

# Global ocean wave statistics obtained from satellite observations

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Data acquired by the GEOSAT radar altimeter is used to determine mean monthly significant wave height climatologies for the globe. In addition, significant wave height values that could be expected to be exceeded at different percentage levels (exceedence probability) are presented. The satellite-derived climatology is shown to compare well with the limited buoy data available. The climatology maps clearly show many synoptic features of the global wave climate. In particular, there is a marked difference in the wave climates of the two hemispheres, with the Southern Ocean having a consistently high sea state. In contrast, the North Atlantic Ocean has a much more variable sea state. Its extreme values are comparable with the Southern Ocean, but it also has periods of relative calm. As expected, the peak wave conditions occur at high latitudes  $(\pm 50^\circ)$  where a strong seasonal influence is evident, whereas the equatorial regions are calm with little seasonal variation.

## **1 INTRODUCTION**

For offshore activities such as the operability of structures, ship routing and general ocean engineering design, information on both mean and extreme wave conditions is required. Although observations of wave conditions upon which such statistics can be determined are invariably inadequate in continental shelf waters, they do exist. In the deep oceans, which comprise the vast majority of the globe, reliable observations are almost nonexistent. The difficulty and expense of operating conventional buoy systems in such deep regions is obvious. An alternative data source which has been utilized is ship observations. The accuracy and nonuniform spatial coverage, however, makes ship observations far from ideal. As an example, ships will obviously attempt to plan their routes so as to avoid extreme wave conditions.

The advent of satellite remote sensing systems such as SEASAT,<sup>1</sup> GEOSAT<sup>2</sup> and ERS-1,<sup>3</sup> which have the capability of imaging wave conditions day and night through all weather conditions, provides the means of obtaining wave observations on a global scale for the first time. In this paper, data from the three-year GEOSAT mission is used to obtain both mean monthly values of significant wave height and extreme (exceedence probability) wave conditions on a global scale. The data clearly reveal many synoptic scale features of the global wave climate previously unreported.

The arrangement of the paper is as follows. Section 2

describes the GEOSAT altimeter mission and the wave height data base obtained from that mission. The data processing used to obtain the global wave parameters is described in Section 3. Section 4 presents mean monthly global wave conditions and describes many of the interesting features of these observations. Extreme wave conditions for the globe are presented in Section 5, followed by conclusions in Section 6.

#### **2 GEOSAT MISSION AND DATA BASE**

The GEOSAT satellite was launched in March 1985, its primary purpose to measure the marine gravity field with high precision. The first 18 months of observations were classified. This classified geodetic mission concluded in September 1986, and during October the satellite's orbit was altered, placing it in a 17-day repeat pattern. The GEOSAT Exact Repeat Mission (ERM) commenced on 8 November 1986 and continued until the satellite finally failed in January 1990. The satellite began to fail, however, in early 1989 and the quantity of useable data gradually declined after this date.<sup>4</sup>

The satellite was in a polar orbit, ascending and descending orbits tracing a diamond-shaped pattern on the earth's surface.<sup>5</sup> As a result of the orbit geometry, the spatial resolution of ground tracks was not uniform. Over a single 17-day ERM the ground track spacing was  $1.475^{\circ}$ , corresponding to a spacing of 163 km at the equator and 82 km at a latitude of  $60^{\circ}.^{6}$  In the analysis

presented in the remainder of the paper, the data will be 'binned' into  $4^{\circ} \times 4^{\circ}$  sampling squares. The global distribution of GEOSAT data can be seen in Fig. 1 which shows the number of GEOSAT passes through each of these sampling squares. The figure represents all available data from the approximately 3-year unclassified period of the GEOSAT mission. As seen in this figure, the spatial coverage is not uniform, although there are typically in excess of 200 satellite passes through any of the  $4^{\circ}$  regions. Although the ground track spacing decreases towards the poles, the extent of the ice boundary in winter limits the amount of reliable data at latitudes greater than 60°. The influence of islands is also apparent (e.g. the reduced data in the region of the Greater Sunda Islands which make up Malaysia, Indonesia and New Guinea).

The GEOSAT Altimeter (ALT) was capable of measuring significant wave height,  $H_s$ , from the slope of the leading edges of radar pulses reflected from the wave-roughened ocean surface.<sup>7</sup> The pre-flight accuracy specification for measurements of  $H_s$  was 0.5 m or 10%, whichever was greater. An initial intercomparison of GEOSAT data with buoy measurements by Dobson et al.<sup>8</sup> showed that ALT measurements were within these specifications. Subsequently, more extensive intercomparisons by Tournadre and Ezraty<sup>6</sup> and Carter et al.4 indicated that the GEOSAT ALT underestimated  $H_{\rm s}$  by approximately 13%. Whether this underestimation is true for all wave climates is yet to be verified. For instance, would a similar result hold for the long swells of the Southern Ocean? Due to these still unanswered questions, no corrections have been made for this possible underestimation in the subsequent analyses.

The spatial resolution of the ALT footprint was approximately 6 km and hence estimates of  $H_s$  are an average over this region. Although this represents no limitation in open ocean regions, it places a restriction

on the use of the data in coastal areas, where significant spatial variability of wave conditions could be expected on such a scale.

#### **3 DATA PROCESSING**

#### 3.1 Quality control

GEOSAT altimeter data is far from error-free. Erroneous data occurs for a number of reasons, typical examples being data spikes at the continental boundaries or where islands fall into the satellite footprint. Although such data errors are obvious to the eye, manual quality control is clearly not feasible with such a huge data base. A two-pass automatic data-checking algorithm was implemented with the following steps.

#### Pass 1

- (1) The satellite-derived values of  $H_s$  are the average of 10 satellite observations. The averaging of these observations was performed onboard the satellite. The mean value of  $H_s$  and the standard deviation of the 10 observations,  $\sigma$ , were transmitted to the ground station. If  $\sigma/H_s$  was greater than 0.1, the observation was discarded as there was obviously significant spatial variability.
- (2) A 1/12° land mask was used to determine the positions of land masses. Any data corresponding to land, according to this mask, were discarded.
- (3) Only values of  $H_s$  in the range 0-20 m were retained.

#### Pass 2

(1) The remaining data was divided into blocks of 50 points, ensuring these passes had no spatial



Fig. 1. Gray scale shaded image showing the number of satellite passes through each  $4^{\circ} \times 4^{\circ}$  sampling square. The shading bar to the right shows the number of passes.

Number of satellite passes

'jumps' corresponding to the passage of the satellite over a continent. The mean wave height  $\bar{H}_s$  and the standard deviation of the 50 points in the block,  $\sigma'$ , were determined. If  $\sigma'/\bar{H}_s > 0.5$ , the entire 50-point block was discarded as it obviously contained multiple spikes.

(2) Individual spikes within the blocks were discarded using the criterion  $|H_s - \bar{H}_s|/\sigma' > 3$ .

The data from an extensive number of satellite passes were visually examined and the above technique appeared to be capable of discriminating between quality data and data errors with a high degree of accuracy.

#### 3.2 Data partitioning

As mentioned previously, the latitude-longitude information for each ALT observation was used to 'bin' the individual passes into  $4^{\circ} \times 4^{\circ}$  sampling squares. In addition to the number of passes through individual sampling squares varying geographically as shown in Fig. 1, the number of individual observations associated with each pass through a sampling square also varied. The satellite returned one measurement of  $H_s$  approximately each second and hence a typical pass through a sampling square corresponded to approximately 100 individual observations. Consequently, there were of the order of 30 000 individual observations of  $H_s$  for each square during the full satellite mission.

## **4 MEAN MONTHLY WAVE HEIGHTS**

A number of previous investigators have used radar altimeter data to investigate global wave conditions. Chelton *et al.*<sup>1</sup> produced a global three-month average wave field for the limited data available from the SEASAT altimeter. Mognard *et al.*<sup>5</sup> used this same data set to produce mean monthly wave-height conditions for the Southern Hemisphere winter of 1978. Challenor *et al.*<sup>9</sup> and Carter *et al.*<sup>10</sup> processed the first year of GEOSAT data to investigate the seasonal variations in global wave height. Romeiser<sup>11</sup> used mean monthly values of wave height obtained from GEOSAT data to validate a global wave prediction model.

For the present application, the full three years of GEOSAT data have been utilized. Mean monthly values of  $H_s$  were formed by averaging all observations of  $H_s$  in individual sampling squares on a monthly basis. In order to assess the validity of this approach, comparisons of these mean monthly values of  $H_s$  were made with the buoy data of Steedman<sup>12</sup> from the Southern Ocean site of Macquarie Island (-54°30'S, 159°E). These buoy data were obtained from a single year of measurements between November 1988 and October 1989, a period largely independent of the GEOSAT data



Fig. 2. Seasonal variation in mean monthly values of significant wave height for the Southern Ocean site of Macquarie Island  $(-54^{\circ}30'S, 159^{\circ}E)$ . The buoy data of Steedman<sup>12</sup> is compared with data from GEOSAT for the sampling square centred at  $-54^{\circ}S$ ,  $158^{\circ}E$ , the SEASAT data of Mognard *et al.*<sup>5</sup> and the USSR Climatological Atlas (ship observations).

set. Figure 2 compares the results of Steedman<sup>12</sup> with the present data. The same seasonal trends are clear, with the most extreme waves occurring in the Southern Hemisphere winter. The satellite data produce a lower extreme value, peaking at 4.4 m in May, whereas the buoy data yield a maximum in this same month of 5.3 m. In contrast, the satellite data yield slightly higher values during summer. It should be remembered that the buoy data are from only a year of observations and some annual variability must be expected. The difference between a temporal average at a single point (buoy data) and a spatial average at a number of almost



Fig. 3. Seasonal variation in mean monthly values of significant wave height for three neighbouring sampling squares at the same latitude  $(-54^{\circ}S)$ .



Fig. 4(a). Gray scale shaded images showing mean monthly values of significant wave height for the Southern Hemisphere summer. The shading bar to the right of each image shows values of the significant wave height in metres.



Fig. 4(b). Mean monthly values of significant wave height for the Southern Hemisphere autumn.



Fig. 4(c). Mean monthly values of significant wave height for the Southern Hemisphere winter.



Fig. 4(d). Mean monthly values of significant wave height for the Southern Hemisphere spring.

instantaneous but intermittent times (satellite data) could also be expected to produce some differences. Clearly, the size of the region (sampling square) over which the satellite data are considered should not be so large as to span areas with significantly varying climatology, nor should it be so small as to undersample the data. Tournadre and Ezraty<sup>6</sup> have investigated this problem and found spatial averaging scales comparable with that adopted here introduce no measurable bias.

The limited SEASAT data of Mognard *et al.*<sup>5</sup> are also shown in Fig. 2 as well as values taken from the USSR Climatological Atlas.<sup>13</sup> The data of Mognard *et al.*<sup>5</sup> are in reasonable agreement with both the buoy data and the GEOSAT results. The USSR Climatological Atlas data, however, clearly showed the unreliability of ship observations, particularly in a geographic region where there is little regular shipping.

A measure of the statistical stability of the data can also be obtained by comparison of neighbouring sampling squares at the same latitude. In regions far from land, such as the Southern Ocean, little spatial variability should occur over this scale. Figure 3 compares the sampling square previously discussed in Fig. 2 with its neighbours immediately to the east and west. The results are very similar, indicating that there are sufficient passes in each sampling square to form reliable mean monthly values.

Figure 4 shows contoured plots of the mean monthly values of  $H_s$  for the globe, based on the GEOSAT data. The figure is divided into four sub-figures, one for each season. Examination of these plots reveals many interesting features of the global wave climate. The most striking feature of the plots is the north-south seasonal variability. Maximum waves occur at the



Fig. 5. The annual variation in values of the mean monthly significant wave height from points in the Southern Ocean (dashed line) and the North Atlantic (solid line). These points represent the most extreme wave climates for each of the hemispheres.



Fig. 6. Seasonal variation in the values of mean monthly significant wave height at Hawaii. The GEOSAT data for the sampling square centred on 22°N, 198°E is compared with the buoy data of Zambresky.<sup>14</sup>

higher latitudes in each hemisphere during their respective winters. This was already clear in the data presented in Fig. 2. Although peak wave conditions in the North Atlantic are as large as those in the Southern Ocean, the Southern Ocean has a higher year-round wave climate. This is clearly shown in Fig. 5 which compares points from the North Atlantic and Southern Oceans. These two points represent the most extreme wave climates from each hemisphere. Interestingly, they occur at the same relative latitudes  $\pm 50^{\circ}$  and have almost identical maximum values of  $H_s$  of 6 m. During summer, however,  $H_s$  falls to 1.7 m in the North Atlantic, whereas the summer value for the Southern



Fig. 7. Variation in the values of mean monthly significant wave height along latitude  $-50^{\circ}$ S. The months of July, September and January are shown. The longitudes corresponding to the land masses to the north of this latitude are shown at the top of the figure.

Ocean is still 3.1 m. The Southern Ocean has a higher mean annual wave climate.

In contrast to the extreme conditions at high latitudes, the equatorial regions are, not surprisingly, calm all year round. There is little seasonal variability in this region. As one moves either north or south from the equator both the extreme values and the seasonal variability increase. As an example, Fig. 6 shows the seasonal variability at Hawaii (22°N, 198°E). This figure also shows available buoy data from Zambresky.<sup>14</sup> The buoy and satellite data are in excellent agreement, both showing the moderate seasonal trend at this latitude.

The respective wave climates on the west coasts of Africa, Australia and South America are significantly more extreme than the east coasts of these respective continents. This is presumably due to the predominantly westerly winds over the Southern Ocean and resulting sheltering and fetch limitations on the eastern coasts. It may also be possible, however, that these continental land masses influence the wind velocities, resulting in reduced wind climates on their eastern coasts. Due to the significantly smaller oceanic basins, similar features are not apparent in the Northern Hemisphere.

Despite the fact that the Southern Ocean is largely free of land masses, the wave climate is not uniform across this region. The largest waves occur in the region south of and between Africa and Australia. This feature was also observed by Mognard *et al.*<sup>5</sup> Figure 7 shows values of  $H_s$  along latitude  $-50^{\circ}$ S for the months of July, September and January. A maximum, in the region between Africa and Australia, is clearly apparent during July. This can also be seen in the contour plot of Fig. 4(c). Mognard *et al.*<sup>5</sup> indicated that this maximum appeared to migrate eastwards in the months following July. This is not supported by the present



Fig. 8. Variation in the values of mean monthly significant wave height along longitude 62°E (Indian Ocean). The months of January, August, July and October are shown.

data. By September the maximum still exists in the region between Africa and Australia, although a second maximum has developed south of Australia. During the Southern Hemisphere summer these local maxima vanish and there is a relatively uniform wave climate in the region from Africa to South America (Figs 4(a) and 7). The influence of New Zealand in reducing the wave climate during winter is also clearly apparent in Figs 4(c) and 7. Even though the southern tip of New Zealand is approximately 10° north of the latitude  $-54^{\circ}$ S shown in Fig. 7, there is still a marked influence. Drake Passage to the south of South America has a major influence in reducing the wave climate all year round. Indeed the wave height is reduced substantially in the region from South America to Africa as a result of this feature.

The influence of the high wave region in the Southern Ocean south of and between Africa and Australia can also be seen at lower latitudes. The Indian Ocean consistently has a higher wave climate than either the South Pacific or South Atlantic Oceans at the same latitude. This is presumably as a result of swell generated in the Southern Ocean propagating into these regions.

Other features of the Southern Ocean wave climate are also interesting. The peak sea states are concentrated near  $-50^{\circ}$ S. It might be expected that the position of this high wave belt may migrate north-south on a seasonal basis. This, however, is not supported by the data. Figure 8 shows the monthly variation of  $H_s$  along longitude 62°E (Indian Ocean). Within the variability of



Fig. 9. Comparison of the probability distribution function obtained from the GEOSAT data (lines) with that derived from the buoy data of Steedman<sup>12</sup> (squares) for the Southern Ocean site of Macquarie Island  $(-54^{\circ}30'S, 159^{\circ}E)$ . The GEOSAT results are presented for three sampling squares in the vicinity of Macquarie Island. The three curves to the left were obtained using the 'mean' values of individual passes through each sampling square, the curves to the right from the 'maximum' values of individual passes through each sampling square.



Fig. 10(a). Gray scale shaded images showing values of significant wave height expected at probabilities of exceedence of 10, 20 and 30%. The shading bar to the right of each image shows values of the significant wave height in metres.



Fig. 10(b). As for Fig. 10(a) but for probabilities of exceedence of 40, 50 and 60%.



Fig. 10(c). As for Fig. 10(a) but for probabilities of exceedence of 70, 80 and 90%.

the data there appears to be no seasonal variation in the region of the Southern Ocean maxima, although the variation in the magnitude of the conditions clearly varies seasonally as noted earlier. It has been observed that Southern Ocean swell can propagate across the Pacific Ocean with little decay.<sup>15</sup> Hence, it would be reasonable to assume that a significant proportion of the equatorial wave climate would be determined by high latitude swell. As the Southern Ocean swell peaks in July and the Northern Pacific swell peaks in January, one might speculate that the equatorial Pacific regions may have two annual peaks. This, however, is not evident in the data, a relatively uniform distribution throughout the year being evident. Moving from west to east across the Pacific along the Equator the wave climate is also quite uniform. This occurs despite the fact that the western region of the basin would be significantly more protected from Southern Ocean swell than the eastern regions. Apparently, the natural dispersion of the swell is sufficient to mask such effects.

Smaller scale events are also evident in the data. For example, a very localized region of high wave activity develops in the Arabian Sea between June and September (Fig. 4(c) and (d)). This is also clear in the transect along longitude  $62^{\circ}E$  shown in Fig. 8. Mean monthly wave heights in this small region reach values as high as 4 m in July. This characteristic is caused by the strong south-west winds which develop in this region as a result of the Asian Summer Monsoon. These strong winds are confined to a jet relatively close to the coast and have typical mean monthly wind speeds of approximately  $12 \text{ m/s.}^{16}$ 

#### **5 WAVE HEIGHT OCCURRENCE STATISTICS**

In addition to the determination of seasonal variability of mean wave conditions, the GEOSAT data set can also be used to determine the global distribution of extreme wave conditions or wave height exceedence probability values.

The multiple observations of  $H_s$  associated with the passage of the satellite through a single 4° sampling square will not, generally, be statistically independent. On the spatial scale of the square, the same meteorological event is likely to have generated all the imaged waves. Hence, each satellite pass through the square is assumed to provide only one independent observation of the wave conditions at that point and time. Two different means of determining the values of these observations have been implemented: (a) the mean value of each independent pass or (b) the maximum value of each pass. The most appropriate technique is difficult to assess and presumably depends upon the ultimate use of the results. In the limit, as the size of the sampling square approaches zero, the two techniques become identical.

Once the independent observations of  $H_s$  were evaluated for each sampling square, they were ranked in descending order of magnitude from m = 1 to N. The probability of exceedence,  $P_r$ , was then determined using the simple plotting position formula<sup>17</sup>

$$P_{\rm r} = \frac{m}{N+1} \tag{1}$$

Figure 9 compares the probability distribution functions evaluated for the Southern Ocean site of Macquarie Island using the two averaging techniques described above and the buoy data of Steedman.<sup>12</sup> For each of the satellite-derived distributions, the curves for the square centred on Macquarie Island (i.e.  $-54^{\circ}$ S, 158°E) and those immediately to the east and west are shown. The values of  $P_r$  from the neighbouring squares are very similar, indicating that there is sufficient data to provide stable estimates of the exceedence probabilities. Not surprisingly, the satellite technique which determines the observations of  $H_s$  using the maximum value for each pass through the sampling square yields higher values than the 'average value' method. The buoy observations are in very good agreement with both of these satellite techniques, agreeing best with the 'average' method for the higher values of  $P_r$  and with the 'maximum' method for the lower values of  $P_r$ . The 'average' method has been adopted for the remainder of this study.

Figure 10 shows global shaded contour charts of the wave heights that could be expected at different exceedence probability values. Many of the features observed in the mean monthly values are also clear in this figure. The most extreme sea conditions can be found in the North Atlantic Ocean and the Southern Ocean south of and between Africa and Australia. In each of these regions, values of  $H_s$  between 6 and 7 m can be expected 10% of the time. Although the extreme wave conditions of the two hemispheres are very similar, the more uniformly high sea state of the Southern Ocean is clear in Fig. 10(c). Significant wave heights between 2 and 3 m can be expected in the Southern Ocean 90% of the time compared with values between 1 and 2m for almost all of the remainder of the globe, including the North Atlantic. Although the North Atlantic has very extreme conditions, there are times when it is calm, something which almost never occurs in the Southern Ocean.

#### **6 CONCLUSIONS**

The data presented in this paper provide the first quantitative estimates of the global wave climate. Results for both mean monthly conditions and the percentage occurrence of various sea states are presented. Comparison of both these mean monthly and percentage occurrence estimates with buoy data shows that approximately three years of GEOSAT data is sufficient to provide stable estimates of wave conditions.

Although the data is considered to provide accurate estimates of the wave climate in deep oceans, estimates close to shore are likely to be less reliable. This is mainly due to the relatively sparse spatial coverage resulting from the distance between satellite ground tracks.

In principle, the data could also have been used to

determine extreme wave statistics. Extrapolation of the relatively short 3-year data set to extreme events is likely to be unreliable and hence this has not been attempted. As the length of record for which satellite data is available lengthens, however, this will eventually be feasible. For instance, the ERS-1 satellite is presently operating and successors are planned. In order for satellite data to replace the extensive coastal monitoring systems presently in place in many countries, however, multiple platforms will probably have to be launched, so as to decrease the effective ground track separation.

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