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Coastal Engineering 37 (1999) 283–307

COASTAL ENGINEERING

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Satellite wave measurements for coastal engineering applications

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Abstract

Measurements from the GEOSAT, ERS-1 and 2 and Topex/Poseidon satellites have now accumulated to over 15 years of global ocean wave and wind data. Extraction of wave height, wind speed and wave period from the satellite altimeters and directional wave spectra from the synthetic aperture radars are reviewed along with recent validation and calibration efforts. Applications of the data to a variety of problems illustrate the potential of satellite wave measurements.

Keywords: Satellite wave measurements; Coastal engineering applications; Wind speed

1. Introduction

Ocean wave measurements from satellites combined with global wave and atmospheric numerical models are dramatically changing our way of obtaining ocean wave information both for climatological and operational purposes. Whereas wave climatology used to be produced from rather crude ocean atlases based on visual ship observations or time and site limited in situ observations, satellite observations are now at the point of providing reliable global long term wave statistics. At the same time, often through data assimilation in operational numerical models, satellite observations are contributing to improved short term wave forecasts. Satellite wind observations assimilated into atmospheric models contribute indirectly by improving the atmospheric forecast and hence the wind forcing in the wave models.

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PII: S0378-3839(99)00030-7

The sampling and coverage properties of satellite wave measurements are, nevertheless, quite different from common and well-proven in situ measurements such as wave buoys. We are at present far from having the 3-h sampling regularity we are used to with buoys, and for small scale coastal monitoring, direct on-location satellite measurements are far from being sufficient.

The two measurement systems that have so far been directly used for wave measurements are the satellite radar altimeter (RA) and the Synthetic Aperture Radar (SAR). The RA is a vertically pointing pulsed radar designed to measure the range to the ocean surface with a few centimetres accuracy. The backscatter of the pulse is influenced by the roughness of the surface caused by the surface waves. The amount of distortion, in particular in the return pulse leading edge, is related to the significant wave height over the footprint of the radar (a few kilometres across). In addition, it has been observed that the wind speed may be derived from the strength of the backscatter signal. The SAR produces images with very high resolution by tracking the phase and the amplitude of the return signal as the satellite moves, typically about 7–10 kilometres. Apart from occasional satellite optical imagery, SAR is currently the only satellite instrument which can measure directional characteristics of ocean waves. However, a SAR image is not a true image of the surface, and the SAR-to-wave algorithms are all rather complicated.

Satellite data are offered to the users in various forms. For the European satellites ERS-1 and -2, the fast delivery (FD) products are available in near real time, whereas the off-line products (OPR) undergo a more thorough processing. Nevertheless, both the FD and OPR need additional corrections and calibrations. In the present paper we therefore start by summarising, without going very far into the technical details, the status of algorithms and calibration/validation efforts for satellite wave measurements. We then give some examples of coastal applications of altimeter data based on data from the US Navy's GEOSAT Exact Repeat mission (1986–1989), the European Space Agency's ERS-1 and ERS-2 missions (1991–present), and the US/French Topex/Poseidon mission (1992–present). Examples of SAR data from coastal regions are also showed

Today there are several university, governmental and private institutions which offer satellite data to the coastal engineering and maritime communities, and references to some of the information available on the *Internet* have been included for the reader's information.

2. Principles and algorithms

2.1. Sampling and coverage

Whereas in situ wave measurements are typically taken at 3-h intervals at a fixed location, satellite measurements necessarily have to follow the motion of the satellite. There are, however, at the outset some choices for the satellite tracks. The satellite track inclination angle with respect to the equator determines how far north and south the satellite reaches, and, for obvious reasons, near polar orbiting satellites are most suitable for globally covering wave measurements. An exact repeat track means that the satellite returns to the same position after a certain number of days, the exact repeat period. There is an inherent compromise in the choice of orbit between the regularity of measurements at a point on the ocean surface and the spatial resolution of the satellite's coverage. For example, although the Topex/Poseidon mission returns to a cross-over point of the ground tracks each 5 days on average, there is a relatively large distance between adjacent cross-over points. This is illustrated in Fig. 1 where ground tracks for the Mediterranean and Atlantic coasts of Europe are displayed for ERS-1 and ERS-2 (35 day repeat track mission), GEOSAT, and Topex/Poseidon. A resolution of the order of 150–300 km is not critical for wave climate applications in the open ocean, but in coastal areas there may be considerable spatial variability on this scale. For the radar altimeter the resolution is limited to about 7 km along the track, and the quality of the data is often degraded for the first few measurements after the satellite passes from land to the sea.

Even if the satellite measurements are quite intermittent compared to 3 h in situ measurements, it should be noted that to determine the long term distribution of significant wave height, H_s, 3 h is unnecessarily dense (this sampling is primarily driven by operational rather than climatological needs). In fact, it has been demonstrated that for the Norwegian Sea, the information content in a data set of significant wave height is equivalent to a subset of independent measurements taken every 40 to 50 h. Even longer intervals are found for monsoon and trade wind climates. On the other hand, for areas affected by infrequent tropical storms (hurricanes etc.) even many years of continuous measurements may be insufficient to determine the long term statistics.

Apart from the different regularity between in situ and satellites measurements, the measurement principles are also quite different. In situ systems typically record a time series over, say 20 min from which the sea state parameters are obtained by spectral analysis. The satellite measurement is, on the contrary, a spatially extending measurement taken virtually instantaneously. A common question is how the measurements compare with respect to accuracy and sampling variability. For wave parameters derived from time series records, this is well known. The same cannot be said for spatial measurements although it is possible to derive analytic expressions in ideal cases. If we aim to measure the significant wave height, H_s, and assume that we have the ideal remotely sensing instrument measuring the sea surface height over, say a circular region with diameter d, the sampling variability may be expressed by the *coefficient of variation*, $\text{C.O.V.} = \text{std}(\hat{H}_s)/E(\hat{H}_s)$ ('^' signifies *estimate of*). With a standard wind wave directional spectrum the following approximate lower bounds may be derived (Krogstad et al., this issue):

$$\text{C.O.V.}_{\text{time}} \approx 0.5(T_p/T)^{1/2},\ \text{C.O.V.}_{\text{space}} \approx 0.33\lambda_p/d. \tag{1}$$

Here T is the recording interval, T_p the spectral peak period, d the diameter of the region, and λ_p the peak wavelength of the spectrum. Since the peak period and wavelength increase with increasing significant wave height, it is clear that also the coefficient of variation increases with increasing wave height. The expressions in Eq. (1) are lower bounds, and although buoy measurements basically reach the bound, there is presently no spatially observing instrument which comes close to the bound. Since,

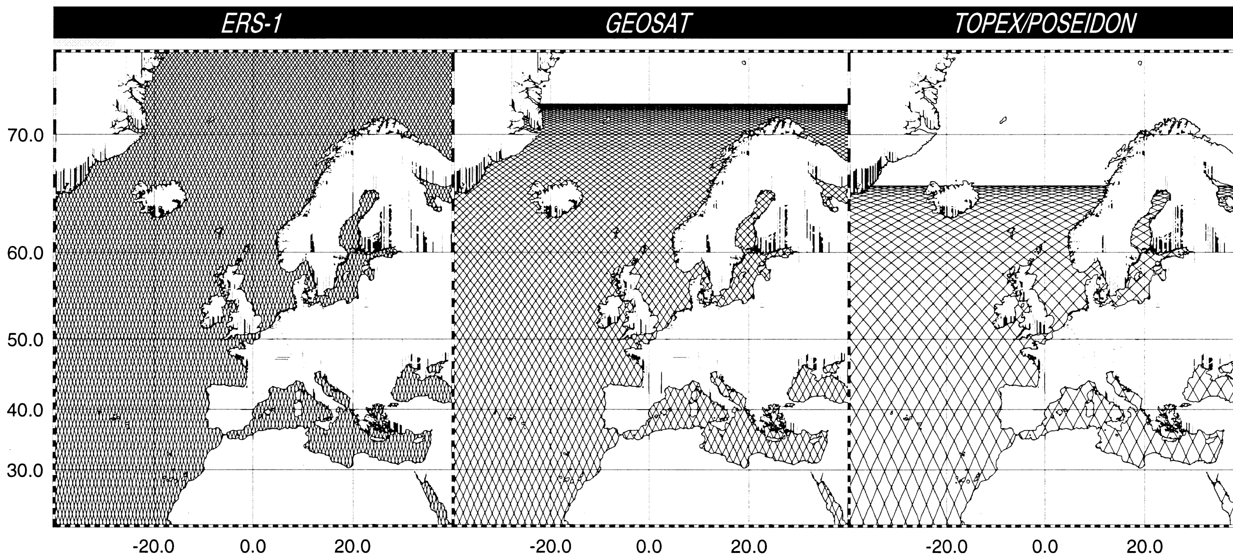

Fig. 1. Satellite tracks for the Atlantic coasts of Europe and the Mediterranean. A dense grid necessarily implies longer time intervals for the satellite to return to the same location.

$\lambda_p \propto T_p^2$ in deep water, the coefficients of variation behave somewhat differently when T_p varies (an obvious modification is necessary for very shallow water).

The satellite altimeter measures H_s exactly below the satellite, and the typical radar footprint diameter varies with the wave height from two to ten kilometres. The standard product for H_s is one estimate every second, that is, about every 7 km along the track. Each estimate is an average of several (typically 10) individual measurements taken every 0.1 s. Presently, Topex/Poseidon and ERS-2 are fully operational and provide altimeter data routinely. The GEOSAT *follow-on* was launched on 10 February 1998, but no data have at the time of writing been released.

The ERS-2 and the Canadian RADARSAT both fly a SAR, but the restrictive data dissemination policy of the latter makes it less interesting for regular wave observations. The ERS-2 SAR, as its predecessor ERS-1, has two products of interest for wave analysis. The regular SAR image product covers a square area 100×100 km along the swath and consists of 5000×6300 pixels. The *Wave Mode* product is a SAR image spectrum obtained from a 400×600 pixel *imagette*. The spectrum is distributed as spectral values averaged into 12 directional and 12 wavenumber bins ranging from 100 to 1000 m in wavelength and covering a 180 degree sector. Wave Mode spectra are recorded approximately every 200 km along the track. Locations of ERS-1 Wave Mode spectra received during a 14 day period in the North Sea/Norwegian Sea are displayed in Fig. 2. These spectra (every second spectrum recorded) are distributed operationally to all meteorological offices around the world on the Global Telecommunication System (GTS). Even though the resolution of the SAR images and the imagettes may resolve waves up to 0.18 Hz, the current data format limits the frequency in the Wave Mode spectra to 0.125 Hz in deep water (corresponding to 100 m waves) and even less in shallow water. The power consumption prevents the full ERS SAR from being switched on more than about 12% of the time, but Wave Mode may be run continuously. An improved processing scheme is currently being implemented for ERS-2. The full resolution SAR imagery is excellent for detailed coastal studies, but, unfortunately, much too infrequent for operational monitoring. However, collecting historical SAR images over a longer period, say a couple of years, is nevertheless interesting for climatological studies. The coverage of full resolution SAR data during the SCAWVEX field experiments is reported below. In late 1999, ESA's *Envisat* will be launched with improved altimeter and SAR instruments for wave measurements.

2.2. Algorithms for altimeter data

The feasibility of measuring ocean wave heights and wind speeds from space was first demonstrated over twenty years ago with the launch of NASA's GEOS3 satellite in April 1975 and the short-lived SEASAT mission in 1978. Since then algorithms have been refined, and validation against in situ data has been extensive. However, the routinely processed data provided by the space agencies have to be carefully quality controlled and calibrated. An overview of currently used calibration relations in the form $H_{s\ coor} = aH_s + b$ are shown in Table 1. All calibration relations for the Topex altimeter give more or less the same correction for the most frequent medium sea states. However, there is a 1/2 m difference in the range of calibration functions at $H_s = 10$ m. This

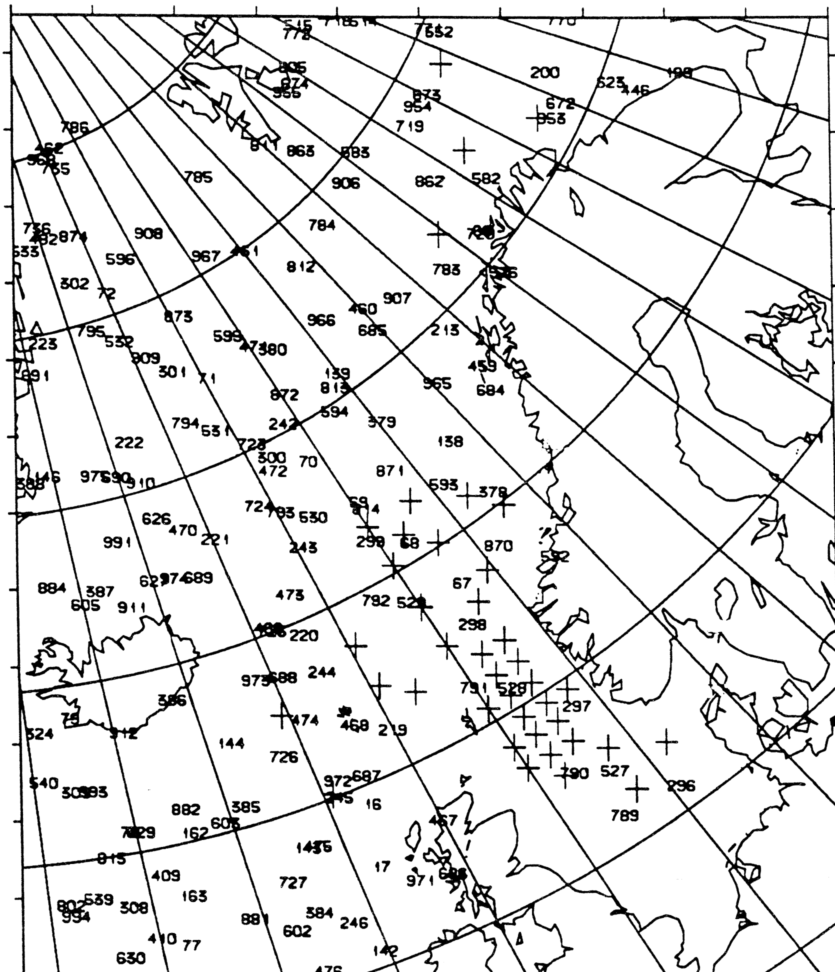

Fig. 2. Locations (indicated by numbers) of ERS-1 Wave Mode spectra over the Norwegian Sea 8–22 November, 1993. The crosses are grid points in DNMIs numerical wave model where spectra are available for first guess wave spectra.

highlights the necessity of validating altimeter data against as large a set of buoy data as possible before using the data for extreme wave analysis (Cotton, loc. cit.).

Recently, we have compiled an offshore data set consisting of co-located NOAA buoy and Topex altimeter data. The reference data set contains quality checked data from 13 buoys, altogether 1365 data records. The data were quality controlled by a careful manual inspection, and only data from tracks that passed within 100 km and 1 h with respect to the buoy observations have been included. The three closest altimeter measurements were averaged and the calibration in Table 1 (Barstow et al., 1998)

Table 1
Calibration functions for data from Geosat, Topex/Poseidon, ERS-1 and ERS-2. $H_{s\ corr} = aH_s + b$

Satellite	a	b [m]	Conditions	Reference
GEOSAT	1.13	0		Carter et al. (1992)
	1.06	0.089		Cotton et al. (1997)
	0.85	0.5	Att. $< 1°$ and $H_s < 1.77$ m	Barstow et al. (1998)
	1.13	0	Att. $> 1°$ or $H_s > 1.77$ m	
Topex (ku band)	1.09	−0.19		Cotton and Carter (1994)
	1.075	−0.03		Gower (1996)
	1.049	−0.082		Cotton et al. (1997)
	1.1	−0.165		Barstow et al. (1998)
ERS-1 (FD)	1.099	0.165		Cotton et al. (1997)
ERS-1 (OPR)	1.267	0.136		Cotton and Carter (1994)
	1.126	0.333		Cotton et al. (1997)
	1.01	0.47	$H_s < 1.95$ m	Barstow et al. (1998)
	1.25	0	$H_s > 1.95$ m	
ERS-2 (FD)	0.48	0.69	$H_s < 1.5$ m	Cotton et al. (1997)
	1.05	0.04	$H_s > 1.5$ m	
	1.053	0.189		Cotton et al. (1997)

applied. The resulting scatter plot between the buoy and altimeter wave heights is shown in Fig. 3.

It may be proved by simulation (see Krogstad et al., this issue) that the scatter seen in the plot for significant wave heights above 2 m, is not larger than the scatter between two 17 min buoy measurements experiencing different realisations of the same sea states. The somewhat increased scatter below 2 m is most likely due to spatial

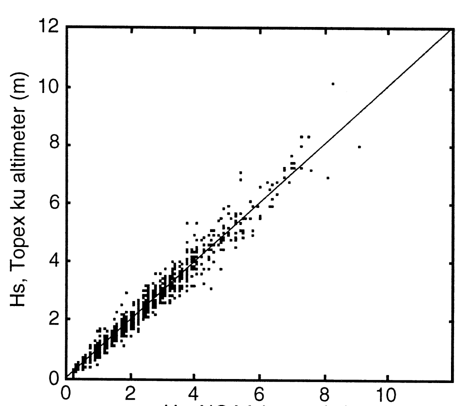

Fig. 3. Significant wave height from NOAA buoys and the Topex altimeter for 1365 coincidences.

inhomogeneity. This actually shows that single point altimeter measurements averaged over about 25 km along the track and buoy measurements have comparable accuracy.

The easy availability and the coverage of the satellite altimeter data have made it interesting to try to obtain additional information from the measurements. It was realised early on that wind speed is related to the backscatter signal strength (σ_0) through the amount of short scale wind generated waves, and since this also relates to the RMS slope of the surface, one may even derive a so-called altimeter wave period from the data.

For the Topex altimeter, a recent 3-stage non-linear fit of buoy wind speed (13 NOAA buoys) to the satellite σ_0 gave the following algorithm:

$$\mathrm{Wsp}[\mathrm{m/s}] = \begin{cases} 44.274 - 3.263\sigma_0, & \sigma_0 < 11.916 \\ 4.531 - 2.083\log(\sigma_0 - 11.256), & 11.916 \le \sigma_0 < 17.5 \\ 2.199 - 0.0848\sigma_0, & 17.5 \le \sigma_0 < 25.93 \end{cases} \quad (2)$$

(Barstow, 1995).

A similar 2-stage algorithm had earlier been developed for GEOSAT:

$$\mathrm{Wsp}[\mathrm{m/s}] = \begin{cases} 51.91 - 4.115\sigma_0, & \sigma_0 < 11.87 \\ 5.773 - 0.228\sigma_0, & 11.87 \le \sigma_0 < 25.83 \end{cases} \quad (3)$$

(Barstow, 1993).

In both cases, only a few high wind speed validation records were available and, therefore, linear extrapolation to very high winds inherent in the algorithms above is somewhat speculative. Nevertheless, Barstow et al. (1994) showed that the GEOSAT algorithm gives realistic hurricane force winds compared to island winds during the passage of a tropical cyclone in the Cook Islands in the South Pacific.

The derivation of wave periods from altimeter data is still in its early development (Carter et al., 1992; Davies et al., 1997). Their idea is to define a non-scaled altimeter wave period as $T_a = H_s^{1/2}\sigma_0^{1/4}$ and then obtain the mean wave period T_z by regression from a calibration data set. Actually, by applying a similar approach based on the significant wave height, wave period and wind speed from an off-shore buoy in the Norwegian Sea, we fitted a non-linear regression of the form

$$T_z = \max(T_{z\min}(H_s), a(H_s) + b(H_s)\mathrm{Wsp}), \quad (4)$$

where $T_{z\ \min}$ is the minimum wave periods from the T_z/H_z scatter plot (a limitation imposed by the upper saturation range in the wave spectrum), and $a(H_s)$ and $b(H_s)$ are regression parameters for wind speed vs. the wave period. This empirical expression was then applied to a set of 455 carefully selected coincidences between the Topex/Poseidon altimeter and a set of NOAA buoys. Using the significant wave height and the wind speed from the altimeter, we arrived at the comparisons shown in Fig. 4. The agreement is fair, but not perfect with a bias towards longer wave periods for the buoys. This is explained by the more swell dominated climate around the NOAA buoys as compared to the storm dominated Norwegian Sea wave climate. Swell contributions would be impossible to pick up properly by this method, and a more direct and independent

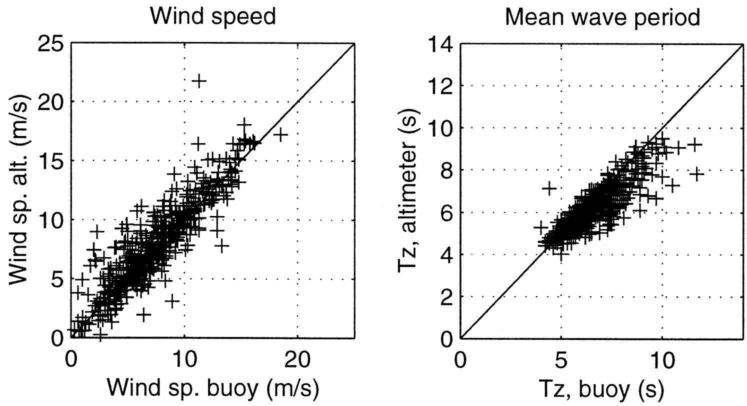

Fig. 4. Comparison of the Topex altimeter derived wind speed and wave period against buoy data ($N = 455$).

estimation of the wave periods from signatures in the altimeter signal would be preferable.

2.3. Algorithms for synthetic aperture radar data

The Synthetic Aperture Radar produces an image of the sea surface, and the analysis starts by a 2D spectral analysis of subsets of the image. However, the SAR image spectrum has turned out to be far from the actual wave spectrum and a rather complicated post-processing is necessary for extracting quantitative wave information. The core of the methodology is Hasselmann's non-linear *ocean-SAR spectral transform* developed in the early nineties. The transform T gives an analytical expression for the SAR image spectrum, $S(\boldsymbol{k})$, corresponding to a given wave spectrum $\Psi(\boldsymbol{k})$, $S = T(\Psi)$. The full expression, which encompasses SAR specific effects such as range and azimuth bunching, azimuth smearing, tilt and hydrodynamic modulations is rather complicated and will not be given here. However, what is of interest is the inverse problem, namely to find the wave conditions, i.e., the wave spectrum, which produces the observed SAR image spectrum. Hasselmann and Hasselmann (1991) formulated this by means of Tikhonov regularization where an a priori spectrum $\Psi_0(\boldsymbol{k})$ from a numerical wave model or by some intelligent guess), is used in an optimisation functional of the form $J(\Psi)\|\Psi - \Psi_0\|^2 + \|T(\Psi) - S_{\mathrm{mes}}\|^2$. The norms contain weight functions and the minimisation incorporates the constraint $\Psi(\boldsymbol{k}) \geq 0$. A simplified algorithm for the minimisation is described in (Krogstad et al., 1994), but several versions based on the full non-linear transform are now operational (Heimbach et al., 1997).

Despite intensive research over several years, there is still quite some way to go before the SAR-ocean inversion reaches the accuracy for the significant wave height obtained from the altimeter. The SAR backscatter mechanisms are incompletely understood and strongly dependent on centimetre waves generated by the local wind. The current resolution of space borne SAR also limits the observations to waves longer than about 50 m. Moreover, the SAR image spectrum is from the outset symmetrical and thus suffers from a 180 degree ambiguity in direction. This is the main reason for introducing the a priori spectrum in the inversion functional. In most cases, for example in coastal areas, the choice between the two possible wave directions is obvious. An intrinsic weakness in all SAR image spectra is a marked attenuation in the direction parallel to the radar propagation. This *azimuth cut-off*, which is due to the random apparent shifts of the scatterers caused by the motion of the surface, masks waves travelling parallel to the satellite. Unfortunately, the cut-off is most severe for high sea states and for radars seeing more out to the side from the track. Moreover, the so-called speckle noise in the images, caused by the formation of real images from the coherent processing, leads to a noise level which masks parts of the spectrum. Both the 180 degree ambiguity and the speckle noise can be avoided by applying SAR image cross spectra (Engen and Johnsen, 1995). The standard SAR processing usually splits the data into several images of approximately the same scene. By averaging the images, the speckle noise is reduced, and at the same time, because the time between the recordings may be of the order of 0.5 s, the wave pattern has moved and the scene is somewhat blurred. By computing cross spectra between the images, the speckle noise is substantially reduced and the motion which took place between the images shows up in the cross spectrum such that the directional ambiguity is resolved for the components which are visible (and more are visible due to the reduced speckle level).

3. Applications

In the following some of the many potential applications of satellite data are shown by reference to a number of studies carried out over the last 10 years by the authors. In all cases described here, the use of satellite data significantly improves the accuracy of the results than would be the case if these data had not been available.

3.1. Altimeter

3.1.1. Direct use of satellite measurements in shallow water

The spatial resolution of satellite altimeter data is no better than 7 km or so along the track. Further, generally, altimeter data are only useful when the satellite moves from the sea towards the coast as measurements are often either missing or biased for the first few measurements after passing from land to sea. However, in some cases, when the shallow water area is rather large compared to the altimeter resolution or the satellite track is oriented alongshore, then altimeter data can nevertheless be very useful. An example of the former type is given first, from the North Sea, which is a shallow basin of large extent. Next, an example where the satellite is oriented alongshore is given from Norwegian waters.

Fig. 5 shows two examples of ERS-1 and Topex altimeter tracks on the Dutch coast during the first SCAWVEX field experiment in winter 1995/96. For the period from 25 Dec. 1995–8 May 1996 a total of 11 passes from Topex and 11 from ERS-1 were obtained from the Maasmond area (ERS-2 data passing about 1 day later than ERS-1

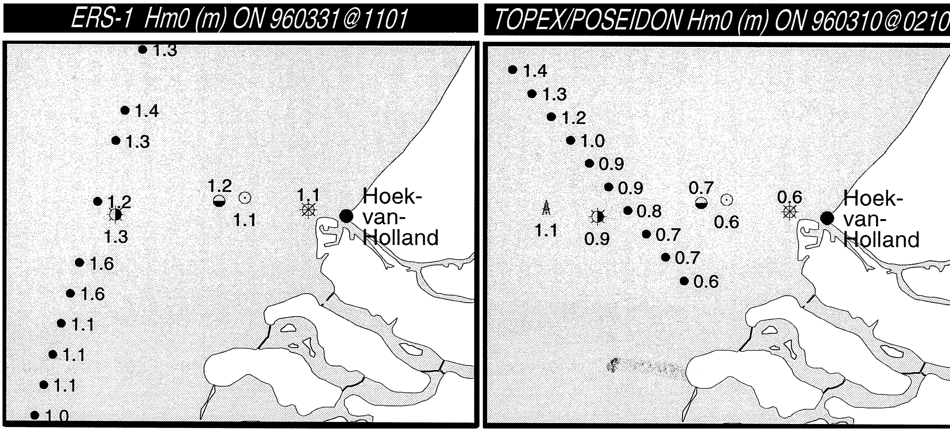

Fig. 5. Examples of altimeter tracks off the Dutch coast collected during the SCAWVEX Maasmond experiment. Note strong gradients, but good correspondence to the Rijkswaterstaat's in situ measurements. Distance between the altimeter data points is about 7 km.

was actually available but not used). The examples are chosen because they show a quite strong gradient in the wave height. The field measurements are from the Rijkswaterstaat's operational network. The buoy data were somewhat intermittent, but from a careful analysis of each coincidence, it is clear that the altimeter data show excellent agreement with the in situ buoys for the whole period. However, this also illustrates that the amount of data at a given coastal site in any given period will be rather limited. It is obvious that unless several satellites are working in parallel, the coverage at a given site will be much too sparse for operational monitoring.

In fortunate situations, it is possible to use altimeter data for model verifications also in coastal waters. During early June 1994 the oil company Conoco Norway carried out a full scale towing test of a tension leg of the Heidrun TLP due to be deployed in the Haltenbanken area in summer 1995. The authors were approached to try and give a best estimate of the wave conditions during the test which took place in the semi-enclosed sea *Frohavet*. Available data included wave data from the offshore long term station on Haltenbanken and altimeter data from ERS-1 (no SAR data were directly useful). The altimeter data were used to validate the results of a backward raytracing model which, based on digitised bottom topography for the area, transformed measured deep water directional wave spectra into the location of interest. The comparison of significant wave height between the raytracing model and altimeter data where the tests were carried out, showed excellent agreement for a pass at the time of the tests, see Fig. 6. This gives one example of the need to combine in situ measurements, models and satellite measurements to give the best results in many cases.

3.1.2. Studies of temporal and spatial representativity

In more remote and data sparse regions of the world the altimeter provides an efficient means to extend short period wave measurements both temporally and spatially. In connection with a feasibility study for building a Tapered Channel (Tapchan) wave

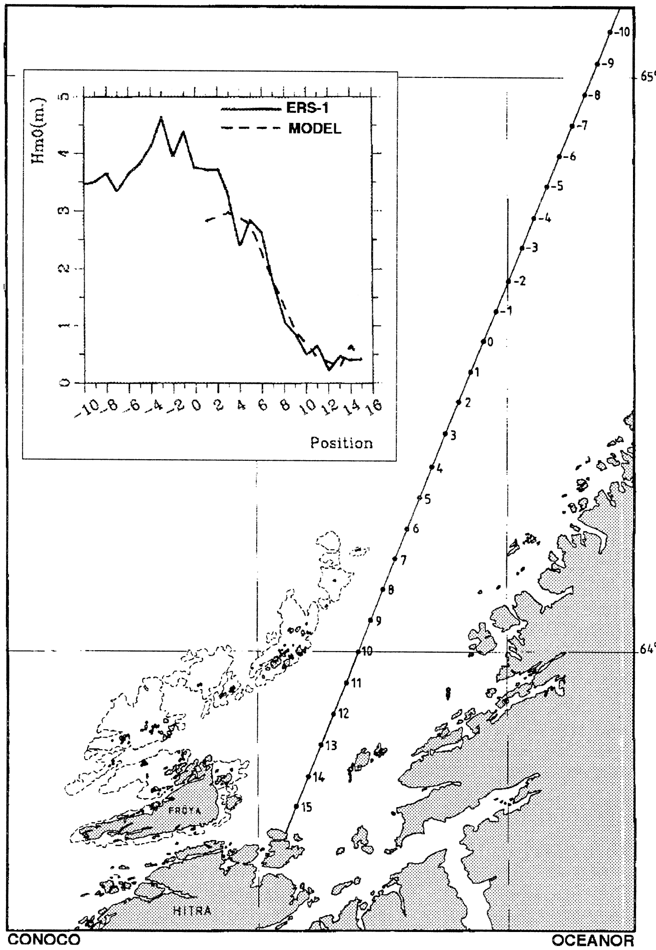

Fig. 6. The ground track of ERS-1 through Frohavet compared to the results from the wave model.

energy converter and power plant on the southern coast of the Indonesian island Java, one of the authors (SFB) was contracted to carry out a wave energy resource study at the site. Wave measurements existed for a 3-month period during October–January 1991 to 1992 and the representativity of the data was unclear. Using the Geosat data it was demonstrated that the buoy data were reliable and representative for the time of the year. Further, the altimeter data clearly showed that the seasonality of the wave climate in this area is such that November to January are relatively low energy months, allowing the estimated annual wave energy resource to be significantly adjusted upwards. Contour maps based on the Geosat data (Fig. 7) showed that the mean wave conditions along the chain of islands, which includes Java, were about the same over a distance of some 1000 km., meaning that, if this project is successful, then there is a rather large expansion potential. The Tapchan wave power plant is now being constructed.

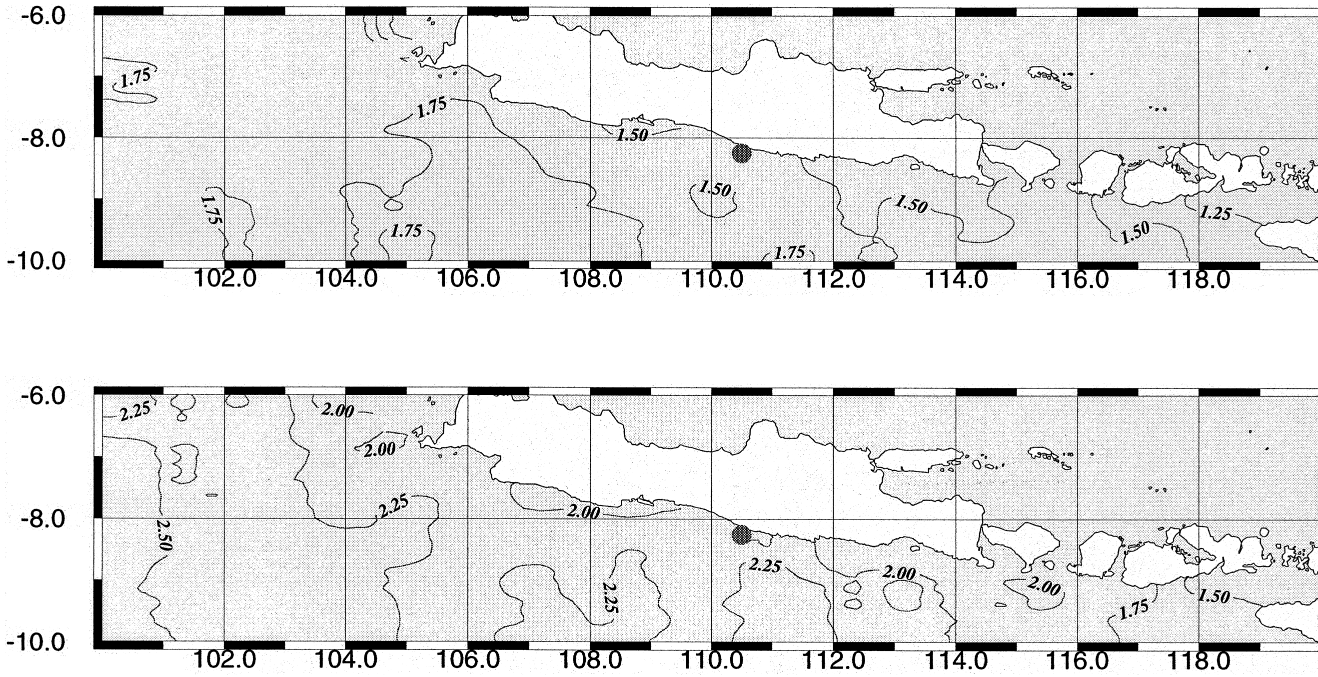

Fig. 7. Mean summer (November–January, upper panel) and winter (June–August, lower panel) significant wave heights along the Java south coast. Limited field measurements from a Waverider were available at the location indicated by the spot.

Nevertheless, altimeter data have often been employed over the years also in more data rich waters such as the North Sea and Norwegian Sea to, for example, evaluate the spatial representativeness of a long term measured series from one location for a second site in the same area. Another example is related to an apparent shift in the winter wave climate, which occurred in 1989 in the North East Atlantic. Design conditions had been specified for a number of oil fields in Norwegian waters, based on 10 years of measurements in the area, prior to this shift. Altimeter data were used together with wave model data to better document the longer term wave climate and to have a re-look at the extreme predictions (Barstow and Krogstad, 1993, 1994).

3.1.3. World-wide wave climatologies

The fact that altimeter data are available globally over a regular 'net' (the ground tracks), allows us to relatively easily make global comparisons of wave conditions. An example of one such application was in connection with the development of the Norwegian ConWec wave energy converter. Topex/Poseidon data were recently used to estimate the wave energy resources along all coasts globally (Barstow et al., 1998). Two years of the altimeter data were used in constructing the global map of the available wave energy resources in deep water (Fig. 8). For all cross-over points of the Topex/Poseidon ground tracks located close to coasts world-wide, time series of significant wave height were first constructed. One measurement in the time series corresponded to the average of the closest 3 measurements at the closest approach to the cross-over point. For each H_s measurement, a value of the wave energy period, $Tm_{-10} = m_{-1}/m_0$, was assigned and the wave power was calculated from $J = 0.49\ H_s^2\ Tm_{-10}$ where J has units kW/m. The assigned value of Tm_{-10} was based on various buoy data sets from around the world. Scatter plots were made of Tm_{-10} against H_s for various available buoy data sets which had this parameter available as follows: various data sets from the South Pacific islands with varying exposure to wind seas and swells (Western Samoa, Tonga, Fiji, Tuvalua and Vanuatu collected for the South Pacific Geoscience Commission, SOPAC in Fiji), various Norwegian data sets and also data from a swell dominated wave climate off Portugal. A linear or power function was fit to each data set to give a direct relationship between Tm_{-10} and H_s. For each location world-wide, a value of Tm_{-10} was calculated for each H_s measurement from the relationship corresponding to the climate best suiting the actual climate at the site in question (with respect to the relative importance of wind seas and swells). Although the choice was somewhat subjective, it is clear that the square dependence on H_s in the calculation of wave power, gives Tm_{-10} secondary importance. The purpose here was really to give a quick overall picture of the variation in the wave power resource globally. Other methods (combining wave model and altimeter data) are used to make more accurate estimates.

Fig. 8 shows clearly that the most energy rich coastlines in the world straddle the high latitudes of the Southern Hemisphere, including southern Australia and New Zealand, southern Chile as well as to the west of the British Isles and southern Iceland. However, it should be pointed out that different wave energy devices are adapted to different parts of the wave spectrum, some more tune in to the swells and others to wind seas. A high energy level does not, therefore, necessarily, imply a relatively high

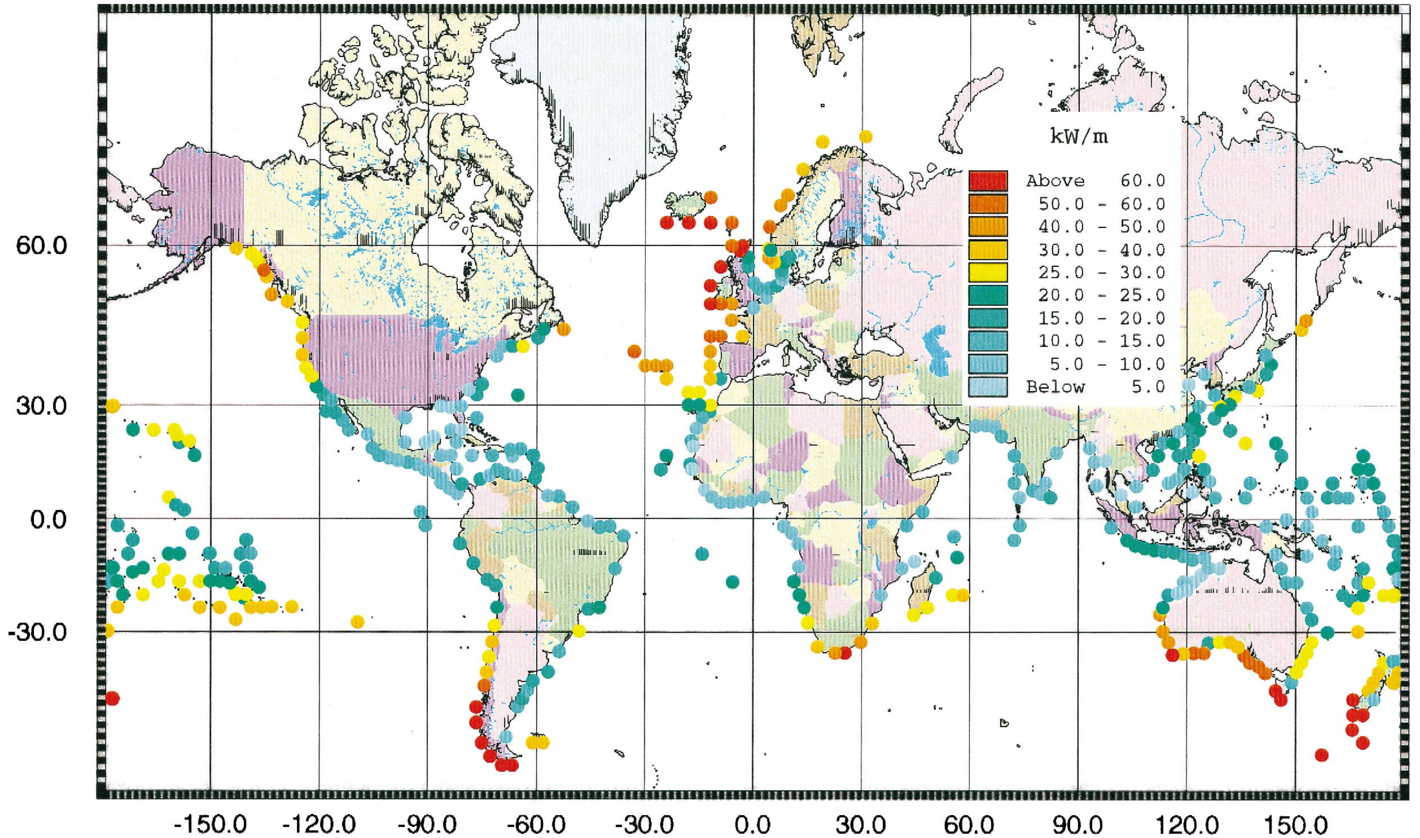

Fig. 8. Wave energy estimates (in kW/m) along most of the global coastlines from two years of Topex/Poseidon altimeter data, with best estimates of wave period (required for estimating wave power) derived from various buoy data sets from around the world. We note that altimeter derived wave period could potentially also have been used.

potential. There are many other factors involved including the wave energy spectrum, the stability of the resource in strength and direction, the occurrence of extreme storms and the exposure of a coastal site, where first generation wave power plants are being built, relative to the offshore. Thus, in reality, parts of the tropics and sub-tropics where the stable trade winds blow may be more interesting for wave energy although the average wave energy resource is not high. We refer to Barstow et al. (1998) for a discussion of further applications of altimeter data in wave energy studies.

3.1.4. Coastal wave statistics

Both in wave energy and other coastal applications, offshore wave conditions will not be representative of conditions at the coast. Although spatial gradients along-coast offshore are relatively small in most cases, the transformation in wave conditions from deep water in to the coast may be large even over a relatively short distance. In some cases, if one is lucky to have a satellite track passing from the offshore and close to the site of interest, it is possible to make a simple transfer function from deep water to the site. However, this is only useful where one can accept a spatial resolution of no better than 20 km or so. Nevertheless, this method is often useful to give a quick, rough estimate of the wave conditions at a site. In order to provide more accurate wave conditions at a coastal location, in the absence of on-site measurements, satellite wave measurements are not sufficient alone and the best approach is to validate and, if necessary, calibrate data from an existing global or regional wave model archive using satellite data. The resultant time series can then be used as input to a suitable shallow water wave model to perform the transformation to the coastal locality of interest. We are presently using a 10-year archive (1986–1996) from the UK Met. Office's global wave model (see Foreman et al., 1994 for more details). Other existing global archives, which could be used alternatively, are those derived from the Fleet Numerical's Spectral Global Ocean Wave Model (SGOWM) and the global WAM model operated by the European Centre for Medium-Range Weather Forecasts (ECMWF).

The Met Office Wave Model archive consists of the hindcast fields of winds and waves produced during the operation of the atmospheric and wave model forecast. We are using a sub-set of the main archive consisting of a set of wave parameters (i.e., significant wave height, period and direction both overall and for the wind sea and swell separately) on an, initially, approximately 150 km grid globally, improved to about 85 km in June 1991. Parameters were initially updated 12 hourly, but this was improved to 6 hourly in June 1988. The model is a second generation, deep-water model. It is important to realise that the model archive consists of the results of a steadily evolving system, as a number of small improvements have been included in the model over the years. A time series of wave parameters at one location can, therefore, not be considered to be homogeneous. This is where satellite altimeter data are invaluable as these data represent a close to homogeneous data set covering November 1986 to September 1989 and September 1992 to present. We can thus use the satellite data to first validate and, if necessary, to calibrate the model results. This is done by extracting all satellite altimeter data from a representative area around the model grid point and plotting simultaneous significant wave heights from the model and the satellite measurements for a number of time periods to investigate the homogeneity and variability of the archive. In some areas it may be advantageous to validate several neighbouring grid points in this way, particularly where the along coast climate varies only weakly. This improves the statistical significance of the results by increasing the data set to be compared. Along track variability can also be used to assess the spatial variability in the area in question.

In a few studies, it has also been possible to validate the model against buoy data, e.g., in the South Pacific, against NOAA buoys around the US, and also against various buoys in European waters. Both buoy and altimeter validations carried out over the years at many locations had shown consistent results. The only really significant change in the accuracy of the archive, which is seen at practically all locations, occurred in June 1993 when the Met. Office began assimilating real time fast delivery data from the ERS-1 satellite altimeter (see Foreman et al., 1994). It had also become clear that the model tends to underestimate the significant wave height, particularly the swell height, due to problems with the retention of swell in the model. In June 1993, this bias decreases significantly. For enclosed seas, into which long distance swells do not penetrate, the agreement with the reference data is much better. These features are clearly shown in Fig. 9 which shows the results of validating the model significant wave height both before and after June 1993 in Mexican waters. There is little difference in the range of wave conditions during the two periods. A change to lower bias is found throughout, but is most marked in the Pacific waters. A residual model underestimate along the Pacific coasts, after June 1993, is probably related to the fact that the fast delivery ERS altimeter wave height data are assimilated into the model without correction. The

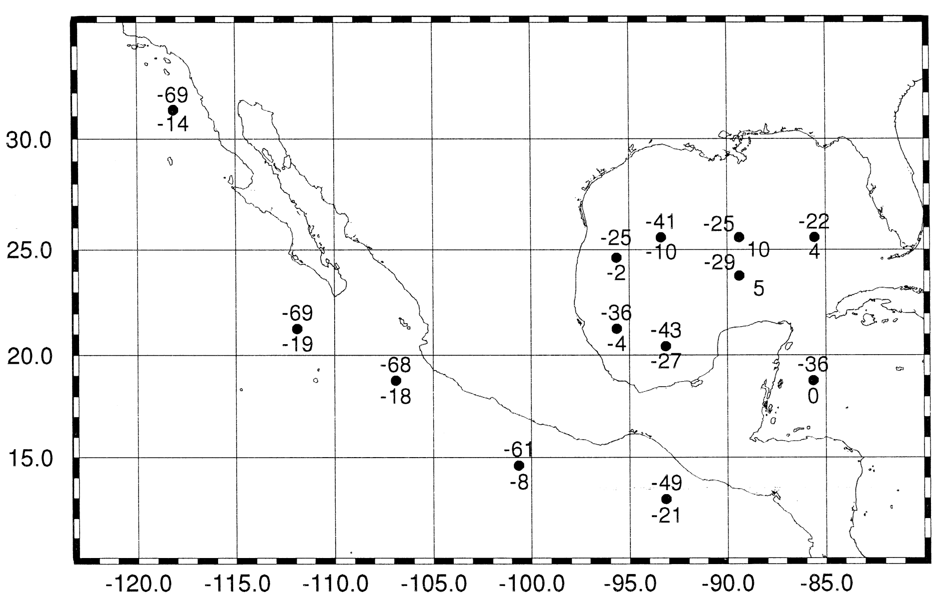

Fig. 9. Wave model significant wave height bias (cm.) relative to Topex altimeter data for a number of grid points around the coasts of Mexico. Negative bias implies that the model underestimates. Above the points is given the bias for the period September 1992 to May 1993 and below the bias for October 1993 to October 1996.

ERS-data are themselves biased somewhat low compared to buoy data (e.g., Cotton et al., 1997).

In a recent project to develop a European wave energy resource atlas (EU Joule WERATLAS project), a re-run of ECMWF's global WAM model for the Atlantic, on a 3° grid, and an operational version of the model, on a 0.5° grid, for the Mediterranean, were validated using Geosat and Topex data (see also, Barstow et al., 1998). Results were consistent with the buoy-model validations for the bias and the scatter was only slightly higher from the model-altimeter comparisons confirming the accuracy of the altimeter data.

In the EU MAST project Eurowaves, a European wide toolbox is being developed with the aim to provide accurate wave statistics throughout Europe by combining bathymetric data, wave models and wave model data throughout Europe to specify the deep water input. For most of Europe, the wave model data derive from the WAM model run at ECMWF in the UK. Topex altimeter data are being used to validate and calibrate the WAM data throughout the region (Cavaleri et al., 1999) to provide uniform quality offshore wave statistics.

3.1.5. Wave atlases

Traditionally, wave atlases based on visual observations have provided wave statistics covering the global oceans. With many years of satellite data available, there now exist several global wave atlases based on satellite altimeter data. However, it was early realised during the development of the *World Wave Atlas* (WWA) (see Internet address below) that many users of wave data are interested in wave statistics for only one or a few areas around the world. Therefore, it was decided that rather than producing one atlas for the whole globe with low resolution and accuracy, WWA should provide basically all available data for smaller areas at the highest resolution and accuracy. Thus, World Wave Atlas is, in fact, a composite of atlases, including every maritime country world-wide. The current version of WWA may contain the following data:

- GEOSAT data (1986–1989)
- Topex/Poseidon (1992–1997); measurements still ongoing and can be updated annually.
- Available buoy data (e.g., the US NOAA buoy network)
- Data from a global wave model (currently UK Met. Office data) after calibration against satellite data

As an example of the customer's diversity, country and regional atlases have recently been sold to customers in Mexico, Korea, India, Australia, the Chukchi Sea and the Caribbean. Wave atlases for a number of larger regions or sea areas (e.g., North America, the Far East, Europe, the Mediterranean, the North Sea etc.), and atlases for major shipping lanes are also under preparation.

The atlases are flexible with respect to the parameters to be presented, and the customers' own site specific measurements and model data can be integrated with WWA. Data can be presented both geographically or as wave statistics, and any area or time period can easily be selected for analysis. The statistical module allows calculation of the most commonly used wave and wind statistics (univariate and bivariate frequency distributions, exceedence curves, extreme statistics for significant, maximum and crest wave heights, spatial and temporal variability including along track variations, seasonal and inter-annual variability, direction roses etc.).

3.2. SAR

3.2.1. SAR imagery from coastal regions

In SCAWVEX, one of the experiment sites was the Maasmond area near Rotterdam in the Netherlands (Wyatt et al., 1998). All available SAR images for the site were collected for the period from January 28 to April 7 1996. During this period both ERS-1 and ERS-2 were operating in parallel and altogether 27 full resolution SAR scenes were received corresponding to 15 different events. However, only 4 images corresponding to 2 different events had visible waves. This again illustrates very well that satellite data are not particularly useful for continuous monitoring of given sites. An excerpt of an image from 13 Feb. 1996 in Fig. 10 shows the wave pattern off the harbour of Rotterdam. It is possible to follow a group of large waves all the way into the channel where a large ship is entering.

There are actually numerous SAR images from coastal regions showing refraction and even breaking waves. One striking example from the Portuguese coast is shown in (Barstow and Krogstad, 1995). During the Holderness 1 experiment five SAR scenes were collected. Unfortunately, none of these cases featured high waves, but there was a visible wave pattern in the scene from January 27. However, the modulation was too

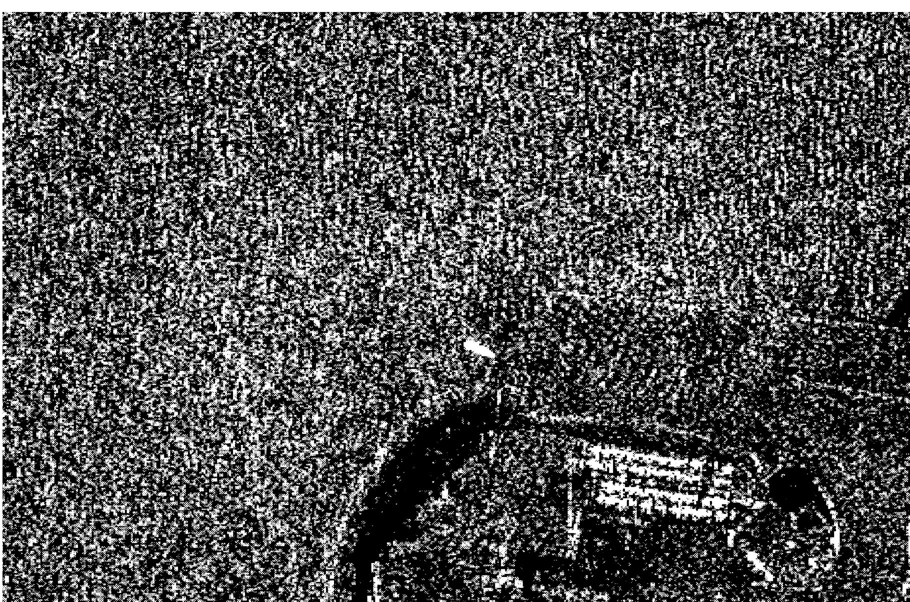

Fig. 10. Excerpt of ERS-1 SAR image from 13-FEB-1996@10.38. Inlet to Rotterdam harbour. Note clearly visible ship and refracting waves in the channel south of the breakwater (Indicated bar is 1000 m).

weak for a meaningful inversion with wave heights probably only around 1 m. An automatically traced spectral peak direction from parts of the scene is shown in Fig. 11. We expect this to be approximately equal to the wave direction in this case. There is actually a large portion of the scene where the wave pattern disappears, indicating a significant spatial variability over a relatively short distance (An increased wave steepness and hence increased azimuth cut-off in the spectra could actually mask the wave signatures in part of the image, but this appears to less likely, judging from a visual impression of the spectra).

Only a couple of the SAR images collected during SCAWVEX had sufficient wave modulation for a really meaningful spectral inversion. The best scenes were from February 17 where contour plots of the significant wave height and the mean wave period obtained from a SAR/wave spectral inversion are shown in Fig. 12. Whereas the upper right corner shows wave heights up to 3.4 m, the wave height drops to only 1.8 m in the southern part. In situ measurements from the time of pass were reported to be near 3 m at the harbour inlet (outside the plot about half way up on the right side, and 3.8 m at the EURO 15 platform situated 2/3 up in the middle of the plot. The inverted wave heights are therefore somewhat low whereas the inverted wave periods are slightly longer than the periods measured in situ. The inversion was in the present case based on the quasi-linear algorithm described in (Breivik et al., 1998) and based on SAR image spectra from 4×5 km subscenes on a 10×10 km grid. The inversion was free to adapt to the data starting from a somewhat arbitrarily chosen start (1 m waves from NW).

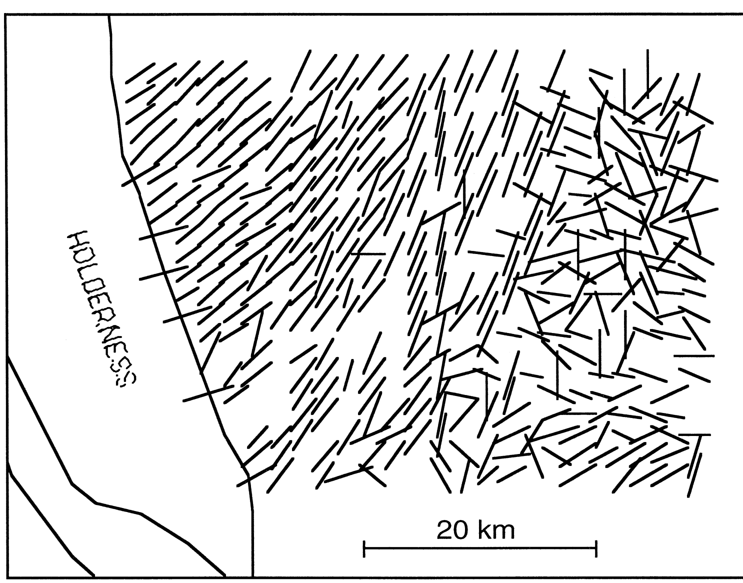

Fig. 11. Dominant wave direction automatically computed from a dense grid of SAR image spectra offshore Holderness 27 January, 1995. The procedure produces near random directions in the lower right corner indicating low wave modulation in that part of the image and hence considerable sea state variability over relatively small distances.

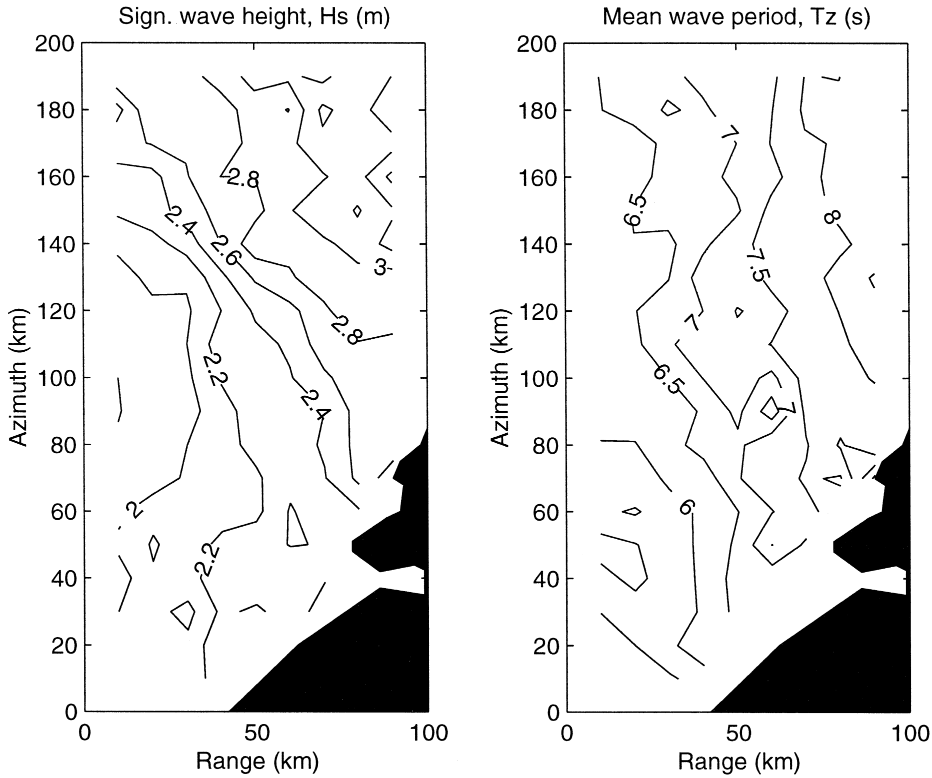

Fig. 12. Contour plots of significant wave height and mean wave period obtained from SAR-ocean spectral inversion obtained from a composite of two SAR images from the Dutch coast 17 February 1996.

3.2.2. Assimilation of SAR observations into numerical models

As mentioned in Section 1, one of the best ways of using satellite wave observations operationally appears to be through assimilation of the data in numerical wave models. The general techniques for assimilating satellite data are treated in (Komen et al., 1994), although their discussion of data availability and reliability is now quickly becoming outdated. The scatterometer wind measurements have turned out to be very important for the atmospheric input to the wave models, and the introduction of the ERS-1 altimeter data into the UK Met. office model in June 1993 significantly decreased the bias in H_s as mentioned above. The altimeter data from ERS-1 have routinely been assimilated into the Norwegian wave model at the Norwegian Meteorological Institute (DNMI) since the launch of ERS-1. The assimilation has a small, but significant positive impact, in particular on the short term forecast (Breivik and Reistad, 1994).

The SAR Wave Mode data from ERS-1 and -2 also have a substantial potential in operational wave forecasting. Extensive research is currently ongoing to validate the data (see, e.g., Brüning et al., 1994; Heimbach et al., 1997), and tests of assimilating inverted spectra are being carried out (Dunlap et al., 1998).

The impact of assimilating inverted ERS-1 and 2 SAR spectra into the operational wave model at DNMI was evaluated for a four month period in autumn/winter 1995-1996 (Breivik et al., 1998). It turned out that, overall, the average improvement in the forecast was minor, although in certain cases new information from the SAR spectra affected the output from the model for more than 24 h. A fairly strict automatic data control removed about 50% of the spectra, and only 2–3 observations were available in each assimilation cycle. For the relatively few cases where the assimilation had some effect at the in situ measurement sites, this was definitely positive. Nevertheless, the somewhat negative conclusion from the test was that assimilation of SAR sea state data in the model, with the present analysis system, the ERS coverage, and the amount of data received on the GTS, is not sufficiently useful to warrant an operational set-up. It is, however, quite likely that new SAR processing methods (e.g., the cross spectrum method), together with increased data coverage from additional satellites, may enable an assimilation system for waves with a cost-effective positive impact.

4. Satellite wave data on the internet

With the development of the Internet, large amounts of wave information can be obtained on line. The key point in the future will be the clever combination of several data sources in an intelligent and professional way. The Internet locations listed below are certainly only a small fraction of what is available, but some of the references are likely to stay continuously updated with links to other sites.

In the US, NOAA's *National Environmental Satellite, Data and Information Service* (*NESDIS*) is a good start (**http://ns.noaa.gov/NESDIS/NESDIS_Home.html**). UCSD and Scripps Oceanographic Institution runs the *Coastal Data Information Program* (**http://cdip.ucsd.edu**) where information on the net provides a synopsis of the latest coastal conditions including wave, wind, and temperature measurements and even an El Niño swell forecast. Over 2.5 million accesses since its opening in September 1996 illustrates the popularity of this system. Historical data may be traced by means of the Data Access Viewing Engine (DAVE) in the accompanying *Field Wave Gaging Program.*

An interesting starting point for ocean wave information, and also a system that is likely to stay at the forefront of the development appears to be the Scripps wave surf information located at **http://facs.scripps.edu/surf**.

In Europe, the *Committee on Earth Observation Satellites* (CEOS), of which ESA is a major member, serves as a focal point for application of satellite measurements. The organisation's home page at **http://ceos.esrin.esa.it:8000/infosys** has effective search facilities and links, e.g., to the national earth observation networks within the organisation. The Centre for Earth Observation (CEO) is another European initiative to encourage the wider use of information generated by satellites. Its Web site (**http://ceo-www.jrc.it**) contains much useful information, links and actual application cases for remote sensing data including ocean waves.

Several university groups, in particular the Southampton Oceanography Centre in the UK (**http://www.soc.soton.ac.uk**) are active within altimeter research. There are also commercial companies which provide analyses based on satellite wave data. Satellite Observing Systems (**http://www.satobsys.co.uk**) sells both near real-time wind and wave information and global wave climate analyses. The French company MétéoMer has in cooperation with Ifremer developed the ClioSat wave atlas, but limited information is available on the net. In Norway, Oceanor ASA is selling the World Wave Atlas discussed above (**http://www.oceanor.no/wwa**), and in the Netherlands the ARGOSS company (**http://www.argoss.nl**) is developing several applications of satellite data. So far, most of the above give applications of altimeter data, but a good educational video on the measurement of waves using the ERS-1 SAR Wave Mode data may be obtained from the *Deutsche Klima Rechnung Zentrum* (**www.dkrz.de/dkrz/visu/video/ers-eng.html**). The video, *Measurements of Ocean Waves with the ERS-1 SAR*, explains the principles of SAR imaging, the spectral description of ocean waves, and the problems of retrieving wave spectral information from SAR images. Applications of the data are illustrated by wave forecasts and ship routing. Additional educational material is found on the ESA Internet pages.

5. Conclusions

In the present paper we have reviewed the availability, accuracy and use of satellite wave data. The data are easily available and are now an important part of any larger scale met-ocean study. Altimeter measurements of significant wave height have reached the accuracy of buoy measurements, at least for common sea states, whereas SAR data inversion algorithms have still potential for improvements. However, contrary to the altimeter which only provides an integrated significant wave height, the SAR inversion gives full directional spectra which is much more valuable in wave model assimilations.

A state of the art survey of the validation of satellite data may be found in the proceedings from the *CEOS Wind and Wave Validation Workshop* at ESTEC in The Netherlands in the summer of 1997. The recommendations from the workshop appear to be particularly relevant:

- The availability of quality checked in situ data should be improved to support calibration and validation activities.
- There should be an absolute calibration of the radar altimeter cross section.
- Information on calibration/validation should be distributed regularly.
- Validation is needed over the whole lifetime of the instruments.
- There is a need for further validation of algorithms during extreme wind and wave events.

Another recent source for the applications of satellite data is Journal of Geophysical Research's special volume *Advances in Oceanography and Sea Ice Research Using ERS Observations* (Johannesen et al., 1998).

The current amount of satellite data is too intermittent for operational monitoring of given coastal sites but may be incorporated into coastal surveillance systems in combination with local wave models. There are, however, plans of putting up a network of altimeter satellites which would provide a sampling much closer to the operational needs (Allan and Carter, 1998). The satellite data are becoming a main source for met-ocean studies and, judging from the present plans for new satellites, will continue to be so for the foreseeable future.

6. Nomenclature

H_s	Significant wave height defined from the wave spectrum
T_z	Mean wave period (also obtained from the spectrum)
T_p	Peak wave period corresponding to the maximum in the spectrum
λ_p	Peak wavelength
σ_o	Radar cross section
T_a	Altimeter wave period
Ψ	Wavenumber spectrum
S_{mes}	Measured SAR spectrum

Acknowledgements

The SAR and ERS altimeter data have been kindly provided by ESA as part of the program AO2.N104 *SAR and Altimeter Data for Ocean Wave Monitoring and Climatology*. Altimeter data from the US/French Topex/Poseidon mission have been provided by *AVISO, France*. Preparation of this paper has been partly carried out in the EC MAST II programme MAS2CTT940103, SCAWVEX.

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