Pergamon

Ocean Engineering 26 (1999) 205–225

OCEAN ENGINEERING

Estimation of extreme wave heights using GEOSAT measurements

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Received 27 May 1997; accepted 1 October 1997

Abstract

Satellite technology has yielded a large database of global ocean wave heights which may be used for engineering applications. However, the sampling protocol used by the satellite leads to some difficulties in making use of these data for practical applications. These difficulties and techniques to estimate extreme wave heights using satellite measurements are discussed. Significant wave heights for a 50-year return period are estimated using GEOSAT measurements for several regions around North America. Techniques described here may be used for estimation of wave heights associated with any specified return interval in regions where buoy data are not readily available. © 1998 Elsevier Science Ltd. All rights reserved.

Keywords: Extreme wave heights; GEOSAT measurements

1. Introduction

Ocean wave height data used for practical applications are usually obtained from three sources: buoy measurements, model calculations, and ship observations. Of these, buoy measurements constitute the only data source that is reliable and readily available. However, the spatial coverage provided by the buoys is extremely limited;

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PII: S0029-8018(97)10026-9

for instance, there are only about 70 wave buoys in operation in all US waters, including the Great Lakes (NDBC, 1992). Elsewhere in the world, buoy measurements are generally even more sparse (Helmsley, 1996). Wave hindcasting (with models such as WAM or the Army Corps' Wave Information Study) provides a database with uniform spatial and temporal resolution, but despite many advances, wave modeling must still be considered an evolving field, the results of which are not fully reliable. In fact, data assimilation using available measurements has to be sometimes performed (e.g. Lionello et al., 1992) to improve model simulations. The third source of wave data, visual ship observations, has been used to construct global wave climatologies (e.g. the US Navy Marine Climatic Atlas of the world, the Canadian Meteorology and Oceanography Center (METOC) wave charts, or the National Center for Atmospheric Research "COADS" dataset). However, ship reports are irregular, e.g. the METOC charts are produced twice a day by averaging ship observations in a $5° \times 5°$ latitude/longitude grid. Also, ship-reported wave observations are usually regarded as highly imprecise and even studies of statistical correlation between ship-reported and instrumental wave data are hampered by the considerable separation between the ship and the instrument (e.g. Laing, 1985). Thus, wave climatologies based on ship observations cannot be considered totally reliable on their own. In fact, use of GEOS-3 satellite data suggest that the US Navy atlas underestimates the frequency of high sea states and overestimates the frequency of low sea states in many parts of the world (McMillan, 1981).

This difficulty with traditional data sets may be overcome to some extent by using the large amounts of data collected in recent years by satellites (GEOS-3, SEASAT, GEOSAT, etc). For almost five years, the US Navy satellite GEOSAT recorded global information for 34 oceanographic parameters (including significant wave heights) every second. After the initial 18 months of its mission (March 1985 to September 1986), the satellite was maneuvered into an exact repeat mission (November 1986 to January 1990), when it executed 17-day repeat cycles. The recorded data have been processed by the National Ocean Service (Cheney et al., 1991) and are disseminated to the user community on CD-ROM's in the form of "Crossover Difference Records" and "Geophysical Data Records". Significant wave heights (SWH) available at 1 second intervals were calculated as an average of 10 recordings made by the on-board altimeter. About 50,000 measurements, made every 6.4 km along track, were reported daily. The SWH data have been shown to be sufficiently reliable for most real-life applications (Dobson et al., 1987; Tournadre and Ezraty, 1990; Siddabathula and Panchang, 1997). An example of the tracks in the Gulf of Maine is shown in Fig. 1, in which the ascending and descending tracks are labeled with suffixes "a" and "d" respectively.

Dobson and Porter (1989) and Young (1994) have used the GEOSAT SWH data to calculate simple averages of global wave conditions. However, they did not undertake the estimation of wave conditions with a specified return interval (e.g. extreme wave statistics). Moreover, their calculations were performed on very large scales (using $2° \times 8°$ and $4° \times 4°$ latitude/longitude grids, respectively). The results of these studies cannot therefore be used for many ocean and coastal engineering applications such as offshore design, providing input conditions (associated with a given fre-

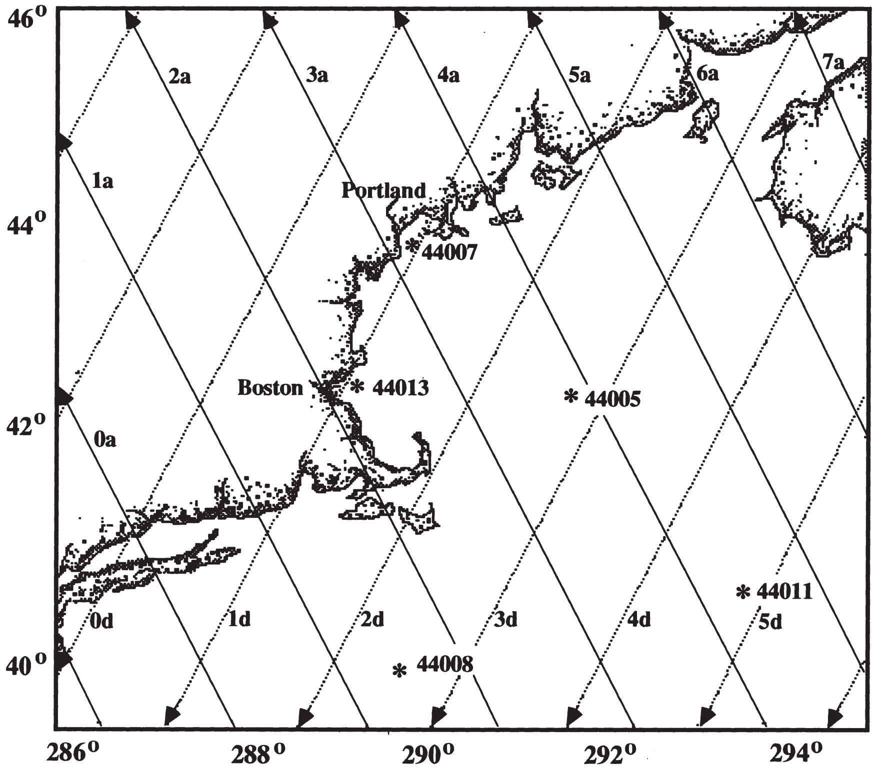


Fig. 1. Ascending and descending GEOSAT tracks in the Gulf of Maine. Asterisks show buoy locations.

quency of occurrence) to wave prediction models like HISWA/SWAN (Holthuijsen et al., 1989, 1993), STWAVE (Resio, 1988, 1990), or CGWAVE (Xu et al., 1996; Xu and Panchang, 1993) that simulate shoreward propagation of waves, etc. (An example of transferring extreme offshore wave conditions to coastal regions may be found in Cavaleri et al., 1986).

From an engineering perspective, the estimation of extreme waves using satellite data poses certain difficulties. As seen in Fig. 1, the satellite may not "overfly" a particular location of interest. Even if it does, measurements are obtained at intervals of 17 days (for GEOSAT's Exact Repeat Mission), thus missing several large wave events that may have occurred in the interim. Deo et al. (1996) used the disaggregation techniques of Bras and Rodriguez-Iturbe (1985) to construct synthetic data for the period between satellite passes over a location, but met with mixed success. For work associated with an oil platform in the North Sea, Tournadre and Ezraty (1990) attempted to overcome the difficulties of infrequent sampling by collecting all available satellite measurements in domains of various sizes around the platform. Using these measurements, they estimated the 50-year return period wave heights (SWH50, defined as the wave height with a 2% chance of being exceeded in a given year) and compared the results with estimates obtained from in-situ data available at the oil platform. It was found that satellite data from a 200 km radius produced the same result as the in-situ benchmark SWH50. We applied a similar technique in the Gulf of Maine using GEOSAT data around buoy 44005 shown in Fig. 1. However, the results, as explained later, were questionable. This problem is therefore explored in detail in this paper using data from regions with diverse wave climates and an alternative strategy is developed for estimating extreme wave heights from satellite measurements.

1.1. Data preprocessing

A prerequisite to the analyses described here is an assessment of the quality of satellite SWH measurements which may be performed by comparing individual measurements with buoy data. Using various windows of separation (in space and time), Dobson et al. (1987) and Tournadre and Ezraty (1990) compared SWH buoy and GEOSAT SWH measurements and found that differences between them become negligible as the size of the window decreased. The analyses of Dobson and Porter (1989) led them to recommend that certain quality control criteria be applied to the data available to the user. During our study, we found that these criteria were inadequate. They allowed several measurements that were clearly suspect to escape detection. These faulty measurements often included inordinately large wave heights that can potentially distort statistical estimates. An example containing such large measurements is given in Fig. 2, which shows a subset of the data for track 2d in the Gulf of Maine. On the other hand, we found that using the quality control criteria of Romeiser (1993) and Young (1994) eliminated vast quantities of acceptable wave data in the Gulf of Maine.

We therefore performed a rigorous examination of all GEOSAT wave data in conjunction with all available buoy data in the Gulf of Maine. Using visual inspection and judgment, a number of faulty measurements were eliminated. As noted by Young (1994), this work was extremely tedious. Our examination led to the following criteria which successfully and optimally eliminated those geophysical data records (as presented on the CD-ROM's) with erroneous SWH measurements: (1) the standard deviation of the 10 "per second" sea surface heights σh $\geq$ 10 cm; (2) the height bias and satellite attitude were out of range; (3) any one of the 10 per second heights was flagged as bad; (4) first record reported after a gap in the time sequence; (5) all records with σswh (standard deviation of the 10 "per second" wave height measurements) greater than 11 cm occurring immediately after a series of records with a land flag or after a record with σh great 10 cm; (6) SWH $\leq$ 0.2 m; (7) record sandwiched between one or more records with instrumentation errors (denoted by "32767" in the SWH or σswh field) or other faulty records. These criteria constitute a combination and/or modification of criteria used previously by various investigators. Justification for the adoption of these criteria and examples using satellite and buoy data in the Gulf of Maine and Gulf of Mexico are provided in Siddabathula and Panchang (1997). The new quality control criteria eliminated about 8% of the measurements in these areas, compared with about 2% eliminated by the criteria of Dobson and Porter (1989). The eliminated data were checked against buoy data for

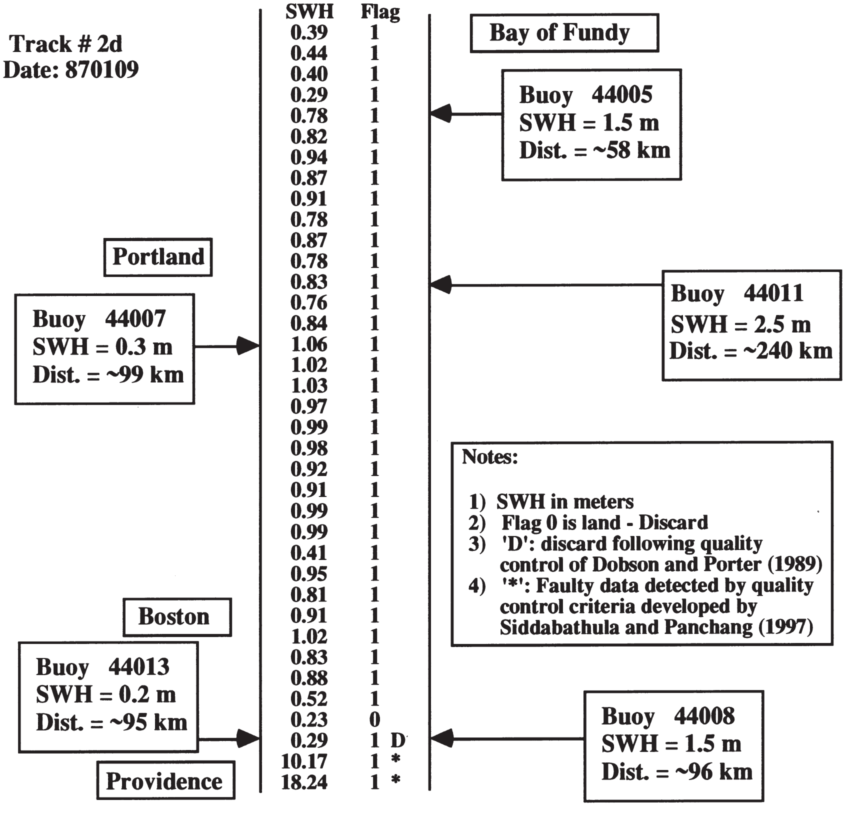


Fig. 2. Wave data in the Gulf of Maine for 9 January 1987. GEOSAT wave heights mostly at 1 second intervals. Buoy data at closest half-hour.

justification. Further, the CD-ROM's (distributed to the user) provide SWH data as part of 34 oceanographic parameters which are not generally used in engineering; also, presentation of the data on the CD-ROM's is sequential in time at 1 second intervals along the satellite's spirograph-like tracks. This makes wave data extraction for a given geographic area cumbersome. A computer program was developed to extract only the SWH data for any region described by 4 latitude/longitude coordinates and to then filter the data according to the new quality control criteria. The program may be obtained by contacting the authors.

2. Methods and rationale

As noted earlier, Tournadre and Ezraty (1990) calculated the 50-year SWH near an oil platform in North Sea using about two years of satellite data. To overcome the problem of undersampling near the site of interest, they expanded their dataset

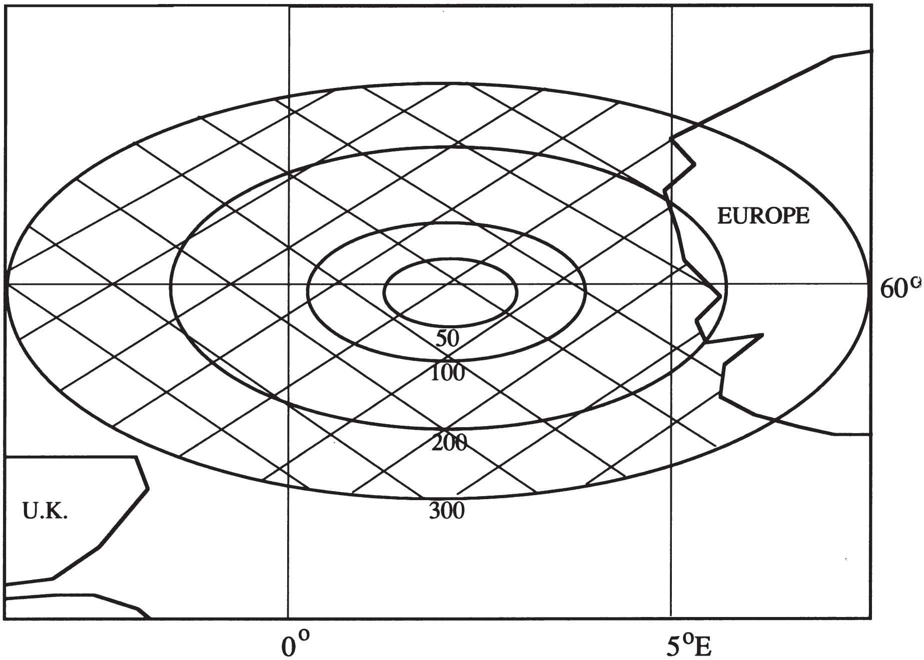


Fig. 3. North Sea study area, after Tournadre and Ezraty (1990), showing tracks contained in circles of different radii (in km).

to include measurements from several tracks in the area (Fig. 3). All tracks contained within circles of various sizes around the oil platform were identified. The dataset used to calculate SWH50 contained every fifth measurement along track for each pass through the circle. For comparison, a benchmark SWH50 was established using in-situ data from the oil platform; this dataset contained three-hourly measurements from a two-year time series. SWH50 was calculated using the Gumbel distribution (also known as the FT-1 distribution) along with the plotting position method for parameter estimation. The results, shown in Table 1, enabled Tournadre and Ezraty (1990) to recommend estimation of extreme wave statistics by using satellite data contained in a 200 km radius around the location of interest.

Table 1
North Sea results of Tournadre and Ezraty (1990)

Radius km	# of data N	Gumbel law SWH50 m
50	155	15.9
100	718	14.9
200	2266	14.9
300	4126	13.8
in situ	5524	15.1

We performed a similar analysis using (filtered) satellite measurements for a location near the center of the Gulf of Maine, where data from buoy 44005 were available to provide the in-situ benchmark solution. Buoy data used in this study were obtained on CD-ROM's from the National Data Buoy Center (NDBC, 1992). Two years of data (11/1986-11/1988) were used along with the Gumbel distribution in our analysis. Instead of plotting position formulas, the method of maximum likelihood[1] was used for parameter estimation. In all other respects, the same techniques as of Tournadre and Ezraty (1990) were applied. Our results for the Gulf of Maine, shown in Table 2, would appear to suggest that satellite measurements from a radius of approximately 50 km around buoy 44005 yield the same result as that from the in-situ data.

Several questions can be raised regarding the above results and the techniques used to obtain them. First, the 50 km domain of influence in the Gulf of Maine seems extremely small compared with the North Sea results; it is also surprising that as few as approximately five arbitrary measurements per month (corresponding to $N = 132$ in Table 2) enable us to estimate the extreme wave conditions so well. Second, the estimated SWH50 for this region of the Gulf of Maine is considerably smaller than those obtained in previous studies (Panchang et al., 1990; Walker, 1984; Palao et al., 1994). Third, the benchmark estimates in Table 2 are based on 3-hourly buoy values. Using such a dataset constitutes the "total sample method" (Goda, 1989) or the "initial distribution method" (van Vledder et al., 1993). Although such datasets are sometimes used to estimate extreme wave statistics (e.g. van Vledder et al., 1993; Tournadre and Ezraty, 1990), Goda (1989; 1990) has surmised that using all available data may be "statistically unsound" and that it "violates the condition of statistical independence between individual data, because regularly recorded wave heights are mutually correlated". This may be particularly true if the regular measurements are separated by small time intervals (e.g. three hours). The benchmark solutions in Tables 1 and 2 cannot therefore be accepted at face value. Goda (1989) has also

Table 2
Initial estimates of SWH50 in the Gulf of Maine using 2 years of data

Radius km	# of data N	Gumbel law SWH50 m
50	132	9.81
100	250	9.75
200	1249	9.48
Buoy 44005	5097	9.92

[1] Although this method is usually acknowledged to be superior to other methods (since it provides consistent estimates for large datasets and no other unbiased estimator has a smaller variance), it has been often considered as problematic from a computational viewpoint (e.g. Goda, 1989; Isaacson and MacKenzie, 1981) and hence rarely used. For the Gumbel and Weibull distributions often used in extreme wave statistics, however, extremely efficient maximum likelihood solvers have been developed (Panchang (1967); Panchang and Gupta (1989); Kite (1977)).

noted that considerable ambiguity prevails in the selection of a suitable time unit for calculating long-term return period wave heights and that maximum values taken from different interval lengths may produce different results. Finally, the SWH50 estimates in Tables 1–3 are obtained by extrapolating from rather short duration datasets. A rule of thumb is that the datasat must be at least one-third the length of the return period to which extrapolation is desired (Thompson, 1997; see also Hogben, 1988). Young (1994), too, has surmised that the GEOSAT data, which cover a period less than five years, may be inadequate for extreme wave calculations. Hence the validity of all estimates obtained by us in the Gulf of Maine and by Tournadre and Ezraty (1990) in the North Sea are open to question.

We therefore first investigated the dependence of the time interval and overall length of the data on the estimated SWH50 values for establishing an acceptable benchmark. SWH measurements at 1-hour intervals are available for the 1985-1989 period representing the GEOSAT mission at several buoy locations around the US. To examine the effect of the overall duration, data for the full 14 years (1979-1992) for which measurements were available were also used. Five buoys in the Gulf of Maine (44005, 44007, 44008, 44011, and 44013), two off the US mid-Atlantic coast (41001 and 44004), four in the Gulf of Mexico (42001, 42002, 42003, and 42007), two in the Gulf of Alaska (46001 and 46003), and three in the eastern Pacific off the central US west coast (46002, 46005, and 46006) were selected. (The buoy locations are shown in Figs. 7–11). Time intervals of Δt (in days) = 0.125, 0.5, 1, 3, 7, 10, 15, 21, and 30 were chosen. Nine datasets consisting of the maximum wave heights in the respective intervals were constructed for each buoy. These datasets were used to obtain the maximum likelihood estimators for the Gumbel distribution:

$$Pr(SWH < x) = \exp[-\exp -a(x-b)] \qquad (1)$$

where a and b are parameters of the distribution and x is a given wave height. The N-year return period significant wave height SWHN was then calculated according to the following (Carter, 1981; Petruaskas and Aagard, 1971):

$$SWHN = (1/a)[-\ln(-\ln P)] + b \qquad (2)$$

where

$$P = 1 - \frac{1}{SN} \qquad (3)$$

and S is the number of data points per year[2].

The results are shown in Fig. 4. (For clarity, results are shown for only one buoy in each study area since data from the other buoys produced essentially the same trends, even though some buoys suffered from missing data; final results for the other buoys are given in Figs. 7–11). Fig. 4 indicates that SWH50 stabilizes for large

[2] Tournadre and Ezraty (1990) have used slightly different formulas. They have also used a constant value for S = 2920, which is the number of 3- hourly buoy measurements per year, for all calculations including those involving satellite data, which seems inappropriate.

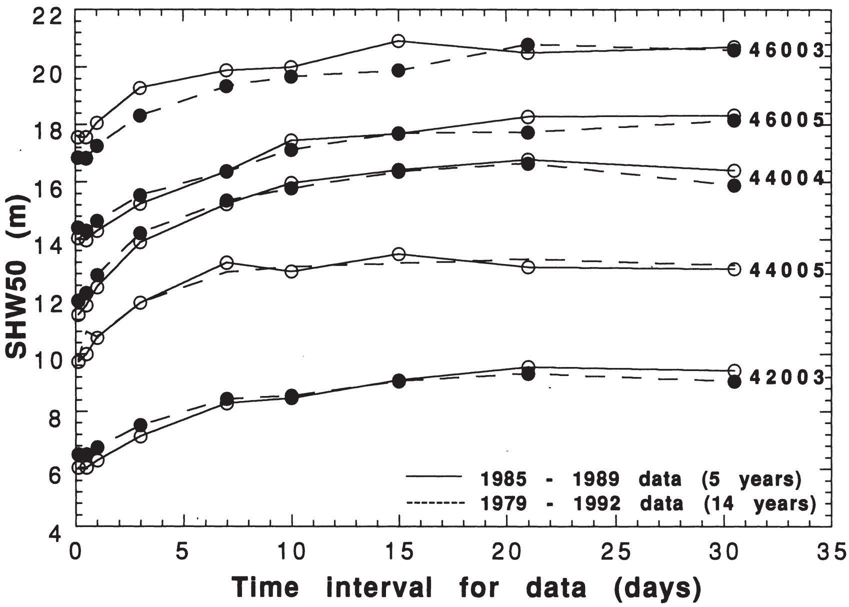


Fig. 4. Dependence of SWH50 on time interval.

Δt; maximum values from intervals of 8 days or greater may reasonably be assumed to be independent events. In fact, the relative flatness of the curves for larger values of the time interval also justifies using monthly maxima for reduced computational effort. Three-hourly values, on the other hand, lead to significant underestimation and suggest that the benchmark values in the North Sea results of Tournadre and Ezraty (1990) and the Gulf of Maine results described earlier were probably erroneous. Further, the proximity of the curves obtained from the two datasets proves the consistency of the maximum likelihood estimators (which are expected to converge as the number of data points increase; e.g. Muir and El-Shaarawi, 1986). This enhances our faith in the results obtained from only five years of data and suggests that GEOSAT data may indeed be used for extreme wave calculations.

Fig. 4 shows that the stable SWH50 for buoy 44005 is about 13 m, which is not matched for satellite data from any of the domains considered in Table 2. It is of course possible that satellite data from a domain larger than 200 km would match this value. In the Gulf of Maine, however, it is not possible to expand the domain further without incorporating land areas. Even when possible, such a domain would be excessively large and its size would probably vary from place to place, thus diminishing the usefulness of the satellite data. This difficulty stems largely from an attempt to compensate for the deficiencies of temporal undersampling at a particular location (caused by the satellite missing many significant wave events between passes) by ignoring spatial separation, i.e. measurements from remote locations are added to the dataset. These measurements, however, merely constitute additional random (rather than extreme) measurements and their incorporation does not necessarily lead to the appropriate population for extremal analyses, even if the spatial separation is ignored.

In view of the above difficulties, we have explored a different strategy which recognizes that satellite data constitute random measurements and that using these to estimate SWH50 must, in principle, result in a discrepancy compared with extreme estimates obtained with peak wave heights in a given interval. In other words, we acknowledge at the outset that the two datasets may not necessarily belong to the same population. Also, we use data only from the immediate vicinity of the location under consideration. By doing so, the discrepancy may be attributed entirely to random temporal sampling by the satellite. The problem of spatial correlation that hampered the Gulf of Maine analysis described earlier is eliminated. It then remains to quantify the discrepancy, which may be cast in the form of a relationship between the statistics associated with random measurements and those associated with maximum values in an interval. That such a relationship should exist seems intuitively apparent: in a region with a rough wave climate (and consequently large SWH50), the frequency of large waves in a random sample (if large enough) should be higher than in a region with a milder climate. Whether the relationship is simple or not is of course not known *a priori*.

Since we know the interval after which a particular point in the ocean is sampled by the satellite, one can attempt to determine this relationship using only buoy data. The continuous long-term record of buoy measurements (which provides monthly peak values) can be used to estimate the correct benchmark statistical parameters (and hence SWH50), as described above. A subset of the continuous buoy data, consisting of values taken at the same interval as the sampling frequency of the satellite, would constitute a random analog of satellite measurements. (Deo et al. (1996) have also used buoy data to construct satellite analogs to check the validity of the synthetic data generated for the period between passes). The statistical parameters associated with this subset can be compared with the benchmark values to establish the desired relationship, which may then be applied to calculations made with actual satellite measurements for regions where no buoy data are available.

3. Relationship between monthly maxima and random measurements

As noted in Section 1, GEOSAT tracks repeated themselves every 17 days. An examination of Fig. 1 indicates, however, that the best resolution for constructing global wave statistics can be obtained by centering a grid at track intersections. Thus two tracks would be available every 17 days at the intersection point. An average interval of 8.5 days between passes was initially assumed. Values of SWH separated by an interval of 8.5 days were selected from the sixteen buoys noted earlier to construct random analogs of the satellite data. Eight datasets of this type were constructed for each buoy, where each dataset was offset compared with the previous one by one day. These datasets were then used with (1)-(3). For each buoy, the eight datasets resulted in largely the same values for the parameters a and b which were then averaged. Since the actual interval between the ascending and descending passes over a point differs from place to place, the effect of varying the intervals was also examined by performing similar calculations using buoy values taken at intervals of 3 hours, 12 hours, 1 day, 3 days, 8.5 days, and 15 days.

Table 3 shows the average parameter values estimated for the various buoys for each interval. For brevity, results are shown for only five of the sixteen buoys studied. Similar results were obtained for the other buoys. The results show that for any given buoy, the parameters *a* and *b* are largely constant for the various datasets, suggesting that the statistics associated with a random sample of ocean wave heights is largely insensitive to the sampling interval of the satellite (provided, of course, that the interval is of the order of a few days)[3]. This is fortunate, because in some places, the ascending and descending tracks are separated by irregular intervals; e.g. in the Gulf of Alaska, the separation periods were about 1 day and 16 days. Further, the constancy allows us to relate these parameters to the benchmark extreme wave parameters fairly easily. Figs. 5 and 6 show the relation between the average *a* and *b* values obtained from the 8.5 day random samples and those associated with monthly maxima. Formulas for the best-fit curves are also given in the figures. Considering the fact that the buoys belong to quite different geographic locations with significant variation in the wave climate and also the variability in the number of data points available for analysis, the curves appear to represent the relationship rather well. We note that in Fig. 5, one data point (buoy 42007 in the Gulf of Mexico) appears to be somewhat of an outlier. This point pertains to a region with a much smaller wave climate than most of the other points; the SWH50 is only 4.5 m. The best fit curves obtained by including and excluding this point are, however, are almost indistinguishable; both formulas are given in Fig. 5.

In the development of Figs. 5 and 6, we have used the extremal Gumbel distribution along with the 8.5 day sample (or other similar periodic samples described

Table 3
Gumbel distribution parameters for various samples

Buoy	42003		44004		44005		46003		46005	
Sample	a	b	a	b	a	b	a	b	a	b
3-hour	2.36	0.69	1.28	1.50	1.48	1.24	0.83	2.51	1.02	2.03
12-hour	2.36	0.68	1.28	1.50	1.49	1.23	0.83	2.50	1.03	2.03
1-day	2.32	0.68	1.28	1.49	1.50	1.22	0.82	2.51	1.02	2.03
3-day	2.35	0.68	1.34	1.49	1.52	1.21	0.83	2.56	1.04	2.03
8.5-day	2.37	0.69	1.28	1.51	1.47	1.23	0.83	2.53	1.02	2.03
15-day	2.33	0.68	1.33	1.49	1.46	1.20	0.85	2.59	1.02	1.96
Monthly max.	0.89	2.48	0.54	4.69	0.69	3.84	0.44	6.53	0.47	4.99

[3] This insensitivity influences the results in Tables 1 and 2 also; the satellite values with sampling on the order of a few days and the buoy values sampled at 3 hours belong to the same population and hence lead to identical, albeit incorrect, SWH50 estimates.

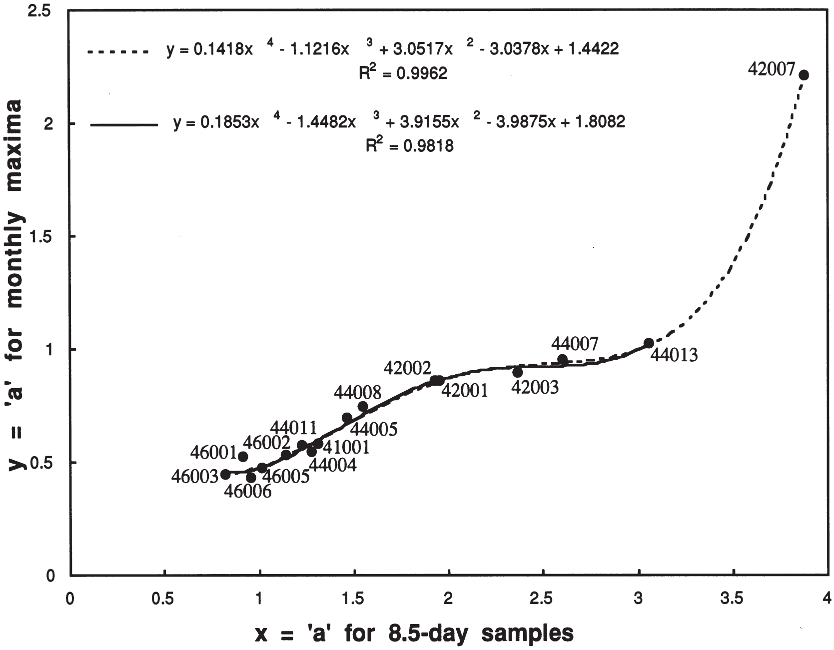


Fig. 5. Gumbel distribution parameter "a" for samples containing monthly maxima and 8.5 day data.

above), in spite of the fact that these data do not represent extreme values in an interval. This can be justified by assuming that these data represent the extreme values for some other "artificial" sea state. The statistical properties of this lesser artificial sea state can be related to those of the actual sea state through Figs. 5 and 6. In contrast, Tournadre and Ezraty (1990) have made probability calculations directly from the periodic satellite samples; in a sense, therefore, their probability estimates pertain to this artificial sea state rather than the actual sea state.

4. Calculations with GEOSAT data

The above results indicate that using GEOSAT data at track intersections with (1), estimating the parameters, correcting them according to the equations in Figs. 5 and 6, and using (2) and (3) would produce an acceptable estimate of SWH50. (Note that although we present results for SWH50 only in this paper, wave height estimates with other recurrence intervals can also be easily calculated.) While using (3), a value of $S = 12$ was used even though the actual number of satellite measurements was different. This is because the parameters are eventually related to those associated with a dataset consisting of monthly maxima. (It must be noted that considerable confusion appears to prevail in the specification of S. Even though parameter estimates may be the same, varying S can substantially alter SWH50

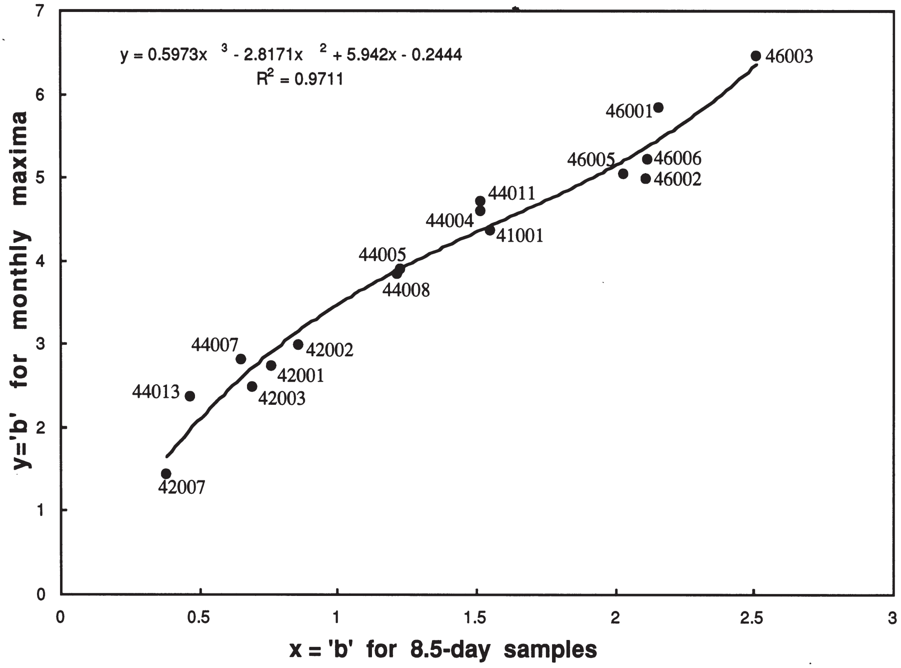
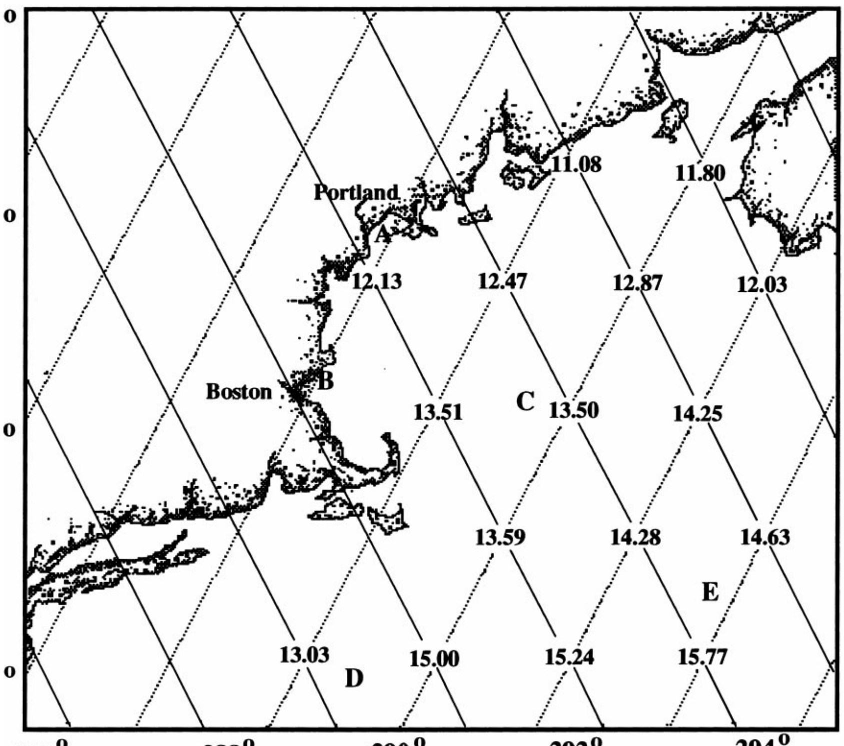


Fig. 6. Gumbel distribution parameter “b” for samples containing monthly maxima and 8.5 day data.

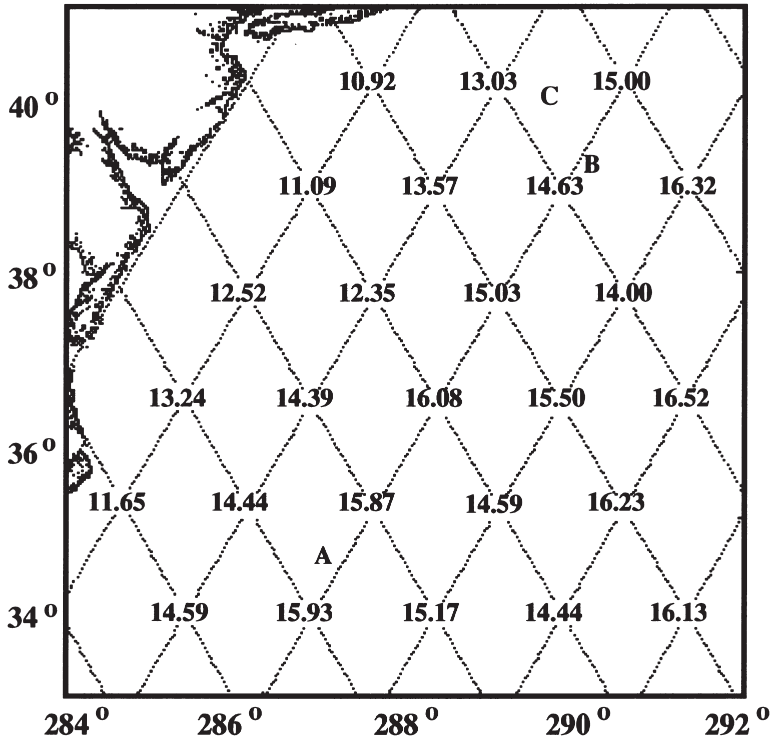
estimates). In order to extend the analysis to a region somewhat larger than the track intersection point, the study area was divided into grids centered on track intersections. The grid sizes were approximately 0.5° × 0.5° (latitude/longitude) in the study areas. All tracks in each grid were assembled; however, each pass within a grid produces about 20 satellite measurements. More than one of these measurements should perhaps not be used for analysis, since measurements within a pass essentially constitute a snapshot of the grid. We therefore examined the effect of using the mean SWH measurement and the maximum SWH measurement within the pass. (Young (1994) did a similar examination while calculating simple statistics of GEOSAT data.) Using the maximum SWH in the pass has the effect of accommodating to some extent the evidence provided by Dobson et al. (1987) and Carter et al. (1992) that GEOSAT measurements underestimate ocean wave heights somewhat compared with buoy measurements. It was generally found that in deep water, using the maximum SWH value from the pass produced the best match with the nearest buoy estimates; elsewhere, using the mean SWH measurement within the pass was effective. The differences were of the order of 1 m or less. However, the amount of data available also had an influence on the results. For simplicity, therefore, we show results obtained with the mean SWH measurement in the pass. Further, GEOSAT data from the geodetic phase of its mission were included along with the ERM data in our calculations. Since relatively small amounts of crossover data at the locations of the track intersection were available, all available crossover data in the grid were used.

Results obtained with GEOSAT data in the five study areas are shown in Figs. 7–11. At some locations, the number of available GEOSAT measurements was too small. Where the available GEOSAT measurements were less than 50% of the expected number of measurements (based on a 17-day measurement protocol), no calculations were made; these locations are shown by an asterisk (Fig. 11). Where track intersections are close to buoy locations, the results in all figures compare favorably with estimates derived from the buoy measurements, in spite of the varying amounts of satellite measurements available at each location. Perhaps the best match



Buoy	Buoy No.	SWH50 (m)
A	44007	9.56
B	44013	9.10
C	44005	13.00
D	44008	12.31
E	44011	15.89

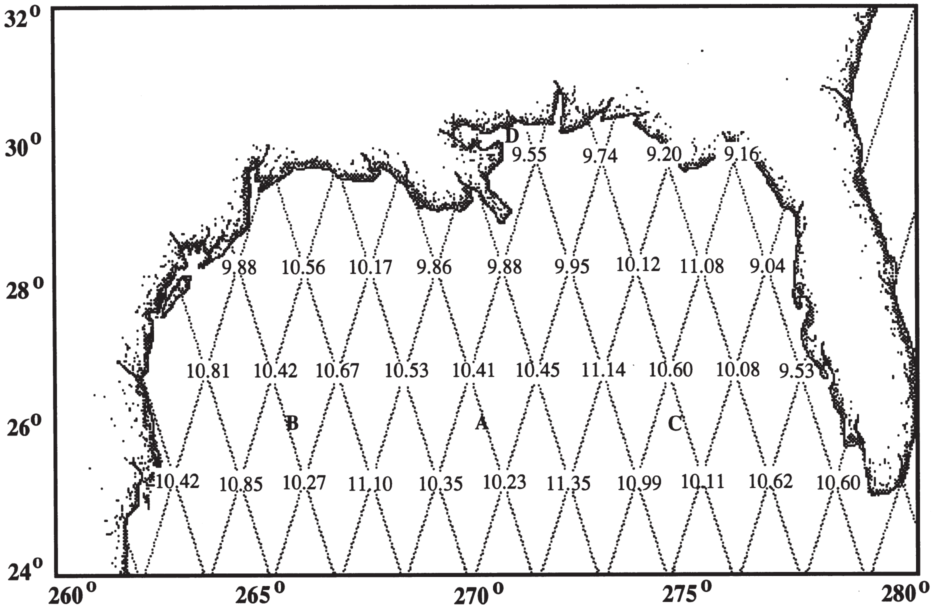
Fig. 7. Estimated SWH50 (meters) in the Gulf of Maine.



Buoy	Buoy No.	SWH50 (m)
A	41001	15.78
B	44004	16.41
C	44008	12.31

Fig. 8. Estimated SWH50 (meters) off the US mid-Atlantic coast.

is found for the Gulf of Alaska (Fig. 9), where the GEOSAT dataset was nearly full. The comparison is considerably less favorable for the Eastern Pacific (Fig. 11). In this region, however, the number of GEOSAT measurements was the smallest. On the eastern side of the US, the comparison appears to be poor near buoys 44008 and 44004 (Figs. 7 and 8). However, wave conditions change appear to change substantially in this region. In fact, buoys B and C in Fig. 8 show a difference in SWH50 of over 4 m although they are fairly close to each other. This may partly be explained by the fact that buoy B is located in 3.2 km of water whereas buoy C is located in only 60 m of water. (Note that buoy D in Fig. 7 and buoy C in Fig. 8 are the same, i.e. 44008). In all cases, the differences between SWH50 estimates obtained from satellite data and nearby buoy data are of the same order as those inherent in statistical estimation of extreme wave heights using different techniques even when a complete dataset consisting of hourly buoy values for several years is available. For



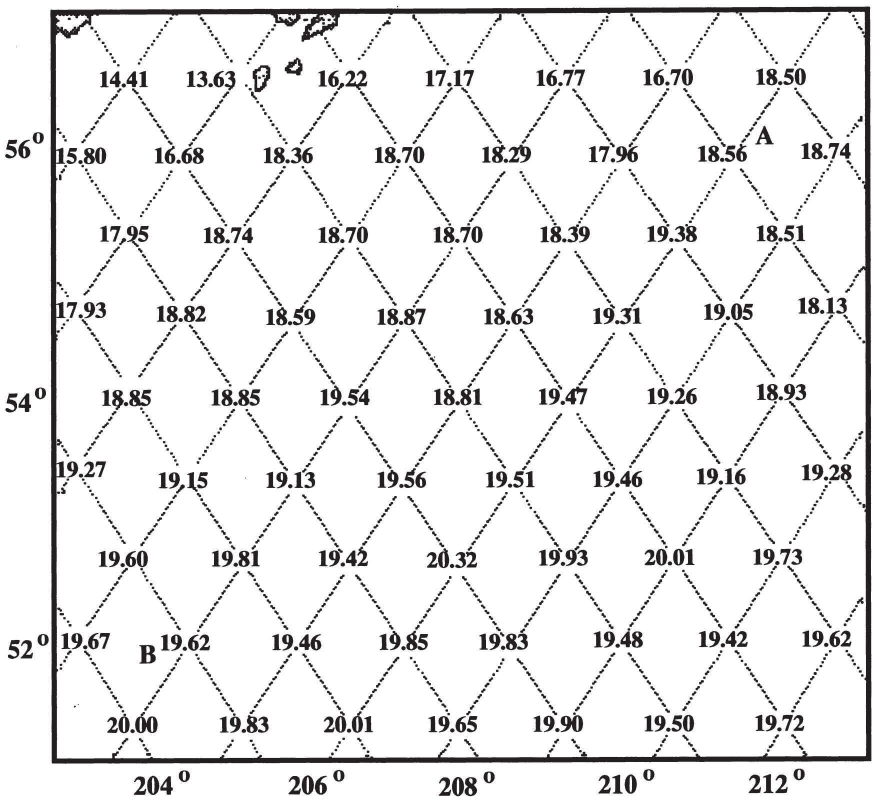
Buoy	Buoy No.	SWH50 (m)
A	42001	10.13
B	42002	10.37
C	42003	9.44
D	42007	4.30

Fig. 9. Estimated SWH50 (meters) in the Gulf of Mexico.

example, Palao et al. (1994) estimated the SWH50 value to be 16.64 m (which is very near our estimate) at buoy 44004 using 13 years of data and the method of maximum likelihood. On the other hand, censoring the bottom one-third of the monthly maxima led them to an estimate as low as 14.07 m. However, the results are extremely sensitive to the degree of censoring, as acknowledged by them; furthermore, Eqs. (1)–(3) do not directly apply to censored data, as noted by Muir and El-Shaarawi (1986). Where no buoys are available, rigorous validation of the satellite-derived results in Figs. 7–11 cannot (obviously) be provided. However, in most regions, the results appear to be consistent with the overall pattern indicated by the buoys. In the Gulf of Maine, a decreasing trend in extreme wave conditions as one goes from the southeast to the northwest has been reported in previous studies (Neu, 1982). That trend is apparent in Fig. 7 as well. Similarly, a decreasing trend is also seen in the Gulf of Mexico (Fig. 9) as one moves towards the coastal areas.

5. Concluding remarks

Global measurements of wave heights have been obtained in recent years at considerable expense by satellite technology. The usefulness of these data for practical

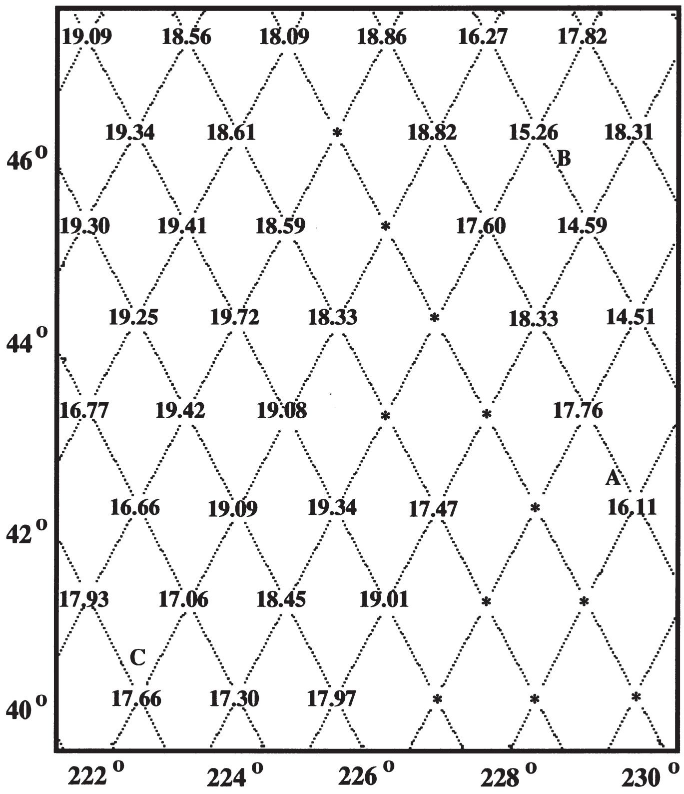


Buoy	Buoy No.	SWH50 (m)
A	46001	18.06
B	46003	20.71

Fig. 10. Estimated SWH50 (meters) in the Gulf of Alaska.

applications must be explored. The estimation of extreme wave heights using GEOSAT measurements has been described in this paper. Previous efforts by Tournadre and Ezraty (1990) have attempted to obtain these estimates by simultaneously addressing the issues of spatial separation (between satellite measurements and the point of interest) and infrequent temporal sampling. It was found that this approach and its results were unsatisfactory.

Data from sixteen buoys in diverse wave climates show that SWH50 value estimated from 5 years of data and from 14 years of data are nearly identical. This is counter to the general expectation that small datasets such as those resulting from the GEOSAT mission are of little use for estimating extreme wave conditions (e.g. Young 1994) or to the rule of thumb that the dataset must be at least one-third as long as the duration to which wave heights are being extrapolated. The buoy data also show that random samples taken at different intervals of time (on the order of



Buoy	Buoy No.	SWH50 (m)
A	46002	18.75
B	46005	18.33
C	46006	19.31

Fig. 11. Estimated SWH50 (meters) off the central US Pacific coast.

a few days) possess essentially the same statistical properties. These properties may be related to the properties of the monthly maxima through the equations given in Figs. 5 and 6 which are based on an analyses of data from a fairly diverse range of wave climates. Using satellite measurements contained in grids centered on track intersections along with these equations resulted in acceptable SWH50 values in the study areas. The results in Figs. 7–11 indicate that satellite data may indeed be used to obtain extreme wave heights in areas where no buoys are available and show that the SWH50 in the five study areas vary widely. They are: about 13 m off the north-eastern US; about 16 m off the mid-Atlantic; about 10 m in the Gulf of Mexico; about 19 m off the US west coast and near the Gulf of Alaska. The results also suggest that the extreme wave climate is largely the same over large areas (except where coastal influences are present, of course). While this tends to corroborate the conclusions of Tournadre and Ezraty (1990) that the domain of spatial correlation is of the order of 200 km in radius, the actual SWH50 estimate is quite different from that obtained by simply using available satellite data in this domain with the Gumbel distribution.

A final remark regarding the choice of distributions is appropriate. This study is based on the assumption that the extreme wave statistics can be described by the Gumbel distribution. While this is generally regarded as acceptable for many regions, other distributions (e.g. the Weibull and the lognormal distributions) are found to better describe some seastates and are also used (Palao et al., 1994; Isaacson and MacKenzie, 1981). Petruaskas and Aagard (1971); Goda (1989) describe some techniques to identify the suitable distribution. In this study, too, the suitability of the Gumbel distribution was examined by first using the plotting position method. This yielded correlation coefficients well in excess of 0.9 between the reduced variate and the wave height, justifying our choice. We therefore proceeded to obtain final estimates of the parameters by the method of maximum likelihood. If other distributions are preferred, the results obtained from the buoy data and the satellite data would be slightly different, but using satellite measurements to estimate extreme wave heights would still be based on first identifying a relationship as demonstrated in this paper.

Acknowledgements

This work was supported in part by NASA and NOAA (GOM-RMR Program).

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