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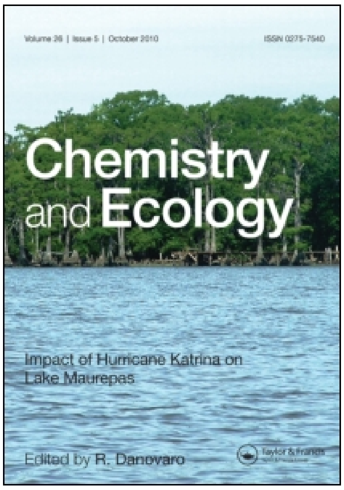

Chemistry and Ecology
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713455114

Applications of Satellite Remote Sensing to Marine Pollution Studies

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To cite this Article Park, P. Kilho , Elrod, Jane A. and Kester, Dana R.(1991) 'Applications of Satellite Remote Sensing to Marine Pollution Studies', Chemistry and Ecology, 5: 1, 57 — 73
To link to this Article: DOI: 10.1080/02757549108035244
URL: http://dx.doi.org/10.1080/02757549108035244

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Chemistry and Ecology, 1991, Vol. 5, pp. 57–73
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APPLICATIONS OF SATELLITE REMOTE SENSING TO MARINE POLLUTION STUDIES

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(Received July 16, 1990)

There are two approaches in the application of satellite sensors to marine pollution studies. Satellite sensors are used to observe and characterize ocean pollutants such as industrial wastes and oil. In addition, satellite observations provide information useful in illuminating processes such as eutrophication or air–sea exchange of CO_2, that are important in determining the distribution and fate of pollutants.

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INTRODUCTION

Satellite remote sensing has become a useful tool for observing the world's oceans. It is not feasible to observe the entire ocean surface in a few days by any other method. Ocean basins can be scanned in a few hours by some satellites and smaller regions can be scanned in a few minutes. This synopticity is useful for observing features in two dimensions.

Besides the relative synopticity of large-scale coverage, satellite remote sensing has the additional advantages of observing hard-to-reach places for long periods of time. Therefore, questions of variability can be addressed and anomalous regions or periods can be identified.

There are some limitations to satellite remote sensing. In general, only sea surface or near-surface effects can be observed. The accuracy of measurements are more limited than for *in situ* observations. But for many types of studies, these limitations are not serious.

Therefore satellites are able to serve as watchdogs for the vast oceans. They can monitor large areas with high frequency and detect anomalies that might occur, if the satellite data are routinely processed and monitored themselves. This capability makes them excellent instruments to study marine pollution, assuming the sensors are able to detect the pollutant signals. Salient features of marine pollution that can be studied by remote sensing are changes in the reflectance of the water through pollutants' ability to absorb and scatter light and change the surface roughness (through the wave-damping effect of oil, for example).

SENSOR CHARACTERISTICS

Spatial and temporal resolution become essential considerations when evaluating satellite remote sensing applications and their comparison with ship-based, *in situ*, or aircraft measurement capabilities. A variety of different sensor systems aboard satellites have been used to image the marine environment (Table 1; NOAA-NASA, 1987). Sea surface temperature can now be imaged by thermal infrared sensors with a spatial resolution of about 1.1 km and a frequency of about twice a day. This capability provides excellent synoptic representation of features with scales ranging from 10 to 10^3 km, and their evolution with time can be determined. Unfortunately, the infrared radiation image is blocked if clouds are present.

Sensors operating in the visible range of the spectrum (Table 1) are also limited to cloud-free conditions. The Coastal Zone Color Scanner (CZCS; Hovis *et al.*, 1980; Feldman *et al.*, 1989), operational between 1978 and 1986, provided a spatial resolution of about 825 m at nadir and a potential image frequency of nearly one each day. The Land Remote-Sensing Satellite (Landsat) thematic mapper (TM) yields a 30-m spatial resolution and an image once every 18 days. The French SPOT system has a spatial resolution of 10–20 m and an image frequency of once every 2.5 days.

Visible spectrum sensors are used to observe the "colour" of the ocean. Water

Table 1 Some satellite oceanographic sensors. (After Robinson, 1985)

Part of spectrum	*Examples*	*Physical parameter measured*	*Application*	
Visible and near infrared	MSS, TM, CZCS, SPOT-HRV	Backscattered solar radiation from below and by sea surface	Ocean colour, pigment concentration, bathymetry, surface slicks, suspended sediment concentration	Passive
Thermal infrared	AVHRR, VHRR	Thermal emission from sea surface	Sea surface temperature	
Microwave	SMMR	Microwave emission from sea surface, reflected solar and atmospheric emission	Sea surface temperature, surface slicks, surface heat flux, sea state, ice, wind and wave conditions	
	ALT	Return time and shape of pulse	Sea surface height and slope, currents, tides, surface roughness	Active
	SASS, SAR	Strength of return pulse	Surface roughness, wind speed and direction, surface slicks, interval waves, topography	

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absorbs light strongly at longer wavelengths and scatters strongly at shorter wavelengths in the visible region (Figure 1). The characteristic blue of oceanic water is the result of strong absorption of red and strong scattering of blue light. The presence of chlorophyll in plant cells can be readily detected in the open ocean because it reduces the blue light reflectance, turning the water colour to green (Stumpf, 1987). Therefore, the chlorophyll concentration is often estimated by the ratio of reflectance of blue to green light. This approach has been followed in development of phytoplankton pigment algorithms for the CZCS. Other substances in sea water, such as suspended solids and dissolved organics, also contribute to the "colour" signal.

Several microwave sensors have been very useful for marine studies (Table 1). The passive microwave radiometer provides a swath image of the radiation emitted by the ocean in the microwave region. It has been used to obtain information on wind speed, water vapour, rainfall rate, sea surface temperature, and ice cover. Active microwave radar systems include the altimeter for measuring distances between the satellite and earth surface, the scatterometer for determining a swath image of surface roughness, and the Synthetic Aperture Radar (SAR) for observing high spatial resolution (25 m) surface characteristics (Fu and Holt, 1982).

Microwave scatterometers view the ocean obliquely and measure the backscattered microwave energy. The amplitude of the return signal is related to surface wind speed and stress or to the surface wave field, depending on the frequency of the microwaves used. The Seasat-A Satellite Scatterometer (SASS) uses a frequency of 14.6 GHz (or a wavelength of about 3 cm) and, therefore, is sensitive to surface capillary-gravity waves of a few centimeters in length. By employing a pair of antennae at right angles to each other, the SASS, in theory, could be used to deduce the true wind direction along with 1 or 3 aliases. The use of a third antenna would reduce the ambiguity in wind direction. In general, SASS winds can be accurate to about ±1.7 m s^{-1} in speed and ±17° in direction (Robinson, 1985).

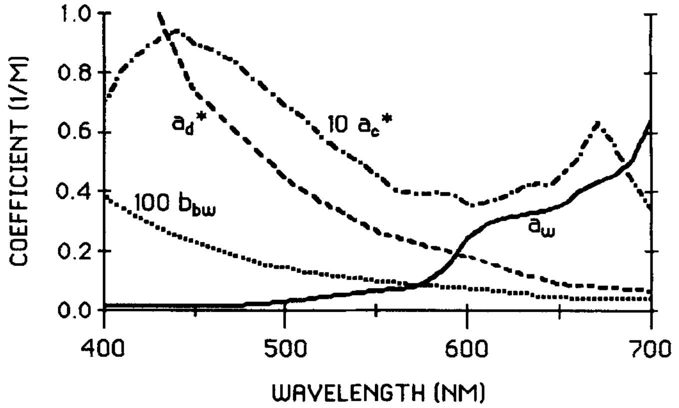

Figure 1 Absorption (a_w) and backscatter (b_{bw}) coefficients for water, and absorption coefficients for chlorophyll (a_c^*) and dissolved pigments (a_d^*) as functions of wavelength. After Stumpf (1987).

One source of interference in scatterometer measurement of wind speed is the presence of surface films, produced, for example, by local biological populations or through petroleum releases. The films damp the surface waves by lowering the surface tension of water. This effect can be exploited to detect surface slicks of oil.

The Seasat SAR operates at a frequency of 1.275 GHz or about 23.5 cm, making it sensitive to surface gravity waves. It can obtain a surface resolution of 25 m and has a swath width of 100 km. SAR imagery is also influenced by the presence of surface oil slicks, as well as rainfall, bottom topography, internal waves, wind stress and ship wakes (Maul, 1985).

Quantitative measurement of sea surface properties have been achieved for temperature and chlorophyll on oceanic regions. Except in these instances, the use of satellite imagery for quantitative assessments is not yet routine. Considerable attention must be given to the algorithms used to process irradiance data received by the satellite and specific properties of the sea surface. Factors such as sun angle, atmospheric attenuation and scattering, and scattering by particles suspended in the water column must be evaluated. As the spectral resolution of future satellite sensors such as the Moderate-Resolution Imaging Spectrometer (MODIS, planned for launch in the late 1990s) increases in the future, the ability to resolve chemical and biological features in the marine environment will improve.

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DIRECT APPLICATIONS OF REMOTELY-SENSED IMAGERY TO POLLUTION STUDIES

Sewage and Industrial Wastes

Aircraft sensors are often forerunners of similar satellite sensors. In the 1970s, several studies investigated the optical characteristics of man-made wastes that were disposed of at designated dump sites off the U.S. coast using aircraft sensors (Hall and Pearson, 1977; Lewis and Collins, 1977; Johnson and Ohlhorst, 1981). Plumes resulting from the ocean dumping of sewage sludge and industrial wastes can be identified and mapped because they possess spectral characteristics that distinguish them from unpolluted waters (Johnson and Ohlhorst, 1981). The different spectra arise from differences in the absorption and scattering of light by the various materials suspended or dissolved in the water. Johnson and Ohlhorst (1981) studied four types of ocean-dumped wastes using aircraft sensors. The data were normalized using an in-scene background elimination technique. Typical spectra of sewage sludge, acid-iron wastes, petrochemical and pharmaceutical wastes dumped in several locations are shown in Figure 2. All but the pharmaceutical wastes had higher radiances than that of unpolluted water. The higher radiances were probably due to increased backscattering by the particulates in the wastes, whereas the lower radiance of the pharmaceutical wastes was due to increased absorbance of light. The acid-iron waste shows a strong radiance-ratio peak at 600 nm wavelength, whereas the sewage sludge radiance ratio has a broad peak in the 700 to 800 nm range. The petrochemical waste had lower overall radiance ratios. Both the Landsat Multispectral Scanner (Klemas *et al.*, 1974 and Ohlhorst, 1981) and CZCS (Elrod, 1988) satellite sensors have also

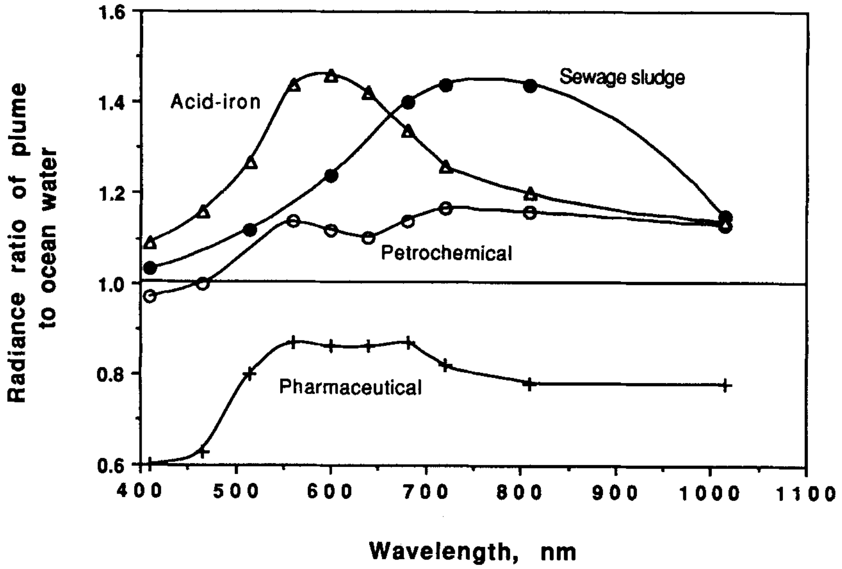

Figure 2 Characteristic spectra of sewage sludge, acid-iron, petrochemical and pharmaceutical wastes. After Johnson and Ohlhorst (1981).

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observed similarly enhanced radiances for plumes of ocean-dumped acid wastes. Acid-iron waste plumes are often persistent, and they have been seen for several days after dumping (Bowker and Witte, 1977; Klemas *et al.*, 1977; Klemas and Philpot, 1981; Ohlhorst, 1981). In contrast, the sewage sludge, petrochemical and pharmaceutical waste plumes usually disappear from the surface within 4–8 hours (Johnson and Ohlhorst, 1981).

The quantitative distribution of ocean-dumped wastes has been mapped using aircraft-generated remote-sensing data of suspended solids in sewage sludge plumes in the New York Bight (Figure 3) (Johnson, 1977 and Johnson *et al.*, 1977). Additional work on acid-iron waste plumes was carried out by Ohlhorst (1978).

Oil Spills

About 6 million tonnes a year of petroleum and its products enter the ocean inadvertently (Wolfe, 1985), mostly from non-point land sources. Oil tanker accidents contribute some too. On 24 March 1989, the supertanker Exxon Valdez grounded in Prince William Sound in Alaska, spilling approximately 21,000 tonnes of crude oil. On 19 December 1989, the Iranian Supertanker Khark 5 exploded in the Atlantic Ocean about 600 km north of Las Palmas in the Canary Islands, eventually spilling 70,000 tonnes of petroleum. Both oil spills formed huge oil slicks and threatened ecologically sensitive coastal habitats nearby.

In the Arabian-Persian Gulf, an oil spill from Kharg Island, nearly continuous since 1982, has been destroying the local fishing industry, forcing the closing of desalination plants (UCAR-ONR, 1989). Space shuttle astronauts aboard the Challenger in 1983 observed and photographed the area. The astronauts readily

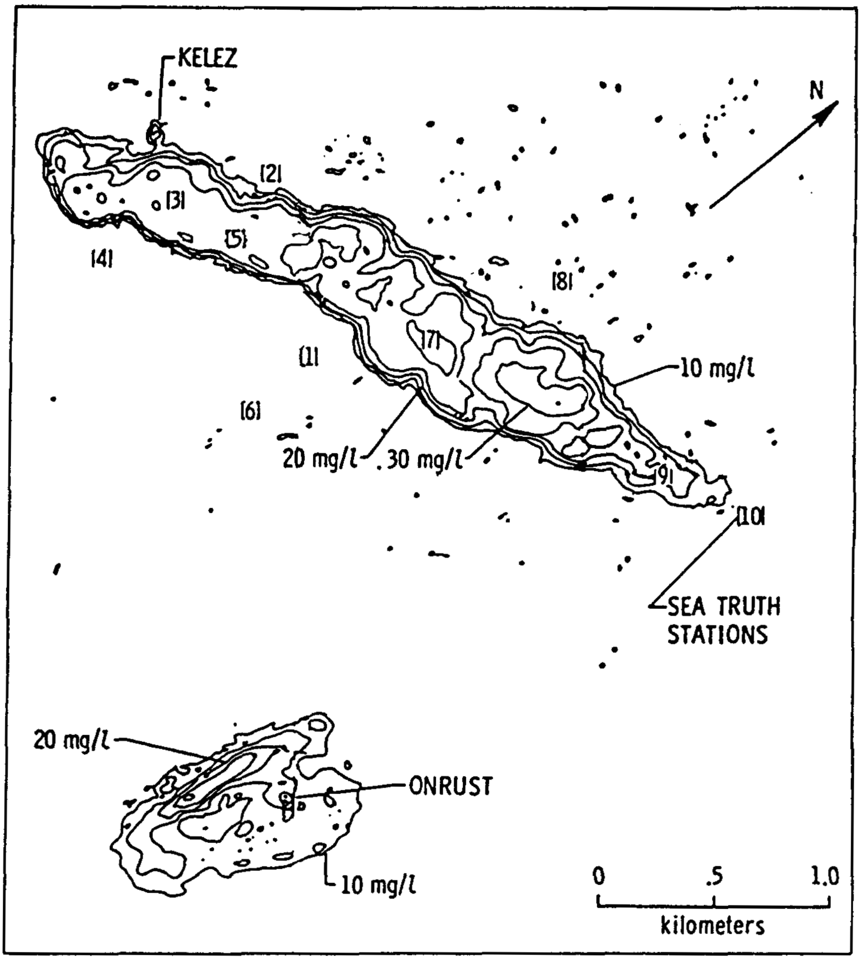

Figure 3 Quantitative distribution of suspended solids in sewage sludge plumes in the New York Bight on 22 Sept. 1975. After Johnson *et al.* (1977).

recognized the surface oil by the iridescent colours appearing in the sun's glitter pattern (UCAR-ONR, 1989). Some selected photographs illustrating oil spills in the Gulf and at the supertanker anchorage off Oman are in the report entitled "Oceanography from the Space Shuttle" (UCAR-ONR, 1989). Satellites, too, have recorded oil slicks frequently. For instance, a persistent oil-slick-like signature between the United Arab Emirates and Iran during 22–29 May 1989 was detected by the National Oceanic and Atmospheric Administration (NOAA-11) polar orbiting satellite's Advanced Very High Resolution Radiometer (AVHRR), but no sea-truth information was available to substantiate it. Also, Asanuma *et al.* (1986) used NOAA-7 AVHRR data without benefit of sea truth to try to distinguish oil spills near the damaged Nowruz oil fields in the Arabian-Persian Gulf in 1983. They examined the difference in night time and day time temperatures and the "apparent thermal inertia" of the targetted water

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mass and attributed a larger temperature difference and a smaller apparent thermal inertia to the presence of an oil slick.

Albuisson *et al.* (1981) reported retrospectively the cumulative area covered by hydrocarbons each year in the Mediterranean Sea to be about 175,000 km^2, based on their examination of 800 Landsat images from 1972, 1973 and 1975. It should be possible to perform a similar analysis with more recent data in the Mediterranean Sea to determine whether the extent of oil coverage has changed.

Several types of remotely-sensed data in the Alaskan waters were used after the Exxon Valdez oil spill. The U.S. Coast Guard used Side-Looking Airborne Radar (SLAR) on 7 April 1989 to determine the distribution of sheen, windrows and mousse originating from the spill in Prince William Sound (Weller, 1989), as

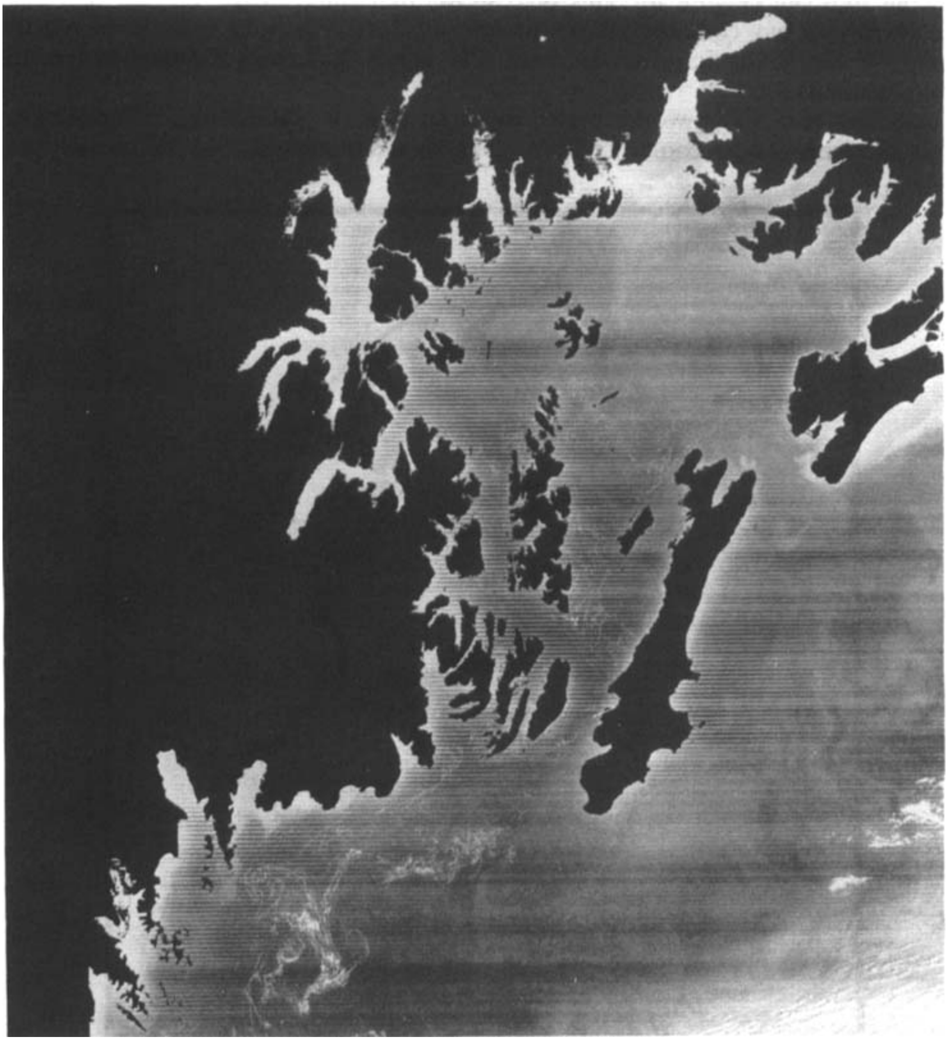

Figure 4 Landsat Thematic Mapper imagery of Prince William Sound on 7 April 1989. Note the spread of the oil slick (bright area in lower left). From EOSAT (1989).

well as off the Cook Inlet in the Gulf of Alaska on 8 April 1989. Concurrently, EOSAT's Landsat 4 satellite obtained Thematic Mapper (TM) imagery of the spill area on 7 April 1989 (EOSAT, 1989). Heavy overcast conditions prevented satellite data acquisition for the first 13 days after the spill occurred, and the 7 April 1989 imagery showed the oil slick already widely dispersed (Figure 4).

W. Stringer of Alaska SAR (Synthetic Aperture Radar) Facility reports that an Interactive Image Analysis System (IIAS) had been used successfully to help track the Exxon Valdez oil spill by providing other spill researchers with satellite-derived background information, such as ocean temperature, currents, and suspended sediment patterns (Stringer, 1989). One interesting result he obtained is a highly enlarged Landsat TM image of Eleanor Island, 70 km south of the spill site (Figure 5). This map shows that some of the oil that had been retained in a bay contaminating a previously clean beach. Stringer obtained this map by combining information from TM bands 1, 2, and 5 (blue, green and mid-infrared).

Stringer and his co-workers also reported that the NOAA-11 AVHRR gave radiant temperatures cooler by 1.5 to 2.0°C at the leading part of the oil spill than

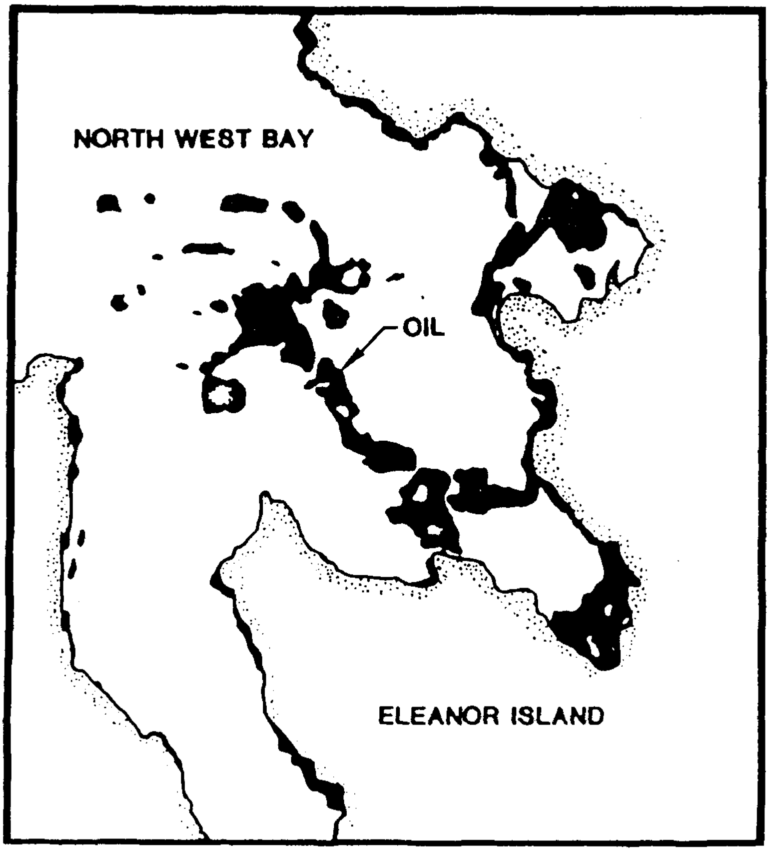

Figure 5 Location of oil spill in Prince William Sound on 7 April 1989. From Stringer (1989).

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in the surrounding sea water on 7 April 1989 (Stringer *et al.*, 1989). The leading edge of the spill then was 180 km south southwest of Bligh Reef in Prince William Sound, where Exxon Valdez ran aground 24 March 1989. Therefore, the spill had moved at an average speed of 15 cm s^{-1} through the combined effects of wind and the Alaskan Coastal Current. These researchers deduced that oil on the water surface and at the temperature of the surrounding water would require an emissivity of about 0.975 to appear that much colder than the surrounding water, which has an emissivity of about 0.993.

The first satellite data available for the Exxon Valdez oil spill was obtained 13 days after the accident, due to persistent, heavy overcast conditions prevailing over the Alaskan region. In the future, however, oil spills can be investigated by SAR that can penetrate through heavy overcasts (Weller, 1989). For instance, Seasat's SAR imagery over the Santa Barbara Basin off California showed oil slicks that come from natural seeps (Figure 6, from Fu and Holt, 1982). Estes *et al.* (1980) reported that the slick patterns observed on the image were consistent with their numerical modelling based on concurrent meteorological and oceanographic data. They also showed that at low wind speeds of about 2 m s^{-1}, oil slick signatures were masked on SAR imagery.

The European Space Agency plans to launch a remote sensing satellite carrying a SAR sensor in early 1991. Japan intends to launch one in early 1992. When these active microwave sensors are in operation, we will have an oil spill

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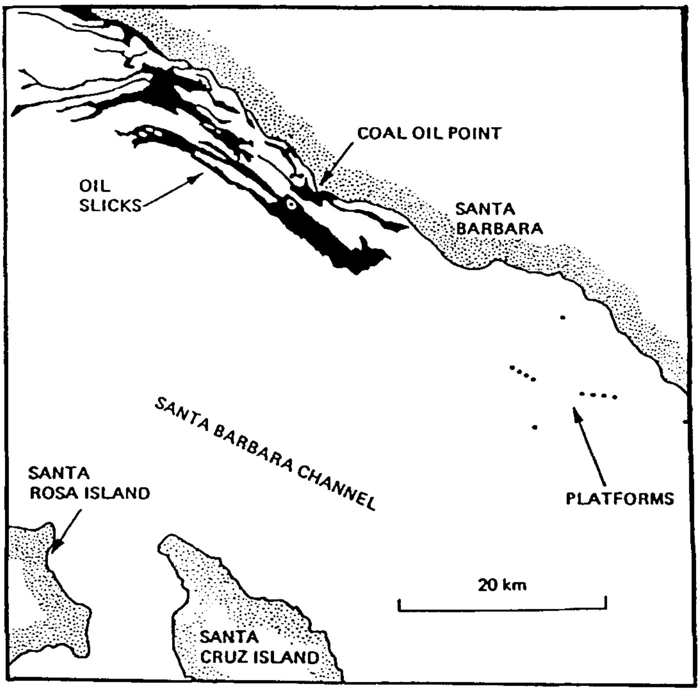

Figure 6 Diagram derived from SAR imagery, showing location of natural oil slicks off Santa Barbara coast. From Fu and Holt (1982).

monitoring capability that is not dependent upon clear skies. A knowledge of the distribution and type of oil makes it possible to deploy recovery, containment, and other mitigation resources more effectively. We strongly encourage the use of satellite technology to alleviate oil spill damage. Some additional theoretical and development work, similar to that of Johnson and Ohlhorst (1981), is needed to understand satellite signatures generated by SAR, TM, and NOAA polar orbiting satellites' AVHRR.

SATELLITE IMAGERY AS A TOOL IN POLLUTION STUDIES

Uptake of Anthropogenic CO_2 by the Ocean

There are a number of applications for satellite remote sensing in marine pollution studies that do not depend on the direct detection of pollutants. One of the important issues that must be resolved in order to assess the effects of fossil fuel CO_2 on climate change is the air–sea flux of CO_2. Evaluation of this flux on a global basis requires good estimates of wind speed, surface roughness, and waves. Satellite microwave scatterometer data is being applied to this problem.

The CO_2 concentration in the atmosphere has been steadily increasing in recent years due to human activities. It has risen from about 270 ppm to 350 ppm over the last 100 years (Figure 7, U.S. JGOFS, 1989). When the industrial emission of CO_2 is compared with the net CO_2 increase in the atmosphere, about 50% of the emitted CO_2 is unaccounted for. A plausible partial explanation for this difference is the ocean's capacity to absorb some portion of the CO_2 emitted. An equally important consideration is the uptake by land vegetation and the consequences of man's impingement via deforestation. Historically, CO_2 concentration fluctuated with glacial and interglacial periods (Barnola *et al.*, 1987). As shown in Figure 7, the anthropogenic increase in CO_2 for the last 100 years of 80 ppm is comparable to the change in CO_2 between a glacial and interglacial period observed in Barnola *et al.* (1987). Man's activities are now a major CO_2 forcing agent.

The exact exchange between the ocean and atmosphere has not been determined scientifically. Furthermore, CO_2's capacity to trap escaping heat to warm the planet surface, including the ocean, can cause a significant change in the oceanic circulation as a feedback mechanism (Washington, 1990). Therefore, in time, the air–sea exchange of CO_2 can be complicated further.

Nevertheless, an important first step of determining the CO_2 exchange coefficient at the ocean–atmosphere interface by satellites has been undertaken by several French scientists (Thomas *et al.*, 1988; Etcheto and Merlivat, 1988 and 1989). Their work is described below.

The CO_2 flux between the ocean and atmosphere is described by $\phi = ks\,\Delta P$ where ϕ is the CO_2 flux, k is the transfer velocity, s is the solubility, and ΔP is the partial pressure difference of CO_2 at the air–sea interface. Etcheto and Merlivat (1988) call the product ks, the CO_2 exchange coefficient K.

The transfer velocity, k, is dependent on the physical factors of wind speed, sea surface state and sea surface temperature, as well as the biochemical state of the sea surface, such as the capacity of the ocean to absorb CO_2 via acid-base titration and the presence of surface-active organic films. For the sake of

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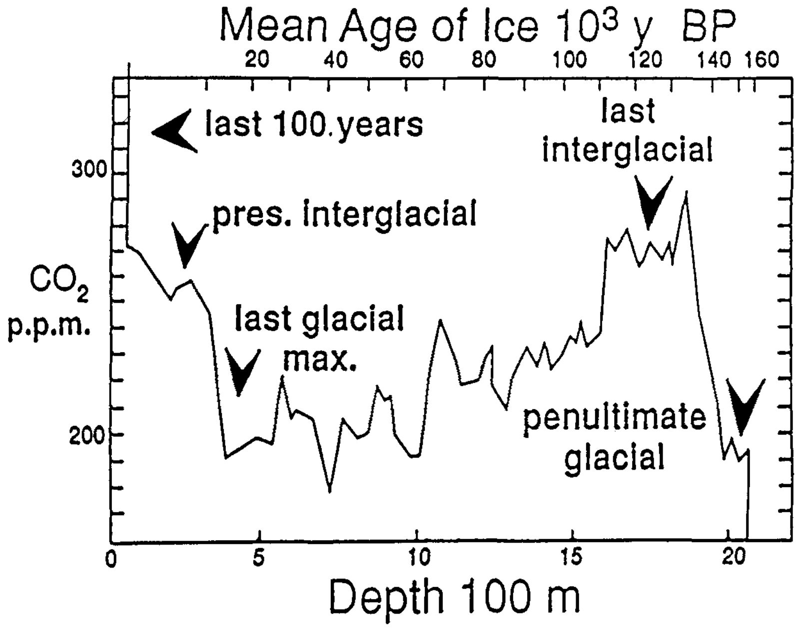

Figure 7 Record of atmospheric CO_2 concentrations derived from Vostok ice core. The increase over the last 100 years due to anthropogenic activities is also shown. After U.S. JGOFS (1989).

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simplicity, these biochemical considerations are not dealt with here. The CO_2 solubility in sea water, *s*, depends much on temperature and less on salinity (Weiss, 1974). At present, satellites can measure sea surface temperature (SST) and can construct the wind speed field.

By a series of approximations and the use of wind tunnel and lake experiments of Liss and Merlivat (1986) that relate the transfer velocity *k*, to the wind speed, Etcheto and Merlivat (1988) computed the CO_2 exchange at the air–sea interface using the wind speed field generated from the scatterometer flown on the Seasat satellite (operational from 7 July to 9 October 1978). They next mapped the net CO_2 flux using the map of CO_2 partial pressure given in Broecker *et al.* (1986) and their computed exchange coefficient, *K*, over the world oceans. The net flux thus obtained was an absorption of CO_2 by the ocean of $1.17 \times 10^{15}\,\mathrm{g\,C\,y^{-1}}$. Climatological wind field data sets yielded higher values of up to 15%. Furthermore the Seasat value is lower than that usually expected from the global budget of the carbon cycle of 2.0 to $2.5 \times 10^{15}\,\mathrm{g\,C\,y^{-1}}$ (Siegenthaler, 1983). Further reconciliation of these estimates is needed.

Despite the limits of the data set used, the global coverage of wind measurements on the ocean provided by spacecraft enabled the establishment of a global map of the CO_2 exchange coefficient and the quantification of the role of individual oceans in accepting the excess anthropogenic atmospheric CO_2 (Etcheto and Merlivat, 1988). Since extensive CO_2 measurements at sea are to be carried out by the World Ocean Circulation Experiment (WOCE) and the Joint Global Ocean Flux Study (JGOFS) in the 1990s, concurrent satellite missions to determine the CO_2 exchange coefficient over the ocean will improve our ability to assess the role of the oceans in accommodating anthropogenic CO_2. Also, it is important to return to the experiment of Liss and Merlivat (1986) to improve the relation between the transfer velocity, k, and the wind speed measured at sea.

In addition to a scatterometer, there are other satellite sensors that can be used to construct wind fields. Wentz *et al.* (1986) compared the wind field derived from a Scanning Multichannel Microwave Radiometer (SMMR) aboard Seasat with that of the scatterometer on the same satellite. They found that at wind speeds between 3 and 17 $m\,s^{-1}$, the difference between the two data sets was very small, but that SMMR underestimated wind speeds below 3 $m\,s^{-1}$ and overestimated wind speeds above 17 $m\,s^{-1}$ by 1 to 2 $m\,s^{-1}$. Etcheto and Merlivat (1989) found the variance of SMMR data to be larger than that of the scatterometer. Furthermore, for SMMR, the wind measurements within 350 km of land or ice were masked and not considered. The Geosat altimeter during the Geosat's exact repeat mission (ERM), 8 November 1986 to 3 October 1989, also could yield a wealth of information to reconstruct the wind field at a range of 1 to 18 $m\,s^{-1}$ with a precision of $\pm 1.8\ m\,s^{-1}$ (MacArthur *et al.*, 1989).

Contaminated Suspended Material

A major issue in marine pollution studies is the partitioning of organic and inorganic pollutants between solution and particulate phases. There have been several studies that have estimated total suspended matter from satellite imagery in coastal regions. Jensen *et al.* (1989) illustrated how estimates of total suspended matter in Laguna de Terminos, Mexico, derived from a numerical model of shipboard measurements, could be related to Landsat Thematic Mapper (TM) data. Their study also indicated the difficulty of coordinating *in situ* data collection with limited frequency satellite imagery. In two instances, cloud cover precluded contemporaneous data sets, and in another instance the satellite data were not recovered. Doerffer *et al.* (1989) also used TM data to evaluate suspended matter concentrations in the German Bight to assist in marine pollution studies. They presented methods to evaluate the atmospheric aerosol correction that must be applied to the irradiance data. Using a statistical method, they identified three principal factors in the irradiances from the seven wavelength bands of the TM. Factor 1 was derived mainly from TM channels 1, 2 and 3 and was attributed to water-column suspended particles. Factor 2 was related primarily to TM channels 5 and 7 and was attributed to atmospheric turbidity because water is nearly black in this wavelength range. Factor 3 was related to channel 6 and represented the surface temperature signal. They were not able to isolate the contributions of phytoplankton chlorophyll or "Gelbstoff" due to the high suspended particulate concentrations (20–80 mg/l) in their region of investigation.

A third example in which satellite imagery can be applied to marine pollution problems is provided by the study by Tyler and Stumpf (1989). They showed the relationship between ship-board data, AVHRR, and CZCS imagery in the Potomac River and Chesapeake Bay, U.S.A., during April 1982. Satellite imagery revealed the presence and dynamics of a phytoplankton bloom with a spatial and temporal resolution that is not possible with ship-based measurements alone. Capabilities of this type can be used to evaluate eutrophication effects of nutrient loading.

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A fourth example is the discharge from the Po River in the northern Adriatic Sea (Figure 8). On 9 October 1984, the U.S. Space Shuttle Challenger crossed the Adriatic coast on a descending pass. The Challenger photograph taken then shows the coastal current spreading the discharge southward from the Po River mouth (Figure 8, given in UCAR-ONR, 1989, pp. 10–11). The light brownish hue of the river plumes is due to calcareous rocks in the Po's drainage basin. The Po River outflow is about 1500 m^3 s^{-3} (Barale *et al.*, 1986). In the river plumes, both domestic and industrial pollutants, including large amounts of nutrients, are transported and dispersed in the Adriatic Sea. These pollutants are frequently claimed to cause catastrophic eutrophication events between the Po delta and the Ancona headland 270 km south (Barale *et al.*, 1986). The available CZCS data over the Adriatic Sea were used by Barale *et al.* (1984, 1986) to study the surface dynamics, and space and time variability of the surface colour field of the Adriatic Sea. It is interesting to note that in the Po River plumes, the concentration of

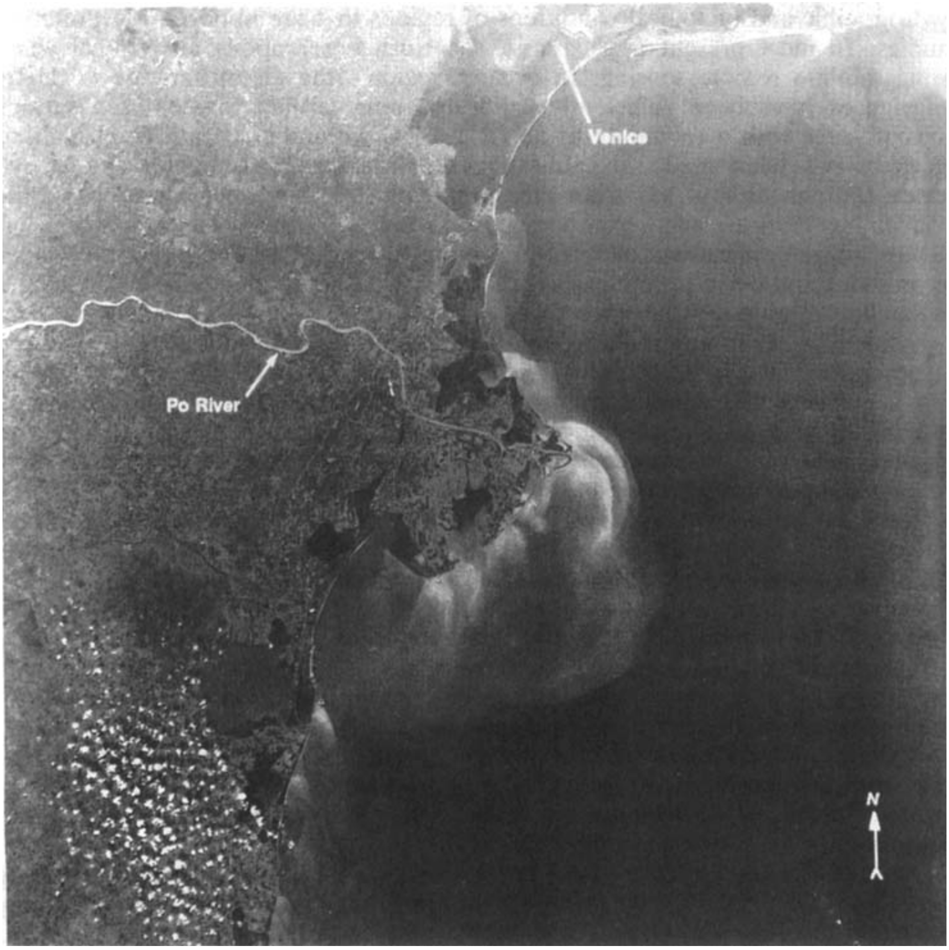

Figure 8 A space shuttle photograph showing the Po River plumes along the Adriatic coast. From UCAR-ONR (1989).

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suspended matter was so high that the algorithms applied to the original CZCS data classified the plume area as land (Barale *et al.*, 1984). Judicious use of satellite remote sensing data, coupled with *in situ* oceanographic studies, would help in understanding the various marine pollution processes that result from interactions among domestic and industrial discharges and the dissolved calcareous bedrock in the Po River outflow.

DISCUSSION

The preceding examples illustrate applications of satellite and aircraft remote sensing to marine pollution studies. In a few instances specific pollutants can be detected at the sea surface because they alter the optical properties of the ocean. In many other instances, satellite imagery can be used to characterize the hydrographic and biological conditions of regions that are important in pollution studies. In most present applications, sea truth observations are critical when using satellite remote sensing. In oceanic regions, the algorithms for AVHRR irradiances have been sufficiently calibrated and verified to yield sea surface temperatures with a reliability of about ±0.1°C without sea truth confirmation. Progress has been made in calibrating CZCS imagery to obtain chlorophyll concentrations without sea truth measurements over large oceanic areas of the mid- to low-latitudes away from the coastal zone.

Most other applications of satellite remote sensing related to pollution studies at present require sea truth measurements to yield quantitative data. Effective use of satellite remote sensing, therefore, depends on developing an integrated data set consisting of the satellite data and *in situ* data acquired using ships or moored sensors. Advances in optical fibre, electrochemical, automated chemical reagent, and acoustic *in situ* sensing systems offer new opportunities of high resolution time-series and high resolution spatial measurements that can be coupled to satellite data sets. Programmes should be established to foster the continuing development and engineering of these *in situ* technologies.

There has been a great deal of innovative development of improved algorithms for extracting useful information from satellite sensors. In many cases, scientists are finding ways to relate satellite data to ocean properties that were not conceived of when the sensors were originally designed and launched into space. This type of post-launch, data analysis innovation, should be encouraged.

A number of studies have shown the great value in having archived data available to test new hypotheses and to gain new insights into the conditions of the marine environment and how they change with time. With nearly two decades of Landsat imagery, it should be possible to examine trends in specific marine environments that have surface films (from petroleum and/or from natural slicks) or near-surface water column turbidity, and thereby detect improvement or deterioration in marine environmental quality.

International cooperation can be a significant factor in remote sensing capabilities. The CZCS satellite ceased functioning in 1986 after a highly successful mission. The U.S.A. was unable to continue the ocean colour system, and we are now faced with a hiatus in ocean colour imagery. The short-lived, but highly productive, Seasat system, provided tantalizing indications of being able to

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characterize properties of the sea surface day or night, under clear or cloudy skies. The U.S.A. has not been able to maintain this capability. The European Space Agency plans to launch a satellite with a SAR sensor in early 1991. Japan intends to launch one in early 1992. This will enhance the entire global remote sensing effort to assure international coordination in satellite remote sensing capabilities, compatibilites, and programme scheduling. It will enable greater redundancy, resolution, and backup capabilities than could be achieved by any nation alone.

SUMMARY

Satellite technology is an important tool in monitoring and studying ocean pollution. Visible sensors have been used to observe and characterize sewage sludge and industrial wastes dumped at sea. Oil slicks have been observed with Landsat, AVHRR and SAR imagery. Besides directly detecting pollutants, satellite sensors are useful for analyzing ocean processes that are influential in the fate of pollutants. These processes include eutrophication of coastal waters and the distribution of suspended matter. The fate of excess CO_2 can be addressed using scatterometer-derived estimates of wind speeds to determine the CO_2 exchange coefficient at the sea surface on a global scale.

ACKNOWLEDGEMENTS

We thank Robert M. Carey of NOAA for providing us with marine pollution information observed from space.

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