shipping and trade. At that time Britain was a major sea power. The canal reduced the distance London - Bombay by more than 4000km compared to the Cape route. By the 1960's some 15% of world seaborne trade used the Canal. As larger ships were built to improve efficiency so the Canal had to be deepened and widened to accommodate them. The Canal was closed from 1967 to 1975. Even larger ships were designed which then used the Cape route and when the Canal re-opened many continued to use the Cape. That remains true today although further extensions allow ships of 250,000 tonnes to transit. Thus traffic is drifting back though it will probably never reach pre-1967 levels.

Out of some 2000 trading ports in the world about 10% lie in the Mediterranean. However, those 200 account for 90% of the total transport of goods in the Mediterranean. 22% of the total world petroleum traffic travels through the Mediterranean.

The largest port in the Mediterranean, and the second largest in Europe, is the port of Fos in the Gulf of Fos, an extension of the port of Marseille. Fos exemplifies the way in which large modern industrial ports are developed. The existence of extensive flat land areas adjacent to deep water with a nearby centre of population and adequate communications, power and other services have encouraged the siting of large dependent industries in the dock estate. These include steel, petroleum, petrochemical, gas and heavy raw

material industries and services to provide a major industrial complex dependent on the import and export of cargoes by sea.

The proximity of mountain ranges around the Mediterranean coastline results in a comparatively narrow coastal strip with few navigable rivers. This has encouraged the development of bay ports, many of which have their origins in antiquity. Harbours, often involving considerable engineering works, were constructed by the Phoenicians in the 11th century BC, the Greeks in the 7th century BC and later the Romans.

Once the 'pearl of the Adriatic', Venice shared its medieval trading prosperity with Genoa and Pisa. Venice is an example of a lagoon port protected by sand bars. One of the major problems is the continual need for dredging. Passenger vessels and small cargo ships use the old port of Venice but tankers, container vessels and bulk carriers must berth at Porto Maghera, 20km along the canal.

The only natural access to the Mediterranean is through the Strait of Gibraltar through which some 200 vessels, mostly tankers, pass each day. It is estimated that over 200 million tonnes of oil are carried through the Strait each year. Trading between the Mediterranean countries adds considerably to the E-W transits and in world terms the Mediterranean sustains a relatively dense ship traffic which of course is reflected in the number of accidents and spillage incidents.

Oil and gas

The search for oil in the Mediterranean started about 25 years ago. The largest producers are Italy, Libya, Egypt, Algeria. The Bouri field of Libya is one of the most active but other countries such as Greece are stepping up their exploration. One field now yields 1.5 million tons per year. Gas is produced off the Egyptian coast and in the Adriatic.

Exploration has so far produced optimistic forecasts of gas reserves - less so for petroleum. Mediterranean countries account for about 5% of the total world reserves of petroleum and about the same ratio for gas.

A significant proportion of the total world oil-refining takes place in the Mediterranean region. Thus, the greatest threat of pollution from oil may arise not so much from offshore exploration as from the transport of oil.

Tourism

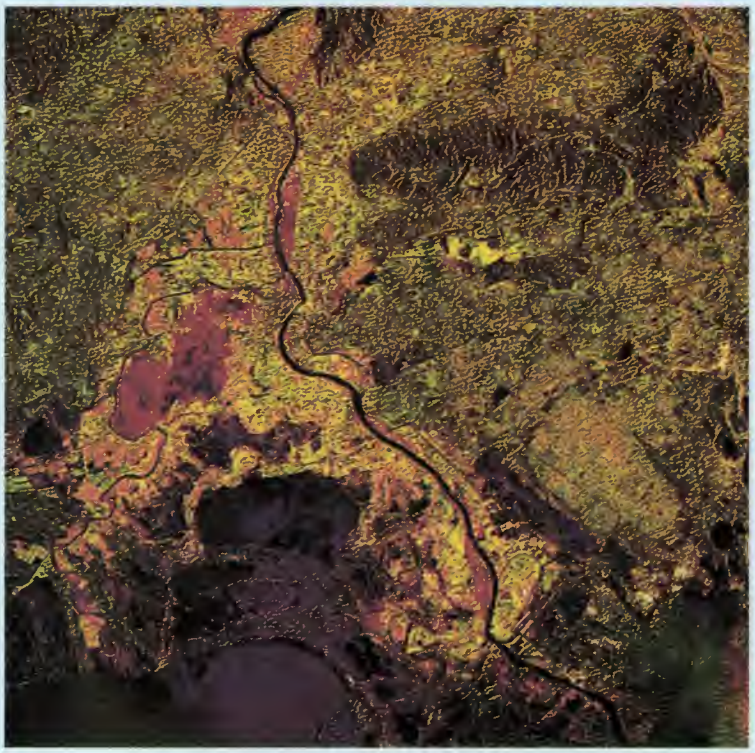
A typical Maltese gondola.

"The grand object of all tourism is to see the shores of the Mediterranean" - Samuel Johnson.

This is still true today. The Mediterranean remains the world's leading tourist resort. Each year some 150 million take up temporary residence. The number is rising and the space available diminishing.

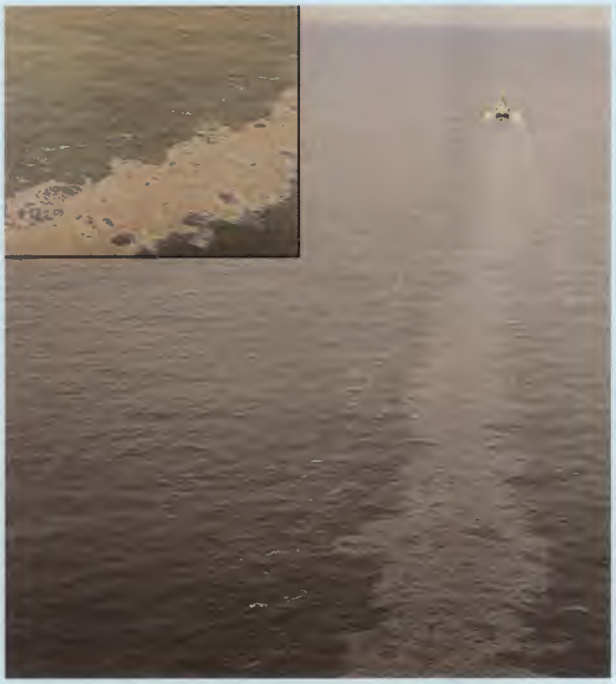
Many of the environmental hazards now threatening many Mediterranean habitats would probably have existed in the absence of tourism. Tourism has intensified the problems - not created them. A fine balance must be sustained and this is probably more difficult for island tourism. Nature allows very little margin of error for people living on small islands.

Cyprus and Malta each face immediate water crises. Desalination plants may be required and these, in turn, demand more power. In Malta a new power plant has been built at the cost of destroying an important coastal area. Malta and Cyprus are already using ground water resources faster than they are being naturally replenished. The depletion of freshwater resources for domestic, industrial and agricultural purposes may become the single most important environmental issue facing Mediterranean countries, and, in particular, their coastal areas and islands.



SAR image of the Rhone delta.

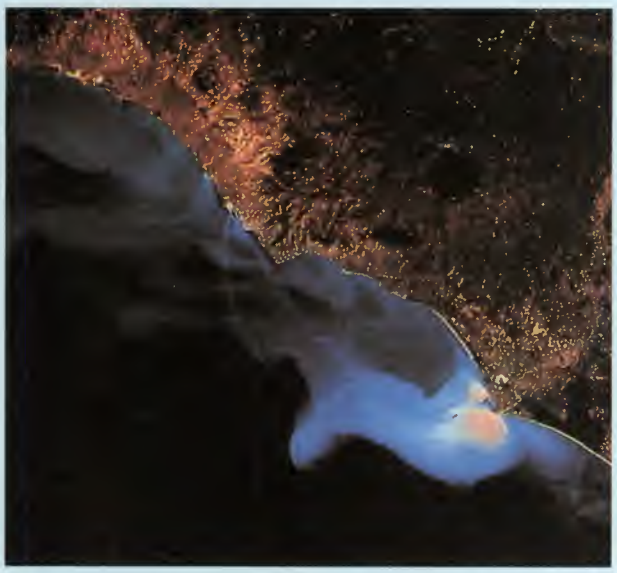
Pollution



Emptying tanks at sea. Oil slicks such as these affect the surface roughness of the water, and may be detected in SAR imagery.

Large-scale pollution from both industrial and domestic sources is seriously affecting the coastal environment of the western Mediterranean. The most heavily polluted areas are along the coasts of north-west Spain, France and around the Gulf of Genoa. Introduction of toxic materials, together with organic pollutants contained in domestic sewage, are both poisoning the coastal aquatic life and starving it of oxygen. Much of the sewage entering the Mediterranean is untreated. Although the sea is virtually landlocked it receives a constant supply of oxygenated water from the Atlantic and as biological productivity is low, due to nutrient deficiency, sufficient oxygen is available for the biodegradation of the lower concentrations of these pollutants occurring away from the coast. More serious in the open sea is the practice of oil tankers discharging waste. Thermal pollution, which so far has not been a problem, is expected to rise due to the increase in thermal generation of power along the Mediterranean coast.

Sediment concentration obtained from Landsat TM data of the Ligurian coast between Genoa and Sturla (north-west Italy). This image was produced as part of a study of coastal water quality using satellite and airborne imaging sensors. Plumes (lightest tones) from two sewage outflow pipes are clearly seen, together with high sediment load in the Bisagno river mouth.



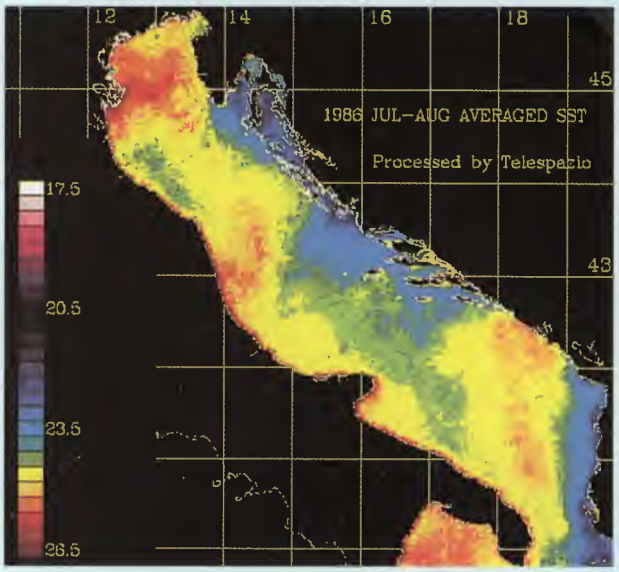
Landsat 5 TM image of the Tyrrhenian coast near Rome showing the change in the littoral current field during a period with heavy spring runoff.

The UN-sponsored Mediterranean Action Plan led to a treaty signed by all but one country in 1980 with the aim of eliminating chemical discharges and fostering a greater degree of co-operation on cleaning up tanker spills.

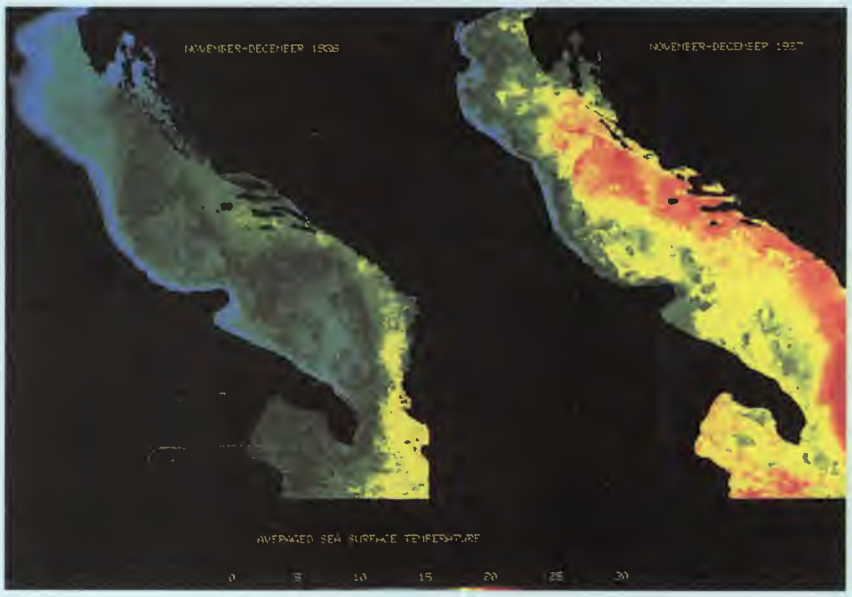
Since many accidental spills go unreported and no one owns up to deliberate spills which exceed accidental pollution, statistics published on oil pollution must be approached with caution.

In the 12-year period 1977-1987, 94 accidents to ships were reported in which oil was lost to the sea in 55 cases. Of the 94 accidents 34% were caused by grounding or sinking and 18% by collision. Of the 55 in which oil was spilled the size of the spill was unknown or unreported in 33% of cases, 34% were small spills (<100 tons), 26% medium-sized (up to 10,000 tons) and 7% were greater than 10,000 tons.

Sea surface temperature in the Adriatic, as calculated from satellite data, averaged over July-August 1986. This composite image indicates that Po river outflow is diverted into the Northern Basin and is retained in the area during the summer. The Po river is characterised by its temperature, shown in red.



SAR image of a slick.



A similar analysis of sea surface temperature averaged over November-December.

Using satellite data in an oil-spill hindcast in the Gulf of Genoa. Oil was lost from the tanker Haven after an incident in April 1991. The extent and location of the slick were modelled, and the results compared with imagery from the SPOT satellite. Data from another satellite were used as input to the model.

(upper) Sea surface circulation as derived from satellite infra-red (NOAA-AVHRR) images for the period covering the accident to the oil tanker Haven. These currents were used as an input to the oil dispersion model.

(lower left) Satellite image (SPOT, visible) obtained on the 14 April 1991, 3 days after the accident, showing extent of the oil slick.

(lower right) Position and extent of oil slick, as predicted by dispersion model.

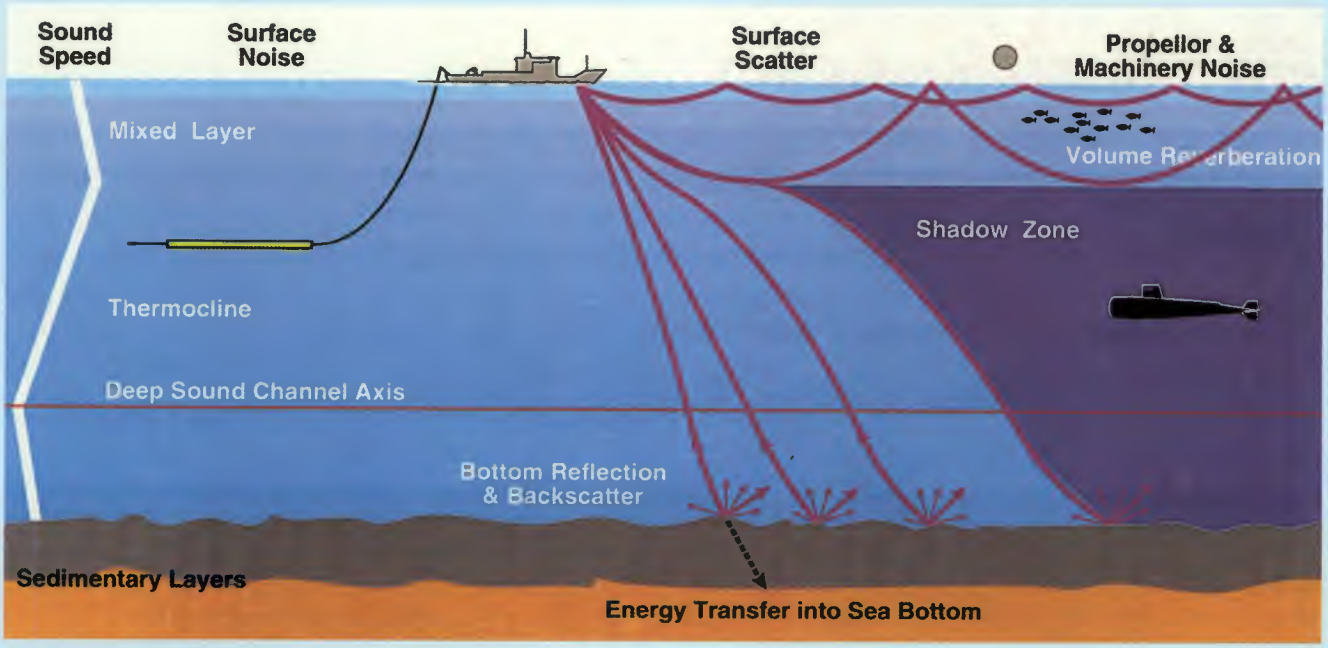
Military Interest

Internal waves in the Strait of Gibraltar, as imaged by the ERS-1 SAR. The passage of these waves has a profound effect on the performance of submarine-detecting sonar systems.

After the break-up of the British Empire, the USA gradually assumed a major role and now maintain a strong presence in the Mediterranean. We need little reminding that the area has been the scene of much conflict since the shift in geo-politics following the end of the Cold War. As a result there is probably a greater demand than ever before for environmental information with satellite surveillance assuming increasing importance.

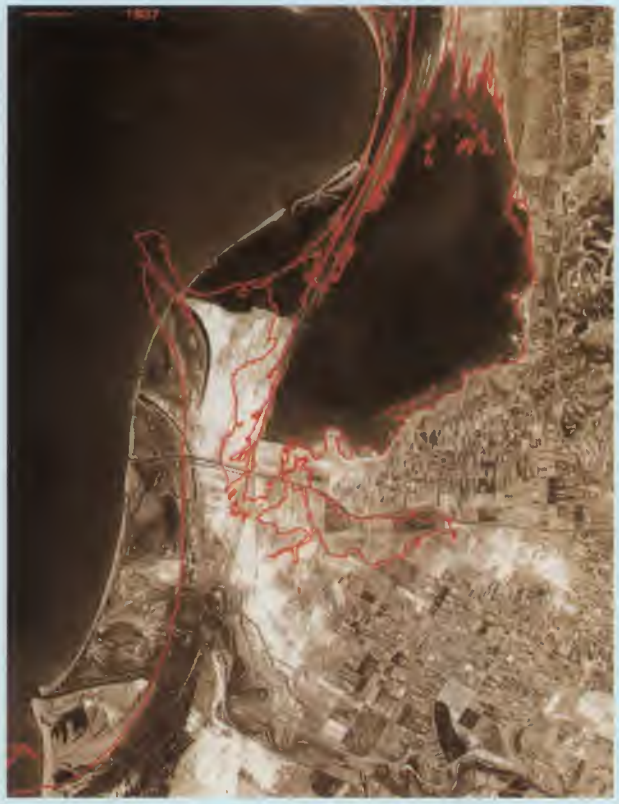
One type of defence research given prominence in the Mediterranean is the detection of submarines by active sonars. These are usually operated from surface vessels but the special conditions of the Mediterranean which is known to support many fronts, eddies and internal wave trains, and especially the strong vertical temperature gradients which may be present in summer, can create the sort of conditions in which a submarine can 'hide' to escape detection. The way in which sound rays emitted by the surface sonar are refracted downwards by strong gradients as shown in the diagram can considerably shorten detection ranges.

For this reason there is considerable defence research carried out in the Mediterranean region on the relationships between sound propagation at sea and the prevailing environmental conditions. Satellite imagery is being used to delineate the positions of semi-permanent surface features.



How sound waves are refracted and reflected according to ocean processes.

Coastal Management



Coastal management may be described as the art of sustaining an acceptable balance between the many conflicting activities and processes described in the previous pages. Natural forces impose their own threat through erosion, storms, algal blooms, floods and the like. But now there is even greater concern over possible human effects on the eco-system - over-fishing, offshore exploration, pollution from ships and effluents, tourist influxes stretching available facilities to breaking point, etc. Accidents can, and do occur. There is a need to maintain a detailed watch on the coastal environment through 'in situ' monitoring. Satellites, by contrast, provide a bird's-eye view and are well adapted to detecting small trends over larger areas. Are pollution levels increasing? How many ships are present in a country's coastal zone? Is there a seasonal upwelling of nutrients and what is its extent? What are the monthly average and extreme conditions of wind and waves? These are some of the questions for which satellite surveillance can provide answers.

As populations increase and the number of tourists grow, the pressures on the environment will become greater. Models to predict its behaviour under certain conditions are becoming more precise as computer power increases. But models, to be effective, require reliable inputs and this is where satellites are beginning to make an impact.

Coastline and lagoon changes for an area in the central part of Albania between Durres and Vlora.
(upper) A SPOT satellite image (10m resolution) acquired in 1992 has been overlaid with the 1937 coastline (in red), derived from maps at a scale 1:50000.

(lower) Maps from 1982 at a scale of 1:25000 were available for some of the area, giving more detail on recent changes.

The ESA Operations Centre at Darmstadt.

Future Developments

In this brochure we have attempted to combine a description of the Mediterranean, and the activities presently pursued within its shores, with an appraisal of the value of monitoring its surface from satellites. After almost two decades of observing the sea surface from dedicated satellites the question now being asked by space agencies, politicians, scientists and commercial operators is, 'What will the next decade bring?'

At the present time satellites are better suited to detecting trends from season to season or year to year. Is the temperature of Mediterranean surface water increasing or decreasing? What conditions lead to phytoplankton blooms, and in what season? Are levels of pollution increasing? What is the range of variability in sea-level? Are mesoscale eddies persistent or transient? Already, remote sensing satellites are contributing valuable information in these areas. Attempts to predict the effects of certain physical, chemical and biological processes through the development of relatively complex computer models must seek to explain the surface structure revealed by satellite signatures.

Although doubts may exist over the long-term environmental effects of man's over-exploitation of the planet's resources, there is universal agreement that we must remain vigilant. For this reason alone, earth-observing satellite programmes are very likely to continue. While climatologists may be more concerned with changes that may affect the global *oceans* it is argued that smaller, semi-enclosed basins such as the Mediterranean may represent an 'early warning' system, changes in its pattern of behaviour reflecting wider, related changes to the global environment.

Another good reason for monitoring the Mediterranean from satellites is to reach a clearer understanding of the many different processes that interact to make it what it is. Already satellites have revealed a complexity hardly contemplated by early scientific investigations. The fundamental goal of all research is to be able to predict behaviour with a degree of confidence and while today this might be possible for some of the Mediterranean's basic characteristics, the details of many processes - and their knock-on effect on others - severely limits our predictive capability. So scientific research will continue until models and observations converge - and, in this, satellites will continue to play an essential role.

Increasingly however, the governments of countries that support earth observation programmes are seeking tangible, operational benefits. In this booklet we have reviewed the type of commercial operations in the Mediterranean that could derive significant benefit from information extracted from satellites. Fisheries, aquaculture development, oil and gas exploration, shipping, and military operations are identified as potential users of satellite data. Equally, regional and national authorities who carry responsibility for managing their coastal zones will benefit from early warning of oil spills, industrial effluents, poisonous algal blooms or, simply, bad weather that may create a hazard to their shores. In such a tight-knit community countries have a right to be protected from the short- (or long-) term effects of illegal dumping of oil at sea. Satellites can detect the culprits.

Slow changes to eco-systems may be taking place unnoticed. Chlorophyll concentrations or temperature patterns may be changing. River discharges or sewage outflows may be reaching levels considered unsafe by local authorities. Satellite surveillance can act as a monitor.

The Mediterranean enjoys reasonably good weather so that the colour and infra-red sensors which rarely glimpse the sea surface in cloud-shrouded northern Europe can be more effective there. However, if a system of day-to-day repeat monitoring is required there is at present no suite of operational satellites comparable, for instance, to the Global Positioning System (GPS).

Although several agencies support marine space missions of one sort or another there is at present little co-ordination between the separate programmes, each of which reflects certain priorities. Thus, there remains an insufficient number of co-ordinated spacecraft to provide the rate of sampling required for 'real-time' monitoring of fast changing situations such as oil spill tracking, day-to-day coastal zone surveillance, ship detection and identification. Such an operational system would require a synchronised multi-satellite system with a well-co-ordinated ground segment for reception and rapid dissemination of data.

But, whatever the problems that the ocean presents to humankind - whether in understanding more clearly its role in determining our climate, whether as a means of safely transporting fuel and other goods, whether as a depository of our waste products, or repository of offshore minerals and oil which require to be extracted with minimum risk, whether as a provider of living resources either farmed or captured from the sea, or whether as the preferred location for holidays to countless millions of people - satellite surveillance of the surface now offers a valuable tool, unavailable to all previous generations.

Acknowledgements

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Notes