JERICHO TECHNICAL REPORT. 14

Analysis of Co-Located JERICHO Coastal *In Situ* and Altimeter Data

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Introduction

This report presents an analysis of co-located altimeter and in situ data, for coastal and inshore locations. The aim of the work presented here was to provide an assessment of the quality of the in situ data, and, where possible, an assessment of the accuracy of the altimeter data in the different locations.

Data Sources

The in-situ data analysed in this report cover 12 locations, and have been acquired from 3 sources, the UK Meteorological Office, Rijkwaterstaat (The Netherlands), and Seadata (FugroGEOS), see Table 1 and FIgure 1. The altimeter data have been extracted from the ERS-1 OPR data set which cover the period 1991-96. The ERS-1 significant wave height and wind speed data have been calibrated according to the calibrations in Cotton [1998] (*Hs*=1.1091 x ERS-1 *Hs* + 0.3355, *U10* = 0.8964 x ERS-1 *U10* + 0.8453), and the wave periods have been calculated from the SOC algorithm; [Davies et al., 1998]). The ERS-1 wave period estimates have not been subject to any further calibration. Altimeter data were extracted from the along track record which was closest to the location of the in situ instrumentation (within at least 50 km). These extracted data were then merged with the buoy data collected on the nearest hour (hence a maximum time seperation of 30 minutes). For the purposes of extraction it was assumed that in situ measurements were made on the hour.

	Name	Lat (°N)	Lon (°E)	Instrument (waves)	owner/source	Period	No of Colocs
1	Seven Stones	50.1	-6.1	LV SBWR	UKMO	95-97	6
2	St Gowan	51.6	-4.7	UKMO OO buoy	UKMO	92-97	18
3	Channel LV	49.9	-2.9	LV SBWR	UKMO	89-97	3
4	Greenwich	50.2	0.0	LV SBWR	UKMO	93-97	11
5	Sandettie	51.1	1.5	LV SBWR	UKMO	93-97	15
6	Leman	53.1	2.1	laser	Seadata	72-93	23
7	Ijmuiden	52.5	4.1	WAVEC buoy	Rijkwaterstaat	81-96	134
8	K13	53.2	3.2	WAVEC buoy	Rijkwaterstaat	81-96	62
9	Efofisk	56.5	3.2	laser/radar/waverider	public/Seadata	80-96	103
10	Forties	57.8	0.9	laser/w'rider/w'staff	BP/Seadata	74-95	145
11	Frigg	59.9	2.1	various,combined	Philips/Seadata	92-98	41
12	N North Sea	61.2	1.1	various,combined	Shell/Seadata	76-97	28

Table 1: Locations of Coastal In Situ Measurements for JERICHO

Analysis

The analysis is presented in four separate sections below: SW Coast (Engalnd and Wales) and English Channel (UKMO data); Southern North Sea (Rijkwaterstaat data); Southern and Central North Sea (Seadata) Northern North Sea (Seadata). In each case principal component linear regressions have been carried out on the co-located altimeter and *in situ* data, deriving the parameters (with standard errors) which define the linear relationship between the data sets, and residual root mean square measures of variability.

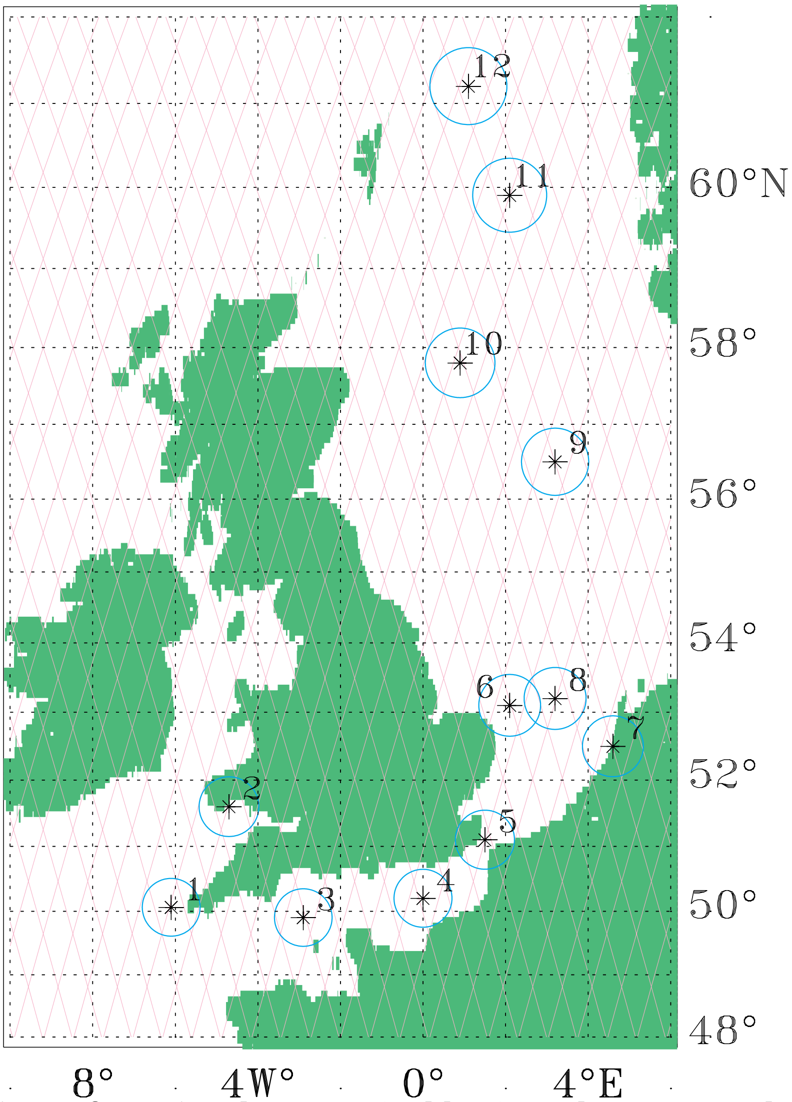

Figure 1: Locations of In Situ data sets (Table 1), and ERS-1 35 day repeat tracks.

The Channel and SW Coastline - UKMO Data (Light Vessel and Buoy)

Figure 2 presents the comparisons of the co-located ERS-1 and UKMO Light Vessel data, and Figure 3 the co-located UKMO buoy and ERS-1 data. Table 2 presents the results of the Principal Component regressions.

Data set	Gradient	std error.	Intercept	std error	R.R.M.S
UKMO LV Hs (m)	0.8056	0.0669	0.4280	0.1340	0.3551
UKMO Buoy Hs (m)	1.2075	0.1229	-0.3543	0.2423	0.4384
UKMO Buoy U10 (m/s)	0.7032	0.0473	0.8935	0.4331	1.3029
UKMO LV U10 (m/s)	0.7295	0.0341	1.0375	0.6426	1.2589
UKMO LV Tz (s)	0.4936	0.1463	1.1176	0.1255	0.8420
UKMO Buoy Tz (s)	0.6596	0.0884	2.1937	0.5184	0.7498

Table 2 - Results of prinicipal components regression on co-located UKMO and ERS-1 altimeter data (R.R.M.S - residual root mean square). The 95% confidence intervals on the estimates for gradient and intercept may be calculated by adding (subtracting) two times the standard error.

Discussion

The aim of this analysis was to establish the reliability and accuracy of altimeter data off south-west Wales and England, and in the English Channel, with particular regard to its suitability for generating boundary conditions for shallow water modelling. Note that the exact situation with regarding to instrumentation of the Light Vessels is uncertain. Some vessels are equipped with Ship Borne Wave Recorders (SBWRs) whilst others (Greenwich) have waverider buoy instrumentation mounted midships.

Unfortunately the analysis is strongly affected by a combination of the rather coarse discretisation of the UKMO *in situ* data (0.5m in *Hs*, 0.5 knots in *U10*, and 0.5 s in *Tz*: a consequence of the report format in which the data were provided to the JERICHO programme) the small range in measured wind and wave values, and the low number of co-locations at each site. This results in a large scatter in the data and inconclusive findings.We will not discuss the results of the regressions for the individual sites but will rather consider the light vessel and buoy data sets as two combined data sets.

Significant Wave Height

The range of co-located wave heights for the light vessel and buoy data is relatively small, 0-5 m. From Figure 2, and Table 2, it appears that with respect to the light vessel measurements, ERS-1 overestimates low wave heights, but underestimates high waves. However, the opposite appears true from the comparisons with the UKMO buoy data, Figure 3 and Table 2, although the estimates for gradient and intercept are not significantly different at the 95% level from the 45° line of perfect match (1.0 and 0.0 respectively). Although there is large scatter in the data, the residual root mean square measure of variability is still less than 0.45m.

Wind Speed

The comparisons of altimeter wind speed with the light vessel and buoy wind data suggest that the altimeter is underestimating wind speeds by about 30% (indicated by gradients in Table 2 of 0.70 and 0.73). The apparent underestimation is consistent with earlier work by Cotton [1998], who found that altimeters underestimated wind speed in the more enclosed seas in the Gulf of Mexico (by 14%), and when the waves were not fully developed. The intercepts of the principal components regression (Table 2) are both greater than 0.0, though that of the light vessel data was not significantly different from zero. The range of measured wind speed data was good, covering 0-20 ms^{-1}. The rrms variability is relatively low, at ~ 1.3 ms^{-1}.

Wave Period

Finally we consider the estimates of wave period. In an earlier study, Cotton [1998] compared ERS-1 Tz estimates with data from 24 US buoys, and derived the following linear relationship.

$$Tz\ (\text{ERS-1}) = 1.4039 + 0.8477 * Tz\ (\text{buoy}) \quad (1)$$

The co-located UKMO and ERS-1 data are illustrated in the lower panels of Figures 2 and 3. Again the discretisation of the UKMO data is clear, and affects the results of the regressions.The retreived wave period data cover the range 4-10 s. The standard errors on the principal component regression estimates for gradient and intercept of the colocated ERS-1 and UKMO wave period data (Table 2) are large and reflect the scatter in the data. The comparisons with ship data indicate a linear relationship between the altimeter and *in situ* estimates of wave period which is significantly different, at the 95% level, from equation (1), with a slightly lower gradient and intercept. However, the buoy altimeter relationship is not significantly different from equation (1). The rrms variability is high, at 0.75-0.84 s, but still indicates an accuracy of better than 1second.

Summary

The general conclusion must be that the UKMO coastal *in situ* wave data sets are not of a suitable quality to allow us to make a complete assessment of altimeter measurements made in the English Channel and off the South-west English and Welsh coasts. However, we can say that the altimeter is seen to underestimate wind speeds with respect to the UKMO in situ data, by up to 30%. We have also seen that there is no equivalent large systematic bias/error in the significant wave height or wave period data, with the co-located data showing rrms variabilities of < 0.45m and < 0.85s respectively.

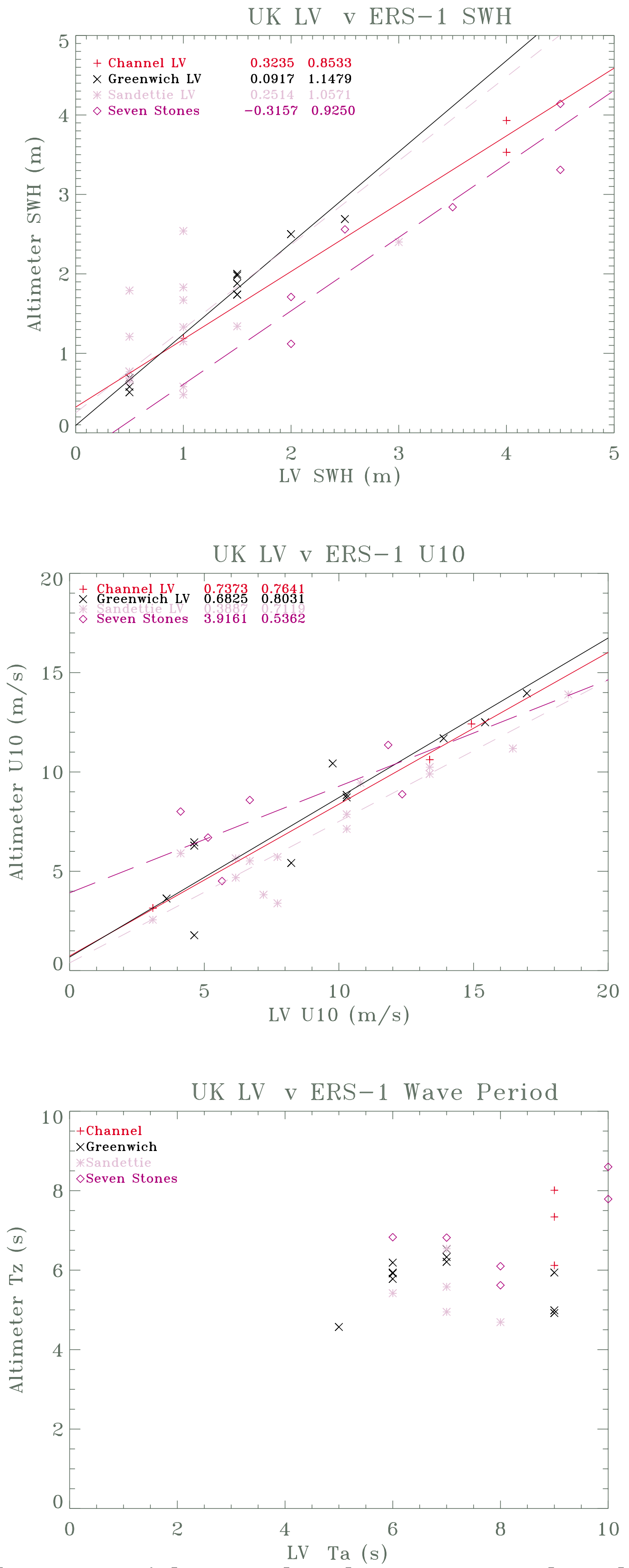

Figure 2: Co-located UKMO Light Vessel and ERS-1 OPR data, lines and parameters from principal component regressions. No regressions were carried out on the wave period data.

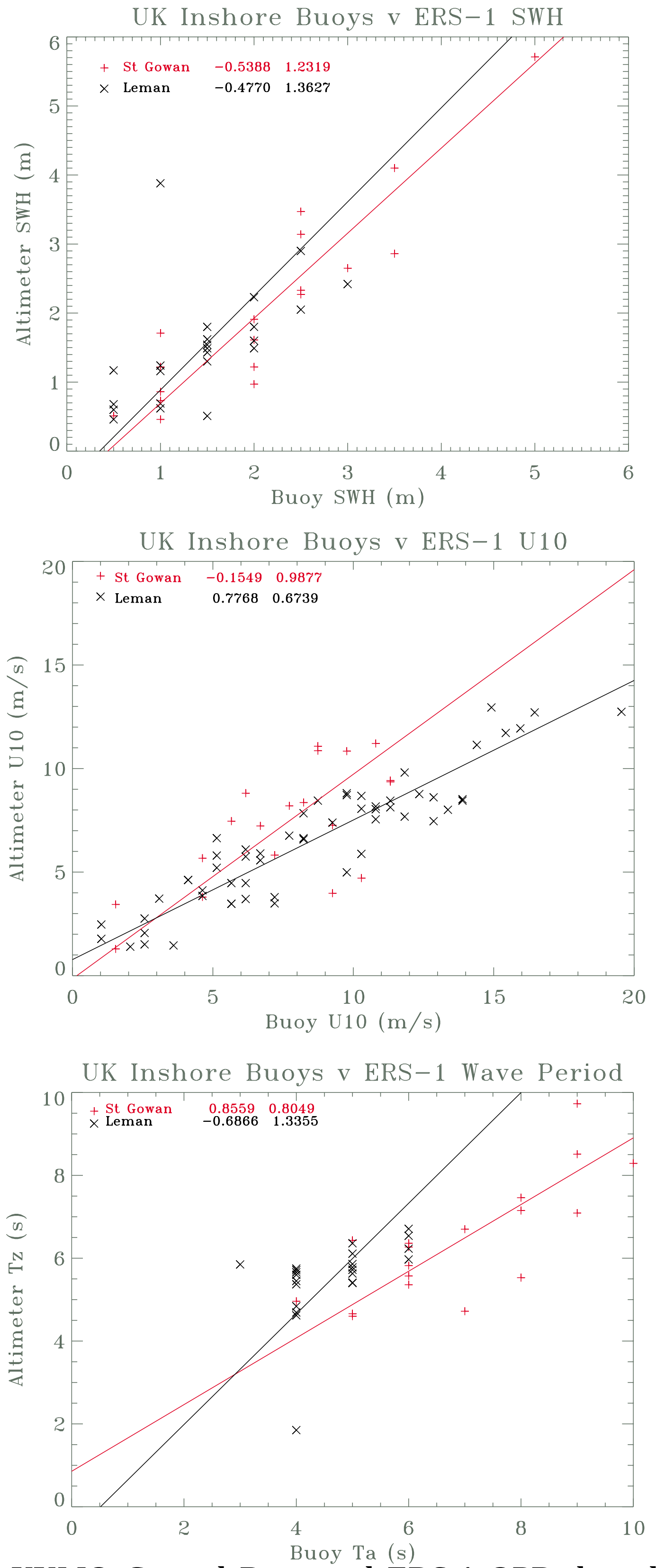

Figure 3: Co-located UKMO Coastal Buoy and ERS-1 OPR data, lines and parameters from principal component regressions.

The Southern North Sea - Rijkwaterstaat Data

Figure 4 presents the comparisons of the co-located ERS-1 and Rijkwaterstaat data in the Southern North Sea at K13 and Ijmuiden. The *in situ* wave data were measured by WAVEC buoys, the Ijmuiden wind speed data are anemometer measurements taken at a site approximately 40km east of the buoy site (the wind speed data were extracted for records within 50km of the buoy site - hence these comparisons may show larger variability). Unfortunately K13 wind data were not available during the time ERS-1 was operating. . These data were available at 0.1 ms^{-1}, 0.1m and 0.1 s resolution, and appear to have been more reliably quality controlled than the UKMO data. Table 3 presents the results of the Principal Component regressions.

Data set	Gradient	std error.	Intercept	std error	R.R.M.S
Ijmuiden Hs (m)	0.9274	0.0316	0.0539	0.0547	0.2372
K13 Hs (m)	0.9159	0.0728	0.1166	0.0822	0.3629
Ijmuiden U10 (m/s)	0.7668	0.0439	0.9202	0.3957	1.2632
Ijmuiden Tz (s)	0.6868	0.0527	2.3634	0.2588	0.4672
K13 Tz (s)	0.7192	0.0728	2.1638	0.0340	0.3629

Table 3 - Results of prinicipal components regression on co-located Rijkwaterstaat and ERS-1 altimeter data (R.R.M.S - residual root mean square). The 95% confidence intervals on the estimates for gradient and intercept may be calculated by adding (subtracting) two times the standard error.

Discussion

Significant Wave Height

The range of co-located wave heights for the ERS-1 and Rijkwaterstaat data is similar to that in the UKMO data, 0-5 m. There is no significant difference between the regression results from Ijmuidena nd K13, although the former do suggest a very slight underestimate in ERS-1 wave heights. Neither intercept (Table 3 rows 1 and 2) is significantly different from zero. There is less scatter in these co-located data, than was seen in the previous section, resulting in lower values for the residual root mean squares of less than 0.4m.

Wind Speed

The initial comparisons of ERS-1 and in situ wind speeds indicated that there were a number of poorly correlated points, which were subsequently removed. The edited data are shown in Figure 4. The comparisons of altimeter and *in situ* wind speed data then indicated that the altimeter underestimates in this region by about 23% (indicated by a gradients in Table 3 of 0.77). Again the co-located wind speed data, covered the range 0-20 ms^{-1}, the comparisons indicated an rrms variability of 1.26 ms^{-1}.

Wave Period

The co-located wave period data are illustrated in the bottom panel of Figure 4. The retreived wave period data cover the realteively small range of 3-8 s, and a ower cut-off in altimeter wave period of 4 s is evident. Whilst the rrms variability is quite low (< 0.5 s), both the K13 and IJmuiden data sets gave intercepts of over 2s, both significantly greater than that indicated by equation 1. The gradient for the co-located Ijmuiden data was also significantly lower than that in equation 1.

Summary

In general the Rijkwaterstaat data appear to be of higher quality than the UKMO data, allowing us in turn to make more substantial comments on the quality of the ERS- data. There is a suggestion of a slight underestimate (by the ERS-1 altimeter) in signficant wave height (7-8%), whilst the accuracy indicated by the rrms variability is better than 0.4 m. The altimeter is again seen to underestimate wind speeds with respect to the *in situ* data, by about 23% in this region. Finally there is an indication that the altimeter wave period may be biased high by about 1 second, when compared to studies using US buoys. However, the range of co-located data is small, and the indicated gradients are lower than those from the US buoy study. These wave period data gave rrms variabilities of less than 0.5 s.

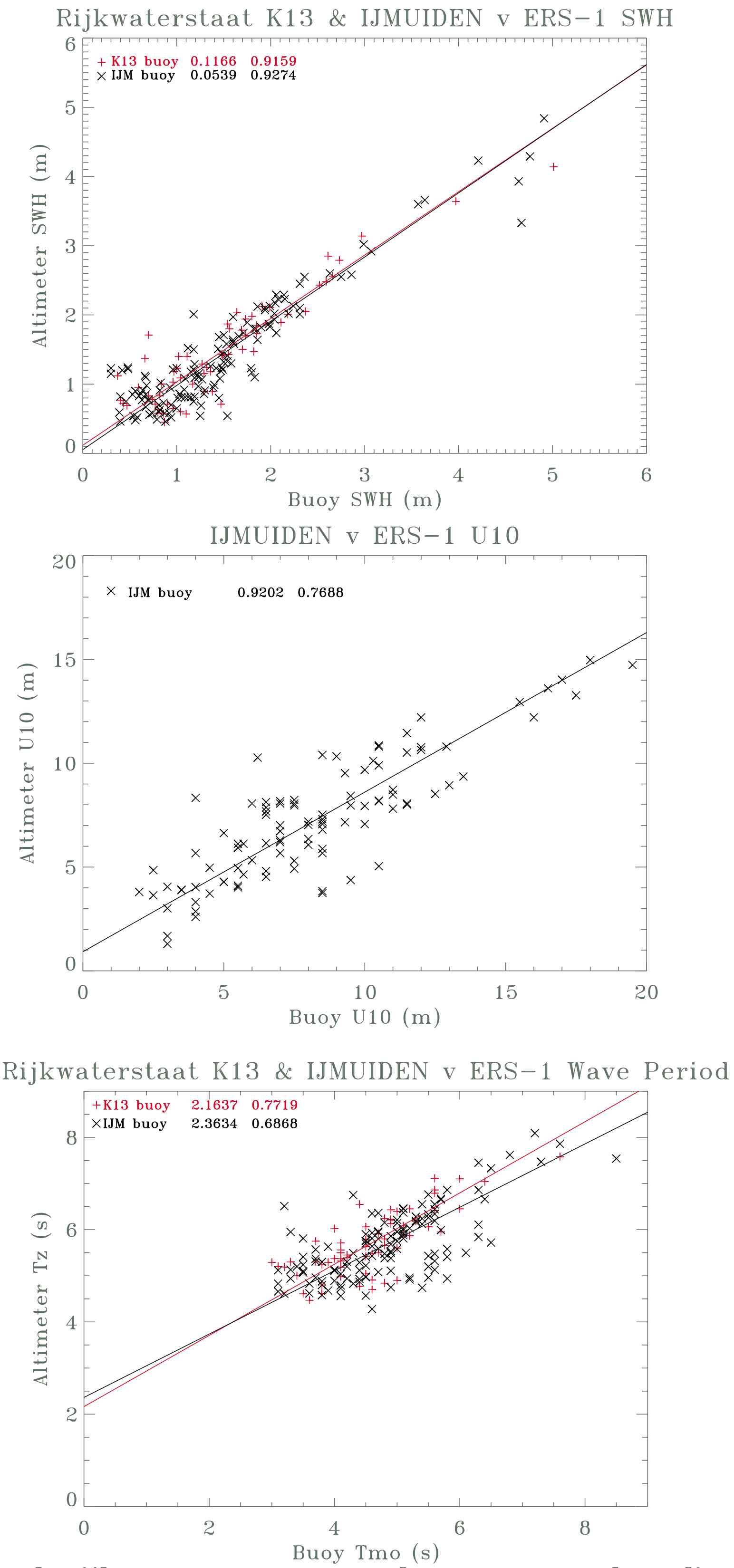

Figure 4: Co-located Rijkwaterstaat Buoy and ERS-1 OPR data, lines and parameters from principal component regressions.

Southern and Central North Sea - Seadata Data

Figure 5 presents the comparisons of the co-located ERS-1 and in situ data at Leman and Ekofisk. Leman wave data were measured by laser, Ekofisk data by laser, radar, and waverider. Seadata archive these data on behalf of their clients in the oil and gas industry, and consequently have spent some time and effort in quality controlling and reconciling the data from different sources. Hence the data are of good quality, and we can see good agreement between the data from different sources at Ekofisk. These data were available at 0.1 ms^{-1}, 0.1m and 0.1 s resolution. Table 4 presents the results of the Principal Component regressions (Ekofisk data were analysed as a single set.), Figure 5 illustrates these data.

Data set	Gradient	std error.	Intercept	std error	R.R.M.S
Leman Hs (m)	1.2821	0.2835	-0.2525	0.3103	0.2281
Ekofisk Hs (m)	0.9903	0.0329	0.0637	0.0869	0.2760
Leman U10 (m/s)	0.6767	0.0697	0.6679	0.5497	0.8153
Ekofisk U10 (m/s)	0.7197	0.0460	1.9576	0.4570	1.2250
Leman Tz (s)	1.2110	0.4008	0.5620	1.6746	0.5515
Ekofisk Tz (s)	0.9222	0.0499	1.3454	0.2864	0.3669

Table 4 - Results of prinicipal components regression on co-located Seadata (southern and central North Sea) and ERS-1 altimeter data.

Discussion

Significant Wave Height

The range of co-located wave heights at Ekofisk was 0-7 m, whereas the Leman data exhibited a much smaller range (0-2m). Both data sets show relatively small scatter (r.r.m.s < 0.3 m). The regressions on the Ekofisk data suggest a linear relationship between altimeter and buoy data very close to the line of perfect fit (gradient=1.0, intercept=0.0), but the Leman data showed a gradient greater than 1.0, and an interceptless than zero.However, the errors on the gradient and intercept on the Leman data were sufficiently large (because of the limited range in the data) that these estimates were not signficantly different from the line of perfect fit.

Wind Speed

The comparisons of wind speed data at both Leman and Ekofisk indicate a systematic underestimate of wind speed in the altimeter data - by 32% at Leman and 28% at Ekofisk. Both sites also showed a positive intercept signficantly greater than zero. Note that the estimates for intercept and gradient for Seadata Leman wind speed data agree well with the UKMO Leman values (Figure 3). The range of *in situ* wind speed data was (again) 0-20 ms^{-1}, these comparisons indicated low rrms variabilities of 1.23 ms^{-1} at Leman and, remarkably, less than 1 ms^{-1} at Ekofisk (0.82 ms^{-1}).

Wave Period

The co-located wave period data are illustrated in the bottom panel of Figure 5. The retreived wave period data cover the range of 3-8 s, and the altimeter lower cut-off at 4 s is again evident. The rrms variability is again quite low (less than or close to 0.5 s). Figure 5 suggests some differences between the different Ekofisk data sets, which on further investigation may yield some interesting insights into the different sensitivities of the different instruments. Unfortunately, we did not have the time to investigate this effect further within the scope of the JERICHO programme. As for the wave height comparisons, the range in Leman wave period data is low, (2-5 s) yielding such large errors in the estimates for gradient and intercept, such that these values (1.2 and 0.5) are not significantly different at the 95% confidence level from the values indicated by equation 1 (0.85 and 1.4). The Ekofisk data give good agreement with equation 1, with smaller standard errors on the estimates.

Summary

The archived data provided by Seadata appear to be of high quality, which should have allowed us to make a confident assessment of the quality of ERS-1 altimeter data. However, the small range of wave parameters in the Leman wave data once again restrict us. Nonetheless, the altimeter wave (height and period) measurements are seen to be within the 95% confidence interval of perfect agreemeent, and with low rrms variability (less than 0.3m for wave height and close to 0.5s for period. There is further confirmation of the altimeter tendency to underestimate wind speeds, by about about 30% in this region..

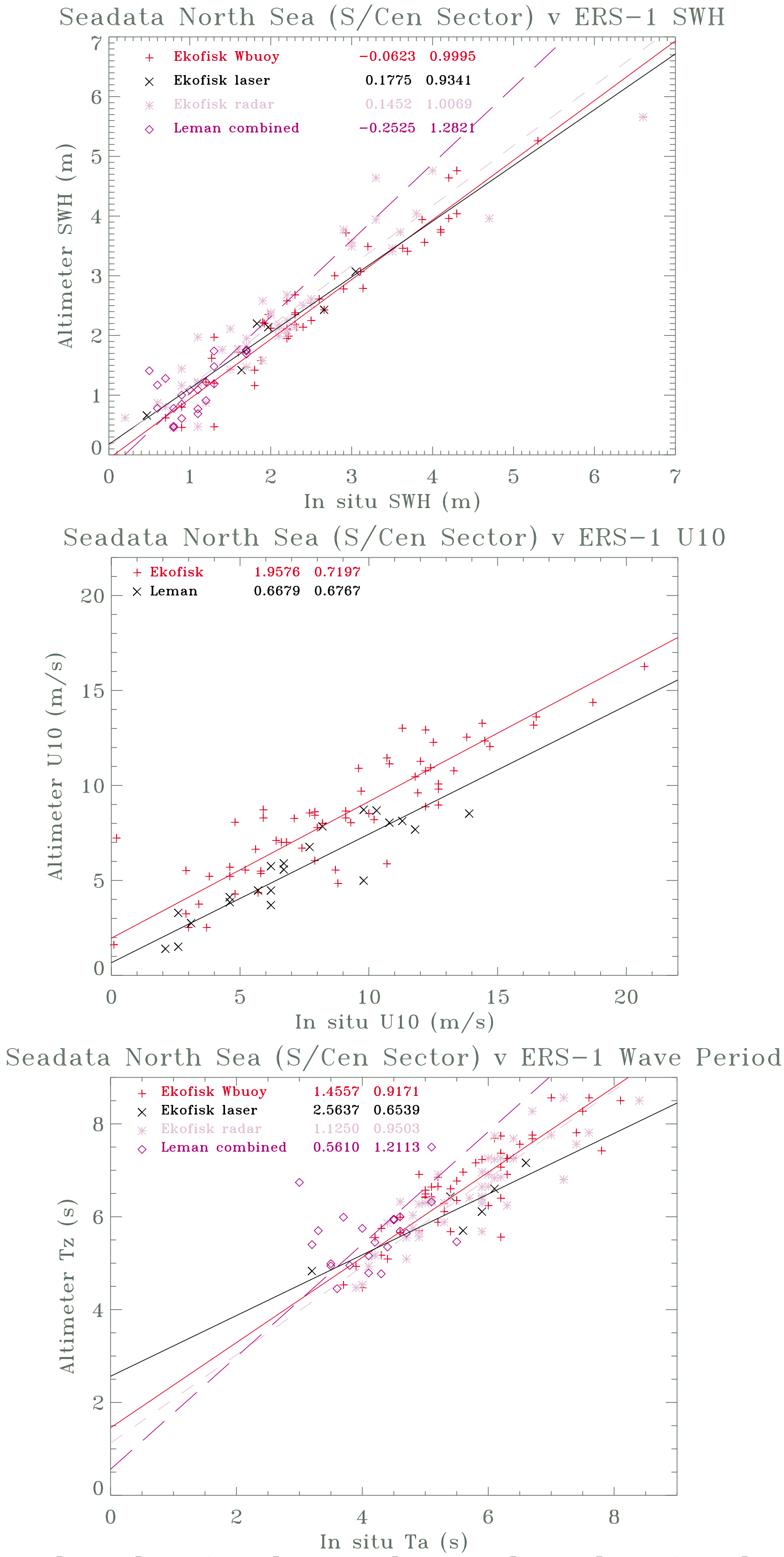

Figure 5: Co-located Seadata (Southern and Central North Sea) and ERS-1 OPR data, lines and parameters from principal component regressions.

Northern North Sea - Seadata Data

Figure 6 presents the comparisons of the co-located ERS-1 and Seadata data at Forties, Frigg and the Shell combined "NNS" data set . Table 5 presents the results of a principle components regression on the data sets at the 3 sites

Data set	Gradient	std error.	Intercept	std error	R.R.M.S
Forties Hs (m)	0.9441	0.0235	0.0292	0.0591	0.2558
Frigg Hs (m)	1.1096	0.0653	-0.2446	0.1722	0.3246
NNS Hs	1.0467	0.0533	-0.0884	0.1451	0.2277
Forties U10 (m/s)	0.7855	0.0518	1.0583	0.4781	1.4816
Frigg U10 (m/s)	0.8893	0.0460	0.7018	0.4059	0.8017
NNS U10 (m/s)	0.9788	0.0912	-0.2955	0.7821	0.9842
Forties Tz (s)	0.7928	0.0354	1.9788	0.2017	0.4092
Frigg Tz (s)	1.0529	0.0922	1.7126	0.4456	0.4122
NNS Tz (s)	0.9594	0.0941	0.8819	0.5944	0.3807

Table 5 - Results of prinicipal components regression on co-located Seadata (Northern North Sea) and ERS-1 altimeter data (R.R.M.S - residual root mean square). The 95% confidence intervals on the estimates for gradient and intercept may be calculated by adding (subtracting) two times the standard error.

Discussion

Significant Wave Height

As would be expected the most northerly data sets, with more exposure to swell waves and larger fetches, contain wave height data with the largest range, 0 - 10 m. None of the estimates of the intercepts from the prinicipal components regression are singificantly different from zero, and the gradients for Frigg and NNS data are within the 95% confidence interval of 1.0. However, the gradient for the Forties data indicates a slight, but significant, underestimate in the altimeter wave height data. All three data sets show relatively low scatter (r.r.m.s less than 0.33 m).

Wind Speed

The comparisons of altimeter and *in situ* wind speed data suggest that the altimeter underestimates less the further North we go , and the more exposure the data locations are subject to. Thus the NNS data (61° N) show no significant underestimate, the Frigg comparisons (latitude 60° N) - suggest a 11% underestimate in the altimeter data, and the Forties data (58 ° N) indicate a 21% underestimate. Only the Forties intercept is significantly different from zero (1 ms^{-1}). The range of *in situ* wind speed data was) 0-25 ms^{-1}, the Frigg and NNS comparisons indicated very low rrms variabilities of less than 1.00 ms^{-1}, that at Forties was larger, at 1.48 ms^{-1}.

Wave Period

The retreived wave period data cover the range of 3-9 s. The rrms variability is lowest of all in this region (less than or close to 0.4 s). The Forties data give a gradient within the confidence limits of that indicated in equation 1 (0.85), but an intercept which is signficantly larger (1.98 cf. 1.40). The Frigg data give a gradient which is (just) outside the confidence limits of that indicated in equation 1 (1.05 cf. 0.85), and an intercept which is within the confidence range. Finally both the gradient and the intercept of the NNS data are in agreement with equation 1.

Summary

The archived Northern North sea data provided by Seadata are again of high quality, and show good internal consistency. We again see that the altimeter wave (height and period) measurements are largely within the 95% confidence interval of perfect agreemeent, and that they demonstrate low rrms variability (less than 0.3m for wave height and close to 0.4s for period). The altimeter tendency to underestimate wind speed is seen to decrease as exposure to larger fetches and non-local swell increases, such that this tendency is not evident in the NNS data set.

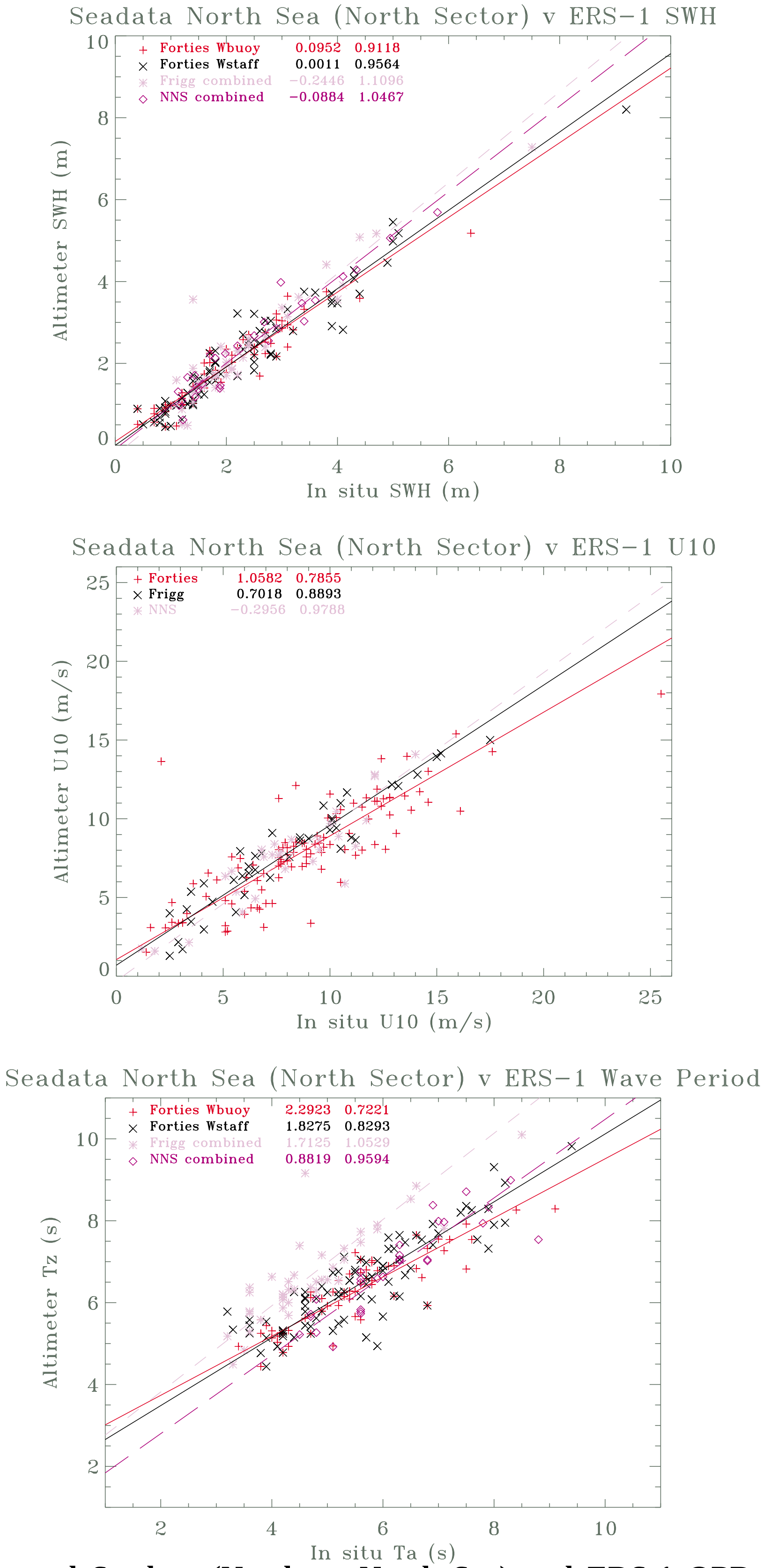

Figure 6: Co-located Seadata (Northern North Sea) and ERS-1 OPR data, lines and parameters from principal component regressions.

Summary

In Situ Data

It is difficult to unravel the separate effects that *in situ* data quality, and restricted data ranges have on the standard errors and r.r.m.s. variability seen in the results of the principle component regressions. All instruments have difficulty in providing accurate measurements at low wind speeds, wave heights and wave periods. However, analysis of this problem is not helped when data are available at a coarse resolution, so we would advise future researchers to attempt to access data at the highest resolution consistent with instrument accuracy.

The regressions of co-located data in the Southernmost areas, which have the lowest range in measured values, exhibit significantly greater errors than those in the more exposed Northerly locations. There is also evidence, from this and other studies, that the Rijkwaterstaat and Seadata in situ data are more carefully quality controlled than the UKMO data set we were able to get access to. Combining this with the effect of lower resolution in the UKMO data meant that we have more confidence in our assessments which are based on analysis of the fortmer two data sets. Without a more detailed analysis of higher resolution UKMO data, it is not possible to say wether it might be possible to generate a comparably reliable archive from the UKMO source data.

Significant Wave Height

The co-located wave height data were seen to exhibit less scatter as the exposure and range in recorded data increased. Thus we see r.r.m.s. variabilities of 0.5m in the Channel, 0.4 in the Southern North Sea, and 0.3 m in the Northern North Sea. Any differences from perfect agreement between altimeter data and in-situ data were small, and there was no consistent pattern of over or underestimation.

The conclusion is that the calibrated altimeter wave height data are reliable, providing accuracies of better than 0.5m across the range of recorded data, with lower accuracy at low wave heights. We have found no evidence (within this or other studies) of any dependence upon wave age.

Wind Speed

It is clear that the altimeter consistently and significantly underestimates in regions which have less exposure to the open ocean. Thus the NNS data (61° N) show no significant underestimate, whereas at Frigg (60° N) ERS-1 underestimates by 11%, at Forties data (58 ° N) by 21%, at Ekofisk (56.5° N) by 28%, and at Leman and in the English Channel (50° - 53 ° N) ERS-1 estimates by 30-32%. At Ijmuiden, at a similar latitude to Leman, but 200 km to the East,so exposed to waves with a longer fetch, ERS-1underestimates by (only!) 23%. At St. Gowan (51°N), exposed to the Atlantic, ERS-1 is not seen to underestimate at all. The r.r.m.s of the co-located data was at all times less than 1.5 ms^{-1}, and in some cases (Leman, Frigg, NNS) lass than 1.0 ms^{-1}.

SOC are developing an altimeter wind speed algorithm which is a function of radar backscatter and significant wave height, and which may help to reduce this tendency to underestimate in more enclosed waters. Until a reliable correction for this exposure effect is developed, we suggest for the purposes of JERICHO that the altimeter wind speed data for Lyme Bay and Holderness are increased by 30%. The St. Gowan data (as we have seen) need not be adjusted. The correction of Holderness data, in particular, may lead to overestimates in wind speed when the sea conditions are coming from a North-Easterly direction. However, without a longer study, we are not able to suggest a more reliable adjustment.

Wave Period

As for the wave height data, the co-located wave period data were seen to exhibit less scatter as the exposure and range in recorded data increased. Thus we see r.r.m.s. variabilities of 0.75s -0.8s in the Channel, and 0.4s -0.5s in the North Sea. Any differences from the relationship indicated by equation 1 were generally small, and there was no consistent pattern of over or underestimation.

The conclusion is that the calibrated altimeter wave period data, if corrected according to equation 1, provide estimates with accuracies of better than 1.0 s across the range of recorded data, with lower accuracy at low wave heights. In more open ocean areas, the accuracy improves to better than 0.5 s