Please see our replies to the three reviewers in the related three single files. We believe we have fully replied to their requests where pertinent. In some cases we have pointed out why their suggestions (e.g. the triple co-location technique) were not pertinent.

The authors

Luigi Cavaleri*, Luciana Bertotti, Paolo Pezzutto

Accuracy of altimeter data in inner and coastal seas

ISMAR – CNR, Venice, Italy

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* corresponding author: luigi.cavaleri@ismar.cnr.it

Abstract

We carry out an inter comparison among four different altimeters, Cryosat, Jason2, Jason3, Sentinel-3. This is done checking the altimeter data versus the same wind and wave model results of a given area, the Mediterranean Sea, for one year period. The four datasets are consistent for wind speed, but they show substantial differences for wave heights. The verification of a Sentinel-3 pass close to coast in the Northern Adriatic Sea shows irregular spiky large wave height values close to coast. The problem worsens using high frequency altimeter data.

1 – Altimeter data

There is no doubt that satellite radar altimetry has revolutionized oceanography with the continuous and abundant flow of data during the last three decades or so. The related surface wind speed and significant wave height data have provided both a crucial information for data assimilation in, and validation of, model activity and results (see, among others, Abdalla, 2007, 2016) and substantial and prolonged information to be used for global statistics over the oceans.

Although officially calibrated, a careful intercompariosn strongly suggests the data from different instruments require specific attention and calibration. See in this respect the keen and prolonged analysis by Young et al. (2017). Starting in 1986 with Geosat, the real continuous flow began in 1991 with the launch of ERS-1, followed in time by Jason1, ERS-2, Jason2, Jason3, Envisat, Altika, Cryosat, ending (for the time being) with Sentinal-3. See also Passaro et al (2014).

The two different principles of interaction with the sea surface for wind and wave information retrieval (respectively back-scattering and specular reflection) imply different calibrations for the two signals, calibrations sensitive to the average conditions where the operation has been done. See in this respect the valuable work by Queffeulou and Bertamy (2007).Being this mainly versus buoy data in the oceans, it is correct to wonder if this calibrations hold also in the rather different conditions of the inner seas. This is particularly true in view of the use of Sentinel-3 in very coastal waters in the attempt to push the use of altimeter data till very close to coast, certainly much closer than the 20-30 km distance of the classical altimetry.

In this short paper we make an intercomparison between the wind and wave data from four different altimeters and the results of two high resolution meteorological and wave models. The area is the Mediterranean Sea. We use Cryosat, Jason2, Jason3, Sentinel-3 data (henceforth Cy, J2, J3, S3). The period is the twelve months from July 2016 till June 2017. The models are COSMO for meteorology (see www.cosmo.model.org/content/model/default.htm) and WAM for waves (see the historical Komen et al., 1994, and the more updated Janssen et al., 2005). The related operational system is the combined effort of the Italian Meteorological Service and the Institute of Marine Sciences (ISMAR-CNR). COSMO is run at 7 km, WAM at 0.05^o resolution. The system provides twice daily three-day forecasts at hourly interval. A full description of the system and its accuracy is available at Bertotti et al. (2013). For the altimeter-model inter comparison we have used the first 12 hour forecasts of the twice-a-day operational activity (hourly fields). The model data have been, bi-linearly in space and linearly in time, interpolated at the position and time of each altimeter datum. The Cy, J2, J3 data have been retrieved from the Delft University website http://rads.tudelft.nl/rads/rads.shtml. The S3 data from https://coda.eumetsat.int.

We stress that for the most part, rather than on the comparison with the model data, the analysis is based on an, although indirect, intercomparison among the different altimeters. We present our analysis and results in the next Section 2. In Section 3 we focus on an example of use of S3 data very close to coast. We summarize our conclusions in the final Section 4.

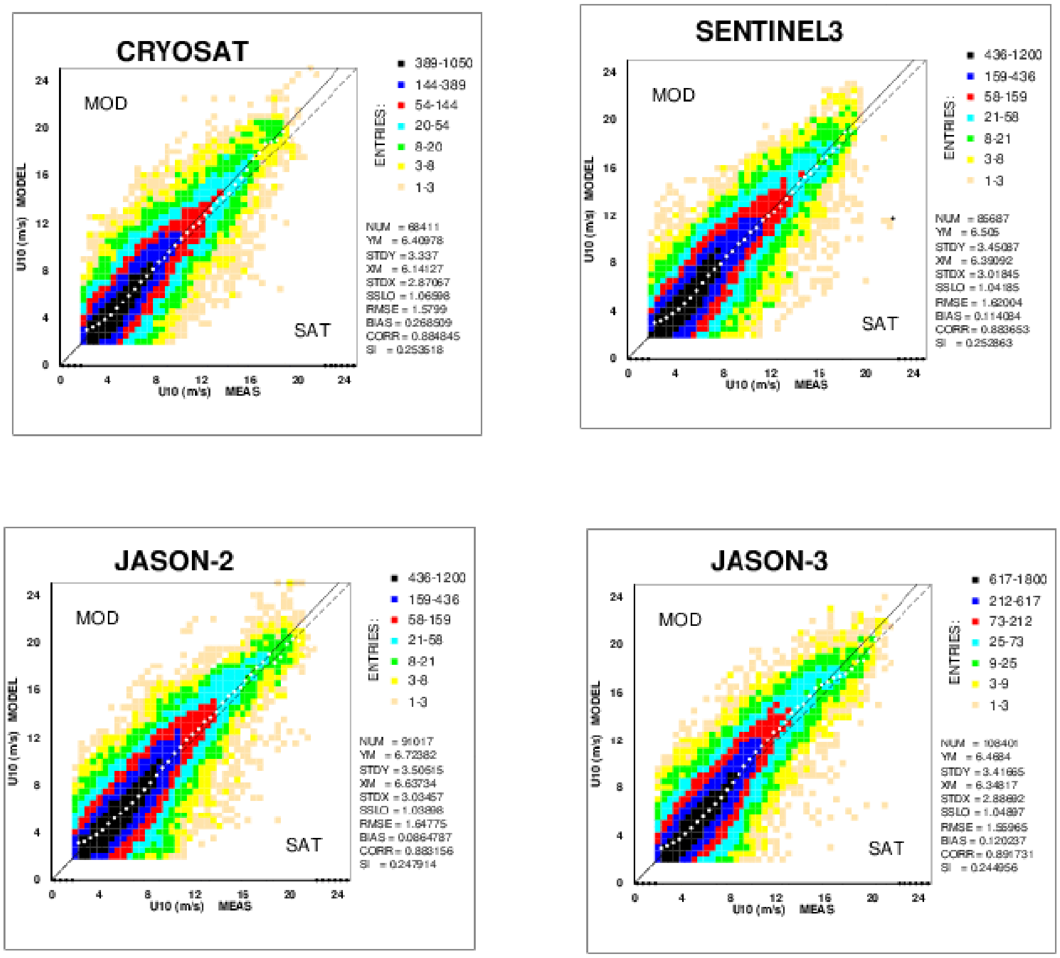

Figure 1 – Scatter diagrams of the COSMO model wind speeds vs the Cy, S3, J2, J3 altimeter data. The area is the Mediterranean Sea. The continuous lines show the respective best-fit slopes. Dash lines would be the perfect fit.

2 – How much altimeters differ one from the other one

Figure 1 provides the scatter diagrams and related statistics for the model surface wind speed vs the altimeter data for the four considered satellites. As usual, the colours (scale on the right side of each panel) indicate the number of data in each pixel.

Varying between 4 and 6%, there is a clear relative overestimate by the model. There is a rather large scatter, with the scatter index SI typically at 0.25. There is some indication of a larger overestimate in the higher value range. However, for the present purpose we focus on the altimeter data, and the results in Figure 1 suggest a consistent performance among the four altimeters.

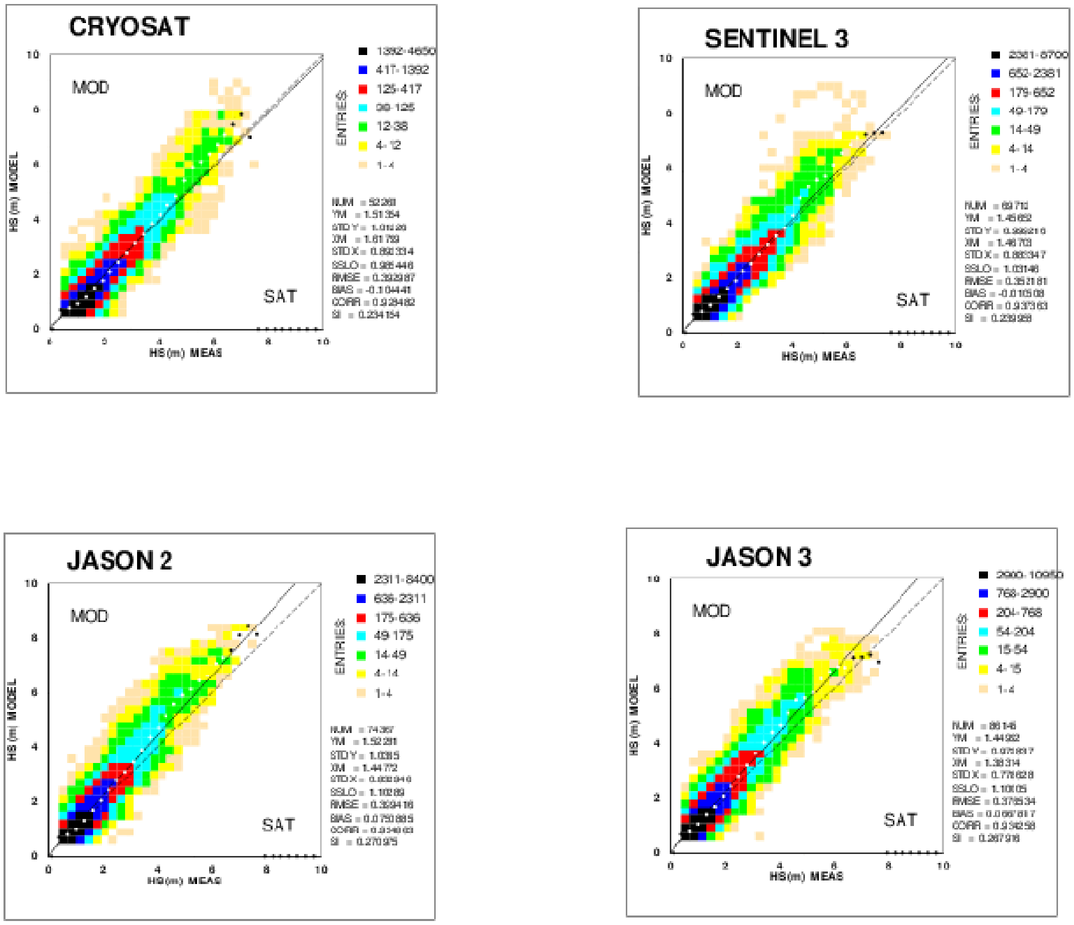

Figure 2 – As Figure 1, but for the significant wave height.

Things are rather different when we consider the significant wave height H_s. The related results are in Figure 2. There are obvious differences among the four altimeters, summarized for waves in Table 1.

alt	Cy	J2	J3	S3
sslo	0.98	1.10	1.10	1.03
SI	0.23	0.27	0.27	0.24

Table 1 – Symmetric best-fit slope (sslo) and scatter index (SI) of the wave model data versus altimeter ones. Cy = Cryosat, J2 = Jason2, J3 = Jason3, S3 = Sentinel-3.

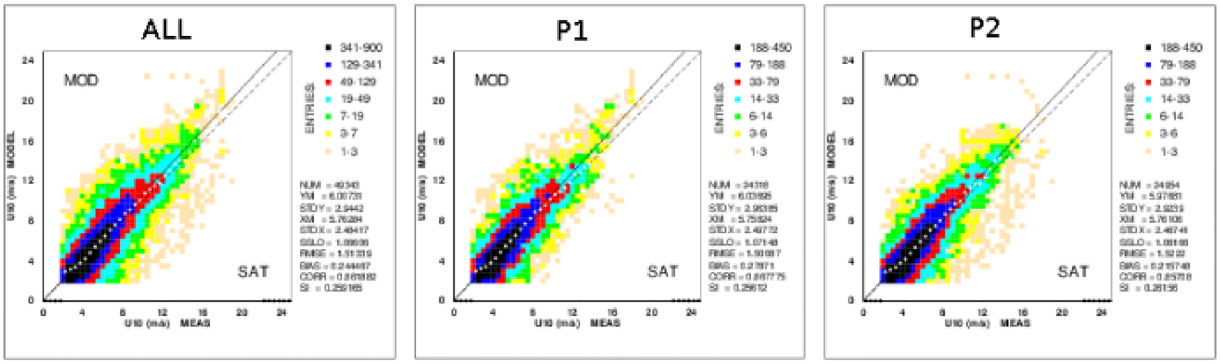

Figure 3 – As Figure 1, but for only the Cryosat data. Left panel (ALL) full dataset, P1 and P2 each one complementary half of the data selected by random sampling.

There is a 12% wave height best-fit difference between the two Jason altimeters and Cy, and still 7% versus S3. Our arguing is the following. Given that the different altimeters have been compared with the same model data (area and period), these results must reflect differences among the four instruments. However, it can be argued that the four instruments have not measured exactly the same wave conditions (in space and time), each satellite sampling at different times and positions, hence on different wave conditions. To explore this possibility, we have split each altimeter dataset in two halves with a random sampling of the different passes, then evaluating a new statistics for each one of the two half of the data. As an example we show in Figure 3 the related results for Cy (similar results hold for each satellite). There is hardly any difference. More in general for each altimeter the differences among the full and half statistics are less than 2% of the single statistical figures. Therefore the results in Table 1 are fully representative of the situation.

3 – A Sentinel-3 coastal track

The Sentinel-3 altimeter acquisition system, somewhat an evolution of the SIRAL mounted on Cryosat-2 satellite, is claimed to enhance the accuracy of sea state measurements close to the coast. S3 altimeter, SRAL, has two distinct operational modes: the conventional LRM and the high along-track resolution, or SAR mode (www.sentinel.esa.int). The latter is synthesized from a composition of 64 Ku-band pulses and two c-band ones. Operating in SAR mode, the SRAL along track resolution is of the order of 300 m with a large (up to 10 km) lateral swath. The reduced sampling area implies obviously a higher noise in the signal, but, especially when flying perpendicularly to the coastline, it allows in principle to go much closer to it with meaningful data. We explore this possibility analyzing one pass in the Northern Adriatic Sea.

The proposed sample is a level 2 product provided from the Copernicus service with identifier "S3A_SR_2_WAT____20170725T094431_20170725T094658_20170725T120008_0146_020_193______MAR_O_NR_002.SEN". The NetCDF file contains also PLRM (pseudo low res mode) data, which is intended as a simulation, starting from Ku-band pulses, of the classical altimeter sampling strategy, LRM.

Figure 4 shows the ground track during an S3 25 July 2017 descending pass over first the Adriatic then the Tyrrhenian Sea. There was a severe mistral storm in the Western Mediterranean (see the H_s scale on the right), but only a tiny bit of it passing between Corsica and Sardinia was touched by the pass. The model and altimeter data are in Figure 5, latitude decreasing, hence following the satellite, from left to right. For a short moment we focus on the Tyrrhenian results,

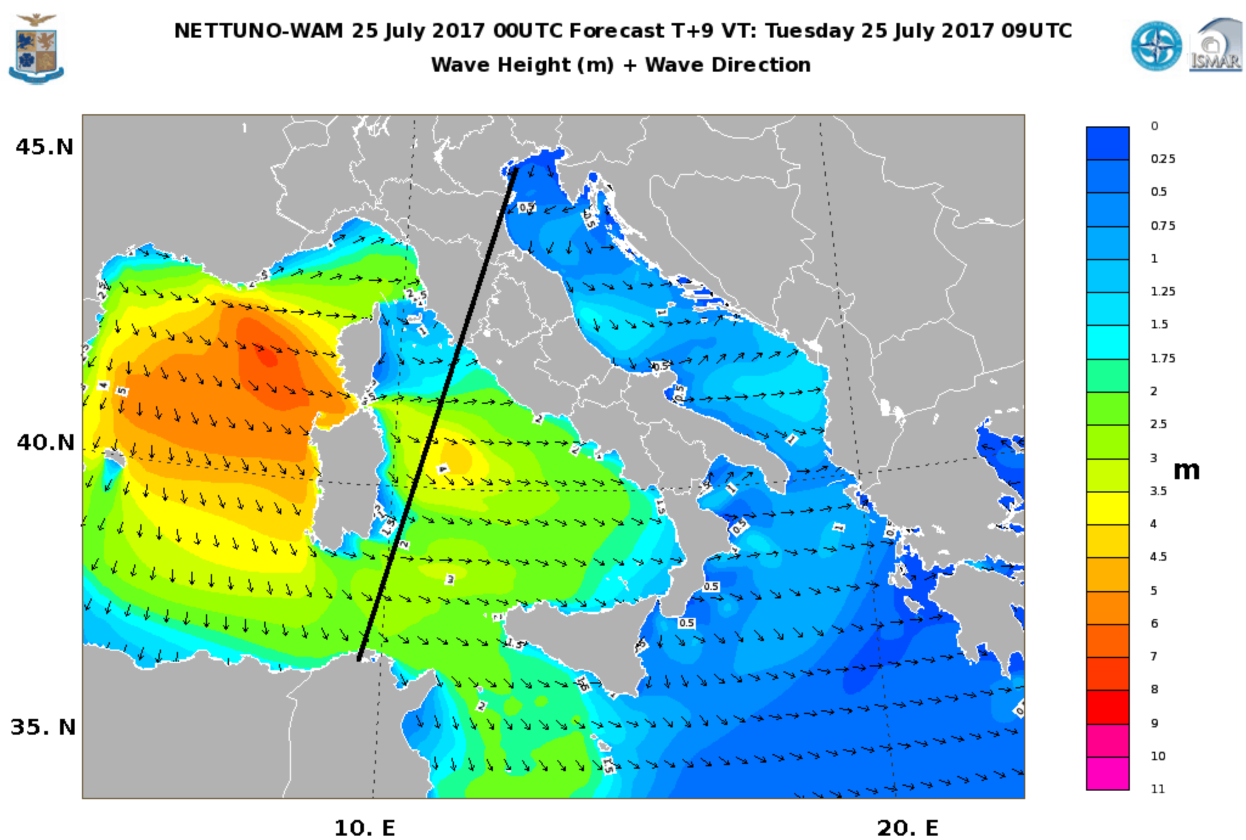

Figure 4 – Ground track of a descending pass of Sentinel-3 altimeter. The background colours and arrows show the significant wave height distribution.

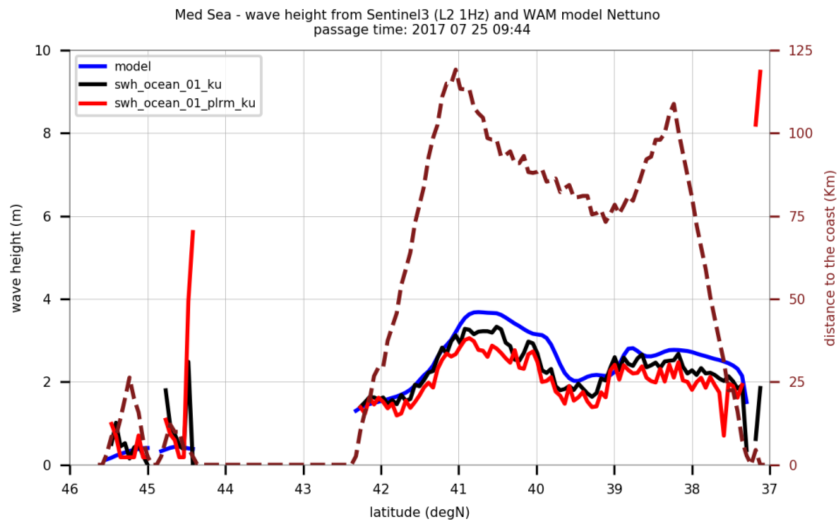

Figure 5 – Intercomparison, along the ground track in Figure 4, between the model significant wave heights and the measurements (ku-, plrm-ku- corrected H_S) by the Sentinel-3 altimeter. The dash line shows the distance (km) of each measurement from the closest coast.

the model H_s following well the measured quantity. The dash line (right scale) shows the distance from the closest coast (km). Note the altimeter spikes when exiting and entering land. In this respect we zoom on the short passage on the Adriatic Sea (the first short section in Figure 5), passage geographically better represented in Figure 6. We recognize the Venice lagoon (about 50 km long) and the protruding Po river delta intersected by the descending satellite ground track. Dots and close-by numbers represent the 1 sec S3 H_s data (ku-band) Note the incoherent data when passing on the Po delta and when entering land again shortly after. The oceanographic situation is in Figure 7. There is a very mild wind sea from North-East with significant wave height close to, mostly less than, 0.5 m (product of the operational ISMAR Adrioper wave forecast system, see Bertotti and Cavaleri, 2009). An independent validation (not shown) of the model results for this day is provided by the data regularly recorded at the ISMAR oceanographic tower (Cavaleri, 2000), located 15 km off the Venice lagoon (see Figure 6). The model-measurement H_s difference close to the time of the pass is less than 10% that, on the base of previous experience and validation (Bertotti and Cavaleri, 2009), we take as characteristic of the overall local field, hence of also the model data corresponding to the S3 ones.

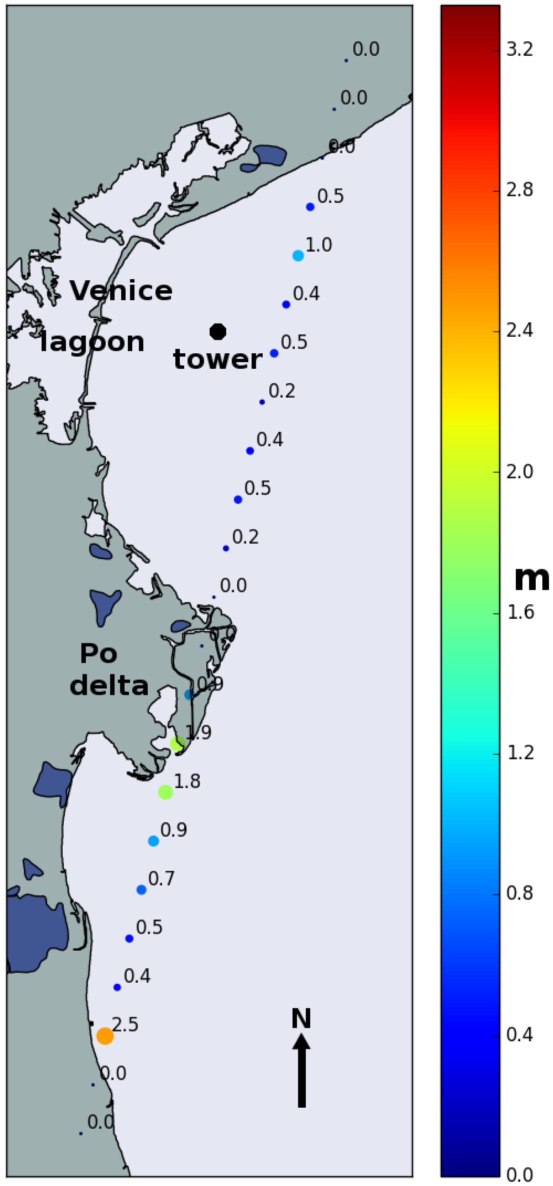

Figure 6 – Detailed geometry, focused on the Adriatic Sea, of the area of the pass in Figure 4, in more details in Figure 7. The positions and the corresponding SAR mode (swh_ocean_01_ku) altimeter significant wave height values (m) are also shown.

Figure 7 – Wave field (very mild conditions) in the Northern Adriatic Sea at 09 UTC 25 July 2017. The arrows show the significant wave height and mean direction. The modelled maximum wave height in the field is close to 0.5 m. Wind and waves were from East-North-East.

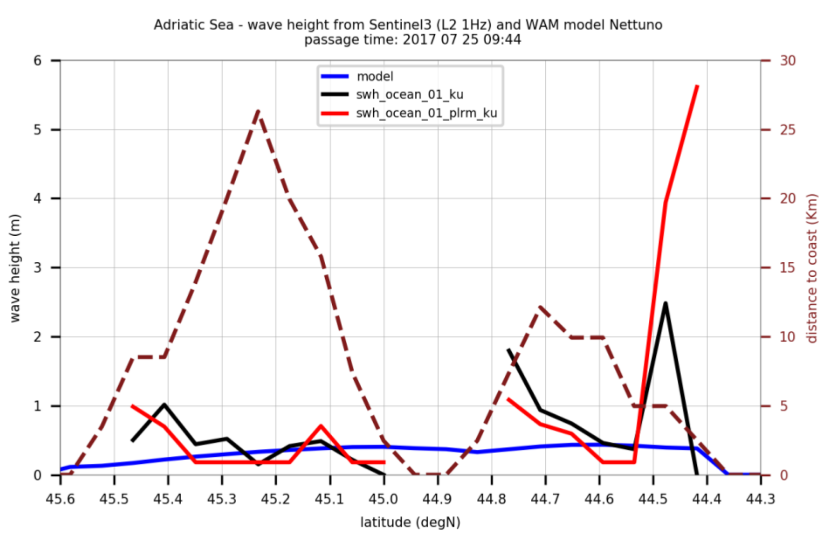

Figure 8 – Intercomparison, for the pass in Figure 6 and the time of Figure 7, between the Sentinel-3 ku-, plrm-ku- wave heights and the corresponding wave model results. The dash line shows the distance from the closest coast (km).

In Figure 8 we show the detailed comparison among the three different (ku-, plrm-ku-) bands and model H_s values plus the distance (km/10) from the closest coast. There are some obviously absurd values by S3 in the two signals, more in the plrm-ku, this when the distance from the coast was less than 10 km.

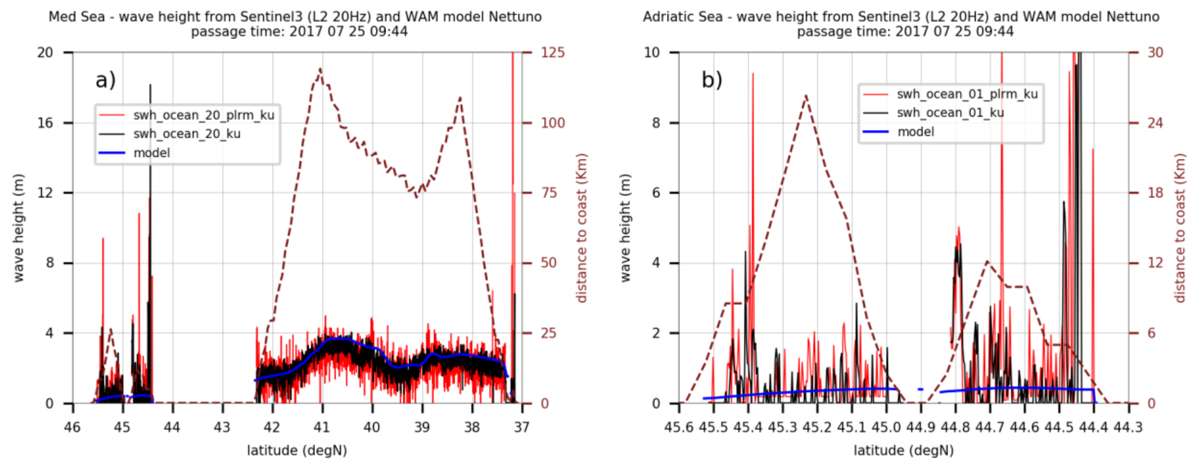

Figure 9 – As Figure 8, but for the 20 Hz altimeter data. Panel a is for the full pass, panel b for the Adriatic Sea section (see Figure 8 for comparison).

Finally in Figure 9 we explore the 20 Hz data. Panel a shows the whole pass (the corresponding of Figure 5). Panel b focuses on the Adriatic Sea. The noise of the signal is evident, also when the distance from the coast was about 20 km. There is a very large variability of the S3 altimeter signal also in the Tyrrhenian Sea, a variability that cannot be justified by geophysical reasons, and it is therefore natural to associate to the instrument and to the sampling variability. Again the S3 approach seems to lead to very large H_s values also when the distance from the coast approaches the classical 20-30 km limit of standard altimetry.

4 – Summary

Following the extensive availability of altimeter data for both wind and waves, and their relevance in validating model results, we have explored the consistency of the data from four different altimeters. Lacking the possibility of extensive triple-colocation analysis (the datasets would be too small for meaningful results), we have followed a different principle, i.e.: we take the model data as reference and, without arguing about right or wrong, we explore how each satellite fits the model data. Should the altimeters being consistent to each other, each altimeter vs model fit should provide the same best-fit slope. On a different line of action we have explored the value of S3 data close to coast. In summary, we have carried out two tests: 1) an extensive one on four different altimeters (Cy, J2, J3, S3, see Table 1), and 2) a sample one on one S3 pass. The purpose of 1) was an, indirect but significant, intercomparison among these four altimeters. 2) was meant to explore one case of sampling by S3 in coastal waters. In this case we have also checked the value of the 20 Hz data. We itemize our results as follows.

1 - the surface wind speed values derived from the four altimeters are consistent to each other, differing on the average less than 2%,

2 - large differences are found in a similar intercomparison for the significant wave height H_s. There is on average a 12% difference between the best-fit slopes of Cy and the J2-J3 data, the latter ones measuring larger wave heights. The S3 values lay more or less in the middle,

3 - the S3 1 Hz data close to coast are noisy, with spikes of obviously wrong large values. Use of 20 Hz seems to increase the noise, wrong large values appearing also relatively far (20 km) from the coast,

4 - the use of 20 Hz leads to a high variability of the H_s data also in the open sea, far from the coasts, implying this variability is practically associated to the instrumental measurement and to its sampling variability.

Acknowledgements

Luigi Cavaleri, Luciana Bertotti and Paolo Pezzutto have been partially supported by the EU contract 730030 call H2020-EO-2016 'CEASELESS'. Jesus Portilla and Robert Jensen, plus another anonymous reviewer, have provided useful suggestions to improve the readability of the paper.

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