INVESTIGATION OF LARGE SCALE AND REGIONAL FEATURES OF WAVE HEIGHTS FROM ALTIMETER MEASUREMENTS

Pierre Queffeulou & Denis Croizé-Fillon

IFREMER, LOS, BP70, 29280 Plouzané, France, pierre.queffeulou@ifremer.fr

ABSTRACT

Significant wave height (SWH) data from six altimeter missions are analyzed to investigate the large scale and regional features of wave height over a fifteen year period. First, the long time series of TOPEX-Jason measurements over the same ground track network are used to construct seasonal maps of long term mean value and standard deviation of SWH. These maps reveal SWH features associated for instance with meteorological characteristics as in the Trade Winds, or with wave current interactions as in Gulf Stream and Agulhas currents. Second, the possibility of constructing virtual buoy measurements using multi-altimeter mission data is investigated. The goal being to estimate monthly SWH characteristic time series in any oceanic location, particularly where very few in situ measurements are available or where wave model outputs are not always reliable.

1. INTRODUCTION

To help regional wave statistics, data from buoys, numerical wave models or satellites are readily available. The number of wave buoys over the oceans increases; it consists of several national operational buoys networks. However, buoys are often located in coastal areas, non uniformly distributed in space and, because of the difficulty to maintain at sea, long time series are rare. For this reason buoy data can only be useful for wave climates in some particular locations but are not fully adapted to estimate wave description anywhere. During the last years the quality of numerical wave model analyses improved considerably thanks to improved wind estimates and to the development of assimilation techniques using buoy and satellite measurements [1,2,3]. The skill of altimeter assimilation in wave models is under discussion [4]. Still, an important question is the quality of numerical wave models. For instance, the ECMWF 40-year Re-Analysis (ERA-40) presents both underestimation of high SWH and time heterogeneity which have to be corrected before application to wave climate studies [5,6]. The third source to derive wave characteristics is the direct use of satellite measurements, mainly from SAR and altimeter.

For regional SWH statistics, the altimeter is very useful because almost 16 years of data are presently available, providing global, continuous and long term measurements. A strong interest stems also from the along track altimeter high resolution sampling, of the order of 6 km, which enables to measure local SWH gradients induced for instance by fetch or sheltering and current effects. A drawback of the altimeter is the time and space sampling scheme, which is a compromise between revisiting the same ground track frequently, as with the 3-day repeat cycle orbit of ERS-1 during the commissioning phase, but with a coarse spatial resolution (about 8° in longitude inter-track separation at 40°N), or revisiting at a longer time period (35-day for ERS-2) but with a better spatial sampling. The past and present altimetric missions lead to various repeat cycle samplings: 3-day, 168-day or 35-day for ERS-1; 10-day for TOPEX-Poseidon and Jason, 17-day for GEOSAT Follow-On (GFO) and 35-day for ERS-1&2 and ENVISAT. In this paper, both along track high resolution for TOPEX and Jason ground track network and multi-satellite altimeter sampling in any oceanic location are used to demonstrate the ability of altimeters for estimating SWH time and space features.

2. ALTIMETER DATA and PROCESSING

The altimeter data are the Geophysical Data Records (GDR), or equivalent, distributed by the space agencies: ERS-1&2 Radar altimeter Ocean Product (OPR) [8]; TOPEX Poseidon Merged Geophysical Data Record [9]; Jason GDR [10]; GEOSAT Follow On GDR [11] and ENVISAT RA-2 GDR [12]. Altimeter SWH measurements are selected according to the specific quality flags described in the user guides. Specific tests are performed for Jason and ENVISAT, based on the ratio of SWH standard deviation to SWH mean value established during the validation [13]. These quality flags and tests are not sufficient to discard all the erroneous SWH data. Spurious measurements are still observed and eliminated using a screening method based on the analysis of the differences between successive along track SWH measurements and comparison with threshold values. For TOPEX and Jason, in order to compute long term along track statistics, new data sets are also produced in interpolating the data, along track, every 0.05° in latitude, corresponding more or less to the initial along track one second time sampling of the altimeter. The last step consists in correcting the altimeter SWH measurement. All the applied corrections are provided in Table 6 of [13]. Daily multi-altimeter corrected SWH data files were then constructed, forming the basis of the following analyses. More details on data sampling and processing can be found in [7].
3. **TOPEX & JASON TRACK ANALYSIS**

The idea is to keep the opportunity of the fine along track sampling to study long term characteristics of short scale spatial variations of SWH. The longest time series over the same ground track network is provided by TOPEX, from September 25, 1992 to August 11, 2002, followed by Jason from cycle 22 (August 11, 2002) to today (cycle 187, February 2, 2007). Obviously the 10-day TOPEX and Jason repeat cycle sampling is not appropriate to estimate the along track mean value of SWH over a month or even over a 3-month time period [7]. Nevertheless, one can expect that over a very long time period, such as 15 years, the seasonal meteorological events can be assumed statistically uniformly distributed relative to the altimeter sampling, so that the 10-day sampling does not affect the estimate of the mean value over such a long time period. An example of winter map (December to February) of along track mean value of SWH over 16 years is shown in Figure 1.

![Figure 1. 16-year mean SWH and Brittany buoy location](image)

The mean value of SWH in each along track location is estimated from at least 100 measurements. SWH features are globally consistent over ascending and descending tracks. Northern to southern and eastern to western variations of SWH are shown, corresponding to the mean winter regional meteorological situation. Highest SWH values are observed in the North-eastern region and the lowest ones in the eastern of 'la Manche' and in the Mediterranean Sea. Figure 2 shows mean SWH values over the North Atlantic Ocean in summer and winter. In summer, SWH varies between 0.4 m and 2.5 m. The relative maximum associated with the Trade Winds is well indicated, as the minimum associated with the Azores high pressure region. In winter the northern SWH maximum increases up to 5.5 m. Standard deviations (std) are shown in Figure 3: in summer the Trade Winds region is characterized by low variability, corresponding to the general steadiness of the wind and waves over this season. It is suggested that the relatively high values of SWH std for both summer and winter in the north-western region is associated with wave-current interactions in the Gulf Stream.

![Figure 2. 16-year summer and winter mean SWH](image)

Figure 3. 16-year summer and winter SWH std

![Figure 3. 16-year summer and winter SWH std](image)

Figure 4 is relative to the southern Africa region and reveals the SWH mean value and std increases when going off-shore from the southern continental shelf, as shown by the bathymetry associated with the northern limit of the Agulhas current. The relative high values also observed near 40°N and between 20°E and 30°E could result from wave current interactions in the Agulhas retroflection. This was already shown on individual TOPEX passes [14] but not from such long time series.

SWH features observed in Figure 5 are also interesting, showing clearly that the Drake Passage, between Cape...
Horn and the South Shetland Islands plays the role of a barrier to high SWH generated in the southern Pacific Ocean, with a relatively low SWH region in the eastern of Southern Argentina. These few examples illustrate the interest of the joint TOPEX Jason long term SWH data to investigate seasonal features of SWH over any oceanic region. Furthermore such informations are very useful to test the capacity of numerical wave models to retrieve particular SWH features.

4. MULTI-MISSION ANALYSIS

One satellite like TOPEX, with a 10-day repeat cycle, is not able to describe the monthly SWH statistics but merging data from all the altimeter missions can be helpful. The goal is not to estimate the SWH extreme event distribution at a given geographical location, which is not feasible using the actual altimeter data, but rather, more modestly, to estimate monthly mean values and standard deviations. The major difficulty comes from the particular time and space sampling schemes of the altimeters.

Figure 6 shows the SWH mean values deduced from ERS-2 and TOPEX altimeter measurements for January 1998. Mean SWH is estimated over a 1°x1° latitude longitude grid, from the average of altimeter measurements during the month within 150 km of the centre of each grid point. Obviously the satellite tracks appear on the map as some unrealistic modulation of SWH. For instance, on the zoomed map, the SWH value is 4 m in location E, and 6.5 m in F, these two locations being separated by only 365 km. The track features are those of ERS (ERS tracks are less inclined on the equator than the TOPEX ones) and can be explained by the time and space sampling. ERS tracks (Figure 7) for the 7 first days of January (blue) and for the 7 following days (red) show that the two locations E and F are sampled at different time periods in the month.
blue) corresponds to very high SWH (up to almost 14 m) while the E location sampling (in red) corresponds to lower SWH values, so as over the second half of the month. The high SWH event during the 7 first days of the month is sampled over the F region only and not over the E region. This clearly demonstrates that a 150 km radius is not large enough to enable a correct sampling in this particular case with 2 altimeters.

Figure 9. SWH mean value and std at location E and F

When increasing the radius of the selection region the mean SWH values in E and F are converging (figure 9): increasing in E up to about 5.2 m for a 300 km radius, and decreasing in F down to a nearly similar value. Same converging is observed for the standard deviation. Increasing the radius results in a larger number of altimeter passes and in a better time sampling.

Two parameters are of interest to estimate the quality of the altimeter sampling: the number of day sampled in the month (Nd) and the size of the maximum data gap (Gmax) i.e. the number of consecutive days without altimeter sample over the area. These parameters depend on the number of satellites, on the relative phasing of the orbits and on the latitude location, the sampling being larger at high latitudes. Figure 10 shows that in location E with a 200 km radius only 16 days in the month are sampled which is insufficient to estimate a monthly mean value. Furthermore there is a maximum gap of 5 days at the beginning of the month, as seen above. In location E the radius has to be increased up to 400 km to get a Nd value of 25 and to 550 km for 31 days, which leads to too wide regions to assume the same SWH statistics. In location F the sampling is better: Nd and Gmax are equal to 27 days and to 3 days respectively with a 300 km radius.

Figure 10. Nd (left) and Gmax(right) as a function of the sampling region radius, at locations E and F

Further test were performed using comparisons with the SWH measurements from the Brittany buoy moored west of the French coasts and maintained by Météo France and UK Metoffice. Measurements are available from 1995 to 2005, with some gaps in the data. Figure 1 shows the mooring location together with the 200 km and 400 km limits around the buoy. For this particular region the meteorological conditions are known to be different for instance in the north of the north-western Spanish coast and in the south of Ireland, so that selecting all altimeter data within the largest region defined by the 400 km radius might result in statistics biased relatively to the real ones at the buoy location. Nd and Gmax are shown in Figure 11 for each month over the 1995-2005 time period, for various radius: 150 km (black), 200 km (green), 300 km (red) and 400 km (blue). A 150 km radius is not sufficient to estimate a monthly average, Nd varying between 10 and 25 and Gmax reaching 7 days. For 150 km (black curve) Nd varies between 17 and 21 during 1995 to mid-1996. During this time period 3 altimeters are in operation: ERS1&2 and TOPEX. The tandem mission is such that ERS-2 ground track coincides exactly with that of ERS-1 24h earlier. This particular configuration is in favour of an improved time sampling. After mid-1996 only ERS-2 and TOPEX are in operation and Nd decreases to 11-17 days till beginning of year 2000 when it increases up to 25 days with at least 3 altimeters in operation: ERS-2/ENVISAT, TOPEX/Jason and GFO. TOPEX
and Jason, and ERS-2 and ENVISAT are measuring at the same location with a short time difference of 5 min and 20 min, respectively. For this reason in the present context the measurements from the couples TOPEX/Jason or ERS/ENVISAT cannot be considered as independent. Increasing the radius to 200 km (green) Nd increases significantly up to 25 days in 1995 to mid-1996, less between mid-1996 and 2000, and exhibits relatively large variations in the period 2000 to 2006. Gmax decreases with values between 1.5 and 3.5 days.

Figure 12. Comparisons of monthly SWH mean values from altimeter and Brittany buoy, for various sampling region radii.

For 300 km (red curve) and with 3 satellites (after 2000) Gmax is less than 2 days and Nd is close to 26 to 30 days, which could be sufficient to estimate monthly SWH mean values. Results are of course much better when increasing the radius to 400 km (blue) but one can question about the representativeness of such a wide region for local wave statistics.

The altimeter and buoy SWH mean values can be compared as a function of the size of the sampled area. For this the buoy measurements are selected when the number of hourly measurements represents more than 27 days per month. Scatter plots are shown in Figure 12 for various radii and as a function of Nd. For each radius the differences are generally larger when the number of days sampled per month is low, particularly in the 150 km and 200 km cases. The scatter decreases with the radius from 20 km at 150 km to 10 cm at 300 km, while the negative bias increases, which could be attributed to a sampling bias, the altimeter taking into account sea state further away from the buoy location.

From above, a way to estimate SWH monthly mean values from altimeter measurements could be to impose critical thresholds for Nd and/or Gmax. For instance a minimum value of Nd about 27 days (which could be further adapted to the exact number of days in each month) and a maximum Gmax value of 2 days. The following example illustrates this sampling problem.

In Figure 13 the hourly SWH buoy data are plotted in cyan and the along track (1s) altimeter measurements within the selection area are reported for ERS-2 (blue), TOPEX (blue) and GFO (green). Monthly mean values are reported as dashed line in cyan for the buoy and in black for the altimeters. This example relative to April 2000, with 3 altimeters in operation could be considered as an extreme situation: the two highest events during the month (about 9 m maximum SWH on days 3 and 20) are not sampled by the altimeters when the sampling radius is set to 150 km (Figure 13, top), with Nd and Gmax equal to 17 and 4.8 respectively. Enlarging the selection region improves the situation. At 200 km (middle) Nd increases to 25 and Gmax decreases to 2.6 and the sampling of the second high SWH event is better. Note that on days 3 and 26 the altimeters sample SWH events which are not measured at the buoy location. The 250 km sampling does not significantly improve the situation, and the radius has to be increased to 300 km (bottom) to be able to begin to sample the maximum of SWH associated with the first event on day 4 (Nd=28; Gmax=1.49). At 350 km the sampling is much better (Nd=30; Gmax=1.18).

Figure 13 Time series of buoy and altimeter SWH for various sampling region radii, at Brittany location.
5. CONCLUSION
Fifteen years of altimeter SWH measurements from six satellite missions have been analyzed. One advantage of the altimeter is the fine along track spatial resolution. The data from both TOPEX and Jason missions enable to construct seasonal maps of along track SWH mean values and standard deviations, revealing short scale and regional sea state features associated with specific meteorology and oceanography of oceanic regions.

It has been shown that thanks to multi-satellite missions and homogeneous corrections of the altimeter data, monthly altimeter mean values and std of SWH could be estimated in any location. This opens the opportunity to construct ‘virtual buoy’ time series of monthly SWH. Nevertheless it has been shown that the number of satellites and also the relative phasing of the orbits are critical parameters determining the accuracy of the monthly estimates. Further improvement will consist in investigating Nd (number of sampled days per month) and Gmax (maximum data gap length) thresholds to consider for the best estimates of monthly altimeter SWH statistics.

6. REFERENCES


11. GEOSAT Follow-On GDR Users Handbook, NOAA Laboratory for Satellite Altimetry, NOAA/NESDIS/ORA/E/RA31, 1315 East-West Highway #3620, Silver Spring, MD 20910-328, USA.

