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Coastal Engineering 41 (2000) 155–176

COASTAL ENGINEERING

www.elsevier.com/locate/coastaleng

Satellite earth observation in operational oceanography

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Abstract

The role and contribution of satellite data in operational oceanography is reviewed, with emphasis on northern European seas. The possibility to observe various ocean parameters and processes by existing satellite sensors, such as optical instruments, infrared radiometers, passive microwave radiometers, and active microwave systems (altimeter, scatterometer, SAR) is discussed. The basic parameters are: sea-surface temperature observed by infrared radiometers, ocean colour by spectrometers, sea-surface elevation by altimeters, and surface roughness by active and passive microwave systems, which can be used to derive surface wind and waves. A number of ocean processes can be derived from synoptic mapping of the basic parameters of larger sea areas, such as current patterns, fronts, eddies, water mass distribution, and various water quality parameters (chlorophyll, surface slicks, suspended sediments). The suitability of existing satellite data to fulfil the operational requirements for temporal and spatial coverage, data delivery in near-real-time, and long-term access to data is discussed in light of the fact that optical/infrared data in northern Europe are severely hampered by frequent cloud cover, while microwave techniques can provide useful data independent of weather and light conditions. Finally, the use of data assimilation in oceanographic models is briefly summarised, indicating that this technique is under development and will soon be adopted in operational oceanography.

Keywords: Chlorophyll; Operational oceanography; Satellite observations; Suspended sediments; Temperature; Waves

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0378-3839/00/$ - see front matter
PII: S0378-3839(00)00030-2

1. Introduction

This paper provides a review of available satellite Earth Observation data, and their potential and suitability for use in operational oceanography for northern European waters. The article reflects the view of the authors and is, therefore, not intended to be comprehensive. We intend to provide a general overview of remote sensing methods applicable at high latitudes where cloud cover often restricts use of optical and infrared data. Sea-ice monitoring, which is essential in polar regions, is not addressed. The relevance of satellite data in numerical modelling and prediction in shelf seas is briefly addressed.

The survey and the protection of coastal waters and shelf seas require comprehensive knowledge, forecasting capability, and the ability to assess environmental impacts. Terrestrial discharges, oil spills, harmful phytoplankton blooms, and coastal erosion, are examples of the kinds of processes and incidents that take place, with great consequences for human health, economic activities, and the local, regional, and global environment. Considerable economic and social benefits are expected from operational services as numerical coupled forecast models improve, partly due to more frequent and higher quality remote sensing data and advanced assimilation techniques. This will benefit and increase safety for the merchant fleet, and the fisheries, offshore, and aquaculture industries. It will also assist coastal zone management, provide early warning of floods, protect the marine environment, and improve the monitoring of large-scale climate change.

Pre-operational models are routinely used to supply information in statistical or time series format pertaining to specific locations and time intervals for policy development, management options, engineering designs, and in associated scientific research studies. Fully operational models are required for real-time forecasts of flood levels, oil spill tracks, ship routing, and for the operation of storm-surge barriers in the Thames and near the mouths of the Rhine. Also, harbour traffic control systems (Vessel Traffic Systems [VTS]) require real-time forecasts of wave heights and tide levels for optimal use of dredged access channels. In the future, reliable forecast systems will be required for applications such as the management of ecologically sensitive areas. Validation as well as assimilation of field measurements and remote sensing observations will be a major step in the development of fully operational models. Pre-operational modelling in oceanography shares the analogous need with meteorology for internationally organised monitoring and communications networks and for rationalisation of the range of models used. Satellite Earth Observation techniques have over the last two decades matured to such a stage that quality products of ocean wind, waves, temperature, eddy and frontal location, and propagation and water quality (chlorophyll concentration, suspended sediment) can be produced routinely (e.g., Ikeda and Dobson, 1995; Johannessen et al., 1997). However, so far, the most frequent variables retrieved from satellite sensors used in national and international pre-operational and operational systems are wind, waves, and temperature and ice conditions. Fig. 1 gives a summary of geophysical features and processes that can be observed with different remote sensing techniques available today.

Supplementing in-situ observations with remote sensing data will greatly add to their value, particularly in monitoring ocean wave, wind, and current fields in the coastal

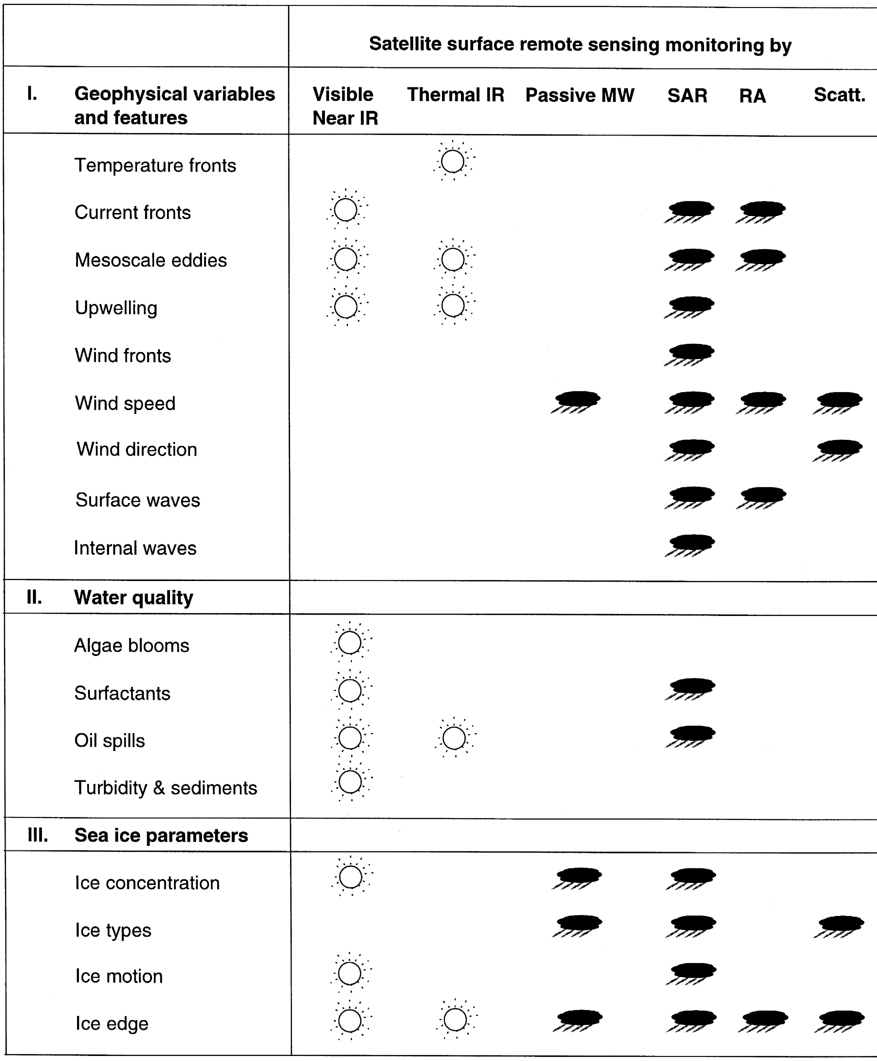

Fig. 1. Geophysical oceanographic feature and process observed by remote sensing techniques. Adapted from Johannessen et al. (1993).

areas considered. The natural variability of marine parameters, which can be observed using satellite remote-sensing techniques, means that the near-real-time acquisition of satellite data will be very important in coastal monitoring applications.

2. Data from Earth Observation satellites

To monitor key relevant ocean parameters, a wide range of different satellite systems and sensors is and will become available during the next decade. Large-, regional-, and mesoscale weather and ocean features can be monitored by polar orbiting satellites with sensors operating in a wide part of the electromagnetic wave spectrum. Microwave sensors acquire data independent of sunlight and clouds, and are used to monitor wind, waves, ocean currents, oil spills, and sea-ice. Visible and infrared (IR) sensors (e.g., NOAA/AVHRR (Advanced Very High-Resolution Radiometer), ERS-ATSR (Along Track Scanning Radiometer), IRS-P3-MOS, SeaWiFS) monitor sea-surface temperature (SST), fronts, currents, eddies, and ocean colour. Small-scale features such as oil slicks, near-shore circulation, and wave fields, can, under favourable meteorological conditions (normally the wind speed must be in the range of 3–11 m s^{-1}), be monitored with high-resolution polar orbiting radar sensors.

2.1. Temperature

The distribution of SST provides significant information related to a wide range of marine processes and phenomena such as ocean currents, fronts, mesoscale eddies, and up-welling phenomena. This allows use of satellite derived SST information in the mapping of ocean circulation (Johannessen et al., 1991, 1993, 1996, 1997), fisheries (Pettersson, 1990), algal blooms (Johannessen et al., 1989) and in assimilation of SST data in physical circulation models (Stanev, 1994). SST is observed from space by thermal infrared imagery, during cloud-free conditions, using the thermal infrared channels of the NOAA/AVHRR and from the ERS ATSR sensor systems. These instruments measure the SST distribution at a spatial resolution of 1 km and an accuracy of 0.5°C or better (NOAA, 1995). The structure of mesoscale ocean circulation features in the North Sea tidal front and the Norwegian coastal current were early documented through use of this type of Earth observation data (Johannessen, 1986; Johannessen et al., 1989). An example of an AVHRR scene is shown in Fig. 2.

It is not yet possible to observe sea-surface salinity from space, but techniques using passive microwave radiometry are under development (Lagerloef et al., 1995). So far,

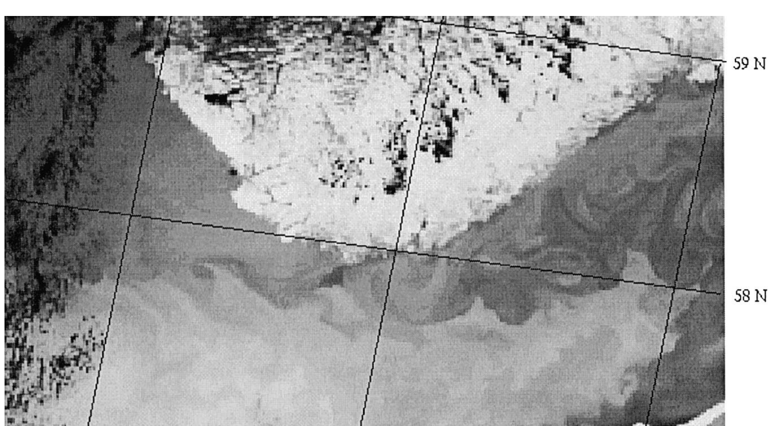

Fig. 2. NOAA/AVHRR thermal infrared image of southern Norway, 20 September 1995.

successful results have been obtained by airborne L-band radiometry in the coastal zone (Miller et al., 1998), and satellite systems using this method have been proposed (Kerr, 1998).

2.2. Sea surface elevation

Information on sea-surface elevation is important for predicting tides and storm surges. This can be obtained from radar altimetry, but detailed information on the satellite orbit is required. Such information can be obtained for the purposes of tidal analysis, but is not generally available soon enough in order for near-real-time assimilation into storm-surge prediction models. In the absence of a sufficiently accurate geoid model, altimetry can, so far, only provide information of the variable part of the topography due to ocean dynamics, but this variability can be related to the eddy kinetic energy of the surface circulation (Samuel et al., 1994). In order to resolve mesoscale features at high latitudes, the altimeter ground track should have a cross-track spacing of the order of a few tens of kilometres and a repeat period of a few days. This should be possible using data from two radar altimeter satellites flying simultaneously such as ERS-1/2 and TOPEX/Poseidon. Also, for coastal applications, improvements in the antenna tracking mechanism are necessary to prevent loss of data when the ground track crosses over from land to sea.

2.3. Currents

The mechanisms for driving ocean currents in northern European waters are wind forcing, density differences, sea-surface gradients and tidal forcing, and current patterns are usually modified by topographic features. Currents can be identified in thermal infrared images through gradients in SST and ocean pigment distribution due to the differences of water masses of different origin. In Synthetic Aperture Radar (SAR) images current features are mapped due to changes in surface roughness across fronts. In waters near the coast, land-based Doppler HF radar has proven to be a suitable system that can provide quantitative measurements of surface currents (Crombie, 1955; Lipa and Barrick, 1986; Andersen and Smith 1989; Prandle, 1991; Shay et al., 1993). Large-scale monitoring studies have suggested that it is possible to observe currents using over-the-horizon radar, which utilise ionospheric reflections (Georges et al., 1996).

SAR is able to image the surface expressions of features such as eddies, meanders, fronts, and jets, thereby providing qualitative information on their structure and evolution (Lyzenga, 1991; Johannessen et al., 1991, 1994). Products that may be considered for operational use include manually interpreted images and geographical coordinates of the relevant observed features.

Even though SAR is capable of seeing through clouds and in the absence of daylight, it is unable to image circulation features at very low or high wind speeds, and its capability can also be degraded in the presence of heavy rain. Reflecting the water masses of various origin, these circulation features frequently also have an expression in the surface temperature and ocean colour field. Hence, they may be detectable by visible and infrared radiometers under cloud-free and/or daylight conditions. Thus, products combining information from these different types of sensors will be useful under varied environmental conditions and, therefore, more suited for operational use.

Although circulation features can be imaged by SAR, it is not generally possible to make a good quantitative estimate of the magnitudes of the currents involved, although a number of numerical models exist, which aim to predict the radar backscatter variations produced in association with various types of surface current pattern, oceanic fronts, internal waves, etc. Interferometric SAR analysis is able, under suitable circumstances, to give direct quantitative measurements of surface currents (Shemer, 1993; Graber et al., 1996), but is, at present, only deployed on aircraft for marine applications.

The use of satellite radar altimetry to the determine geostrophic currents by means of measuring sea-surface slope is possible for determination of large-scale time variant current fields. The variance in the elevation gradients can be used to obtain an estimate of the eddy kinetic energy of the circulation, which is a useful parameter to quantify the mesoscale eddies.

2.4. Wind

Wind speed and direction over the global ocean can be determined from the radar scatterometer on the ERS-1/2 satellites (Stoffelen and Anderson, 1997a,b,c), and is used in operational marine weather forecasting. It is also possible to determine detailed patterns of wind speed, and sometimes direction, from SAR images, and, at a lower resolution, from real-aperture satellite side-looking radar data. Satellite altimeter data can also be used to determine wind speed along the orbit (Witter and Chelton, 1991; Carter et al., 1992; Monaldo, 1988).

Scatterometer observations over the ocean provide direct estimates of the global wind vector field at spatial resolution of 50 km, with an accuracy of 2 m s^{-1} in speed, 15° in direction, but usually with a directional ambiguity of 180°. For some applications such as in semi-enclosed seas, in straits, in coastal regions, and in estuaries, this resolution is, however, too coarse. In these regions, wind field estimates retrieved from high-resolution SAR images can be very useful. Today, SAR is the only space-borne instrument that can provide high spatial resolution images (30 m ground resolution) for quantitative measurements of mesoscale wind field at a spatial resolution of typical 10×10 km. The spatial and temporal coverage of ERS data is limited, and not suitable for operational monitoring. However, wide swath SAR data from RADARSAT and ENVISAT offer better data coverage, which can be important for wind monitoring.

Fig. 3 shows a conceptual overview of the wind field estimation as further described below (Korsbakken and Johannessen, 1996).

2.4.1. Wind retrieval algorithms

The SAR Wind Algorithm (SWA) proposed by Vachon and Dobson (1996) and further examined by Chapron et al. (1995) and Kerbaol et al. (1996) is based on a relation between the smearing effects (Hasselmann and Shemdin, 1982) in the SAR image and the wind field. Smearing effects tend to increase the coherence (correlation) length of the radar returns in the image spatial domain, and influence the spectral

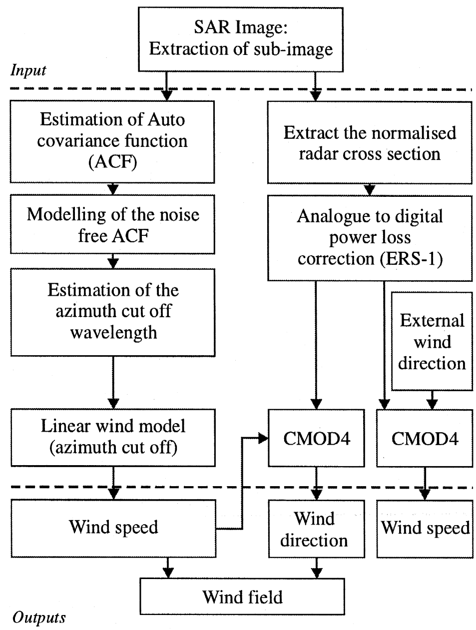

Fig. 3. Conceptual overview of wind retrieval models (Korsbakken and Johannessen, 1996).

properties of the SAR image. In the case of a fully developed sea (no fetch limitation) the empirical relation, based on evaluation of 1200 SAR wave-mode 'imagettes' with a central incidence angle of 20.2° is given by Chapron et al. (1995) as

$$U_{10} = 4.75\left(\frac{\lambda_c - 30}{110}\right) \tag{1}$$

where U_{10} is the wind speed in m s^{-1} at 10 m above the surface and λ_c is the azimuth cut-off wavelength in metres, which can be estimated from the SAR image power spectrum. An example of a wind field derived by this algorithm is shown in Fig. 4.

2.4.2. The CMOD4 model function

The CMOD4 wind retrieval model (Stoffelen and Anderson, 1993, 1997a,b,c) is developed for the ERS-1 C-band scatterometer, but it is also shown to give good estimates of wind speed when applied to ERS-1 SAR images (Johannessen et al., 1994; Vachon and Dobson, 1996; Vachon et al., 1995; Wackerman et al., 1996).

The CMOD4 empirical algorithm gives a theoretical σ^0 (normalised radar backscatter cross-section) value as a function of wind speed and direction. The accuracy in the model is $\pm 20°$ in relative wind direction and ± 2 m s^{-1} in wind speed when applied to scatterometer data. The CMOD4 model is derived for a neutral stratification. In order to compute the wind speed from the radar backscatter accounting for the stratification in the atmospheric boundary layer (ABL), the CMOD4 derived wind speed must be

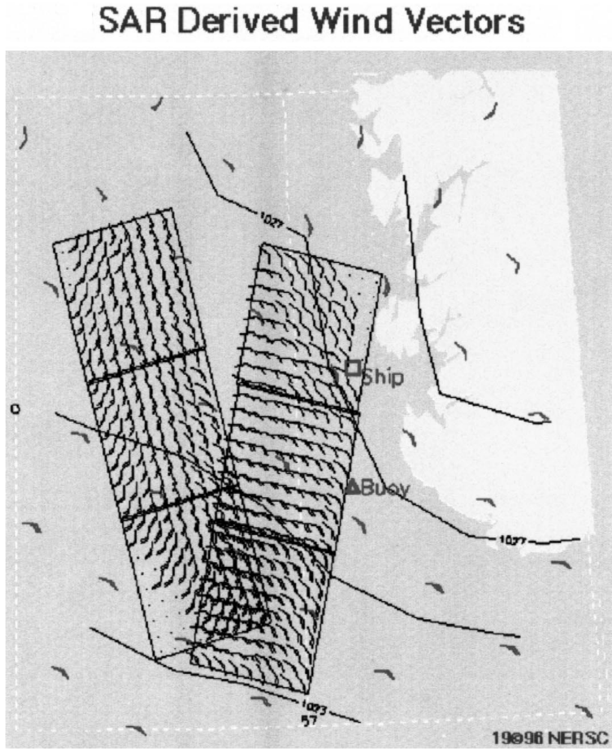

Fig. 4. Wind field derived from an ERS-1 SAR image on 17 September 1995. Wind speed ranges from 7 to 13 m s^{-1}. SAR wind vectors derived from two SAR passes, each 300×100 km, off the coast of southwest Norway. Red arrows indicate the standard meteorological analysis grid points.

modified. A correction for this can be derived from expressions relating unstable and stable stratification to neutral stratification as suggested by Wu (1993) and Smith (1988). The saturation of the analogue-to-digital conversion (ADC) in the satellite must also be accounted for, as described by Meadows and Willis (1995), Laur et al. (1996), and Scoon et al. (1996). The effect is strongest over the ocean in the near range and increases with radar backscatter intensity (i.e., at high winds) and leads to an underestimation of σ^0.

The wind direction can also be estimated from the CMOD4 model for different incidence angles provided the wind speed, derived from the SWA method, can be associated with the corresponding measured radar backscatter. In such cases, four solutions, i.e. two pairs, each with a 180° ambiguity can be found, except in the cases when the direction is close to upwind (the wind blowing towards the radar) or downwind, for which only one pair is found. (Note that for the three-beam scatterometer on ERS-1/2 the number of solutions is reduced to a single pair with a 180° ambiguity.) It has also been demonstrated by Johannessen et al. (1994) that wind rows manifested in SAR images can be used to indicate the near surface wind direction during the SAR integration time. In such cases the number of wind direction solution pairs is also reduced to one (180° ambiguity).

2.5. Waves

Significant wave height (H_S) can be determined using satellite altimeter measurements (Rufenach and Alpers, 1978; Bauer et al., 1992; Guillaume and Mognard, 1992), and such measurements have been used to validate numerical wave forecasting models (Wu et al., 1994). The use of ERS and TOPEX/Poseidon altimeter data for significant wave height in conjunction with ERS scatterometer data for wind produces encouraging improvements in wave forecast model predictions (Le Meur et al., 1996). Present operational products include assimilation of satellite altimeter derived significant wave heights into an operational regional wave forecasting model (Breivik et al., 1996), and significant improvements in the wave analysis and short-term forecasts for the North Sea were found.

Another significant remote sensing data type for wave observation is radar altimeters (ERS-1/2, TOPEX/Poseidon, Seasat, GEOS-3), which can provide climatological wave height information as well as wind speed (Paci and Campbell, 1996; Lasnier et al., 1996). The along-track resolution for the radar altimeters is typically 7 km. These data can be used for offshore oil industry design and operational planning purposes, as well as for coastal engineering design, naval architecture, ship routing, etc.

Wave direction and wavelength can be determined using ERS-SAR, both in image mode and globally in 'wave mode', and also in the high-resolution modes of RADARSAT. The typical resolution of satellite SAR, about 30 m, means that only waves with periods of about 5 s or more can be resolved. The wave pattern visible on an SAR image may be very different from the in-situ wave field, as well as having a 180° directional ambiguity, and a complex post-processing of the image is usually necessary to extract the directional wave spectrum. It is usually necessary to start from an initial 'first guess' spectrum, from, say, a numerical model simulation (Hasselmann and Hasselmann, 1991; Krogstad et al., 1994). Progress in reducing the directional ambiguity and in improving the signal-to-noise ratio has recently been made by employing Single Look Complex data from ERS-SAR (Engen and Johnsen, 1995).

SAR does appear to give convincing images of swell waves propagating onto coasts, including the effects of depth refraction, shadowing, and diffraction. The ability of SAR in image mode to provide rather detailed pictures of wave fields near shorelines, at least for the longer swell waves, should be useful in monitoring the coastal environment and its changes, including the locations of rip currents, long-shore drift, and other currents, which impact the transport of sediments. Wave refraction by bottom topography and the resulting change in surface roughness monitored by SAR, may be used to monitor the evolution of sandbanks in shallow-water areas, as well as in charting bathymetry in poorly-surveyed regions (Calkoen, 1996; Calkoen and Wensink, 1993; Calkoen et al., 1991; Hesselmans, 1996).

SAR wave mode data are now used to provide corrections to forecast wave directions in operational wave forecasting models, though assimilation of these data is still at a preliminary stage (Breivik et al., 1996; Paci and Campbell, 1996). The impact of these data is not very significant at present, mainly because of the sparse data coverage, but new processing techniques (e.g., Engen and Johnsen, 1995) are being evaluated and may improve the situation.

2.6. Water quality

Water quality is measured through a series of bio-geophysical parameters and processes at the sea surface or in the water column. Some of the key parameters are dissolved or suspended substances in the water column, such as chlorophyll concentration, suspended sediment, and dissolved organic matter and biological and chemical films at the sea surface. All these substances have the property to modify the characteristics of the light field that interact with the water body, and thus, have impact on the signal measured by remote sensor. Other quantities and phenomena can be derived from the above parameters, which are also good indicators of water quality, e.g. primary production, algal bloom, sediment transport.

A review of algorithms and domain of applications, as well as an assessment of Earth observation capability with respect to water quality can be found in Durand et al. (1999).

2.6.1. Natural films and oil spills

Under suitable conditions, an oil slick will dampen capillary and short gravity waves, and appear as a dark slick in an SAR image of the ocean surface. This effect has been used for decades in aircraft-based oil spill monitoring systems, especially in the North Sea. Now, the radar satellites ERS-2 and RADARSAT are used in routine satellite-based oil spill monitoring services http://www.tss.no/). However, these services rely upon visual interpretation of SAR images, and a number of oil spills ‘lookalikes’ may complicate the analysis (Espedal, 1998).

To improve the performance of satellite-based SAR oil spill detection and monitoring, in coastal zone, a combination of model data and SAR data has been developed (Espedal, 1998). Such concepts may include oil drift components (Furnes, 1994) and SAR image models (Lyzenga and Bennett, 1988; Tanis et al., 1989). If a possible oil spill is detected in an SAR image, the models are used to try to reconstruct the spill (given wind, current and wave height history of the area). The discharge rate and type of oil giving the best possible match to the observed spill, is then searched. Examples of slick signatures in SAR images are shown in Fig. 5.

2.6.2. Ecological aspects

The light scattering and absorbing characteristics of the phytoplankton itself and other water constituents is the basis for the use of ocean colour Earth observation sensors. The US Coastal Zone Color Sensor (CZCS) from 1978 to 1986 proved the usefulness of this type of Earth observation technique to map the marine chlorophyll distribution.

Typically, only 10% of the satellite measured signal origin from the water surface. Hence, appropriate algorithms for atmospheric signal correction must be applied (Moore et al., 1999). Further, a number of algorithms have been developed for the retrieval of phytoplankton pigment concentration from ocean colour data (see Morel and Prieur, 1977; Gordon and Morel, 1983; Gordon et al., 1980; Morel 1988; Sathyendranath et al., 1994, for CZCS algorithms; O’Reilley et al., 1998 for SeaWiFS and OCTS algorithms; Morel and Antoine, 1997 for MERIS).

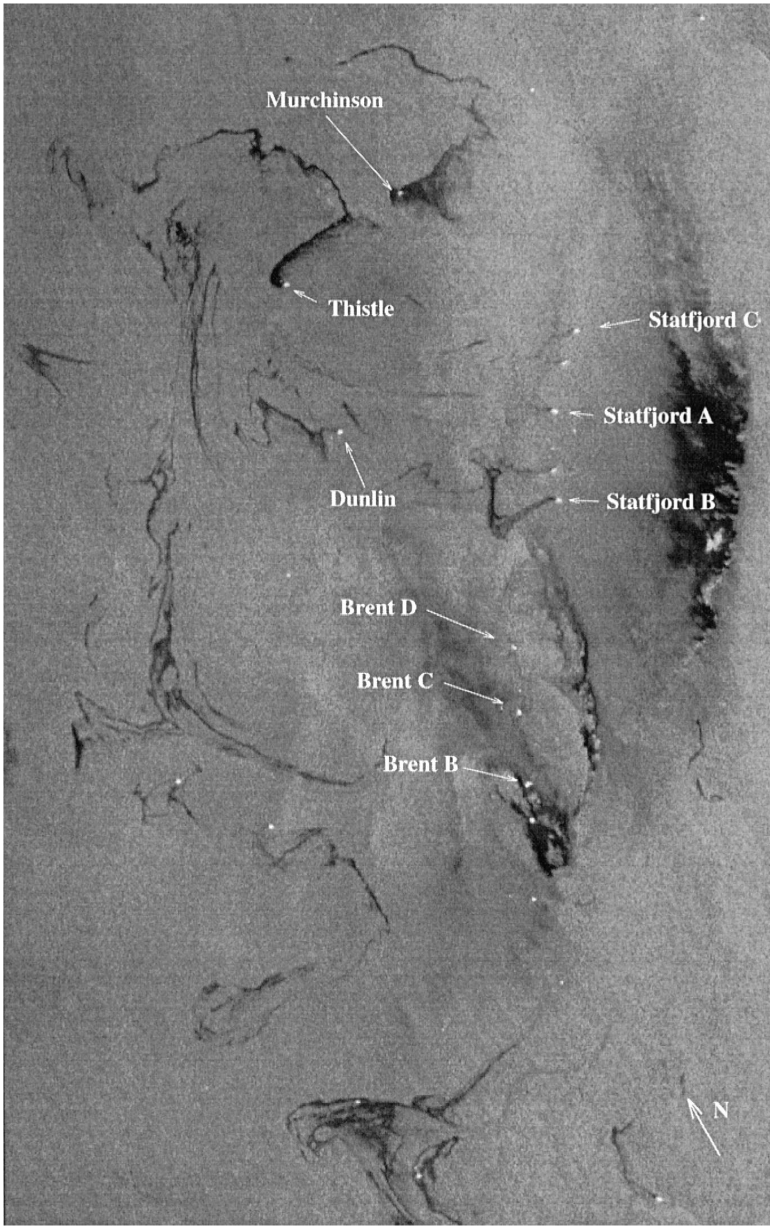

Fig. 5. This ERS-1 SAR image from 30 October 1994 contains a number of possible oil slicks, release of produced water and natural film, connected to or located near oil platforms in the Norwegian and British sectors in the North Sea (Espedal and Johannessen, 1999, in press).

Phytoplankton biomass and primary production estimation can be derived from photosynthetic pigment concentration in the upper water column and Photosynthetic

Available Radiation (PAR), which can be both estimated from the data acquired by radiometers measuring ocean colour (Bricaud et al., 1987; Platt and Sathyendranath, 1988, 1993; Morel, 1991; Antoine and Morel, 1996; Behrenfeld and Falkowski, 1996). Almost all the models deal with so-called case I water (dominated by phytoplankton as the only coloured substance), as defined by Morel and Prieur (1977). Empirical or semi-empirical models relating atmosphere-corrected radiances and water constituent concentrations are used. They are based on spectral band ratios (mainly blue/green bands) and are thus dependent upon the spectral bands' characteristics of each sensor.

In the open ocean, the complexity of the ocean optics is not as severe as in the coastal areas (case II waters), where the sediments and coloured dissolved organic matter (CDOM) also significantly contribute to the signal measured by the satellite sensors. Deriving water quality parameters with a sufficient accuracy, in case II waters is one of the main challenge of the coming years in marine optics. The current development includes new sensors with improved capability, i.e. more and narrower spectral bands, and new algorithms with improved atmospheric correction scheme and/or global approach (inverse methods). The most advanced work is undertaken in connection with the development of the next generation of optical ocean colour sensor, i.e. the US MODIS and the European MERIS instruments. The state-of-the-art in chlorophyll concentration retrieval in case II waters can be found in, e.g. Moore et al. (1999) and Schiller and Doerffer (1999). It concerns, in particular, inverse method, including artificial neural network techniques, and improved atmospheric correction algorithms.

One of the main issues of surveying phytoplankton distribution and concentration is the operational monitoring of harmful algae blooms, and potential fishery areas (Dundas et al., 1989; Johannessen et al., 1993). The development of extreme algal bloom situations (harmful or not) generally depends on the following environmental conditions: (i) hydrodynamics, (ii) supply of macro-nutrients to the euphotic layer, (iii) surface solar radiation, and (iv) the optical properties of the water column (Johannessen et al., 1993). An algal bloom may have its peak activity below the surface, and hence, may not be detected by remote sensors. The algae themselves have limited mobility, and hence, a measure of the advection of an identified bloom may be done indirectly through monitoring of the currents and ocean circulation pattern.

An example was the extensive bloom of the toxic algae *Chrysocromulina polylepis* in the Skagerrak region in spring 1988 (Aksnes et al., 1989; Dundas et al., 1989), where the advection of the bloom front was consistent with the warm water front. The bloom originated in the Skagerrak, and the algal front was subsequently advected with the warm water out of the Skagerrak region. During this event, the Norwegian aquaculture industry suffered losses of the order of ECU3.5 million, while caged fish of a value of ECU140 million were towed northward and into the fresher and colder water in the fjords and saved. The monitoring efforts during this event included the combined use of field observations, numerical modelling simulations, and satellite and airborne remote sensing and reconnaissance.

During other bloom events, water discoloration is detectable to the human eye. An example of this is the presence of the alga *Emiliania huxleyi*, which causes a milky-white water colour during the phase when the coccoliths (plates composed of calcite) become detached from the cells. Such blooms are seen annually in coastal and fjord areas as well as in the open ocean all over the world but in particular, at mid-latitudes. The high reflectance of water with coccoliths makes these blooms even visible in the optical channel of the AVHRR sensor (Holligan et al., 1993). An example of two such blooms in the North Sea is shown in Fig. 6.

On the other hand, the estimation of primary productor biomass and production at regional and global scales are also of great interest for global and regional climate change forecasting. Such information is needed to improve coupled physical and biogeochemical models, which are used for studying, e.g. the carbon cycle in the atmosphere/ocean system and its influence on the climate.

Fig. 7 shows a SeaWiFS (left) and a NOAA/AVHRR (right) image from May 1999, covering the North Sea and Skagerrak area (Pettersson et al., 1999). The images resolve the pigment concentration in the water, which is correlated to the phytoplankton concentration and other coloured pigments and the SST, respectively. Major circulation and current patterns can be observed in both images. In particular, the cool and mesotrophic inflow of Atlantic water (in blue) in the Skagerrak is well observed, as well as the outflow from of warm and eutrophic water from the Baltic as well as solar heating

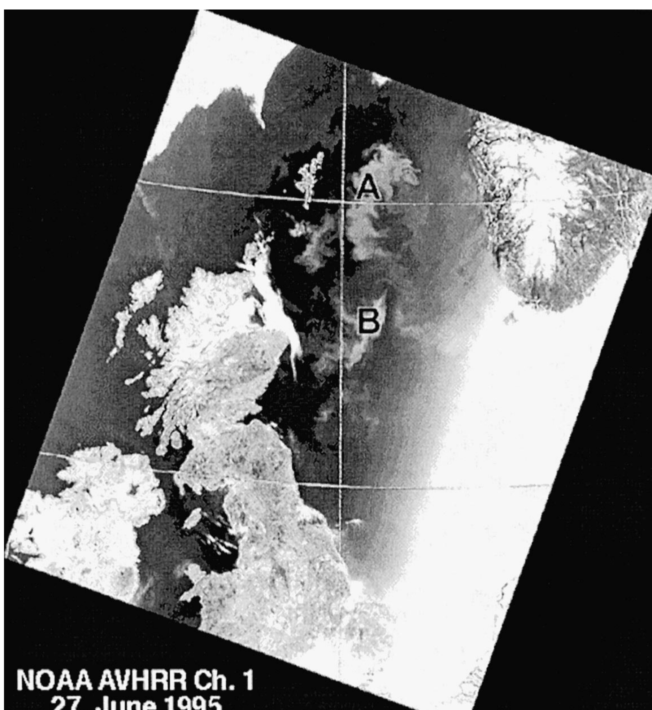

Fig. 6. This NOAA/AVHRR image from June 1995 shows two cocolithophorid blooms of *E. huxleyi* (A and B, covering 22 000 and 7500 km^2, respectively) between Scotland and Norway. The high reflectance caused by the calcite plates, which characterised this family of algae, is particularly well observed in the visible part of the spectrum (first channel of AVHRR) (Pettersson, 1995).

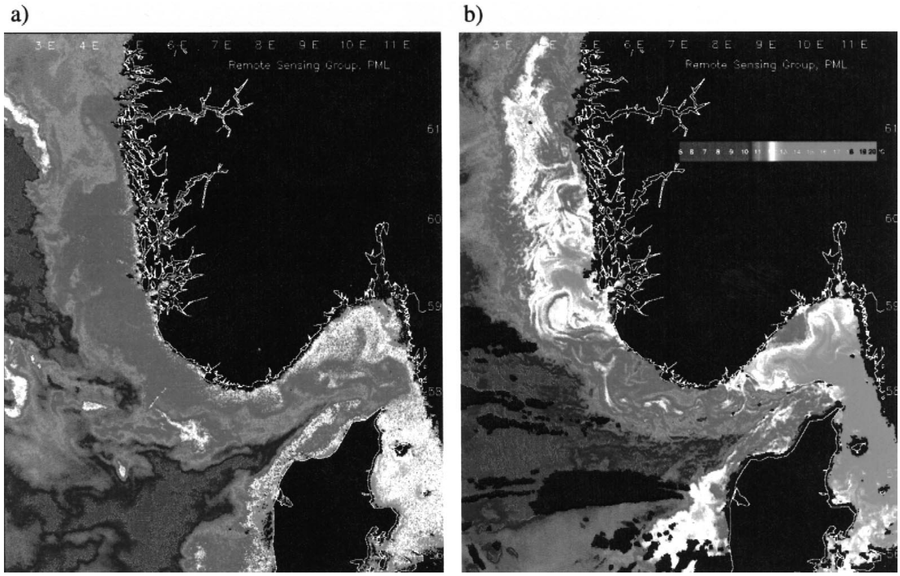

Fig. 7. Circulation patterns as observed by ocean colour and thermal infrared sensors. (a) Chlorophyll pigment concentration product from SeaWFS over the North Sea and the Skagerrak on 19 May 1999. © Orbital Imaging and NASA SeaWiFS project. (b) Sea surface temperature as derived from NOAA/AVHRR for 19 May 1999 over the same region. Data provided by Steve Groom, Centre for Coastal and Marine Sciences, Plymouth Marine Laboratory.

during the day. We may notice that the inflow is better seen in the SeaWiFS image. This can be explained by the fact that the signal measured by ocean colour sensor integrates the upper layer of the water column (typically to the depth where irradiance equals 10% of its value just below the surface), whereas SST only concerns the surface micro-layer, which is affected by warm water from the Baltic. In the same region, the outflow from the Oslofjord, characterised by high concentration of pigments, can be observed in the SeaWiFS image, as well as its spreading along the southern coast of Norway and western coast of Sweden. High values are also observed in the SeaWiFS image, along the coast of Denmark. These originate from the high concentration of suspended matter as well as the sea-floor contribution to the measured signal in this shallow water area. The mesoscale eddy circulation currents along the west coast of Norway is also well reproduced in both images in which similar circulation patterns are observed.

2.6.3. Suspended sediment and sediment transport

In studies of marine transport of sediments, for applications to coastal erosion, changes in bathymetry, transport of deposited material, associated adsorbed pollutants, etc., it is possible to obtain a measure of suspended particle concentration from multi-channel optical and near-infrared radiometer observations.

Remote sensing measurements of suspended sediment have been studied by Tassan (1988), Curran and Novo (1988), Harwar et al. (1995), and Althuis et al. (1996). A synthesis on remote sensing measurements with respect to suspended sediment and numerical modelling has been performed recently by Xia (1993). Other work in this field have been performed by, e.g. Puls et al. (1994) and Vos and Schuttelaar (1995).

Monitoring sediment transport requires knowledge of the wave amplitude and direction, coastal currents, bathymetry, bottom topography, and the distribution of suspended sediment. These are all potentially recoverable by remote sensing, e.g. using SAR data for wave, currents, bottom topography, and optical sensors for bathymetry, bottom topography, and distribution of suspended sediment.

The images obtained using optical and infrared radiometers are potentially capable of retrieving bathymetry (Lyzenga, 1978; Bierwirth et al., 1993; Durand et al., 1998; Lee et al., 1999), bottom type (Lyzenga, 1978, 1981; Estep and Holloway, 1992; Estep, 1994), and total water column suspended material content (see above) in the case of shallow water not exceeding 30 m depth.

Pre-operational services that integrate satellite-based remote sensing for sediment transport assessment and monitoring are currently available. New capability of the next generation of ocean colour sensors (MERIS, Orbview-4, etc.), as well as the increase number of sensors in orbit, should provide the required step forward to achieve a real operational monitoring of water quality in the near future.

3. Suitability of remote sensing data for operational requirements

3.1. Data coverage

There is generally a trade-off between the spatial resolution of satellite data and their available temporal coverage. Continuous, nearly global coverage is afforded by geostationary meteorological satellites, and coverage several times daily is available from the polar orbiting NOAA/AVHRR. Cloud cover significantly reduce the nominal coverage rate of optical and infrared sensor systems. Only regions under cloud-free conditions are available — a significant disadvantage for mid-latitude locations, which are subject to frequent poor weather. High latitude polar regions also suffer from limitations due to the winter darkness.

Passive microwave and radar sensors can penetrate cloud cover, but the former sensors generally have rather too poor resolution for covering North Sea scales (1 km and more). The spatial resolution of SAR images are sufficient for most marine applications; however, both limitations in swath width and repeat cycles limit their operational use. The new era starting with the Canadian RADARSAT satellite has improved the SAR sensor coverage, however operational coverage is still difficult.

3.2. Availability in near-real-time

Satellite receiving stations such as Tromsø Satellite Station (TSS; in Norway), KNMI (in The Netherlands) and RAIDS (in the UK) downlink and process SAR and other satellite sensor data, and distribute them in near-real-time to institutions providing value-added products, which are sent out to end-users. The time needed for acquisition, processing, and distribution is typically a few hours for SAR data. The requirement for near-real-time data is essential in operational oceanography. The time delay, which is acceptable between satellite overpass and access to data depends on application and type of products. Wind and wave data are needed within 1–2 h, while weekly SST can accept a longer time delay.

An example of near-real-time use of SAR is for operational oil spill monitoring in Norwegian waters. TSS performs screening of SAR images for possible oil spill for the Norwegian State Pollution Control Authority (SFT). TSS inspects the SAR images in near-real-time and alerts the SFT surveillance aircraft on possible pollution events (Pedersen et al., 1996).

For specific types of data (e.g., significant wave height from altimeter and SAR Wave Mode data), the data are processed on a routine basis and distributed via the Global Telecommunications System to national meteorological centres, for use in their meteorological analysis, modelling, and forecasting services.

3.3. Programme continuity and long-term data access

Operational users require long-term access to consistent data sets. There is a clear demand to provide more products from satellite data in near-real-time to improve operational use of the data. For operational oceanography it is most important to:

- continue and improve satellite programmes for altimetry, SAR, scatterometer, as well as spectrometers and infrared radiometers;
- improve spatial and temporal coverage of SAR;
- establish efficient distribution and processing services, including algorithms to derive geophysical parameters.

3.4. Data assimilation

When interpreting remote sensing data, it is important to consider that satellites only observe the Earth's surface. In order to achieve three-dimensional marine information and forecasts, remote-sensing data together with in situ data must be assimilated in numerical models.

In the last decade, various data assimilation methods have been developed, which can be used with ocean hydrodynamic and ecosystem models. At present, however, none of these methods are used operationally, at least partly because the necessary observational data are too inaccurate, have insufficient coverage, or do not provide sufficiently good coverage.

In a fully operational system, the access time for the most recent observations also becomes important. Real-time analyses and predictions from the European weather services must be used to ensure a proper forcing of the model and to make it possible to generate realistic predictions of the marine system.

Operational ocean forecasting systems relies on an integrated use of observations of physical, biological, and chemical variables and coupled physical and marine ecosystem models. Thus, the true state of the ocean is observed from in-situ and satellite observing systems, and this information is used to reinitialise the ocean and marine ecosystem model, which is then used to compute predictions.

The integration of observations and dynamics is formally made using the so-called data assimilation techniques. These are mathematical techniques, which are usually based on some prior statistical assumptions about the accuracy of the observations and dynamical models. Essentially, these techniques provide a way for introducing the information about the true ocean state into the models, which are then kept 'on track' and will not drift away from the real state of the ocean. In fact, when properly used, data assimilation methods will lead to an ocean state estimate, which is better than what can be obtained when using a model or the observations separately. Further, in a monitoring and prediction system, the use of data assimilation will provide a best possible state estimate at the current time, which can be used as initial conditions for a forecast.

The new operational data assimilation systems, which is currently being developed at several centres, also demand observations that are available in real-time. Thus, an extensive effort must be invested in the development of real-time data analysis and processing, e.g. for satellite-derived sea-surface heights, SST, and ocean colour. There is also a need for real-time analyses and predictions of atmospheric fields, which are used to force the ocean models.

4. Concluding remarks

The paper provides a review of satellite remote sensing data and derived geophysical and biological parameters, which can be useful in operational oceanography. The most important data that are available today are as follows:

1. Surface wave data from satellite altimeter and SAR. Altimeter can provide significant wave height, while SAR gives directional wave spectra.
2. Mean geostrophic ocean currents and eddy kinetic energy by radar altimeter.
3. Surface wind by scatterometer (50 km resolution) and SAR ($\approx$ 10 km resolution).
4. Surface slick and circulation patterns (eddies, fronts) from SAR.
5. SST variations, water mass distribution, fronts, and eddies from infrared radiometers.
6. Ocean colour, chlorophyll, and suspended sediments by spectrometer data (SeaWiFS)

To fully benefit from remote sensing data in operational oceanography, it is necessary to use the data in synergy with models through data assimilation methods. This has been successfully demonstrated for altimeter data in ocean circulation models and SAR-derived wave spectra in wave forecasting models. The challenge is to develop models and assimilation methods further to include spectrometer data and other SAR-derived parameters.

Acknowledgements

This study has been supported by the European Commission through the PROMISE project (MAS3-CT950025), COASTMON (ENV4-CT960360), Marie Curie Fellowship (ENV4-CT96-5017, ENV4-CT97-5088), the Norwegian Space Centre and the Norwegian Research Council.

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