WorldWaves wave energy resource assessments from the deep ocean to the coast

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Abstract

WorldWaves is a global wave and wind climate package developed through EU and industry sponsorship over many years. The offshore data incorporates global hindcast and operational wave and wind data from ECMWF, validated and calibrated with independent satellite and buoy data worldwide. These data, which may comprise full directional wave spectra time series, are used as boundary conditions to the latest version of the SWAN model for calculation of nearshore wave climate parameter and spectral time series and statistics. The WorldWaves methodology was originally developed in the late 1980s as part of a large wave energy resource mapping project being performed by OCEANOR at that time for SOPAC (South Pacific Geoscience Commission) in Fiji for many South Pacific island nations. Based on the WorldWaves global database, Fugro OCEANOR have created various high precision offshore wave energy resource and variability maps. In this paper some of the peculiarities of the global wave energy climate are discussed. Further, areas worldwide exhibiting a stable energy-rich wave climate are pinpointed as are areas with a favourable ratio of extreme to mean annual wave power density, a rough indicator of the economic potential of a site. Use of shallow water models such as SWAN together with short-term in-situ wave measurements (buoys) is generally needed at the feasibility stage for a proposed wave farm. At the pre-feasibility stage, the nearshore mapping of coastal wave energy resources is often required over larger areas (e.g., a country or state) and full SWAN modelling is usually too expensive. An alternative, utilising the offshore WorldWaves data together with nearshore satellite observations is a cost-effective alternative. This method is described and validated against nearshore buoy data on the US West Coast.

The package will also be demonstrated live at the conference exhibition to interested parties.

Keywords: WorldWaves, Wave Energy, Satellite Altimeter, SWAN

1 Introduction

The roots of the WorldWaves database and software package can be traced back almost 20-years. In the late 1980s OCEANOR were working on a comprehensive wave energy resource project for 6 South Pacific nations for the South Pacific Geoscience Commission in Fiji (SOPAC). Long-term buoy measurements had been made off the coasts of 6 different islands and we needed to evaluate the representativeness of these measurements for other locations. Geosat altimeter data had just been made available for 1986 to 1989 and we combined those data with long-term numerical wave model data from the UK Meteorological Office and an in-house backward raytracing model for calculating coastal wave conditions. In Section 2, we describe the various data sets used in constructing the WorldWaves offshore database: from buoys, satellite altimeters and numerical wave model. In Section 3, we use this global data set to describe the global wave energy resources and, in Section 4, we describe the role of satellite altimeter data can play in mapping larger-scale coastal wave energy resources.

2 Data Sources and Methodology for Resource Assessment

Ocean wave climate varies considerably on various temporal and spatial scales, in particular in coastal waters where most interest in wave energy

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is currently focussed. Wave buoys, both scalar or directional (see Figure 1) can give good estimates of the sea state from a 20 or 30 minute sample, but may be too expensive to maintain for long term wave climate estimation, except at a small number of key reference sites.

Wave climate estimates have therefore come to rely largely on computer hindcast wind-wave models. For example, the WAM model [1] run at the European Centre for Medium-range Weather Forecasts (ECMWF) now provides global coverage, and has been used, for example, to produce a wave energy atlas (WERATLAS) for European waters, [2].

Members of the WERATLAS project team have continued to work over the last decade in the development of what became known as WorldWaves (Barstow et al., 2003). This is an integrated Matlab toolbox for calculating time series of directional wave spectra, wave and wind parameters and associated statistics anywhere worldwide both in offshore and shallow waters. In a typical project, long term predictions would be made with the models and this would be validated with a few months of in-situ (coastal) buoy measurements. A comparison of synchronous wave model predictions would then allow any model errors to be removed over the longer term.

Normally, data is required for a period of at least 10 years, to allow for seasonal, year-to-year and longer-term variability (such as the El-Nino/Southern Oscillation in the Pacific). For sites in depths of less than 100 metres, specific consideration of local bathymetry is necessary. Various numerical shallow water models are available that can be used to calculate the inshore wave climate, starting from data for a deep water reference site. For instance, WorldWaves can now provide up to 50-years of wave energy time series at a coastal site, integrating the long-term ECMWF wave model data with multi-mission satellite altimetry (used for validation and calibration purposes), long-term buoy data in a few sites, global coastline and bathymetric data in addition to the state-of-the-art SWAN (version 40.51) coastal wave model for transferring the offshore time series of directional spectra to the target coastal location.

In the following sub-sections, a review of the main sources of wave data for wave energy resource mapping is given. Although there are many different types of measurement principle and various types of numerical wave models, only the most important for wave energy applications are described. A full review was published recently by [3].

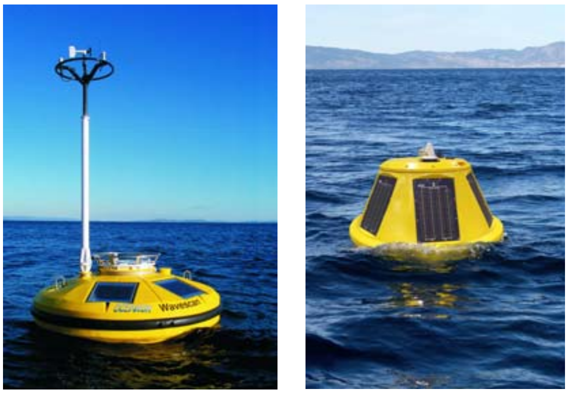

Figure 1: The WAVESCAN heave/pitch/roll metocean data buoy (left) has been used worldwide for directional wave measurements since 1984; The SEAWATCH Mini mk. II (right) is used for coastal and on-site directional wave data collection (for instance, 8 of these buoys form the core of an instrumentation network at the Wave Hub site off the South West of England)

2.1. Buoys

Buoys have been used for measuring waves since the early 1960s. The most successful has been the Datawell Waverider. The OCEANOR WAVESCAN buoy (see Figure 1), introduced in 1985, has been particularly successful and continues to collect directional wave data today, almost 25 years after its introduction. It is a so-called heave/pitch/roll buoy. Datawell also paved the way for more reasonably priced directional measurements through its Directional Waverider, launched in the late 1980s. This buoy measures the heave and displacement rather than the heave, pitch and roll of the slope following buoys which preceded it. This meant that a more compact spherical hull could be used as a measurement platform.

In offshore waters around the world, long-term buoy wave measurement networks are still relatively few and far between. Networks with directional measurements (directional information is essential for coastal prediction) are even scarcer. Probably the most important networks are a) the NOAA-NDBC buoy networks in the US; b) The Indian National Data Buoy Programme network (the best directional network); c) National networks in Spain, Greece, France and Italy and d) long term measurements carried out in Norwegian waters and the North Sea for the offshore industry (many of these data set are public domain).

2.2. Satellite altimeters

The back-scattered signal from satellite altimeters, when properly interpreted, can provide significant wave height measurements close to the accuracy of a buoy, from an orbit of typically 1,000km. (see, for example, [4]). Measurements are

made each second, whilst the satellite flies over a repeat net of ground tracks at about 6km/s. This provides enormous amounts of wave data worldwide, and with, at present, a steady flow of new data from 3 or more operational satellites, millions of new observations are becoming available each month. Global long-term satellite altimeter measurements have been performed during 1985 to 1989 by the US Navy's Geosat and the Geosat-Follow-on mission (from 2000 to 2008), by ESA's ERS-1 (from 1991 to 1996), ERS-2 (1996 to 2003), EnviSat (from 2002), and most importantly for our purposes due to its longevity, the US/French Topex/Poseidon mission from 1992 to 2005 augmented by the Topex-Follow-on mission (Jason) which has provided data since 2002 on the same orbit as Topex and, from 2009, Jason-2, also on the Topex orbit. Full resolution altimeter significant wave height and wind speed data for most of these satellites can be found on the demo of World Wave Atlas which can be downloaded from:
http://www.oceanor.com/services/index.htm#WaveClimateProducts

Each satellite altimeter has to be validated and calibrated in order to remove altimeter-dependent biases on significant wave height and this is generally and most reliably done by comparing with long-term offshore buoy data.

Emphasis is given here to the Topex satellite altimeter as this is the most successful mission to date. Altimeter data from both the ERS missions as well as Envisat have routinely been assimilated into the ECMWF wave models (next section) and are therefore not independent of the model data. Algorithms for the correct interpretation of the back-scattered radar return pulse from satellite altimeters have been gradually improved (see, for example, [4] and [5]). The accuracy of the Topex altimeter can be seen in the satellite – buoy comparison shown Figure 2. All Topex altimeter data globally for 1992 to 2002 have been analysed applying the bias corrections described above as well as an automatic data control, removing, for example, unphysical along-track variations in wave height.

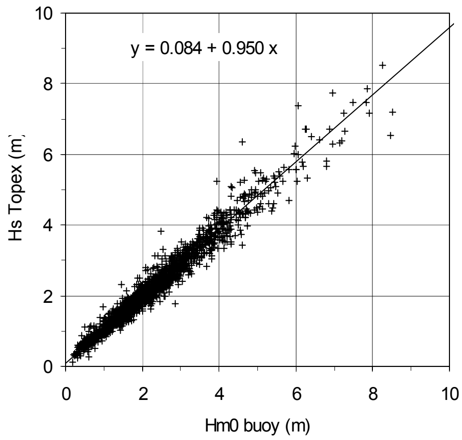

Figure 2: Comparison of significant wave height between the Topex Side B altimeter for 1999-2002 and 13 NOAA buoys; coincident data for Side B. The best fit regression is used to calibrate the satellite wave heights before use.

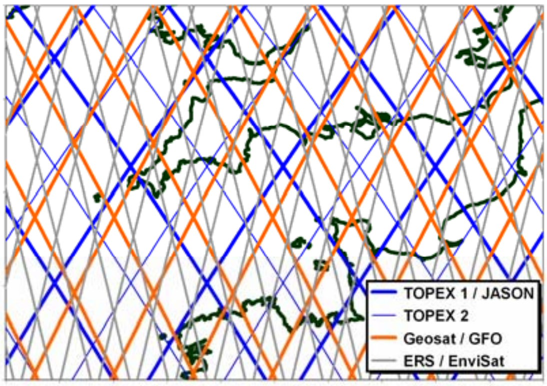

Figure 3: Satellite altimeter ground tracks for a number of missions over south west England and northern France. The different satellites fly on different exact repeat orbits, returning to exactly the same ground track on each repeat which varies from 10 to 35 days.

2.3. *Global wave models*

Many meteorological centres today run wave models regionally and a few run global models. Dedicated long-term hindcasts have also been performed. The wave models simulate the growth, decay and propagation of ocean waves based on input winds over the area in question. In the aforementioned WERATLAS project, it was confirmed that the ECMWF (European Centre for Medium-Range Weather Forecasts) wave model data were the best available at that time and we have seen that ECMWF have maintained that lead, mainly as a consequence of the high quality of the ECMWF wind fields but also due to, for example, the assimilation of, in particular, satellite altimeter and synthetic aperture radar wave data into the models. The WAM wave model [6] has been operational at ECMWF since 1992. Further details of the model itself with references can be found at the ECMWF website. The development of the WorldWaves package, through various EU projects, also adopted the ECMWF data and this is therefore discussed in detail in this section.

The current global wave model data base adopted by the WorldWaves project are 0.5º lat/lon resolution data from ECMWF's operational global WAM model covering the period December 1996 to present (updated monthly). In addition, for the Mediterranean, Baltic and Black Seas, data are sourced from the finer resolution Mediterranean model. In order to reduce the amount of data, only

1.5 degree data points are retained in the open ocean areas (see Figure 4). In addition, ECMWF have also completed a long-term global ocean wind and wave hindcast (ERA-40) which can provide data back to 1957, and, when combined with the operational data we can make up to 50-year time series are available to clients. The ERA-40 data are, however, run on a coarser 1.5° grid, reducing their usefulness in some enclosed sea areas.

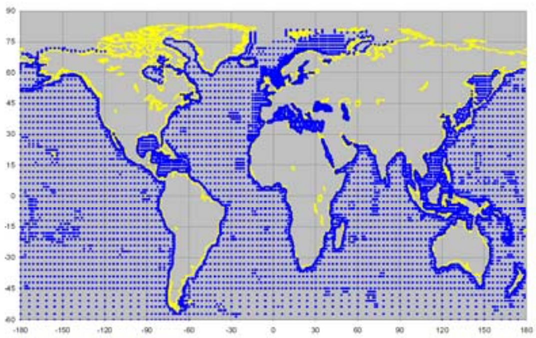

Figure 4: All WorldWaves grid points are shown; note that full resolution model data are retained in coastal waters.

The basic output from the WAM model is the full directional spectrum each 6 hours. When the model data are used as input to a shallow water model (SWAN in WorldWaves), the best accuracy is attained when using the full directional spectra time series offshore. These data are, however, voluminous, and, instead, the wave parameters in Table 1 are the default data currently available globally under WorldWaves. Based on the significant wave height, energy period and direction for wind sea and swell separately together with the peak wave period, the full directional wave spectrum is then synthesised when carrying out offshore to nearshore transformations. The full directional spectra files from ECMWF are nevertheless available from mid-1998 from the operational model at 0.5º resolution and for the entire ERA-40 hindcast period from mid-1957 to mid-2002 with 1.5º resolution.

In some parts of the world (e.g., the Pacific coasts of South America), two or more swells can frequently coexist. In such areas, the three parameters describing the swell spectrum will then poorly describe the swell energy-direction spectrum and the full directional spectra data must then be used when trying to predict coastal wave conditions. At any offshore location in the Pacific in the northern winter (October to March), crossing northerly and southerly swells will frequently occur. Using parameter data for predicting coastal wave energy resources will for this reason either over- or under-predict, often significantly, even if the models had been perfect.

Parameter long name and units	Alternative short name
Significant wave height, m.	H_{m0} or H_s
Mean wave direction, deg.	
Peak period of 1d spectra, s.	T_p
Mean wave energy period, s.	T_{m-10}, T_{-10} or T_e
Significant wave height for the wind waves, m.	H_{m0ws} or H_{m0w}
Mean direction of wind waves, deg.	M_{dirws}
Mean period of wind waves, s.	T_{m-10ws} or T_{m-10w}
Significant wave height for the swell, m.	H_{m0sw} or H_{m0s}
Mean direction for the swell, deg.	M_{dirsw}
Mean period for the swell, s.	T_{m-10sw} or T_{m-10s}
Wind speed equivalent to 10m height, 10 min. average, m/s	W_{sp} or U_{10}
Wind direction eq. to 10m height, 10 min. average, deg.	θ_w

Table 1: Wave and wind parameters currently installed worldwide on the standard WorldWaves package .

2.4. *Model validation and calibration*

The satellite altimeter data represent a high quality, independent and globally covering wave and wind data set which can be used for the direct validation of the wave model data, although this is limited to significant wave height and wind speed. That the satellite data are close to the accuracy of buoy data are confirmed in the following analysis, using long-term data from the NOAA wave buoy network. We compare the model significant wave heights first against 13 NOAA buoy data sets and then, subsequently, against satellite altimeter data sampled from the area around each of the same buoys. From the resultant scatter plots for each of the 13 locations, various statistics were calculated. The results in the form of the bias and the scatter index are presented in the maps in Figures 5 and 6. As can be seen, the results are more or less identical independent of whether one chooses the buoy or satellite data for the validation. This gives us the confidence to use the Topex data globally as a reliable reference, as if a worldwide buoy network had been available.

The wave model data are available on a regular 0.5º lat-lon grid. The satellite data are, on the other hand, available about each 6 km each N-days (where N is the exact repeat period for each satellite) along ground tracks globally. As an example, for South America and for the Topex mission, the tracks, colour-coded according to the mean significant wave height are shown in Figure 7.

In the WorldWaves project, a global offshore wave model data set was created using the corrected (against buoy data) Topex combined with

Jason data from 1997 to 2006 to validate and subsequently calibrate the ECMWF model data. This was found to be worthwhile as there was typically a systematic bias on the raw model data. Removing that bias significantly improves the data quality, particularly in enclosed seas such as the Mediterranean. Not all grid points are close enough to a Topex satellite track to be useful for validation purposes. Thus, a sub-set of calibration points were identified. Of a total of over 10,000 wave model grid points globally about 5,700 are calibration points (in oceanic areas, practically all points are validation points as there are no strong wave climate gradients in such areas) and a larger spatial separation between model and satellite data for calibration purposes is acceptable. In near coastal waters, the selection of calibration points and satellite data extraction locations used for validation has to be done manually as it is not necessarily the closest point which is the best choice in such areas with strong wave gradients.

The results of the global model validation are presented in Figure 8 (correlation coefficient) and Figure 9 (linear regression coefficients). This shows that although the correlation is largely very high, the model tends to underestimate the significant wave height in a systematic way. Using the regression coefficients to calibrate the model data then removes the bias and gives more accurate offshore boundary conditions for coastal wave modelling. In data delivered to clients, we perform an additional calibration including all satellite altimeter missions and may also check seasonal changes (e.g., in monsoon climates) and other homogeneity problems. Using multiple satellites is particularly advantageous in areas with relatively strong wave climate gradients as can be seen in the example in Figure 10.

The ECMWF model data were then finally calibrated on a global basis for inclusion in the WorldWaves software package. This was done by adjusting significant wave heights and, analogously, the wind speed, not shown here, on a point-by-point basis for all global grid points. For oceanic points, the wave periods were not adjusted (decision based on various buoy validations), but wave periods were adjusted to conserve the wave steepness in most enclosed seas where wind sea dominates. Directional wave spectra data are also calibrated on a case-by-case basis when these data are used for coastal modelling.

A big advantage of the WorldWaves data is that they are continually updated so that a client performing short-term wave measurements at a given site can be provided with WorldWaves derived data, either offshore or nearshore in order to validate the long-term model predictions.

3 The Global Wave Energy Resources

In the previous section, we have seen how 10-years of high quality 6 hourly wave and wind parameter data have been derived for 10,000 offshore grid points worldwide on a 0.5º grid through combining the best quality wave model data with high precision satellite altimetry. Based on these data, we have produced a number of global maps. These are referred to when discussing the world's wave energy resources in the following.

First, Figure 11 shows the 10-year mean annual wave power for all global points in the WorldWaves database. This map shows clearly that the most energy-rich areas of the global oceans are in the mid to high latitude temperate storm belts of both hemispheres, in particular between 40 and 60º. However, this figure gives, a slightly wrong impression of the relative energy levels in both hemispheres. The much higher resources in the southern hemisphere, where seasonal variations are much lower (compare Figure 12 and 13 showing January and July means), are seen more clearly in Figure 14 where we have plotted the mean wave power for all grid points as a function of latitude both annually and for the months of January and July.

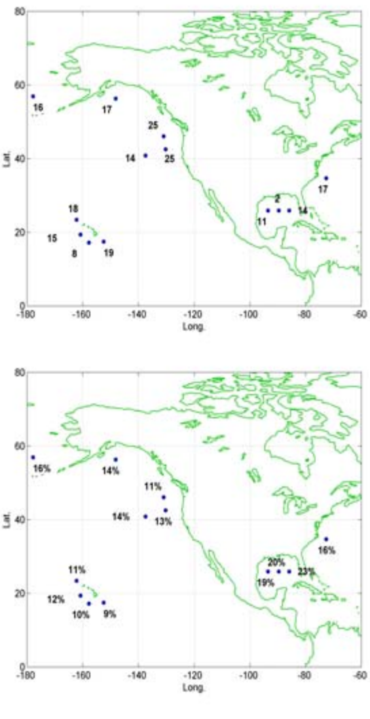

Figure 5: Validation statistics of Hm0 from WAM against NOAA buoy data for 1996 to 2002. Above: Mean difference in cm; Below: Residual Scatter Index in %.

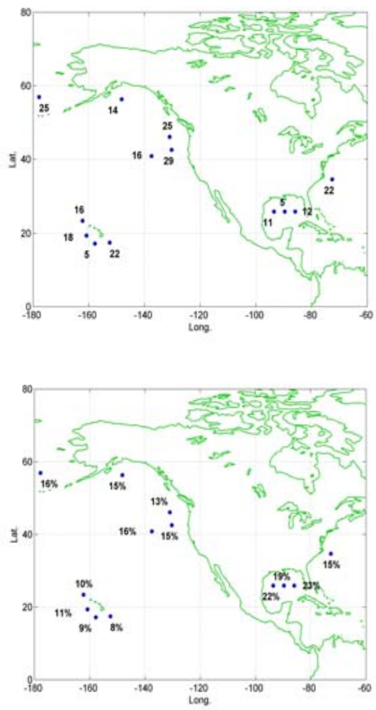

Figure 6: Validation statistics of Hm0 from WAM against calibrated Topex data for the locations of the NOAA buoys in Figure 5 for 1996 to 2002. Above: Mean difference in cm; Below: Residual Scatter Index in %.

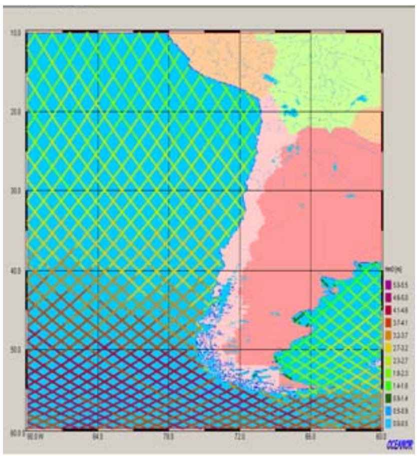

Figure 7: Mean significant wave heights (1992-2002) off South America, along all Topex/Poseidon ground tracks (from Fugro OCEANOR's World Wave Atlas 2.0).

Where in the world do we find the highest wave power levels? Its turns out, not surprisingly to be in the Southern Ocean's Roaring Forties, around 48ºS, 90ºE which is about 1,400 km east of Kerguelen Island. Here, the annual average exceeds 140 kw/m! In the Northern Hemisphere, peak energy levels are found at 57ºN, 21ºW, some 400 km west of Rockall. Here, we find a "modest" 90 kW/m! On a monthly basis (Figure 14), the Northern Hemisphere power levels are up to twice of that both hemispheres, at or just above 200 kW/m.

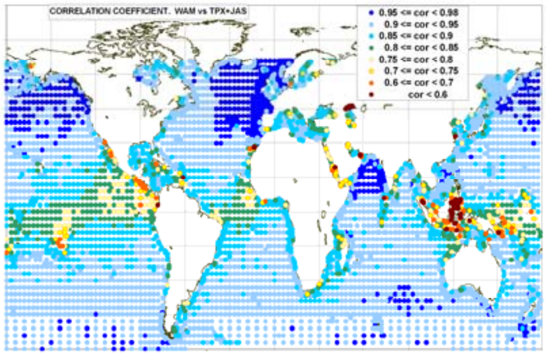

Figure 8: Global map showing the correlation coefficient between the ECMWF WAM operational model data and Topex/Poseidon data for all global validation points for 1997 to 2006. Correlation coefficients are naturally lower in areas with very low steady wave heights over most of the year.

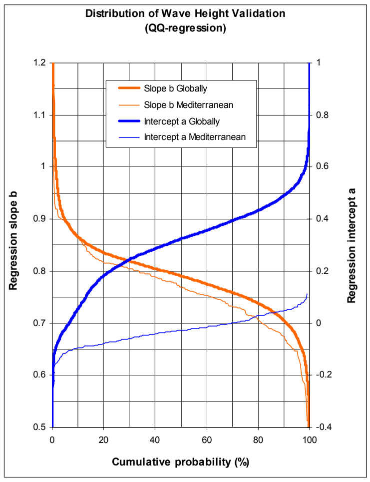

Figure 9: Summary statistics for the global validation. The cumulative distributions for the QQ-linear regression slope and intercept is presented for all global validation points for the global and Mediterranean ECMWF operational models separately.

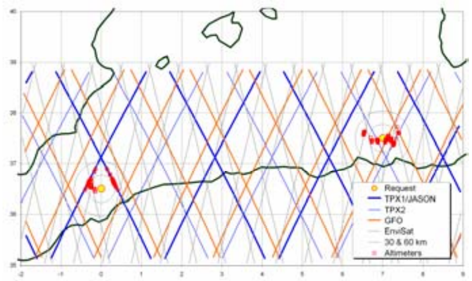

Figure 10: Example from a recent data request for two model points in the Eastern Mediterranean where one point is close to two Topex/Jason tracks (one of the global validation points), whereas the other point is too far from the Topex tracks, but quite close to GFO , Topex 2 and Envisat tracks. In such cases, all satellite data can be utilised to refine the calibration in order that the end-user is provided with as accurate data as possible.

in the Southern Hemisphere at the same time of year. The maximum global monthly power level is practically the same in the two hemispheres ,at or just above 200 kW/m.

What about the wave energy resources near to coast? (remember that the data shown here are offshore deep water statistics and coastal conditions can be quite different to this due to wave refraction sheltering and other nearshore effects). On an annual basis (Figure 11), the highest levels in the Northern Hemisphere are off the west coast of the British Isles, Iceland and Greenland, with somewhat lower energy levels in the Pacific off the western seaboard of the US and Canada. Not surprisingly, we find the highest overall coast-near energy levels in the Southern Hemisphere, notably off Southern Chile, South Africa and the entire south and south west coasts of Australia and New Zealand.

In equatorial waters, we find power levels of 15-20 kW/m on an annual basis over parts of all the ocean basins, the highest coastal resources being off Northern Peru and Ecuador, although there may be significant El-Nino induced inter-annual variability in this area. Finally, in medium latitudes, western Australia comes out best, with California also having a relatively high for latitude resource.

Figure 12 and 13 give an indication of the seasonality of the global resources. However, if we instead plot the ratio of the minimum monthly power level against the annual mean, we get a clearer idea of how the resource varies over the year (Figure 15): Figure 16 presents these data in a different way showing the variation of this statistic against latitude. There is, as we can see, a dramatic difference between hemispheres as far as the stability of the wave energy resources is concerned with large summer to winter changes in the north, the largest being, of course, in ice impacted waters. There are also large seasonal changes in the monsoon areas of South East Asia due to the seasonal switch in wind direction in these areas. This is particularly large along seasonally downwind and upwind coastlines due to the influence of fetch on wind wave growth and is particularly strong in the South China Sea due to the fact that there is little swell to smooth out these seasonal wind sea changes. This is also a dominant feature of the Arabian Sea which, along, with the Bay of Bengal, are the only sea areas in the Northern Hemisphere with larger summer than winter energy levels, due to a combination of stronger summer monsoon winds and higher swell influx at that time of year (southern ocean winter). Another interesting feature is the area of the southern Indian Ocean to the south and west of Australia which shows regionally surprisingly large seasonality. This is due to the fact that this area roughly corresponds to the location in January of the Indian Ocean Anticyclone. This anticyclone has a remarkably large seasonal displacement towards the west during winter, leading to a large seasonal change in storm frequency.

In coastal areas, we can see that there are particularly stable wave energy resources off Chile, Namibia, Eastern Australia, Sierra Leone and Liberia, the Pacific coasts of Mexico and most of the South Pacific island nations, although these nations, particularly the low lying ones, are perhaps nowadays rather concerned with the power of the waves for other reasons.

Finally, Figure 17 plots the relationship between the extreme and mean significant wave height. One can consider, in very simple terms, that the lower this ratio is, the more feasible a wave energy project might be as the extreme conditions relate to design and to a certain extent operational costs and the mean represents the resource or the income (see also Hagerman, [7], who introduced a similar ratio, his Figure of Merit).

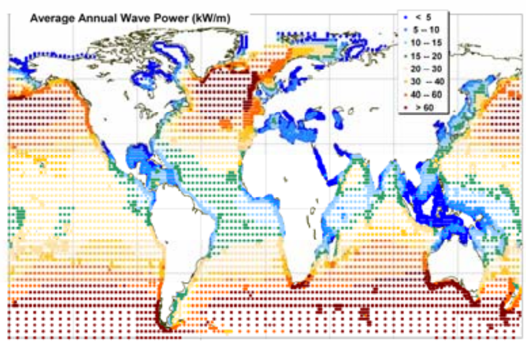

Figure 11: Global annual mean wave power estimates in kW/m *(the data originate from the ECMWF WAM model archive and are calibrated and corrected by Fugro OCEANOR against a global buoy and Topex satellite altimeter database)*

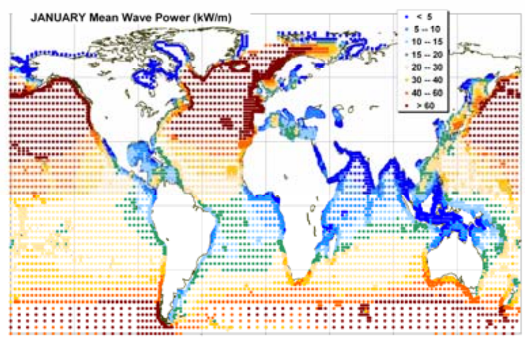

Figure 12: Global January mean wave power estimates in kW/m *(the data originate from the ECMWF WAM model archive and are calibrated and corrected by Fugro OCEANOR against a global buoy and Topex satellite altimeter database)*

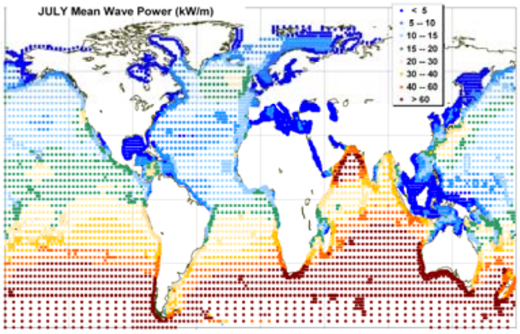

Figure 13: Global July mean wave power estimates in kW/m

4 Shallow Water Modelling

In projects requiring the highest quality coastal wave data, we utilise the complete WorldWaves coastal modelling toolbox which fully integrates the state-of-the-art SWAN model with tools to quickly and easily create computational grids, modify bathymetry, SWAN input parameters and oceanographic conditions. Typically, a long-term

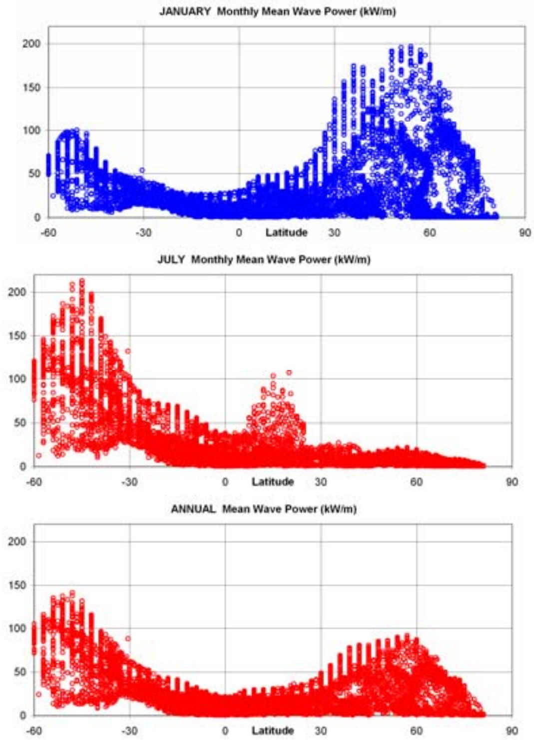

Figure 14: Variation in mean January, July and (bottom) annual wave power against the latitude for all global grid points.

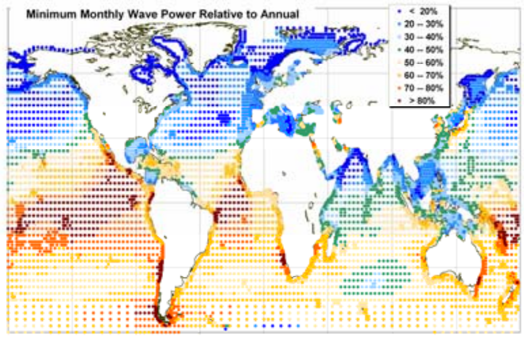

Figure 15: The ratio (in %) of the minimum of the individual monthly wave power estimates to the annual value gives an indication of the seasonal variability of the resource.

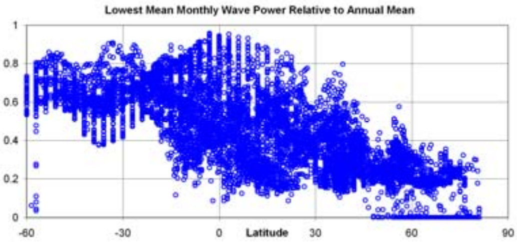

Figure 16: Variation in the ratio of the minimum of the individual monthly wave power estimates to the annual value against latitude shows clearly the much lower seasonality in the far south. Note that the grid points with zero are from areas impacted by ice in the northern hemisphere.

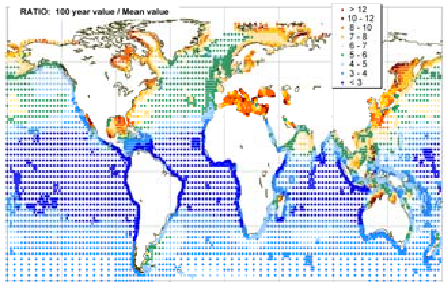

Figure 17: The ratio of the 100-year significant wave height to the mean wave height, inspired by Hagerman's Figure of Merit , [7], roughly reflects the ratio of design costs for a wave energy plant against its income (the resource) *(the data originate from the ECMWF WAM model archive and are calibrated and corrected by Fugro OCEANOR against a global buoy and Topex satellite altimeter database).*

time series of full WorldWaves directional spectra will be input on the outer boundary and time series can then be output at the chosen nearshore site. Figures 18 to 20 show output examples of a single run of SWAN under WorldWaves off Stockholm.

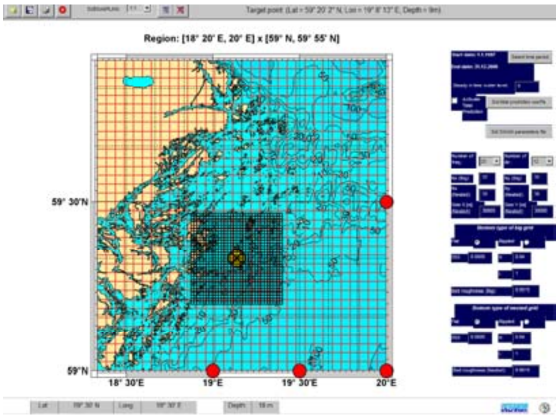

Figure 18: SWAN/WorldWaves computational grid user-interface off Stockholm. The red dots are the offshore directional spectra time series input points.

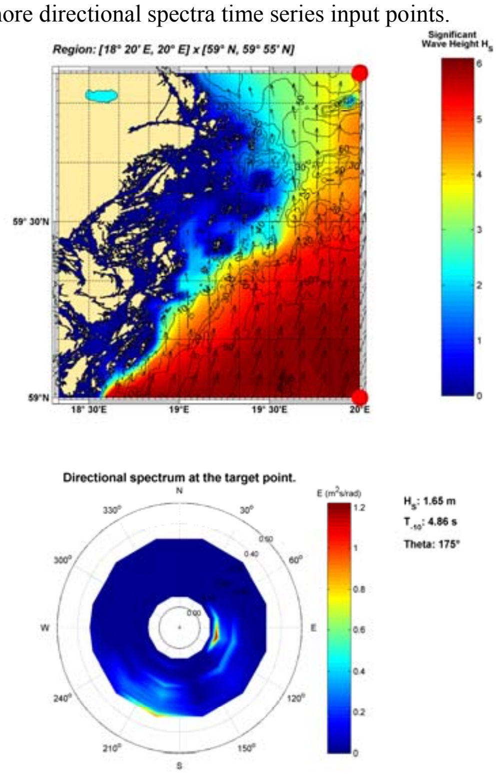

Figure 19: Output for a single run of the SWAN model under WorldWaves for a 6m offshore storm in the Baltic; (above) fields of Hs and (below) the directional spectra at the target location in Figure 18.

We are often asked by utilities and companies whether we can supply higher resolution nearshore countrywide wave energy resource data than provided with our global and regional wave energy resource maps (Figures 11 to 13). To do this with the SWAN model would be prohibitively expensive. A cost-effective alternative which can provide highquality statistics nearer the coast is to utilise the along-track variation in significant wave height from the satellite altimeters together with the offshore WorldWaves data and this method is described and validated in the following.

4.1 Cost-effective country-wide coastal resource data using satellite altimetry

In Figure 20, we show the Topex/Poseidon ground tracks off the West Coast of the USA. This satellite flew the "Topex 1" ground tracks from 1992 to 2002 passing along each track roughly every 10 days and profiling the significant wave height with an along-track resolution of about 6km. From September 2002 to 2005, Topex continued to measure, but on a new orbit, and is referred to as "Topex 2" in the figure, midway between the original orbit. A selection of offshore deep water WorldWaves model grid points are shown by the white dots. At these offshore points we accessed the 10-year series of calibrated against Topex WorldWaves model data (as described in section 2.3), as the offshore "boundary conditions".

In brief, we use the fact that each time a satellite passes from offshore to nearshore it measures a practically instantaneous profile of the significant wave height. In Figure 20, the small orange and white circles are locations on the Topex tracks roughly 6 km apart at which we extract measurements of Hs each time the satellite passes. Over the entire lifetime of the mission, we can for each point calculate the ratio of nearshore-to-offshore Hs and this along-track ratio is displayed on the right hand panel of Figure 20 for each track. Note that each offshore location is close to a WorldWaves model grid point. For a given nearshore location, which clearly has to be on or near to a satellite track, we apply the appropriate reduction factor to the offshore time series. In this transformation, we do not change the wave period, generally a good approximation. We can finally calculate various statistics at each nearshore site and in this way build up maps for countries or regions with both offshore and nearshore statistics, albeit rather coarse.

In monsoonal wave climates there may be a large seasonal gradient in the nearshore-to-offshore ratio and in such areas different factors can be applied according to the wind direction.

The other available altimeter data (GFO, Geosat and Envisat) all fly from east to west (opposite that for Topex and Jason). As the quality of near-coast satellite data is degraded due to the altimeter taking time to retrack the surface after passing over land, we only use missions flying from sea to land. On the US East Coast we would then use the other satellites.

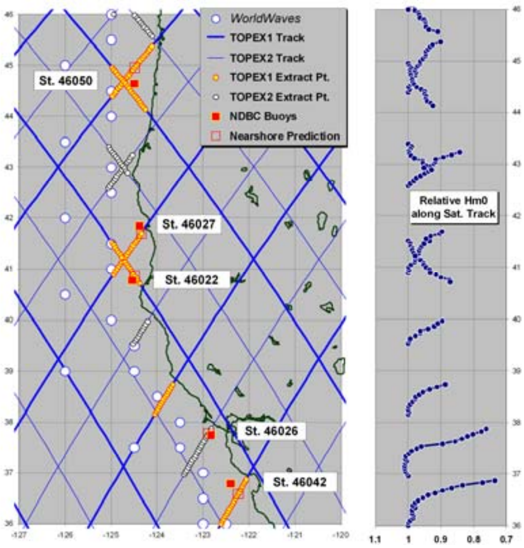

Figure 20: Nearshore wave energy prediction methodology explained.

4.2 Validation

As each nearshore satellite point reprents a spatial average, we were keen to validate the results of the method against site specific measurements. How well can the method predict nearshore resource data. On the US West Coast, we identified 5 coastal NOAA/NDBC wave buoys which were close enough to the satellite ground tracks to be used for validation purposes (Figure 20). In the following we used 3 hourly time series of Hs and Tm02 from each buoy to validate the WorldWaves offshore-to-nearshore transformed data. As the wave energy period, Tm-10, was not available from the buoys, we carried out a linear regression analysis for each buoy between Tm-10 (from WorldWaves) and

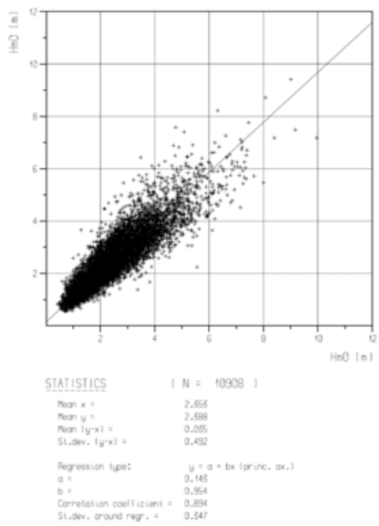

Figure 21: Scatter plot of simultaneous transformed WorldWaves against buoy Hm0 for NDBC buoy 46022 off Eureka, CA. The bias is very small (3.5 cm) and the correlation close to 0.9.

Tm02 for each buoy measurement, and hence allowing us to calculate the buoy measured wave energy more accurately.

We finally calculated seasonal and annual wave power from both buoys and WorldWaves and some of the results are shown in Table 2 and Figure 20. The model predictions can be seen to be match remarkably well.

Lon	Lat	Annual	Mar-May	Jun-Aug	Sep-Nov	Dec-Feb
-124.49	44.96	39.7	34.0	10.9	40.5	73.9
-124.5	44.64	40.6	37.0	12.1	45.3	73.7
-124.34	41.7	34.2	29.7	16.4	33.0	58.2
-124.38	41.85	30.5	26.9	12.0	31.0	54.8
-124.49	40.86	37.7	32.5	16.5	36.4	65.7
-124.54	40.78	37.9	35.5	15.5	35.7	65.5
-122.88	37.78	24.7	23.6	13.9	22.0	39.7
-122.83	37.76	24.1	23.1	12.6	20.0	40.2
-122.24	36.59	31.8	30.9	15.9	27.8	53.2
-122.4	36.79	31.0	30.9	15.5	28.5	49.8

Table 2: Seasonal mean wave energy prediction comparisons between the WorldWaves offshore-to-nearshore satellite transformation methodology (first row in each pair) and NOAA/NDBC buoy data (second row).

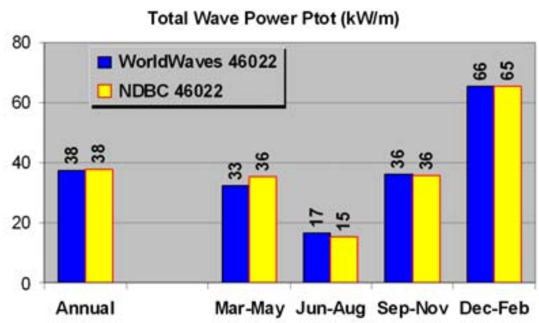

Figure 22: Nearshore seasonal mean wave energy (kW/m) prediction comparison for NDBC buoy 46022 off Eureka, CA.

Acknowledgements

Thanks are due to the National Data Buoy Centre for access to the coastal and offshore buoy data used to validate our WorldWaves based wave climate data.

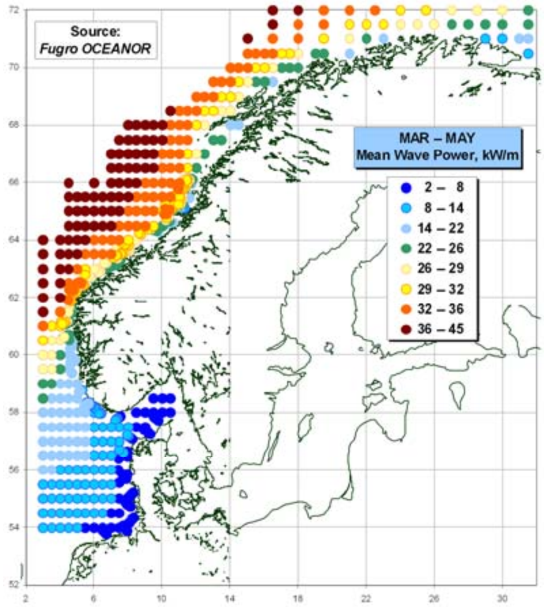

Figure 23: A seasonal map of mean wave energy off the western coasts of Denmark and Norway combining offshore WorldWaves data and nearshore statistics derived from transforming the offshore time series data by the described along-track Topex transformation methodology.

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