ASSIMILATION OF ENVISAT ASAR WAVE MODE LEVEL 2 PRODUCT

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ABSTRACT

The wave mode (WM) of Synthetic Aperture Radar (SAR) instruments provides detailed description of the surface sea state with global coverage. However, the azimuthal cut-off (i.e. inability of SAR to resolves small scale waves in the flight direction), restricts its usability for some applications. ECMWF had been assimilating SAR WM Level 1b (L1b) product operationally from ERS-2 and ENVISAT since January 2003. The operational assimilation of ENVISAT ASAR WM Level 2 (L2) product has never been realised due to its minor negative impact. The results of various assimilation experiments are presented and the results are discussed. The proper selection of quality control (QC) criteria is critical in the success of WM L2 product assimilation. The impact of assimilating WM L2 ranges from being slightly positive to being slightly negative.

1. INTRODUCTION

The wave mode of the Synthetic Aperture Radar (SAR) provides a wealth of information regarding the detailed description of the surface sea state with global coverage. Unfortunately, SAR is not able to sense the whole spectrum of ocean waves especially in the azimuthal direction and misses quite a large range of short waves. Although this range usually carries the most energetic part of the ocean surface spectrum, the resolvable part of the spectrum can be very useful in a wide range of the oceanic applications including data assimilation in ocean wave models. The European Centre for Medium-Range Weather Forecasts (ECMWF) has been assimilating SAR Wave Mode (WM) Level 1b (L1b) product operationally since January 2003. This work started with the ERS-2 SAR WM L1b product. The corresponding product from ENVISAT ASAR replaced the ERS-2 SAR product on the first of February 2006. WM L1b SAR spectrum product is inverted in-house using the iterative MPI (Max Planck Institute for Meteorology) nonlinear mapping scheme [1 and 2] to obtain the ocean wave spectra before assimilation. The assimilation of L1b product, both from ERS-2 and ENVISAT, proved to be beneficial [3 and 4].

For ENVISAT ASAR WM, the European Space Agency (ESA) distributes a Level 2 (L2) ocean spectrum product alongside L1b. This product is in principle ready to be used by the end users without worrying about the inversion process. However, operational assimilation of ASAR WM Level 2 product has never been realised at ECMWF. Several experiments were carried out to assess the impact of assimilation of L2 product on wave model predictions. Results of earlier experiments were not encouraging. The change in ASAR processing chain of PF-ASAR 4.05 at the end of October 2007, which resulted in much cleaner products, motivated further experimentation with the assimilation of WM L2 product in the wave model of ECMWF. This was further motivated by the fact that current ESA plans for the coming Sentinel-1 mission do not accommodate the distribution of any Wave Mode Level 1b product.

A short description of the monitoring and validation of ASAR WM products is provided in Section 2. Brief description of the ECMWF wave model including data assimilation is given in Section 3. This latter section includes a brief description of the model set-up that is used for the data assimilation experiments. Results of these experiments are presented and discussed in Section 4. Finally, Section 5 summarises the conclusions of this work.

2. VALIDATION OF ASAR WM PRODUCTS

ENVISAT ASAR WM L1b and L2 products received routinely from ESA are segregated based on time into the 6-hour time windows centred at major synoptic times (i.e. at 00, 06, 12 and 18 UTC) each day. The flow of data is monitored and the mean delay of each product is also monitored. On average, about 80% of all products with each 6-hour time window arrive with one hour after the closure of the window (the critical time to include any observation in initialising the operational forecasting). More than 90% of the data are available for the main analysis, with a minimum cut-off of 5 hours after the closure of the window. Therefore, the timing of the ASAR products is suitable for operational assimilation.

Before the validation of the WM products, several basic quality control (QC) criteria are used to remove products of questionable quality. Products with missing parameter values or with values outside the physical range are discarded. Products contaminated by ice (according to the model sea ice cover) or land (according to the associated Land/Sea flag) are also discarded. If L1b product is not invertible using the MPI scheme, both L1b and L2 products are discarded.

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WM L1b products are then matched with the corresponding wave model spectrum. This spectrum is used as a first guess for the iterative inversion procedure. Integrated parameters such as significant wave height and mean wave period are computed from the inverted spectrum and from the wave model spectrum. Statistics scatter and maps are produced for monitoring and validation. Fig. *1* shows an example of the global significant wave height (SWH) comparison between the inverted L1b and the operational wave model during the whole 2011 with various statistics. It is clear that SWH from both products compare very well especially for the bulk of the data. This is the case for most of the other integrated parameters (see [4, 9 and 10]).

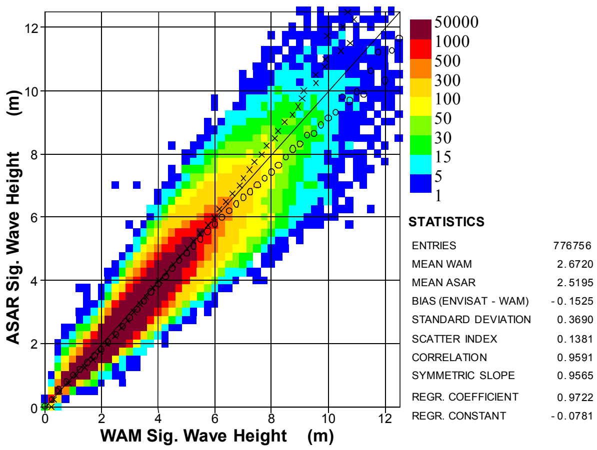

Figure 1. Global comparison between inverted ASAR WM L1b and WAM model SWH for 2011.

The integrated parameters from both ASAR WM L2 and the corresponding wave model spectrum are then computed within the azimuthal cut-off wavelength (as reported within the L2 product). Various statistics and plots are then generated using those integrated parameters. Fig. *2* shows an example of the global swell (not the total value) SWH comparison between the L2 and the operational wave model during the whole 2011 with various statistics. The bulk of the L2 product swell SWH agree well with the corresponding parameter from the wave model. However, there are few hundreds of outliers where L2 has significantly less energy (lower SWH). This impacts the statistics of the comparison. Comparisons of other integrated parameter, show less successful agreements (see [4, 9 and 10]).

3. ECMWF WAVE MODEL

The third-generation wave model WAM is part of the ECMWF operational Integrated Forecast System (IFS). It is based on the standard WAM model [5] with several modifications [6 and 7]. The model was built on the action density conservation with explicit source terms to account for energy input from wind, energy dissipation due to wave breaking and nonlinear energy transfer among wave components themselves. Other finite-depth processes are also included.

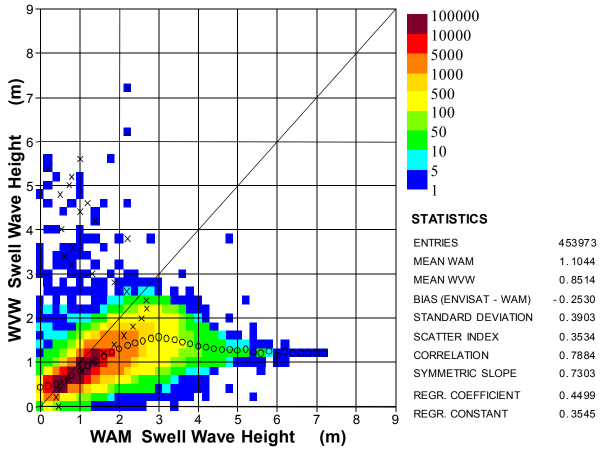

Figure 2. Global comparison between ASAR WM L2 and WAM model swell SWH for 2011.

The wave model is tightly coupled with the atmospheric model. The wave model uses wind velocity, wind gustiness and air density from the atmospheric model and provides it with the sea-surface roughness.

IFS mixes a model first-guess (FG), which is a short model forecast from a previous initial state and available atmospheric and wave observation to produce the best model state, called analysis (AN). IFS then runs in the forecast mode to predict the future atmospheric state (called forecast, or FC). While the atmospheric model implements a sophisticated data assimilation scheme called 4DVAR, WAM implements a simplified optimum interpolation (OI) technique.

The ASAR WM ocean wave spectrum, either as received as L2 or after the inversion from L1b, is split into sea state systems using an inverse watershed technique. The collocated model ocean wave spectrum is decomposed into its systems. The corresponding individual systems from ASAR and the model are paired. Any model or ASAR system that is not possible to pair it with a counterpart system, it is ignored. The integrated parameters from both paired systems are computed and an Optimum Interpolation scheme is used to find the increments that are used to update the FG partitions.

For the purpose of the current work, the WAM model was run in stand-alone mode (i.e. it is not coupled with the atmospheric model) forced by operational wind fields for the months of August and September 2008 and for the months of January, February and March 2012 (after a 10-day warm-up period in both cases). The model configuration in the experiments reflected the operational set-up at the time as close as possible. The globe was discretized into a grid with a resolution of about 40/28 km for the 2008/2012 runs (in respective order) in both directions. The spectral space was discretized into 30/36 frequency bins and 24/36 direction bins for 2008/2012 runs (in respective order). The runs were configured to run using analysis winds for 12 hours ending at 00 and 12 UTC each day. Data assimilation is carried out for the 6-hour time windows centred at major synoptic times. This set-up reflects the configuration of the operational analysis. Further 5-day runs follows the analyses at 00 and 12 UTC using operational forecast winds.

4. DATA ASSIMILATION IMPACT

To assess the impact of the data assimilation, a reference model run without any data assimilation was carried out. Another reference model run was carried out with the assimilation of ASAR WM L1b data product, which used to be assimilated operationally.

Several experiments were carried out to assimilate WM L2 data product using various quality control (QC) criteria. One experiment made use of the product after passing basic quality control checks to ensure the validity of the data. Several runs were carried out using further quality control filters, including the officially recommended ones (cf. [11]). Note that altimeter data is not assimilated in any of the above experiments.

To assess the performance of each experiment, significant wave height data from Radar Altimeters aboard ENVISAT (RA-2) and Jason-1/2, ECMWF operational analysis (which is usually assumed to be the best known state of the weather) and available ocean wave buoy and platform observations are used in the verification process.

Using the ASAR WM L2 ocean spectra directly just with basic quality control (ASAR_L2_No_QC) led to the deterioration of the model results. Fig. *3* shows the standard deviation of the difference (SDD) between the SWH from three experiments and that from the operational analysis as function of forecast range in the Tropics (within ±20°) during August and September 2008. The experiments compared in Fig. *3* are the experiment without any data assimilation (no-data), the experiment that assimilates ASAR L1b product only (ASAR_L1b) and the experiment that assimilates ASAR L2 product only without any QC (ASAR_L2_NoQC). It is clear that while ASAR_L1b shows quite an improvement compared to the no-data run, the ASAR_L2_NoQC deteriorated the model performance leading to larger error compared to the no-data.

To improve the situation several quality control criteria were used. One needs to make a compromise between rejecting, as much as possible, L2 spectra that either look suspicious or deviate from the model counterpart on one hand and retaining, as much as possible, the useful information on the other hand. Too strict quality control allows very few observations to be assimilated and, therefore, results in very minor or no impact.

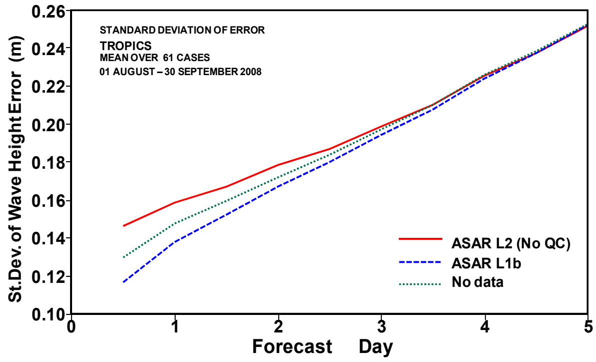

Figure 3. Impact of the assimilation of WM L2 Product with almost no QC on the standard deviation of the SWH error in the Tropics as verified against ECMWF operational analysis.

The quality control criteria considered to filter L2 products before data assimilation are:

I. Rejection Criteria for the Whole Spectrum:
  1. The corresponding Level 1b SAR spectrum is valid and invertible. This implies that there is nothing missing in the product, it is located inside the wave model domain (on land away from ice), and the MPI inversion scheme provides something meaningful.
  2. The "Land/Sea"flag in L2 product indicates it is over the ocean.
  3. The product indicates acceptable SWH Confidence (a flag in L2 product).
  4. The signal to noise ratio as reported by the L2 product is between 3 and 200.
  5. The wind speed as reported by the L2 product is between 3 and 16 m/s.
  6. The“image normalized variance” (INV) is an important parameter that is provided in the WM L2 product and can be used for QC. However, this parameter was not ready for our use due to its absence from the BUFR (Binary Universal Form for the Representation of Meteorological data) template. Therefore, the INV values were extracted from the original WM L2 PDS product and all spectra corresponding to INV values below 1.05 or above 1.5 were flagged as corrupt. This is done to avoid the complicated process of modifying the BUFR template. Only the experiments of 2012 used this QC criterion.

II. Rejection Criteria for Parts of the Spectrum:
  7. If most of the wave components of wave system in the L2 spectrum have wavelengths outside an ellipse of a major axis in the range direction dictated by the ASAR resolution and a minor axis in the azimuthal direction dictated by the azimuthal cut-off wavelength reported by the L2 product, all wave components of the system are rejected.

8. After the spectrum partitioning, any system with a peak located within 3 bins from the edge of the accepted wavelength range in 7 above and the other edge of the maximum ASAR wavelength is rejected. This is done to ensure that significantly incomplete systems are rejected.
9. If a wave system in the ASAR L2 product cannot be matched with a model counterpart (within acceptable frequency and direction separation), the ASAR partition is rejected.

Applying 8 QC criteria of the 9 above (criterion 6 was not used at the time), improves the situation for the assimilation of L2 product as can be seen in Fig. *4*. Although, the impact against operational analysis shown in Fig. *4* is only neutral, the comparison against in-situ (buoy) measurements reveals positive impact in the Tropics during August 2008 as can be seen in Fig. *5* which shows the scatter index, defined as the SDD normalised by the mean of the buoy measurements. Positive impact is also revealed when comparing against radar altimeter measurements from both and ENVISAT and Jason-1 as can be seen in Fig. *6*.

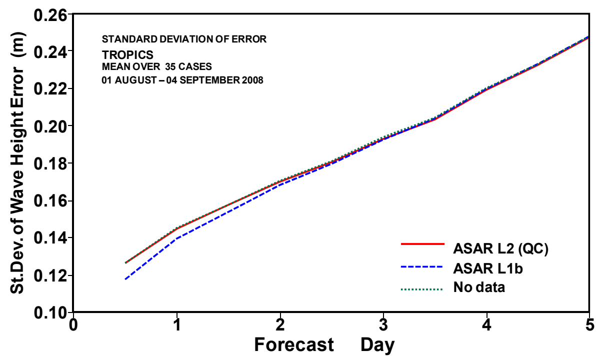

Figure 4. Same as Fig. 3 but with assimilating WM L2 product after passing the QC criteria 1-9 except 6 (and a shorter verification period).

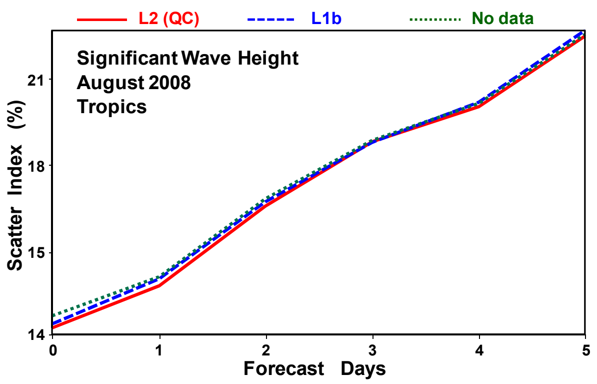

Figure 5. Impact of assimilating quality controlled WM data on the SWH scatter index (=SDD / mean of buoy data) in the Tropics as verified against ocean wave buoy data.

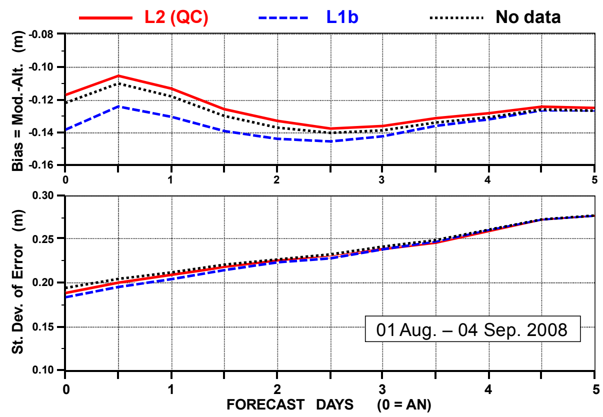

Figure 6. Impact of the assimilation of WM L2 Product after passing quite strict QC on the SWH bias and SDD in the Tropics as verified against ENVISAT and Jason-1 altimeter SWH data.

The addition of the QC criterion 6 based on INV gives rise to a slight reduction of impact as can be seen in Fig. *7* which shows the impact of data assimilation as a reduction of error compared to the model run without any data assimilation in the Tropics for first three months of 2012. The error reduction is defined as the difference between the SDD of the no-data run and that of the assimilation run normalised by the former. Both SDD values are computed with reference to in-situ measurements.

It is worthwhile mentioning that the impact of data assimilation lasts for more than 5 days in the Tropics as can be seen in Fig. *7*. The maximum impact on SWH error reduction is happening, as one would expect, at the analysis time reducing with going further in the forecast. The error reduction due to assimilating L2 product is about 2% while that due to assimilating L1b product is twice as much (about 4%). For comparison, the impact of assimilating radar altimeter data from ENVISAT peaks at more than 8%.

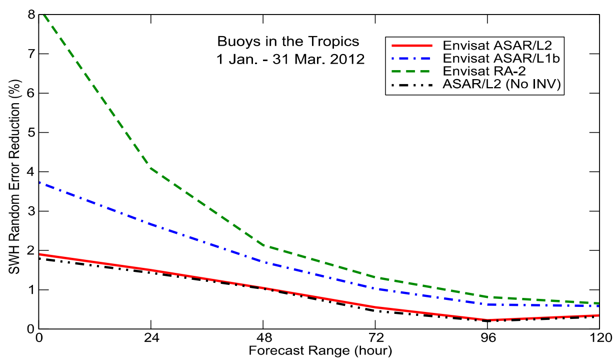

*Figure 7. Impact of assimilating WM data on reducing the SWH random error with respect to the no-data run =($SDD_{no\text{-}data}$ - $SDD_{assim.}$) / $SDD_{no\text{-}data}$ *100 in the Tropics as verified against in-situ data. "No INV" refers to the run with INV as an additional QC criterion. RA2 impact is also shown for comparison.*

The peak wave period is defined as the wave period corresponding to the peak of the 1-D wave frequency spectrum. Several buoys report this parameter. While positive impact on the peak wave period is achieved by assimilating L1b product, the impact of assimilating L2 product is negative at the analysis time and in the short forecast range as can be seen in Fig. *8*. L2 assimilation results in positive impact on the peak wave period, though, at day 3 and beyond in the Tropics. A possible explanation for this is that some of the WM L2 products with questionable quality (but not detected) contribute with the correct level of energy when assimilated but at incorrect frequency (and possibly direction) bins. This leads to positive or neutral impacts on analysis SWH and deterioration of the analysis peak wave period. During the forecast phase, the model starts to remove these incorrect additions and thus improves the forecasts. This clean-up process takes about 2-3 days after which only positive impact is retained.

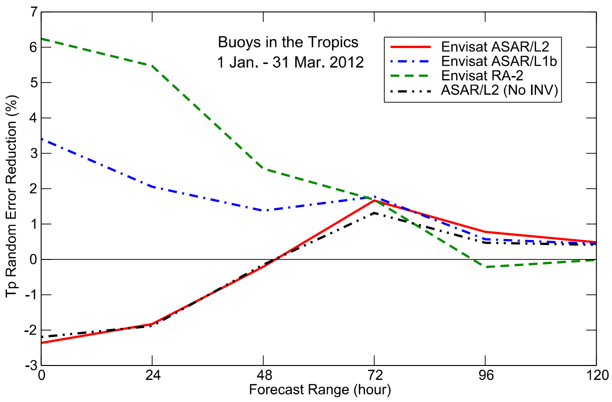

Figure 8. Same as Fig. 7 but for the peak wave period random error.

In short, the impact of assimilating ASAR WM L2 on wave model analysis and forecasts in the Tropics can be either slightly positive, neutral or slightly negative.

Outside the Tropics (for latitudes higher than 20° both N and S), the impact is even more towards the negative side. Fig. *9* shows the impact of assimilating ASAR WM L1b and L2 after quality control on SWH SDD in the Southern Hemisphere (SH) when compared to operational ECMWF analysis. L2 assimilation leads to slight degradation in model SWH forecast in the SH while assimilating L1b gives slight improvement. Similar conclusion can be drawn when the comparison is done against in-situ measurements which are mainly in the Northern Hemispheric (NH) extra tropics (with few in the Tropics, though) as can be seen in Fig. *10*. While slight improvement for SWH compared to in-situ data can be witnessed in Fig. *11*, degradation in peak wave period is seen in Fig. *12*.

A hint to understand this negative impact can be found by examining the scatter plots comparing swell SWH of ASAR L2 with that of the wave model in Tropics and in the SH as shown for the year 2009 in Fig. *13* (note that although the period does not coincide with the period of any of the assimilation experiments, same conclusion will be drawn from any other period). The number of outliers in the Tropics is small. The model was able to absorb the negative impact of this small amount of incorrect products and the degradation becomes of limited impact Even if the degradation becomes dominant, the model is able to remove it within few days as in the case of the peak wave period shown in Fig. *8*.

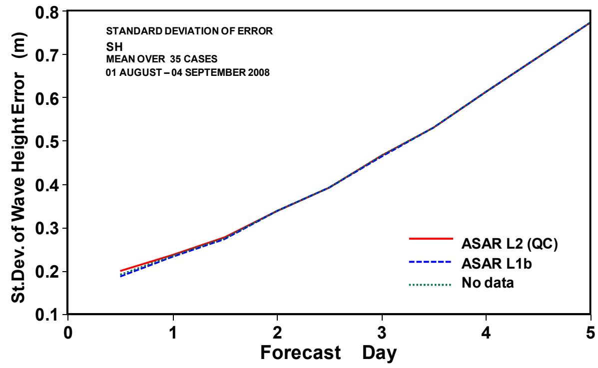

Figure 9. Same as Fig. 4 but for SH.

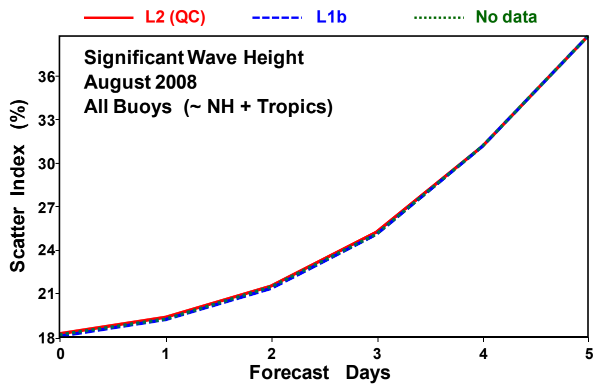

Figure 10. Same as Fig. 5 but for all buoys which are mainly in the NH and, to less extent, in the Tropics.

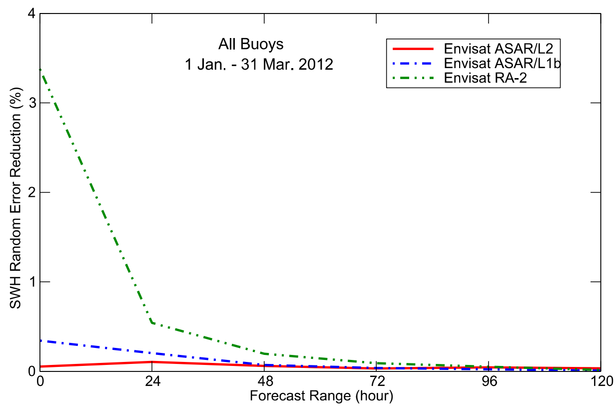

Figure 11. Same as Fig. 7 but for all buoys which are mainly in the NH and, to less extent, in the Tropics.

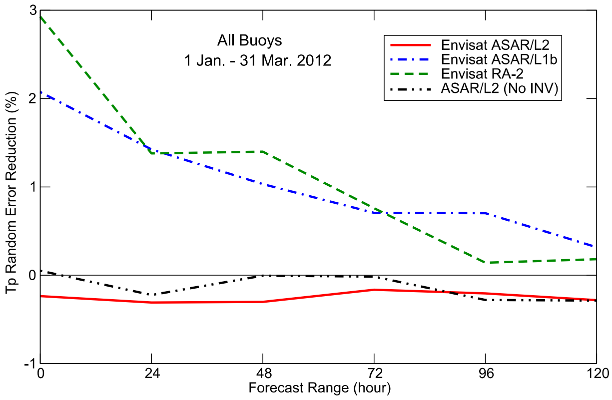

Figure 12. Same as Fig. 8 but for all buoys which are mainly in the NH and, to less extent, in the Tropics.

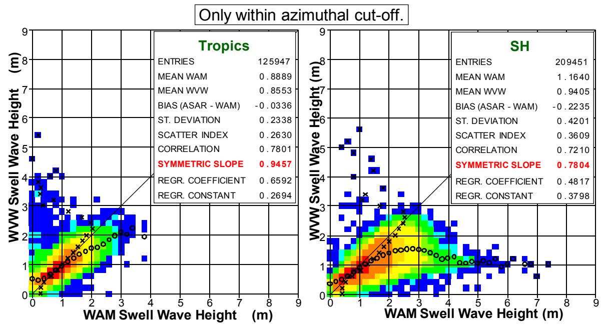

Figure 13. Comparison between ASAR WM L2 and model swell SWH (within azimuthal cut-off wavenumber) during the whole year of 2009 in the Tropics and the SH.

The number of outliers in the extra tropics is relatively large. A number of those outliers, or partitions associated with those outliers, pass the basic quality control procedure. Apparently, the model is not able to totally remove their relatively overwhelming negative impact causing the degradation of the model results. It is clear that there is a need either to eliminate those outliers or to flag them properly in order to stop them intruding the assimilation process and harming the model output.

5. CONCLUSIONS

The wave mode (WM) of the Advanced Synthetic Aperture Radar (ASAR) on-board ENVISAT proved to be generally of good quality. ECMWF had been assimilating ASAR WM Level 1b (L1b) product operationally since February 2006. The operational assimilation of ENVISAT ASAR WM Level 2 (L2) product has never been realised due to its minor negative impact on the model predictions. Various assimilation experiments were conducted and their results were analysed. With the current QC criteria, the impact of assimilating WM L2 ranges from being slightly positive (mainly in the Tropics) to being slightly negative (mainly in the Extra Tropics). It is clear that proper selection of quality control (QC) criteria is critical in the success of WM L2 product assimilation.
On average, more than 80% of ENVISAT ASAR Wave Mode products used to be received within the one hour from the closure of the analysis time window. The percentage increases to more than 90% received within five hours. This makes them suitable for operational assimilation.

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REFERENCES

1. Hasselmann, K. and Hasselmann, S. (1991). On the nonlinear mapping of an ocean wave spectrum into a synthetic aperture radar image spectrum. *J. Geophys. Res.,* **91**, 10,713-10,729.

2. Hasselmann, S., Bruning, C., Hasselmann, K. and Heimbach, P. (1996). An Improved Algorithm for the Retrieval of Ocean Wave Spectra from Synthetic Aperture Radar Image Spectra. *J. Geophys. Res.,* **101**, 16,615-16,629.

3. Abdalla, S., Bidlot, J. and Janssen, P.A.E.M. (2004). Assimilation of ERS and ENVISAT Wave Data at ECMWF. *Proc. ENVISAT-ERS Symposium*, Salzburg, Austria, 6-10 Sep. 2004.

4. Abdalla, S., Bidlot, J. R., Janssen, P. A. E. M. (2006). Global Validation and Assimilation of ENVISAT ASAR Wave Mode Spectra. *Proc. SeaSAR 2006*, 23-26 Jan. 2006, Frascati, Italy, (ESA SP-613, Apr. 2006). Available at: http://earth.esa.int/seasar06/proceedings/papers/s1_7_abd.pdf

5. Komen, G.J., Cavaleri, L., Donelan, M., Hasselmann, K., Hasselmann, S., and Janssen, P.A.E.M. (1994). *Dynamics and Modelling of Ocean Waves*, Cambridge University Press, Cambridge, UK, 532 p.

6. Janssen, P.A.E.M. (2004). *The Interaction of Ocean Waves and Wind*, Cambridge University Press, Cambridge, UK, 300+viii pp.

7. Janssen, P.A.E.M. (2008). Progress in ocean wave forecasting, *J. Comp. Phys.*, **227**, 3572–3594.

8. Hasselmann, S., Lionello, P., and Hasselmann, K. (1997). An Optimal Interpoltion Scheme for the Assimilation of Spectral Data. *J. Geophys. Res.*, **102**(C7), 15823-15836.

9. Abdalla, S. (2005). Global Validation of ENVISAT Wind, Wave and Water Vapour Products from RA-2, MWR, ASAR and MERIS. Final Report for ESA contract 17585, ECMWF, Reading, UK. Available at: http://www.ecmwf.int/publications/library/

10. Abdalla, S. (2013). Global validation of ENVISAT wind, wave and water vapour products from RA-2, MWR, ASAR and MERIS (2011-2012). Final Report for ESA contract 21519/08/I-OL, ECMWF, Reading, UK. Available at: http://www.ecmwf.int/publications/library/

11. Johnsen, H. (2005). Envisat ASAR Wave Mode Product Description and Reconstruction Procedure. *Report for ESA Contract* 17376/03/I-OL.