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SARAL/AltiKa Wind and Wave Products: Monitoring, Validation and Assimilation

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Abstract

SARAL/AltiKa surface wind speed (WS) and significant wave height (SWH) measurements are monitored and validated against operational ECMWF atmospheric and wave model results in addition to available in-situ observations to access their suitability for various applications, especially SWH data assimilation. The quality of SWH is very high while that of WS is very good except for an underestimation of high wind speeds. The impact of assimilating SWH in the ECMWF Integrated Forecast System was assessed using several numerical experiments. The results show good impact. Operational assimilation of SWH at ECMWF model is part of the forthcoming model change.

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1. Introduction

There is always a need for altimeter surface wind and sea-state conditions for oceanographic and meteorological applications. Surface wind speed (WS) and significant wave height (SWH) from satellite altimeters partially meet this need.

SARAL (or Satellite with ARgos and ALtiKa), which is an Indo-French mission for the monitoring of the earth environment developed and operated by the French Space Agency (CNES) and the Indian Space Research Organization (ISRO), contains the first oceanographic radar altimeter that operates in Ka-band enabling higher resolution altimetry measurements (Verron, et al., 2014). The satellite, which has a design lifetime of 3 years, was launched on 25 February 2013 and reached its final orbit on 13 March 2013. SARAL follows the same sun-synchronous orbit that was occupied by the European Space Agency (ESA) satellites ERS-2 and ENVISAT during their nominal operations (altitude of about 800 km). The main payload of this mission is a Ka-band (35.75 GHz) altimeter called AltiKa which is the first space-borne oceanographic altimeter to operate at this radar frequency (Bronner et al., 2013). The smaller footprint and the higher Pulse Repetition Frequency, enable the short-wavelength (~ 1 cm) Ka-band altimeter to make finer-resolution measurements compared to other altimeters operating traditionally at Ku-band with wavelength of about 2.2 cm (Tournadre et al., 2009a). However, this comes at a cost of being very sensitive to several atmospheric factors like liquid water and water vapour which have adverse impact on Ka-band measurements (Tournadre et al., 2009a).

With the exception of few airborne Ka-band radar altimeter campaigns (e.g. Vandemark et al., 2004), there is no previous experience with Ka-band altimeters before the launch of SARAL. Therefore, Tournadre et al. (2009a and 2009b) conducted a study before the launch to assess the potential degradation level of various Ka-band products (specifically, range, significant wave height, and backscatter). Numerical simulation combined with results from Jason-1 mission estimated the data loss due to rain can be between 5 and 10%. Part of this loss is in tropical areas. The rain-related degradation also occurs during stormy conditions when altimeter measurements are highly needed.

SARAL surface wind speed (WS) and significant wave height (SWH) are validated against available in-situ measurements and the model fields from ECMWF Integrated Forecast System (IFS). WS and SWH from SARAL Operational Geophysical Data Record (OGDR) products available in near real time (NRT) have been monitored and validated routinely. The data and their processing are described briefly in Section 2. The results of the wind speed and SWH validation are summarised in Sections 3 and 4, respectively. Data assimilation experiments and the results obtained are presented in Section 5. Finally, conclusions are listed in Section 6.

2. Methodology and Data

For the current study, the long term (March 2013-April 2014) assessment of WS and SWH was done based on the SARAL Geophysical Data Record (GDR) dataset that was reprocessed after the implementation of Version ñTò patch 2 processing in February 2014 (A. Guillot and N. Picot; Personal communication, 2014). Earlier processed data products were not used due to several issues especially in the WS product (e.g. Abdalla, 2014). Patch 2 has been

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used operationally since early February 2014. This dataset was obtained from Aviso (http://www.aviso.oceanobs.com) in netCDF format.

On the other hand, routine monitoring and validation is based on the BUFR (Binary Universal Form for the Representation of meteorological data) version of the Operational Geophysical Data Record (OGDR) of SARAL radar altimeter made available in NRT by EUMETSAT through EUMETCAST (which 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). This timely availability (within ~3 hours) makes OGDR-BUFR product suitable for operational use in atmospheric and ocean wave forecasting systems. The common belief is that OGDR product may be of slightly degraded quality compared to the final GDR. The latter product, however, is available with a delay of several weeks. Even the interim product (IGDR) has a delay of several days. This latency makes those ñhigher qualityò products not suitable for operational meteorological systems. Nevertheless, the quality of the SWH and the surface wind speed parameters does not differ between the OGDR and the GDR (unlike products from earlier satellites like Jason-1). It is only the retracker which is of lower quality. Statistics resulted from the validation of GDR and OGDR WS and SWH products against the model and the in-situ counterparts confirmed that this is indeed the case (not shown 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. This includes the exploitation of land and ice flags provided within the OGDR product. The standard deviation of altimeter range and SWH are also used to reject observations with high variability which are usually adversely affected by land, ice or other sources of footprint contamination. The data is then averaged along the track to form super-observations with scales compatible with the model scales of around 75 km. It is worthwhile mentioning that model scale typically is several (4~8) model grid spacing (e.g. Abdalla et al., 2013). This corresponds to 11 individual (1 Hz) SARAL observations (7 km each) and 13 individual Jason-2 observations (6 km each).

After passing this quality control process, the data is closely monitored and verified using the model products. On a weekly and a monthly basis, the data are verified against available in-situ data in addition to the model data. Internal weekly and monthly reports summarising the quality of SARAL products for that week or month are produced for future reference. In general, the rate of SARAL data timely reception is quite good which indicates the reliable operational status of the data so far.

Other sources of data are used for verification and quality assessment of SARAL products. The genuine independent (from both the model and the altimeter data) source of data for this 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 the Global Telecommunication System (GTS) managed by World Meteorological Organisation (WMO). 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 a couple of 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 unless it covers a long time period (several years). The term ñbuoyò 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). The maximum acceptable collocation distance/time between SARAL and in-situ measurements is rather relaxed (200 km and 2 hours) to generate enough collocations for statistical analysis. To ensure that SARAL and in-situ within one collocation represent the same truth, it is required that model SWH at both SARAL and in-situ should not differ by more than 5%. This ensures homogeneous weather conditions at least from the model point of view. It should be noted that buoys within close proximity from the coast are not included in this study which has a global coverage. The altimeter, global model and sometimes even the buoy data cannot be trusted very close to the coast due to the lack of information about the local environmental conditions (e.g. topography and human activities). Therefore, this study cannot make any statement regarding the ability of AltiKa to make high resolution measurements which is of importance in coastal areas.

The IFS model products provide the required global coverage. IFS is a comprehensive atmospheric forecasting model. It includes three components: a global spectral atmospheric model, an ocean wave model and an ocean model to simulate the ocean circulation and sea ice. At the time of writing, the global high-resolution spectral model (HRES) uses a grid spacing of about 16 km and 137 vertical levels with the model top at an altitude of about 80 km. The model includes a sophisticated four-dimensional variational data assimilation scheme for atmospheric data. The atmospheric model is coupled to a spectral ocean wave model with a two-way interaction (Janssen, 2004). The ocean wave field is discretized into several hundred individual wave components (1269 for HRES) referred to as the wave spectrum. The ocean wave model solves the energy balance equation that describes the evolution of the energy action density of each wave component explicitly, accounting for processes such as wind forcing, wave breaking and waveï wave interaction and the impact of shallow water processes. The wave model configuration is similar to that of the atmospheric model, except for the horizontal grid spacing of 28 km and the assimilation technique where a simple Optimum Interpolation is used.

Twice a day (at 00 and 12 UTC), IFS operationally creates the first guess (FG) of the atmospheric conditions (including sea-state) from the previous analysis cycle. Data assimilation merges measurement data available within the analysis time window (which is typically 12 hours) with the model FG to produce the best estimate of the atmospheric conditions which is referred to as model analysis (AN). Finally, IFS uses the AN conditions to produce 10- to 15-day

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weather forecasts. Since altimeter wind speed is not assimilated in IFS, this parameter is compared against the best available model counterpart which is the AN wind. On the other hand, altimeter SWH is usually assimilated in the model.

Therefore, model AN and altimeter data are not independent. ECMWF operational model assimilates Jason-2 SWH but not SARAL. However, since both altimeters implement the same principle of measurements and the same algorithms, an indirect dependency between SARAL data and the model AN may be formed (e.g. Janssen et al., 2007). The dependency becomes weaker further along the forecast range. Therefore, model FG and forecasts can be used to assess altimeter SWH data 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 SWH can be verified against model FG while the altimeter data can be used to assess the impact of assimilation on the model forecasts.

The NRT Jason-2 OGDR-BUFR data are used for the verification purposes and for data assimilation in this study. Jason-2 data covering same period when SARAL data were available are compared to in-situ and model data and the results are compared to the results obtained for SARAL. This provides a mean to make conclusions regarding the relative quality of SARAL data. Jason-2 OGDR-BUFR dataset is routinely obtained by ECMWF through EUMETCast and GTS and later archived in MARS (ECMWF Meteorological Archival and Retrieval System). Jason-2 data are processed in the same way as that of SARAL except for the number of 1-Hz data used in the super-observations (13 of them). While Jason-2 wind speed values are used as received, SWH values are corrected to remove the bias with respect to the model. In general, uncorrected SWH are verified against model and in-situ data while the corrected SWH values are used for data assimilation.

Furthermore, the NRT Cryosat-2 altimeter product produced by NOAA is used as an ñindependentò data set to verify the impact of data assimilation. This type of data in made available by NOAA in ASCII format and is retrieved using widely-used file transfer protocol, ftp. Cryosat data are converted into BUFR format and processed in a similar manner to that of SARAL using the same number of 1-Hz data to form the super-observation (11 of them). Similar to other altimeter data, wind speed data are used as received while bias correction is applied to SWH when used for data assimilation.

3. Quality of SARAL Surface Wind Speed Product

Surface wind speed (WS) product from altimeters is not assimilated at IFS. Instead, it 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 very important.

Comparison of SARAL WS against in-situ measurements gives only general idea about the quality of SARAL winds at in-situ locations which are limited mainly to offshore Europe and Northern America. 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 SARAL wind speed data compare well with the in-situ observations and the ECMWF model AN data as can be seen in *Figure 1* for a full year covering the period from 1 May 2013 to 30 April 2014. 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* represent two-dimensional (2-D) histograms showing the number of observations in each 2-D bin of 0.5 m/s x 0.5 m/s of WS. SARAL WS data over the full year are slightly lower than the in-situ observations (by about 0.4 m/s) and almost unbiased compared to the ECMWF model AN. The latter result is an expected outcome as SARAL wind speeds are computed using Lillibridge et al. (2014) algorithm which was based on a fit between the corrected SARAL backscatter coefficient and ECMWF model forecasts during SARAL cycle 3 (23 May ï 27 June 2013). The standard deviation of the difference (SDD) is about 1.30 m/s and 1.14 m/s when compared against the in-situ observations and the model AN, 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 AN) values of about 16.8% and 14.9%, respectively. These values are comparable to those resulted from Jason-2 similar comparisons (not shown).

One, however, cannot miss the underestimation of the wind speed at higher wind speed values (in excess of ~ 13 m/s). The Ka-band wind speed algorithm developed by Lillibridge et al. (2014) was implemented for SARAL as part of the ñpatch 2ò mentioned in Section 2 above.

However, this underestimation does not show in the work of Lillibridge et al. (2014). This underestimation emerges from the implementation of the algorithm. It turned out that there is a cut-off in the backscatter coefficient at 5 dB (N. Picot; personal communication, 2014). This corresponds to a wind speed value of 21.8 m/s. The averaging of 11 SARAL 1-Hz measurements smears this impact towards smaller wind speeds and its impact appears to affect averages of about 13 m/s and higher as can be seen in *Figure 1* (and *Figure 2*).

To get more insight of the quality of the WS product at various wind speed regimes, the SARAL WS bias (altimeter-model) and SDD with respect to the ECMWF model are plotted against the WS values as shown in *Figure 2* for the whole globe over a whole year (1 May 2013-30 April 2014). Plotted bias and SDD curves are the mean of the corresponding statistics computed for given model WS values (i.e. the model is assumed to be the reference) and those computed for given altimeter WS values (i.e. the altimeter is the reference). Since the ñtrueò reference is not known, the simple use of the model by itself as the reference increases the risk of interpreting model discrepancies as altimeter issues. Note that the horizontal axis in *Figure 2* is the mean of the model and altimeter values for the same reason. The bias and SDD of Jason-2 WS data with respect to the model for the same period are also plotted in *Figure 2* for comparison. It is clear that SARAL WS is almost unbiased compared to the model up to about 13 m/s. However, there is relatively large bias beyond 13 m/s. The SARAL WS SDD with respect to the model is almost constant (about 1.1 m/s) irrespective of the wind strength. The SDD from SARAL and Jason-2 comparison is comparable between 4 m/s and 12 m/s. Irrespective of the WS underestimation of SARAL at high wind speeds; it is clear that compared to Jason-2, SARAL is more consistent with the model at wind speeds above 12 m/s (and below 4 m/s).

The time series of the global wind speed monthly bias (defined as the difference between the altimeter product and the model output) and monthly SDD of SARAL with respect to the in-situ measurements and ECMWF model AN during the period from 14 March 2013 to the end of April 2014 are shown in *Figure 3*. Due to the noisiness of the in-situ comparison (limited number of collocations in each month), 3-month running means are plotted to make it easier to get the main trend of the statistics. Similar time series from Jason-2 data are also shown for comparison. Time series plots of the error statistics are powerful tools to detect any irregularities in the quality of the satellite data. The comparison with the model shows a clear continuous reduction of SARAL wind speed with an abrupt jump in November 2013 before it starts to decrease again. Ka-band signal suffers severe attenuation due to the atmospheric conditions especially liquid water and water vapour (e.g. Lillibridge et al., 2014). This attenuation is compensated for using the information from the on-board microwave radiometer. The measurements of radiometer are drifting. The SARAL project team adjust for this drift from time to time. There was an adjustment on the 22 October 2013 (N. Picot and A. Guillot, personal communication, 2014).

The SDD time series shows that SARAL winds are slightly better than those of Jason-2 until the radiometer adjustment late October 2013 when Jason-2 winds became slightly better. Towards the end of the period, SARAL wind became better again. This may indicate that the

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radiometer adjustment was not optimal. The seasonal signal in the comparison against in-situ data is just a reflection that the in-situ measurements are mainly located in the NH.

4. Verification of SARAL Significant Wave Height Product

Altimeter SWH is the most important product as far as the wave prediction is considered. It is used for data assimilation to improve the model analysis and forecast. Therefore, there is great interest at ECMWF to monitor, validate and assimilate such data products.

SARAL SWH is compared against in-situ measurements (as done for the wind speed product) and against ECMWF wave model first guess (FG). As stated in Section 2, the model analysis in general cannot be considered an independent source of data for the verification of altimeter SWH as this product is assimilated by the model. FG fields can be considered of ñless dependencyò as they contain traces of SWH data assimilated at earlier time windows (not exactly the same data to be verified). As SARAL SWH product is not assimilated in the operational ECMWF model, one could have used model analysis. However, some degree of dependency cannot be ruled out as SWH product from various altimeters implement the same method of measurement and share the same algorithms. Therefore, model FG was adopted.

In general, the OGDR SARAL SWH data compare very well with the in-situ observations and the ECMWF model FG data as can be seen in *Figure 4* for a full year covering the period from 1 May 2013 to 30 April 2014. Note that verification against in-situ measurements is limited to the Northern Hemisphere (near the coasts of Europe and North America) and parts of the Tropics while the verification against the model represents a truly global verification. The 2-D histograms in *Figure 4* show the number of observations in each 0.25 m x 0.25 m bins of SWH. While SARAL SWH data agree very well with both the in-situ and the model counterpart at SWH values below 4 m (which includes most of the SWH conditions), they tend to be overestimated at high SWH values (above about 6 m) relative to the model. The overestimation is much less obvious relative to the in-situ data, particularly at very high SWH values (above about 8 m) when the scatter is large. The overall bias is around 0.05 m. This overestimation corresponds to about 2% of the mean SWH. The SWH SDD is 0.23 m and 0.26 m when compared to SWH from the in-situ and model, respectively. These SDD values correspond to SI values of 10.9% and 10.4, respectively. These values are comparable to those resulted from Jason-2 similar comparisons (not shown) except for the SDD between SARAL and the model possibly due to the fact that Jason-2 SWH is assimilated in the operational ECMWF model.

SARAL SWH bias (altimeter-model) and SDD with respect to the ECMWF model FG are plotted against the mean model and SARAL SWH values at each bin as shown in *Figure 5* for the whole globe over a whole year (1 May 2013-30 April 2014). As for the corresponding WS plot (*Figure 2*), the bias and SDD curves are the mean of the corresponding statistics computed for given model SWH values (i.e. the model is assumed to be the reference) and those computed for given altimeter SWH values (i.e. the altimeter is the reference). Note that the horizontal axis in *Figure 5* is the mean of the model and altimeter values. The absolute differences are shown in panel (a) while the relative differences (normalised by the SWH value itself) are shown in panel (b) of *Figure 5*. The SWH bias and SDD curves are generated the same way as for the wind speed. The corresponding curves of Jason-2 SWH data are also plotted in *Figure 5* for comparison. *Figure 5* (a) shows that SARAL SWH product is almost unbiased below ~ 3 m. The bias is proportional to SWH for higher wave heights. Jason-2 SWH bias follows the same trend of SARAL in general for SWH higher than 0.5 m, except that Jason-2 unbiased part extends to about 4 m and the linear trend has less gradient. The SDD is almost constant for SWH lower than 2 m and becomes proportional to the SWH for higher wave heights. SWH SDD of both SARAL and Jason-2 are very close to each other with SARAL SWH tends to agree slightly better with the model. Although, the differences with respect to the model appear small (few 10ǒs of centimetres), there relative values are very large at smaller wave heights as can be seen in *Figure 5* (b). Therefore, one needs to be cautious when dealing with low altimeter wave heights.

The time series of the global SWH monthly bias (altimeter - model) and monthly SDD of SARAL with respect to the in-situ measurements and the ECMWF wave model FG values during the period from 14 March 2013 to the end of April 2014 are shown in *Figure 6*. The curves representing the verification against in-situ measurements are smoothed by plotting the 3-month running means. Similar time series from Jason-2 data are also shown for comparison. The slight overestimation of SARAL SWH both against the in-situ measurements and the model FG is a permanent feature since May 2013. The weak seasonal cycle in the bias between the altimeter and the model (panel a of *Figure 6*) can be attributed to the model as a similar seasonal cycle is present when the model is compared against in-situ observations (not shown). The global monthly SDD between SARAL and the in-situ measurements is lower than the corresponding Jason-2 SDD for almost the whole period. According to the model comparison, however, the difference in SDD between SARAL and Jason-2 is small and vanishes between November 2013 and March 2014. It is worthwhile recalling that Jason-2 SWH is assimilated in the model and this may mould the model SWH to follow Jason-2 SWH, to a certain extent and thus adding advantage to Jason-2 - model comparison. Although *Figure 6* hints that the SDD difference between SARAL and Jason-2 follows a seasonal cycle, the microwave radiometer adjustment towards the end of October 2013 may have a slight adverse impact on SARAL SWH. Precise statement regarding this will be only possible at later stages (2 or more years of comparison). Overall, it is possible to conclude that SARAL SWH product is as good as that of Jason-2 if not slightly better.

5. SARAL SWH Data Assimilation

Unlike atmospheric data assimilation, which started in the 1960ŝs, ocean wave data assimilation emerged only in the 1980ŝs. 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), Abdalla et al. (2004 and 2011) showed that assimilation of satellite radar altimeter wave heights from ERS-2, ENVISAT, and Jason-2 reduces the model wave height errors with respect to in-situ observations by about 10-20%.

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 (c.f. Lionello et al., 1992) 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 altimeter data, only SWH is available. SWH is a prognostic parameter that is only computed from the wave spectrum for the output. Therefore, the SWH measurements 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).

ECMWF runs IFS operationally 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 part of IFS and coupled tightly with the atmospheric model. 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) and Abdalla et al. (2011). Operational assimilation of ERS-1 altimeter fast delivery (FD) SWH at ECMWF started on 15 August 1993. ERS-2 altimeter FD SWH replaced that of ERS-1 on 1 May 1996. Assimilation of Envisat altimeter FD SWH started on 22 October 2003 after the loss of ERS-2 global coverage due to the failure of its on-board tape recording facilities. Assimilation of Jason-1 Operational Sensor Data Record (OSDR) SWH started on 1 February 2006 on top of Envisat product. Jason-1 SWH assimilation stopped in January 2009 due to its orbit change. Assimilation of Jason-2 OGDR on top of Envisat was realised on 10 March 2009 and Jason-1 assimilation was resumed on 8 June 2009. This resulted in the most resilience data assimilation system so far with SWH data from 3 different satellites (Envisat, Jason-1 and Jason-2). On 1 April 2010, assimilation of Jason-1 was stopped when the satellite started to be unstable. Envisat was also lost on 8 April 2012. Since then, only Jason-2 SWH product has been assimilated at ECMWF.

The high quality of SARAL OGDR SWH product encouraged the immediate use of the product in several assimilation experiments to assess its impact on the ECMWF forecasting system. Since running the full operational configuration of IFS for a long period is very expensive, first stand-alone wave model experiments were conducted with operational horizontal resolution (~28 km) and then the full IFS was run with reduced horizontal resolution (~55 km). The need for running the full IFS system is due to the fact that 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.

The stand-alone wave model runs are forced by 10-m winds from the operational runs updated every 6 hours. The reference for the stand-alone runs was taken as a wave model run without any data assimilation. Experiments covering a wide range of assimilation possibilities and combinations were conducted. For the full IFS system (coupled) runs, the wind and other driving forces are being updated every model time step. The reference run mimics the operational configuration in the sense that only Jason-2 SWH product is assimilated. Only limited assimilation configurations were tested.

Figure 7 shows the impact of altimeter data assimilation on the model SWH and peak wave period (PWP) analysis and forecasts for three stand-alone high resolution experiments against the model run without data assimilation. The SDD between the model (AN and FC) and the independent in-situ measurements for the model run with data assimilation (SDD_{assim}) and that without data assimilation (SDD_{none}). The random error reduction is computed as the difference between SDD_{none} and SDD_{assim} normalised by SDD_{none} (then multiplied by 100 to get the percentage).

The model run with Jason-2 SWH data assimilation (mimics the current operational system) reduces the model SWH and PWP errors by about 3.5% and 2.5%, respectively, at analysis time and the reduction decreasing to almost zero on the third day in the forecast as can be seen in *Figure 7* (dash-dot red curve). Note that the error reduction in the tropics (between latitudes 20°N and 20°S) is much higher (more than 5%) and lasts longer (~6 days) in the forecast (not shown). Assimilating SARAL SWH product as received (i.e. without any calibration) in addition to Jason-2 SWH results in more SWH error reduction (~6%) at the analysis and slightly more error reduction in the short forecast (dashed yellow curve). However, the positive impact on the PWD is limited to the analysis and the first day of the forecast (with half the impact of Jason-2 SWH only run). Further in the forecast range, the model FC PWP deteriorates (*Figure 7*, b).

As was discussed in Section 4, SARAL overestimates high wave heights relative to the model and the in-situ data (see *Figure 4* and *Figure 5*) and this overestimation is almost a linear function of the SWH itself. It is clear that the model cannot assimilate easily this kind of overestimation. The bias in *Figure 5* (a) was approximated by the two linear segments indicated by the dash-dot line in *Figure 5* (a). SARAL SWH values are corrected by subtracting the mean bias as approximated with the two dash-dot linear segments in *Figure 5* (a) before assimilating into ECMWF model. The SWH error reduction due to assimilating bias-corrected (BC) SARAL SWH on top of Jason-2 SWH is slightly lower that the case of SARAL without bias correction as can be seen in panel (a) of *Figure 7* (continuous green curve). However, the impact on reducing the PWP error compared to that of no bias correction is considerable as shown in *Figure 7* (b).

The geographical distribution of mean SWH difference between model analysis when bias-corrected SARAL and Jason-2 SWH are assimilated and model analysis using Jason-2 SWH only over the period between 20 February and 31 March 2014 is shown in *Figure 8*. This is a result from the full IFS runs (with 55-km grid spacing). It is clear the SARAL assimilation increases the model AN SWH by up to 0.10 m on average in most of the globe. However, there are few areas where SARAL assimilation causes SWH reduction especially in the Southern Ocean and near the ice edges. In particular, there is the region at latitude 70°S and extending between 100°W and 170°W where SARAL causes a mean reduction in SWH of up to 0.33 m. This is clearly a model issue as all the altimeters on-board Jason-2, SARAL and Cryosat-2 indicate a drastic difference with the model at that region.

The results from the full IFS assimilation experiment using bias-corrected SARAL and Jason-2 SWH and the similar experiment that assimilates only Jason-2 SWH were further verified using Cryosat-2 SWH. The impact was slightly positive at all regions. As an example, *Figure 9* shows the impact of using bias-corrected SARAL SWH data on the SWH bias, SDD and the correlation coefficient with respect to Cryosat-2 SWH in the extra-tropical Southern Hemisphere (SH) for the period from 14 February to 31 March 2014. The slight positive impact, especially in the short forecast range, is very clear.

The tight two-way coupling between the atmospheric and ocean wave models within IFS requires that any wave model change including data assimilation does not introduce any degradation to the atmospheric fields. As an example, *Figure 10* shows the mean impact of assimilating bias-corrected SARAL SWH in addition to Jason-2 SWH on the anomaly correlation (which is a standard statistic used in numerical weather prediction field and represents the correlation of the model deviations from the climate) of the model 500 hPa geopotential height forecast in the Northern (NH) and the Southern (SH) Hemispheres (latitudes higher than 20°) with respect to operational analysis for the period from 14 February to 1 April 2014. Positive values in *Figure 10* indicate positive impact and vice versa. It is clear that the impact is almost neutral in terms of statistical significance at 95% level with a tendency towards positive impact in the NH.

6. CONCLUSIONS

SARAL near real time wind and wave products (from both GDR and OGDR) have been monitored and verified at ECMWF since the beginning. The rate of data reception and its timing are within the operational requirements. SARAL wind speed product is very good apart from the underestimation at high wind speeds due to an issue with the implementation of the wind speed algorithm. Ka-band atmospheric attenuation is compensated for by using the microwave radiometer which suffers from gradual drifting. The drift and its adjustment will produce a saw-tooth bias in the wind speed over the years.

SARAL significant wave height (SWH), on the other hand, is of high quality. It is slightly higher than the in-situ measurements and the model counterpart. Once the bias is removed from SARAL SWH, the impact of its assimilation is quite good. The operational assimilation of SARAL SWH at ECMWF is part of the coming model changes expected towards the end of the year.

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Meteorological Satellites (EUMETSAT) and National Oceanic and Atmospheric Administration (NOAA). Jean-Raymond Bidlot helped with the model forecast verification against in-situ data. The constructive comments of the two anonymous reviewers are appreciated.

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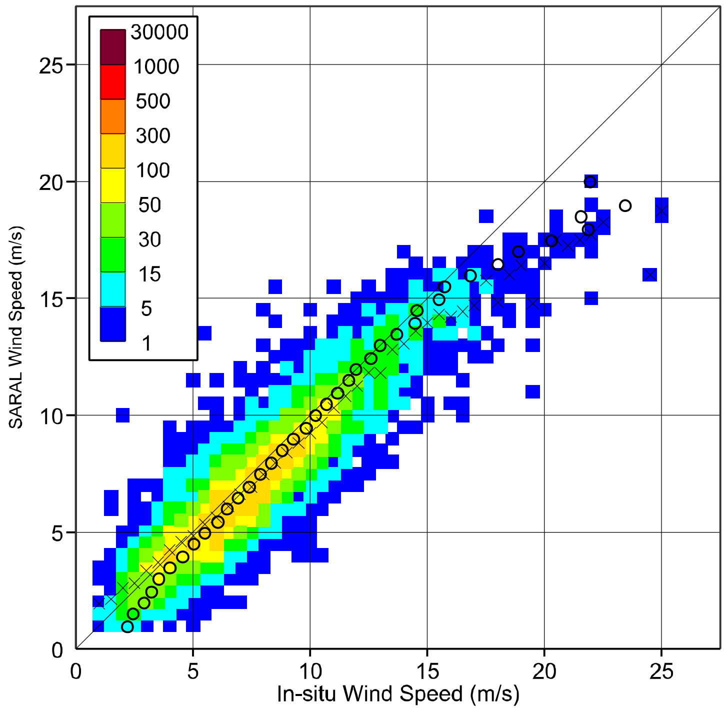
(a)



(b)

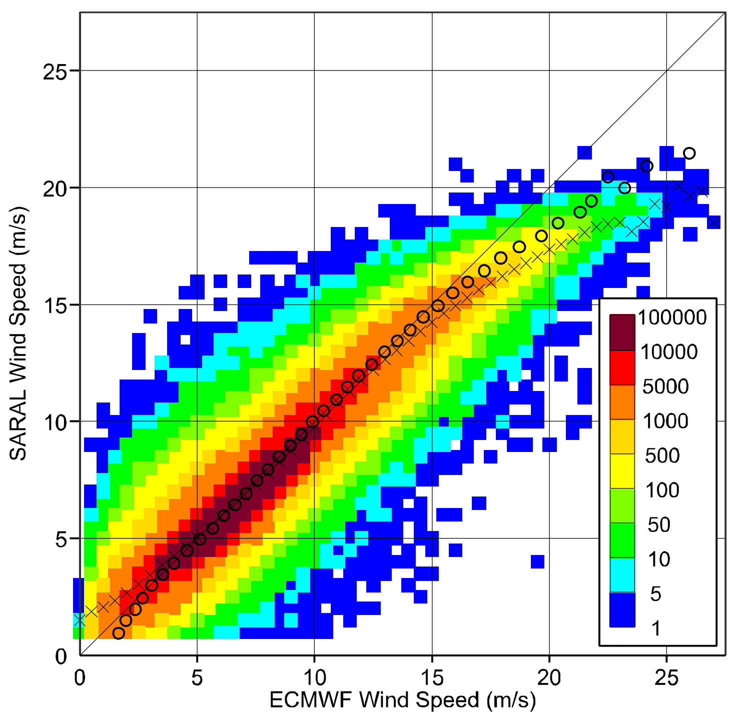


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Figure 1: Global comparison between SARAL surface wind speed and both (a) all in-situ measurements (which are mainly in the NH) and (b) ECMWF model analysis counterparts during the period from 1 May 2013 to 30 April 2014. The number of collocations in each 0.5 m/s x 0.5 m/s 2-D bin is color-coded as in the legend. The ñxò symbols are the means of the bins for given x-axis values (in-situ or model) while the ñoò symbols are the means for given y-axis values (SARAL).

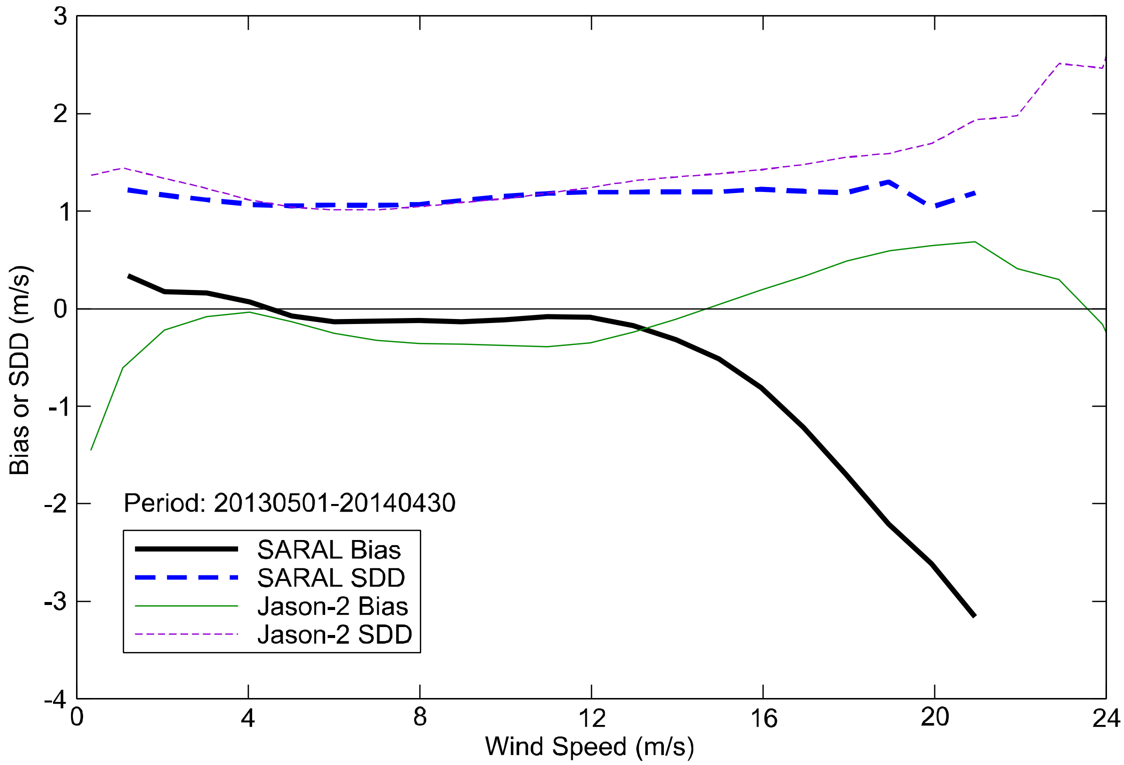


Figure 2: Mean differences and SDD between SARAL and the model surface wind speed as functions of wind speed values. Only absolute differences are shown.

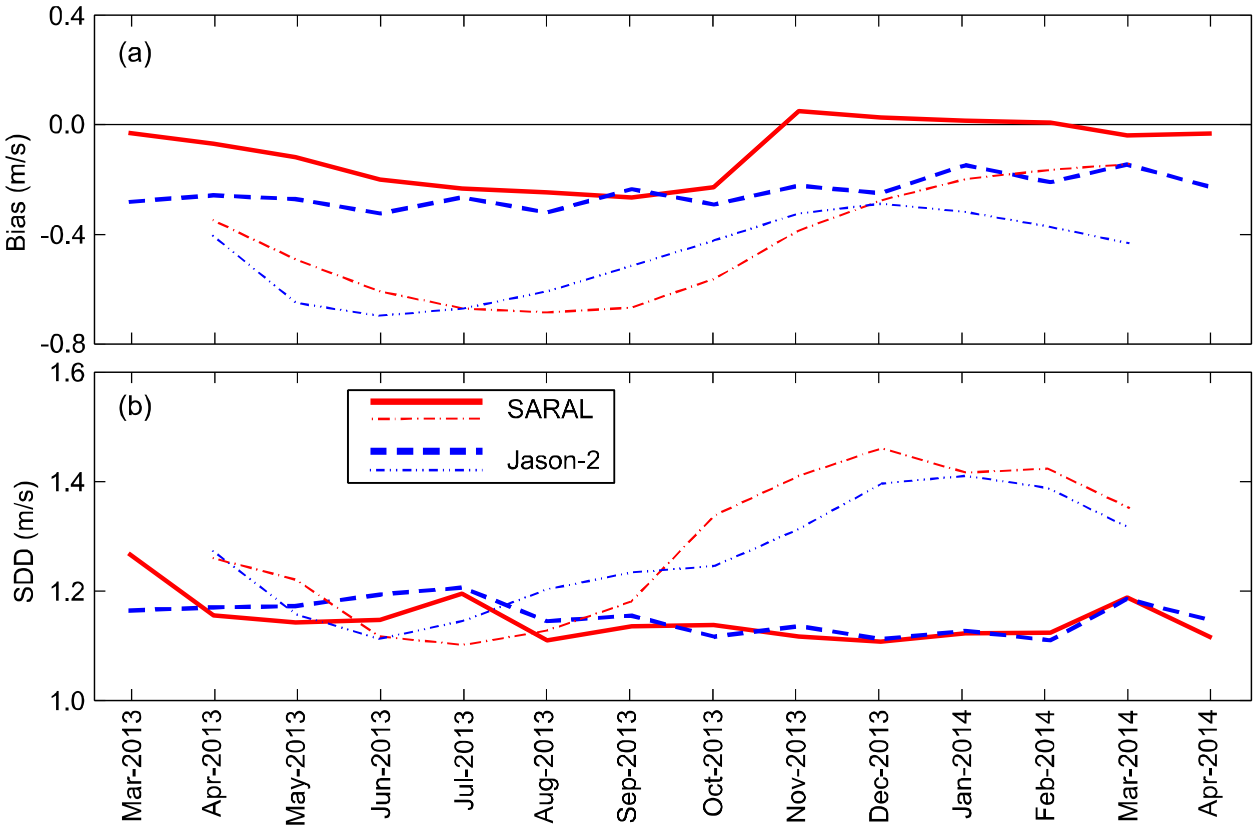
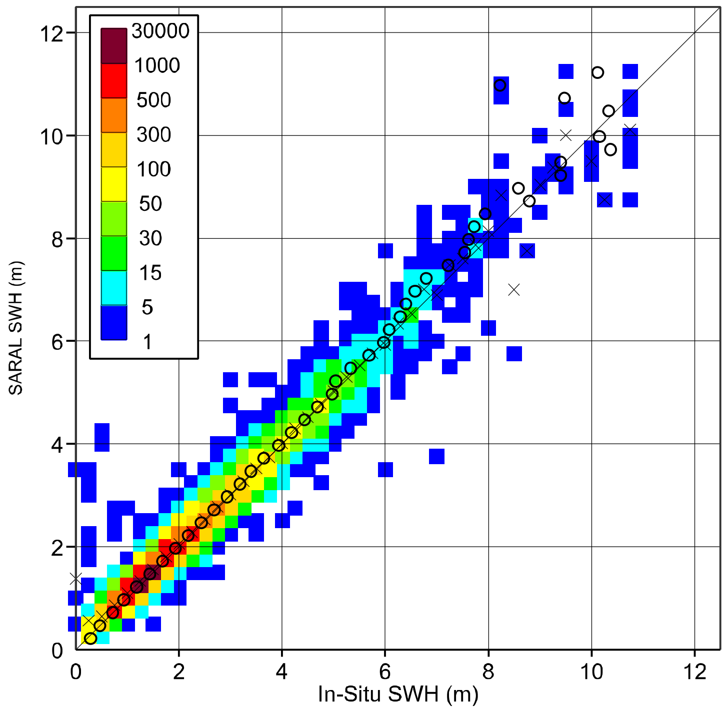


Figure 3: Time series of monthly (a) mean difference (bias) and (b) standard deviation of the difference (SDD) between altimeter (SARAL and Jason-2) surface wind speed from one side and all available in situ measurements and all model analysis values from the other side. The in-situ curves (thin dash-dots) are running means over 3 months.

(a)


30000
1000
500
300
100
50
30
15
5
1
SARAL SWH (m)
In-Situ SWH (m)
0
2
4
6
8
10
12

(b)

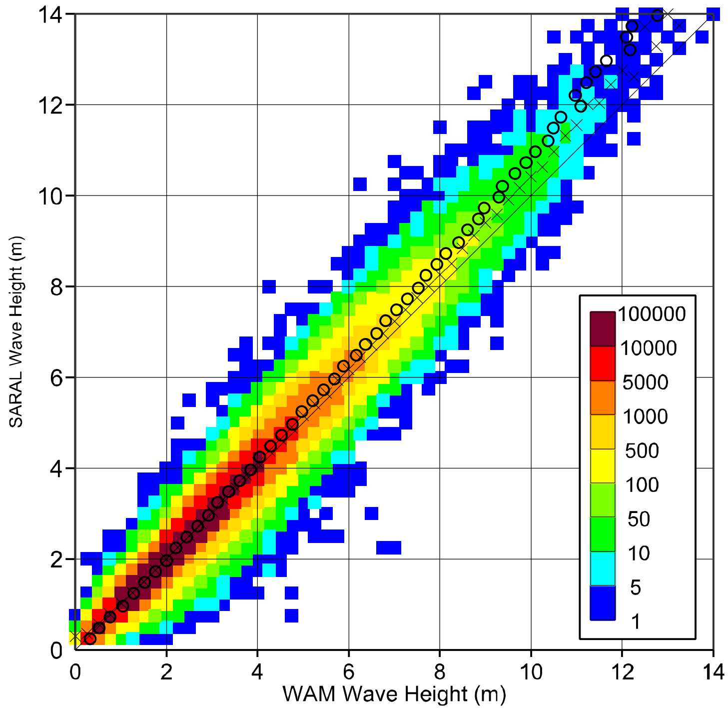


Figure 4: Comparison between SARAL SWH from one side and (a) all available in situ measurements (mainly in the NH) and (b) all model first guess values from the other side between 01 May 2013 and 30 April 2014. For the color-coding and the ñxò and ñoò symbols, refer to Figure 1.

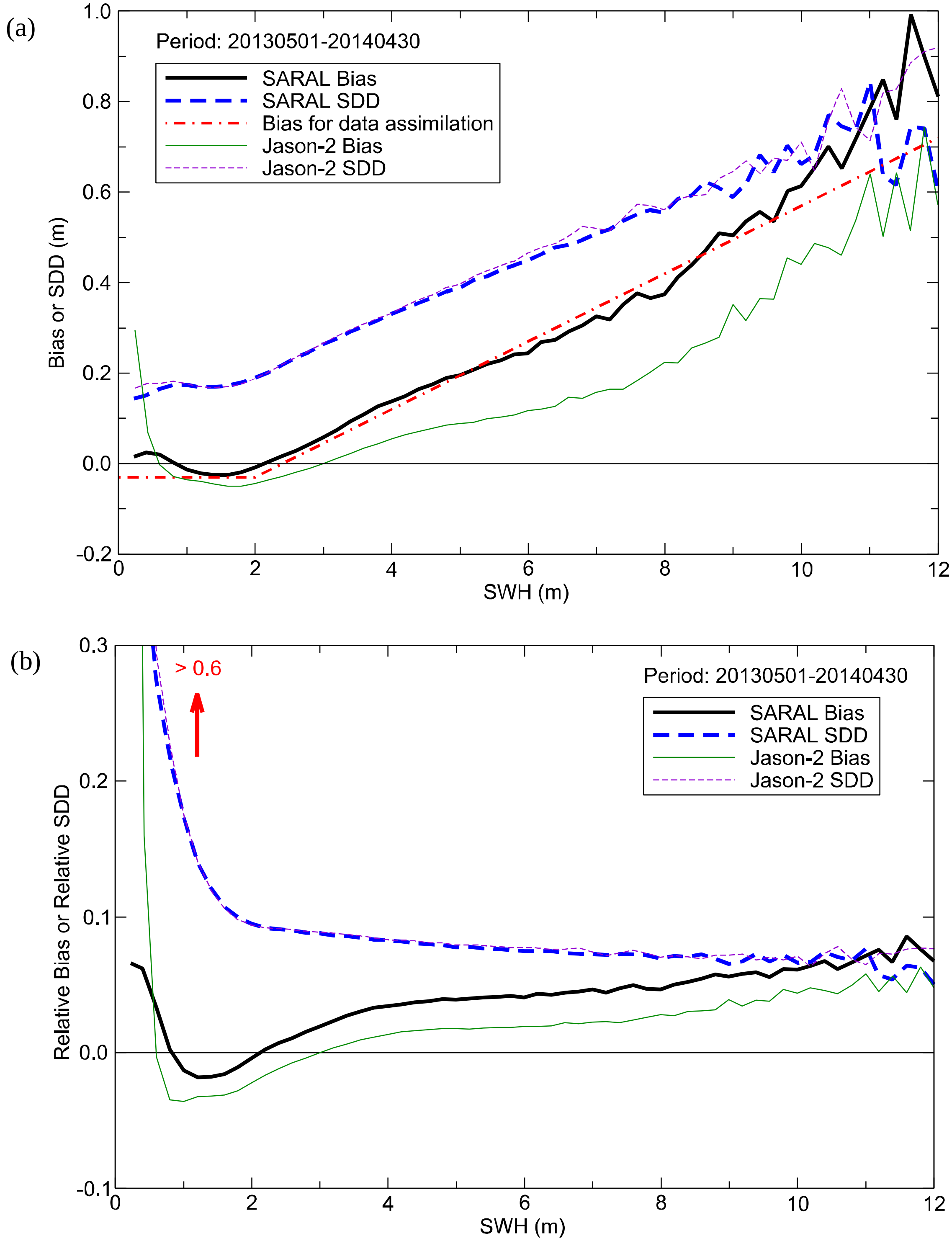

(a)
Period: 20130501-20140430
SARAL Bias
SARAL SDD
Bias for data assimilation
Jason-2 Bias
Jason-2 SDD
Bias or SDD (m)
SWH (m)
(b)
> 0.6
Period: 20130501-20140430
SARAL Bias
SARAL SDD
Jason-2 Bias
Jason-2 SDD
Relative Bias or Relative SDD
SWH (m)

Figure 5: Mean differences and SDD between SARAL and the wave model SWH as functions of SWH values. Both (a) absolute differences and (b) differences relative to SWH are shown.

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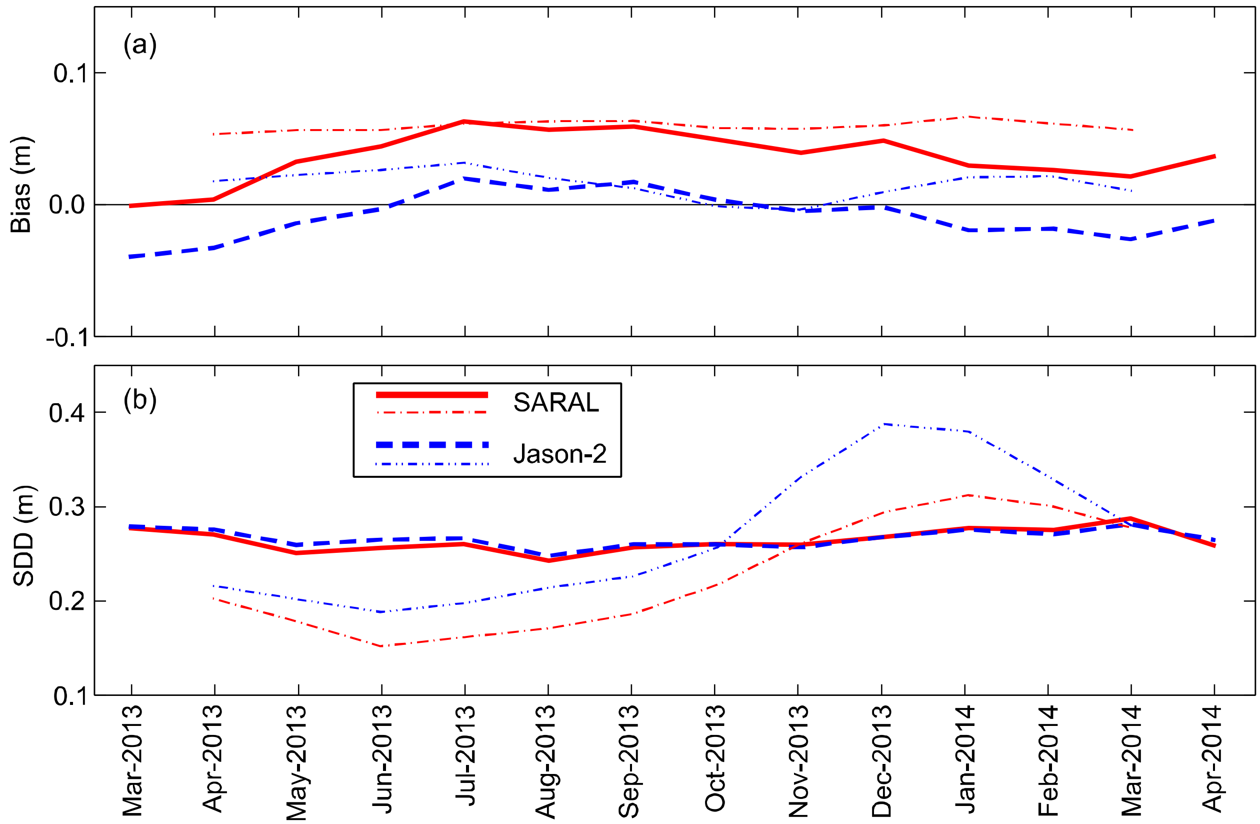
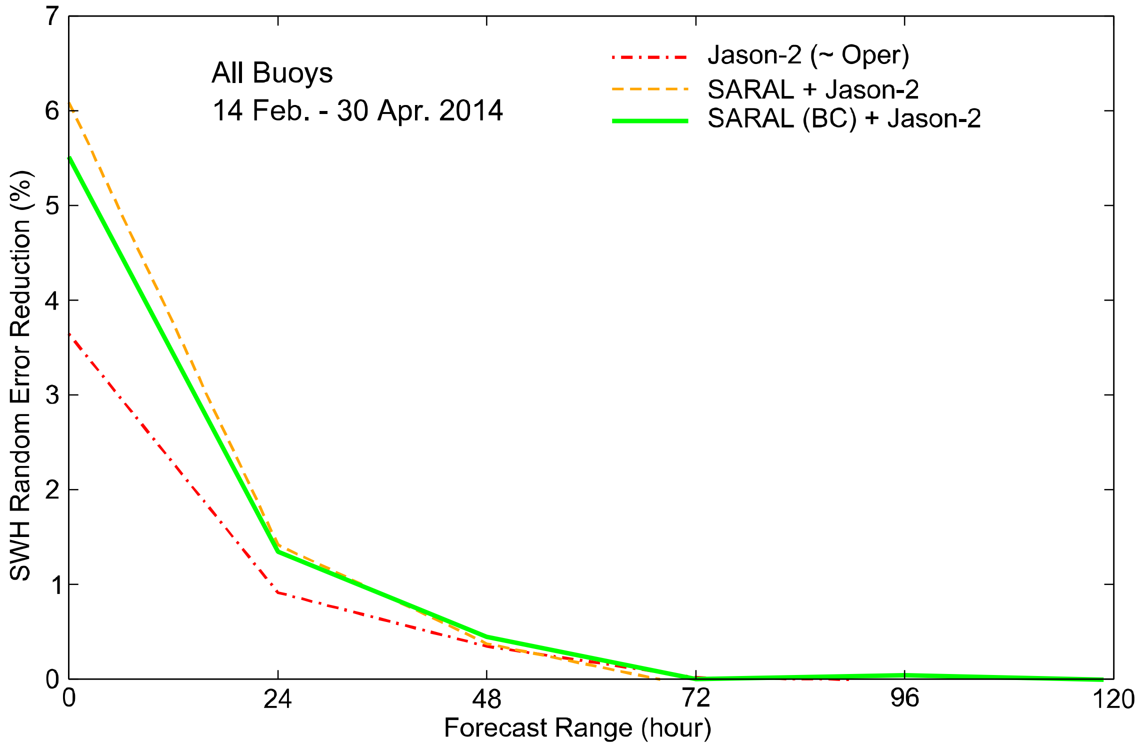


Figure 6: Time series of monthly (a) mean difference (bias) and (b) standard deviation of the difference (SDD) between altimeter (SARAL and Jason-2) SWH from one side and all available in situ measurements and all model first guess values from the other side. The in-situ curves (thin dash-dots) are running means over 3 months.

(a)


All Buoys
14 Feb. - 30 Apr. 2014
Jason-2 (~ Oper)
SARAL + Jason-2
SARAL (BC) + Jason-2
SWH Random Error Reduction (%)
Forecast Range (hour)
0
1
2
3
4
5
6
7
0
24
48
72
96
120

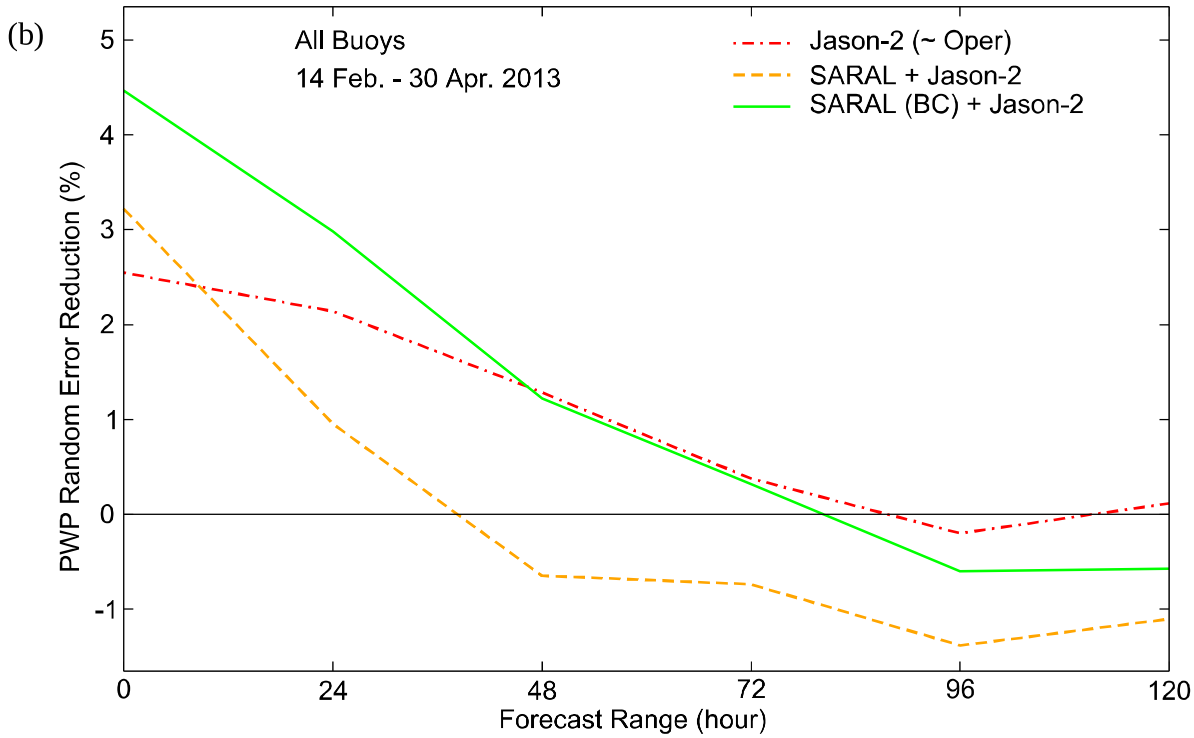


Figure 7: Impact of SARAL SWH assimilation on the model (a) SWH and (b) peak wave period (PWP) forecast during the period from 14 February to 30 April 2014 as verified against all available in-situ data. Forecast range of 0 hour represents the model analysis.

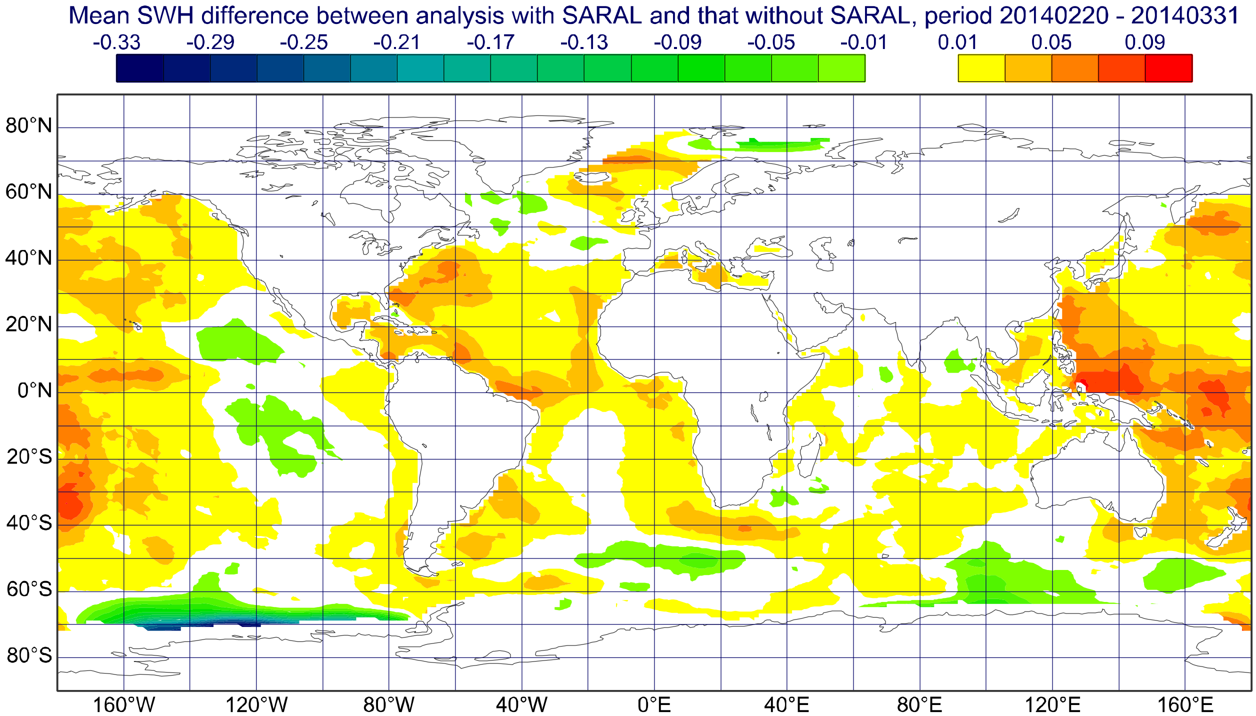


Figure 8: Mean SWH difference in model analysis due to assimilating bias-corrected SARAL SWH on top of Jason-2 SWH for the period 20 February - 31 March 2014. (Coupled wave-atmospheric model runs; grid spacing is 55 km)

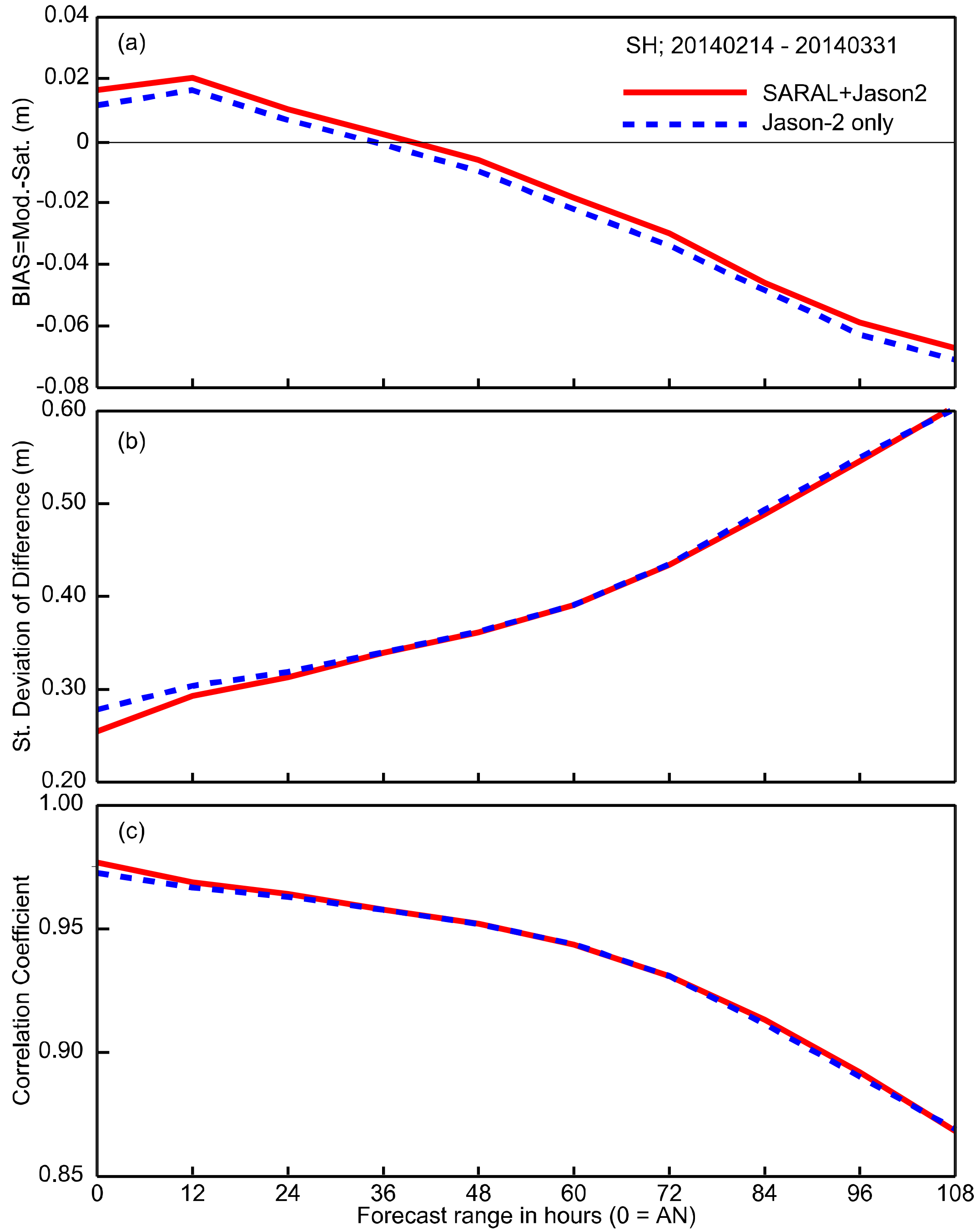


Figure 9: Impact of SARAL SWH assimilation as an addition to Jason-2 SWH (current operational system) on the model SWH forecast errors (a: bias, b: standard deviation of the

difference, and c: correlation coefficient) in the extra-tropical Southern Hemisphere (SH) compared to Cryosat-2 altimeter SWH for the period from 14 February to 31 March 2014.

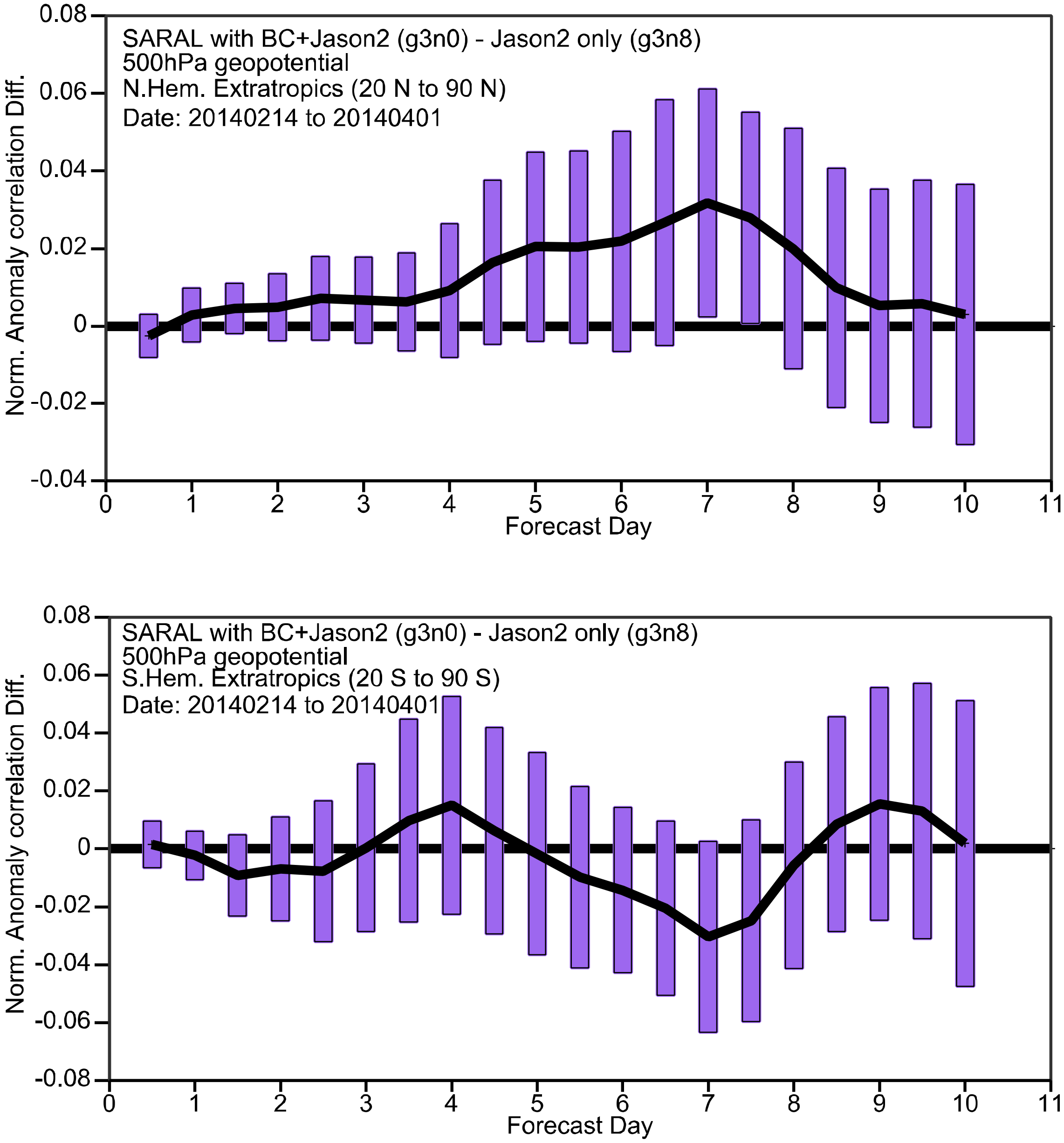


Figure 10: Mean impact of assimilating bias-corrected SARAL SWH in addition to Jason-2 SWH on the anomaly correlation of the model 500 hPa geopotential height forecast in (a) the

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Northern and (b) the Southern Hemispheres with respect to operational analysis for the period from 14 February to 1 April 2014. Vertical bars are the 95%-level of statistical significance.

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