THE JOINT CALIBRATION OF ALTIMETER AND IN SITU WAVE HEIGHTS

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ABSTRACT

The changes in the world's wave climate are subtle, and to investigate them we need long-term and well-calibrated global measurements. One source of good quality consistent measurements of significant wave height is the radar altimeter. Such instruments have flown on a number of satellites and, apart from a short gap in 1989-1991, we have continuous global data since 1985. However, this data set involves a number of different satellites and sensors, each of which has a slightly different calibration.

In this paper we look at the problem of producing a coherent well-calibrated set of buoy and satellite altimeter data. In the classical method of calibration, a well-known and more accurate standard is used to calibrate an instrument. If we try to calibrate a radar altimeter against a set of wave buoys we do not have such a standard. The buoys are no more accurate than the altimeter itself. Thus, we need to use more sophisticated statistical techniques than simple linear regression which can take into account errors in both variables. We present calibration results for all radar altimeters since Geosat and discuss the drift in the TOPEX measurement of wave height. We demonstrate that it is necessary to apply these calibration results to altimeter data if measurements from different satellites are to be used to assemble multi-year climate data sets.

In addition, we discuss the possible use of radar altimeters as 'standards' for the cross-calibration of buoys around the world. We compare results from four different buoy data sets (operated by the US NDBC, Canadian MEDS, the UK Met Office, and the Japan Meteorological Agency). We demonstrate that the biggest obstacle to generating a coherent blended buoy/in situ data set are different reporting standards. We will also discuss the comparison of altimeter data with wave information from Voluntary Observing Ships (VOSs) using comparisons between individual satellite and ship observations.

INTRODUCTION

To produce a coherent, long-term wave climatology for the world's oceans we need to be able to combine data from a number of sources. In particular, we need to use data from buoy networks, satellites and VOSs. If well-maintained, buoys can produce good quality regular data, not only significant wave height but also other spectral parameters including directional information. However, the number of buoys deployed at any one time is limited, and buoy networks will never produce more than a very limited areal coverage. Over the last few years the Southampton Oceanography Centre (SOC) has been trying to discover as many buoy deployments in deep water as possible. So far we have only found four significant networks. These are deployed around the USA, Canada, Japan and the UK. Other data are available from oil companies, but these data are often of a short duration and are sometimes confidential. We have discovered no buoy data from the Southern Ocean. The positions of these buoys are shown in Figure 1.

Our second source of data is radar altimetry from satellites. Apart from a short gap in 1991, radar altimeters have been continuously flying since 1985. Altimeters produce good quality significant wave height information (see Carter *et al.*, 1992; Cotton and Carter, 1994 and below). Altimeters also measure wind speed, and recently it has been shown that it is possible to extract data on wave

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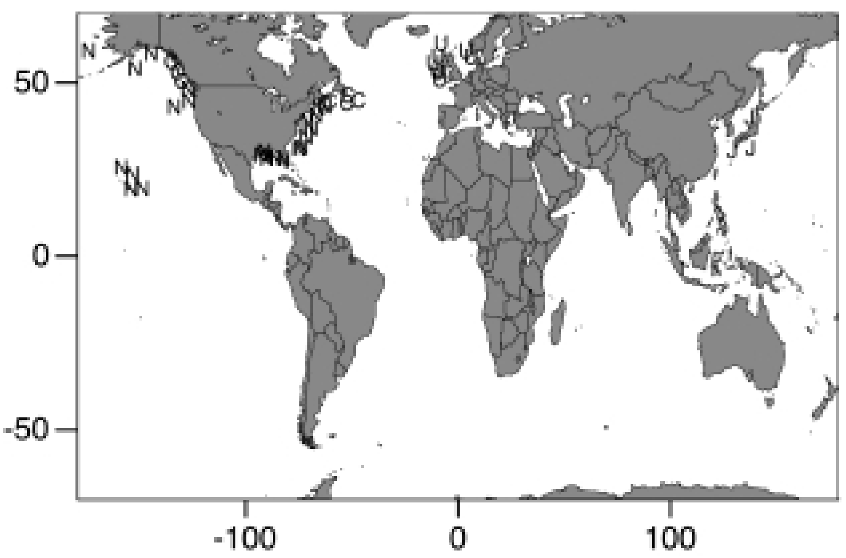


Figure 1 — The positions of the NDBC (N), UK Met Office (U), Japan Meteorological Agency (J) and the Meteorological Service of Canada (C) buoys.

period as well (Davies *et al.*, 1997), but we will concentrate on significant wave height in this paper. In general, altimeters have been shown to produce significant wave height data with a similar accuracy to wave buoys, but with a bias (Carter *et al.*, 1992). This is discussed below.

Although altimeters deliver data over the entire globe, there are gaps. For instance, TOPEX/POSEIDON has an inclination of only 66° so no data are recovered poleward of a latitude of 66°. The altimeter also has no swath, so data are only collected directly beneath the satellite. This means that there are gaps between satellite tracks where no data are ever collected. The size of these gaps depends upon the repeat period of the satellite. The more often the ground track is repeated, the larger the gap between tracks. An example of TOPEX/POSEIDON tracks is shown in Figure 2. This pattern is repeated every ten days. Note that the track separation is not constant but varies with latitude.

An alternative to altimeter data which also has quasi-global coverage are wave observations from ships of opportunity. These are not instrumental as with the other data but consist of subjective estimates of wind sea and swell height, direction and period. Although in principle the visual ship data are global, in practice there are very large gaps away from the shipping lanes, particularly in the Southern Ocean.

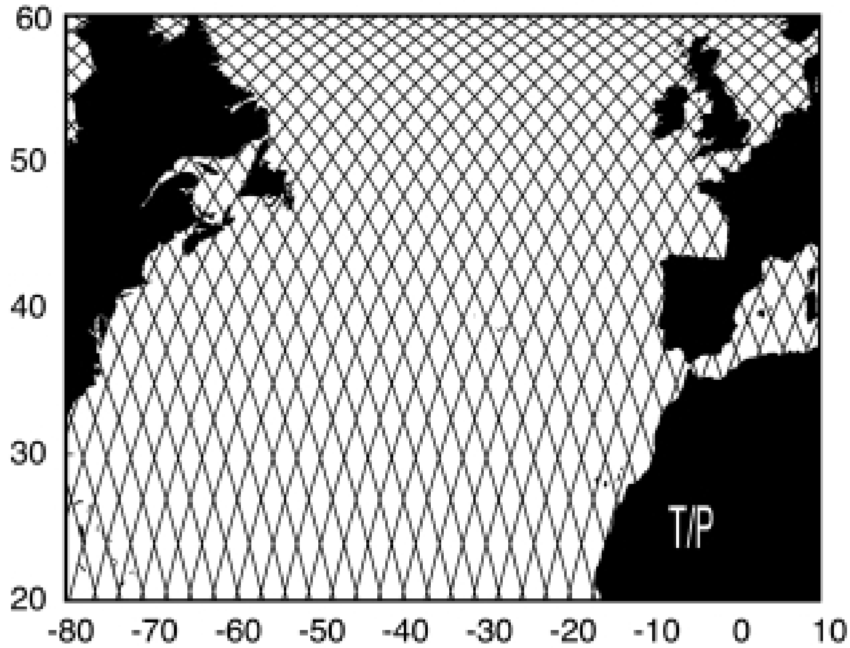


Figure 2 — The coverage from the TOPEX/POSEIDON altimeter over the North Atlantic. Data are only collected directly below the satellite.

In this paper we will look at these three sources of information about significant wave height (Hs) and how we can make them consistent. Our basic plan is to use the US NDBC buoys as a standard and calibrate everything relative to these using calibrated altimetry as a transfer standard. Unlike the standard calibration problem, however, we cannot assume that our standard, the NDBC buoys, have such a small error that it can be neglected. We know from previous work (e.g. Cotton and Carter, 1994) that the random error on buoys and altimeters is similar, and that the visual data from ships can be expected to have a larger error, but even then, we cannot assume that the altimeter error is zero. Standard regression techniques demand that the ‘x’ variable is without error, so we need to use a more sophisticated method which does not make this assumption. There are a number of such techniques available and we will use two of them. The simplest is principal component regression. Here we take the line which passes through the mean of the two data sets and has a slope equal to the geometric mean of the ‘x on y’ regression and the ‘y on x’ (this line is also the first principal component of the data, hence the name). This is appropriate when the variables being regressed have approximately the same errors. We use this technique for comparing altimeter and buoy data. A more complex method which can be used in situations where the errors cannot be assumed to be the same, or where more complicated linear (or even non-linear) models are required, is orthogonal distance regression (ODR) (Boggs and Rogers, 1990). This minimizes the orthogonal distance to be line from the 2-d dataset and provides error estimates for both the ‘x’ and ‘y’ variables. We will use this method to find trends in altimeter data and for altimeter/COADS comparisons. A comparison of the ODR and principal component regression for the buoy/altimeter comparisons showed negligible differences.

THE NDBC DATA SET

The ‘reference’ set of buoys we use consists of 24 buoys around the US coast which are run by the US NOAA Data Buoy Center (NDBC). We have selected these buoys because they are in deep water and are not too close to any coasts and, therefore, should be representative of deep water conditions. The buoy locations can be divided into four areas: the North Pacific (including buoys off Alaska), the North Atlantic, the Gulf of Mexico and off Hawaii. This data set therefore covers a range of conditions from areas off Hawaii where swell dominates, to places such as the coast of Alaska where the wave climate is dominated by large storms.

CO-LOCATION CRITERIA

Initially we followed other authors and used co-location criteria of 1 h and 100 km. However, after experimenting with varying the criteria, we decided that the optimum for use with the NDBC buoys (which report hourly) was to use 30 minutes and 50 km. The altimeter data were not averaged in any way and the nearest 1 Hz value, as provided by the space agencies, was used.

ALTIMETER CALIBRATIONS

GEOSAT

Geosat was a US Navy satellite that operated from 1985-1989. The early part of the mission was in a very long repeat orbit (168 days) to make geodetic measurements, while from 1987 the satellite went into a 17-day repeat. During 1989, the satellite started to degrade and the data became much less reliable.

The calibration equation for the years 1985-1988 is given by (standard errors in parenthesis):

$$\underset{}{H_s(\mathrm{Geosat}) = -\underset{(0.0142)}{0.0943} + \underset{(0.0054)}{0.9092}H_s(\mathrm{NDBC})} \qquad \mathrm{rrms}=0.28\ \mathrm{m}$$

This is shown in Figure 3. The inclusion of the 1989 data gives a slightly different equation:

$$H_s(\mathrm{Geosat}) = -\underset{(0.0190)}{0.0798} + \underset{(0.0073)}{0.8976}H_s(\mathrm{NDBC}) \qquad \mathrm{rrms}=0.38\ \mathrm{m}$$

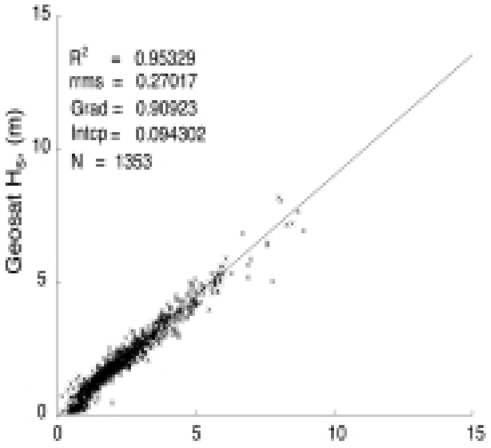


Figure 3 — Geosat H_s plotted against NDBC Buoy H_s for the period 1985–1988. The line shows the best fit calibration.

ERS-1

The next altimeter to be launched was ERS-1. There are two main classes of data from the ERS series of satellites. There are fast delivery (FD) data that are produced within three hours of collection. One use of this sort of wave data is assimilation into wave forecast models. The other class of data is off-line products (OPR) data. These data are reprocessed on the ground and are, therefore, more accurate than the fast delivery data. For climatological purposes we are interested in this latter class of data, so we will only discuss the calibration of the off-line products. To further confuse matters two versions of the off-line data for ERS-1 are available. Data collected between the launch of the satellite in August 1991 and March 1995 form part of version 3. A new version of the processing software was then introduced (version 6), and this was used until May 1996 when the ERS-1 satellite was put into 'storage' and ERS-2 became the source of data.

For the version 3 data we obtain a calibration equation:

$$\begin{array}{l} \mathrm{H_s(ERS\text{-}1)} = -\underset{(0.0229)}{0.3025} + \underset{(0.0094)}{0.9016}\mathrm{H_s(NDBC)} \end{array} \qquad \text{rrms=0.45 m}$$

This is shown in Figure 4.

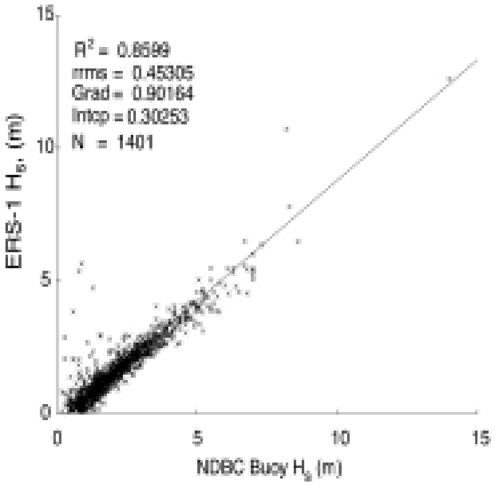


Figure 4 — ERS–1 OPR(v3) H_s plotted against NDBC buoy H_s. The line shows the best fit calibration.

Early forms of the version 6 software were faulty, resulting in lower quality H_s data for ERS-1 cycles 144-148, covering the period 04/95 to 07/95. Subsequent data are of better quality and gave the calibration equation:

$$\begin{array}{l} \mathrm{H_s(ERS\text{-}1)} = -\underset{(0.0444)}{0.1906} + \underset{(0.0181)}{0.8871}\mathrm{H_s(NDBC)} \end{array} \qquad \text{rrms=0.36 m}$$

ERS-2

ERS-2 succeeded ERS-1 and was launched in April 1995. Although it is still producing data, we only use data to the end of 1997. All the data were processed with version 6 of the software but without any of the problems associated with ERS-1. The calibration is given by:

$$H_s(\text{ERS-2}) = \underset{(0.0163)}{-0.0330} + \underset{(0.0070)}{0.9425}H_s(\text{NDBC}) \qquad \text{rrms=0.30 m}$$

The plot is shown in Figure 5.

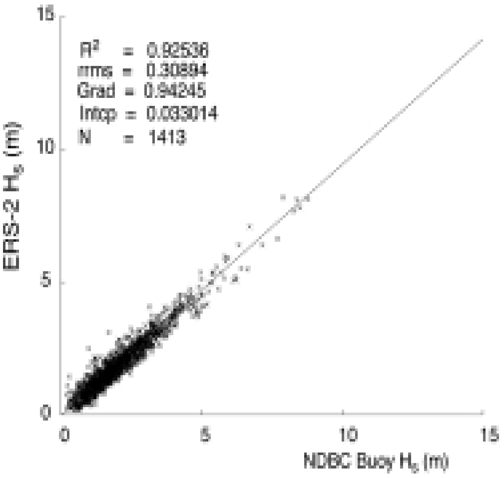


Figure 5 — ERS–2 H_s plotted against NDBC buoy H_s. The line shows the best fit calibration.

TOPEX/POSEIDON

The TOPEX/POSEIDON satellite is a US/French mission that was launched in 1992. The satellite has two on-board altimeters: the US TOPEX and the French POSEIDON. Because they share certain hardware components, in particular the antenna, both altimeters cannot operate at the same time. TOPEX operates for 90 per cent of the time, with POSEIDON providing data for the remaining 10 per cent.

The calibration of POSEIDON is shown in Figure 6. The calibration equation is:

$$H_s(\text{POSEIDON}) = \underset{(0.0362)}{-0.0340} + \underset{(0.0154)}{1.0214}H_s(\text{NDBC}) \qquad \text{rrms=0.28 m}$$

The final altimeter we shall consider in this section is TOPEX. Using all the data from 1992 to 1997, the equation:

$$H_s(\text{TOPEX}) = \underset{(0.0113)}{-0.0895} + \underset{(0.0048)}{0.9503}H_s(\text{NDBC}) \qquad \text{rrms=0.26 m}$$

is obtained. The fit is shown in Figure 7.

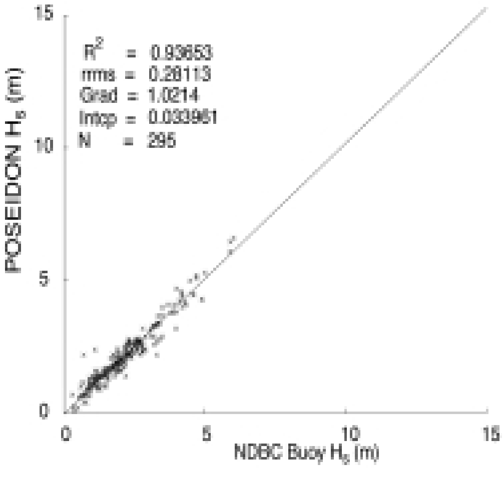


Figure 6 — POSEIDON H_s plotted against NDBC buoy H_s. The line shows the best fit calibration.

However, if we plot the daily mean difference between the buoys and the TOPEX altimeter against time, as shown in Figure 8, we find that there is a trend apparent in the latter part of the data. It appears that the instrument characteristics have been changing since the launch (Hayne, pers. comm.), but the effect on the estimated significant wave height only becomes apparent towards the end of 1996. We estimate that after day 1730 since the start of 1992 (26th September 1996), there is a trend of 0.4 mm day^{-1} in the TOPEX significant wave height measurement. In January 1999, the TOPEX electronics were switched to the alternative 'B' side and since then there has been no discernible trend; however a new calibration of wave height is now required. This is given by:

$$\begin{array}{c} H_s\left(\mathrm{TOPEX}-\mathrm{B}\right) = -0.0800 + 0.9676 H_s\left(\mathrm{NDBC}\right) \\ \left(0.0357\right) \quad \left(0.0185\right) \end{array} \qquad \text{rrms}=0.19 \text{ m}$$

Figure 7 — TOPEX H_s plotted against NDBC buoy H_s. The line shows the best fit calibration.

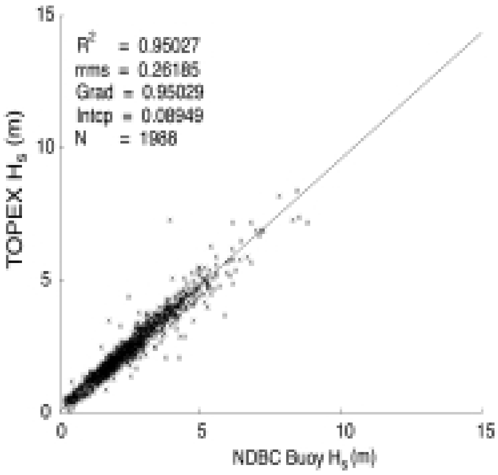
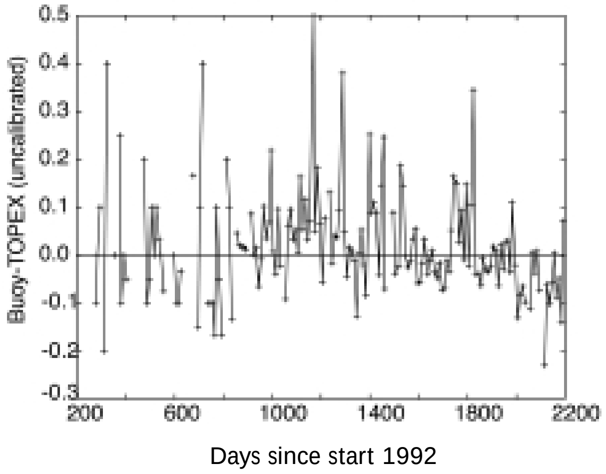


Figure 8 — Ten day averages of the difference between TOPEX and NDBC buoy significant wave heights. Note the trend in the latter part of the data.



COMPARISONS WITH OTHER BUOY NETWORKS

We have now calibrated the altimeter data to be internally consistent and consistent with the NDBC buoy network. The consistency of the calibration across missions is such that we can now use the calibrated altimeter set to look at and map wave climate change in the North Atlantic (Cotton and Challenor, 1999).

Once we have this 'standard' data set we can use it to check the calibrations on other instruments and measuring systems. In this section we look at the consistency of the buoy networks around the world. In the next section we do some initial work with visual wave observations from the COADS data set.

As stated in the introduction, we have data from three buoy networks in addition to the NDBC data used so far. These are the UK Met Office (UKMO), the Japan Meteorological Agency (JMA) and the Meteorological Services of Canada (MSC) (supplied to us by the Canadian Marine Environmental Data Service

(CMEDS)) buoy networks. Their positions are shown in Figure 1. If these data are calibrated to the same 'standard' as the NDBC buoys, then a comparison with the calibrated altimeter set will be the same for all buoy networks. Note that if we have a difference between calibrations in the buoys, we cannot say which is right with this method; we can only say whether they are consistent with the NDBC buoys. A summary of the buoy data sets is given in Table 1. One of the differences that must be taken into account is the reporting standards of each network. For example, the JMA buoys only report every three hours, whereas the other three networks report every hour. To obtain a meaningful number of co-locations with the satellites we have had to relax the time co-location criterion to 1 h rather than 30 minutes.

Figures 9 to 11 show scatterplots of the combined calibrated altimeter data against each of the buoy networks. Although it may seem circular, we have included the NDBC data in this analysis both as a check on our analysis and as a means of identifying possible 'rogue' buoys. See Fedor and Brown (1982) for an example where an apparently miscalibrated buoy is identified. The comparisons with the other buoy networks are more interesting.

It is immediately apparent that the UKMO buoys only report significant wave height to the nearest 0.5 m. This will clearly be reflected in the calculation of any accuracies. Table 2 gives the details of the buoy 'calibrations'. There are significant differences between the buoy networks in terms of their slopes (UKMO, MSC) or intercept (JMA). Thus, we expect UKMO buoys to read about 4 per cent high compared to NDBC, MSC to be 5 per cent low and the JMA buoys to have a bias of about 30 cm. We stress again that these are relative measures and we cannot say which calibration is correct. The residual rms values for the non-NDBC buoys are higher. Because we fitted the altimeter to the NDBC set, this rrms is depressed relative to the other buoy networks, so any comparisons must be made with caution. To get a true measure of the NDBC rrms we should hold back data from the fitting process and use these independent data to estimate the rrms. However, it is clear from Figure 10 that there are a number of very poor comparisons between MSC and the altimeter data set for low buoy Hs values. Removing these has little effect on the regression line but does reduce the rrms. Similarly, the rrms for the UKMO data are increased by the 0.5 m resolution. Degrading the NDBC data to 0.5 m resolution increased the rrms from 0.335-0.354 m. As regards the JMA data, the co-location criteria were relaxed since the buoys only report every three hours, and this will increase the rrms.

FURTHER STUDIES

When all the calibrated altimeter-NDBC buoy co-located data are combined, they provide us with a large data set (about 5 500 data pairs) with which to study possi-

Source	*Coverage*	*Data Type*	*Dates*
US NOAA Data Buoy Center (NDBC)	24 selected buoys in N. Atlantic, N. Pacific, Caribbean Sea	Hourly wave spectra, met. data	1972-97
UK Met Office (UKMO)	7 open ocean buoys in N. E. Atlantic and North Sea	Hourly summary wind and wave data, met. data	1991-97
Japan Meteorological Agency (JMA)	3 open ocean buoys around Japanese Coast	3 hourly summary wind and wave data, met. data	1985-96
Meteorlogical Services of Canada (MSC)	7 open ocean buoys. N. Atlantic, N. Pacific	Hourly wave spectra, met. data	1988-96

Table 1 - Sources of Buoy Wave Data.

Figure 9 — NDBC buoys plotted against the combined, calibrated altimeter data set.

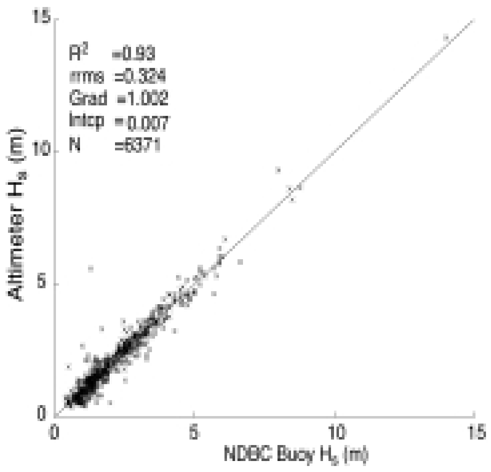


Figure 10 — MSC Buoy H_s plotted against the combined, calibrated altimeter data set.

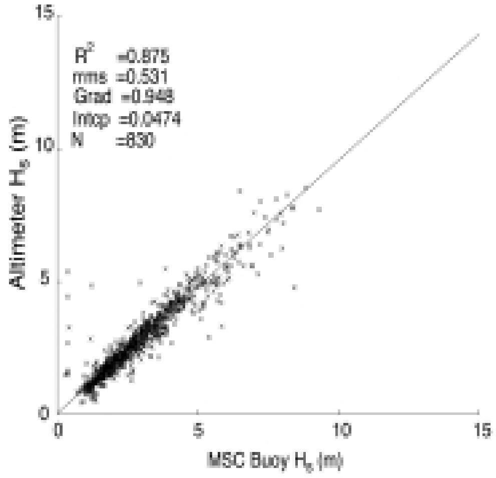


Figure 11 — JMA Buoy H_s plotted against the combined, calibrated altimeter data set.

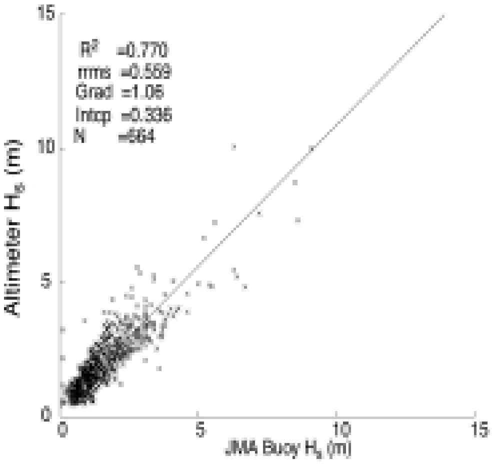


*Table 2—Principal component regression parameters from comparisons of co-located altimeter and buoy significant wave height data. *Co-located data within nearest hour, rather than 30 minutes.*

Data Source	*No*	*Slope*	*Std. err.*	*Int. (m)*	*Std. err.*	*rrms (m)*
NDBC	6371	1.002	0.007	-0.007	0.016	0.325
UKMO	1228	1.041	0.021	-0.124	0.072	0.604
JMA*	664	1.062	0.041	0.337	0.080	0.559
MSC	830	0.948	0.024	0.047	0.079	0.531

ble dependencies of alt/buoy wave measurement. One such study tested for a possible dependency of the altimeter/buoy H_s relationship on buoy size. Although the buoy platforms range from 3-12 m in diameter, we found no significant change in the gradient (or intercept) of the ODR regression which might have indicated a change in the sensitivity of the buoy measurement.

Furthermore, it had been suggested (Janssen, pers. comm., 1998) that the altimeter measurement may be less accurate under certain sea conditions (e.g. steep young seas), when the assumption of Gaussian distributions of sea surface heights may not hold. To test this assertion the normalized altimeter-buoy error in H_s was plotted against wave age. No dependency on wave age was found. Further tests are planned against buoy data which contain more spectral information.

COMPARISONS WITH COADS DATA

The third source of global, or near-global, wave height information are visual observations from ships of opportunity. Such data are collected in the COADS data set. Unlike our other data, the visual estimates do not give a simple estimate of significant wave height. Instead, there are at least two estimates, one for the wind sea (or waves travelling in the same direction as the local wind) and one for swell. (Occasionally secondary swell trains are also identified but this is rare and we ignore such data). There are a number of formulae to compute an estimate of significant wave height from these two components. Hogben (1988) uses the formula:

$$H_s(\text{Hogben}) = \sqrt{h_w^2 + h_s^2}$$

where h_w and h_s are the wind sea and swell estimates, respectively. Wilkerson and Earle (1990) use the maximum of h_w and h_s, whereas Barratt (1991) uses a combination of the two: Hogben’s formula when the direction of the wind sea and swell differs by less than a certain angle, and Wilkerson and Earle’s when it is greater. Gulev and Hasse (1998) suggest using an angle of thirty degrees. Although we have analysed all three definitions, since the results were very similar, we will only report the results for Hogben’s definition.

It is non-trivial to co-locate data from moving ships with altimeters which, because of orbital dynamics, have a complex sampling of the sea surface. So far we have co-located COADS for the three years 1993-1995 inclusive with altimeter measurements from TOPEX. Over the three years, this gives us 21 150 data points with a visual estimate of either sea or swell from the ships. Using orthogonal distance regression we obtain the following equation:

$$H_s(\text{Hogben}) = -\,0.5331 + 1.0274\ H_s(\text{Alt})$$

which means that on average the individual visual estimates of significant wave height are fairly good although both the slope and intercept are significantly different from 1 and 0, respectively, at the 95 per cent level. The intercept is higher than for the buoys but may reflect our decision to place the visual estimates at the top of the range, so an estimate between 1 and 1.5 m was set to 1.5 m in calculating H_s. However, the residual root mean square is 1.04 m, showing that while good climatologies should result from averaging large quantities of visual data, individual observations should be used with caution.

CONCLUSIONS

We have shown that by calibrating against a buoy network, in our case the NDBC buoys, it is possible to produce a consistent long-term inter-mission altimeter data set for significant wave height. The accuracy of each individual data point in this data set is better than 0.5 m. However, the drift in the TOPEX altimeter has shown the need for continual monitoring of satellite systems throughout their lives, rather than simply relying on a three- or six-month ‘calibration’ phase at the start of the mission. This implies that we need well-maintained and calibrated buoy networks to provide such calibrations. The altimeter systems are a valuable addition to the buoy networks and not a substitute for them. Ad hoc deployments of buoys for special purposes (including satellite calibration!) are of much less use. It is difficult to validate the altimeters at both very high and very low wave heights. Since high sea states are rare, we have little data to work with, while all measurements appear to have difficulty in measuring waves lower than about 0.5 m H_S. A further problem is the lack of calibration data in the southern hemisphere. We can expect wave conditions to be different here with larger fetches and more swell. We would therefore like to confirm our calibrations and the altimeter algorithms in these regions.

Once created, we can use the combined altimeter set as a ‘standard’ to check the calibration of other wave measuring systems, both long-term networks and ad hoc deployments. Our work on this so far shows that there are differences between the calibrations of the different buoy networks and a large proportion of these are probably due to different reporting standards and quality control. If all buoy operators worked to the same standards, we believe that most of these differences would disappear. So far, the work carried out on COADS has been very limited but would appear to show that on average the data are of good quality (with a possible bias). The quality is very variable though, and the data should only be used in averages.

ACKNOWLEDGEMENTS

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