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Technical Note

An intercomparison of GEOSAT, TOPEX and ERS1 measurements of wind speed and wave height

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Abstract

Mean monthly values of altimeter wind speed and wave height are compared with data from NDBC buoys. As a result of these comparisons, corrections are made to the raw data products available from these satellites. Data from the GEOSAT, TOPEX and ERS1 missions corrected in this fashion are used to show that there have been no measurable changes in the global wind and wave climate during the 10 years spanned by these various missions. It is proposed that the corrected values of wind speed and wave height provide the basis for the formation of a long-term global data base which spans the periods of these multiple missions.

Keywords: Wind; Waves; Satellite; Altimeter; Remote Sensing

1. Introduction

Global values of wind speed and wave height can be obtained from satellite-based radar altimeters. Such data are invaluable for applications including long term climate

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studies and engineering design. As satellites generally have a relatively short life (less than 5 years), the long-term data set must be obtained from a series of satellites. As a result, it is important to ensure that each satellite altimeter is accurately calibrated. Cotton and Carter (1994) have compared mean monthly altimeter values of significant wave height, H_s, from GEOSAT, TOPEX and ERS1 with both buoy data and each other. Their results show that the use of mean monthly values is an acceptable method for the calibration of such instruments. This technique has the advantage that exact colocation with buoys is not required and that satellites with no temporal or spatial overlap can be intercompared.

The present study follows the same approach as that of Cotton and Carter (1994) except that wind speed intercomparisons are considered in addition to significant wave height. Also, the satellite data periods for TOPEX and ERS1 are significantly longer, resulting in greater confidence in the derived mean monthly values.

2. Satellite data

Satellite data were compiled for the GEOSAT, TOPEX and ERS1 altimeters. Data from the following periods were utilized:

- GEOSAT (Geophysical Data Records): November 1986 to January 1990;
- TOPEX (Merged Geophysical Data Records): September 1992 to October 1995;
- ERS1 (CERSAT OPR Data Products): August 1991 to August 1995.

Hence the GEOSAT and TOPEX data each span periods of a little over 3 years whereas the ERS1 data spans 4 years. Young (1994) and Young and Holland (1996) have shown that a period of 3 years is sufficiently long to form reliable global estimates of mean monthly values of wind speed, U_{10} and significant wave height, H_s.

The data sets were independently scanned, data suspected to be erroneous were rejected using the criteria set by Young and Holland (1996) and values of H_s and the radar cross-section, σ_0, were binned into $4° \times 4°$ squares. The values of σ_0 were then converted to U_{10} using a combination of the Chelton and Wentz (1986) ($U_{10} < 20$ m/s) and Young (1993) ($U_{10} \geq 20$ m/s) wind speed algorithms.

Mean month values of U_{10} and H_s were then formed for each of the $4° \times 4°$ squares.

3. Buoy data

Data from a total of 16 NDBC buoys were analyzed. Buoys were selected such that neither the buoy data nor the satellite data, from a corresponding $4° \times 4°$ square, would be influenced by proximity to shore. The locations of the buoys selected are shown in Fig. 1. Details of the buoy locations and the available data for the periods spanned by each of the three satellites are shown in Table 1. The buoy data were partitioned into periods corresponding to each of the three satellite periods and monthly means determined for each of these periods. Buoy 46004 was only oper-

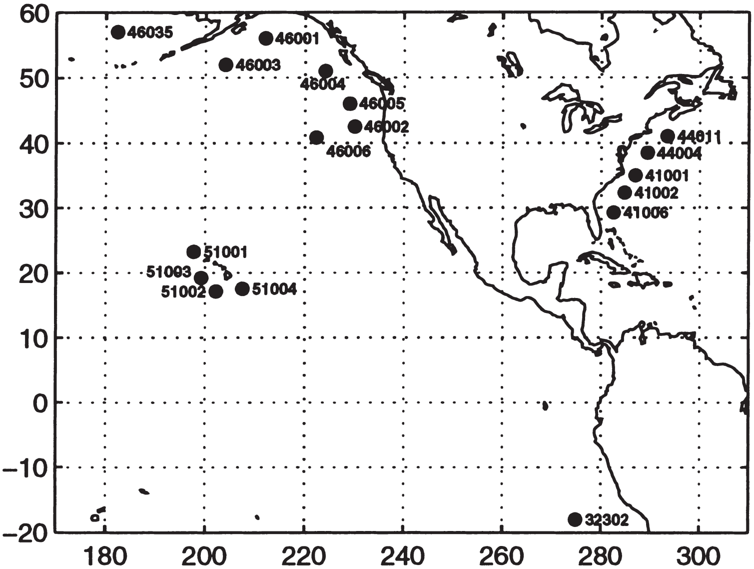

Fig. 1. Locations of the NDBC buoys used for the comparison of U_{10} and H_s values with GEOSAT, TOPEX and ERS1 satellite altimeter values.

ational during the GEOSAT mission. Although the other buoys have periods where data were not available, all buoys had sufficiently long records to produce statistically reliable estimates of mean monthly values of U_{10} and H_s corresponding to each of the satellite periods.

The buoys selected in Table 1 measure wind speed at a variety of heights above mean sea level and also use averaging periods of both 2 and 8.5 minutes. As the altimeter wind speed algorithm used here determines the wind speed at a height of 10 m, U_{10}, a boundary layer correction has been applied to estimate U_{10} from the buoy observations. Following Simiu and Scanlan (1978) a power law representative of the marine boundary layer has been adopted:

$$U_{10} = U_x\left(\frac{10}{x}\right)^{0.11} \tag{1}$$

where x is the anemometer measurement height.

Adoption of an appropriate averaging period for comparison with the satellite altimeter data is complicated by the fact that none of the studies used to develop relationships between wind speed and radar cross-section (Brown et al., 1981; Fedor and Brown, 1982; Chelton and McCabe, 1985; Goldhirsh and Dobson, 1985; Chelton and Wentz, 1986; Dobson et al., 1987; Witter and Chelton, 1991; Freilich and Dunbar, 1993) have stated the averaging period used for their respective calibration data sets. As 2-minute mean values are commonly used, this has been adopted for the present study. Wind speed averaging periods can be related by (Simiu and Scanlan, 1978)

Table 1
Summary of the NDBC buoy data. Quantities shown include: the reference number of the buoy, the location of the buoy (latitude, longitude), the number of months of data available during the periods of each of the satellite missions and the percentage of this data collected using the GSBP payload package

Buoy Number	Latitude °N	Longitude °E	GEOSAT		TOPAX		ERS1	
			Months of Data	Percent GSBP	Months of Data	Percent GSBP	Months of Data	Percent GSBP
32302	−18.0	274.9	39	0	32	0	45	0
41001	35.0	288.0	35	97	33	0	44	0
41002	32.3	284.7	35	80	38	0	47	0
41006	29.3	282.6	30	100	37	0	43	0
44004	39.0	289.5	37	89	37	0	46	0
44011	41.1	293.5	38	97	32	0	42	0
46001	56.3	211.7	39	100	34	0	47	4
46002	42.5	229.7	33	100	38	0	48	0
46003	51.9	204.3	34	79	33	0	44	0
46004	51.0	224.0	20	100	0	–	0	–
46005	46.0	229.0	38	100	35	0	46	0
46006	40.6	222.4	35	49	38	0	39	0
46035	57.0	182.4	38	21	38	24	49	24
51001	23.3	197.7	35	100	36	100	46	100
51002	17.2	202.2	32	100	34	100	45	100
51003	19.2	199.2	33	100	38	100	49	100
51004	17.5	207.5	30	100	38	100	49	100
			GSBP = 82%		GSBP = 27%		GSBP = 28%	

$$U_{10}(t) = U_{10}(3600)\left[1 + \frac{0.98c(t)}{\ln(10/z_0)}\right] \tag{2}$$

where $U_{10}(t)$ is the wind speed averaged over a period of t, U_{10} (3600) is the wind speed averaged over a period of 1 hour (3600 s), z_0 is the surface roughness length and $c(t)$ is a coefficient which varies with the averaging time t and the turbulence level. Adopting $z_0 = 0.05$ m, $c(2) = 2.8$ and $c(8.5) = 2.4$ (Simiu and Scanlan, 1978) yields the averaging period correction $U_{10}(2)/U_{10}(8.5) = 1.05$ which has been utilized for the present data.

4. Satellite–buoy data comparisons

Cotton and Carter (1994) have shown that the comparison of buoy and satellite mean monthly values is a valid method for the calibration of satellite altimeter values of H_s. The use of mean monthly values greatly increases the available data as colocated measurements in both space and time are not required.

Fig. 2 shows a comparison between buoy mean monthly values of H_s and the GEOSAT mean monthly values. A total of 203 points were available from the 16 buoys. A least-squares linear regression yields the result

$$H_s(\text{buoy}) = 1.144H_s(\text{GEOSAT}) - 0.148 \tag{3}$$

This result is shown in Fig. 2. Carter et al (1992) compared GEOSAT values of H_s with data from 13 NDBC buoys and concluded that GEOSAT values were consistently low by 13% (i.e. H_s(buoy) = 1.13H_s(GEOSAT)). This result is also shown in Fig. 2 and is clearly in close agreement with the present data as represented by Eq. (3). This agreement adds confidence that the use of mean month values, together with a satellite averaging region of 4° × 4° yield reliable results.

Fig. 3 shows the comparison between buoy mean monthly values of H_s and the TOPEX mean monthly values. Based on the 192 available values a linear regression yields

$$H_s(\text{buoy}) = 1.067H_s(\text{TOPEX}) - 0.079 \tag{4}$$

As shown in Fig. 3 this result is in excellent agreement with the result obtained by Cotton and Carter (1994), based on a smaller data set (i.e. H_s (buoy) = 1.089 H_s(TOPEX)-0.172).

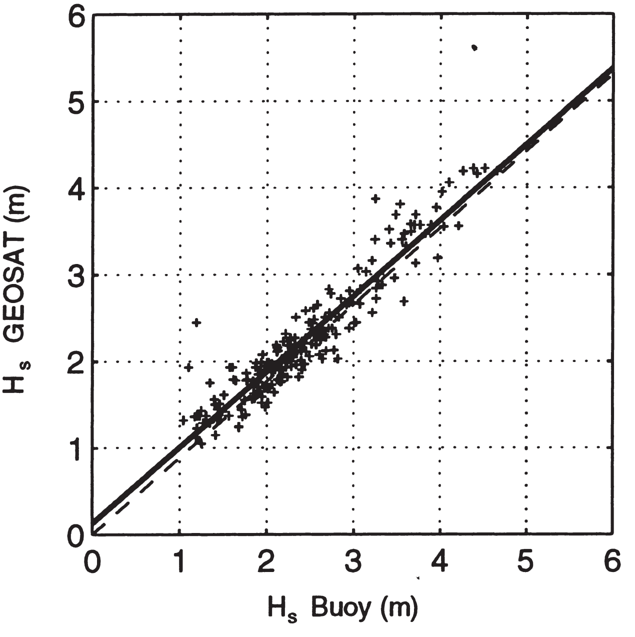

Fig. 2. Mean monthly values of buoy H_s compared with mean month values of GEOSAT altimeter H_s. The solid line is Eq. (3) and the dashed is the relationship proposed by Carter et al (1992).

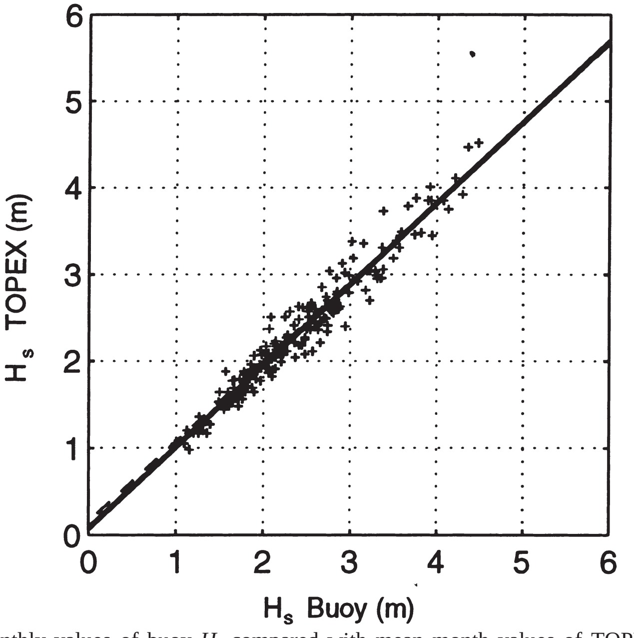

Fig. 3. Mean monthly values of buoy H_s compared with mean month values of TOPEX altimeter H_s. The solid line is Eq. (4) and the dashed is the relationship proposed by Cotton and Carter (1994).

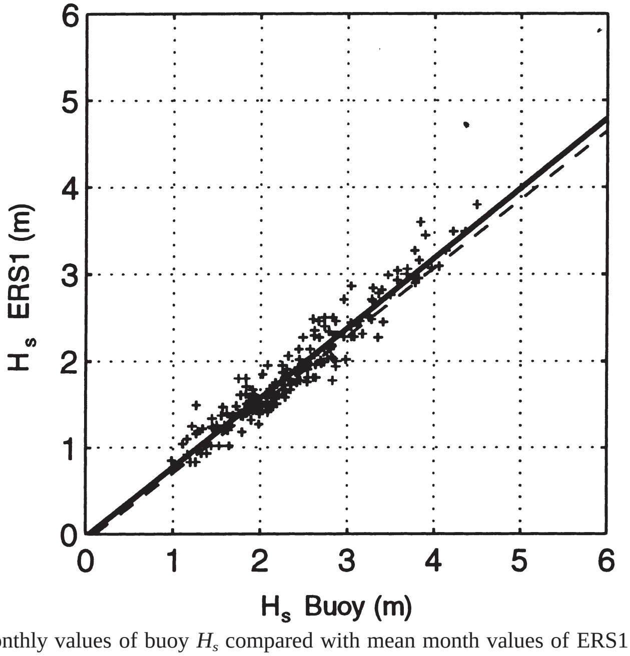

Fig. 4. Mean monthly values of buoy H_s compared with mean month values of ERS1 altimeter H_s. The solid line is Eq. (5) and the dashed is the relationship proposed by Cotton and Carter (1994).

The ERS1 intercomparison is shown in Fig. 4. Based on the 192 points in the intercomparison a linear regression yields

$$H_s(\text{buoy}) = 1.243H_s(\text{ERS1}) + 0.040 \tag{5}$$

This result is again in very good agreement with the result obtained by Cotton and Carter (1994) (i.e. $H_s(\text{buoy}) = 1.267H_s$ (ERS1) + 0.107).

Fig. 5 shows the comparison between buoy mean monthly values of U_{10} and GEOSAT values. A linear regression yields the result (196 points)

$$U_{10}(\text{buoy}) = 0.874U_{10}(\text{GEOSAT}) + 0.337 \tag{6}$$

Forcing the regression through zero yields $U_{10}(\text{buoy}) = 0.913U_{10}(\text{GEOSAT})$, apparently indicating that buoy data is approximately 9% lower than the GEOSAT observations. Such a result appears at variance with the large number of validations performed for GEOSAT wind speed data. Indeed, the relationship between altimeter σ_0 and U_{10} utilized in this study (Chelton and Wentz, 1986) was developed for GEOSAT data.

As shown in Table 1, the vast majority of the buoy data available during the GEOSAT mission were obtained with the GSBP buoy sensor package. The GSBP

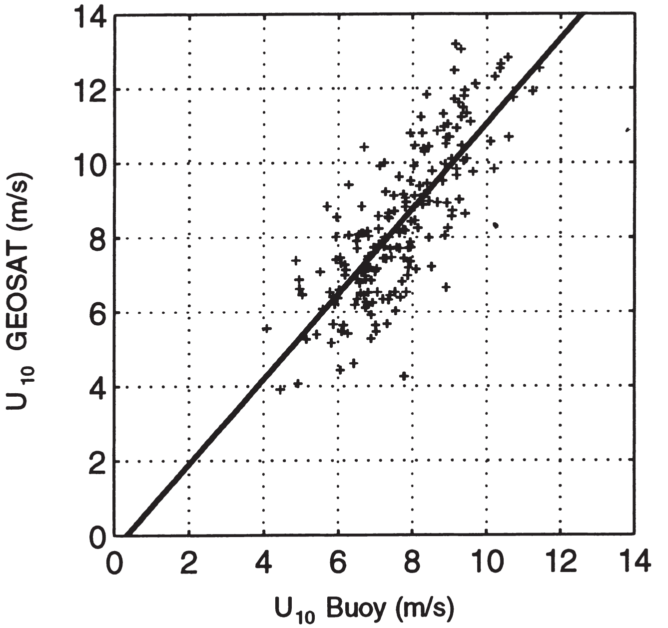

Fig. 5. Mean monthly values of buoy U_{10} compared with mean month values of GEOSAT altimeter U_{10}. The solid line is Eq. (6).

package determined wind speeds using a vector average, whilst later sensor packages (i.e. those available during the TOPEX and ERS1 missions) used a simple scalar average. Gilhousen (1987) has reported that NDBC buoy wind speeds calculated using the GSBP vector averaging method are approximately 7% low. A similar result has been reported by Gower (1996). Hence, Eq. (6) should be treated with caution, the apparent difference between GEOSAT values of U_{10} and buoy results probably being due to the manner in which the buoy wind speed was determined.

Fig. 6 shows the comparison between TOPEX mean monthly values of U_{10} and buoy values (190 points). The TOPEX values of U_{10} are clearly lower than the buoy data, consistent with the recommendation by Callahan et al. (1994) that TOPEX values of σ_0 should be reduced by 0.7 dB. A linear regression to the data of Fig. 6 gives

$$U_{10}(\text{buoy}) = 0.943U_{10}(\text{TOPEX}) + 1.847 \quad (7)$$

Fig. 7 shows the intercomparison between mean monthly buoy values of U_{10} and ERS1 values. A linear regression based on 192 points gives

$$U_{10}(\text{buoy}) = 0.849U_{10}(\text{ERS1}) + 1.217 \quad (8)$$

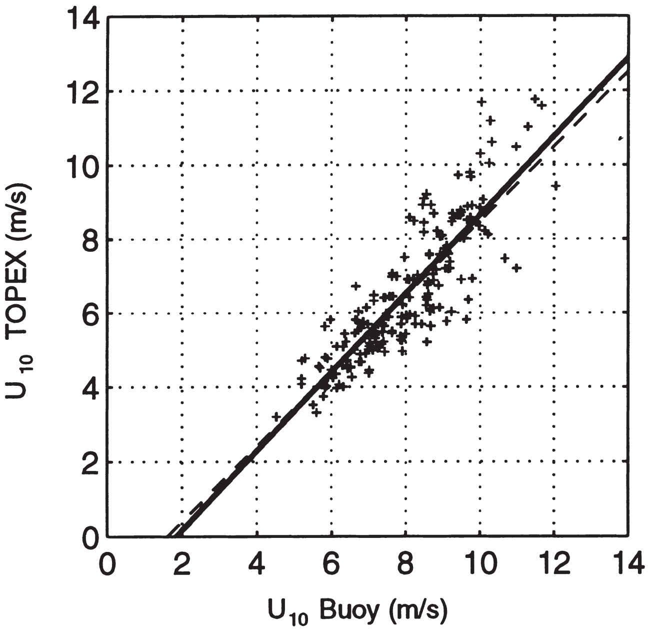

Fig. 6. Mean monthly values of buoy U_{10} compared with mean month values of TOPEX altimeter U_{10}. The solid line is Eq. (7) and the dashed line is Eq. (10).

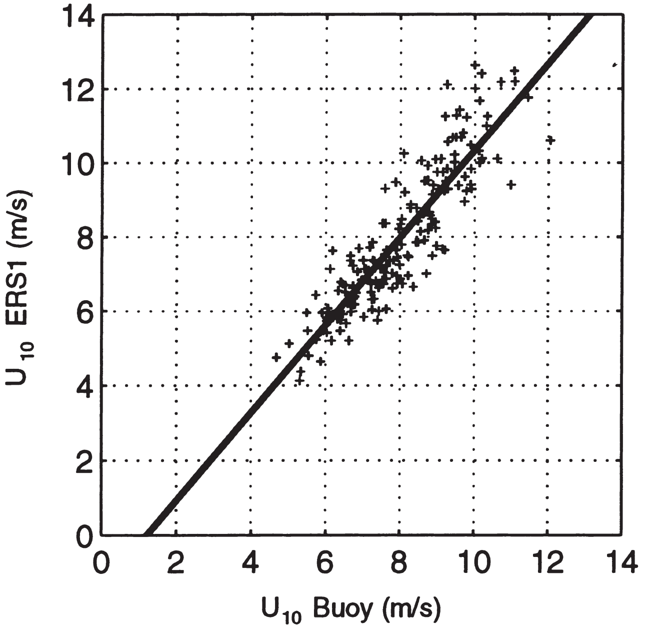

Fig. 7. Mean monthly values of buoy U_{10} compared with mean month values of ERS1 altimeter U_{10}. The solid line is Eq. (8).

Close inspection of the data shows that the large zero offset in Eq. (8) is largely a result of the scattered values above approximately 10 m/s. If these values are excluded from the fit and the regression is forced to pass through zero, an acceptable fit to the data can be achieved with the result

$$U_{10}(\text{buoy}) = 0.998U_{10}(\text{ERS1}) \tag{9}$$

Eq. (9) indicates that the ERS1 values of U_{10} are unbiased.

5. Satellite–satellite data comparisons

Adopting the calibration relationships developed in Section 4, it is possible to carry out cross-validations between the satellite missions. Examining all the $4° \times 4°$ squares on the Earth's surface, a total of 15,095 were identified which had sufficient passes of the respective satellites to yield reliable mean monthly values of H_s. Eqs. (3)–(5) were applied to the respective raw values of the satellite H_s and the mean

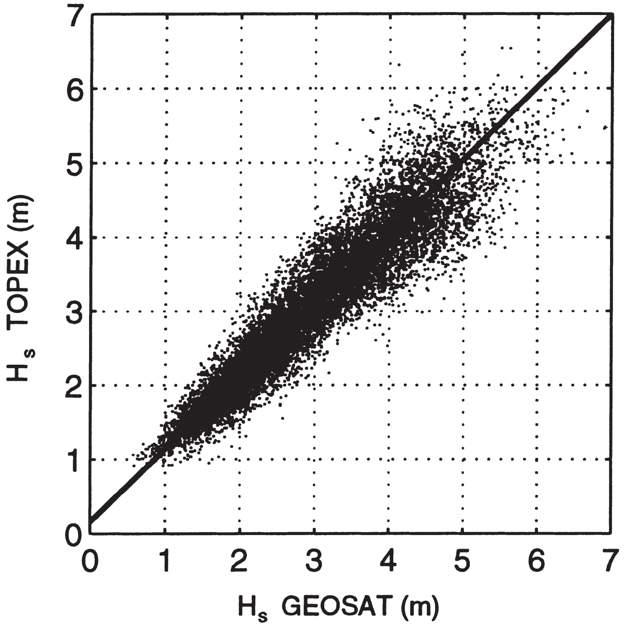

Fig. 8. Global mean monthly values of corrected GEOSAT altimeter H_s compared with mean monthly values of corrected TOPEX altimeter H_s. The solid line is the regression result H_s(TOPEX) = 0.978H_s(GEOSAT) + 0.158.

monthly values determined. The results are shown in Fig. 8 (GEOSAT vs. TOPEX), Fig. 9 (GEOSAT vs. ERS1) and Fig. 10 (ERS1 vs. TOPEX). Linear regression for these data sets yield the results: H_s(TOPEX) = 0.978H_s(GEOSAT) + 0.158, H_s(ERS1) = 0.998H_s(GEOSAT) + 0.046 and H_s(TOPEX) = 0.980H_s(ERS1) + 0.111. These results indicate that for all practical purposes the three satellite missions have recorded the same global average wave conditions. This is not surprising for TOPEX and ERS1 as the mission periods analyzed largely overlap. There is, however, no overlap between these satellites and GEOSAT. Hence, the present results indicate that there has been no measurable change in the global wave field over the period of time spanned by the satellite missions. This is consistent with the conclusions of Cotton and Carter (1994). Not surprisingly, the comparisons between GEOSAT and TOPEX, and GEOSAT and ERS1 have greater scatter than between ERS1 and TOPEX since the latter satellites largely overlap.

A similar intercomparison can be carried out between satellite values of U_{10}. As the global mean monthly wave fields measured by the various satellites are essentially the same, the global mean monthly wind fields could also be expected to be the same. As altimeter measurements of U_{10} are less reliable than altimeter measurements of H_s (Young and Holland, 1996), the global 4° × 4° data set is smaller,

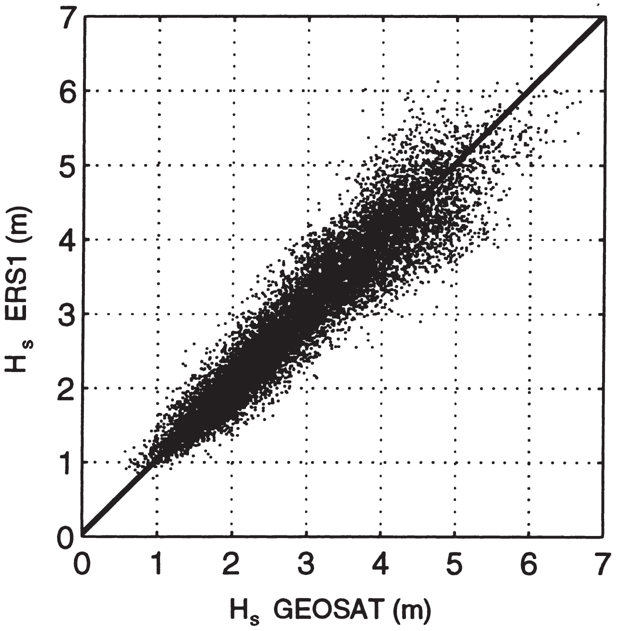

Fig. 9. Global mean monthly values of corrected GEOSAT altimeter H_s compared with mean monthly values of corrected ERS1 altimeter H_s. The solid line is the regression result H_s(ERS1) = $0.998H_s$(GEOSAT) + 0.046.

consisting of 11,457 points. The GEOSAT U_{10} data were assumed to be unbiased. Eqs. (7) and (9) were used to 'correct' the TOPEX and ERS1 U_{10} data respectively, and global mean monthly values were determined. As expected, ERS1 and GEOSAT U_{10} data agreed well. Correlations of both ERS1 and GEOSAT values of U_{10} with TOPEX values showed a clear difference. As TOPEX and ERS1 overlapped, it would be surprising if such a difference really existed. Also, the more reliable H_s data showed no such trend. This leads to the possible conclusion that the correction to the TOPEX values of U_{10} represented by Eq. (7) may be in error. An alternative fit between the buoy and TOPEX mean monthly values of U_{10} was investigated which would remove this bias between the TOPEX values of U_{10} and the other satellites. A relationship which achieves this is

$$U_{10}(\text{buoy}) = 0.99U_{10}(\text{TOPEX}) + 1.61 \tag{10}$$

Eq. (10) is shown in Fig. 6 and provides a fit which is visually equal to Eq. (7). The final intercomparisons between satellite values of U_{10} using Eqs. (9) and (10) are shown in Fig. 11 (GEOSAT vs. TOPEX), Fig. 12 (GEOSAT vs. ERS1) and Fig. 13 (ERS1 vs. TOPEX). Linear regression for these data yield the results:

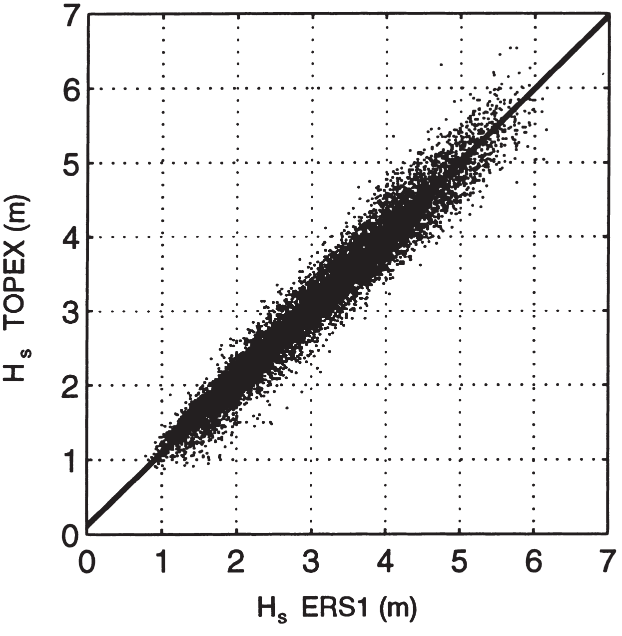

Fig. 10. Global mean monthly values of corrected ERS1 altimeter H_s compared with mean monthly values of corrected TOPEX altimeter H_s. The solid line is the regression result H_s(TOPEX) = 0.980H_s(ERS1) + 0.112.

U_{10}(TOPEX) = 1.004U_{10}(GEOSAT) − 0.117, U_{10}(ERS1) = 0.999U_{10}(GEOSAT) − 0.233 and U_{10}(TOPEX) = 1.006U_{10} (ERS1) + 0.111.

6. Conclusions

Mean monthly values of H_s and U_{10} obtained from altimeters on GEOSAT, TOPEX and ERS1 have been compared with NODC buoy data. As a result of these comparisons and the requirement that intercomparisons of H_s and U_{10} between the satellites must yield consistent results, calibration relationships have been developed for each of the satellites. The recommended equations are

$$H_s = 1.144H_s(\text{GEOSAT}) - 0.148 \quad (11)$$

$$H_s = 1.067H_s(\text{TOPEX}) - 0.079 \quad (12)$$

$$H_s = 1.243H_s(\text{ERS1}) + 0.040 \quad (13)$$

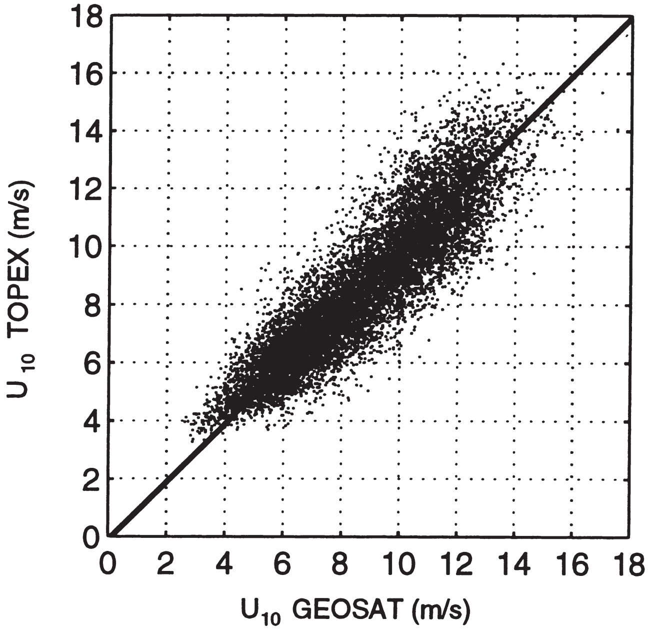

Fig. 11. Global mean monthly values of corrected GEOSAT altimeter U_{10} compared with mean monthly values of corrected TOPEX altimeter U_{10}. The solid line is the regression result $U_{10}(\text{TOPEX}) = 1.004U_{10}(\text{GEOSAT}) - 0.117$.

$$U_{10} = U_{10}(\text{GEOSAT}) \tag{14}$$

$$U_{10} = 0.99U_{10}(\text{TOPEX}) + 1.61 \tag{15}$$

$$U_{10} = U_{10}(\text{ESR1}) \tag{16}$$

These results extend and refine previous comparisons between the altimeter data sets and buoy data. They provide the basis for the development of long-term data series of both wind speed and wave height from the multiple altimeter missions.

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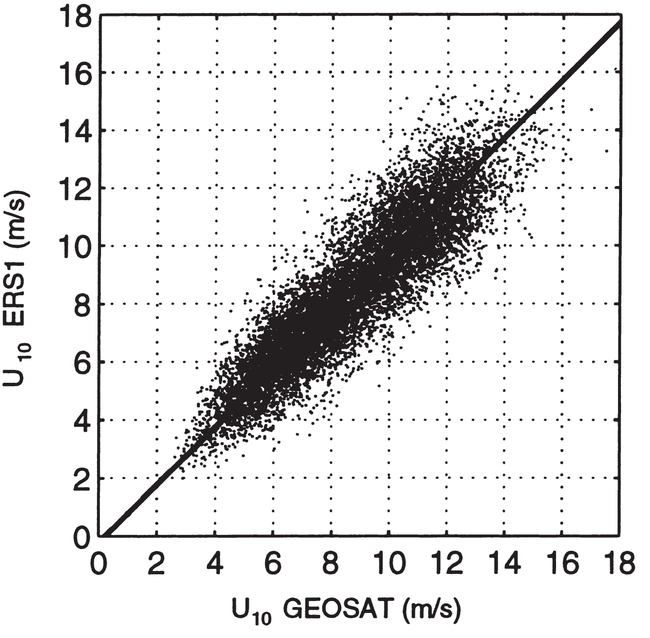

Fig. 12. Global mean monthly values of corrected GEOSAT altimeter U_{10} compared with mean monthly values of corrected ERS1 altimeter U_{10}. The solid line is the regression result $U_{10}(\mathrm{ERS1}) = 0.999U_{10}(\mathrm{GEOSAT}) - 0.233$.

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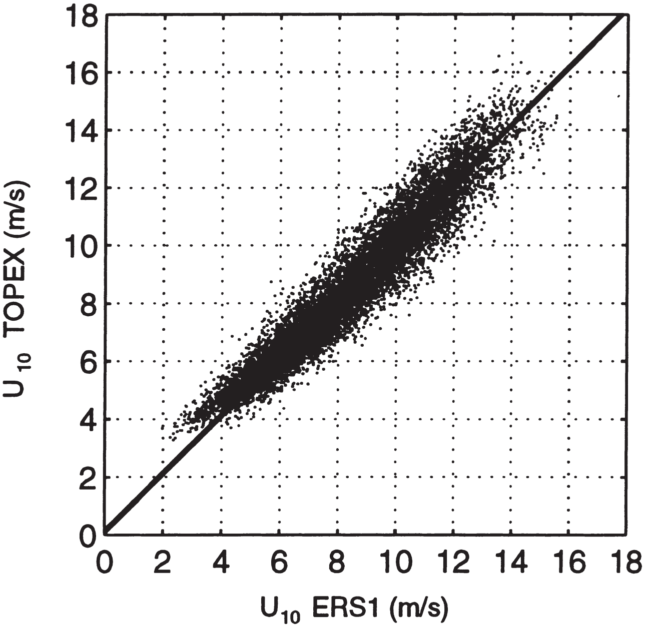

Fig. 13. Global mean monthly values of corrected ERS1 altimeter U_{10} compared with mean monthly values of corrected TOPEX altimeter U_{10}. The solid line is the regression result U_{10}(TOPEX) = $1.006U_{10}$(ERS1) + 0.111.

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