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Jason-2 OGDR Wind and Wave Products: Monitoring, Validation and Assimilation

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Abstract

Jason-2 fast delivery OGDR-BUFR products have been received at ECMWF since August 2008. Altimeter surface wind speed and Ku-band significant wave height (SWH) products are monitored and validated against operational ECMWF atmospheric and wave model results in addition to the available observations. It was found that those products are, in general, of good quality. The Ku-band SWH, in particular, is better than its Jason-1 counterpart. However, the wind speed algorithm is in need of some improvements.

Several experiments were carried out to assess the impact of assimilating Jason-2 SWH in the ECMWF wave model. The model analysis and forecast fields were verified using available observations and the model own analysis. The results show good impact of the data. This led to the operational assimilation of Jason-2 SWH (in addition to Envisat data) into the operational ECMWF model replacing Jason-1 SWH on 10 March 2009. Further experiments were carried out to assess the impact of adding Jason-1 SWH data after the shift to a separate orbit than Jason-2. The impact is positive but rather limited. This led to the reintroduction of Jason-1 SWH product into the ECMWF wave model on 8 June 2009.

1 Introduction

The European Space Agency (ESA) launched its first ERS mission in 1991 providing radar altimeter (RA) significant wave height (SWH) data in near-real time (NRT) or what is commonly known as RA fast delivery product. This enabled the operational assimilation of the SWH in the third generation ocean wave model (WAM) that runs operationally at the European Centre for Medium-Range Weather Forecasts (ECMWF) from 15 August 1993 onwards (c.f. Janssen et al., 1997). This had a significant impact on the wave model analysis and forecast. ESA launched ERS-2 in 1995 to replace ERS-1. The RA onboard ERS-2 was similar to that of ERS-1 but with better accuracy. In 2002, ESA launched its environmental satellite Envisat with a RA (known as RA2) similar in principle to those of ERS satellites to replace the ERS mission. Envisat RA2 is better than its predecessors.

Jason-1 satellite, which is a continuation to TOPEX/Poseidon, is the result of the collaboration between the French Space Agency (Centre National d'Etudes Spatiales, CNES) and the US National Aeronautics and Space Administration (NASA). It was launched on 7 December 2001. Unlike TOPEX/Poseidon, Jason-1 RA provides NRT wave height data as part of what is known as the Operational Sensor Data Record (OSDR) which makes it suitable for operational ocean wave analysis. Jason-1 OSDR wave height data have been assimilated operationally into ECMWF wave model since 1 February 2006. Jason-2, which is a continuation for Jason-1, was launched on 20 June 2008 as a collaboration effort between CNES, NASA, the US National Oceanic and Atmospheric Administration (NOAA) and the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT). This work is dedicated to the assessment of the quality of the wind and wave products, especially the significant wave height, which is used in ocean wave data assimilation.

Section 2 provides an overview of the data used in the current work. The results of Jason-2 SWH verification is presented in Section 3. A brief description of the ocean wave forecasting and analysis system and the results of assimilating Jason-2 SWH in the ECMWF wave model are both provided in Section 4. Verification of Jason-2 surface wind speed product is given in Section 5. Finally, conclusions are listed in Section 6.

2 Data Used

The main data set used in this study is the BUFR (Binary Universal Form for the Representation of meteorological data) version of the Operational Geophysical Data Record (OGDR) of Jason-2 radar altimeter. This data stream is produced and disseminated by EUMETSAT and NOAA in NRT within few hours which makes it suitable for operational use in atmospheric and ocean wave forecasting systems. This data can be obtained either through EUMETCast or the Global Telecommunication System (GTS). The former is the broadcasting system of EUMETSAT for the dissemination of its environmental data using the standard Digital Video Broadcast (DVB) technology available on commercial telecommunication geostationary satellites to a wide user community. On the other hand, GTS is a global network for the transmission of meteorological data from weather stations, satellites and numerical weather prediction centres. This network is accessible by the World Meteorological Organisation (WMO) member states.

The OGDR product may be of slightly degraded quality compared to the final Geophysical Data Record (GDR). The latter product is available with a delay of several weeks. Even the interim product (IGDR) has a delay of few weeks. This latency makes those higher quality products not suitable for operational atmospheric systems. Nevertheless, the quality of the SWH and the surface wind speed parameters does not differ between the OGDR and the GDR (unlike Jason-1 data). It is only the retracker which is of lower quality.

Jaosn-2 altimeter is a dual-frequency instrument. It operates using two different radar frequencies: one in the Ku-band and the other in the C-band. The Ku-band altimeter is the more reliable as far as the ocean waves are concerned. This study assesses Jason-2 Ku-band SWH and surface wind speed only.

For the assessment of model performance and the data verification and quality assessment, other sources of data are used. The genuine independent (from both the model and the altimeter data) source of data for verification and assessment is the in-situ ocean wave data collected by wave buoys or various wave gauging instruments mounted on offshore platforms. It is commonly believed that this type of data represents the ground truth. This type of data, which usually consists of SWH and in some cases peak (or mean) wave period in addition to other atmospheric surface parameters like wind speed, is obtainable by meteorological centres via GTS. Spectral information in the form of one-dimensional (1D) wave spectra from a number of stations and in terms of two-dimensional (2D) spectra from a limited number of stations are made available by some data providers. In-situ spectra are typically available after few weeks on the Internet. Unfortunately, the total number of in-situ stations is very limited (slightly above 100) and most of them are located in the Northern Hemisphere (NH) around the North American and European coasts including two buoys in the Western Mediterranean. The exceptions are a few buoys in the Tropics (mainly around Hawaii) and off the South African coasts. Other stations may be available for limited time periods at other parts of the world. Therefore, any assessment restricted to in-situ data would not be very conclusive. The term ‘buoy’ is usually used to refer to this type of data even if it is originated from a different in-situ source (e.g. a wave staff at an offshore platform). More information about in-situ ocean wave data, including the pre-processing method used for the quality control and averaging, can be found in Bidlot et al. (2002).

For global coverage, the NRT altimeter data from Envisat and Jason-1 are used for verification and quality assessment. The former data stream is available to ECMWF through two file transfer protocol (ftp) sites made available by ESA. In particular, Level 2 of RA2 Fast Delivery Marine Abridged Records (FDMAR) product is used. For Jason-1, OSDR product is used for verification. SWH from both FDMAR and OSDR products are assimilated in the ECMWF ocean wave model. As far as Jason-2 data verification is concerned, these are not totally independent data sets as all altimeters share the same principles of measurements and algorithms. Furthermore, this type of data is usually assimilated into wave models. Therefore, the model output has some degree of dependency on them. The dependency becomes weaker further along the forecast range. Therefore, altimeter data can be used to assess the model first guess (FG) and forecast (FC) assuming that those products are independent of the satellite observations at the verification time. This is a valid assumption, especially for forecasts beyond 2-3 days except for any possible systematic errors in the observations. Hence, the altimeter data is used to assess the impact of assimilation on the model first guess and forecasts. Similar to Jason-2, both Jason-1 and Envisat altimeters are dual-frequency instruments. Jason-1 implements the same frequencies as Jason-2 while Envisat operates with the Ku-band and the S-band frequencies. Only Ku-band products from both instruments are used here.

The altimeter data are pre-processed in a way similar to the approach outlined in Abdalla and Hersbach (2004) with slightly modified parameters. The data go through quality control process to remove erroneous and inconsistent observations. The data is then averaged along the track to form super-observations with scales compatible with the model scales of around 75 km. This corresponds to 13 individual (1 Hz) Jason-1 and Jason-2 observations and to 11 individual (1 Hz) Envisat observations.

A third option, which can be used only for the model forecast assessment, is the use of the model analysis which can be assumed to be the best representation of the (unknown) truth by the model. This is a common practice in the field of numerical weather prediction. However, the same argument used regarding the use of the satellite data can be made here.

One last option is the use of a combination of those options in a form of multiple collocation analysis (see Janssen et al., 2007). This option was not utilised for the current work.

3 Verification of Jason-2 RA SWH Data

Jason-2 OGDR-BUFR product has been routinely streamed to ECMWF since August 2008. After passing the quality control process mentioned in Section 2, the data is closely monitored and verified using the model first guess data. On a monthly and an annual basis, the data are verified against available in-situ data in addition to the model data. Internal monthly reports summarising the quality of Jason-2 products for that month are produced. In general, the rate of Jason-2 data timely reception is quite good which indicates the reliable operational status of the data so far.

In general, the OGDR Ku-band SWH data compare well with the in-situ buoy and platform observations as can be seen in Figure 1 and against ECMWF wave model FG as can be seen in Figure 2 for a full year from 1 October 2008 to 30 September 2009. It should be stressed that the former verification is limited to the Northern Hemisphere (near the coasts of Europe and North America) and parts of the Tropics while the latter represents a global verification. The scatter plots in Figure 1 and Figure 2 represent two-dimensional (2-D) histograms showing the number of observations in each 2-D bin of 0.25 m x 0.25 m of SWH. One can notice that Jason-2 SWH data are almost unbiased compared to the in-situ observations and to the ECMWF model FG. The standard deviation of the difference (SDD) is about 0.39 m and 0.27 m when compared to the in-situ observations and the model FG, respectively. Those values correspond to scatter index (SI, defined as the

SDD normalised by the mean of the reference which the in-situ or the model FG) values of about 17% and 10%, respectively.

The time series of the global SWH bias (defined as the difference between the altimeter product and the model output) and SDD of Jason-2 with respect to the ECMWF wave model FG values during the period from 1 August 2008 to the end of September 2009 are shown in Figure 3. To get representative statistics, 7-day data windows are used. Similar time series from Jason-1 and Envisat data are provided in the same figure for comparison. Time series plots of the error statistics are powerful tools to detect any irregularities in the quality of the satellite data. It is clear that Jason-2 SWH is almost unbiased (the maximum weekly bias is around 0.04 m) compared to the model for the whole year. On the contrary, both Jason-1 and Envisat SWH values are consistently higher than the model by about 0.08 m. The SDD plots suggest that although Jason-2 SWH product is better than that of Jason-1 by about 7%, it is worse than Envisat SWH by about 7% as well.

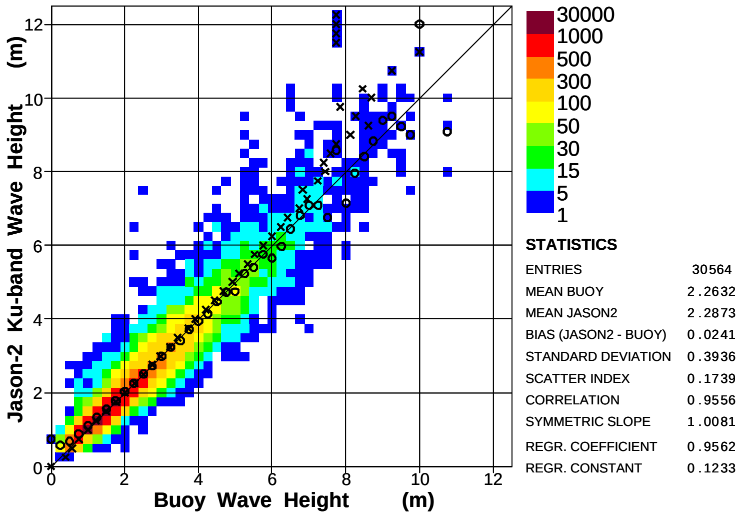

Figure 1: Global comparison between Jason-2 Ku-band and buoy SWH values during the period from 1 October 2008 to 30 September 2009 (mainly in the NH).

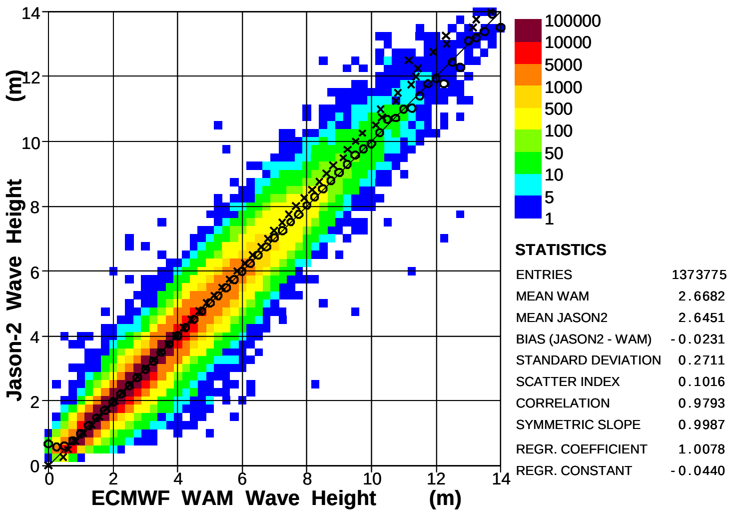

Figure 2: Global comparison between Jason-2 Ku-band and ECMWF model SWH values during the period from 1 October 2008 to 30 September 2009.

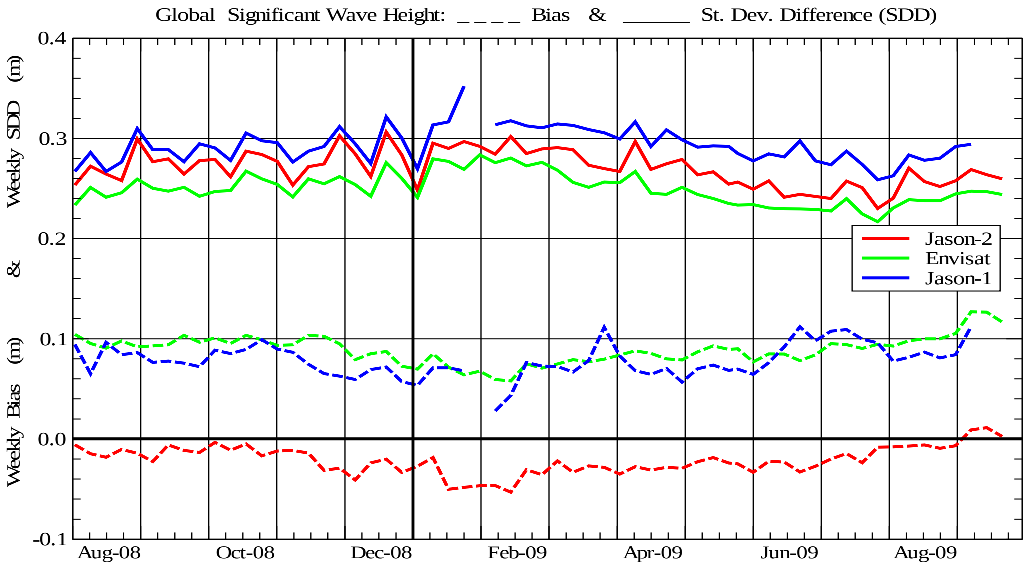

Figure 3: Time-series of the global SWH difference (bias) and standard deviation of the difference between Jason-2 and ECMWF model since 1 August 2008 (red). Similar plots for Envisat (green) and Jason-1 (blue) are also given for comparison.

4 Jason-2 RA SWH Data Assimilation

Unlike atmospheric data assimilation, which started in the 1960's, ocean wave data assimilation emerged only in the 1980's. Satellite wave data are assimilated to produce the analysis (AN), and to improve the forecast (FC) of the wave model. This has proved to be of great value (see, e.g. Komen et al., 1994). As an example, Bidlot et al. (2002) and Abdalla et al. (2004) showed that assimilation of satellite radar altimeter wave heights reduces the model wave height errors with respect to in-situ observations by about 10-20%.

ECMWF runs operationally a meteorological forecasting system called the 'integrated forecast system (IFS)' twice a day at analysis times of 00 and 12 UTC. The wave model WAM (c.f. Komen et al., 1994 and Janssen, 2004) is coupled tightly with IFS. Further descriptions can be found in Janssen et al. (2005). Further verifications of the ocean wave part of the system can be found in Janssen et al. (1997). Operational assimilation of ERS-1 RA fast delivery SWH at ECMWF started on 15 August 1993. This was followed by the transition to ERS-2 on 1 May 1996 and to Envisat on 22 October 2003 after the loss of ERS-2 global coverage due to the failure of its onboard tape recording facilities. Assimilation of Jason-1 OSDR SWH started on 1 February 2006 on top of Envisat products. This continued until it was replaced by the assimilation of Jason-2 OGDR SWH product on 10 March 2009. Jason-1 SWH assimilation was resumed on 8 June 2009. Furthermore, ERS-2 synthetic aperture radar (SAR) wave mode data were assimilated between 13 January 2003 and 31 January 2006. The corresponding Envisat advanced SAR (ASAR) wave mode product replaced its ERS-2 counterpart on 1 February 2006.

Wave data assimilation at ECMWF is based on a simple optimal interpolation (OI) technique as described by Lionello et al. (1992). In short, the model uses the best wave conditions available at any time and produces a first guess (FG) 6 hours later. Wave observations are assimilated at that time using the OI technique producing the best possible model wave conditions which is called analysis (AN). At 00 and 12 UTC, the model runs for 10 days (5 days in the limited area model) without any use of data to produce wave forecasts (FC).

4.1 Assimilation Scheme

Optimisation procedures are used to find the best or the optimal model state from the model FG and the observations. Assimilation schemes used for wave data analysis can be classified into sequential and variational. The former modifies the model FG to bring them as much as possible towards the observations available within the time-window centred at the analysis time in an independent manner. Such modifications may not be consistent with the model dynamics and may cause some kind of discontinuities. On the other hand, the variational schemes try to find the model solution that minimises the differences with the observations over the whole analysis time window. This implies proper correction to the driving wind fields, which may not be consistent with the atmospheric model dynamics. However, the resulted AN wave fields are consistent with the wave model dynamics. Although variational schemes possess more desirable properties than the sequential schemes, the computational requirements and some practical difficulties like the lack of up-to-date wave-model adjoint prevent them from being used in global operational wave forecasting systems. Furthermore, the main source of error in ocean wave data assimilation is the distribution of SWH analysis increments on the whole wave spectrum which is currently done with several approximations due to the lack of other alternatives.

The optimal interpolation (OI) technique is one of the simplest sequential data assimilation methods. This technique is used at ECMWF for the assimilation of satellite wave data from altimeters (ERS-1/2, Envisat and Jason-1/2) and from SAR (ERS-2 and Envisat). In the case of RA, only significant wave height (SWH) is available. SWH is a prognostic parameter that is only computed from the wave spectrum as an output parameter. Therefore, the SWH observations together with FG SWH are blended using the OI scheme to create an AN SWH field. The AN SWH field together with the model wave growth laws are used to construct the AN spectra by resizing and reshaping the FG spectra. This, of course, implies plenty of assumptions as can be found in Lionello et al. (1992).

4.2 Impact of Assimilation of Jason-2 Ku-Band SWH

The high quality of Jason-2 OGDR SWH product encouraged the immediate use of the product in several assimilation experiments to assess its impact on the ECMWF forecasting system. The product was assimilated without any calibration or penalisation (i.e. no weight reduction). The model first guess, analysis and forecast fields were verified using available observations and the model own analysis. The results show good impact of the data assimilation. For example, Figure 4 shows the impact of assimilating Jason-2 SWH data on the analysis (at zero forecast hour) and forecast model SWH bias (top panel) and standard deviation of the difference (lower panel) in the tropical zone between 20o N and 20o S compared to a combination of Envisat and Jason-1 SWH observation for the period from 01 August to 21 September 2008. The model run with no data assimilation has the largest model SWH errors followed by the model run with assimilating data from one satellite (Jason-2). Runs that assimilate SWH data from two satellites produce the lowest errors. Compared to the experiment of no data assimilation, the impact of assimilating Jason-2 data, both alone or in combination with Envisat RA2 data, resulted in significant improvement of the model analysis and forecast results up to day 4 in the forecast. Of course, more or less similar impact would be expected if SWH product from any other altimeter is used (see, e.g., Abdalla et al., 2004). This shows the importance of ocean wave data assimilation from at least one altimeter. Using Jason-2 data instead of Jason-1, which was assimilated operationally at the time, together with Envisat data leads to slight reductions in the errors of the model forecast. The impact of data assimilation in the extra-tropical zones (at latitudes higher than 20o) is usually smaller than that of Figure 4.

Similar impact was observed comparing the model forecasts against the independent in-situ observations. For example, Figure 5 shows the impact of altimeter SWH on the scatter index of the model peak wave period forecasts compared to all in-situ data received through GTS during the period from 1 August to 21 September 2008. Again, the assimilation of altimeter SWH data reduces the wave peak period SI error significantly. The use of Jason-2 data instead of Jason-1, slightly improves the model peak wave period.

Due to the tight two-way coupling between the atmospheric and ocean wave models at ECMWF, any changes to the wave model should be tested in a coupled mode in order to ensure that no degradation was introduced to the atmospheric fields. Along this line, the full operational setup of the IFS system was used to test the impact of assimilating Jason-2 SWH data instead of Jason-1 counterpart for the period from 1 August to 30 September 2008. It turned out that run utilising Jason-2 data has slightly improved atmospheric scores compared to that of Jason-1. Figure 6 shows the impact of Jason-2 SWH data assimilation on the model 500 hPa geopotential height forecast anomaly correlation (which is a standard statistic used in numerical weather prediction field and represents the correlation of the model deviations from the climate) with respect to operational analysis in the Northern Hemisphere for the period from 1 August to 30 September 2008. The positive improvement (i.e. the increased correlation between the model forecast and the operational analysis) due to the use of Jason-2 data instead of Jason-1 can be clearly seen.

It was clear that Jason-2 adds a considerable value to the model analysis and forecast. However, there was a decision to make. At the time, Jason-1 and Jason-2 were flying close to each other on the same orbit. Data

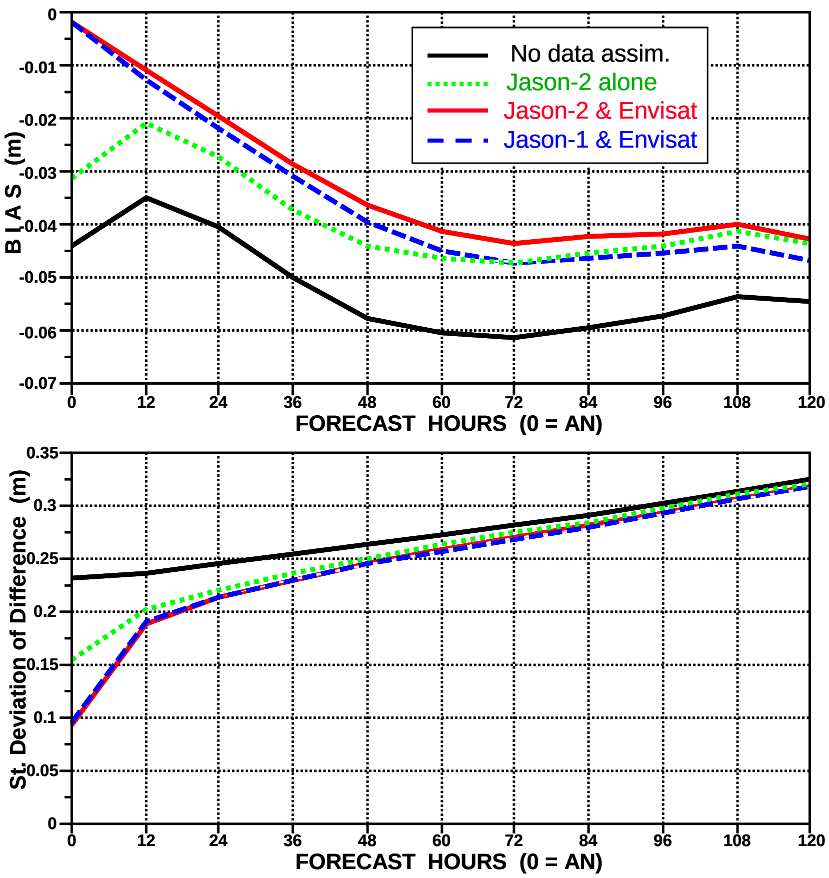

Figure 4: Impact of Jason-2 SWH assimilation on the model SWH forecast errors (bias in the top panel and standard deviation of the difference in the bottom panel) in the Tropics compared to Envisat and Jason-1 altimeter SWH for the period from 01 August to 21 September 2008.

from only one of them could be used. The higher quality of Jason-2 and the plan to shift Jason-1 orbit which imposes extra risk on Jason-1, motivated the use of Jason-2 instead of Jason-1 data in the ECMWF operational system. This was realised on 10 March 2009.

4.3 Impact of Assimilation of Jason-1 SWH on Top of Jason-2 and Envisat

Jason-1 was shifted to a new orbit during the period from 26 January to 14 February 2009. This was a welcome move as it provides more coverage of the ocean surface. The main reason behind the abandoning of Jason-1 SWH data was removed. After few weeks of monitoring Jason-1 OSDR data, it was clear that the instrument did not suffer any degradation. Several tests were carried out to assess the impact of reintroducing Jason-1 Ku-band SWH data into the ECMWF model. The period between 10 February (just after Jason-1 inhabited its new orbit) and 18 May 2009 was selected for those tests. Table 1 shows the bias and the SI errors between the model analysis and the in-situ measurements. It is clear that assimilating Jason-1 SWH data on top of Jason-2 and Envisat data has small but positive impact on the model SWH, mean wave period and peak wave period. The SI of SWH reduced from 15.1% to 14.7% due to the existence of Jason-1 data. The reductions of the other error statistics are relatively marginal.

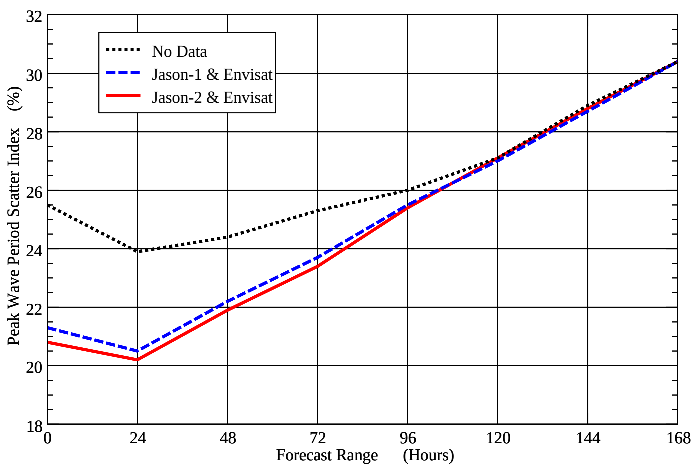

Figure 5: Impact of Jason-2 SWH assimilation on the model peak wave period forecast scatter index at all buoys received through the GTS for the period from 01 August to 21 September 2008.

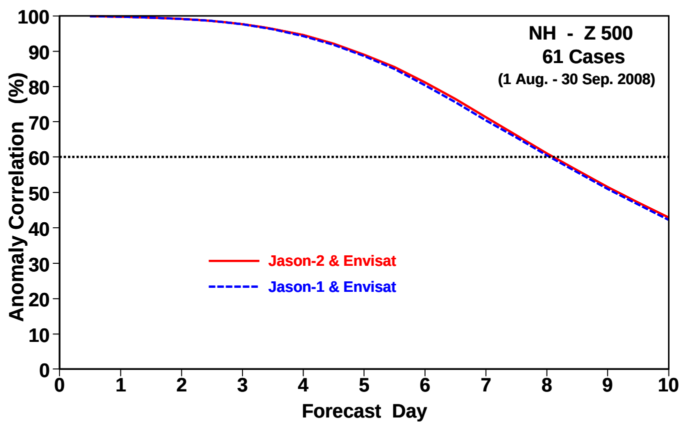

Figure 6: Impact of Jason-2 SWH assimilation on the anomaly correlation of the model 500 hPa geopotential height forecast in the Northern Hemisphere with respect to operational analysis for the period from 1 August to 30 September 2008.

Table 1: Impact of Jason-1 OSDR SWH assimilation on top of Jason-2 and Envisat as verified against all available in-situ observations received through GTS during the period from 10 February to 18 May 2009 (mainly in the NH).

Parameter	**SWH**		**Mean wave period, T_z**		**Peak wave period, T_p**	
Number of collocations	38,174		28,986		23,288	
	Bias (m)	**SI (%)**	**Bias (s)**	**SI (%)**	**Bias (s)**	**SI (%)**
Jason-1 + (Jason-2 + Envisat)	-0.035	14.7	-0.168	10.8	0.080	15.6
Jason-2 + Envisat	-0.037	15.1	-0.172	10.9	0.082	15.7

Examinations of other statistics and plots did not show any degradation in the model performance. At the same time, the improvements, if any, were very limited. This led to the reintroduction of Jason-1 Ku-band SWH data into the ECMWF operational system on top of Jason-2 and Envisat data on 8 June 2009.

5 Quality of Altimeter Surface Wind Speed

The other parameter of interest is the surface wind speed. This product is not assimilated at ECMWF. However, altimeter wind speed in general is used for independent verification of the model winds. For example, it is used to assess various model changes. Therefore, verification of this product and monitoring its quality are also very important.

Similar to the wave height, the comparison is done against in-situ measurements and against model analysis. In the current study, a gauging station is only trusted when it provides acceptable SWH value. Therefore, rejection of wave height in a record invalidates the wind speed measurement in the same record. In fact the same assumption is used for the quality control of altimeter data.

In general, the OGDR surface wind speed data compare well with the in-situ measurements as can be seen in Figure 7 and against ECMWF wave model analysis as can be seen in Figure 8 for the full year from 1 October 2008 to 30 September 2009. Again, it is stressed that the in-situ verification is limited to the Northern Hemisphere while the latter represents a global verification. The scatter plots in Figure 7 and Figure 8 represent 2-D histograms with 0.5 m/s x 0.5 m/s of wind speed. One can notice that Jason-2 wind speed product is about 0.2 m/s lower than the in-situ data. On the other hand, Jason-2 is about 0.1 m/s higher than the ECMWF model analysis. The SDD between Jason-2 data and the in-situ data is about 1.5 m/s which corresponds to SI of around 18%. Against the model analysis, the SDD of Jason-2 wind speed is about 1.2 m/s or about 16%. Those values are slightly higher than values resulted from Jason-1 and Envisat similar comparisons (not shown, but can be deduced from Figure 9).

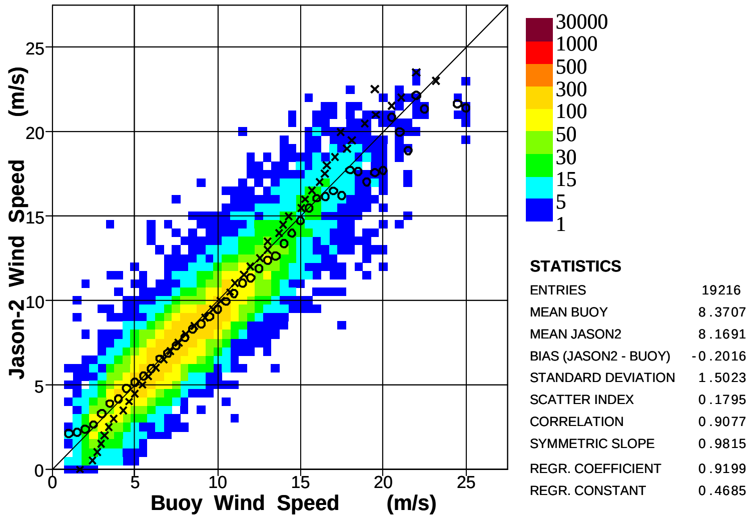

Figure 7: Global comparison between Jason-2 and buoy surface wind speed products during the period from 1 October 2008 to 30 September 2009 (mainly in the NH).

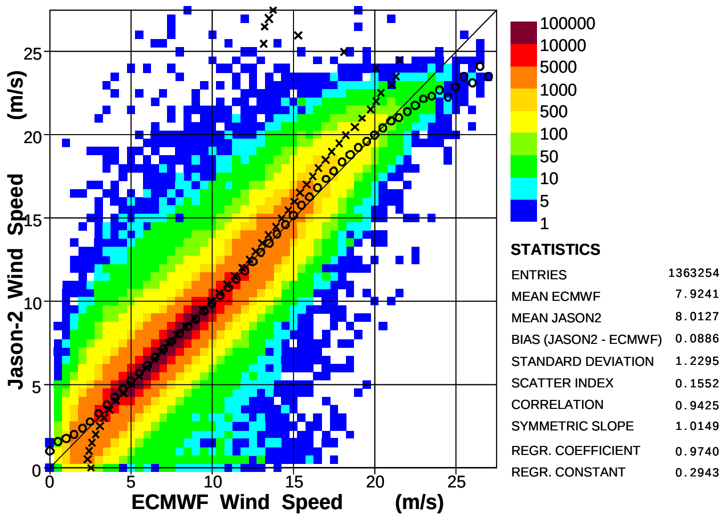

Figure 8: Global comparison between altimeter and ECMWF model analysis surface wind speed values for the period from 01 October 2008 to 30 September 2009.

Figure 9 shows the time series of the global wind speed bias and SDD of Jason-2 with respect to the ECMWF wave model analysis values during the period from 1 August 2008 to the end of September 2009. Similar to Figure 3, 7-day data windows are used to get representative statistics. The corresponding time series from Jason-1 and Envisat data are provided in the same figure for comparison. It is clear that Jason-2 wind speed product used to be unbiased compared to the model analysis before mid February 2009 when the product increased and started to have a small positive bias varying between zero and 0.3 m/s in line with both Jason-1 and Envisat. This was due to a change in the processing chain. The SDD plots suggest that Jason-2 wind speed product is slightly worse than that of Jason-1 by about 2% and even worse than that of Envisat (which implements a one parameter algorithm of Abdalla, 2007a and b) by about 8%. Therefore, fine tuning of the wind speed algorithm of Jason-2 is needed to match the quality of Jason-1 or preferably Envisat products.

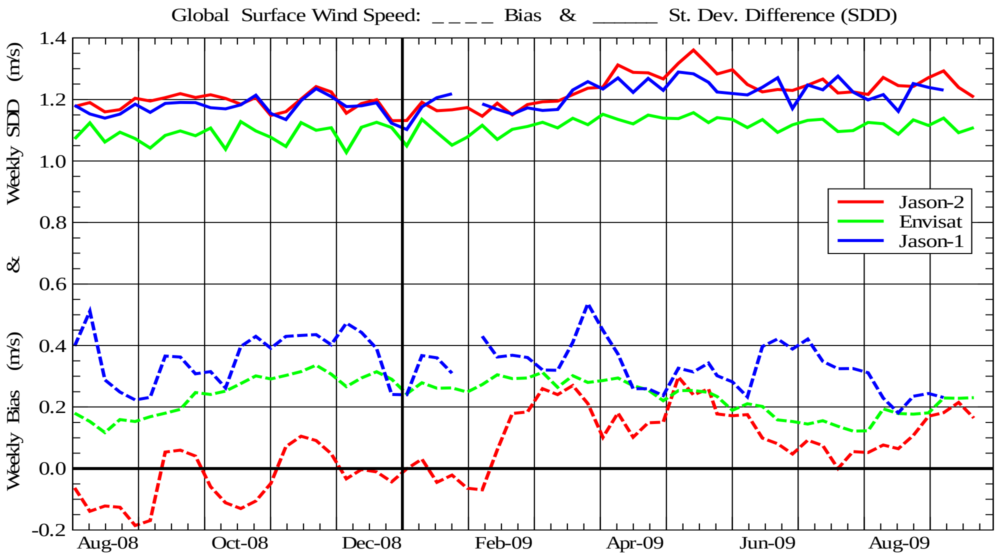

Figure 9: Time-series of the global surface wind speed difference (bias) and standard deviation of the difference between Jason-2 and ECMWF model since 1 August 2008 (red). Similar plots for Envisat (green) and Jason-1 (blue) are also given for comparison.

6 Conclusions

Jason-2 near real time OGDR-BUFR wind and wave products have been monitored and verified at ECMWF since early August 2008. The rate of data reception and its timing are within the operational requirements. Ku-band significant wave height product is of high quality with almost no bias compared to the model. Although it is of slightly lower quality than that of Envisat, it is as much better than that of Jason-1. Assimilation of Jason-2 significant wave heights in the ECMWF ocean wave model has positive impact on the model analysis and forecasts. Operational assimilation of the Jason-2 data started on 10 March 2009 replacing Jason-1. After the shift of Jason-1 orbit, it was possible to show that adding Jason-1 wave height product to the system provides some value. This led to its reintroduction on 8 June 2009.

Similarly, Jason-2 wind speed product is of good quality. However, it is slightly worse than those of Jason-1 and Envisat. A fine tuning of the wind speed algorithm of Jason-2 is needed to enhance the quality of the product. There was an increase in the Jason-2 wind speed product in mid February 2009.

Acknowledgments

This work depends mainly on altimeter and in-situ data made available by various data providers around the world including, but not limited to, Centre National d'Etudes Spatiales (CNES), European Space Agency (ESA), European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) and National Oceanic and Atmospheric Administration (NOAA).

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