ECMWF EXPERIENCE IN GLOBAL MONITORING AND VALIDATION OF RADAR ALTIMETRY PRODUCTS

Saleh Abdalla [(1)], Peter A.E.M. Janssen [(2)], Magdalena Alonso Balmaseda [(3)], Kristian Mogensen [(4)], Jean-Raymond Bidlot [(5)] and Sarah Keeley [(6)]

European Centre for Medium-Range Weather Forecasts, Shinfield Park, RG2 9AX, Reading, UK.
(1) saleh.abdalla@ecmwf.int
(2) peter.janssen@ecmwf.int
(3) magdalena.balmaseda@ecmwf.int
(4) kristian.mogensen@ecmwf.int
(5) jean.bidlot@ecmwf.int
(6) sarah.keeley@ecmwf.int

ABSTRACT

ECMWF a world leader in the numerical weather prediction (NWP) field, has a long history in calibration, validation, monitoring and assimilation of radar altimeter products. Wind and wave products from satellites like ERS-1/2, ENVISAT, Jason-1/2 have been used for more than two decades while sea-surface height anomaly products have been used for more than a decade. The formation of the Marine Prediction Section enhanced such capabilities and added the sea-ice freeboard to the list of products that can be handled by the team at a later stage. The experience of ECMWF regarding the cal/val activities of these parameters will be summarised. This experience can be routed to the cal/val activities of Sentinel-3.

1. INTRODUCTION

The European Centre for Medium-Range Weather Forecasts (ECMWF) is a world leader in the numerical weather prediction (NWP) field. The comprehensive earth-system model developed at ECMWF forms the basis for all the data assimilation and forecasting activities. All the main applications required are available through one integrated computer software system called the Integrated Forecast System (IFS). IFS is a comprehensive atmospheric forecasting-system that simulates the dynamics, thermodynamics and composition of the Earth's fluid envelope and interacting parts of the Earth-system. Apart from the main component which is an atmospheric model, the system includes WAM which is a third generation ocean wave prediction model and NEMO which is a software for numerical simulation of the ocean including ocean circulation and sea ice. IFS provides a wealth of global data that can be used for the geophysical validation of various satellite products. Furthermore, ECMWF receives and archives a wide range of in situ observations that are received in near real time (NRT). Such data products are also used for the cal/val activities.

ECMWF has a long history in calibration, validation and monitoring of wind, wave and water vapour products from various Altimeter (RA) and Microwave (MWR) instruments. It contributed to the cal/val efforts for the past and current missions including: ERS-1/2, Envisat, Jason-2, Cryosat and SARAL/AltiKa Altimetry missions with plans to support such activities for the future missions including: Sentinel-3 and Jason-3 and Jason-CS missions.

Almost all RA and MWR products can be monitored or used at ECMWF. The list includes significant wave height (SWH), surface wind speed (SWS), water vapour content (TCWV), sea surface height anomaly (SSHA), and sea-ice freeboard. Apart from the cal/val activities, these parameters are used for data assimilation (SWH and SSHA), monitoring of model performance, and assessment of model changes.

There is a reciprocal benefit between altimeter and model products. Altimeter products benefit from model products for cal/val activities, quality monitoring, anomaly detection and assessment of processing chain changes (e.g. [1] and [2]). On the other hand, model products benefit from altimeter products for data assimilation, monitoring of model performance and assessment of model changes (e.g. [3] and [4]). Furthermore, reprocessed altimeter products benefit the reanalysis exercise (e.g. ERA-CLIM). Mutual benefit is also possible through error estimates by using, for example, triple collocation technique ([4] and [5]).

Historically, wind and wave data used to be the only RA parameters monitored and used. The SSHA was added to the list. The formation of the Marine Prediction Section (MPS) joined the capabilities of monitoring and validation of the full list under one unit. The sea-ice freeboard was the last addition with limited capability at the time being.

At ECMWF more value is given for the near real time (NRT), also known as fast delivery (FD), products due to the nature of its activities being built around operational services. Nevertheless, offline (data produced with few weeks of delay) and reprocessed

Proc. 'ESA Living Planet Symposium 2013', Edinburgh, UK
9–13 September 2013 (ESA SP-722, December 2013)

(data produced after several months or years with improved and consistent algorithms and tools) data products are of importance for model reanalysis and for operational seasonal forecasting systems.

The experience and capabilities of ECMWF regarding the cal/val activities of the global wind and wave products are summarised in Section 2. Those related to ocean modelling are summarised in Section 3. The potential capabilities regarding sea ice are presented in Section 4. Finally, Section 5 lists several concluding remarks which support the feasibility of routing the ECMWF experience and capabilities to the cal/val activities of Sentinel-3.

2. OCEAN WIND AND WAVE PRODUCTS

The prospect of global observations of surface winds and waves gave a significant stimulus to wave model development in the 1980's, while the need to have reliable wave predictions stimulated the development of operational altimeters that could provide accurate wind and wave products. Over the past two decades there has been a continuous interplay between ocean wave forecasting and altimeter sea state products resulting in improvements in both. Altimeter sea state data are presently used in the wave height analysis and wave forecast verification, in the monitoring of the quality of the modelled surface wind and in obtaining global wave height and wind speed climatology. An extensive review of the uses of altimeter sea state products is given by [6].

Early investigations into the quality of the WAM model results were based on a comparison with SEASAT altimeter wave height data [7]. Generally, modelled wave heights, obtained by forcing the WAM model with ECMWF winds showed good agreement with observed wave heights, but there were also considerable differences. For example, WAM underestimated wave height by about 20 % in large parts of the Southern Ocean and the Tropical oceans. These discrepancies could be ascribed to shortcomings in the wave model physics and in the ECMWF wind fields, which at the end of the 1980's were too low in the Southern Hemisphere because the atmospheric model had a fairly low resolution (190 km).

The shortcomings in the wave model physics were treated with the introduction of a WAM Cycle 4 ([8] and [9]) which became part of the ECMWF wave prediction system in 1991. Furthermore, 1991 witnessed an increase in the horizontal and vertical resolutions of the ECMWF atmospheric general circulation model to produce a better representation of surface winds.

Therefore, in late 1991 there was sufficient confidence in the quality of the ECMWF wind-wave forecasting system that it could be used for the validation of ERS-1 altimeter wind and wave products. Since the launch of ERS-1 in July 1991, ESA has kept disseminating the NRT altimeter (from ERS-1, ERS-2 and ENVISAT) wind and wave products almost uninterruptable for about 21 years (until the loss of ENVISAT in April 2012). ECMWF engaged in the cal/val activities of ERS-1, ERS-2 and ENVISAT altimeter wind and wave products since the start. One of the main achievements was the improvement of the retrieval algorithms; e.g. [2].

2.1. Cal/Val of RA Wind and Wave Products

Wind and wave model products have been quite useful in the validation and calibration (cal/val) of ESA's altimeter wind and wave products. The necessary cal/val of a satellite sensor requires large amounts of ground truth which should cover the full range of possible events. In particular the number of reliable wave in situ measurements is very limited and, because of financial restrictions, dedicated field campaigns are possible only at a few sites and for very short periods. In contrast to that, model data are relatively cheap and provide global data sets for comparison. Thus, the combination of both in-situ observations and model data seems to be an optimal cal/val dataset. During the ERS-1/ERS-2 and ENVISAT cal/val campaigns the altimeter-model comparisons have been very effective in identifying errors and problems in the altimeter processing and retrieval algorithms. Here are few examples extracted from [6]:

- Just after the launch of ERS-1, the global mean altimeter wave height was about 1 m higher than computed by the model. The investigation of the detected bias led to the discovery of a small offset in the pre-launch instrument characterization data. When the processing algorithm was updated at all ground stations the performance of the altimeter wave height was found to be satisfactory as follows from an almost zero wave height bias and a standard deviation of error of 0.5 m when compared with modelled wave height.
- The second example occurred during the operational phase of ERS-1. A bug was discovered in the processing algorithm which led to unrealistically shaped wave height distributions. This bug was removed at the beginning of 1994 and resulted not only in a much improved shape of the wave height histograms, but also in a reduction of mean wave height of about 30 cm [10].
- For the wind speed, a different approach needs to be followed as engineering and geophysical calibration cannot be separated since there is no absolute calibration of the backscatter against independent data from manmade targets or stable known targets of opportunity readily available. For the initial ERS-1 data calibration, the system gain as determined by pre-launch instrument characterization was used while for the initial geophysical calibration, algorithms from previous missions were used. First comparisons with ECMWF winds uncovered several

problems in the initial algorithm. The problems were solved in a couple of weeks but differences of 20% remained. This difference corresponds to a small (0.8 dB) bias in antenna gain. After thorough validation of the ECMWF reference set it was shown that the observed antenna gain was well within the error budget for pre-launch calibration. The data calibration was updated in early December 1991 and since that date the quality of the ERS-1 altimeter wind speeds reached an acceptable level.

- Having learned from the ERS-1 experience, the cal/val of the subsequent ERS-2 and ENVISAT altimeter wind and wave products was relatively straightforward. In addition, when ERS-2 and ENVISAT were launched another satellite (ERS-1 for the former and ERS-2 for the latter) was still operational allowing an inter-comparison between the products from both altimeters, using the corresponding model products as a go-between. The tandem mission with the previous satellite, the accumulated experience and the availability of model wind and wave products made the cal/val activities a rather straightforward process. However, there was a problem related to the determination of the antenna gain factor. By comparing the histograms for the radar backscatter from the two satellites the mean difference between the two gave the antenna gain bias. The retuned altimeter wind speeds gave a favourable agreement with the ECMWF surface winds, showing that the tuning procedure was sound.

A more recent example is the CryoSat-2, which is a cryosphere mission, cal/val activities. The ocean operations are performed on a best-effort basis. The cal/val activities of wind and wave products from CryoSat-2 were not as smooth as the ones of ENVISAT. It took three iterations to properly calibrate the SWH product as can be seen in Fig. *1*. This was done mainly by comparison with ECMWF wave model results.

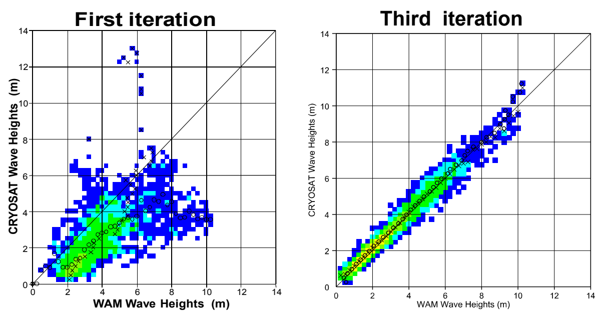

Figure 1. Cal/Val of CryoSat-2 SWH.

The last example was the wind speed of the AltiKa altimeter on-board the Indo-French SARAL satellite (Satellite with ARgos and ALtiKa). AltiKa is the first ever space-borne oceanographic altimeter that operates at Ka band. The lack of experience with this band led to few unanswered questions including the wind speed algorithm. The project team decided to use Jason-2 algorithm until enough measurements are gathered and a proper calibration is done. A proper disclaimer is included in the AltiKa handbook. The ECMWF surface wind speed product was used to develop two approaches for AltiKa wind speed algorithms [11]. Fig. *2* shows a comparison between AltiKa wind speed computed using Jason-2 algorithm and as computed using one of the developed algorithms using model data.

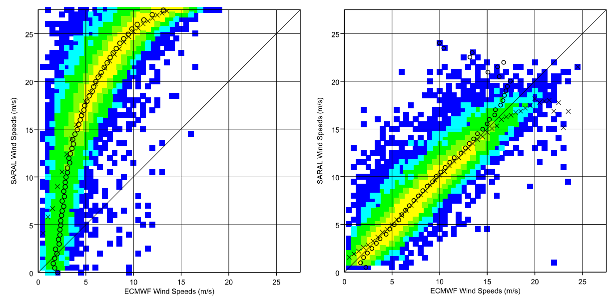

Figure 2. SARAL/AltiKa wind speed comparison against ECMWF model, 18-28 March 2013. Due to lack of experience with Ka-band, original product was not optimum. A first calibration attempt was carried out.

2.2. Altimeter Data Monitoring

After the cal/val campaigns, there is a need to monitor the products produced by the instrument. The ground truth in a form of in-situ measurements is usually of limited availability is space and most of the time in time as well. Such measurements are usually expensive and need a lot of maintenance efforts. ECMWF collects the in-situ measurements that arrive mainly through the Global Telecommunication Systems (GTS) in MARS (the ECMWF Meteorological Archive and Retrieval System). This data base is used to validate the quality of the received products as can be seen on the left hand side panel of Fig. *3*.

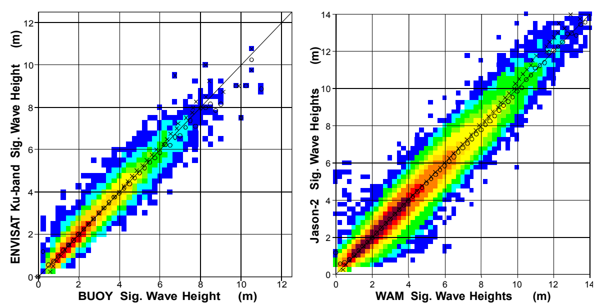

Figure 3. Validation of altimetry data by comparing against (left) in-situ data (NRT ENVISAT RA-2 vs. in-situ SWH, Global, 2011) and (right) the model (NRT Jason-2 vs. WAM Model SWH, Global, 2011)

The number of in-situ measurements is usually very small and only covers few (hundreds of) locations mainly in the northern hemisphere (NH) around North America and Europe. Moreover, there is a lack of absolute calibration across the different buoy networks (see below). The global model fields on the other hands, represent an invaluable reference for the assessment of the altimeter measurements, any changes in the altimeter or the processing chain and the anomaly detection on a global scale (see the right hand side panel of Fig. *3*).

In addition to scatter plots similar to those in Fig. *3*, time-series plots are produced for a large number of statistics for each product. Fig. *4* shows the time-series plots for the weekly bias and standard deviation of the difference (SDD) of ENVISAT Ku-band RA-2 SWH with respect to the ECMWF model. It is clear that the RA-2 processing chain introduced early February 2010 reduced the bias considerably and made RA-2 SWH comparable with the model values. However, it is clear that there was an increase in the SDD. Later on, it was discovered that the new processing chain of RA-2 introduces more noise at smaller wave heights.

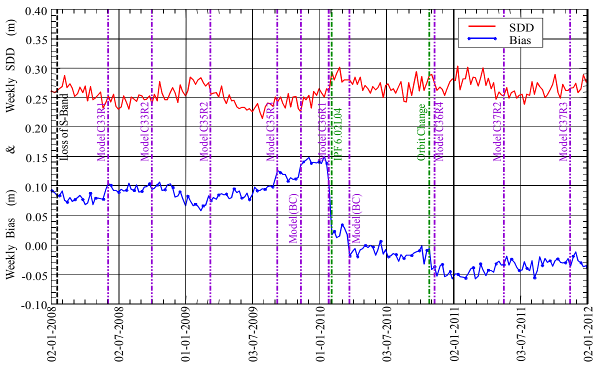

Figure 4. Changes in satellite data requires special care: Time series of ENVISAT Ku-band SWH bias & St.Dev.Diff. Jump in statistics due to altimeter data processing in early Feb. 2010 is visible.

The time series plots of the statistics obtained from comparison of the altimeter products against their model counterparts are very useful in detecting anomalies. For example, Fig. *5* shows the time series plots for the bias and SDD of ERS-2 RA SWH with respect to the ECMWF model values from January 1999 to December 2001. The gyroscopes loss of ERS-2 in January 2001 is reflected as abrupt increases in the bias and the SDD.

This approach of monitoring proved to be sound for monitoring of altimeter wind and wave products and is being used since the days of ERS-1 in the early 1990's. Since then, it has been in operational use at ECMWF as can be seen in the ECMWF web pages at http://www.ecmwf.int/products/forecasts/d/charts/monitoring/satellite/

2.3. Wave Data Assimilation

As mentioned earlier, the benefit is reciprocal in a sense that the model also benefits from altimeter data. The main application is the data assimilation.

The prospect of the advent of satellite data encouraged NWP centres to study the possibility of including wave data assimilation schemes in their operational wave forecast suites. For wave analysis, the wind fields are provided from the analysis of the atmospheric model. Satellite wave data are assimilated to improve the initial sea-state used for the wave forecast. The first operational implementation of SWH assimilation in the global ECMWF IFS was realised on 15 August 1993. The history of ocean wave data assimilation in terms of instruments used is shown in Fig. *6*.

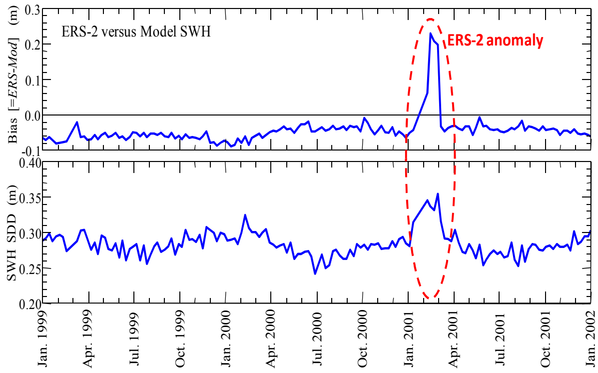

Figure 5. Anomaly detection: Degradation of ERS-2 wind and wave products after the loss of gyros in Jan. 2001.

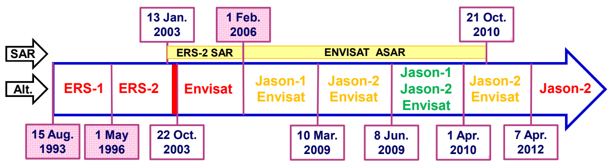

Figure 6. History of wave data assimilation at ECMWF

The positive impact of altimeter wave height data assimilation on wave model prediction lasts between about 2 days in the extra-tropical area and about 5 days in the tropical areas. Fig. *7* shows the impact of assimilating ENVISAT RA-2 SWH on model forecast in the southeast Pacific during the period between 1 January and 31 March 2012 as assessed by comparison with Jason-2 data. At analysis time (time 0), the impact is the largest with an error reduction of about 8%. This positive impact reduces in the forecast range and almost vanishes after about 5 days. This is summarised in Fig. *8* which is for the same case as in Fig. *7* but the assessment was done against the available in-situ measurements in the Tropics. Clearly, forecast impact of data assimilation is much larger and longer lasting in areas where swell systems (which give a long memory to the forecast system because their lifetime is large) dominate and where there are significant systematic errors; e.g. Tropical areas.

The assimilation of altimeter SWH also has positive impact on the mean wave period which is another important wave parameter. Fig. *9* shows such positive impact in the case of Jason-1, Jason-2 and ENVISAT altimeter SWH data assimilation as assessed by comparison with all available in-situ measurements for the period from 1 August to 21 September 2008.

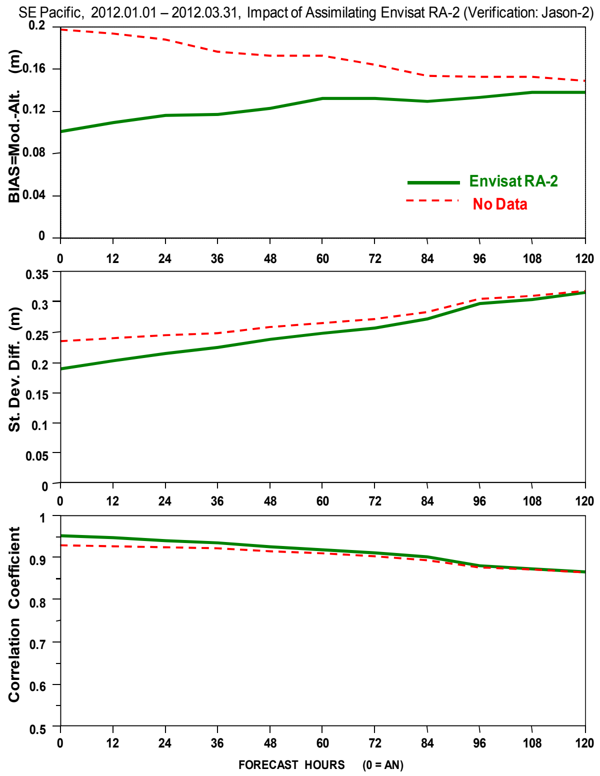

Figure 7. Impact of assimilating ENVISAT RA-2 SWH on model forecast in SE Pacific from 1 Jan. to 31 Mar. 2012 as assessed by comparison with Jason-2 data.

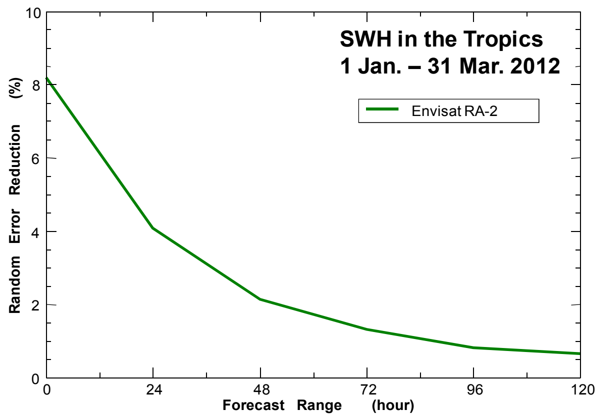

Figure 8. Reduction of model forecast random error in the Tropics due to assimilating ENVISAT RA-2 SWH as assessed by comparison with in-situ data.

2.4. Assessment of Model Changes

Altimeter products are useful in the assessment of model performance and the model changes. This is the inverse of the assessment of the altimeter products mentioned above. For example, Fig. *10* shows the global surface wind speed SDD between the ENVISAT RA-2 and ECMWF model. There were two drops in the SDD values, one was due to altimeter processing chain in October 2005 and the second was due a model change in June 2007. However, there was also a slight increase in SDD due to another model change in March 2009. The list of model changes in June 2007 includes the assimilation of ASCAT wind velocity (in fact this was switched on few days after the main model change).

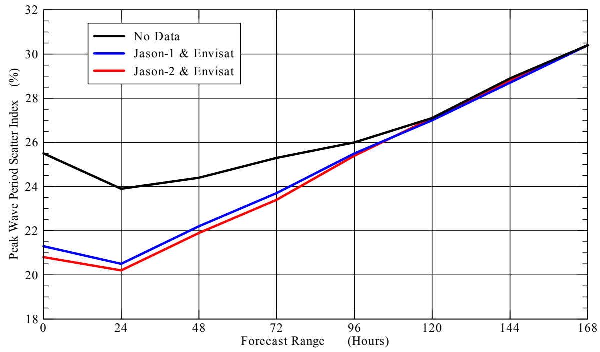

Figure 9. Impact of assimilating ENVISAT, Jason-1 and Jason-2 SWH data on model forecast of peak wave period as assessed by comparison with all available in-situ data (1 Aug. - 21 Sep. 2008).

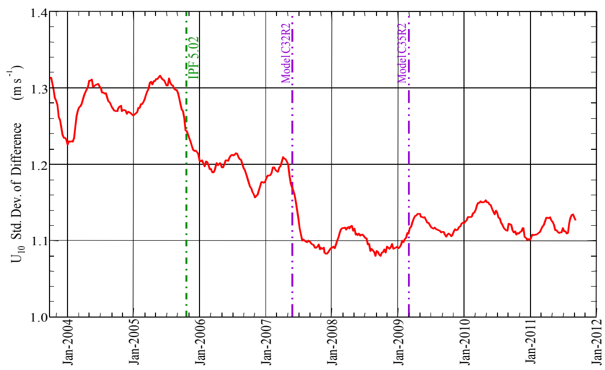

Figure 10. Monitoring of model performance and changes: Change of SDD between ENVISAT RA-2 and ECMWF model wind speed. Changes in statistics due to model changes (in addition to an altimeter data processing change) are visible.

2.5. Error Estimation

The triple collocation method to estimate the random errors in three (independent) sources of data was introduced to the meteorological community by [12]. Further improvements and uses have been introduced since then. It is straightforward to show that with three data sets which have uncorrelated errors, the random error of each data type can be estimated from the variances and covariances of the data sets. However, unless additional assumptions are being made, it is not possible to perform an absolute calibration among the data sets, simply because there are not enough equations. A possible way out of this dilemma is to use a minimization procedure. Assume that the random errors are not correlated and that the errors of the three data sets are estimated using the triple collocation method. Given these estimated errors, calibration is then performed using a neutral regression approach based on the minimization of the error in both variants. For an extensive discussion of this approach and a number of applications see [4] and [5].

Using the triple collocation method it was possible to estimate the random errors of the ENVISAT, ERS-2, Jason-1 and Jason-2 NRT altimeter SWH and wind speed. In this case, it is emphasized that Fast delivery products are used which are averaged over a length scale which is compatible with the effective resolution of the ECMWF wave model (~75 km). The errors of the model and the buoys are also found. The wind speed and the SWH errors are shown in the top and lower, respectively, panels of Fig. *11*.

The availability of consistent global altimeter data set enabled the detection of systematic differences between SWH measurements by different in-situ/buoy networks in 2008 (see Fig. *12* and [16]). This difference can be up to about 10% when SWH measurements from very close U.S. and Canadian buoys are compared. This led to the initiation of the joint WMO DBCP-ETWS Pilot Project on Wave measurement Evaluation and Test (PP-WET), which is still ongoing. It is working on the development of the basis for the continuous testing and evaluation of existing and planned wave buoy measurements, in order to establish confidence in the user community of the validity of wave measurements from the various moored buoy systems. See: http://www.jcomm.info/index.php?option=com_content &task=view&id=90

3. OCEAN MODELLING

Ocean reanalysis is a historical reconstruction of the ocean climate, based on the objective synthesis of the information provided by ocean models, atmospheric forcing fluxes and ocean observations, combined via data assimilation methods. Ocean reanalysis is now an established activity in several research and operational centres like ECMWF (see [13] for more information). Some of the reanalysis products are continuously brought to NRT, with the model and data assimilation methodology kept frozen. This is the case of the ocean reanalyses produced at ECMWF for the initialization of coupled (seasonal, monthly and, by end of 2013, medium range) forecasts. To initialize the coupled forecasts, ocean initial conditions are needed for the real time and for the historical record. The a posteriori calibration of model output requires an estimate of the model climatology, which is obtained by performing a series of coupled hindcasts during some historical period. These hindcasts are initialized from the ocean reanalysis. A historical record of hindcasts is also needed for skill assessment. The interannual variability represented by ocean reanalyses will have an impact on both the calibration and on the assessment of the skill [14]. Often the impact of forecast skill can be used as a metric for the reanalysis quality. Ocean reanalyses are potentially a valuable resource for climate variability studies and have the advantage of being continuously brought up to real time, which allows monitoring of relevant climate variables.

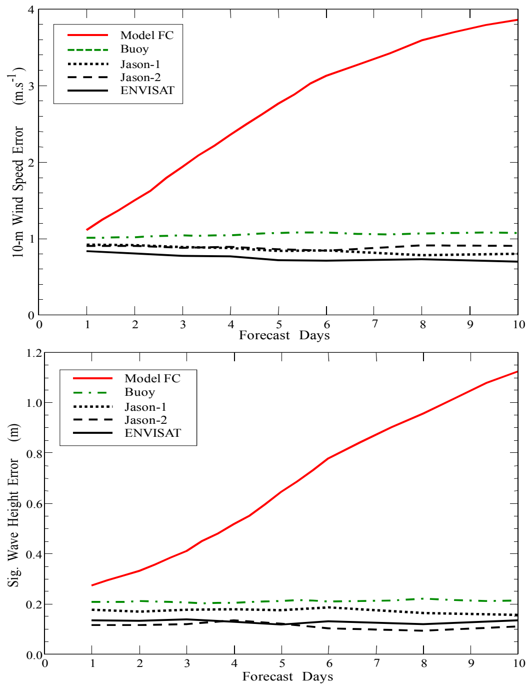

Figure 11. Random error estimation using triple collocation technique.

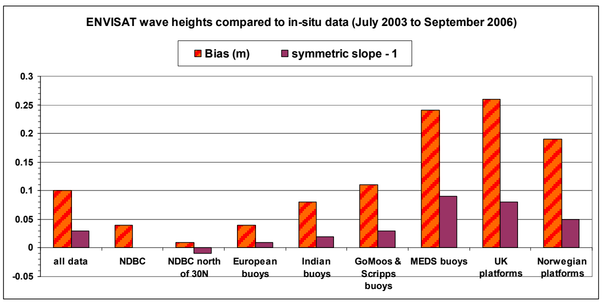

Figure 12. Discrepancies in wave observations: large systematic differences (in terms of bias and symmetric slope) between different observing networks, including a systematic 10% difference in SWH measurements between U.S. (NDBC) and Canadian (MEDS) networks.

The production of a robust ocean reanalysis with uncertainty estimates is a major challenge. In addition to the three-dimensional estimation of the ocean state at a given time (the analysis problem), the estimation of the time evolution is also required in a reanalysis. The time evolution represented by an ocean reanalysis will be sensitive to the time variations of the observing system, to the errors of the ocean model, atmospheric fluxes and assimilation system, which are often flow-dependent, and not easy to estimate. Therefore, before the data of a reanalysis are used, the validation and intercomparisons of the reanalysis output with other independent products become essential. A series of objective metrics that can be used to validate any reanalysis product are presented in [13].

3.1. System Description

The Ocean ReAnalysis System 4 (ORAS4) has recently been implemented operationally at ECMWF. It replaces the previous system ORAS3. Both the ocean model and ocean data assimilation system have been changed. ORAS4 includes the Nucleus for European Modelling of the Ocean (NEMO) model and the variational assimilation system NEMOVAR [13].

Other features of ORAS4 include the use of ERA-Interim forcing fluxes, revised quality-controlled datasets with corrections to the eXpendable Bathy-Thermographs, Argo data for the estimation of model bias, and a revised ensemble generation strategy that improves the uncertainty sampling in the deeper ocean.

ORAS4 uses version 3.0 of the NEMO ocean model in the so-called ORCA1 horizontal discretization. ORCA is the generic name that refers to the tri-polar grids used by the NEMO model; the ORCA1 configuration corresponds to a horizontal resolution of 1° in the extra-tropics and refined meridional resolution in the Tropics with a minimum value of 0.3° directly at the Equator. ORCA1 has 42 vertical levels, 18 of which are in the upper 200 m. The first level has a 10 m thickness. The vertical discretization scheme uses partial steps to have better representation of the flow over steep topography. A weak (20-year time-scale) relaxation to temperature and salinity climatological values is applied throughout the water column.

The analysis cycle in ORAS4 is 10 days; every 10 days, the NEMO model is integrated forward forced by daily surface fluxes, relaxed to sea-surface temperature (SST) and bias corrected to produce the first guess and background trajectory. The model equivalent of each available observation is calculated to construct the innovation vector, and a quality control (QC) of the observations is performed. This information is the input for the 3D-Var minimization. In the final phase of the analysis cycle, the assimilation increment computed by 3D-Var is applied during a second model integration spanning the same time window as for the first guess.

3.2. Data Assimilation

NEMOVAR assimilates temperature and salinity profiles, and along-track altimeter-derived sea-level anomalies. In addition, information of SST and global mean sea-level variations is used to modify the heat and fresh-water budget, respectively. Fig. *13* shows schematically the different datasets used for the production of ORAS4.

Figure 13. Timeline of changes to the reanalysis forcing and assimilation datasets for ORAS4 [13].

The altimeter-derived sea-level anomalies provided by AVISO (Archiving, Validation and Interpretation of Satellite Oceanographic data) are assimilated in ORAS4. This data set composed of the sea level anomalies (SLA) relative to the 7-year period from 1993 to 1999.

The used SLA data are in a form of altimeter along-track measurements. A super-observation (superob) scheme has been developed to assimilate the high spatial resolution along-track SLA data into the fairly low-resolution model set-up. In this scheme, a superob grid is constructed, with a resolution comparable to that of the model (typically 1° latitude/longitude). For a given point on this superob grid, the observations for the same day which have this grid point as the closest of all superob grid points are collected to form a statistical sample from which the superob is created. The sample mean of the SLA value and space/time positions become the superob SLA value and position.

ORAS4 can assimilate the sea-level trends as well. There is clear evidence that the global sea level is rising, due to the combined effect of thermal expansion (steric) and mass changes over the ocean [15]. The steric component of the global mean sea level cannot be represented by the ocean model since, in common with most ocean models used for climate activities, the Boussinesq approximation is made, which means that the ocean model preserves volume. Therefore, if not treated correctly, the trend in sea level can be problematic when assimilating altimeter observations. To avoid inconsistencies, the spatial mean of the sea-level background field and of the input sea-level superobs is removed before assimilation.

The information about the global mean sea level is not neglected, however, as it is used to close the fresh-water budget, thus helping with the attribution of sea-level rise. Although the steric height is not a prognostic variable of the ocean model, it can be diagnosed by vertically integrating the density field of the ocean analysis. By comparing trends in the global mean sea level from the altimeter data with the trends in steric height from the ocean analysis, it is possible to estimate the component of global mean sea level change due to mass variations. The information given by the altimeter data maps about trends in the global mean sea level is compared every assimilation cycle with the trends in the ocean analysis steric height. The trends are relative to the values of model SSH and altimeter data at the beginning of the inclusion of such data (i.e. November 1992). The estimate is applied as a spatially uniform fresh-water flux. The partition between volume change and mass change is quite valuable information since it can help to close the fresh-water budget over the oceans, which is currently a large source of uncertainty in the analysis of the ocean. However, uncertainty remains on the spatial distribution of the global fresh-water residual.

3.3. Verification

It is important to evaluate the impact of assimilation in ORAS4 by comparing it with a simulation that does not assimilate data. This simulation, which is called the control integration (CNTL), uses the same set-up as the full ORAS4 except that no data assimilation or additive bias correction is applied.

The verification is done by comparing with altimeter data. A good fit to the data does not guarantee a good representation of the time variability of the ocean state. The time variability can be gauged by the temporal correlation of the SLA analysis with the altimeter-derived SLA maps provided by AVISO. Fig. *14* shows the correlation of monthly means from the period 1993–2008 for three different experiments: CNTL, the experiment E-TS (which is equivalent to ORAS4 but without altimeter data assimilation), and ORAS4. It can be seen that the assimilation of T and S profiles improves the correlation with the altimeter data in most of the tropical regions, including the Equatorial Atlantic Ocean. However, there is some degradation in few areas like the vicinity of the Iberian Peninsula. As expected, the inclusion of altimeter data in the assimilation further increases the correlation with the AVISO data.

Fig. *15* shows that the assimilation of altimeter data improves the model results along the water column even for parameters like the potential temperature.

4. SEA ICE

The current operational forecast system at ECWMF does not model the dynamic evolution of sea ice. However, research is being carried out towards its implementation. Satellite data are needed to validate and to initialise the sea ice model. Satellite data that can provide information on sea ice concentration and thickness is essential for these efforts. Sea ice assimilation is still in its development phase at ECMWF. Variational techniques of NEMOVAR are used to assimilate ice concentration.

The assimilation of sea ice thickness, which can be derived from freeboard measurements of altimeters, is one of the key elements for providing sea ice predictability on interannual timescales. At the moment it is still uncertain how to use freeboard measurements in the assimilation system. Therefore, depending on availability of resources, it is expected that in the near future ECMWF has the sea-ice modelling and assimilation capabilities to support sea-ice cal/val activities.

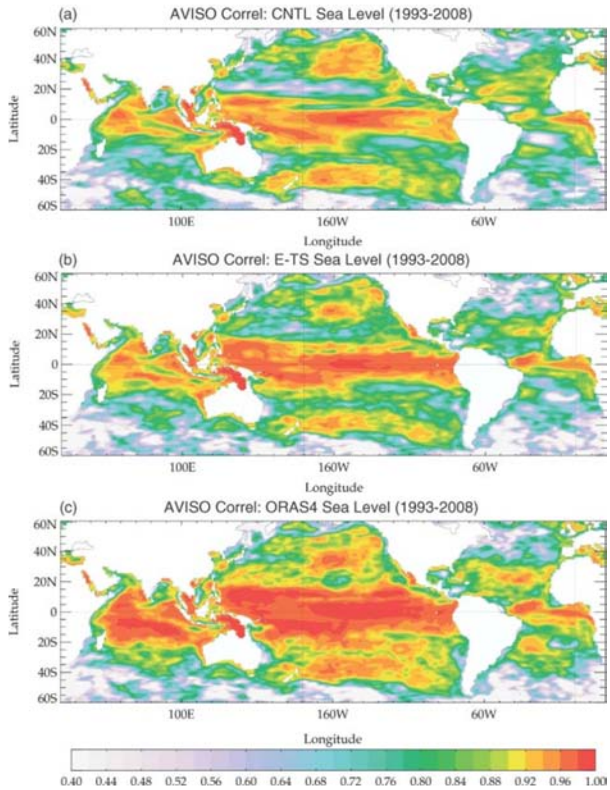

Figure 14. Temporal correlation (in excess of 0.4) between analysis and AVISO sea level for (a) CNTL, (b) E-TS, which assimilates T and S but not altimeter data, and (c) ORAS4. The statistics have been computed with monthly means for the period 1993–2008.

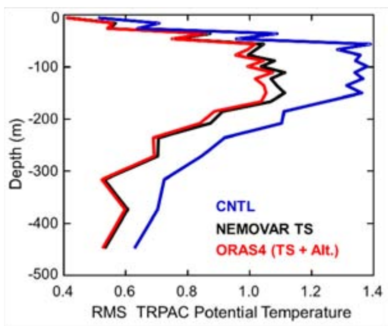

Figure 15. Impact of assimilation of temperature, salinity and altimeter sea surface height anomaly on the model ocean column potential temperature.

5. CONCLUDING REMARKS

ECMWF has a long history in calibration, validation, monitoring and assimilation of NRT radar altimeter products. It contributed to the cal/val efforts for the past and current missions including: ERS-1/2, Envisat, Jason-2, Cryosat and SARAL/AltiKa Altimetry missions with plans to support such activities for the future missions including: Sentinel-3 and Jason-3 missions. Almost all RA and MWR products can be monitored or used at ECMWF. The list includes significant wave height, surface wind speed, water vapour content and sea surface height anomaly with emerging capabilities of including sea-ice freeboard.

There is a reciprocal benefit between altimeter and model products. Altimeter products benefit from model products for cal/val activities, quality monitoring, anomaly detection and assessment of processing chain changes. On the other hand, model products benefit from altimeter products for data assimilation, monitoring of model performance and assessment of model changes. Furthermore, reprocessed altimeter products benefit the reanalysis exercise. Mutual benefit is also possible through error estimates by using, for example, triple collocation technique.

The role of ECMWF in the cal/val activities and in the routine monitoring (during both the commissioning and the routine phases) was demonstrated using several examples. Furthermore, ECMWF assimilated wave height and sea surface height products from various satellites successfully over more than two decades.

We believe that this expertise is very important for the cal/val activities related to Sentinel-3 altimetry products.

6. REFERENCES

1. Abdalla, S. (2013). *Global validation of ENVISAT wind, wave and water vapour products from RA-2, MWR, ASAR and MERIS (2011-2012)*, ESA Cont. Report 21519/08/I-OL, ECMWF, Reading, 48 pp.

2. Abdalla, S. (2012): "Ku-Band Radar Altimeter Surface Wind Speed Algorithm", Marine Geodesy, 35:sup1, 276-298.

3. Abdalla, S., Bidlot, J.R., Janssen, P. (2004). Assimilation of ERS and ENVISAT wave data at ECMWF, *Proc. 2004 Envisat & ERS Symposium*, 6-10 Sep. 2004, Salzburg, ESA Proc. SP-572 (CD).

4. Abdalla, S., Janssen, P.A.E.M., Bidlot, J.B. (2011). Altimeter Near Real Time Wind and Wave Products: Random Error Estimation, *Marine Geodesy*, **34**:3-4, 393-406.

5. Janssen, P.A.E.M., Abdalla, S., Hersbach, H. and Bidlot, J.-R. (2007). Error estimation of Buoy, Satellite and Model Wave Height Data, *J. Atmos. Ocean. Techn.*, 1665-1677.

6. Janssen, P.A.E.M., Abdalla, S., Aouf, L., Bidlot, J.-R., Challenor, P., Hauser, D., Hersbach, H., Lefevre, J.-M., Vandemark, D., Queffeulou, P. and Quilfen, Y. (2008). *15 years using altimeter sea state products*, ECMWF Tech. Memo. No. 552, Feb. 2008., ECMWF, Reading, UK, 37 pp.

7. Janssen, P.A.E.M., Lionello, P., Reistad, M. and Hollingsworth, A. (1989). Hindcasts and data assimilation studies with the WAM model during the Seasat period, *J. Geophys. Res.*, **C94**, 973-993.

8. Janssen, P.A.E.M. (1991). Quasi-linear theory of wind wave generation applied to wave forecasting, *J. Phys. Oceanogr.*, **21**, 1631-1642.

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

10. Bauer, E. and Staabs, C. (1998). Statistical properties of global significant wave heights and their use for validation, *J. Geophys. Res.*, **103**, 1153-1166.

11. Abdalla, S. (2013). Calibration of SARAL/AltiKa Wind Speed, Accepted for publication in *IEEE Geoscience and Remote Sensing Letters*.

12. Stoffelen, A. (1998). Error modeling and calibration: Towards the true surface wind speed, *J. Geophys. Res.,* **103**, 7755-7766.

13. Balmaseda, M.A., Mogensen K. and Weaver, A.T. (2013). Evaluation of the ECMWF ocean reanalysis system ORAS4. *Q. J. R. Meteorol. Soc.* **139**: 1132–1161. DOI:10.1002/qj.2063

14. Balmaseda, M.A., Mogensen, K., Molteni, F. and Weaver, A.T. (2010). *The NEMOVAR-COMBINE ocean re-analysis*. COMBINE Technical Report No. 1. http://www.combine-project.eu

15. Church, J. and White, N.J. (2006). A 20th century acceleration in global sea-level rise. *Geophys. Res. Lett.* **33**: L01602, DOI: 10.1029/2005GL024826.

16. Durrant, T.H., Greenslade, D.J.M. and Simmonds, I. (2009). Validation of Jason-1 and Envisat remotely sensed wave heights, *J. Atmos. Ocean. Techn.*, **26**: 1, 123-134.