Global ocean mean wave period data: Validation and description

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[1] A global comparison of altimeter and ERA-40 mean wave period data is performed for the first time. Altimeter and ERA-40 mean wave period are shown to compare well in non-swell-dominated conditions. Triply collocated altimeter, buoy, and ERA-40 data show that the variance of the random errors is bigger for the ERA-40 data and smaller for the buoy data. A new expression is given to relate altimeter data to wave period in wind-dominated conditions. Provided this correction is applied, altimeter data are adequate for the most needed validation of global model mean wave period data in non-swell-dominated conditions. Triply collocated altimeter, buoy, and ERA-40 also reveal that altimeter mean wave period is reliable even in swell conditions for moderate to high winds, in contrast to previous suggestions which limited its validity to wind-dominated seas.

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1. Introduction

[2] A good description of ocean wave conditions is paramount for the safety of life and structures at sea. The most complete way to describe ocean wave conditions is through directional wave spectra. Although such spectra are available from buoy measurements, wave model results, and satellite-based synthetic aperture radar (SAR) measurements, these are not yet widely used in practice. Design often requires only a synthesized description of the wave spectra by means of the three main integral wave parameters: significant wave height (H_s), mean (zero-upcrossing) wave period (T_m), and mean wave direction. Also, validations and comparisons of observations from different sources are often limited to these quantities.

[3] So far, buoys are considered to provide the most reliable ocean wave observations, being often taken as "sea truth" in comparisons and used directly in design. They are, however, restricted to coastal regions and located mainly in the Northern Hemisphere, offering neither global validation data sets nor global descriptions of wave conditions. Global descriptions of wave conditions can be obtained from wave models and satellite observations. There are, however, questions about the precision and accuracy of both model and satellite observations. For instance, directional wave spectra retrieved from SAR are still considered unreliable. The only reliable satellite-based wave measurements are those retrieved from altimeters, but they have so far been restricted to H_s. There is also the potential to retrieve T_m from altimetry data, but algorithms so far proposed have been received with skepticism. Still, it is desirable to have global measurements of T_m, not only for their description of ocean wave conditions but also for the purpose of validating wave model results of T_m. H_s provides only limited information about the wave spectra, namely about its height and energy. T_m is an important quantity in fatigue design and estimation of ship bending moments, and therefore knowing its precision and accuracy is important.

[4] Recently, a new empirical model has been suggested by *Gommenginger et al.* [2003] to obtain mean wave period measurements from TOPEX altimeter data. The authors postulate, based on heuristic arguments, that T_m is related to

$$P = \left(\sigma_0 H_s^2\right)^{0.25}, \quad (1)$$

where σ_0 is the normalized radar cross section. On the basis of buoy observations they obtain the following linear relationship:

$$T_m = -0.895 + 2.545P. \quad (2)$$

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Gommenginger et al. [2003] also fitted $\log_{10}T_m$ against $\log_{10}P$, and while the log-log model gives better results and is indeed recommended by the authors, it will not be considered here since it changes the nature of the relationship between T_m and P, and may obscure possible insights to be gained by comparing the altimeter data with the ERA-40 data. Assessment of the above model with buoy observations reveals a root-mean square-error (rmse) below 1 s. So far, there has not been any study assessing the validity of this model globally.

[5] The European Centre for Medium-Range Weather Forecasts (ECMWF) has recently completed the computations of the ERA-40 data set, a reanalysis of global meteorological variables, among which are ocean surface wind waves, from September 1957 to August 2002. The reanalysis was produced by ECMWF's Integrated Forecasting System (IFS), which uses variational data assimilation [*Simmons*, 2001]. In terms of sea state data, this reanalysis is the first in which an ocean wind wave model is coupled to the atmosphere. Moreover, its final product consists of the longest and most complete wave data set available. It is given on a $1.5^\circ \times 1.5^\circ$ latitude/longitude grid covering the whole globe. A large subset of the complete ERA-40 data set, including H_s, mean wave period (unfortunately not the mean zero-upcrossing wave period, but the one based on the -1 spectral moment, m_{-1}/m_0), and mean wave direction on a $2.5^\circ \times 2.5^\circ$ latitude/longitude grid can be downloaded from http://data.ecmwf.int/data/d/era40_daily/. The continuous 45-year length of the ERA-40 data set makes it especially suitable to study climate variability and to estimate extreme values of certain wave parameters, for example, the 100-year return wave height [*Caires and Sterl*, 2005b]. As part of the ERA-40 project, we have extensively assessed the quality of the ERA-40 H_s data against buoy, altimeter, and other model data [*Caires and Sterl*, 2003, 2005a; *Caires et al.*, 2004]. However, the validation of ERA-40 T_m data has so far been restricted to comparisons with buoy data. Overall, the results of these validations indicate that ERA-40 data describes the monthly mean of T_m data quite well; the 6-hourly fields compare reasonably well with the buoy data, and four different periods can be identified in terms of its error characteristics:

[6] 1. Data for the periods from September 1957 to November 1991 and from June 1993 to December 1993 had no altimeter H_s data assimilation. The T_m data have in general a rmse below 2 s with the highest errors occurring in the tropics, where along with the North Pacific the periods are overestimated (swell-dominated seas); in the North Atlantic, there is a tendency for underestimation of T_m.

[7] 2. ERS-1 Fast Delivery Product (FDP) altimeter H_s data were assimilated in ERA-40 from December 1991 onward. The data are, however, of poor quality during the first 2 years due to an external processing error. The assimilation was halted as soon as this error was realized, the production having reached May 1993. The problem was detected thanks to the continuous assessment of the produced data against observations, and it was visible in the error statistics of T_m which clearly showed T_m from December 1991 to May 1993 to be systematically overestimated.

[8] 3. Assimilation of ERS-1 altimeter H_s data was resumed in January 1994 using good but uncalibrated ERS-1 FDP data up to May 1996. The known calibration correction to the ERS-1 FDP data was not applied because, even though it would have improved analyzed wave heights, it would have given poorer, too high, T_m data. The quality of the T_m data is indeed quite high, with monthly rmse often below 0.5 s.

[9] 4. FDP ERS-2 measurements of wave height have been assimilated in ERA-40 from June 1996 onward. This assimilation has improved the H_s analyses, especially in the tropics. The mean wave periods compare quite well with observations, although slightly worse than they do for the third period.

[10] In this article, we will use the empirical model proposed by *Gommenginger et al.* [2003] to obtain global T_m observations from TOPEX measurements from June 1993 to December 2001 and compare them with ERA-40 data. We will also estimate the accuracy and precision and identify the restrictions of both data sets using triple collocation of buoy, altimeter, and ERA-40 T_m observations.

2. Data Description and Collocation

[11] The buoy, altimeter and ERA-40 data represent different time and space scales. The ERA-40 reanalysis data comes on a 1.5° by 1.5° grid at synoptic times. The data are representative of the average condition in the area occupied by a grid box. Buoy measurements are available hourly and come from the processing of 20-min records at a single location. Altimeter measurements are available every second and at distances of about 7 km apart. In the following, we will briefly describe how the observations were processed in order to make the time and space scales of the different systems compatible. More details, including the quality controls applied and collocation procedure, are given by *Caires and Sterl* [2003] and *Bidlot et al.* [2002].

[12] The buoy data to be used in this study come from the NOAA database (National Data Buoy Center, http://seaboard.ndbc.noaa.gov/). From all the NOAA data buoy locations available during the period of interest, we have selected a total of 17: one off the coast of Peru (buoy 32302), three in the Gulf of Mexico (42001, 42002, and 42003), four in the Northwest Atlantic (41001, 41002, 41010, and 44004), two off the coast of Alaska (46001 and 46003), three in the northeast Pacific (46002, 46005, and 46006), and four around the Hawaiian Islands (buoys 51001, 51002, 51003, and 51004). Only deep water locations were chosen, since no shallow water effects are accounted for in the wave model; we also require them not to be too close to the coast in order for the corresponding model grid point to be located at sea. The buoy T_m measurements are available hourly from 20-min-long records. Quality-checked buoy hourly time series of T_m are used to produce a new time series at synoptic times by averaging the data over 3 hours around synoptic times.

[13] The TOPEX along-track altimeter measurements of H_s and σ_0 were obtained from Southampton Oceanography Centre (SOC) (GAPS interface; see http://www.soc.soton.ac.uk/ALTIMETER/, [*Snaith*, 2000]). From these we form satellite "super observations" by grouping together the consecutive quality checked deep water observations crossing a 1.5° by 1.5° latitude-longitude region. The TOPEX wave height observations from 1997 to 1999 (cycles 170 to

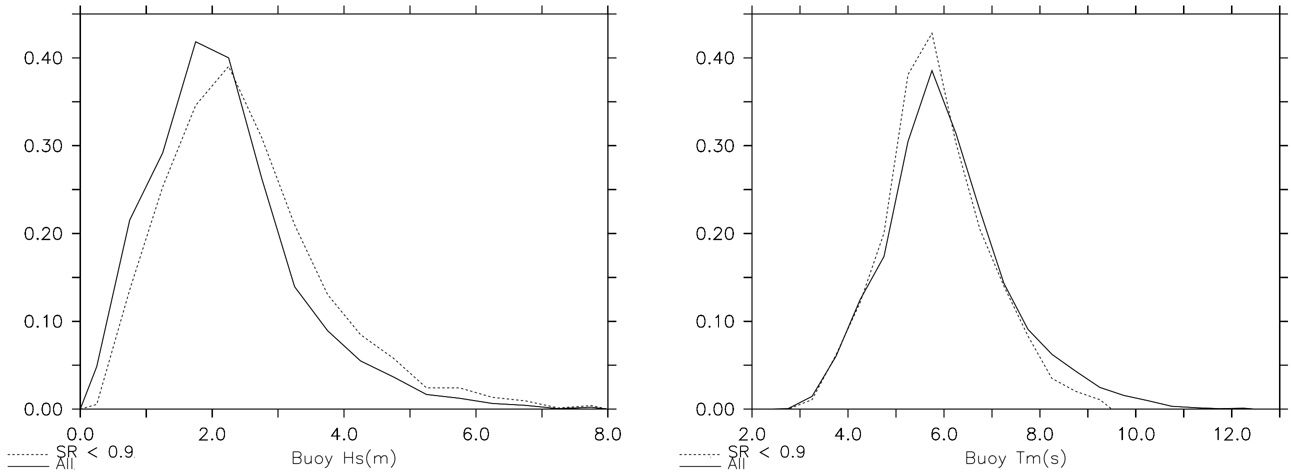

Figure 1. Histograms of buoy data that were collocated with the TOPEX and ERA-40 data. The solid lines correspond to the whole data set, and the dashed lines correspond to data for which $SR < 0.9$. (left) H_s. (right) T_m.

235) have drifted; the drift is corrected according to P. Challenor and D. Cotton (Trends in TOPEX significant wave height measurement, 1999, available as pdf document at http://www.soc.soton.ac.uk/JRD/SAT/TOPtren/TOPtren.pdf). Once this drift is corrected for, we assume the TOPEX H_s measurements to be consistent from January 1993 to December 2001. Besides this there were no further corrections applied to the raw data.

[14] When collocating buoy, satellite, and ERA-40 data, we chose the satellite super observations created from altimeter observations within a 1.5° by 1.5° latitude-longitude region centered at the buoy location. The ERA-40 data at the synoptic times before and after the time of the satellite super observation is interpolated bilinearly to the buoy location, and these two data points are then linearly interpolated in time to the time of the super observation. The buoy synoptic data are also linearly interpolated to the time of the super observation. The resulting data set has a total of 3715 triple observations, of which 60% are in swell-dominated conditions. The panels of Figure 1 present histograms of H_s and T_m for the whole data set and excluding the swell-dominated cases.

[15] Collocations with ERA-40 data were performed using ERA-40 T_m products easily available to users, rather than by trying to match up the buoy observations with the ERA-40 wave spectra, which are not easily available to users outside ECMWF. Since T_m is calculated as $\sqrt{m_0/m_2}$, the use of T_m to characterize sea state is sensitive to the spectral cut-off chosen to calculate the spectral moments. A typical cut-off frequency for wave buoys is around 0.4–0.5 Hz, corresponding closely to the maximum frequency reported in the wave model used in ERA-40—WAM [*WAMDI Group*, 1988]. However, it has emerged that the spectral moments used to calculate the standard ERA-40 T_m (zero-upcrossing) products are calculated by integrating the model wave spectra up to infinity and assuming an f^{-5} high-frequency tail (J.-R. Bidlot, personal communication, 2004). When comparing buoy T_m measurements (which have a cut-off around 0.5 Hz and no high-frequency tail) against T_m computed from ERA-40 wave spectra with and without high-frequency tail, for the period January 2001 to August 2002, the positive bias (overestimation) of the ERA-40 T_m relative to the buoy measurements is reduced by 0.33 s when the high-frequency tail is included in the calculations of ERA-40 T_m (J.-R. Bidlot, personal communication, 2004). The effect of the high-frequency tail on the standard deviation is, however, negligible. The precise origin of this result is still unclear and would warrant further investigation. For the purpose of this paper, however, we proceed with the standard ERA-40 T_m product. The reader should keep in mind that the bias between the buoy and ERA-40 T_m would be more positive if the frequency cut-off of ERA-40 and the buoys were made to match. (Intuitively, it is easy to grasp that if energy is added to the spectrum at high frequencies then the mean wave period estimate decreases. What is not so obvious is how much this reduction of mean wave period will be. Let m^*_i denote m_i computed without the tail; m_i refers to the i-th spectral moment computed with the tail. The tail contribution to m_i is given by $\int_{f_0}^{\infty} \frac{S(f_0)}{f_0^{-5}} f^{i-5} df = \frac{f_0^{i+1} S(f_0)}{(4-i)}$ for $0 \le i \le 4$, where f_0 is the frequency at which the tail is added. In terms of relative weight of the tail, $w_i = \frac{m_i - m_i^*}{m_i}$, the lower i is, the lower w_i is, so the effect of using the tail will be greater in those parameters which involve higher moments. Using buoy spectra from 1996 to 2001, we found that the addition of the tail would provide a negligible average contribution to $H_s = 4\sqrt{m_0}$, an average contribution of 0.16 s to the mean wave period based on the first moment (m_0/m_1), and an average contribution of 0.32 s to the mean wave period based on the second moment ($\sqrt{m_0/m_2}$), the one considered in this study.)

3. Triple Data Comparison and Error Analysis

[16] We start by comparing the collocated ERA-40 and TOPEX observations. Figure 2 compares global ERA-40 and TOPEX observations in 2 months of the period considered. The situation in these 2 months is representative of what happens in other months. Although there seems to be some correspondence between the altimeter and ERA-40 data, the correspondence is quite poor: The scatter is rather large. The correlation between the data sets in different months is always below 60%.

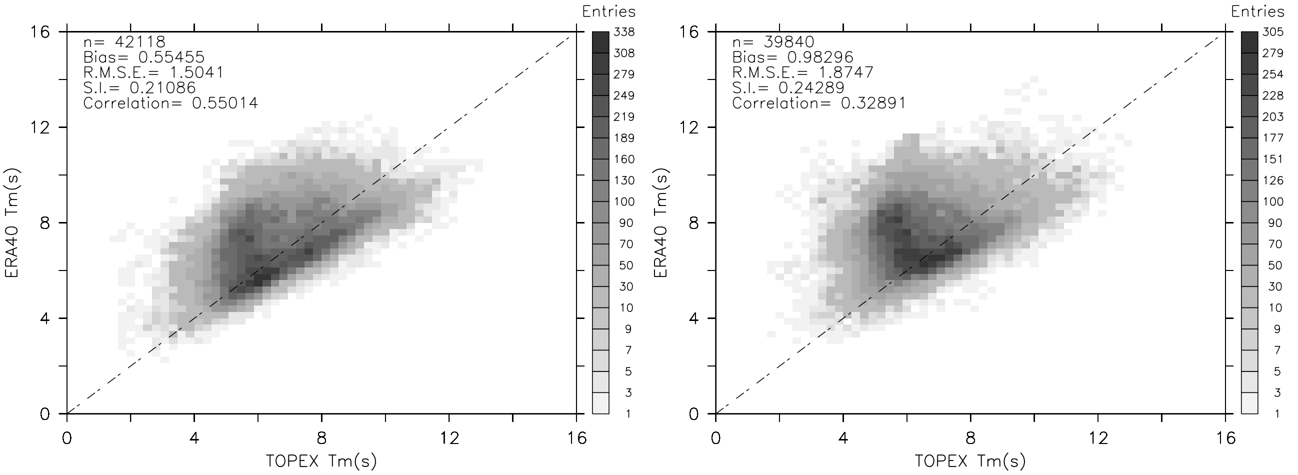

Figure 2. Scatter diagrams of TOPEX and ERA-40 T_m data for (left) May 1994 and (right) January 2001.

[17] Because their model compares better with buoy observations from the Gulf of Mexico than with buoy observations around Hawaii, *Gommenginger et al.* [2003] suspected that their model may not work so well in swell conditions. Also, our validations of the ERA-40 data against buoy data show that ERA-40 tends to overestimate the period in swell-dominated sea states, especially in the Pacific Ocean [*Caires and Sterl*, 2001]. This overestimation is due mainly to the insufficient damping of swell energy (islands that are small relative to the model's resolution are missed, and swell energy that in reality is damped by these islands travels undamped in the model; other possible explanations are currently under investigation) and to a modeling deficiency which hinders wind sea growth in the presence of swell (J.-R. Bidlot, personal communication, 2004). Since there are reasons to believe that both data sets are faulty in swell-dominated sea states, we have removed those observations from the data set. We have informally defined swell-dominated sea states as sea states for which the "swell ratio" (*SR*), the ratio between the ERA-40 swell wave height and the ERA-40 H_s, is greater than or equal to 0.9. (In WAM, the part of the wave spectrum that is under direct influence of the wind, the wind sea part of the spectrum, is defined by $1.2\ (28/c)\ u_* \cos(\theta - \theta_w) \geq 1$, where $c = c(f)$ is the phase speed of the wave with frequency f, u_* is the friction velocity (if τ is the surface stress then $\tau = u_*^2 = C_d * U_{10}^2$, where C_d is the drag coefficient and U_{10} the 10 m wind speed), θ is the propagation direction of the wave and θ_w is the wind direction. What is not wind sea is then classified as swell. Note that with the finite frequency range used in WAM, there might be cases for which the condition for wind sea is never satisfied and therefore WAM returns zero wind sea energy.) Figures 3 and 4 compare ERA-40 and TOPEX observations for which $SR \geq 0.9$ and $SR < 0.9$, respectively, for the same 2 months considered in Figure 2. The figures show that restricting the data to sea states in which $SR < 0.9$, the correspondence between the ERA-40 and the TOPEX T_m data is indeed quite good. This is true for all the data considered, and monthly correlations between the two fields are always above 80%. In swell-dominated seas the altimeter and the ERA-40 data show little correspondence. The

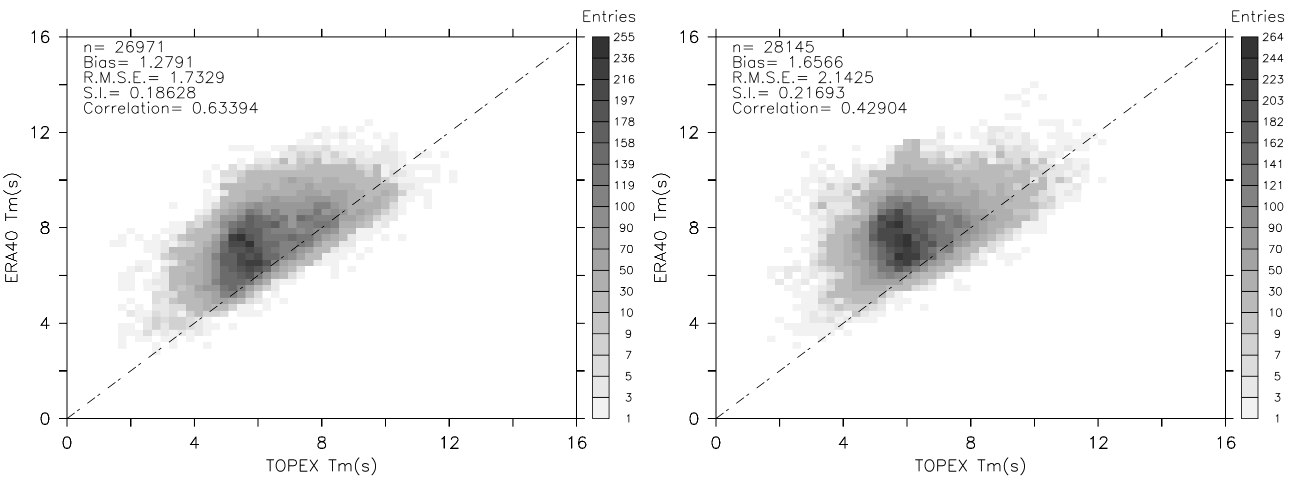

Figure 3. Scatter diagrams of TOPEX and ERA-40 T_m data for (left) May 1994 and (right) January 2001 including only observations for which $SR \geq 0.9$.

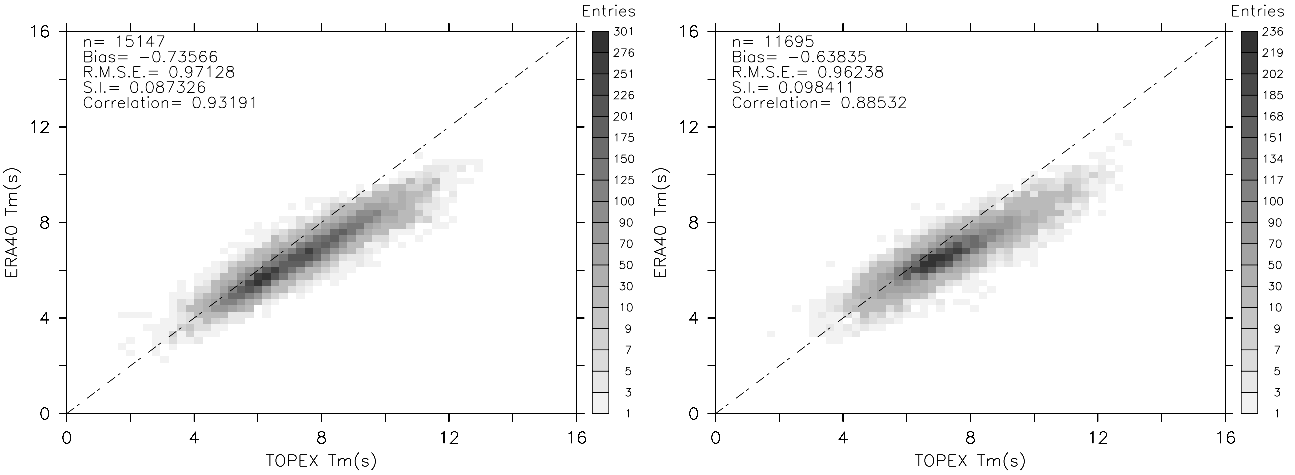

Figure 4. Scatter diagrams of TOPEX and ERA-40 T_m data for (left) May 1994 and (right) January 2001 including only observations for which SR < 0.9. Equations (1) and (2) were used to obtain the TOPEX data.

criterion SR < 0.9 rejects about 60% of the whole data set, but the coverage of the data is still global. Figure 5 shows, at each ERA-40 location and in each of the 2 months considered, the percentage of data which comply with SR < 0.9. The two panels in Figure 5 illustrate how the number of cases for which SR < 0.9 varies depending on season (summer/winter) and hemisphere. Regions in the tropics display the smallest amount of data complying with the low swell (SR < 0.9) criterion, and display little seasonal variability. In the Antarctic Ocean, the low swell criterion is valid all year round, thus confirming that the Antarctic Ocean features wind-dominated seas all year round [*Young*, 1999]. Figures 4 and 5 show that even though no Antarctic Ocean data were used in the development of the altimeter wave period model, the ERA-40 and TOPEX T_m can be expected to give comparable results globally.

[18] In spite of the evident agreement, Figure 4 shows that even when restricting our attention to sea states in which SR < 0.9, there is still an offset between ERA-40 and TOPEX. In order to check which of the two types of data is more accurate, we need to resort to buoy data.

[19] The presence of three data sets makes it possible not only to estimate systematic errors between the data sets, but also to estimate the variance of the random errors of each data set [*Stoffelen*, 1998]. We will proceed by computing functional relationship estimates between collocated buoy, altimeter, and ERA-40 data and by estimating their random error variances using the model proposed by *Caires and Sterl* [2003]. For completeness, we will present the model formulation and its estimators.

[20] Given three sets of n observations (x_i, y_i, z_i), i = 1, .., n, it is assumed that these observations correspond to measurements of certain deterministic underlying variables, T_i, i = 1, .., n, made with certain systematic deviations and subject to zero mean, independent random errors (e_{xi}, e_{yi}, e_{zi}), i = 1, .., n. More precisely, omitting the indexes in the subscripts, the model is

$$x = X + e_x \equiv T + e_x$$

$$y = Y + e_y \equiv \alpha_1 + \beta_1 T + e_y$$

$$z = Z + e_z \equiv \alpha_2 + \beta_2 T + e_z.$$

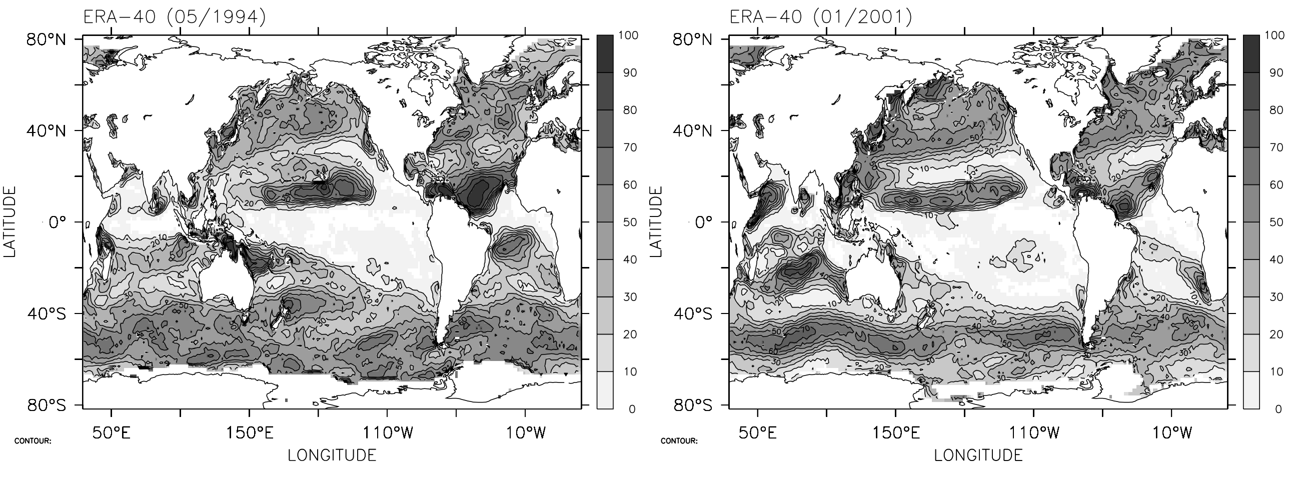

Figure 5. Percentage of observations for which SR < 0.9 in (left) May 1994 and (right) January 2001.

Table 1. Estimates, for Different Years, of the Functional Relationship Coefficients Between ERA-40(x), Buoy(y), and TOPEX(z) T_m Observations, and of the Variances of the Errors[a]

Year	n	$\langle x \rangle$	α_1	β_1	α_2	β_2	α_3	β_3	$\langle e_x^2 \rangle$	$\langle e_y^2 \rangle$	$\langle e_z^2 \rangle$
1993	122	5.38	0.92	0.91	−1.35	1.36	1.82	0.67	0.26	0.07	0.11
			(0.57,1.27)	(0.84,0.98)	(−1.93,−0.76)	(1.25,1.48)	(1.59,2.06)	(0.62,0.72)	(0.19,0.33)	(0.00,0.14)	(0.02,0.19)
1994	221	5.44	1.03	0.90	−1.18	1.35	1.81	0.67	0.18	0.07	0.11
			(0.64,1.41)	(0.82,0.97)	(−1.70,−0.65)	(1.24,1.45)	(1.56,2.05)	(0.62,0.71)	(0.11,0.24)	(0.01,0.12)	(0.03,0.19)
1995	181	5.24	0.64	0.97	−1.47	1.41	1.65	0.69	0.19	0.11	0.11
			(0.24,1.04)	(0.89,1.06)	(−2.03,−0.92)	(1.30,1.53)	(1.35,1.96)	(0.63,0.75)	(0.11,0.28)	(0.01,0.20)	(0.02,0.19)
1996	192	5.51	0.26	1.02	−2.08	1.50	1.68	0.68	0.21	0.06	0.17
			(−0.14,0.66)	(0.95,1.10)	(−2.66,−1.50)	(1.39,1.61)	(1.42,1.93)	(0.64,0.73)	(0.13,0.28)	(0.00,0.15)	(0.08,0.26)
1997	165	5.58	0.33	0.99	−1.03	1.30	1.11	0.76	0.23	0.08	0.14
			(−0.04,0.71)	(0.92,1.06)	(−1.56,−0.49)	(1.20,1.39)	(0.81,1.42)	(0.71,0.81)	(0.15,0.30)	(0.02,0.14)	(0.06,0.22)
1998	154	5.67	0.65	0.92	−0.35	1.20	0.91	0.76	0.19	0.09	0.07
			(0.23,1.07)	(0.84,0.99)	(−0.80,0.11)	(1.11,1.29)	(0.57,1.25)	(0.70,0.82)	(0.12,0.26)	(0.02,0.16)	(0.00,0.15)
1999	151	5.42	0.61	0.93	−1.56	1.39	1.66	0.67	0.26	0.08	0.12
			(0.07,1.16)	(0.83,1.03)	(−2.28,−0.84)	(1.25,1.52)	(1.27,2.05)	(0.61,0.74)	(0.17,0.35)	(0.02,0.15)	(0.02,0.22)
2000	121	5.67	0.27	1.01	−1.65	1.39	1.47	0.72	0.23	0.07	0.19
			(−0.32,0.87)	(0.89,1.12)	(−2.38,−0.93)	(1.26,1.53)	(1.07,1.86)	(0.66,0.79)	(0.15,0.31)	(0.00,0.16)	(0.08,0.29)
2001	179	5.66	0.21	1.01	−1.80	1.40	1.51	0.72	0.20	0.08	0.13
			(−0.26,0.69)	(0.92,1.10)	(−2.42,−1.17)	(1.28,1.52)	(1.16,1.85)	(0.66,0.78)	(0.09,0.30)	(0.00,0.19)	(0.02,0.24)
all	1486	5.50	0.59	0.95	−1.38	1.37	1.56	0.70	0.22	0.08	0.13
			(0.43,0.76)	(0.92,0.99)	(−1.59,−1.17)	(1.32,1.41)	(1.44,1.67)	(0.68,0.72)	(0.18,0.26)	(0.04,0.13)	(0.09,0.18)

[a]The limits of the confidence intervals are given in parentheses below the estimates. The sample size, n, and the average of the ERA-40 data, $\langle x \rangle$, are also included. Year 1993 only comprises data from June to December. All results are based on data for which $SR < 0.9$.

Estimators of the parameters (indicated by hats) can be obtained as

$$\hat{\beta}_1 = \langle y^* z^* \rangle / \langle x^* z^* \rangle,$$

$$\hat{\beta}_2 = \langle y^* z^* \rangle / \langle x^* y^* \rangle,$$

$$\hat{\alpha}_1 = \langle y \rangle - \beta_1 \langle x \rangle,$$

$$\hat{\alpha}_2 = \langle z \rangle - \beta_2 \langle x \rangle,$$

$$\left\langle \hat{e}_x^2 \right\rangle = \left\langle x^{*2} \right\rangle - \langle x^* y^* \rangle \langle x^* z^* \rangle / \langle y^* z^* \rangle,$$

$$\left\langle \hat{e}_y^2 \right\rangle = \left\langle y^{*2} \right\rangle - \langle x^* y^* \rangle \langle y^* z^* \rangle / \langle x^* z^* \rangle,$$

$$\left\langle \hat{e}_z^2 \right\rangle = \left\langle z^{*2} \right\rangle - \langle x^* z^* \rangle \langle y^* z^* \rangle / \langle x^* y^* \rangle,$$

where $\langle \rangle$ denotes the average of the variables and * indicates the variable minus its mean.

[21] One feature of this model is its symmetric nature: The result of applying the model to data is independent of which variables are chosen to be x, y, or z. In particular, this implies that from the above expressions one can compute the coefficients in the relationship between Y and Z, $Y = \alpha_3 + \beta_3 Z$, as $\alpha_3 = \alpha_1 - \alpha_2\beta_1/\beta_2$ and $\beta_3 = \beta_1/\beta_2$.

[22] Table 1 presents, for sea states in which $SR < 0.9$, estimates of the triple collocation functional relationship along with their confidence intervals (estimated using the bootstrap method) for the different years for which the data are available and considering all data together. In 1993 only data from June to December were considered because until May 1993 the ERA-40 ocean wave data had faulty ERS-1 fast delivery product (FDP) H_s data assimilated. The characteristics of the ERA-40 T_m data changed further during the period considered due to the assimilation of different altimeter data. These changes, however, had no great impact in the estimates presented in Table 1 in the different years considered, so from now on we will concentrate only on the estimates obtained from the whole data set.

[23] Undoubtedly, the buoy measurements are the most precise, with the standard deviation of their random errors being about 0.28 s. The slope coefficients (and intercepts) between ERA-40 and buoy data, β_1 (α_1), are closer to unity (zero) than those between the TOPEX and buoy data, β_3 (α_3), thus indicating that the ERA-40 data compare better than the TOPEX data with the buoy measurements. However, the TOPEX data have lower random errors than the ERA-40 data, the former having a standard deviation of about 0.36 s, and the latter having a standard deviation of about 0.47 s. Figure 6 presents the scatter diagrams of the comparisons between the three data sets from June 1993 to December 2001. Superimposed are the functional relationship lines obtained from the parameter estimates given in the last line of Table 1.

[24] Assuming that the functional relationship found between the buoy and altimeter data from June 1993 to December 2001 is valid globally, and referring to the corrected TOPEX measurements as $T_m^{t'}$, we have

$$T_m^{t'} = 1.6 + 0.7 T_m^t, \tag{3}$$

and substituting equation (2) in equation (3), we get

$$T_m^{t'} = 0.97 + 1.78P. \tag{4}$$

We propose this equation, instead of equation (2), to be used to obtain altimeter T_m measurements in sea states in which $SR < 0.9$.

[25] Equation (3) was used to correct the T_m^t data in Figure 4. The result is shown in Figure 7. The correction naturally did not change the correlation between the ERA-40 and the TOPEX data, but it reduced the average difference between the two data sets and almost halved the rmse between the two to about half a second. This is an excellent agreement between the data sets, although limited to non-swell-dominated conditions.

[26] We have used equations (1) and (4) to obtain altimeter T_m observations from altimeter measurements of

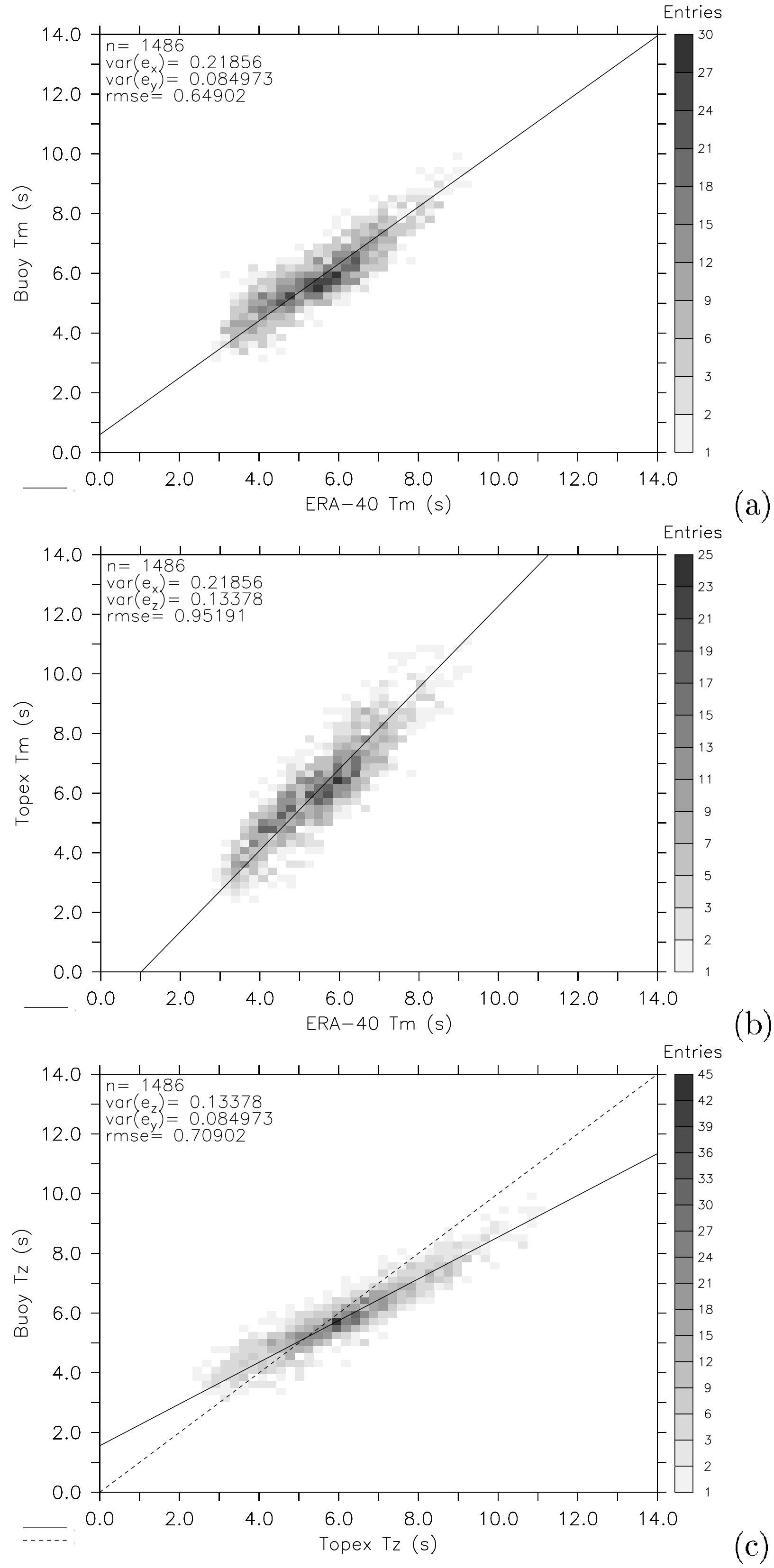

Figure 6. Scatter diagrams with estimated FR models (solid lines) for T_m triple collocation of ERA-40, buoy, and TOPEX data from June 1993 to December 2001 including only observations for which $SR < 0.9$. (a) ERA-40 versus buoy, (b) ERA-40 versus TOPEX, and (c) TOPEX versus buoy. The dashed line in Figure 6c represents the calibration of *Gommenginger et al.* [2003] obtained for all wind and swell conditions.

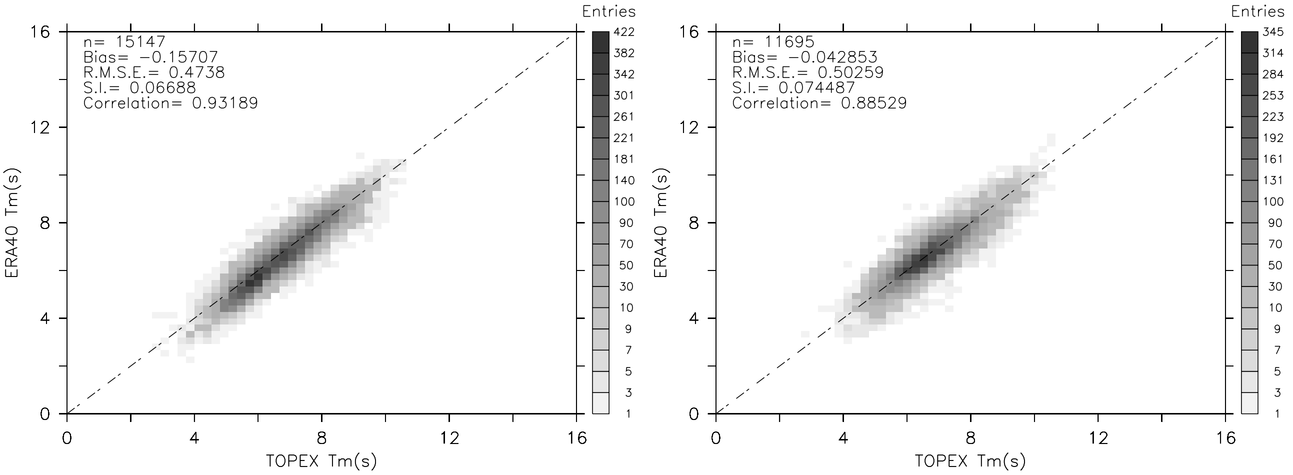

Figure 7. Scatter diagrams of TOPEX and ERA-40 T_m data for (left) May 1994 and (right) January 2001. Only data for which $SR < 0.9$ and equations (1) and (4) were used to obtain the TOPEX data.

H_s and σ_0 from 1993 to 2001 and then computed the rmse between the altimeter and the ERA-40 data in non-swell-dominated conditions ($SR < 0.9$). The results are presented in Table 2 for the different years and for different ocean basins. The table also presents the percentage of data considered in each basin which obeys the $SR < 0.9$ criterion. The comparisons are worse for 1993, when the ERA-40 data suffers from the assimilation of faulty ERS-1 altimeter H_s observations from January to June. The comparisons do not vary much in the following years, the global rmse being always below 0.5 s. The comparisons seem to depend on the ocean basin being considered, with the higher rmse being found in the North Atlantic and Pacific.

4. Discussion

[27] *Gommenginger et al.* [2003] proposed a model to obtain T_m measurements from altimeter data. The definition of the model involved calibrating altimeter measured quantities against buoy T_m observations from 1993 to 1998 (equation (2)). We compared TOPEX T_m data obtained using their method with ERA-40 data from 1993 to 2001. Using swell information from ERA-40, we found that the ERA-40 and TOPEX T_m data are well correlated in wind-dominated seas (corresponding to some 40% of the global ocean conditions) but compare poorly in swell-dominated conditions. Analysis using triple buoy/ERA-40/TOPEX collocations indicated that further calibration of TOPEX T_m against buoy data was necessary (equation (3)) when considering only data from wind-dominated sea conditions. After correction, the rmse between TOPEX and ERA-40 is less than 0.5 s for wind-dominated sea conditions globally.

[28] To explain the difference between the two calibration equations (equations (2) and (3)), we note that in the *Gommenginger et al.* [2003] study all sea states were considered while here we have only considered sea states for which $SR < 0.9$, and that the error characteristics of the model depend on the sea state. Figure 8 presents the scatter diagrams of the comparisons between the three data sets considering all sea states. The functional relationships obtained from the restricted triple data set for which $SR < 0.9$ are superimposed in the plots and were not used at this stage to calibrate the data. It is clear that the relationships found do not fit well the whole triple data set. This has to do with the fact that both the errors characteristics of the ERA-40 and TOPEX data are nonlinear; that is, the errors in swell-dominated sea states are different from those excluding these cases. Indeed, when considering all the data, the calibration line of *Gommenginger et al.* [2003] does fit the data better (dashed line in Figure 8c). However, a simple line should not be used to fit all the data. The plot clearly shows that the scatter of the data is not symmetrical. The points previously removed are to the top right of the data considered in the estimation; that is, the *Gommenginger et al.*

Table 2. RMSE Between the ERA-40 and the TOPEX T_m Data[a]

	North Atlantic	Tropical Atlantic	South Atlantic	North Pacific	Tropical Pacific	South Pacific	Indian	Antarctic	Global
1993	0.62	0.51	0.55	0.65	0.56	0.60	0.52	0.54	0.57
1994	0.58	0.42	0.50	0.56	0.46	0.47	0.46	0.44	0.48
1995	0.58	0.41	0.51	0.55	0.46	0.48	0.46	0.44	0.48
1996	0.53	0.38	0.48	0.54	0.44	0.48	0.46	0.44	0.47
1997	0.54	0.28	0.49	0.56	0.47	0.48	0.45	0.44	0.47
1998	0.55	0.37	0.49	0.56	0.46	0.50	0.45	0.44	0.47
1999	0.52	0.38	0.48	0.54	0.44	0.49	0.46	0.45	0.47
2000	0.54	0.37	0.46	0.54	0.44	0.49	0.44	0.45	0.47
2001	0.55	0.40	0.50	0.55	0.47	0.51	0.46	0.45	0.48
Data, %	37.8	22.0	27.5	32.5	15.5	19.7	22.9	50.7	32.1

[a]All results are based on data for which $SR < 0.9$; the percentage of data obeying this criterion is given in the last line of the table. Equations (1) and (4) were used to obtain the TOPEX data.

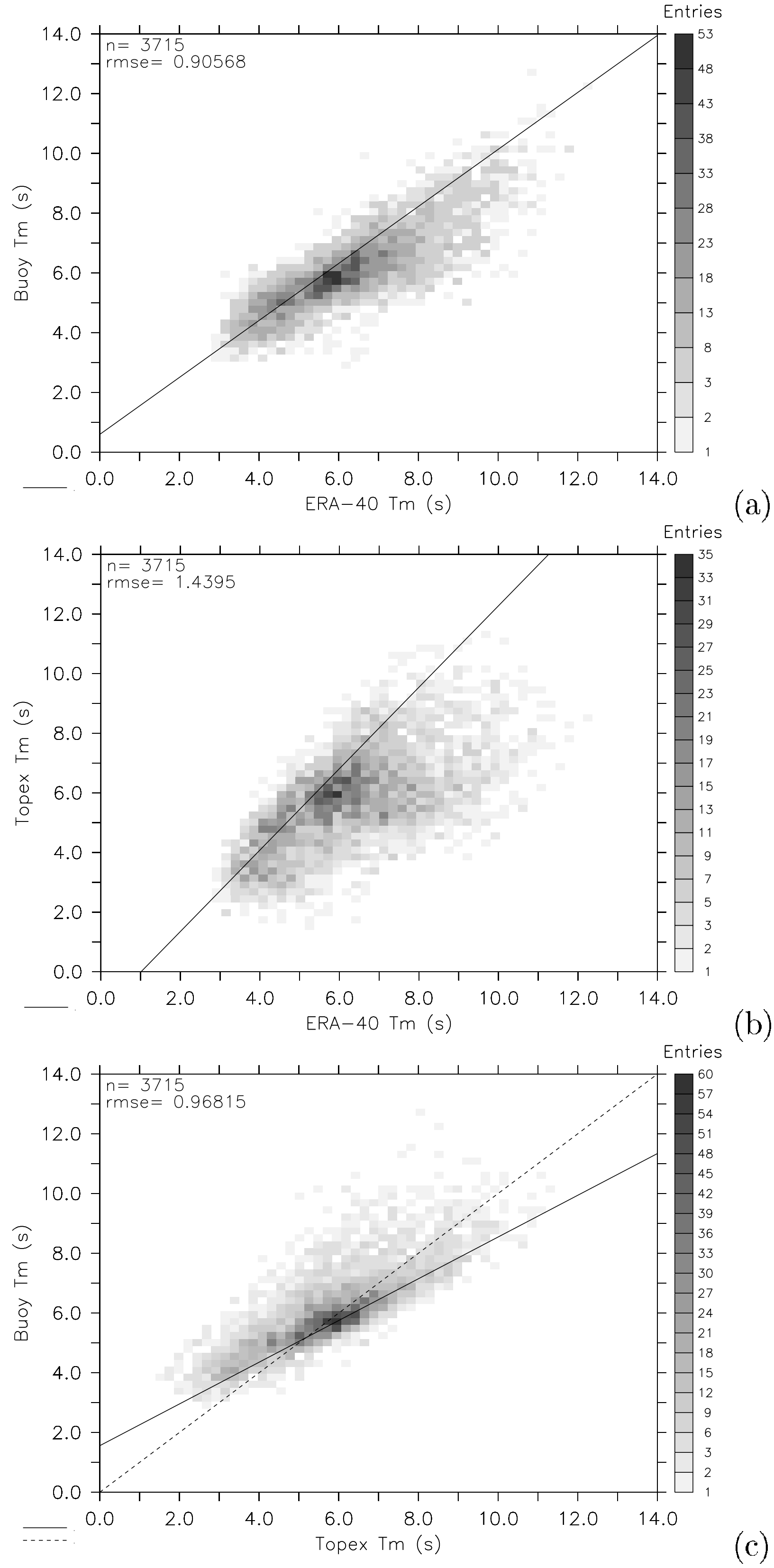

Figure 8. Scatter diagrams for T_m triple ERA-40, buoy, and TOPEX collocated data from June 1993 to December 2001. (a) ERA-40 versus buoy, (b) ERA-40 versus TOPEX, and (c) TOPEX versus buoy. The solid lines are the FR models estimated based on data for which $SR < 0.9$. The dashed line in Figure 8c represents the calibration of *Gommenginger et al.* [2003].

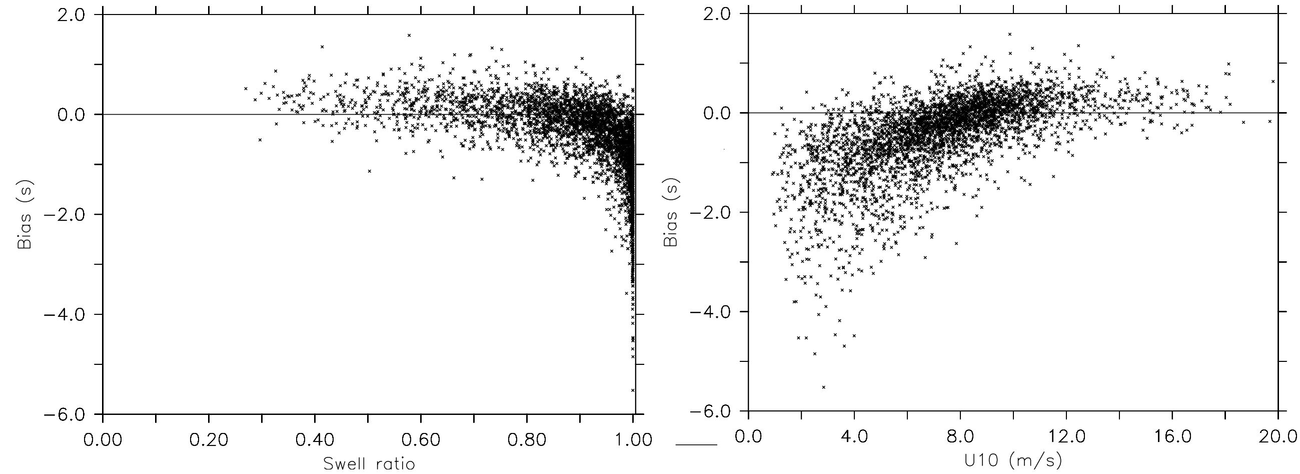

Figure 9. Bias of the TOPEX T_m data versus (left) *SR* and (right) U_{10}.

[2003] model underestimates T_m in swell-dominated sea states.

[29] In order to understand the dependence of the errors on the sea state in the model of *Gommenginger et al.* [2003], we need to look further into how they come up with equation (1). Two assumptions were used in its derivation. First, according to *Barrick* [1974], at nadir, the altimeter radar cross section is inversely proportional to the sea surface mean square slope of the long waves, S^2. Second, the sea surface mean slope is assumed to be proportional to H_s/T_m^2. There is some sea state dependence in the second assumption, since it is assumed that the mean square slope is equivalent to the mean slope squared. Hence both hypotheses may be questionable in the case of swell-dominated conditions, and depending on what roughness length scale one believes controls the radar cross section at nadir. If we believe the dependence of the error on sea state comes from the first assumption, one could expect T_m to be underestimated by equation (1) in swell-dominated seas associated with low-speed winds. In these cases, the small-scale roughness on the surface would attenuate the microwave radar cross section (without affecting H_s), resulting in a larger computed slope and therefore a lower T_m. Another interpretation is that wind and wave measurements from buoys are not reliable in low wind with swell conditions, or that the spectral resolution of the buoy is insufficient to observe those high-frequency components. If our first explanation for the provenance of the nonlinear error structure of the TOPEX T_m observations is correct, then removing observations from sea states at low wind speeds should also be an effective way of removing the underpredicted TOPEX T_m observations.

[30] This hypothesis is supported by evidence in the collocated buoy/altimeter data (not shown), in which outliers are indeed associated with low wind speeds and large wave periods. Similarly, Figure 9 shows the dependence of the TOPEX T_m bias (TOPEX observation minus the respective buoy T_m observations) on *SR* and on the TOPEX 10-m wind speed, U_{10}, computed from the TOPEX σ_0 observations using the algorithm of *Gourrion et al.* [2002]. The TOPEX T_m error dependence on *SR* indicates that removing all the observations for which $SR \geq 0.9$ is probably too

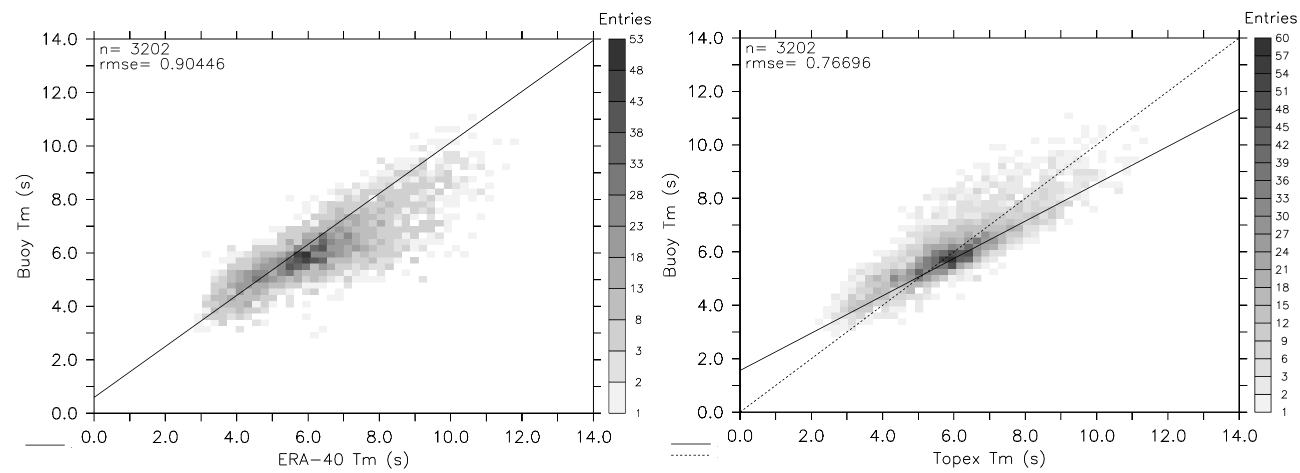

Figure 10. Scatter diagrams with estimated FR line for T_m triple ERA-40, buoy, and TOPEX collocated data from June 1993 to December 2001. (left) ERA-40 versus buoy. (right) TOPEX versus buoy. Only data for which $U_{10}{}^t > 4$ m/s were used.

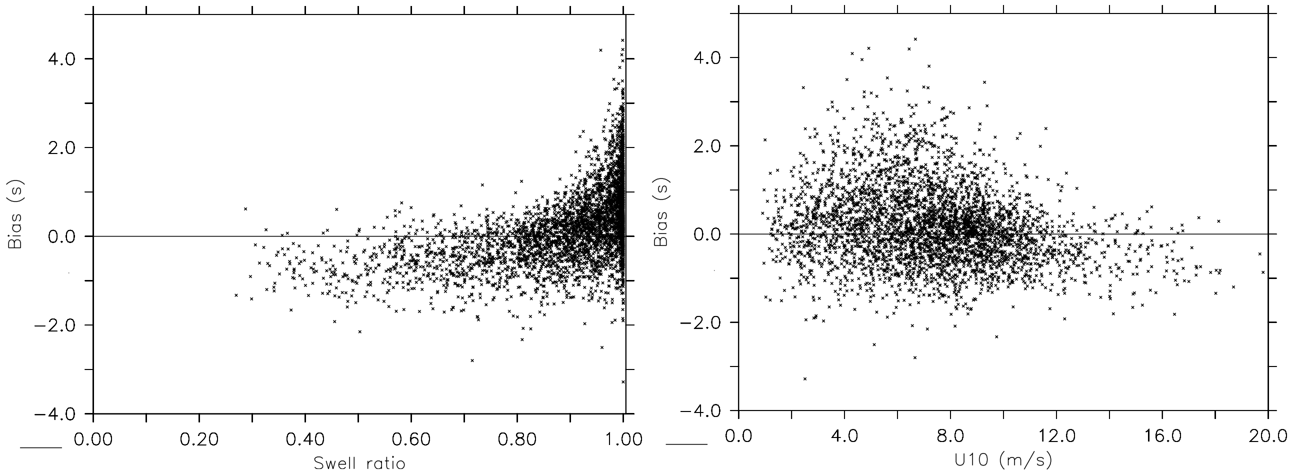

Figure 11. The same as Figure 9 but for ERA-40 data.

stringent. This can also be inferred by comparing Figures 6 and 8. When considering all sea states (Figure 8) the agglomeration of data in the most populated region increased, indicating that good observations were excluded in the comparisons of Figure 6. The above result, that most of the altimeter T_m measurements in swell-dominated conditions are not faulty, is quite an important one and could not be seen just from buoy/TOPEX comparisons, and shows that triple collocation provides a better understanding of what is going on.

[31] The TOPEX T_m error dependence on U_{10} (right panel of Figure 9) indicates that a less wasteful way of removing bad observations would be to exclude observations for which U_{10} < 4 m/s, removing only 14% of the data as compared to 60% in the case of the SR criterion. We note, however, that this wind speed based discrimination is not ideal since it will eliminate perfectly valid wave period measurements at low wind speed while allowing occasional outliers for wind speeds above 4 m/s. It is questionable also whether it is appropriate to use an altimeter wind speed criterion given the known wave age related bias in altimeter wind speed models (including *Gourrion et al.* [2002]; see *Gommenginger et al.* [2002]). Nevertheless, a quality criterion for the data produced by the *Gommenginger et al.* [2003] model depending solely on U_{10} is much more desirable than a criterion depending on *SR*, since U_{10} can be inferred from altimeter data but *SR* cannot.

[32] Figure 10 presents the scatter diagrams of the triple collocated buoy, TOPEX, and ERA-40 data for which TOPEX observations of U_{10} are above 4 m/s. Comparing the panel of TOPEX versus buoy data of Figure 10 with that of Figure 8, we can conclude that we succeeded in removing most of the outlying observations. However, when we compare the panels of ERA-40 versus buoy data in the two figures, we see that most of the outlying ERA-40 T_m observations were not removed. This leads us to conclude that the bias of the ERA-40 data, although depending on *SR*, does not depend on U_{10}, or at least that it is not larger at low wind speeds. This conclusion is confirmed by Figure 11. Our inability to use the ERA-40 T_m data in combination with the TOPEX T_m data in swell-dominated seas makes it impossible to validate further the TOPEX T_m data using the ERA-40 data.

5. Conclusions

[33] We compared ERA-40 and newly derived TOPEX T_m data with the objective of defining reliable global data sets for T_m. On the basis of a swell ratio criterion derived from ERA-40, we found good agreement between TOPEX and ERA-40 T_m in non-swell-dominated sea states.

[34] Triple buoy/TOPEX/ERA-40 collocations helped to establish the relationship between altimeter and buoy wave period measurements under different sea conditions. We found that the relationship proposed by *Gommenginger et al.* [2003], derived for both wind seas and swell-dominated conditions, needs adjusting in order to be applicable to wind sea conditions data alone. After correction, global rmse under 0.5 s were obtained between TOPEX T_m and ERA-40 for wind-dominated conditions. These conditions represent some 40% of cases and exhibit global geographical distribution.

[35] Combined use of ERA-40, buoy, and altimeter information helped establish that the altimeter wave period model can offer reliable measurements even in swell conditions for moderate to high winds (above 4 m/s). This challenges previous suggestions [*Gommenginger et al.*, 2003] which limited the validity of altimeter wave period to wind-dominated seas. In the case of swell in low wind conditions, the altimeter model still underestimates T_m. A criterion based on altimeter wind speed was tentatively proposed as a way to assess the quality of altimeter T_m from satellite data alone. The nature of the errors in the TOPEX and ERA-40 T_m made it impossible to perform comparisons in swell-dominated sea states.

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