JERICHO TECHNICAL REPORT 01

Report on Analysis of Co-located UKMO Open Ocean buoy and Altimeter Data

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3rd July 1998

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1. Introduction

This report analyses co-located wind wave data from satellite radar altimeters and the UK Meteorological Office Open Ocean Buoys in the North Eastern Atlantic and The North Sea. This report concentrates on data from 7 buoys, known as K1, K2, K3, K4, K5, K16 and K17 (Table 1).

2. Data Sets

2.1 Buoy Data

Table 1 lists the locations of the 7 UKMO data buoys used in this study:

Name	GTS ref.,	Lat .(∞N)	Long. (∞E)	Params.	Reporting Freq.	Availability
K1	62029	48.7	-12.4	Hs,U10,Tz	hourly	10/12/91-31/12/97
K2	62081	51.0	-13.3	Hs,U10,Tz	hourly	09/12/91-31/12/97
K3	62108	53.6	-15.3	Hs,U10,Tz	hourly	01/12/91-31/12/97
K4	62105	55.5	-13.0	Hs,U10,Tz	hourly	01/01/92-31/12/97
K5	64045	59.3	-9.9	Hs,U10,Tz	hourly	08/07/94-31/12/97
K16	62109	57.0	0.0	Hs,U10,Tz	hourly	31/07/95-31/12/97
K17	62026	55.3	2.3	Hs,U10,Tz	hourly	01/07/95-31/12/97

Table 1: Details of the UK Meteorological Office Open Ocean Buoys used for this Study. Buoys also report air and sea temperature, humidity, and sea level pressure.

We understand that the instrumentation on all UKMO open ocean data buoys is identical, consisting of duplicate sensors for wind direction and speed (including maximum gust), air and sea temperature, humidity and pressure, and a single sensor for significant wave height and wave period. The wind sensors are Vector Instruments cup anemometers, and the wave sensor is a Datawell Mark 3 heave sensor. The platform is 2.8m in diameter, with hull fins to stop rotation. The anemometers are mounted on a stainless steel mast at 4m above sea level. The maintenance and replacement schedule allows for a six-monthly sensor replacement, and a three yearly complete mooring recovery and replacement.

The data provided to SOC are extracted from a UK Met. Office report format, in which the wind speeds are corrected to 10m, and reported to an accuracy resolution of 1 knot. Significant wave heights are reported to the nearest 0.5m, and average wave period to the nearest 1.0 second. For the sake of these comparisons we have assumed that the buoy measurements are reported at the hour, and are time averages representative of local conditions at this time.

2.2 Altimeter Data

Altimeter wind and wave data (significant wave height -*Hs*, wind speed - *U10*, and radar backscatter, $\sigma 0$) from the offline geophysical data records of the ERS-1, ERS-2, TOPEX and Poseidon satellite radar altimeters, as provided by CERSAT and AVISO/CNES, are employed in this study. The *Hs* and $\sigma 0$ values are combined using the *Davies et al [1997]* algorithm to generate an altimeter estimate of zero upcrossing wave period, *Tz*. For further information regarding quality tests and the individual satellite altimeter data sets, readers are referred to *Cotton [1998]*

2.3 Extraction of Co-located Data, and Initial Processing

Initial co-location criteria were set at 100 km and 30 minutes, such that all altimeter data taken within 100 km of any of the 5 buoy locations was extracted, and merged with buoy data from the nearest hourly report. These merged data files were archived and form the data set for all further analysis. Typically the merged data files consist of series of several (up to ten) sequential altimeter data records from individual passes merged with repeated hourly buoy data. This allows either individual altimeter data records to be analysed, or for along path averages to be generated.

In this report, data from the individual altimeter 1 Hz data records for the pass which was closest to the buoy location, provided it was within 50 km, have been employed. Calibration corrections for *Hs* , *U10*, and *Tz*, generated through comparisons with US NDBC buoys have been applied separately to data from each of the altimeters *[Cotton, 1998*]. Equations 1-12 detail these corrections.

Significant Wave Height

ERS-1	$Hs_{(adjusted)} = Hs_{(ERS-1)} \times 1.1091 + 0.3355$	**(1)**
ERS-2	$Hs_{(adjusted)} = Hs_{(ERS-2)} \times 1.0610 + 0.0350$	**(2)**
TOPEX	$Hs_{(adjusted)} = Hs_{(TOPEX)} \times 1.0523 - 0.0942$	**(3)**
Poseidon	$Hs_{(adjusted)} = Hs_{(Poseidon)} \times 0.9790 + 0.0333$	**(4)**

Wind Speed

ERS-1	$U10_{(adjusted)} = U10_{(ERS-1)} \times 0.8964 + 0.8453$	**(5)**
ERS-2	$U10_{(adjusted)} = U10_{(ERS-2)} \times 0.8767 + 0.8411$	**(6)**
TOPEX	$U10_{(adjusted)} = U10_{(TOPEX)} \times 0.8752 + 0.6796$	**(7)**
Poseidon	$U10_{(adjusted)} = U10_{(Poseidon)} \times 0.8608 + 0.6325$	**(8)**

Zero Up-Crossing Wave Period

Refer to *Davies et al. [1997]* for the altimeter wave period algorithm (a function of significant wave height and radar cross section)

ERS-1	$Tz_{(adjusted)} = Tz_{(ERS-1)} \times 0.7123 - 0.6038$	**(9)**
ERS-2	$Tz_{(adjusted)} = Tz_{(ERS-2)} \times 0.6344 - 0.5187$	**(10)**
TOPEX	$Tz_{(adjusted)} = Tz_{(TOPEX)} \times 0.6695 - 0.5894$	**(11)**
Poseidon	$Tz_{(adjusted)} = Tz_{(Poseidon)} \times 0.6263 - 0.5464$	**(12)**

3. Aims

The main purpose of this study was to identify periods when the UKMO Open Ocean buoy data are reliable. A secondary aim was to assess the performance and relative calibration of the UKMO buoy wind/wave data set in comparison to that of the US NDBC buoys. For the purposes of this report all altimeter data, once corrected, have been taken to form a single consistent data set. Analysis was carried out separately for each buoy, in the form of a consideration of time series of co-located data, and comparison through principal component regressions. A principal component regression fits a regression line perpendicular to the direction in which the data set shows most variance, thus taking into account errors which occur in both data sets being compared.

4. Validity of UKMO Open Ocean Buoy Data

4.1 Buoy K1 (62029)

Figure 1 presents the time series of significant wave height, wind speed and wave period data for co-located altimeter and K1 buoy data. The bottom half of each panel shows the altimeter-buoy difference.

There are three distinct continuous periods in the data (01/01/92 - 24/02/94, 14/04/94 - 25/06/95, and 13/04/96 - 31/12/97), perhaps representing separate deployments of instrumentation at the K1 location. Each period of data demonstrates different levels of agreement between altimeter and buoy data, which improves as time progresses. Up to the end of February 1994 (day 786) there were clearly problems with the buoy wave data, during which period the buoy repeatedly reported values of 2m (wave height) and 5 s (period). The wind data for this period did not appear to suffer from the same problem. During the second period, March 94 to June 95 (days 835-1272), whilst there are no occurrences of repeated reportings of unchanged measurements, there is a suggestion (see the lower of the two panels in each figure) that is a higher level of variability than in the last period: April 96 (day 1564) onwards. To examine if the variability had changed between these periods, principal component regressions were separately carried out on the altimeter buoy data for each period. Results are given in Tables 2, 3 and 4 respectively for significant wave height, wind speed and wave period.

Period	*N*	*r.r.m.s. (m)*	*Gradient*	*Intercept*
01/01/92-24/02/94	59	1.0069	1.2186	-0.9175
14/04/94-25/06/95	106	0.6665	1.0872	-0.4717
13/04/96-31/12/97	112	0.4057	1.0562	-0.0018

Table 2. Results of Principal Components Regression Between Altimeter and Buoy Significant Wave Heights for buoy ***K1****.*

N number of co-located closest pair data points (separation < 50 km, and < 30 mins)

r.r.m.s residual root mean square,

Gradient and *Intercept*

parameters for the linear adjustment necessary to bring altimeter data into agreement with buoy data.

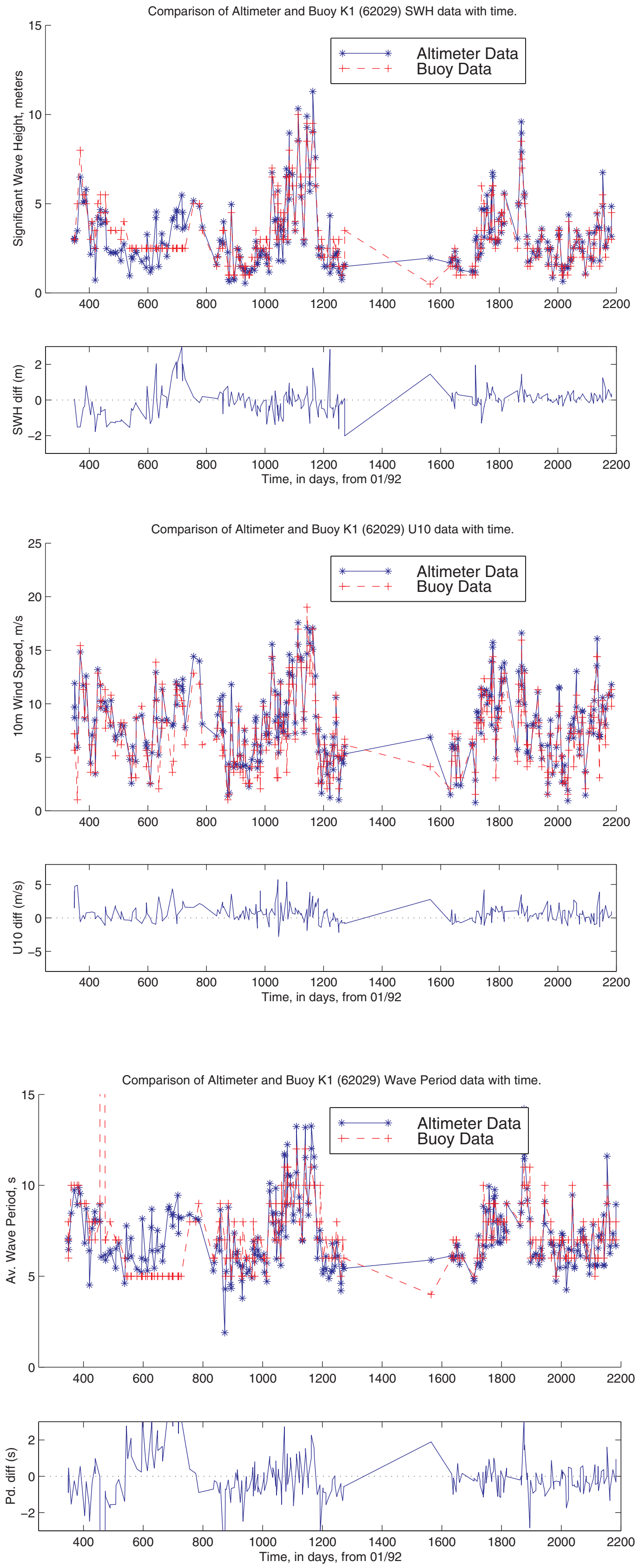

Figure 1 - Time series of altimeter and buoy data at UKMO site K1 (48.7∞N 12.4∞W)

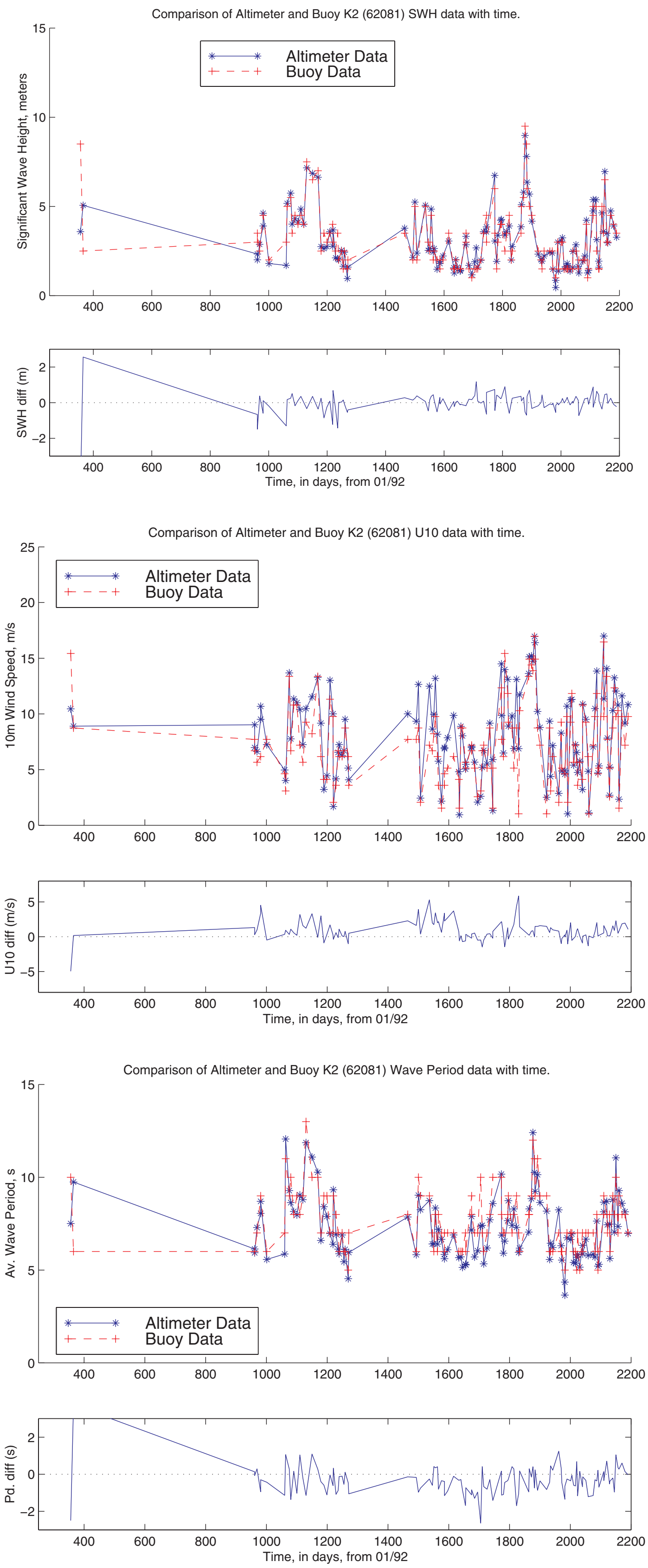

Figure 2 - Time series of altimeter and buoy data at UKMO site K2 (51.0∞N 13.3∞W)

Period	N	r.r.m.s.(ms^{-1})	Gradient	Intercept
01/01/92-24/02/94	59	1.3320	0.8726	1.8601
14/04/94-25/06/95	106	1.4305	1.0573	0.2678
13/04/96-31/12/97	112	1.0453	1.0790	0.2266

*Table 3. Results of Principal Components Regression Between Altimeter and Buoy Wind Speeds for buoy **K1**.*

Period	N	r.r.m.s.(s)	Gradient	Intercept
01/01/92-24/02/94	58	1.4293	0.5349	3.7117
14/04/94-25/06/95	103	0.8422	1.3438	-2.9133
13/04/96-31/12/97	110	0.7175	1.1915	-1.5323

*Table 4. Results of Principal Components Regression Between Altimeter and Buoy Wave Periods for buoy **K1**.*

Discussion

The wave measurements (*Hs* and *Tz*) from the first period of available data are clearly invalid and these data should not be used. The wind data from this period appear from Figure 1 and Table 3 to be valid, although the gradient and intercept calculated does not seem to be consistent with that from the two later periods.

The r.r.m.s. variability for *Hs*, *U10*, and *Tz*, is smallest for the third period of data, but is acceptable for both the second and third periods. These changes in r.r.m.s. do not necessarily indicate adjustments to the buoy instrumentation but may simply be a consequence of variability in general environmental conditions around buoy K1. Further information from UKMO on their maintenance schedule would help provide clarification Our current recommendation is that only wind and wave data gathered after 14/04/94 are used for climate studies.

Finally, we note co-located data for all three parameters cover a wide range of values, *Hs* over 1-12 m, *U10* 1-19 ms^{-1}, and *Tz* 4-13 s

4.2 Buoy K2 (62081)

Figure 2 presents the time series of significant wave height, wind speed and wave period for co-located altimeter and K2 buoy data

Whilst there have been three distinct continuous periods in the K2 data, the first period only provided two co-located data points and these data are therefore removed from further analysis. During the second period, August 94 to June 95 (days 961-1271), there is again a suggestion of a higher level of variability than in the latest period, January 1996 (day 1465) onwards. Principal component regressions were separately carried out on the altimeter buoy data for the last two periods. Results are given in Tables 5, 6 and 7.

Period	N	r.r.m.s. (m)	Gradient	Intercept
18/08/94-24/06/95	34	0.5435	1.0896	-0.5669
04/01/96-31/12/97	96	0.3458	1.0025	0.0856

Table 5. Results of Principal Components Regression Between Altimeter and Buoy Significant Wave Heights for buoy ***K2****.*

Period	N	r.r.m.s.(ms^{-1})	Gradient	Intercept
18/08/94-24/06/95	34	1.1909	1.1147	0.0900
04/01/96-31/12/97	96	1.3424	1.0575	0.5148

Table 6. Results of Principal Components Regression Between Altimeter and Buoy Wind Speeds for buoy ***K2****.*

Period	N	r.r.m.s.(s)	Gradient	Intercept
18/08/94-24/06/95	34	0.6281	1.0818	-0.9573
04/01/96-31/12/97	96	1.0547	1.1218	-1.3896

Table 7. Results of Principal Components Regression Between Altimeter and Buoy Wave Periods for buoy ***K2****.*

Discussion

The tabulated regression results confirm the visual assessment of higher variability in the earlier wave height and wind speed data, although the same is not true for the wave period data. Nonetheless, we regard the indicated levels of variability for all data taken after August 1994 as acceptable, and recommend that buoy data after this date can be used for climate studies. A slighter smaller range of values are covered by these co-located K2 data (*Hs* : 1-9 m, *U10* : 1-15 ms^{-1}, and *Tz* : 4-12 s)

4.3 Buoy K3 (62108)

Figure 3 presents the time series of significant wave height, wind speed and wave period data for co-located altimeter and K3 buoy data

There are four periods in the K3 data: 01/12/92-30/12/93 (days 341-730); 23/09/94-28/06/95 (days 997-1275); 10/01/96-23/03/96 (days 1471-1543); 20/07/96-31/12/97 (day 1662 onwards). The last two periods shall be considered together in the following analysis. Principal component regressions were separately carried out on the altimeter buoy data for three periods and results are given in Tables 8, 9 and 10.

Discussion

From figure 3 we see that, early after initial deployment, the K3 buoy experienced similar wave data problems to the K1 buoy. This effectively renders all K3 wave data before September 1994 useless. The wind speed data from this period also shows a much higher variability than the later data (Table 9). There is some indication from Table 8 that the wave height data show more variability in the second period than the third, but the wind speed and wave period data do not follow this pattern. We therefore recommend that only data recorded from September 1994 onwards are used.

The range of values of co-located data is again relatively large, 1-9 m for *Hs* , 1-15 ms^{-1} for *U10*, and 4-12 s for *Tz* .

Period	*N*	*r.r.m.s. (m)*	*Gradient*	*Intercept*
07/12/92-30/12/93	38	2.6744	0.1202	3.3643
23/09/94-28/06/95	62	0.5243	1.2225	-1.1574
10/01/96 - 31/12/97	41	0.3467	1.0628	0.0006

Table 8. Results of Principal Components Regression Between Altimeter and Buoy Significant Wave Heights for buoy ***K3****.*

Period	*N*	*r.r.m.s.(ms^{-1})*	*Gradient*	*Intercept*
07/12/92-30/12/93	38	2.1416	0.9079	2.0450
23/09/94-28/06/95	62	1.2499	1.0331	0.1150
10/01/96 - 31/12/97	41	1.3317	1.0786	0.4391

Table 9. Results of Principal Components Regression Between Altimeter and Buoy Wind Speeds for buoy ***K3****.*

Period	*N*	*r.r.m.s.(s)*	*Gradient*	*Intercept*
07/12/92-30/12/93	29	1.5622	1.0071	-4.8022
23/09/94-28/06/95	59	0.7687	1.1873	-1.6822
10/01/96 - 31/12/97	41	0.8014	1.2249	-1.8721

Table 10. Results of Principal Components Regression Between Altimeter and Buoy Wave Periods for buoy ***K3***

4.4 Buoy K4 (62105)

Figure 4 presents the time series for co-located altimeter and K4 buoy data

There are four continuous periods in the K4 data: 24/04/92-28/12/92 (114-362); 31/10/93-03/02/94 (642-765); 24/04/94-09/03/95 (845-1164); 12/08/95-31/12/97 (1320 onwards). For the principal component regressions, the second and third periods (days 642-1164) were considered together. Results are given in Tables 11, 12, and 13.

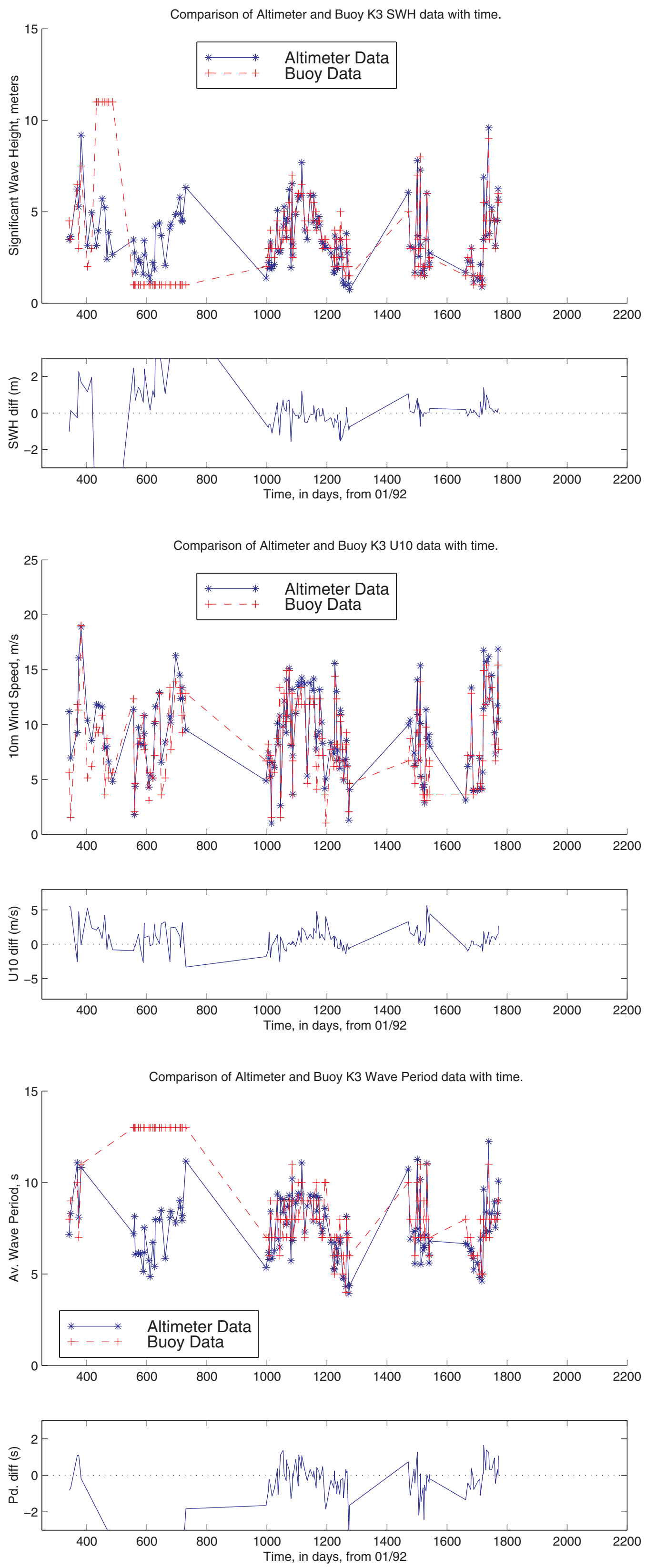

Figure 3 - Time series of altimeter and buoy data at UKMO site K3 (53.6∞N 15.3∞W)

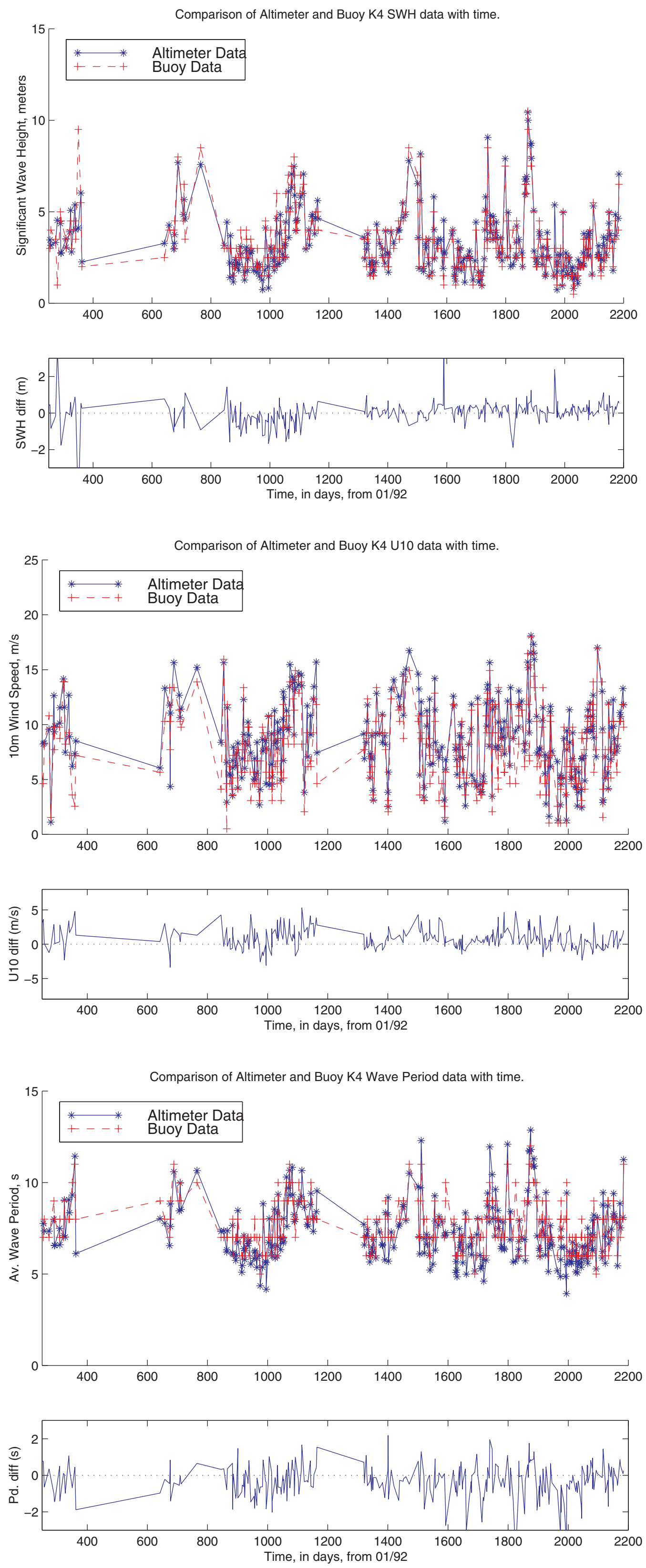

Figure 4 - Time series of altimeter and buoy data at UKMO site K4 (55.5∞N 13.0∞W)

Period	*N*	*r.r.m.s. (m)*	*Gradient*	*Intercept*
24/04/92-28/12/92	28	1.1923	0.6679	0.9963
31/10/93-09/03/95	92	0.6352	0.9858	-0.2147
12/08/95-31/12/97	204	0.5123	1.0375	0.0564

Table 11. Results of Principal Components Regression Between Altimeter and Buoy Significant Wave Heights for buoy ***K4****.*

Period	*N*	*r.r.m.s.(ms^{-1})*	*Gradient*	*Intercept*
24/04/92-28/12/92	28	1.8243	1.0390	0.7748
31/10/93-09/03/95	92	1.6600	1.0155	0.8159
12/08/95-31/12/97	204	1.2604	1.0226	0.4903

Table 12. Results of Principal Components Regression Between Altimeter and Buoy Wind Speeds for buoy ***K4****.*

Period	*N*	*r.r.m.s.(s)*	*Gradient*	*Intercept*
24/04/92-28/12/92	27	0.8516	1.3325	-3.0070
31/10/93-09/03/95	88	0.7371	1.2118	-1.9407
12/08/95-31/12/97	200	0.8696	1.3093	-2.6617

Table 13. Results of Principal Components Regression Between Altimeter and Buoy Wave Periods for buoy ***K4****.*

Discussion

Although Figure 4 shows no evidence of repeated reporting of unchanged wave height values from buoy K4, Table 11 indicated a significantly higher variability in the *Hs* (and to a lesser extent)*U10* comparisons for the first period of data. A further, smaller, reduction in r.r.m.s is indicated in *Hs* and *U10* between the second and third periods of data. We recommend that data from October 1993 onwards are acceptable for the purpose of climate studies.

The ranges of values recorded in co-located data at K4 were, 1-11 m for *Hs* , 1-17 ms^{-1} for *U10*, and 5-13 s for *Tz* .

4.5 Buoy K5 (64045)

Figure 5 presents the time series of co-located altimeter and K5 buoy data

There is only one period of continuous data from K5 data, from January 1996 onwards . Principal component regressions have been carried out for this period and results for wave height, wind speed and wave period are given together in Table 14.

Parameter	*N*	*r.r.m.s.*	*Gradient*	*Intercept*
Sig. Wave Height	155	0.4166m	1.0826	-0.1285
Wind Speed	155	1.3481 m/s	1.0304	0.6656
Wave Period	153	0.9435s	1.4544	-3.5960

*Table 14. Results of Principal Components Regression Between Altimeter and Buoy Significant Wave Heights for buoy **K5**.*

Discussion

The details of figure 5, and regression results from Table 14 indicate all the K5 data to be of acceptable quality, with rrms variability for *Hs*, *U10* and *Tz* below 0.5m , 1.5 ms^{-1}, and 1.0 s respectively. A wide range of values are seen in these co-located data , 1-8 m for *Hs* , 1-19 ms^{-1} for *U10*, and 5-12 s for *Tz* .

4.6 Buoy K16 (62109)

Figure 6 presents the time series of significant wave height, wind speed and wave period data for co-located altimeter and K16 buoy data

As for K5 there is only one period of continuous K16 data (August 1995 onwards) . Principal component regressions have been carried out for this period and results for wave height, wind speed and wave period are given together in Table 15.

Parameter	*N*	*r.r.m.s.*	*Gradient*	*Intercept*
Sig. Wave Height	62	0.3519	1.0815	-0.2085
Wind Speed	62	1.6432	1.0500	0.7613
Wave Period	62	0.6114	1.2295	-1.5469

*Table 15. Results of Principal Components Regression Between Altimeter and Buoy Significant Wave Heights for buoy **K16**.*

Discussion

Figure 6 and Table 15 indicate all K16 data are of acceptable quality. Buoy K16 is located in the Northern North Sea, sheltered from long North Atlantic Swell, and as a consequence a significantly smaller range of wave height and period are seen in the co-located data (1-5 m for *Hs* , and 4-9 s for *Tz*) . The range of *U10* values is also slightly down, at 1-15 ms^{-1} .

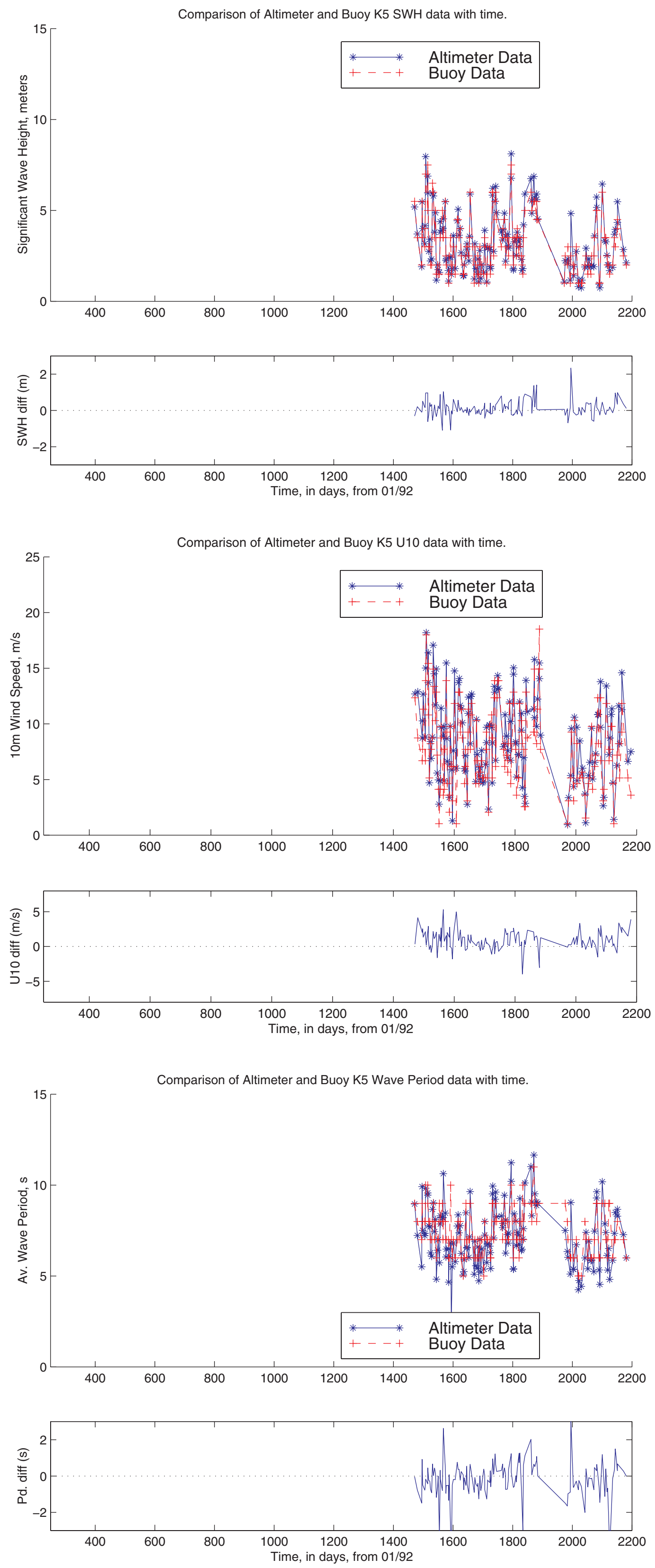

Figure 5 - Time series of altimeter and buoy data at UKMO site K5 (59.3∞N 9.9∞W)

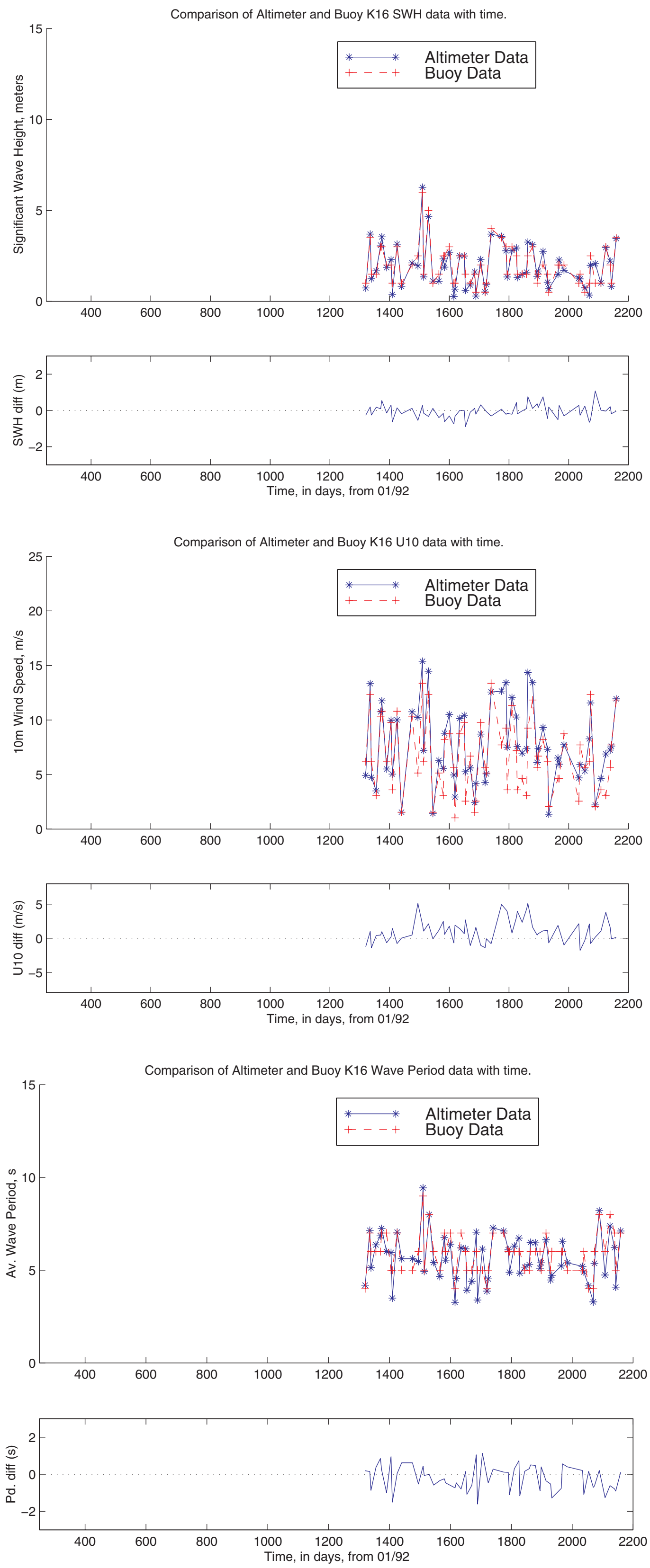

Figure 6 - Time series of altimeter and buoy data at UKMO site K16 (57.0∞N 0.0∞E)

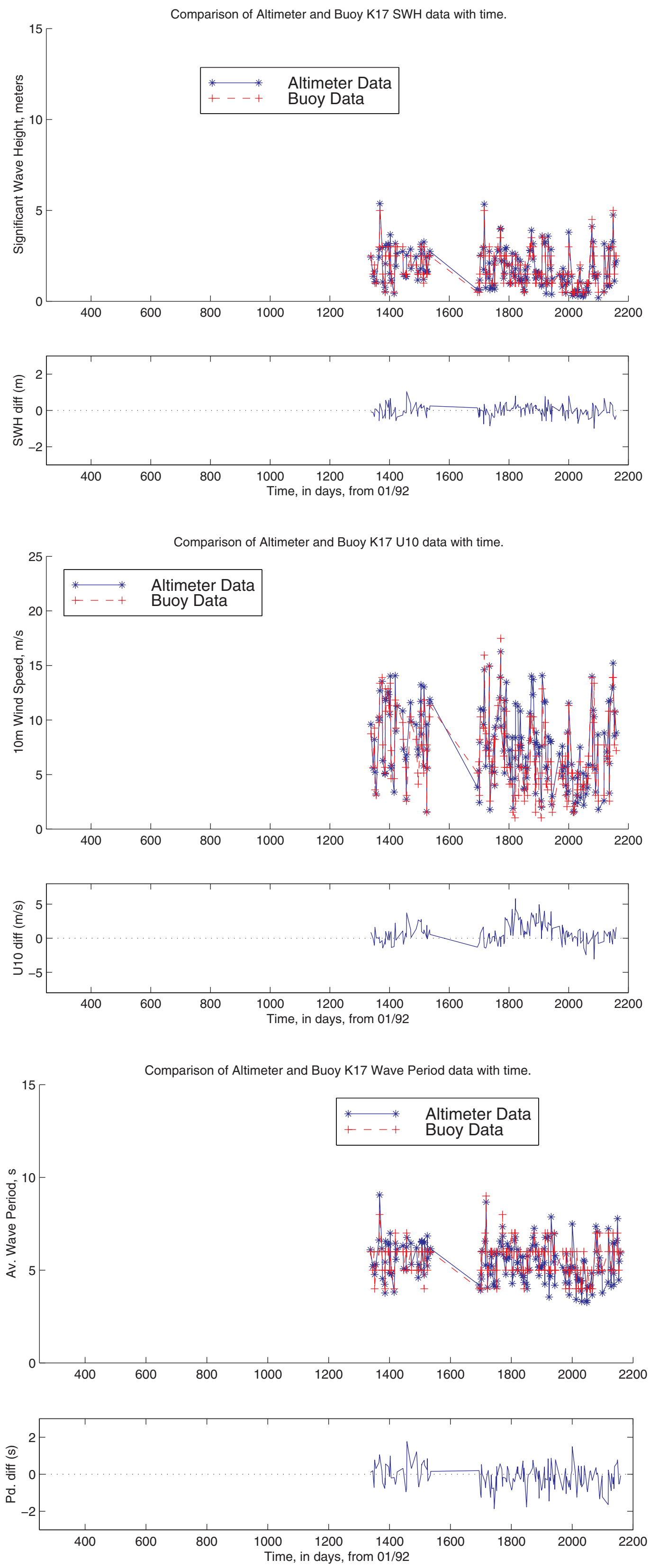

Figure 7 - Time series of altimeter and buoy data at UKMO site K17 (55.3∞N 2.3∞E)

4.7 Buoy K17 (62026)

Figure 7 presents the time series of K17 buoy data

Although there are apparently two periods of continuous K17 data (29/08/95 - 15/03/96, and 21/08/96 - 31/12/97), they have been treated together in our analyses. Principal component regressions have been carried out for this period and results for wave height, wind speed and wave period are given together in Table 16.

Parameter	*N*	*r.r.m.s.*	*Gradient*	*Intercept*
Sig. Wave Height	175	0.3168	1.0930	-0.1760
Wind Speed	175	1.4318	1.0138	0.7010
Wave Period	174	0.5654	1.2184	-1.3464

Table 16. Results of Principal Components Regression Between Altimeter and Buoy Significant Wave Heights for buoy ***K17****.*

Discussion

Figure 7 and Table 16 indicate all K17 data to be of acceptable quality. Like K16, buoy K17 is located in the Northern North Sea, and is sheltered from long North Atlantic Swell. Therefore, it also has recorded a smaller range of wind/wave values than the North Atlantic buoys (1-5 m for *Hs* , 1-16 ms^{-1} for *U10*, and 4-9 s for *Tz*).

4.8 Summary

Serious deficiencies in early data (up to late 1993, mid 1994) from buoys K1, K2, K3 and K4 have been identified, such that it is recommended that these early data should not be used in any climate studies. Buoy wave data for the following periods should be regarded as unreliable: K1 - before 14/04/94; K2 - before 18/08/94; K3 - before 23/09/94; K4 - 31/10/93. Buoy wind speed data are not affected in the same way, although the co-location analysis for early data from buoy K4 showed significantly higher variability than other wind speed data, suggesting that these data too are unreliable.

Although there is evidence of variable levels of accuracy in the more recent data (1994 onwards), the view has been taken that the indicated accuracies for all data after the times indicated above are acceptable for most purposes. The criteria used for this assessment were limits on r.r.m.s. values of 0.7 m for *Hs*, 2.0 ms-1 for *U1*0, and 1.2 s for *Tz*. These criteria for wave measurements are looser than equivalent requirements set on altimeter/buoy comparisons using other buoy data sets (e.g. for US NDBC data, where criteria of 0.5 m for *Hs*, and 1.0 s *Tz* were used). They have been relaxed because it is believed that the quantisation in UKMO buoy values of *Hs* (0.5 m) and *Tz* (1.0s) may reduce the accuracy which these measurements can be expected to achieve.

5 Accuracy of UKMO Open Ocean Buoy Data

A principal components regression analysis was carried out on the co-located altimeter/buoy data for the periods identified in the previous section as providing valid buoy measurements. The analysis was carried out separately for each buoy, and then for the combined data set. Results are presented in Tables 17, 18, and 19 for *Hs*, *U10* and *Tz* respectively. The 95% confidence intervals for the estimates of gradient and intercept have also been calculated. Figures 8, 9, and 10 give the three scatter plots for the whole altimeter-buoy co-located data set, together with the fitted regression lines.

Buoy	*N*	*r.r.m.s. (m)*	*Gradient*	*95% C.I.*	*Intercept*	*95% C.I.*
K1	218	0.5762	1.0690	0.0430	-0.2194	0.1587
K2	130	0.4376	1.0087	0.0499	-0.0023	0.1726
K3	103	0.5456	1.1218	0.0737	-0.5511	0.2841
K4	296	0.5900	1.0107	0.0416	0.0004	0.1528
K5	155	0.4166	1.0826	0.0457	-0.1285	0.1594
K16	62	0.3519	1.0815	0.0901	-0.2081	0.2027
K17	175	0.3168	1.0930	0.05340	-0.1760	0.1091
All buoys	1139	0.5065	1.0496	0.0186	-0.1333	0.0629

Table 17. Results of Principal Components Regression Between Altimeter and Buoy Significant Wave Heights for UKMO buoy data.

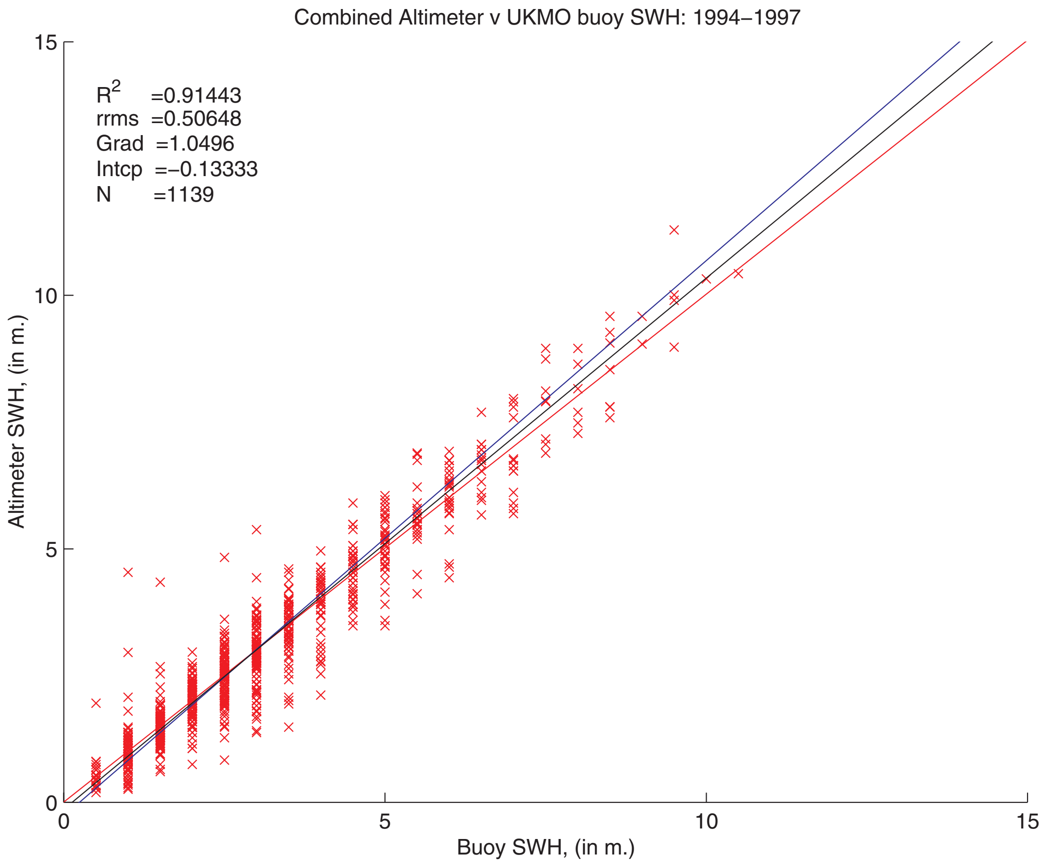

Figure 8. Scatter plot of co-located altimeter and buoy significant wave height data. The two linear regression lines, plus the principal component, are indicated.

5.1 Significant Wave Height

From Table 17 it can be seen that co-located data from buoys K16 and K17 exhibit least scatter (r.r.m.s. < 0.4 m), whilst data at K1, K3, and K4 give r.r.m.s variabilities of more than 0.5 m. The gradient of the principal component line is greater than 1 for data from each of the buoys, significantly at the 95% level in 4 cases. However, there are no significant differences between these values for the individual buoys. A similar picture is found in the intercept estimates, whilst the individual buoy values are not significantly different from those of any of the other buoys, they all (bar one) give negative intercepts, significantly different from zero in 4 cases.

When the buoy data are combined and analysed together the regression gave a gradient of 1.0496 (standard error of 0.0186) and intercept of -0.1333 (standard error of 0.0629). This indicates that on average the UKMO co-locations give results that are significantly different (at the 95% confidence level) from those from the NDBC co-located data, exhibiting a slightly lower sensitivity to changes in altimeter measured wave height. (If they agreed perfectly the gradient and intercept would not be significantly different from 1.0 and 0.0 respectively). However, *Cotton [1998]* carried out a regional analysis of the NDBC buoy data, and found that the retrieved gradients and intercepts for co-located data separated into different regions varied between 0.96 and 1.07, and -0.09 and 0.06. The UKMO results can be seen to lie within this range of variability, and in this sense the results are consistent with those from the US buoy data.

The r.r.m.s in the US data was 0.3248m, less than that found for the UK buoys (0.5065m). The possibility that this higher accuracy may be due to the higher precision in the NDBC *Hs* data (they are reported to the nearest cm) was tested by reducing the precision in the NDBC wave height data to 0.5m (i.e. the same as that in the UKMO data) and repeating the regression. The r.r.m.s. in this comparison then dropped slightly to 0.3541 m. Thus whilst the lower precision in the UKMO data probably does result in a lower accuracy in the altimeter/buoy comparison, it does not explain all of the difference between the comparisons of altimeter data with UKMO and NDBC buoy measurements.

5.2 Wind Speed

From Table 18 it can be seen that co-located wind speed data from buoys K1 and K2 exhibit least scatter (r.r.m.s. <= 1.3 ms^{-1}), whilst data at K16 gives the highest r.r.m.s variability of over 1.6 ms^{-1}. The gradient of the principal component line is greater than 1 for data from each of the buoys, though significantly so only in one case. Again, there is no significant difference between these values from each of the individual buoys. Three of the intercept estimates have intercepts significantly greater than zero, and the remaining four are also greater than zero. Again none of the individual buoy values are significantly different from any of the others.

When all the buoy data are analysed together the regression gave a gradient of 1.0382 (standard error of 0.0241) and intercept of 0.4928 (standard error of 0.2012). This again indicates that the analysis results from the UKMO co-locations are significantly from those of the NDBC co-located data. In an analysis of co-located altimeter and NDBC data, *Cotton [1998]* identified regional and environmental dependencies of retrieval accuracies and regression parameters. Gradients varied between 0.86 in sheltered, limited fetch regions (e.g. Mexican Gulf), to 1.04 in the more open ocean off the North East Coast of the USA. Intercepts varied from -0.24 to 0.34, and r.r.m.s.

variances between 1.12 to 1.53 ms^{-1}. Thus the UKMO wind speed results appear to lie within the range of values retrieved from an analysis of US buoy data.

The r.r.m.s in UK wind speed data (1.3784 ms^{-1}) is comparable with that found in the US data (1.347 ms^{-1} for the whole data set), in this case the quantisation (effectively at 0.5 ms^{-1} over a range of 20 ms^{-1}) in the UK data does not have such a significant effect on the retrieval accuracy. A test on the effect of reduced precision on the NDBC data (i.e. at 0.5144 ms^{-1}, or 1 knot), similar to that reported above in section 5.1, showed only a slight reduction in accuracy to 1.3559 ms^{-1}.

Buoy	*N*	*r.r.m.s. (m)*	*Gradient*	*95% C.I.*	*Intercept*	*95% C.I.*
K1	218	1.2496	1.0663	0.0511	0.1121	0.4193
K2	130	1.3063	1.0668	0.0698	0.4415	0.5614
K3	103	1.3246	1.0524	0.0783	0.2292	0.7014
K4	296	1.4055	1.0224	0.0483	0.5750	0.4226
K5	155	1.3481	1.0304	0.0786	0.6656	0.5377
K16	62	1.6432	1.0500	0.1377	0.7613	1.0230
K17	175	1.4318	1.0138	0.0656	0.7010	0.5040
All buoys	1139	1.3784	1.0382	0.0241	0.4928	0.2012

Table 18. Results of Principal Components Regression Between Altimeter and Buoy Wind Speeds for UKMO buoy data.

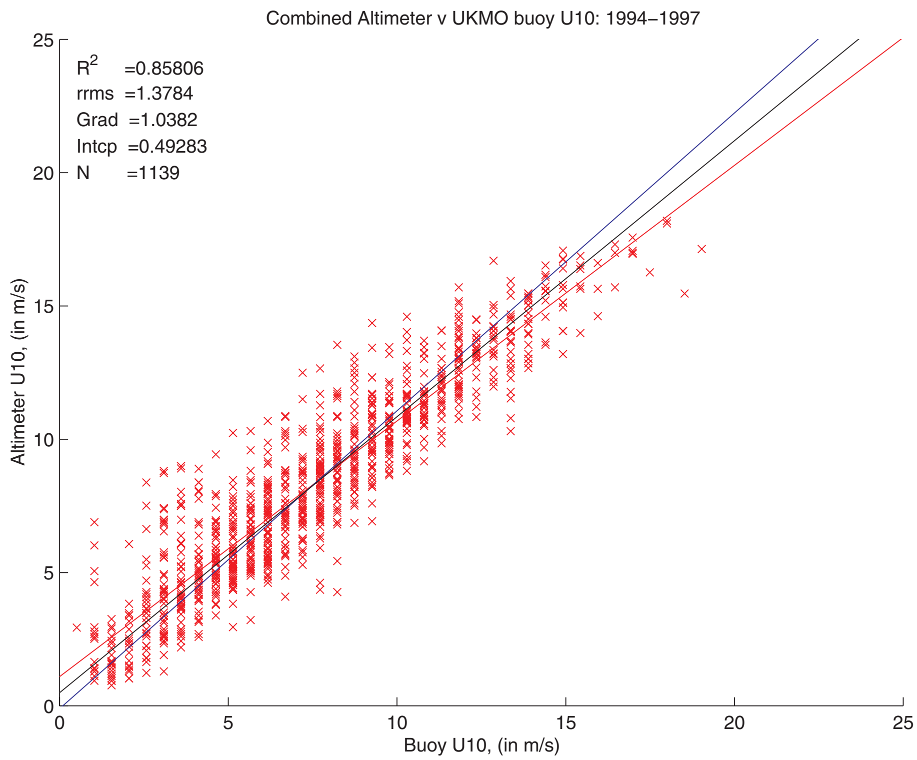

Figure 9. Scatter plot of co-located altimeter and buoy wind speed data. The two linear regression lines, plus the principal component, are indicated.

Buoy	N	r.r.m.s. (m)	Gradient	95% C.I.	Intercept	95% C.I.
K1	212	0.7434	1.2586	0.0767	-2.1223	0.5765
K2	126	0.6307	1.0659	0.0793	-0.8614	0.6099
K3	100	0.7837	1.2047	0.1262	-1.7753	0.9719
K4	288	0.8325	1.2790	0.0944	-2.4408	0.7266
K5	151	0.8575	1.3388	0.1442	-2.6832	1.0830
K16	62	0.6114	1.2295	0.1791	-1.5469	1.0669
K17	174	0.5654	1.2184	0.1166	-1.3464	0.6568
All buoys	1115	0.7904	1.1690	0.0355	-1.4496	0.2579

Table 19. Results of Principal Components Regression Between Altimeter and Buoy Wave Period for UKMO buoy data.

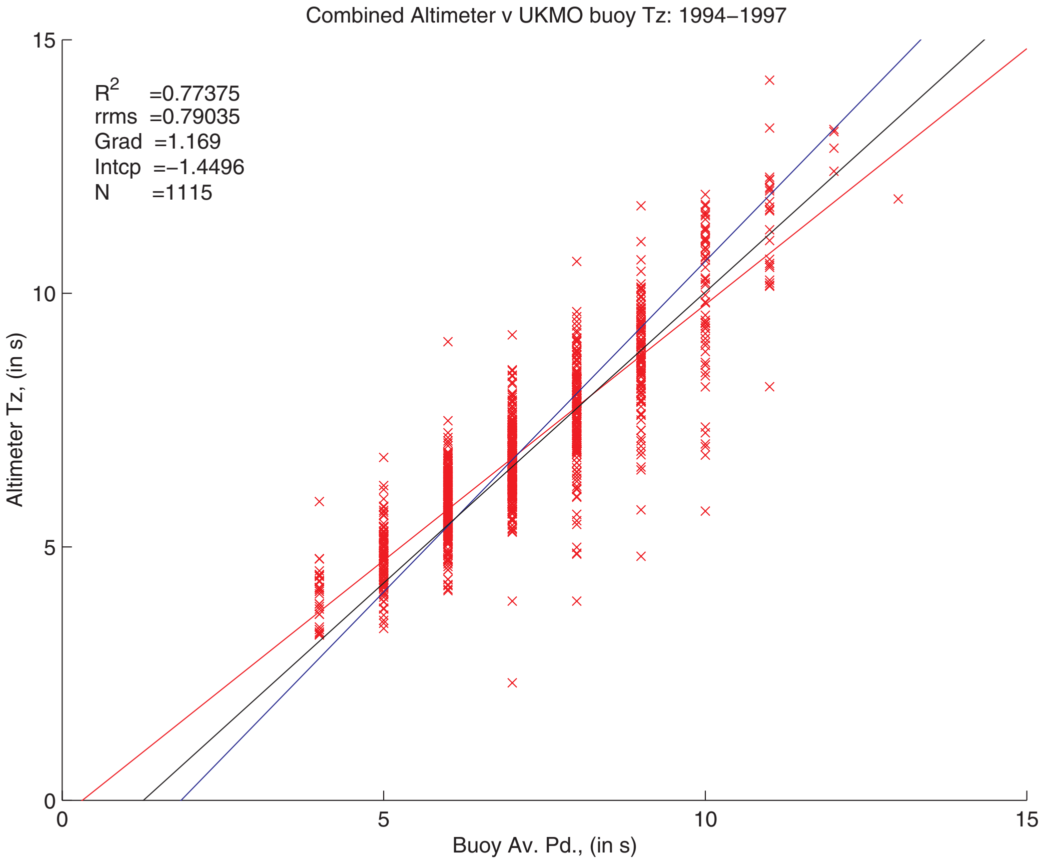

Figure 10. Scatter plot of co-located altimeter and buoy wave period data. The two linear regression lines, plus the principal component, are indicated.

5.3 Wave Period

From Table 19 the co-located wave period data from buoys K16 and K17 can be seen to exhibit least scatter (r.r.m.s. <= 0.6 s), whilst data at K4 and K5 show the most scatter (r.r.m.s. > 0.8 s). As was found for wave height and wind speed, the gradient of the principal component line is greater than 1.0 for data from each of the buoys, and significantly so in all but one case (K2). The intercepts of regressions from all 7 buoys are all (significantly) negative.

The gradient estimated for K2 data is significantly less than that for K1 and K5 data. The intercept for K2 data is also significantly different (closer to zero) from that for K1, K4 and K5. The K2 buoy is located out in the open North-Eastern Atlantic Ocean, in the South Western approaches to the English Channel and so should not experience any particularly unusual set of wave conditions. It seem unlikely therefore that this anomalous set of wave period regression parameters is due to environmental effects, but is more probably due to the presence of outliers in the data, or to instrumental (buoy) problems

When the combined altimeter/buoy wave period data were analysed, a gradient of 1.1690 (standard error of 0.0355) and intercept of -1.4496 (standard error of 0.2579) were calculated. This again indicates that the UKMO co-located wave period data are significantly from those from the combined NDBC co-located data. However, from *Cotton [1998]* the regional analysis of co-located altimeter and NDBC wave period data again showed a range of regression parameters (in gradient 0.75 to 1.21, in intercept -1.30 to 1.65) which spanned the values from the UKMO buoys.

The r.r.m.s. variances from the NDBC wave period data ranged between 0.53 to 0.76 s, with an overall average value of 0.6848 s, indicating a slightly higher accuracy than the UKMO data (r.r.m.s = 0.7904 s). A test on the effect of reduced precision on the NDBC data (1 s in the UKMO data, limiting the number of measurable values to 10 in the range 4-13 seconds), gave a reduction in accuracy of the NDBC comparisons to 0.7373 s. This suggests that the altimeter/ UKMO buoy wave period comparisons could provide accuracies close to those from the US NDBC measurements, if higher precision data were available.

The wave period algorithm is still under development, and the current formulation retains some dependency on wave age and wind speed that needs to be minimised. Nonetheless, these results indicate that with the *Davies [1997*] algorithm the altimeter can currently retrieve wave periods to an accuracy of better than 1 second, possibly to 0.75 s

6. Conclusions

Comparisons of altimeter wind/wave data with data from seven UKMO open ocean buoys have identified periods in data from the UKMO buoys K1-K4 where measurements are unreliable, and should not be used in any climate studies. There is a second period in some data sets where the wave data exhibit a higher variability than more recent data. However, without recourse to buoy maintenance logs, it is not certain whether these different levels of measured variability are simply a reflection of changes in natural variability, or are consequences of changes to the buoy instrumentation. It is recommended that the following data are excluded from any climate analyses: K1- before April 1994, K2-before August 1994, K3- before September 1994, K4- before October 1993. All other data from these buoys, and all data from buoys K5, K16 and K17 appear to be satisfactory.

Once the early problems were dealt with, the general performance of the UKMO buoys appears good, and bearing in mind the observations related to the precision in the UKMO data, on a par with that of the buoys in the US NDBC data set. It is concluded therefore that UKMO Open Ocean buoy data could make a valuable contribution to a global altimeter/buoy wave calibration programme, particularly if buoy data could be made available at a higher precision.

Acknowledgements

We are grateful to the United Kingdom Meteorological Office for making available the buoy data used in this study. We are also grateful to the agencies responsible for provision of the satellite altimeter data : NOAA, ESA, and AVISO

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