A validation of ERS-2 Fast Delivery Significant Wave Height

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CONTENTS

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Abstract

A validation of the Fast-Delivery Significant Wave Height (SWH) product from the altimeter on board the ERS-2 satellite has been performed. Observations over a time period of more than 4.5 years have been compared to *in situ* buoy observations. With a total of 2823 co-locations, the *rms* difference between the two datasets was found to be 0.317 m with the altimeter generally over-estimating low SWH and under-estimating high SWH. Overall, there is a slight negative bias in the altimeter data.

Adjusting the altimeter data according to a two-branched linear model reduces the *rms* difference between buoy and altimeter data to approximately 0.2 m with negligible overall bias. If this bias-correction is applied to the ERS-2 FD observations before including them in a global data assimilation system, it can produce a positive impact on forecast wave fields, particularly in swell-dominated areas such as the central Pacific region and around the Australian coast.

1. Introduction

The Bureau of Meteorology currently runs an operational wave forecasting system which includes the assimilation of ERS-2 Fast-Delivery (FD) Significant Wave Height (SWH) (Greenslade 2001). There is currently no bias correction applied to the ERS-2 data even though FD SWH data from other satellite altimeters are known to contain systematic errors (Cotton and Carter 1994). When the Bureau's system was first developed, a validation of the ERS-2 data produced results that were different from those of other studies (see later for details) so no method to adjust the altimeter data was implemented at that time. However, this initial study was performed when there was only a relatively short time series of data available, and only a limited number of buoys in the Australian region were used. Now that ERS-2 has been in orbit for several years, the opportunity exists to repeat this study with a longer time series of ERS-2 data and also with a larger *in situ* validation data set.

It could be argued that a validation study of ERS-2 data is of limited use, because by the time that there is a long enough time series of data available to perform a validation of the data with any confidence, the satellite is nearing the end of its life. However, improving the quality of the ERS-2 FD dataset has many other purposes, e.g., as validation for hindcast studies, wave climate work etc.

Some previous validation studies are described here in Section 2. In Section 3, the data, method and the results are presented. Section 4 describes a sensitivity study in which the impact of the adjusted ERS-2 SWH data on the current assimilation system is evaluated. A summary is presented in Section 5.

2. Previous work

For many earth observing satellite missions (e.g., GEOSAT, TOPEX/POSEIDON, ERS-1) there is a reasonable amount of literature available on the quality of the altimeter SWH observations. Although ERS-2 has been in orbit since April 1995 there is very little in the general literature on the validation of ERS-2 SWH, and in particular, the Fast-Delivery format, even though it is this version of the data that is used operationally in data assimilation schemes. The stated accuracy in SWH from the ERS-2 altimeter is 0.5 m or 10 per cent of SWH, whichever is greater.

A few studies on ERS-2 SWH have been published (see later for details) as workshop proceedings by the European Space Agency (ESA). The general idea of these studies is to obtain a set of co-located altimeter and buoy observations and find an appropriate adjustment for the altimeter data which results in the best possible match with *in situ* buoy data. If the buoy observations are considered to be error-free, then the correct procedure would be to regress the altimeter data onto the buoy data, i.e., perform a regression with the altimeter data as the independent variable and the buoy data as the dependent variable. However, the buoy data cannot be assumed to be error-free (see below) and an appropriate alternative method is to perform two regressions: one with the buoy data as the independent variable and one with the altimeter data as the independent variable and then take the average of the two regression lines as the final result. This method assumes equal error variance in the altimeter and buoy SWH measurements.

In general, the buoy observational errors are small (< 2 per cent of SWH). The observational error includes both instrument error and error of representativeness, which is a measure of the error caused by the misrepresentation of the signal at all scales smaller than the sampling interval. An additional source of error arises from the fact that the buoy observation is a temporal average at a point, while the altimeter gives a spatial average over a short period of time. The error arising from these different sampling methods has been estimated at 8 per cent of the mean observed SWH (Monaldo 1988). Further errors could arise from the separation distance (in space and time) between the co-located data.

Challenor and Cotton (1997) performed a validation of ERS-2 FD data against a set of 24 US National Data Buoy Center (NDBC) buoys in the Northern Pacific and Atlantic Oceans. Co-location criteria were limited to altimeter overpasses occuring within 100 km and 30 minutes of the buoy observations. With 262 co-locations during 1995, it was found that the altimeter underestimated the SWH overall and there were serious deficiences at low wave heights. The average of two linear regressions provided the following results:

$$SWH_{adj} = 1.22\ SWH_{FD} - 0.366 \qquad \ldots 1$$

Noting that the distribution of SWH is closer to log-normal than Gaussian, the fitting procedure was repeated using log (SWH) instead of SWH. In addition the data were analysed with the SWH limited to various minimum thresholds. This resulted in recommended adjustments of:

$$\log(SWH_{adj}) = 2.44 \log(SWH_{FD}) - 0.44 \quad \text{for } SWH_{FD} < 1.5$$
$$SWH_{adj} = SWH_{FD} \quad \text{for } SWH_{FD} > 1.5 \qquad \ldots 2$$

In a study of 1194 co-locations of buoy and altimeter SWH over a 1-year period, Janssen et al. (1997) found an rms error of 0.39 m and a bias (ERS-2 - buoy) of -0.25 m. This study was restricted to co-locations where buoy SWH > 1.5 m. The average of two linear regressions was found to be:

$$SWH_{adj} = 1.11\ SWH_{FD} - 0.035 \qquad \ldots 3$$

It was noted that when swell is dominant, e.g., around Hawaii, the agreement between altimeter and buoy observations improved. Janssen (2000) therefore considered the issue of the 'peakiness' of ocean waves on the retrieval of altimeter waveheights. It was shown that by adjusting the ERS-2 FD SWH according to the Phillips parameter, α_p, then better agreement could be found between altimeter and buoy SWH. α_p is obtained from modelled wave spectra by parametrising the spectrum as:

$$F(k) = \frac{1}{2}\alpha_p k^{-3}$$

where k is wavenumber. This is the procedure currently followed at ECMWF to apply corrections to the ERS-2 FD data. The overall impact of this correction is that the altimeter SWH is generally increased by approximately 3 per cent.

At Meteo-France, the ERS-2 FD data is adjusted according to (Lefevre, personal communication):

$$SWH_{adj} = 1.09\ SWH_{FD} - 0.12 \qquad \ldots 4$$

Greenslade (2001) used 15 months of ERS-2 FD data and compared this to SWH from buoys situated around the coast of Australia. Co-locations were limited to altimeter overpasses occurring within 0.75^{o} of the buoy location. With a limited number of buoys, there were only 83 co-locations in this study. The *rms* difference between the two datsets was found to be 0.38 m and overall, the altimeter was found to overpredict SWH by 0.21 m. This bias is of opposite sign to that of other studies discussed here. This can be explained by the fact that the Australian region buoys used were mostly quite close to the coast. This means that the altimeter overpasses were generally seaward of the buoy location resulting in SWH values which were generally higher than the buoy SWH.

Tolman *et al.* (2002) considered 12 months of ERS-2 data (March 1997 to February 1998) and compared 10-second along-track averages with wave observations from the NDBC buoys. This provided 1725 colocations. The correction derived from these co-locations was:

$$SWH_{adj} = 1.09\ SWH_{FD} + 0.03 \qquad \ldots 5$$

for $SWH_{FD} \geq 2$ m with a quadratic correction applied for low wave heights.

3. Validation of ERS-2 Fast-Delivery SWH

In this work, global ERS-2 FD data over a time period from 11 March 1997 to 31 October 2001 were used. Figure 1 shows the number of individual altimeter observations for each 24-hour period during the 4-5 years considered here. The SWH data used for validation were *in situ* buoy data from the NDBC and from the Bureau's archives. Details of each buoy are listed in Table 1 and their locations are marked on Fig. 2.

For each buoy location, ERS-2 data were averaged over a region $\pm\ 0.5^{o}$ around the buoy site. (i.e., a 1^{o} box). If any part of the 1^{o} box was covered by land, then wave data from that buoy was not used. This eliminated most of the Australian buoys which had been used in Greenslade (2001) from the data set. Each altimeter overpass takes less than 1 minute to traverse the 1^{o} box. For each overpass, observations greater than $\pm$ 2 standard deviations away from the mean were rejected, and the mean recalculated. This was repeated until all observations were within 2 standard deviations of the mean. Overpasses

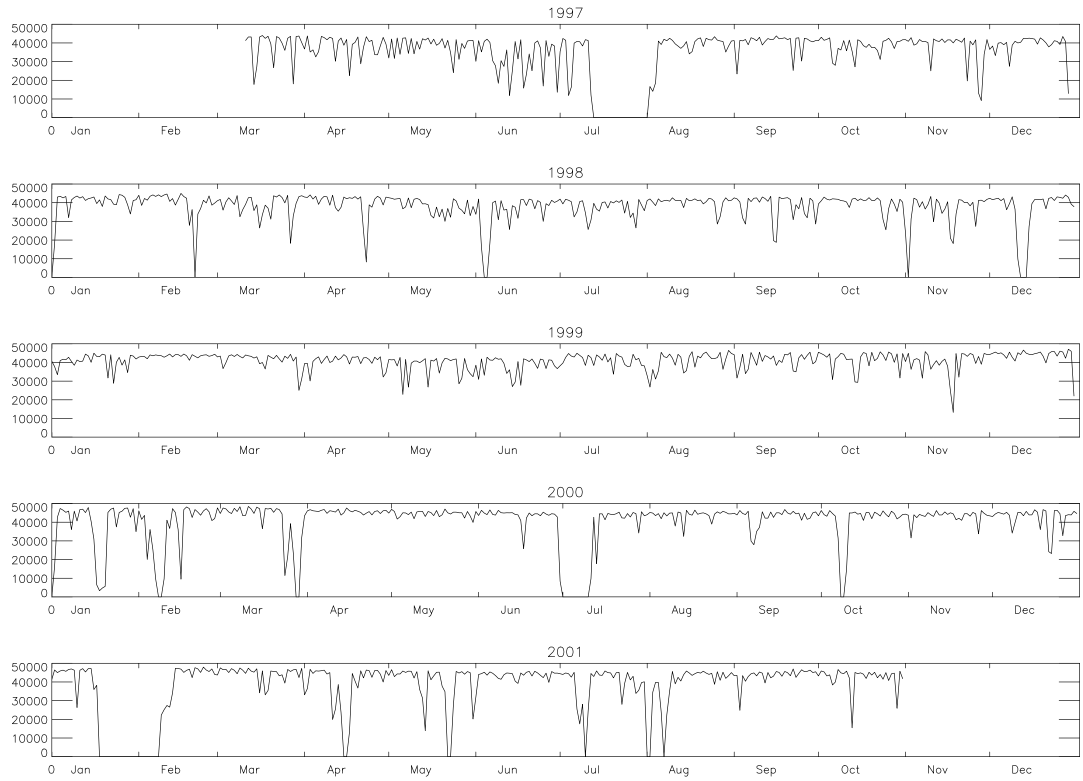

Fig. 1. Number of individual ERS-2 FD observations in each 24-hour time period from 11 March 1997 until 31 October 2001.

were only included in the co-located data set if, after this process, there were at least 6 SWH observations contributing to the average within the box. Most overpasses consisted of 15-18 individual altimeter observations.

The buoy data were then linearly interpolated to the altimeter overpass times for comparison, with the additional criterion that there be at least one buoy observation within 1 hour before and 1 hour after the time of the altimeter overpass. This eliminated further buoys in the Australian region for which observations are available only every 3 hours. The resulting dataset included a total of 2823 co-locations. These co-located datapoints are shown in Fig. 3.

Table 1. **Details of buoys used in this work. A ‘C’ in the final column signifies that data from that buoy is included in the co-located dataset (Section 3.). A ‘V’ signifies that it was used in the model verification (Section) and ‘B’ that it was used in both.**

Region	WMO Code	Location	Owner	Lat.	Lon.	Dates	Use
North-West Atlantic	41001	Hatteras	NDBC	34.7 N	72.6 W	3/97 - 7/00	C
	"	"	"	34.8 N	72.8 W	9/00 - 10/01	B
	41002	S. Hatteras	NDBC	32.3 N	75.2 W	3/97 - 3/01	C
	"	"	"	32.2 N	75.4 W	6/01 - 10/01	C
	41004	Edisto	NDBC	32.5 N	79.1 W	3/97 - 10/01	C
	41010	Canaveral E.	NDBC	28.9 N	78.5 W	3/97 - 10/01	B
	44004	Hotel	NDBC	38.5 N	70.7 W	3/97 - 6/99	C
	"	"	"	38.4 N	70.6 W	6/99 - 10/01	B
	44005	Gulf of Maine	NDBC	42.9 N	68.9 W	3/97 - 3/01	C
	"	"	"	38.4 N	70.6 W	3/01 - 10/01	B
	44008	Nantucket	NDBC	40.5 N	69.4 W	3/97 - 9/01	B
	44011	Georges Bank	NDBC	41.1 N	66.6 W	3/97 - 10/01	B
	44014	Virginia Beach	NDBC	36.6 N	74.8 W	3/97 - 10/01	B
Gulf Of Mexico	42001	Mid Gulf	NDBC	25.9 N	89.7 W	3/97 - 10/01	B
	42002	W. Gulf	NDBC	25.9 N	93.6 W	3/97 - 10/01	C
	42003	E. Gulf	NDBC	25.9 N	85.9 W	3/97 - 10/01	B
	42036	W. Tampa	NDBC	28.5 N	84.5 W	3/97 - 10/01	B
	42039	Pensacola	NDBC	28.8 N	86.0 W	3/97 - 10/01	B
	42041	N. Mid Gulf	NDBC	27.2 N	90.4 W	3/97 - 2/01	C
	42054	E. Gulf	NDBC	26.0 N	87.8 W	7/00 - 5/01	C
East Pacific	46001	Gulf of Alaska	NDBC	56.3 N	148.2 W	3/97 - 10/01	B
	46002	Oregon	NDBC	42.5 N	130.3 W	3/97 - 10/01	B
	46003	S. Aleutians	NDBC	51.9 N	155.9 W	3/97 - 7/99	C
	46005	Washington	NDBC	46.1 N	131.0 W	3/97 - 10/01	B
	46006	S.E. Papa	NDBC	40.9 N	137.5 W	3/97 - 10/01	B
	46035	Bering Sea	NDBC	56.9 N	177.8 W	3/97 - 10/01	C
	46047	Tanner Banks	NDBC	32.4 N	119.5 W	5/99 - 10/01	B
	46059	California	NDBC	38.0 N	130.0 W	3/97 - 10/01	B
	46066	S. Aleutians	NDBC	52.6 N	155.0 W	5/00 - 9/01	B
Central Pacific	51001	N.W. Hawaii	NDBC	23.4 N	162.3 W	3/97 - 10/01	B
	51002	S.W. Hawaii	NDBC	17.2 N	157.8 W	3/97 - 10/01	B
	51003	W. Hawaii	NDBC	19.2 N	160.8 W	3/97 - 10/01	B
	51004	S.E. Hawaii	NDBC	17.4 N	152.5 W	3/97 - 10/01	B
	51028	Christmas Is.	NDBC	0.0	153.9 W	10/97 - 10/01	B
S. Hemis-phere	55020	Eden	MHL	37.3 S	150.2 E	6/01	V
	55026	Strahan	BoM	42.1 S	145.0 E	6/01	V
	55039	Bass Strait	Esso	38.6 S	148.2 E	5/00 - 10/01	C
	56002	N. Rankin	Woodside	19.6 S	116.1 E	6/01	V
	AB	Agulhas Bank	MOSGAS/ CSIR	35.0 S	22.2 E	9/00 - 10/01	C

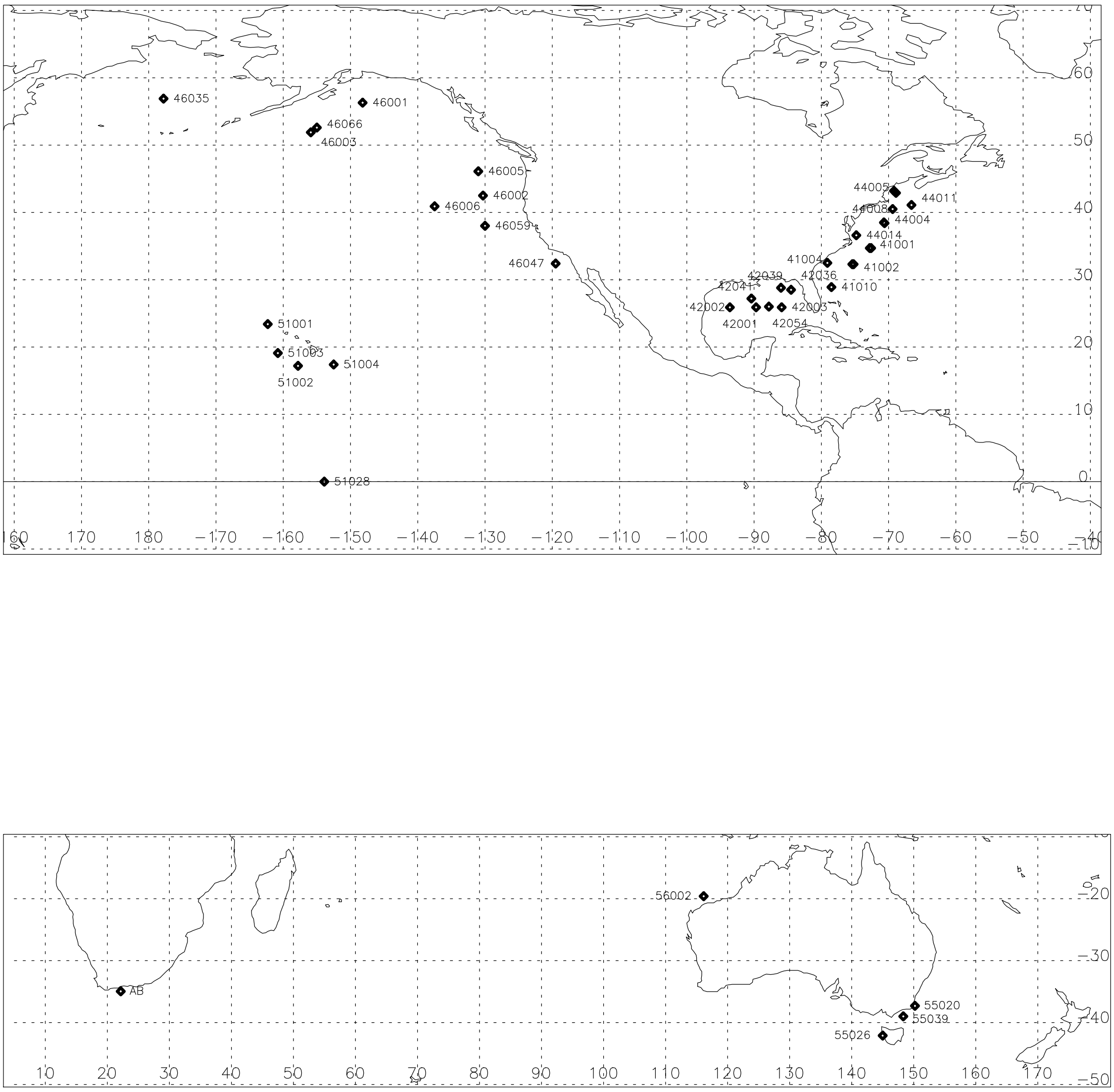

Fig. 2. Location of buoys used in this study.

There is clearly a non-linear relationship between ERS-2 FD SWH and buoy SWH, with the altimeter overestimating for low SWH (< 1 m) and underestimating for medium to high SWH (> 2 m). The first row in Table 2 shows validation statistics for this dataset. The bias, root-mean-square difference (*rms*), Scatter Index (SI) and linear correlation coefficient (R) are defined as:

$$\text{Bias} = \frac{1}{N}\sum_{i=1}^{N} E_i - B_i \qquad \ldots 6$$

$$rms = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(E_i - B_i\right)^2} \qquad \ldots 7$$

$$\text{SI} = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\left(E_i - \overline{E}\right) - \left(B_i - \overline{B}\right)\right)^2}}{\overline{B}} \qquad \ldots 8$$

$$\text{R} = \frac{\sum_{i=1}^{N}\left(E_i - \overline{E}\right)\left(B_i - \overline{B}\right)}{\sqrt{\sum_{i=1}^{N}\left(E_i - \overline{E}\right)^2\left(B_i - \overline{B}\right)^2}} \qquad \ldots 9$$

where E_i is the ERS-2 SWH, B_i is buoy SWH, N is the number of co-locations and an overbar represents the mean value.

Note from Table 2 that the overall bias is quite small. The overestimation for low SWH almost cancels out the underestimation at high SWH. The mean buoy SWH here is 1.95 m so bias represents only 2.5 per cent of the mean SWH. An *rms* error of 0.317 m is well within the stated accuracy of 0.5 m. These results are similar to those of other studies.

Various different functions were examined to find the best fit to these data. Firstly, a simple linear regression was applied, even though the data clearly show that a linear function is not appropriate. The technique used was to find the average of two linear regressions, as described previously. Figure 4(a) shows the co-located dataset (as in Fig.

3) along with the two regression lines. The final averaged regression line lies between these two lines and is given by:

$$
\begin{aligned}
SWH_{adj} &= 0.1 && \text{for } SWH_{FD} \le 0.4 \\
SWH_{adj} &= 1.245\, SWH_{FD} - 0.417 && \text{for } SWH_{FD} > 0.4
\end{aligned} \qquad \ldots 10
$$

Table 2. **Validation statistics for ERS-2 FD data and various adjustment algorithms.**

Data set	Bias (m)	SI	*rms* (m)	R
FD (no adjustments)	-0.048	0.160	0.317	0.979
Linear only	0.000	0.122	0.238	0.979
Quadratic	-0.015	0.114	0.222	0.982
2-branch linear (1.0)	-0.026	0.109	0.214	0.984
2-branch linear (1.5)	-0.005	0.104	0.203	0.985
2-branch linear (2.0)	-0.031	0.106	0.209	0.984

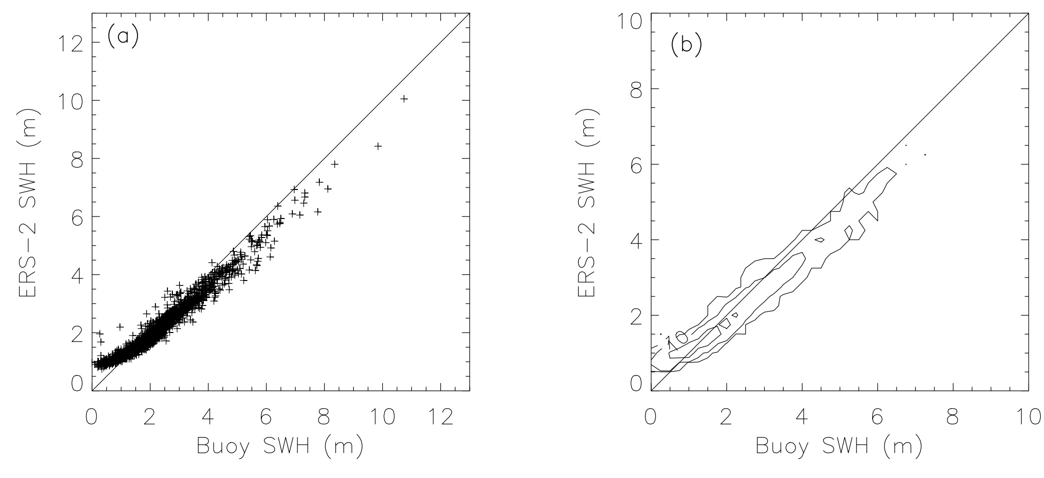

Fig. 3. (a) Co-located ERS-2 and buoy data. (b) The same data as in (a) with the number of co-locations in each 0.5 m bin contoured.

The first line in Eqn 10 is included in order to avoid situations in which the adjusted SWH may turn out to be negative. The minimum ERS-2 FD data in the co-located data set considered here is 0.75 m, and an inspection of one month of global ERS-2 data found a minimum SWH value of 0.6 m, so it is expected that this would not be a major issue.

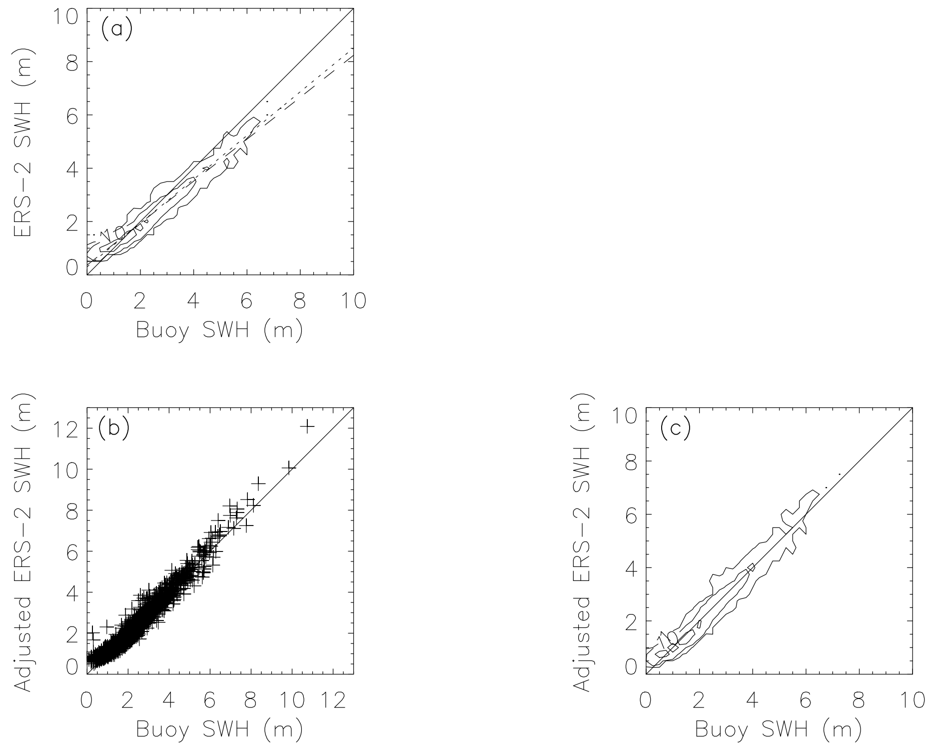

Fig. 4. (a) Co-located ERS-2 and buoy data. The two regression lines are shown (dashed and dotted lines). (b) and (c) Co-located data after a simple linear adjustment.

This bias correction is qualitatively similar to the results of most of the studies described in Section 2, i.e., the linear fit has a slope >1 and a negative intercept. Figures 4(b) and (c) show the altimeter data versus the buoy data after the above adjustment has been made to the ERS-2 data and validation statistics are shown in Table 2. It can be seen that this simple linear adjustment does provide an improvement, but Fig. 4 shows that it still results in overestimated values for low SWH.

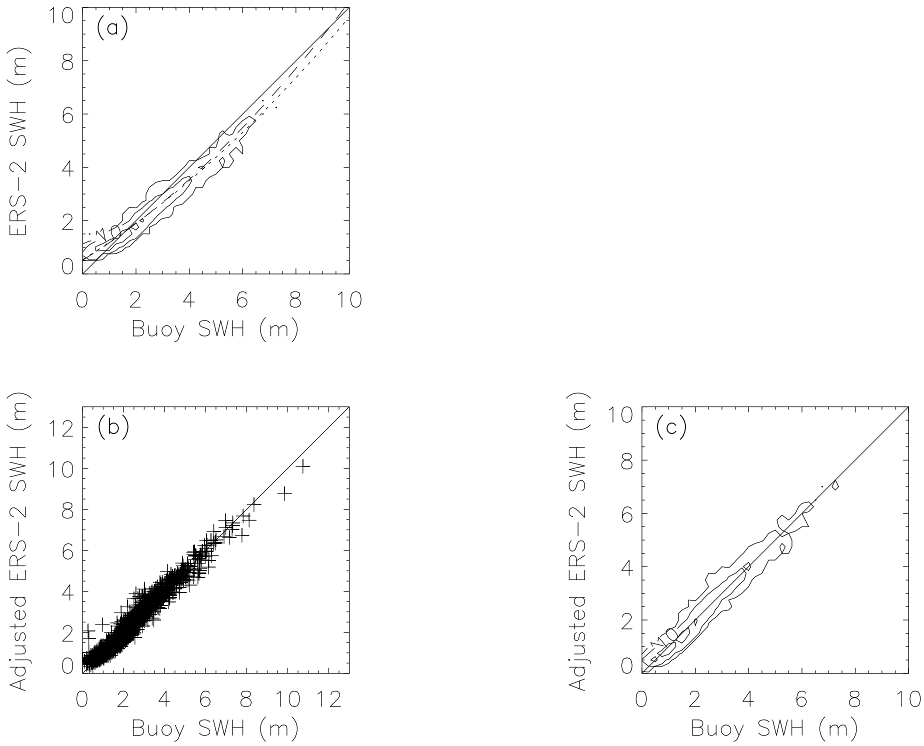

Fig. 5. Same as Fig. 4 but with a quadratic adjustment.

This procedure was also applied with a quadratic function. Figure 5 shows results for this function, for which the best fit was found to be:

$$\mathrm{SWH}_{adj} = 0.1 \qquad \text{for } \mathrm{SWH}_{FD} \le 0.536$$
$$\mathrm{SWH}_{adj} = -9.812 + 5.616\sqrt{2.517 + \mathrm{SWH}_{FD}} \qquad \text{for } \mathrm{SWH}_{FD} > 0.536 \qquad \ldots 11$$

The validation statistics for the ERS-2 FD data after being adjusted according to Eqn 10 are shown in Table 2. The quadratic adjustment is a further improvement over the linear function, but it can be seen in Fig. 5(c) that problems still exist at very low values of SWH and that the highest density of observations does not lie exactly along the $y = x$ line. This suggests that further improvements may still be found.

The third type of function investigated was a two-branched linear function, as in Challenor and Cotton (1997). The co-located data are divided into two segments: high ERS-2 SWH and low ERS-2 SWH, above and below a particular ‘fitting cutoff’ value,

$SWH_{FD} = F_C$, respectively. Linear regression is then applied separately to the two segments of the data. Figure 6 shows an example of the results for F_c= 1.5 m.

In order to avoid a discontinuity at $SWH_{FD} = F_C$, the point of intersection of the final two regression lines was found and the appropriate adjustments applied above and below that intersection point. For the example shown in Fig. 6, although F_C = 1.5 m, the intersection of the two lines actually occurs at ERS-2 SWH = 1.375 m.

Thirteen cases were considered here with F_C ranging from 1 m to 2.2 m in 0.1 m intervals. Validation statistics for three of these cases, F_C = 1 m, 1.5 m and 2 m are shown in Table 2. It was found that the best case (lowest *rms* error and lowest SI) was for F_C = 1.5 m, i.e., the example shown in Fig. 6. As for the previous cases, it is necessary to include a caveat to prevent negative values of SWH. The resulting fit is:

$$
\begin{aligned}
&SWH_{adj} = 0.1 && \text{for } SWH_{FD} \leq 0.72 \\
&SWH_{adj} = 2.187\ SWH_{FD} - 1.582 && \text{for } 0.72 < SWH_{FD} \leq 1.375 \qquad \ldots 12 \\
&SWH_{adj} = 1.153\ SWH_{FD} - 0.160 && \text{for } SWH_{FD} > 1.375
\end{aligned}
$$

Adjusting the ERS-2 FD data according to Eqn 12 will thus result in a dataset which, when compared to *in situ* buoy data has an *rms* error (i.e., goodness-of-fit) of 0.203 m, a SI of 0.104 and negligible overall bias. This is a significant improvement over the non-adjusted FD data and can be expected to produce a positive impact in data assimilation schemes which use ERS-2 FD data. This is examined in the next section.

4. Impact of the adjusted ERS-2 SWH on current data assimilation system

An experiment was performed to evaluate the impact of the above ERS-2 FD adjustments on the current operational ERS-2 SWH data assimilation system. The wave model was run in several modes over the global domain for one month, June 2001.

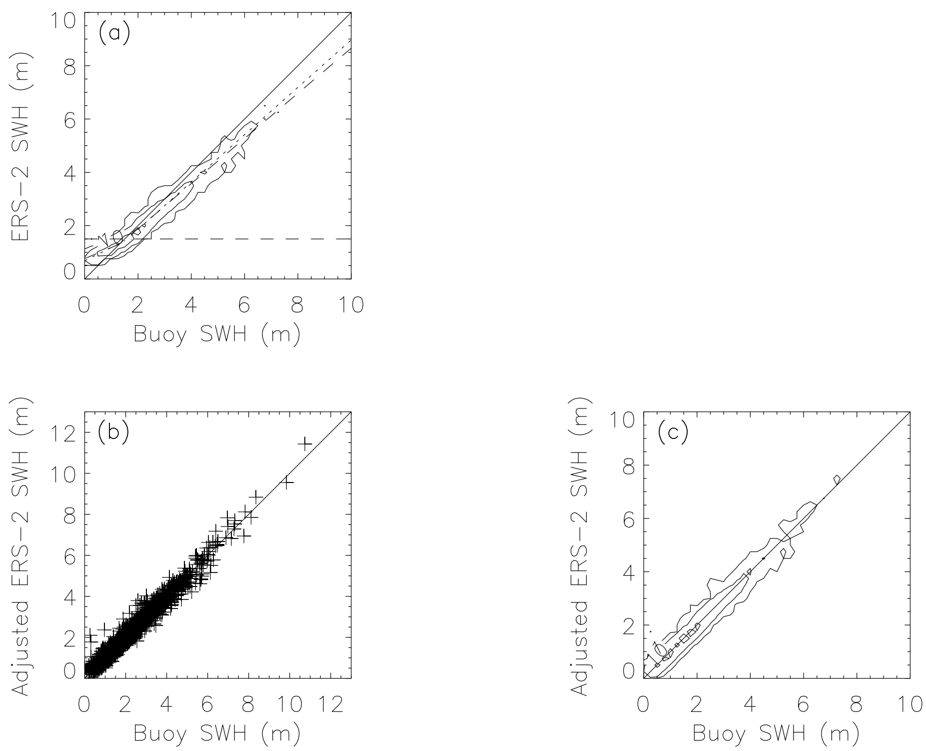

Fig. 6. Same as Fig. 4 but with a two-branched linear adjustment (F_C = 1.5 m).

Although this time period is not independent of that used in the co-locations, the set of buoys used for verification is slightly different to that used in the previous section (see later). The first model run included the assimilation of ERS-2 FD data directly (ASSIM), and the second model run used the ERS-2 data adjusted according to Eqn 12 (ASSIM_ADJ). No other changes were made to the assimilation system, which is described in Greenslade (2001). In particular, the prescribed model *rms* error and the *rms* error of the observations in the assimilation were kept the same for both model runs, even though there are plausible arguments for altering these values (currently they are both set to be 0.5 m). These values were kept constant in order to highlight the effect of the adjustments to the ERS-2 data. In addition, a control run with no data assimilation (NO_ASSIM) was performed.

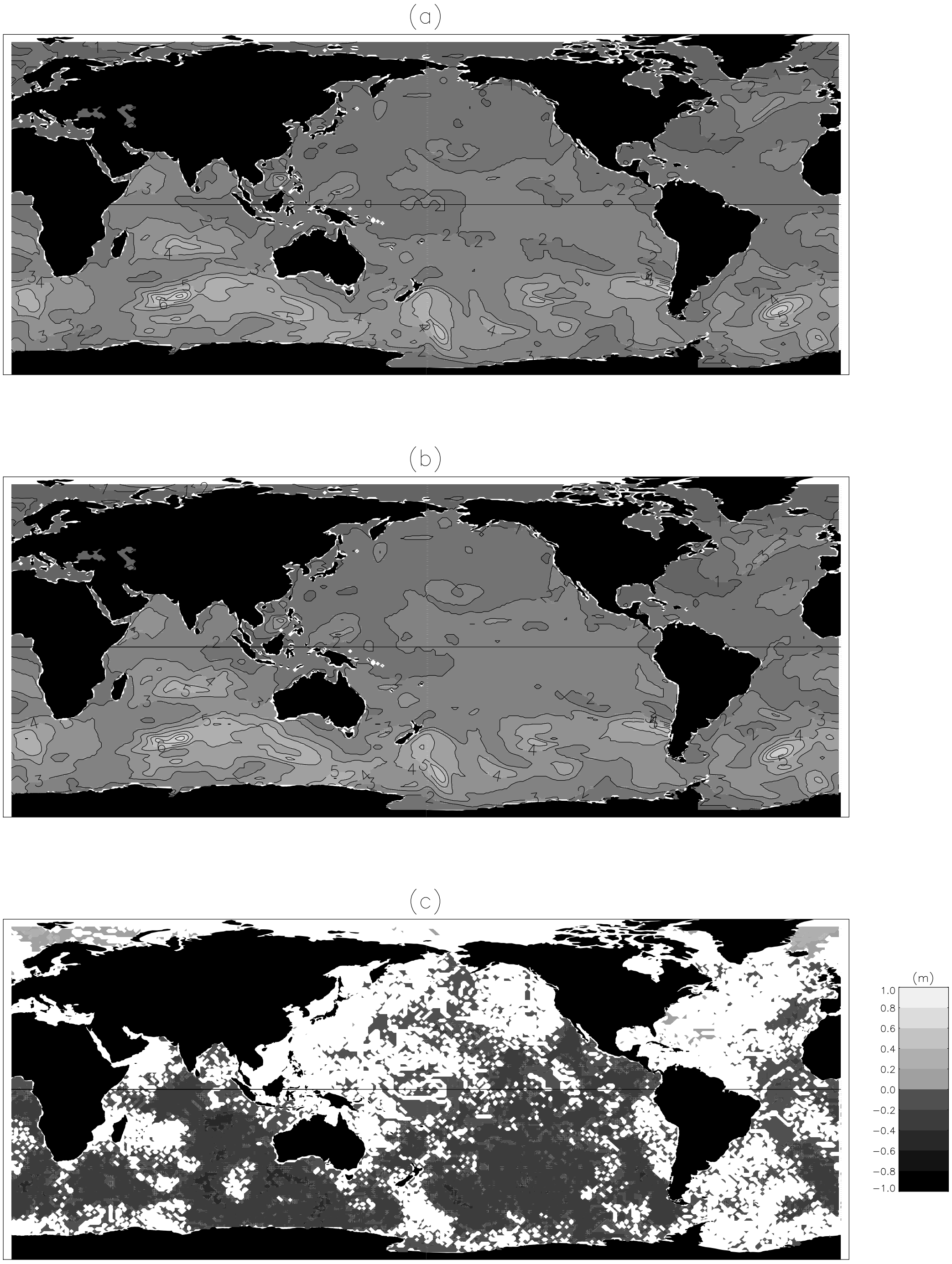

Fig. 7. Modelled 0-hour forecast SWH valid at 12Z on 30 June 2001 for (a) ASSIM, (b) ASSIM_ADJ and (c) ASSIM - ASSIM_ADJ . In (c), only areas where the absolute value of the difference is > 0.1 m are shown.

The spatial resolution of the global wave model is currently 1^o. Operational restart fields valid at 1 June, 00Z were used for all three model runs, and operational global 10m winds were used to force the wave model. During each 12-hour hindcast/assimilation period and 48-hour forecast period, SWH fields were output at 3-hourly intervals.

Figure 7 shows a global analysed SWH field from the two assimilation runs (ASSIM and ASSIM_ADJ) and the difference between the two fields. It can be seen that the adjusted ERS-2 FD data has made a significant impact over most of the domain. For the most part, SWH from the ASSIM_ADJ run is higher than the ASSIM SWH. This is not surprising as over most of the range of SWH, the effect of the adjustment in Eqn 12 is to increase the SWH. For this particular analysis time, the smallest impact is found in the North Atlantic and North-west Pacific Oceans and the largest impacts are found in the Eastern Indian Ocean and the Southern Ocean, where the SWH from the ASSIM_ADJ run is up to 0.5 m higher than ASSIM. In general, the largest impacts can be seen in areas where the highest SWH occurs. The only areas where SWH is decreased are the northern polar regions and the West Atlantic/Gulf of Mexico. As can be seen from Fig. 7(a) and (b), in these areas, the modelled SWH is below 1 m at this time, so the impacts seen in Fig. 7(c) are a direct reflection of the two-branched linear adjustment.

Figure 8 shows the difference between ASSIM and ASSIM_ADJ for the 48-hour forecast SWH valid at same time as in Fig. 7. Although the differences are smaller than for the analysis, it can be seen that the impact of the altimeter data adjustment persists even 48 hours after the end of the assimilation period.

It has been demonstrated here that the adjusted ERS-2 data creates a significant impact on modelled wave fields. However, it is necessary to ensure that these are positive impacts. This is done by performing a verification of the modelled wave fields against *in situ* wave buoy data.

A set of 26 wave buoys was used for verification (see Table 1). This set of buoys is slightly different to that used in the ERS-2 co-locations. In this section, hourly buoy observations are not necessary, so some of the Australian buoys which report data every 3 hours could be included. In addition, some buoys which had been previously excluded due to being too close to the coast could be included here because they are situated either on or very near a wave model gridpoint.

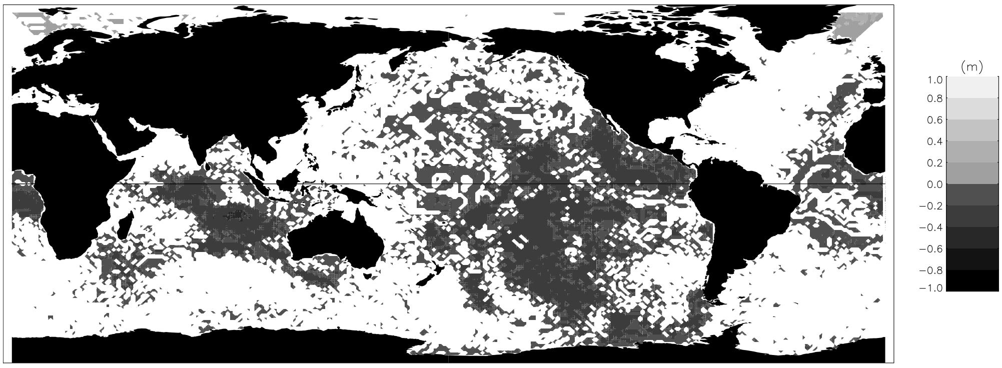

Fig. 8. Same as Fig. 7 (c) but for 48-hour forecast SWH fields.

Figure 9 shows time series of SWH observations at three-hourly intervals from several of the buoys along with the 3-hourly analysed SWH from the three model runs. More precisely, since the modelled wave fields were archived every 3 hours, the model time series shown in this figure represent a repeating sequence of hindcasts at 9, 6, 3, and 0 hours prior to the analysis time. In general, a clear pattern emerges: the model run without data assimilation is biased low compared to the buoy observations, the ASSIM run reduces this bias significantly and the ASSIM_ADJ run reduces it further. This is particularly evident at buoy 51001. It is encouraging to see, however, that areas where the wave model has overpredicted the SWH are not further degraded by the impact of the adjusted ERS-2 data (e.g. around day 15 at buoy 55020).

Verification statistics for all buoys are shown in Table 3. It can be seen that for all forecast periods, the skill of the model (i.e., the *rms* error) is improved with the use of the adjusted ERS-2 FD data. At 24-hours, the *rms* error is decreased by 5 per cent. These improvements in skill are largely due to a reduction in the negative bias of the modelled wave fields, as seen in Fig. 9. However, improvements have been made to the SWH variability - this is reflected in the SI statistic. SI is defined (see Eqn 8) as the standard deviation of error divided by the mean observed SWH, and thus bias is not included in the SI.

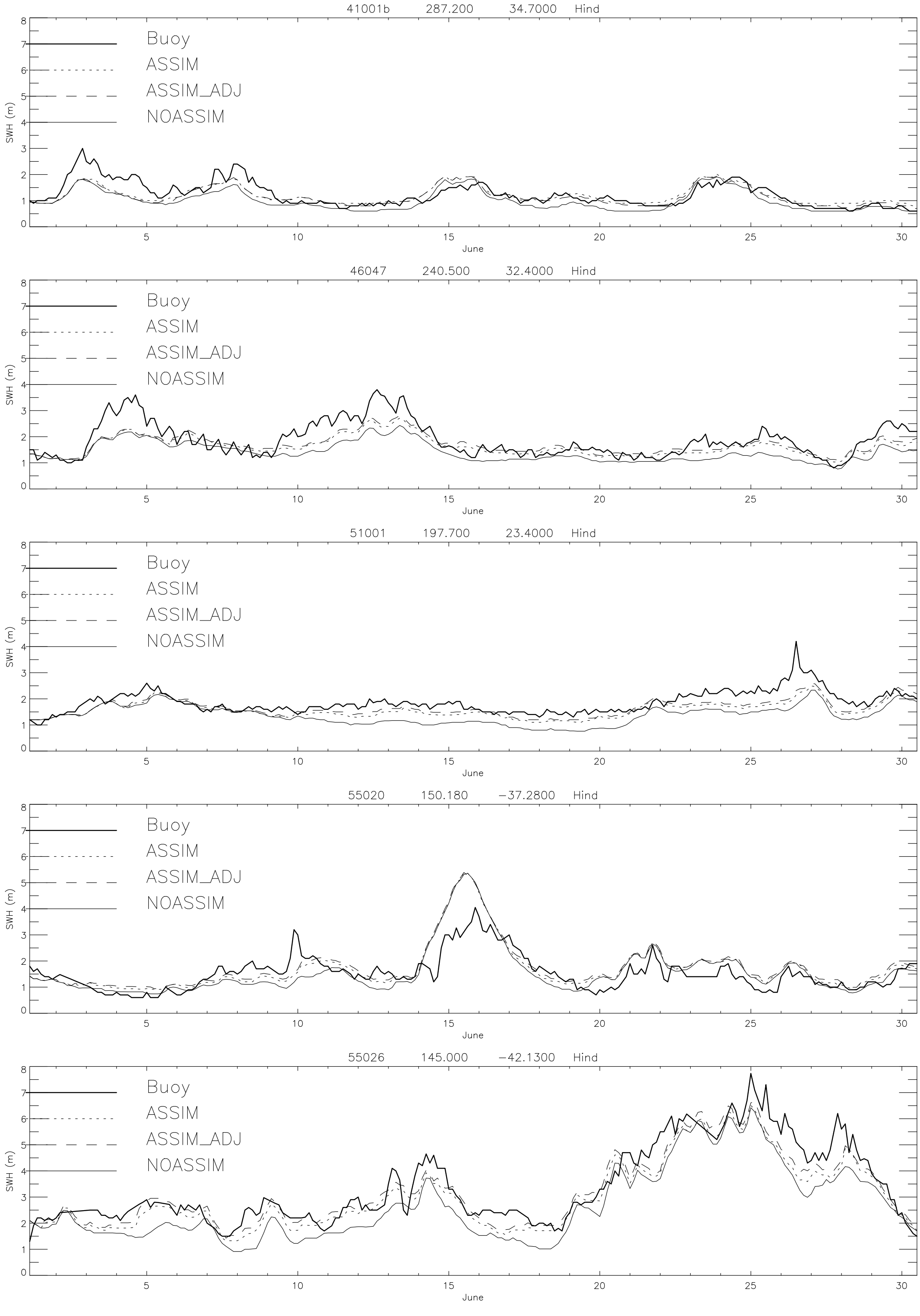

Fig. 9. Time series of hindcast SWH at five buoys with modelled SWH from the three wave model runs. a) 41001 (NW Atlantic), b) 46047 (E Pacific), c) 51001 (Hawaii), d) 55020 (SE Australia), e) 55026 W Tasmania.

Table 3. **Verification statistics for 0-hour (analysis), 24-hour and 48-hour forecasts.**

a) 0-hour forecasts

	NOASSIM	ASSIM	ASSIM_ADJ
Bias	-0.30	-0.10	-0.07
R	0.89	0.90	0.91
SI	0.27	0.25	0.23
rms	0.49	0.37	0.35

b) 24-hour forecasts

	NOASSIM	ASSIM	ASSIM_ADJ
Bias	-0.29	-0.12	-0.08
R	0.88	0.90	0.90
SI	0.27	0.26	0.25
rms	0.49	0.39	0.37

c) 48-hour forecasts

	NOASSIM	ASSIM	ASSIM_ADJ
Bias	-0.28	-0.14	-0.08
R	0.85	0.87	0.87
SI	0.30	0.29	0.29
rms	0.52	0.44	0.42

There are significant regional variations in the impact of the adjusted ERS-2 FD data. The buoys were divided into the five regional groupings shown in Table 1, and verification statistics calculated for each group. These are shown for 24-hour forecasts in Table 4. The greatest improvement is found in the Central Pacific, where the 24-hour forecast rms error is decreased by 13 per cent with the use of the adjusted ERS-2 data. This supports the expectation that there should be a greater impact on SWH fields in swell-dominated areas due to the method used to adjust the wave spectrum. This is described in more detail in Greenslade (2001). For the buoys located around Australia, the 24-hour forecast *rms* error is decreased by 7 per cent, and the systematic bias reduced from -0.15 m to -0.03 m. The least impact is found in the North-west Atlantic and the

Gulf of Mexico, where the 24-hour forecast *rms* error is the same for both ASSIM and ASSIM_ADJ.

5. Summary

A validation of the ERS-2 FD SWH data has been performed. Observations from the ERS-2 altimeter over a time period of more than 4.5 years have been compared to *in situ* buoy observations. Co-locations were limited to those for which buoy and altimeter observations occurred within $\pm 0.5^{o}$ and $\pm$ 1 hour of each other. With a total of 2823 co-locations, the *rms* difference between the two datasets was found to be 0.317 m with the altimeter overestimating low SWH and underestimating high SWH. Overall, there is a slight negative bias (approximately 0.05 m) in the altimeter data. This agrees well with previous work.

Adjusting the altimeter data according to a two-branched linear model reduced the *rms* difference between buoy and altimeter data to approximately 0.2 m with negligible overall bias. It was shown that adjusting the ERS-2 FD data before including it in a global data assimilation system produces a positive impact on forecast wave fields, particularly in swell-dominated areas such as the central Pacific region and around the Australian coast.

Acknowledgments

The authors gratefully acknowledge the National Data Buoy Center, Manly Hydraulics Laboratory, Lawson and Treloar, Woodside Petroleum and the South African Weather Service for providing the wave data used in this report. Comments on the text by Graham Warren (NMOC) and Neville Smith (BMRC) are also appreciated.

Table 4. **Verification statistics for 24-hour forecasts for the regional groupings shown in Table 1.**

a) Australia

	NOASSIM	ASSIM	ASSIM_ADJ
Bias	-0.36	-0.15	-0.03
R	0.89	0.92	0.92
SI	0.27	0.24	0.23
Rms	0.69	0.55	0.51

b) Central Pacific

	NOASSIM	ASSIM	ASSIM_ADJ
Bias	-0.47	-0.27	-0.16
R	0.42	0.55	0.56
SI	0.17	0.15	0.15
rms	0.56	0.38	0.33

c) Eastern Pacific

	NOASSIM	ASSIM	ASSIM_ADJ
Bias	-0.39	-0.20	-0.14
R	0.83	0.85	0.85
SI	0.24	0.24	0.23
rms	0.55	0.43	0.41

d) Gulf of Mexico

	NOASSIM	ASSIM	ASSIM_ADJ
Bias	-0.15	-0.08	-0.10
R	0.78	0.75	0.76
SI	0.36	0.38	0.38
rms	0.33	0.32	0.32

e) North-west Atlantic

	NOASSIM	ASSIM	ASSIM_ADJ
Bias	-0.13	0.05	0.04
R	0.75	0.74	0.74
SI	0.29	0.30	0.30
rms	0.31	0.30	0.30

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