MULTISENSOR VALIDATION OF ERS-1 SAR WAVE MODE AND ALTIMETER-DERIVED SIGNIFICANT WAVE HEIGHTS USING TOPEX, GEOSAT AND SEASAT DATA

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Abstract

A comparison of significant wave heights H_s was performed using satellite altimeter data available between 1978 to 1994 from SEASAT, GEOSAT, ERS-1 and TOPEX. The purpose was to estimate the degree of accuracy between the different instruments. Statistical properties of H_s as obtained from the altimeters are found to be compatible with those from in situ measurements in the North Atlantic. All H_s data sets are fitted to appropriate distribution functions. Furthermore, an assessment and validation of H_s retrieved from ERS-1 SAR Wave Mode (SWM) data with spatially and temporally collocated altimeter data from ERS-1 and TOPEX during 1994 is given. The values of SWM-retrieved monthly mean H_s are generally higher than those of the ERS-1 altimeter and lower than those of the TOPEX altimeter. The SWM-retrieved H_s agree better with TOPEX altimeter data, than with the ERS-1 altimeter data. Regional comparison are performed and an attempt is made to investigate the differing behaviour of pure windsea and swell.

Keywords: global significant wave heights; SEASAT, GEOSAT, ERS-1 and TOPEX altimeter; higher order L-moments; ERS-1 SAR wave mode; spectral retrieval algorithm; windsea and swell partitioning.

1. INTRODUCTION

Since the launch of the first European Remote Sensing satellite ERS-1 in July 1991 ocean surface wave spectra are for the first time being retrieved globally from synthetic aperture radar (SAR) wave mode spectra. These kind of measurements were awaited for a long time to validate spectral wave models and to use these data for routine assimilation into global wave prediction models (see [*Komen et al.*, 1994]). However, an essential prerequisite for successful wave data assimilation is a comprehensive validation of the measured wave data. A first evaluation of ocean wave spectra retrieved from ERS-1 SAR wave mode (SWM) spectra was performed by *Brüning et al.* [1994]. A validation against independent satellite, space shuttle or in-situ measurements have so far been restricted to a few cases because spectral wave measurements are rare (for an overview see *Hasselmann et al.*, [1996], referred to in the following as [*HBHH*], and references therein). An extensive assessment of the data quality and the retrieval fidelity and a statistical intercomparison between spectral wave data derived from ERS-1 SWM data and from the wave model WAM clearly reveals the potential of the observed wave spectra [*Heimbach et al.*, 1997] (referred to in the following as [*H3*]) and [*Heimbach et al.*, this issue]. However, the investigation of [*H3*] need a complementary validation of the SWM-retrieved wave data in order to ascertain more generally the validity of these data.

Measurements of spaceborne altimeters provide global homogeneous measurements of significant wave heights H_s and are thus highly suitable validate H_s^{swm} derived from the ERS-1 SAR wave mode data. For this purpose data are available from ERS-1 (H_s^{ers}) since July 1991 and from TOPEX/POSEIDON (H_s^{top}) since August 1992. Prior to the launch of ERS-1 data from the SEASAT (1978) and the GEOSAT (1985 – 1990) missions were available.

The aim of this paper is twofold. In the first part we assess the quality of H_s obtained from the SEASAT, GEOSAT, ERS-1 and TOPEX altimeters, from the WAM model and from in-situ measurements of the Ocean Weather Ship Mike (OWS M) through a combined statistical analysis. Monthly mean H_s from different data sets are compared and theoretical distribution functions are fitted. Properties of the frequency distributions of H_s are explored. In the second part of the paper we compare H_s^{swm} with collocated H_s^{top} and H_s^{ers} for the year 1994. Although the validation of spectral wave data from SWM spectra against H_s from altimeters appears incomplete the assessment of the SWM-retrieved wave data against entirely independent measurements is highly relevant. Furthermore, an attempt is made to compare H_s retrieved from the ERS-1 SWM spectra and H_s of the altimeters with respect to pure windsea and swell wave heights.

2. STATISTICAL PROPERTIES OF GLOBAL ALTIMETER H_s DATA

In the following we assess the quality of H_s as measured by the SEASAT (H_s^{sea}), GEOSAT (H_s^{geo}), ERS-1 (H_s^{ers}) and TOPEX (H_s^{top}) altimeters, computed with the WAM model (H_s^{wam}) and obtained from in-situ measurements of the OWS M.

Bauer and Staabs [1996] summarized the results of previous intercomparisons between altimeter-derived H_s or comparisons between altimeter and buoy data. As a result no definite conclusion could be drawn as to which of the H_s data corresponds closest to the true sea state. The comparison of satellite data with ground truth data suffered from the small number of collocated data and the incomplete coverage of the typical range of H_s-values typical for buoy samples. Furthermore, the validation of H_s obtained from altimeters using buoy data can be affected by errors in the instruments, the temporal and spatial distance or by insufficient geophysical model functions [*Monaldo*, 1988]. On average, the accuracy of H_s from altimeters was repeatedly confirmed to fall below the specified error bounds of 0.5 m or 10 % whichever value is larger in the range 1 – 20 m.

2.1. Data sets of H_s

All observed H_s data from the SEASAT (7/78 – 9/78), GEOSAT (1988), ERS-1 (1993 – 1994) and TOPEX (1993 – 1994) passed the same quality analysis and averaging procedure (see [*Bauer and Heimbach*, 1997]). We analysed the fast delivery product (FDP) of H_s^{ers} instead of the ocean product (OPR) because we are interested especially in the quality of the FDP data which are used for operational data assimilation purposes. The altimeter data were averaged over a 30 – second along-track footprint corresponding to a spatial resolution of 200 km in accordance with the model resolution.

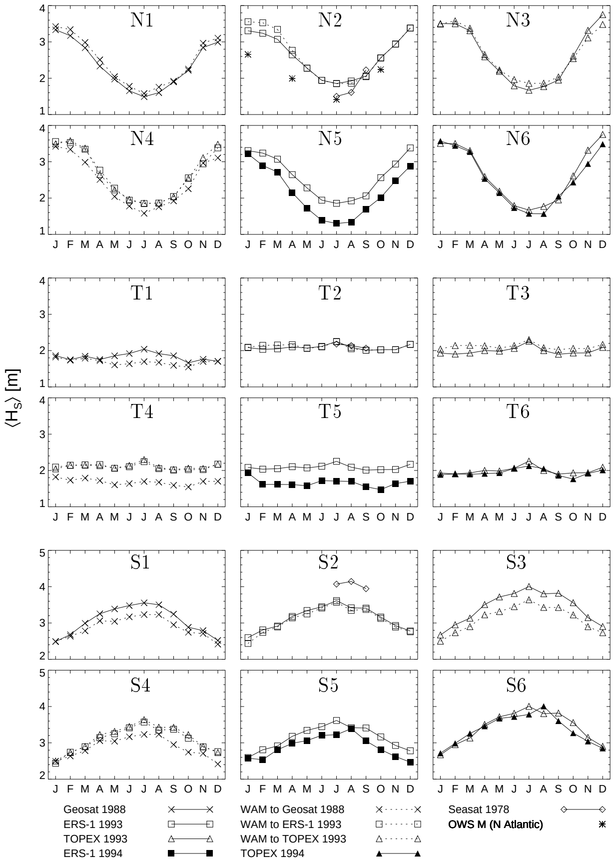

Figure 1: One year time series of monthly mean significant wave heights for different data sets (see text for details).

Model data are computed with the operational WAM model implemented at ECMWF on a global 3° × 3° grid ([*Komen et al.*, 1994]). The model is driven by 6-hourly $\mathbf{u_{10}}$ wind vector fields from the ECMWF analysis. As the WAM has been changed progressively during the past years the comparison comprises date from the WAM cycle 3 as well as cycle 4. Since 16 August 1993 H_s^{ers} data were assimilated into the WAM thus affecting H_s^{wam}.

In addition we use in-situ measured H_s^{ows} from the OWS M in the North Atlantic (63° N, 23° E).

2.2. Time series of monthly mean H_s

Annual time series of montly mean H_s for the Northern (N) and Southern (S) Hemisphere Extra-Tropics and the Tropics (T, between 25° N/S) are presented in Figure 1. Panels 1 to 6 comprise comparable data.

The annual averages of H_s are smaller for the northern (N1 – N6) than for the southern regions (S1 – S6). The amplitude of the annual cycle amounts to

2 m for the northern and to only 1 m for the southern region. The annual averages of H_s of the tropics (T1 – T6) are significantly smaller than those of the extra-tropics and show no annual cycle.

The means of H_s^{wam} collocated to H_s^{geo} exceed those of H_s^{geo} by about 10 cm throughout 1988 in the northern region (N1). In the tropics (T1) H_s^{geo} exceeds H_s^{wam} from May to September by more than 20 cm. This may be due to too little swell in H_s^{wam} and an underestimation of H_s^{wam} in the southern winter (S1). The means of collocated H_s^{wam} and H_s^{ers} show good agreement in 1993 (N2, T2, S2). Means of H_s^{sea} are significantly smaller than H_s^{ers} in the northern region, agree well with H_s^{ers} in the tropics and are significantly larger than H_s^{ers} in the southern region (N2, T2, S2). The means of collocated H_s^{top} are about the same to H_s^{wam} in the north, are smaller than H_s^{wam} in the tropics and are larger than H_s^{wam} by as much as 40 cm in the south (N3, T3, S3). The means of H_s^{wam} are larger for 1993 (WAM cycle 4) than for 1988 (WAM cycle 3) (N4, T4, S4). The differences of as much as 50 cm are largest in the tropics.

Large differences occur between the means of H_s^{ers} for 1993 and 1994 (N5, T5, S5). These differences reflect the impact of a modified sensor algorithm of the ERS-1 altimeter implemented in January 1994. This large change cannot be explained with interannual variations, because the moments of H_s^{top} hardly change from 1993 to 1994 (N6, T6, S6). The smallest mean H_s of the data set are those of H_s^{ers} of 1994. The OWS M data have significantly smaller means than those of H_s^{top} in the northern winter. This can be explained by the fact that the sampling of H_s from OWS M is completely different compared to the other data sets.

2.3. Statistics of univariate distributions of H_s

A histogram of H_s sampled over large space and time regions is usally unimodal. Such distributions can be characterized by the first four linear moments λ_r , i.e. integrals over the quantile function $x(F)$, weighted with Legendre polynomials P^*:

$$\lambda_r = \int_0^1 x(F) P^*_{r-1}(F)\,\mathrm{d}F, \quad r = 1, 2, ...$$

$$P^*_r(F) = \sum_{k=0}^{r} (-1)^{r-k} \begin{pmatrix} r \\ k \end{pmatrix} \begin{pmatrix} r+k \\ k \end{pmatrix} F^k$$

Linear moments of order higher than 2 are scaled with the second linear moment λ_2:

$$\tau_r = \frac{\lambda_r}{\lambda_2} \quad \text{for } r \geq 3$$

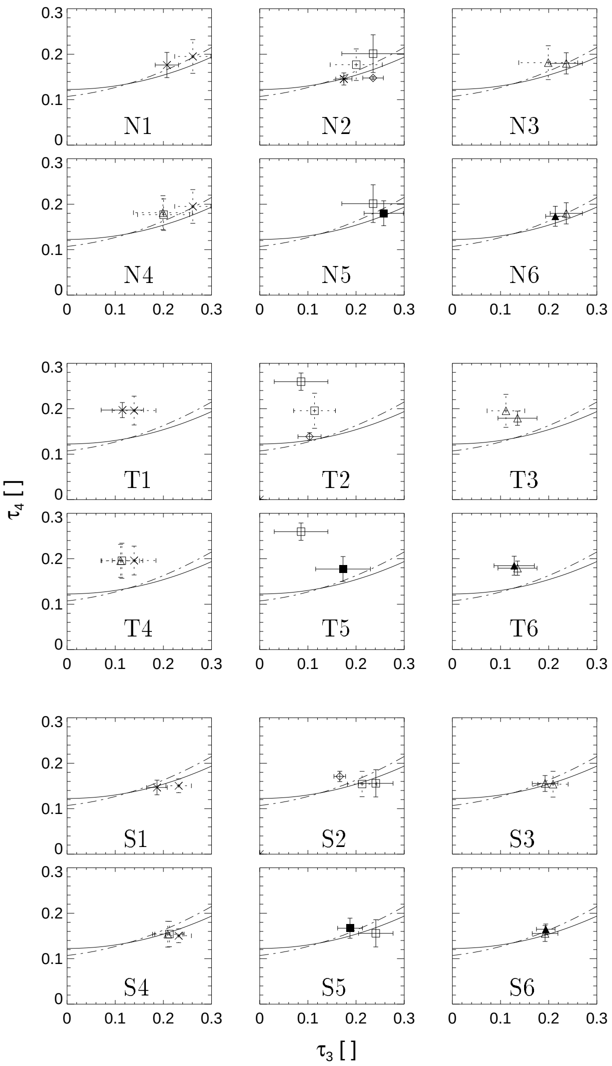

Figure 2: Monthly mean third vs. fourth scaled L-moments (legend as in Figure 1.

The amplitude of random sea surface elevations which obey linear wave theory are characterised by a Rayleigh distribution. However, distributions of H_s are different to the Rayleigh distribution because H_s is nonlinearly related to the wave amplitude. The H_s histograms are fitted to various empirical functions of which the log-normal or generalized normal (GNO) and the general extreme value (GEV) yield the best approximation, confirming increasing evidence that H_s-distributions obey the underlying statistics.

- The GNO distribution is a natural distribution for nonsymmetrically distributed variables, resulting from multiplicative concurrence of random variables:

$$F(x) = \frac{1}{N} \int_{-\infty}^{x} \frac{1}{x'} \exp\left\{ -\frac{[\log(x'-\xi)-\mu]^2}{2\sigma^2} \right\} \mathrm{d}x'$$

with $N = \sigma\sqrt{2\pi}$, μ: mean, σ: rms deviation and ξ: offset.

- The GEV distribution is given by:

$$F(x) = \exp\left\{-\left[1 - \frac{\beta}{\alpha}(x - \xi)\right]^{1/\beta}\right\}$$

with location ξ, scale α and shape β inferred from the first three moments.

2.3.1. Monthly third and fourth L-moments

The third vs. fourth L-moments, τ_3 and τ_4, for several samples are drawn in Figure 2 together with the theoretical curves of the GEV (dotted) and GNO (dashed) distributions.

The distribution of H_s^{wam} is found to be slightly less skewed than that for cycle 3. τ_3 and τ_4 of H_s^{wam},cycle 4, agree quite well with those of H_s^{geo} in all regions. The L-moments inferred from H_s^{ers}show distinct changes associated with changes in the sensor algorithm (see [*Bauer and Staabs*, 1997]). In the southern region L-moments of H_s^{geo},H_s^{wam}, and H_s^{top} exhibit relatively small scattering and agree rather closely to the GNO curves, whereas in the northern region they follow more closely the GEV curves, the scattering being more pronounced. The same holds for τ_3 and τ_4 of OWS M. However, L-moments of H_s^{geo},H_s^{wam}, and H_s^{top}

2.3.2. Histograms of H_s

Bauer and Staabs, [1997] compared histograms of altimeter H_s to those of the WAM for three regions and four seasons. As an example Figure 3 depicts the northern winter (DJF) data except for H_s^{sea} for which only July to October 1978 data are available. The histograms were fitted to the GEV and the GNO distributions.

The histograms of H_s^{sea} and H_s^{ers} for 1993 deviate significantly from the proposed theoretical distributions. The H_s^{sea} histogram shows an abnormal trimodal shape (Figure 3f). The two secondary modes at 2 m and 6 m reflect a defect in the measured signal. The H_s^{ers} 1993 histogram shows an exceptional sharp peak at 2 m. (Figure 3c). This sharp peak is visible in all H_s^{ers} histograms of 1993, but in none of the histograms of the other data. It is caused by an error in the data processing. After implementation of the new sensor algorithm in 1994 the peak disappears (Figure 3d). Although the number of entries for each histograms is large (roughly 20,000) the histograms of H_s^{geo} and H_s^{ers} are rather ragged compared to the quite smooth H_s^{top} and H_s^{wam} histograms. The theoretical distributions show negligibly small differences if the histograms are smooth) (Figure 3b/e). We conclude that deviations of the histograms from the proposed distributions contain valuable information regarding possible data shortcomings.

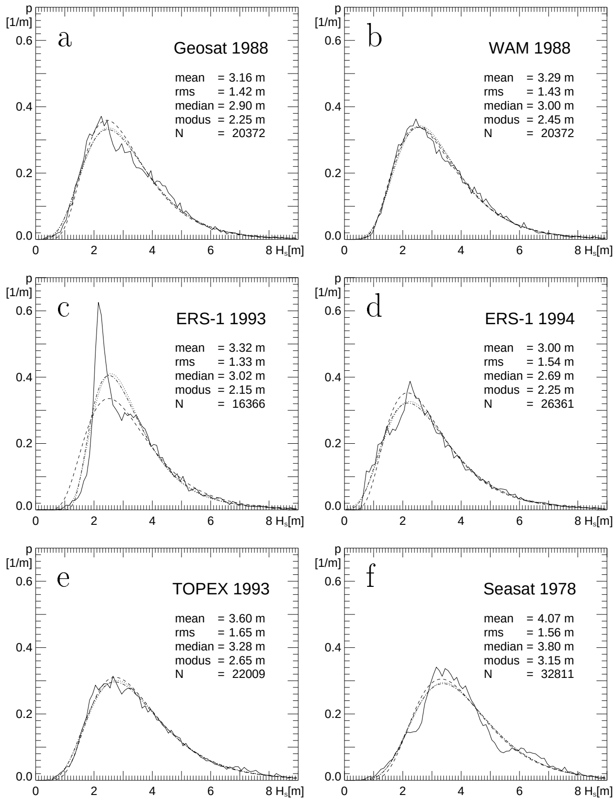

Figure 3: One year histograms of H_s in the northern region for different data sets. Fits of the GEV (dotted), 2-param. GNO (dot-dashed) and 3-param. GNO (dashed) are included.

Based on the available data sets it cannot be proved whether the H_s distribution is strictly consistent with the GNO distribution. In most cases the data failed to pass the Kolmogorov-Smirnov test. The GNO distribution fits slightly better to the H_s histograms of the southern region and the the GEV distribution to those of the northern region.

3. ANALYSIS OF H_s FROM ERS-1 SWM

In the following we use the TOPEX and ERS-1 altimeter data to further assess the ERS-1 SWM retrievals. Putting the results into perspective to the preceding section, deviations between SWM and altimeter-derived H_s are not necessarily attributed to defficiencies in the SWM retrievals. In fact, for the period 1994 ERS-1 altimeter data are low-biassed, whereas TOPEX data seem to be very reliable.

3.1. H_s from ERS-1 SAR wave mode spectra

The ERS-1 SAR wave mode imagette spectra are disseminated in quasi-real time to users as a fast delivery product (FDP). This product is obtained from the SAR operating in the intermittent sampling mode (so-called “wave mode”) during which 5 × 10 km snap shot imagettes of the local ocean surface are taken every 200 km along the satellite track. (for a description see [*H3*]). In the case of ERS-1 SAR imaging is strongly nonlinear, being dominated by the velocity bunching mechanism [cf. the MARSEN review *Hasselmann et al.*, 1985]). Based on the closed nonlinear integral describing the mapping of ocean wave spectra into SAR image spectra [*Hasselmann and Hasselmann*, 1991] (referred to as [*HH*]), an efficient inversion algorithm was developed to retrieve ocean wave spectra from SAR image spectra. This algorithm has since been evaluated [*Brüning et al.*, 1994] and improved [*HBHH*]. Three years of ERS-1 SWM data between January 1993 and December 1995, comprising some 1.2 million spectra have been retrieved using the improved algorithm [*H3*]. The retrievals of 1994 are used for the present intercomparison.

3.2. H_s of TOPEX and ERS-1 altimeter data

H_s data of the TOPEX altimeter are provided as offline product whereas those used from the ERS-1 altimeter are FDP data. Comparisons of H_s data from altimeters with buoy measurements confirmed that the H_s data from altimeters met the performance goal of a 0.5 m or 10 % accuracy and were of exceptional high quality. However, it should be noted that buoy measurements are rare and do not completely span the possible range of H_s values, particularly at high H_s (see [*Bauer and Staabs*, 1997]).

3.3. Collocation

To estimate any systematic difference between the ERS-1 SWM data and the altimeter data with reasonable confidence the H_s measurements should be collocated within spatial and temporal distances small enough to ensure that both measurements encounter the same geophysical condition. Estimates of reasonable collocation windows for open ocean wave conditions are of the order of one hour in time and 100 km in space [*Monaldo*, 1988] and [*Tournadre and Ezraty*, 1990]. However, the achievable distances between collocated data and the number of such events is mainly determined by specific satellite and instrument parameters. As a result of these constraints we had to choose the space window equal to 350 km and the time window equal to three hours (see [*Bauer and Heimbach*, 1997]).

3.4. Global distribution of H_s

Time series of H_s^{swm} collocated to H_s^{ers} (left column) and H_s^{top} (right column) are presented in Figure 4. A more detailed view is obtained by considering the global distributions. To fully exploit the

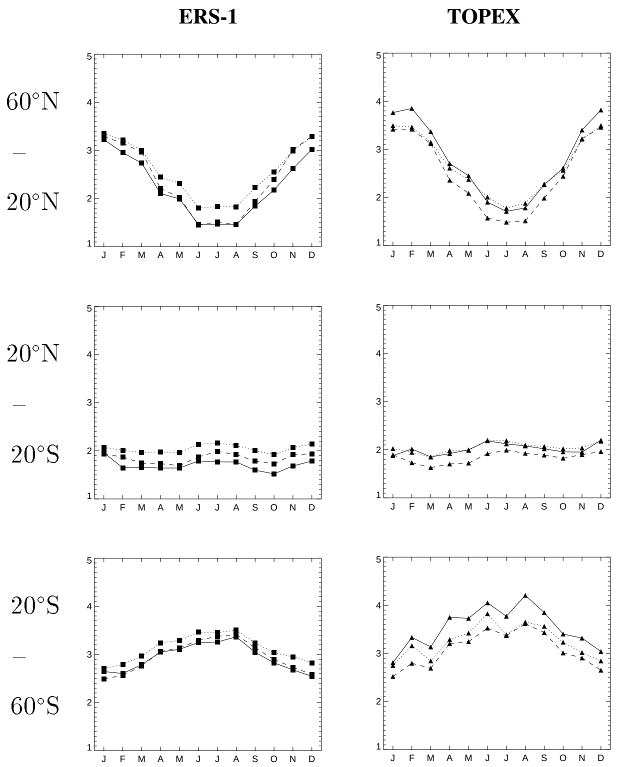

Figure 4: Time series of monthly mean H_s^{swm} (dotted line) collocated to altimeter (solid line) H_s^{ers} (left column) and H_s^{top} (right column). H_s^{wam} is added for comparison (dashed line).

seasonal maxima and minima (high/low sea states in the southern/northern region) maps comprising three month data would be desirable. However, reasonably large sample sizes per grid point are necessary to allow meaningful conclusions to be drawn from these maps. As a compromise we have considered global maps of mean H_s between May and October 1994. The observed data were interpolated onto a $5° \times 5°$ longitude/latitude grid. This leads to about 100 entries per grid box for ERS-1 and to about 10 for TOPEX collocations.

Detailed maps are presented in *Bauer and Heimbach*, [1997]. Mean H_s^{swm} are generally larger than the means of H_s^{ers} and lower than H_s^{top}. This order of succession suggests the H_s^{swm} to be of higher quality than H_s^{ers}. Previous comparisons have shown that the mean H_s^{ers} has dropped unexpectedly low after the new sensor algorithm of the ERS-1 altimeter had been implemented in 1994. The systematic underestimation of H_s^{ers} compared to H_s^{top} was not visible to this extent before 1994 and puts doubts on the validity of H_s^{ers} after 1993. Mean H_s^{swm} being lower than mean H_s^{top} fits to previous findings showing H_s^{top} of 1993 and 1994 to be larger compared to other data sets from ERS-1 (1993) and Geosat (1988) altimeter. A very good agreement is apparent between H_s^{swm}

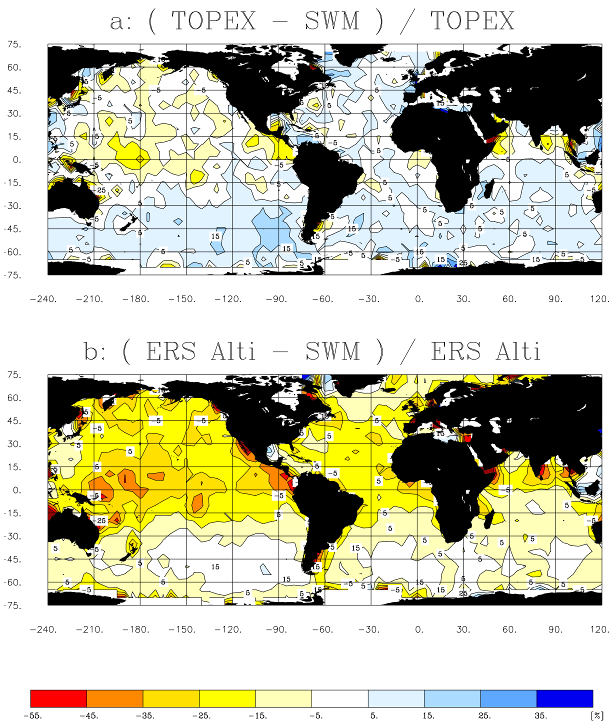

Figure 5: Global distribution of relative bias between altimeter and ERS-1 SWM H_s during 5/94 – 10/94.

and H_s^{top} for low to moderate sea states, assessing the reasonable quality of these H_s^{swm}.

Figure 5 shows the relative bias between H_s^{top} and H_s^{swm} (panel a) and between H_s^{ers} and H_s^{swm} (panel b). The relative bias between H_s^{top} and H_s^{swm} remains below $\pm$ 15 % over almost the entire globe while the relative bias between H_s^{ers} and H_s^{swm} drops below -15 % and even below -25 % in major parts of the Tropical Pacific during SH winter. This confirms the closer agreement between the two former data sets. The strongest differences between mean H_s^{swm} and H_s^{top} are found for high sea states in the mid-latitudes. A slight negative bias for low sea states is found in the Tropics and in a few areas of the Northern Pacific. In contrast, the bias between H_s^{swm} and H_s^{ers} is weakest in these regions and strongest for low sea states in the Tropics and the northern regions, especially in the Pacific.

3.5. Comparison of H_s for windsea and swell

To estimate any possible distinct behaviour between windsea and swell from total H_s alone we have isolated two sets of spectra, one representing spectra which only contain a windsea system, the other representing spectra which only contain swell systems (for details of the partitioning technique see [*HBHH*]). As pure windsea occurs relatively seldom we compare collocated sets of windsea and swell by scatter diagrams obtained for the entire year 1994.

The mean swell wave height measured by the TOPEX altimeter is slightly higher than retrieved from H_s^{swm} (Figure 6) and is significantly higher than from H_s^{ers}. The sets containing windsea systems are much smaller than those containing swell systems, but the former span a range of wave heights exceeding even 10 m. As for the mean swell wave height, the mean windsea wave height from H_s^{top} is larger than retrieved from H_s^{swm} (Figure 7), and the latter is larger than the mean windsea wave height from H_s^{ers}. But the overestimation of the mean windsea from H_s^{top} compared to the mean windsea from H_s^{swm} is more pronounced than for the mean swell. The collocated sets of pure windsea systems from H_s^{swm} and H_s^{ers} have a major principal axis which is very close to the ideal diagonal of the scatter diagram. These findings together with the fact that they are both smaller than windsea from H_s^{wam} indicate that H_s^{swm} is not tightly bounded to the first guess H_s^{wam}.

4. CONCLUSION

Several years of global H_s data from altimeter measurements, the WAM model and in-situ measurements of the OWS M show compatible statistical properties. Histograms of H_s can be reasonably well described by the GNO and the GEV distributions. Data sets which show significant deviations from these curves are likely to be defective. Time series of monthly mean altimeter H_s were compared with each other and with corresponding WAM data, the WAM serving as common base. Despite the overall satisfactory agreement systematic differences between the data sets make the study of long-term trends based upon these data difficult.

A first comprehensive global validation of H_s retrieved from ERS-1 SAR wave mode spectra (H_s^{swm}) with independently measured H_s from altimeters on board the TOPEX (H_s^{top}) and ERS-1 (H_s^{ers}) satellites has been performed. This exercise is highly relevant to ascertain the validity of the H_s^{swm} retrievals.

Considering the entirely different data processing schemes applied to data from SWM spectra, altimeter and WAM the overall agreement is seen to be satisfying. As the study of possible climate changes is of growing interest long time series composed of data of high absolute quality are desirable. However, the assessment of the absolute quality of the corresponding data is difficult as the different processing schemes are accompanied by different errors. In this study some possible error sources have been discussed. Further improvement will highly profit from the availability of 2d spectral data.

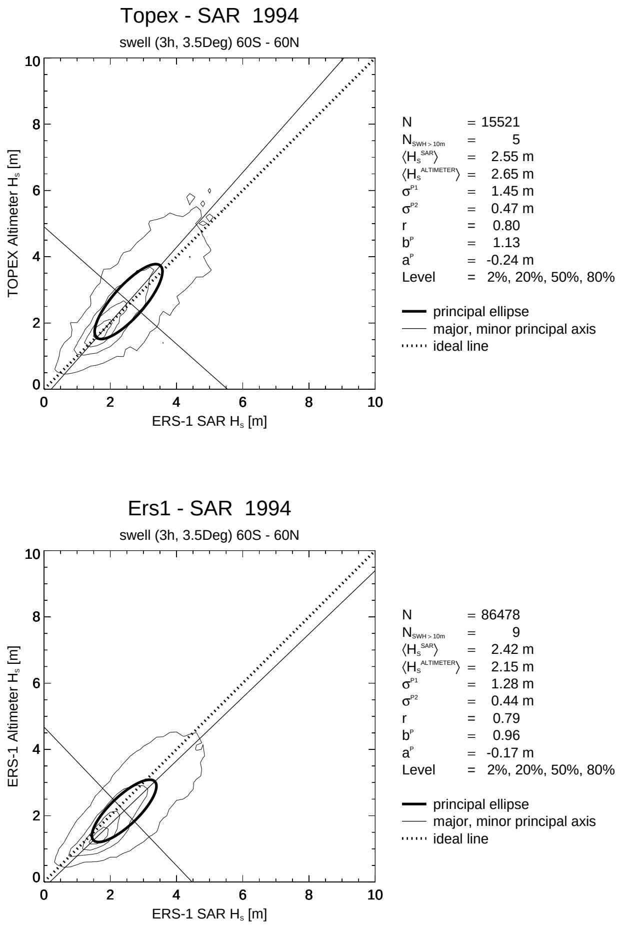

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Figure 6: Regression between altimeter and ERS-1 SWM swell wave heights for 1994.

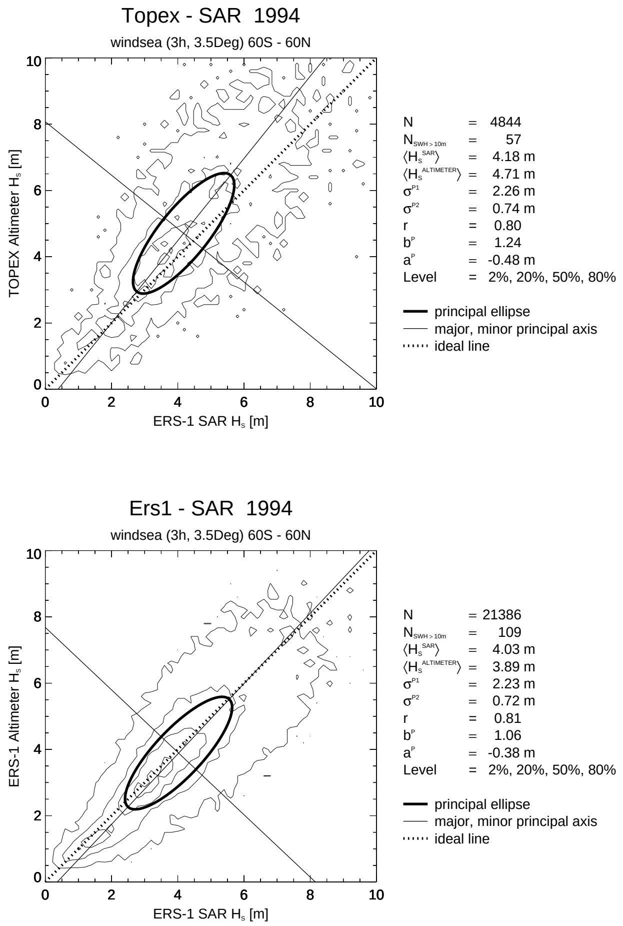

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Figure 7: Same as Figure 6 for windsea.

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