An Intercomparison of Parametric Models of Sea State Bias for the TOPEX, Poseidon and Jason-1 Altimeters

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Abstract. The 'BM4' four-parameter (Gaspar et al., Journal of Geophysical Research, 1994) empirical model of sea state bias based on wind stress and significant wave height (SWH) is applied in both crossover and collinear analyses of all available TOPEX, Poseidon and Jason-1 data provided by the Radar Altimeter Database System at Delft University of Technology. The relative biases are –2%, –5% and –4% of SWH for TOPEX, Poseidon and Jason-1 respectively. Estimates of the uncertainties on the lower-order coefficients are large and unhelpful. For each altimeter, crossover analyses resulted in a greater proportion of the variance in sea surface height differences explained by the calculated model than collinear analyses. From the available Jason-1 data, the calculated crossover model performs as well as the sea state bias model provided with the data.

Keywords. Sea state bias, satellite altimetry, parametric model

1 Introduction

The sea state bias (SSB) is a correction applied to satellite altimeter data in an attempt to estimate the true mean sea level of the oceans. The SSB encompasses the electromagnetic bias, which occurs due to the shape of the ocean waves. The peaks scatter more of the radar return signal than is reflected by the wave troughs and thus the observed, or estimated mean sea level is biased lower than the true mean sea level (e.g. Jackson, 1979). The sea state bias also includes the skewness bias and the tracker bias, making the SSB instrument dependent. Further information can be found in, for example, Fu (1990) and AVISO (1994).

This phenomenon has been addressed in many studies, and became especially important when the TOPEX/Poseidon satellite was launched due to the both expected, and then obtained, smaller error budget (e.g. Nouël et al., 1994). It remains today one of the largest sources of error (Chelton et al., 2001) in satellite altimeter measurements.

Theoretical investigations of the sea state bias include the work of Jackson (1979); Barrick and Lipa (1985); Srokosz (1986); and more recently Elfouhaily et al. (2000), but are still not able to predict the bias well enough without including other techniques, since predictions of wave state and ocean dynamics are complicated. Therefore, empirical analyses provide the best SSB models on a global scale. An empirical analysis using processed and corrected altimeter data means the components of the SSB cannot be independently investigated, resulting in an instrument-dependent correction. Chelton et al. (2001) give a more detailed and recent review of both theoretical and empirical estimation techniques.

An empirical, parametric analysis of the sea state bias, such as the four-parameter model described in Gaspar et al. (1994 hereinafter referred to as GOLZ94) remains, for it's simplicity, one of the best models available. It involves a linear regression on altimeter sea surface height differences (ΔSSH), derived using a variety of techniques, of the form:

$$BM4(\Delta SWH, \Delta U) = \Delta SWH[a_0 + a_1\Delta U + a_2\Delta U^2 + a_3\Delta SWH] \quad (1)$$

where ΔSWH are significant wave height differences and ΔU are wind speed differences.

The GOLZ94 analysis was performed on TOPEX and Poseidon data at crossover locations from cycles 2-30. One main reason for readdressing this issue is due to the vast increase of altimeter measurements now available. Is the GOLZ94 model still valid or can an improved correction be derived with these simple techniques using a much larger dataset?

This paper uses Eq. (1) to estimate coefficients a_0 through a_3 using both crossover and collinear analyses of various (subsets of) TOPEX, Poseidon

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and Jason-1 data. In section 2, the methods common to each analysis will first be addressed, followed by a description of each analysis technique and the data used. Section 3 discusses the results for each altimeter. Determining criteria for comparing the resulting models is not straightforward. The conventional method for determining confidence intervals underestimates the uncertainties in the model, since the residuals are not truly independent (e.g. Chelton, 1994). This paper follows the suggestion of Chelton (1994) to use the standard deviation of the bias models derived from individual cycles, for each coefficient, to provide a rough estimation of the uncertainties (see section 3.1 for more details). Therefore, a comparison of models has mainly been based upon two other methods. First, how much of the ΔSSH variance can be 'explained' by each model (as a percentage). The model residuals are also checked for trends in both |ΔSWH| and |ΔU|. Finally, in section 4 a summery of the main findings are given, conclusions are drawn and a description of future work is provided.

2 Analysis Methods and Data Sets

Altimeter data stored in the Radar Altimeter Database System (RADS), developed at the Delft University of Technology have been used in this study (see http://www.deos.tudelft.nl/altim/rads/). This database contains all altimeter data since the Geosat mission, and special attention has been paid to the calibration and validation of the raw data, and to the "harmonisation" of the geophysical corrections and data themselves (Naeije et al., 2001).

As usual with altimeter data, to obtain the required SSH, SWH and U differences (whichever the method), certain corrections and editing criteria must be applied. The corrections and checks applied that are common to all analyses are shown in table 1. Those corrections specific to a particular analysis method are discussed in the following sections.

All analyses included the removal of outliers (> 3σ) in the ΔSSH, ΔSWH and ΔU data prior to the regression, in an attempt to obtain a more robust bias for the majority of the SWH and U conditions.

2.1 Initial Analysis of TOPEX/Poseidon Crossovers

Table 1. Models used, corrections applied and limits set that are common throughout the various analyses

Correction	Model used and data selection limits
Dry Troposphere	ECMWF model (-2.4 to -2.1m)
Wet Troposphere	Radiometer (-0.6 to 0.0 m)
Ionosphere	Smoothed dual-frequency (-0.40 to +0.04 m)
Inverse Barometer	ECMWF pressure (-1 to +1 m)
Solid Earth Tide	Applied (-1 to +1 m)
Pole Tide	Applied (-0.1 to +0.1 m)
Sea State Bias	Not applied
Significant Wave Height	0 to 11 m
Backscatter Coefficient	7 to 20 dB
Wind Speed	0 to 30 ms^{-1}
Deep Ocean	Ocean depth >2251 m

The main aim of this initial analysis was for validation of the analysis method used by performing a comparison to the results of GOLZ94 who developed the four-parameter model for TOPEX/Poseidon. Differences in SSH, SWH and U were performed at crossover locations for TOPEX and Poseidon cycles 2-30 (4th October 1992 to 28th July 1993). Data were obtained for all TOPEX-only and Poseidon-only (i.e. single-satellite) crossovers. Stringent criteria were placed on the data before processing. The common corrections and editing criteria (table 1) were applied. In addition, for this analysis a number of what are now considered older corrections were used. The vast improvements made to the data and corrections since the beginning of the TOPEX altimeter mission, due to the high quality of the data themselves, have also led to differences in the models being used in this work and those used in GOLZ94, which are:

	Initial analysis	Gaspar et al. (1994)
Orbit model	JGM-3	CNES orbit based on DORIS measurements, not corrected for orbit error
Ocean/load tide	CSR3.0	Cartwright and Ray (1990)
Geoid/mean sea surface height	OSU 95 MSS	Not applied.

The linear analysis (Eq. 1) was performed on crossovers from each individual cycle, and all crossovers for cycles 2-30 collectively, where the difference in time (Δt) between ascending and descending passes is less than 5 days.

2.2 Comprehensive Analysis of TOPEX/Poseidon and Jason-1 Crossovers

Data were obtained for all TOPEX, Poseidon and Jason-1 single-satellite crossovers as shown in table 2.

Table 2. Cycles and corresponding dates of the data used in the comprehensive crossover analyses

Satellite crossovers	Cycles	Dates
TOPEX	2-354	4 Oct 1992 – 4 May 2002
Poseidon	2-307	4 Oct 1992 – 23 Jan 2001
Jason-1	2-25	25 Jan 2002 – 20 Sep 2002

The common corrections and editing criteria (table 1) were applied. In recent years models for the ocean and load tide correction and the mean sea surface model have been improved and updated (e.g. Lefèvre et al., 2000; Ray, 1999; Koblinsky et al., 1999). The following corrections were used, in an attempt to obtain the best possible data (see also section 3.1):

TOPEX/Poseidon orbit model	JGM-3
Jason-1 orbit model	CNES
Ocean and Load tide	GOT00.2
Geoid/Mean Sea Surface Height	GSFC00.1

Section 3.1 provides more detailed information about the choice of the corrections applied.

2.3 Collinear Analyses

The method is the same as the crossover analyses described in sections 2.1 and 2.2, apart from the calculation of the SSH, SWH and U differences. The differences were performed at the same geographical location between data from one cycle and those from the following cycle, a collinear analysis. Since the Poseidon altimeter was active for only approximately 10% of the time, data for consecutive cycles were rarely available. Therefore, results were obtained for TOPEX and Jason-1 only.

Collinear analyses provide a vast amount of data, a computer with a large amount of memory was required to process the 26 subsets used in the initial analysis. Therefore to reduce the amount of data yet increase the number of cycles to be included, average SSH, SWH and U differences were calculated on a global 1° x 1° latitude-longitude grid prior to the regression analysis. These data sets are referred to in the text as TCAi, TCAf and JCAf, for TOPEX initial 1°-averaged collinear analysis (cycles 2-30), TOPEX full 1°-averaged collinear analysis (cycles 2-354) and Jason full 1°-averaged collinear analysis (cycles 2-25), respectively.

3 Four-parameter Models of Sea State Bias

This section explains the various four-parameter models of sea state bias obtained for the various analyses described in section 2. The results are organised so as to first discuss the bias models for each altimeter individually.

3.1 TOPEX Models

Following Eq.1, coefficients a_0 through a_3 were obtained for individual TOPEX cycles 2-30, for the crossover (table 3) and collinear (table 4) data sets.

The TXOi model obtained from over 16,000 crossovers is shown in table 5.

Table 3. Values of coefficient a_0 and model fit for the initial analysis of TOPEX crossover data for cycles 2-30.

Cycles	a_0 as %SWH[a]	ΔSSH variance 'T' cm^2	Variance explained 'E' cm^2 (%E/T)	Number of XOs
02	-1.77	62.09	5.97 (10)	5976
03	-2.04	60.94	7.05 (12)	4092
04	-1.52	61.75	5.57 (09)	4098
05	-2.00	66.35	6.98 (11)	4780
06	-2.13	55.52	5.90 (11)	3694
07	-2.10	68.03	9.43 (14)	6015
08	-1.98	50.31	5.29 (11)	4434
09	-1.87	49.52	5.69 (11)	3422
10	-2.02	54.47	5.89 (11)	6632
11	-2.64	61.26	9.71 (16)	5443
12	-2.20	55.20	7.90 (14)	4410
13	-2.63	61.26	11.05 (18)	5361
14	-2.69	56.94	9.27 (16)	5050
15	-1.88	49.90	5.98 (12)	5798
16	-2.23	61.64	10.17 (16)	4646
17	-2.06	54.31	7.21 (13)	7687
18	-1.85	47.87	5.25 (11)	7614
19	-1.91	70.73	7.84 (11)	7521
21	-1.96	62.84	9.79 (16)	7439
22	-1.80	54.31	5.69 (10)	7322
23	-1.45	61.93	5.34 (09)	7087
24	-1.96	60.21	6.40 (11)	6806
25	-1.90	61.97	6.41 (10)	6713
26	-1.65	60.17	5.90 (10)	6474
27	-1.55	55.14	5.73 (10)	6253
28	-1.96	51.19	4.73 (09)	6109
29	-1.23	56.77	4.12 (07)	5958
30	-1.60	63.60	4.41 (07)	5870
2-30	-1.93	55.33	6.31 (11)	160378

coefficient a_0 is expressed as the 'relative bias' in terms of %SWH

The total variance in ΔSSH is 55.33 cm^2 and the variance in ΔSSH explained by the TXOi model is 6.31 cm^2, i.e. the total variance in ΔSSH is reduced by 6.31 cm^2 after the model has been applied. It is more useful to explain this as a percentage then comparisons can be more quickly made between models obtained from different analysis methods (crossover, collinear, etc.) with different total ΔSSH variance. 11% of the total ΔSSH variance can be explained by the TXOi model.

The main purpose of performing the linear regression on individual cycles is to use the standard deviation of the individual cycle values of each coefficient as error estimates for the coefficients obtained from the combined TOPEX crossover (TXOi) and collinear (TCOi) data sets. The 'i' stands for the 'initial' analysis of cycles 2-30. This method is preferred since the use of the variance of the residuals (the 'unexplained' part of the model) will result in underestimated values because the residuals are somewhat correlated (GOLZ94; Chelton, 1994).

Table 4. Values of coefficient a_0 and model fit for the initial collinear analysis of TOPEX data

Cycles	a_0 as %SWH[a]	ΔSSH variance 'T' cm^2	Variance explained 'E' cm^2 (%E/T)	Number of data points
2-3	-2.03	82.03	9.86 (12)	348372
3-4	-2.20	80.65	8.87 (11)	278309
4-5	-2.19	80.85	8.25 (10)	303343
5-6	-2.15	78.11	7.34 (09)	327568
6-7	-2.21	79.49	7.42 (09)	328932
7-8	-2.09	80.10	8.44 (11)	357893
8-9	-2.09	69.84	6.37 (09)	246393
9-10	-2.09	74.15	6.68 (09)	315733
10-11	-2.54	77.37	8.97 (12)	384557
11-12	-2.55	74.46	9.09 (12)	336305
12-13	-2.65	80.60	11.52 (14)	328544
13-14	-2.64	80.37	12.17 (15)	307527
14-15	-2.42	68.32	8.85 (13)	313262
15-16	-2.12	75.34	7.98 (11)	342191
16-17	-2.34	74.11	7.97 (11)	351223
17-18	-2.00	75.00	7.49 (10)	450078
18-19	-2.00	82.93	8.46 (10)	446023
21-22	-1.97	76.16	6.75 (09)	442754
22-23	-1.73	73.22	5.96 (08)	440002
23-24	-1.63	68.73	4.91 (07)	431737
24-25	-2.05	78.39	7.74 (10)	431069
25-26	-2.00	73.24	7.77 (11)	428082
26-27	-1.97	75.93	7.47 (10)	421886
27-28	-1.76	70.37	5.31 (08)	417908
28-29	-1.86	66.28	4.98 (08)	414270
29-30	-1.62	75.72	4.89 (06)	409061
2-30b	-2.07	76.00	7.38 (10)	9602676
2-30c	-1.97	54.81	5.90 (11)	613774

[a] coefficient a_0 is expressed as the 'relative bias' in terms of %SWH
[b] combined from individual cycles (TCOi)
[c] 1° x 1° latitude-longitude gridded averages of ΔSSH, ΔSWH and ΔU (TCAi)

Difficulties with this method arise with the 'full' data sets where time constrains the processing for each individual cycle. Uncertainties for the TXOi, TCOi, and JCOi models determined in this way are given in table 5. It can be seen that lower order terms yield much greater uncertainties and are not entirely useful for providing statistical evidence that use of certain parameters improves the sea state bias estimation.

In comparison, the model of GOLZ94 (Eq. 17c), which has been regularly applied to TOPEX altimeter data since 1994, is also provided in table 5. The coefficients were obtained from a similar linear regression analysis on crossovers from TOPEX cycles 2-30. Variance in ΔSSH was 127.71 cm^2 and that explained by the GOLZ9417c model was 7.33 cm^2 (only 6% of the total ΔSSH variance).

The intention in this initial crossover analysis was to use as similar data as possible to that used in the GOLZ94 study. It appears from the difference in total variance between TXOi and GOLZ17c that the corrections applied, and data selection criteria have some impact on the model estimation. However, the a_0 coefficients, referred to as the 'relative bias' are around -2% of SWH. It is only the lower-order terms in the models that yield much greater uncertainties. Table 6 shows the coefficients a_0 through a_3 for models obtained from TOPEX cycles 2-30 combined when different corrections and selection criteria for the data are applied.

The mean residuals of the models in Table 6, as a function of |ΔSWH| and |ΔU| are shown in figure 1. The residuals are small, with largest differences between models occurring where the SWH and U differences are greater. The distribution of crossovers in ΔSWH and ΔU is shown in figure 2 (dotted lines) along with those from the TCAi analysis (solid lines).

Less than 0.1% of the data points fall into the category of ±3.5 m in ΔSWH or ±11 ms^{-1} in ΔU. These results indicate that the use of different corrections does not greatly influence the result.

The model that resulted in the largest amount of variance explained when compared to the total variance occurred when the GOT00.2 ocean and load tide model was applied to the data. Similarly, the GSFC00.1 MSS model increased the amount of variance explained by the model when compared to using EGM96, OSU 95 MSS, or not applying a geoid or MSS model altogether. These findings were the basis for using both the GOT00.2 and GSFC00.1 corrections in the more comprehensive analyses.

Table 5. Coefficients obtained for various models of SSB. A breakdown of the model names is: T = TOPEX, P = Poseidon, J = Jason-1, XO = crossover, CO = collinear, CA = collinear 1°-averaged, i = initial analyses and f = full analyses

Model	a_0	a_1 (x10^{-3})	a_2 (x10^{-3})	a_3 (x10^{-3})
TXOi	-0.0193 ± 0.0034	+0.012 ± 0.424	-0.069 ± 0.043	+0.0007 ± 1.4
GOLZ94 (Eq.17c)	-0.0190 ± 0.009	-3.7 ± 0.8	+0.14 ± 0.03	+2.7 ± 1.1
TCOi	-0.0207 ± 0.0028	+0.0062 ± 0.3184	-0.069 ± 0.032	+0.28 ± 1.72
TCAi	-0.0207	+0.054	-0.12	+0.34
TXOf	-0.0204	+0.0028	-0.082	-0.75
TCAf	-0.0202	+0.0083	-0.13	+0.3
PXOf	-0.0485	-0.18	-0.068	-0.04
JCOi	-0.0415 ± 0.0028	+0.067 ± 0.3	-0.019 ± 0.023	+0.42 ± 0.94
JXOf	-0.0354	+0.011	-0.052	-0.58
JCAf	-0.0355	-0.018	-0.047	-0.57

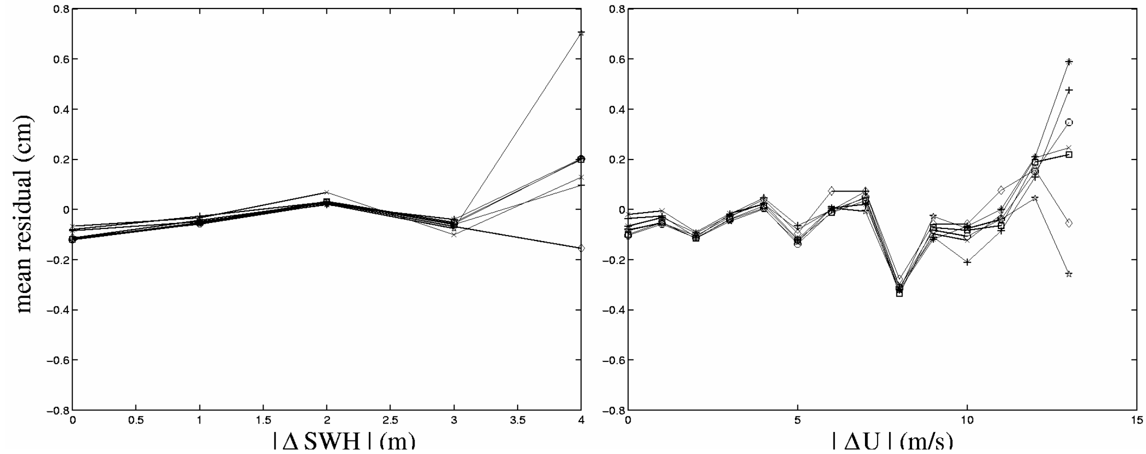

Fig. 1 Mean residuals of regressions shown in table 6 as a function of |ΔSWH| and |ΔU| on data from TOPEX crossovers cycles 2-30, obtained by modifying different corrections and selection criteria. The mean residuals are calculated in bins of 1 m and 1 ms^{-1} for |ΔSWH| and |ΔU| respectively.

Table 6. Values of coefficients a_0 to a_3 for the initial analysis of TOPEX data, cycles 2-30, varying the models used in the selection of the data.

Model used / parameter modified	a_0[a]	a_1[b]	a_2[b]	a_3[b]
EGM96 gravity model	-1.93	0.9	-6.0	2.4
GSFC00.1 MSS	-1.93	1.9	-7.0	2.1
Geoid/MSS model not applied	-1.95	-0.8	-6.9	6.1
FES99 ocean tide & loading	-1.91	4.1	-7.1	-0.3
GOT00.2 ocean tide & loading	-1.89	3.9	-7.1	8.7
'local-global' inverse barometer	-1.93	0.6	-7.0	2.3
Significant wave height < 8 m	-2.00	0.4	-7.8	4.9
Standard deviation of above	0.03	1.8	0.5	3.0

[a] expressed as %SWH
[b] x 10^{-5}

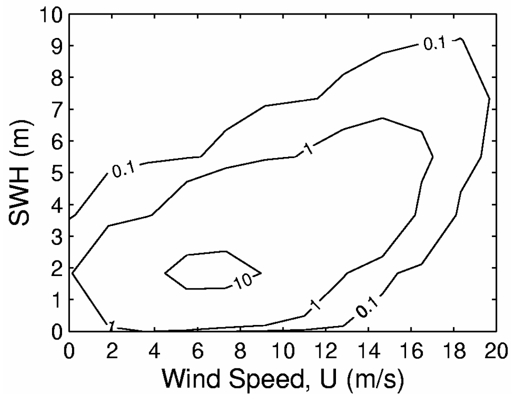

Fig. 2 Contours of the distribution percentage of TOPEX crossovers (dotted) and 1°-averaged collinear (solid) analyses for cycles 2-30 in terms of ΔSWH and ΔU.

An inverse barometer correction based on a global mean air pressure (rather than the fixed 1013.3 mbar resulted in only a minor improvement in the model. The standard inverse barometer correction was applied in all TOPEX analyses.

Not surprisingly, reducing the data set to only include SWH < 8 m also improved the amount of variance explained by the SSB model, but only by 0.1%. Therefore, in the more comprehensive analyses the upper limit of 11 m was still applied.

The coefficients for the model obtained from the TXOf analysis on crossovers from cycles 2-354 is shown in table 5 and in figure 3a as a function of SWH and U, along with the mean residuals as a function of ΔSWH, figure 3b, and ΔU in figure 3c.

At average wave heights (around 2 m) and wind speeds (around 7.5 ms^{-1}), the TXOf bias is < 10 cm. The mean residuals show trends with both ΔSWH and ΔU, indicating the bias could yet be improved. The residuals for ΔSWH are large for TXOf (±4 cm), though between ± 3 m ΔSWH the residuals are ± 1 cm. Having said that, there could still be useful information to be obtained about the SSB in the larger values of ΔSWH and ΔU. Approximately 16% of the total variance in ΔSSH can be explained by this model.

Chelton (1994) conducted a collinear analysis of TOPEX data and found that the four-parameter model obtained agreed to within ±1 standard deviation of the GOLZ94 crossover model. The four-parameter model from all data points in the current collinear (TCOi) analysis, combined from the results from the 26 individual cycle-cycle subsets is shown in table 5.

Again, the bias is approximately -2% of SWH. The total variance in ΔSSH is greater than in the TXOi analysis, 76.0 cm^2, and the amount of variance explained by the TCOi model is 7.38 cm^2 (or 10% of total ΔSSH variance). This result is obtained from over 9.5 million data points!

Table 4 also shows the results from the individual subsets. Despite the time difference (Δt) between SWH and U measurements being approximately 10 days, while for the crossover analyses the maximum Δt was set to 5 days, the standard deviation of the individual coefficients for the two analysis methods are all of the same order, and explain a similar amount of the total ΔSSH variance.

The model obtained from the TCAi (1° x 1° average) is shown in table 5 and figure 4 shows the mean residuals for both TCOi and TCAi as a function of both ΔSWH and ΔU.

Interestingly, the residuals obtained for the TCOi model do not appear to show any correlation with ΔU, and perhaps only a slight correlation with ΔSWH . In terms of numbers of observations this data set was by far the largest. It seems that the bias estimate is robust for the majority (>1%) of ΔSWH and ΔU conditions.

The residuals from TCAi are slightly larger, also show trends with both ΔSWH and ΔU, and are similar to the TXOf (table new) results shown in figure 3. These results are only slightly improved in the more comprehensive analysis, TCAf, shown in figure 3e, where the mean residuals are ±3 cm at ΔSWH of ±4 m. The residuals as a function of ΔU figure 3f and figure 4d are almost identical. The TCAf SSB model is given in table 5 and shown in figure 3d, and is also < 10 cm for average SWH and U conditions.

During 1999 degradation of the TOPEX altimeter data was noticed and a decision was made to change from the TOPEX Side-A altimeter (Alt-A) to the Side-B (Alt-B) altimeter, which was switched on at the beginning of cycle 236. This has two potential impacts on the current study. First, the impact of the degraded parameters, and second the impact of a new instrument on SSB estimations.

Since cycle 130 through to the switch of of the Alt-A instrument at the end of cycle 235, the main parameter affected was SWH. However, for most applications the degradation gave no significant loss in quality (Dorandeu, 1999).

An investigation into the relative bias (%SWH) for a three-parameter SSB model found that there were no significant differences between the two instruments (Dorandeu, 1999). However, this was obtained with only the first 6 cycles of Alt-B data. Separating the TOPEX data into Alt-A and Alt-B subsets, some differences in the coefficients were found, yet the relative bias remained –2%SWH.

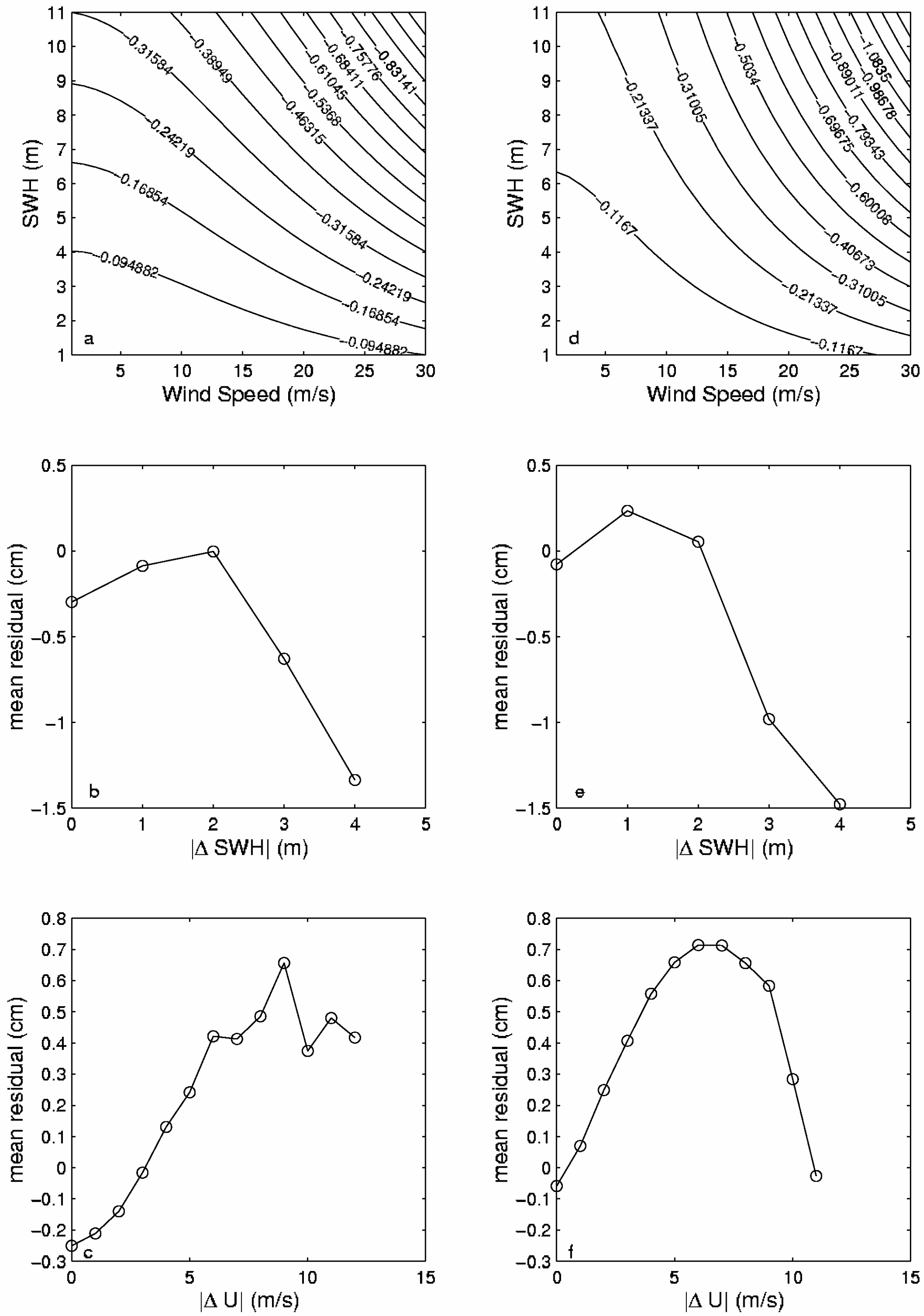

Fig. 3 (a) TXOf sea state bias model as a function of SWH and U and the corresponding mean residuals as a function of (b) ΔSWH and (c) ΔU. (d) TCAf sea state bias model as a function of SWH and U and the corresponding mean residuals as a function of (e) ΔSWH and (f) ΔU.

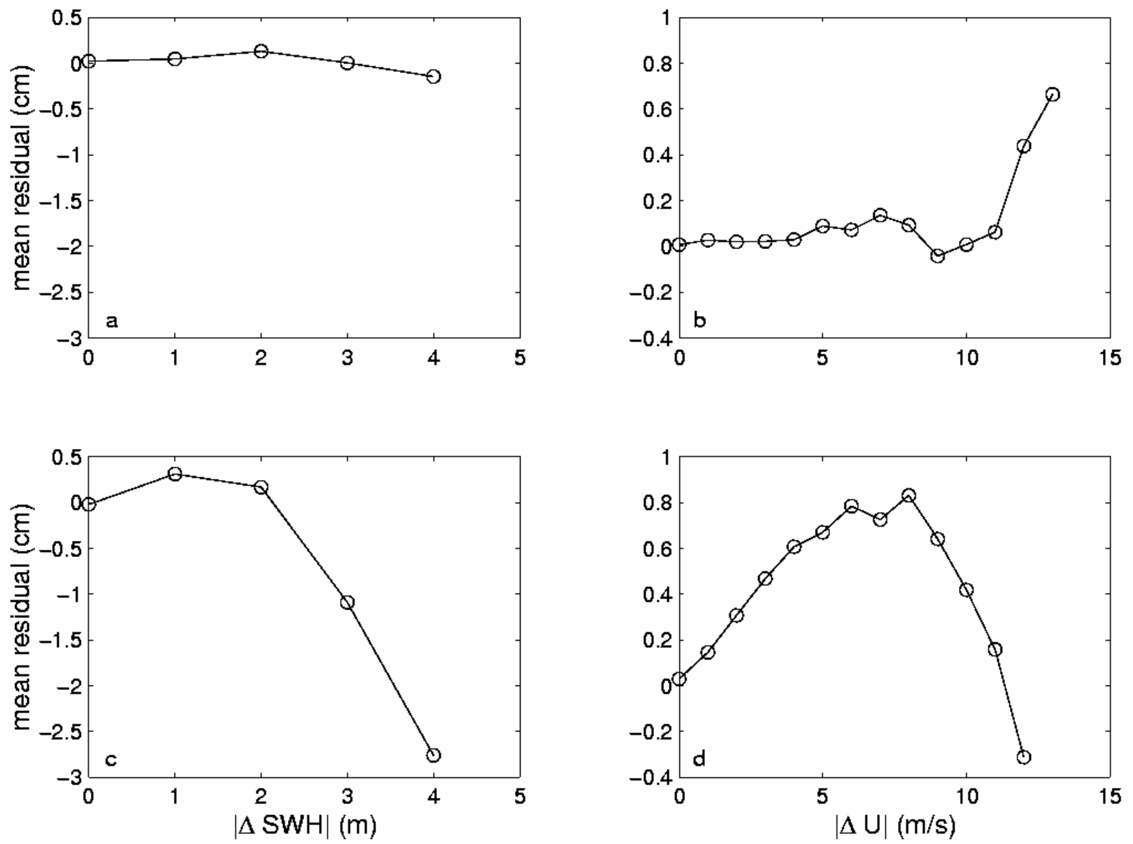

Fig. 4 Mean residuals of regressions as a function of ΔSWH (a and c) and ΔU (b and d) from TOPEX collinear analyses TCOi (a and b) and TCAi (c and d) shown in table 5. The mean residuals are calculated in bins of 1 m for ΔSWH and 1 ms^{-1} for ΔU.

3.2 Poseidon Models

The stringent data selection and editing criteria in the current work resulted in only 52 crossovers for Poseidon cycle 20 compared to X used in the GOLZ94 study. A more comprehensive analysis of Poseidon crossovers for cycles 2-307 gives the PXOf model in table 5, calculated using over 62,000 crossovers (see also figure 5).

The total variance in ΔSSH is higher than that found for TOPEX (TXOf) at 74.41 cm^2, but the Of.

variance explained by the model is 30.45 cm^2 (or 41%). A relative bias of -4.9% SWH is consistent with that of GOLZ94. It is larger than the TOPEX relative bias, due to a larger tracker bias, the instrument-dependent part of the SSB. Mean residuals (not shown) are also consistent with those from the TOPEX analyses, and also yield trends dependent on both ΔSWH and ΔU, with residuals for the latter only slightly larger than those found for TX

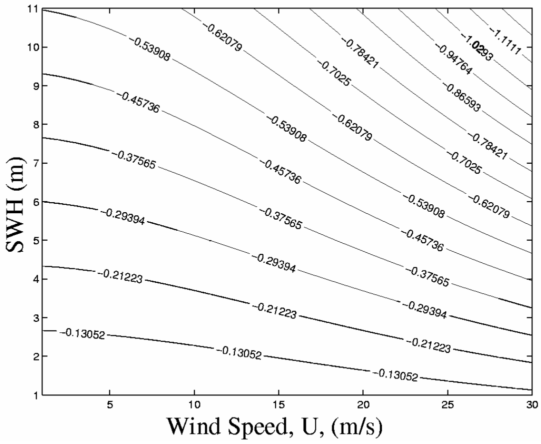

Fig. 5 The Poseidon sea state bias model as a function of SWH and U as calculated from crossovers from cycles 2-307 (PXOf analysis).

3.3 Jason-1 Models

The four-parameter model for Jason-1 crossovers from cycles 2-25 is shown in table 5 and figure 6a, and is based upon almost 120,000 crossovers.

The total variance in ΔSSH is 66 cm^2 and that explained by the JXOf model is 17.49 cm^2 (or 26.5%). When the explained variance is subtracted from the total variance the remaining variance is 48.51 cm^2, and only slightly higher than the total ΔSSH variance of 47.01 cm^2 obtained on the same data when the SSB correction provided with the Jason-1 data was used.

The SSB model calculated for the collinear analysis of Jason-1 data, based on a combined data set from 14 cycle-cycle subsets is shown in table 5. Similar to the TXOi and TCOi analyses, the error estimates for all but the relative bias coefficient are large.

The SSB model calculated for collinear analysis of Jason-1 data, based on a 1° x 1° latitude-longitude average of data from cycles 2-25 is shown in table 5 and figure 6b. The total ΔSSH variance calculated for this model is 73.87 cm^2 and the variance in ΔSSH explained by the model is 14.35 cm^2 (or 19.4%).

The mean residuals for all the Jason-1 models (not shown) are similar to those obtained from the TOPEX (figure 3) and Poseidon analyses.

4 Summary, Conclusions and Further Work

Following GOLZ94, coefficients a_0 through a_3 for a four-parameter model (Eq. 1) were obtained using a subset of TOPEX crossover data (cycles 2-30). The standard deviation of the coefficients provided the error estimate on each coefficient for the initial crossover analysis (TXOi). For all but the a_0 coefficient (the relative bias), these error estimates are large and not very useful. A more appropriate method for determining whether differences between models are significant should be found. This is one goal of future work.

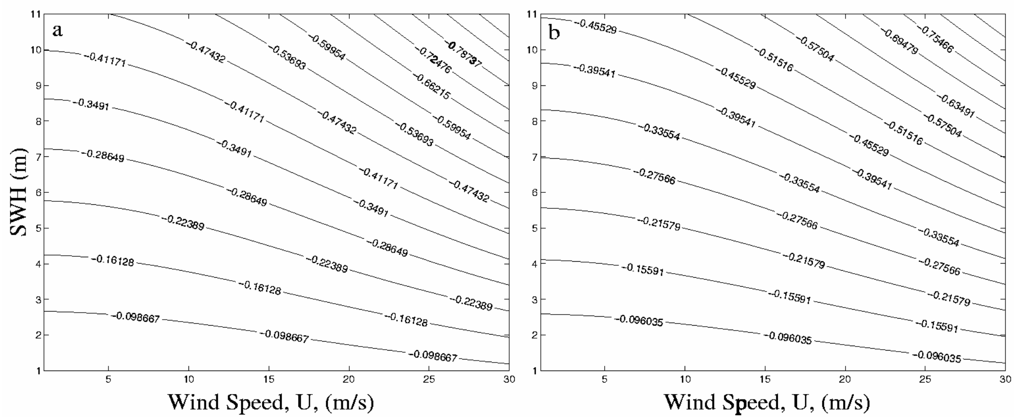

Fig. 6 The Jason-1 sea state bias model as a function of SWH and U, a) calculated from crossovers from cycles 2-25 (JXOf), and b) calculated from the collinear analysis (JCAf) based on averages on a 1° x 1° latitude-longitude grid.

In terms of mean residuals as a function of |ΔSWH| and |ΔU|, the collinear analysis including all data points for cycles 2-30 (TCOi) provided the best model in terms of estimation over the greatest variety of wave conditions. However, the percentage of the total variance explained by the

The model that explained most of the ΔSSH variance was the model based on the comprehensive crossover analysis (TXOf). This was also the case with both Poseidon and Jason-1 altimeters. Since the Jason-1 (JCOi) analysis used data from almost as many cycles as the JXOf data set it does not appear worth the extra computational time to do a 'full' collinear analysis for TOPEX.

The choice of corrections applied to the data did not greatly influence the overall calculations of SSB as was shown in figure 1 and table 6.

The Poseidon sea state bias was found to be -5% SWH, while the best estimate for a Jason-1 four-parameter sea state bias is -4% SWH. Both models explain more of the variations in ΔSSH than the TOPEX four-parameter SSB.

This work provides only an initial study of the Jason-1 data currently available. These data originate from the intermediate geophysical data records (IGDRs) and are currently undergoing calibration and validation. The JXOf four-parameter model explains almost as much of the variance in ΔSSH as the SSB model provided on the IGDRs.

As the mean residuals of most of the SSB models examined here still show some trends with both |ΔSWH| and |ΔU| parameters, SSB models were calculated with different combinations of parameters. This work will be published at a later date.

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TCOi model was slightly lower than the TXOi 'initial' analyses at 10%.

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