PREPARATION AND OPERATIONS OF THE MISSION PERFORMANCE CENTRE (MPC) FOR THE COPERNICUS SENTINEL-3 MISSION

S3-A Wind & Wave Cyclic Performance Report

Cycle No. 022

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Version	Section	Answers to RID	Changes

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1 Summary

This is a cyclic report on the quality of wind and wave observations from the radar altimeter SRAL on-board Sentinel-3A and their timely availability for Cycle No. 022 (period from 04/09/2017 to **28/09/2017 which is 2 day short of the end of the cycle on 30/09/2017**). The product under consideration is the Level 2 Marine Ocean and Sea Ice Areas (SRAL-L2MA) also referred to as S3A_SR_2_WAT that is nominally distributed in near real time (NRT). This work covers the Cal/Val Task SRAL-L2MA-CV-230 (Wind, wave product validation vs models).

Radar backscatter (sigma0), surface wind speed (WS) and significant wave height (SWH) from product S3A_SR_2_WAT are monitored and validated using the procedure used successfully for the validation of the equivalent products from earlier altimeters. The procedure is described in Appendix A. The procedure composed of a set of self-consistency checks and comparisons against other sources of data. Model equivalent products from the ECMWF Integrated Forecasting System (IFS) and in-situ measurements available in NRT through the Global Telecommunication System (GTS) are used for the validation.

2 Events

The major changes and events that may had impact on the results of the validation of Sentinel-3 wind and wave products presented in this report are listed below (items in **bold are satellite related**):

- **16 February 2016**: **Launch of Sentinel-3A**

- 08 Mar 2016: Model change to CY41R2. The main change is the implementation of the new 9-km cubic octahedral grid ($T_{CO}1279$) for the high resolution configuration of IFS.

- **09 April 2016**: **Switch SRAL to LRM Mode**

- **12 April 2016**: **Switch SRAL back to SAR Mode**

- **14 October 2016**: **Implementation of SRAL processing chain IPF-SM-2 version 06.03**

- **17 November 2016**: **Implementation of SRAL processing baseline (PB) 2.9 which includes processing chain IPF versions 06.07 and 06.05 for Level-1 and Level-2, respectively.**

- 22 November 2016: ECMWF model changed to CY43R1. This change has almost no impact on the products assessed here.

- **29 November 2016**: **ADF SR_2_CON_AX (SM-2) Ver. 006: SAR Sigma0 increased by 0.35 dB and PLRM Sigma0 increased by 0.1 dB.**

- **05 December 2016**: **Implementation of further changes to the processing chain "SRAL/MWR L2 IPF (SM-2) Ver. 06.05"**

- **12 January 2017** **Implementation of Level-1 IPF version 06.09.**

- **28 February 2017** **Implementation of PB 2.10 which includes: Level-1 IPF version 06.10, MWR IPF version 06.03 and Level-2 IPF version 06.06. Updated calibrations were introduced.**

- **12 April 2017**   **Implementation of PB 2.12 which includes Level-1 IPF version 06.11 and Level-2 IPF version 06.07. The change targeted the generation of Level-1b-S products with no impact on Level-2 products.**

- 11 July 2017   ECMWF model changed to CY43R1. This change has almost no impact on the products assessed here. However, it impacted the corrections computed from the model fields like dry and wet tropospheric corrections.

All ECMWF Integrated Forecast System (IFS) model changes are summarised at:
http://www.ecmwf.int/en/forecasts/documentation-and-support/changes-ecmwf-model

3 Data Processing

The validation is based on the NRT operational Sentinel-3A Surface Topography Mission Level 2 (S3-A STM L2) wind and wave marine products (S3A_SR_2_WAT) product. For the time being, the product distributed by EUMETSAT in netCDF through their Online Data Access (ODA) system is used after converting into ASCII format but this will be replaced by the formal BUFR (Binary Universal Form for the Representation of meteorological data) format whenever becomes available. The raw data product is collected for 6-hourly time windows centred at synoptic times (00, 06, 12 and 18 UTC).

The data are 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 the model scale is typically several (4~8) model grid spacing (e.g. Abdalla et al., 2013). This corresponds to 11 individual (1 Hz) Sentinel-3 observations (7 km each).

To achieve this, the stream of altimeter data is split into short observation sequences each consisting of 11 individual (1-Hz) observations. A quality control procedure is performed on each short sequence. Erratic and suspicious individual observations are removed and the remaining data in each sequence are averaged to form a representative super-observation, providing that the sequence has enough number of "good" individual observations (at least 7). The super-observations are collocated with the model and the in-situ (if applicable) data. The raw altimeter data that pass the quality control and the collocated model data are then investigated to derive the conclusions regarding the data quality. The details of the method used for data processing, which is an extension to the method used for ERS-2 RA analysis and described in Abdalla and Hersbach (2004), are presented in Appendix A.

The data are closely monitored and verified using the ECMWF IFS model products. Similar products from other altimeter missions are also used for verification. 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 plots summarising the quality of Sentinel-3 products for that week or month are also produced, examined and archived for future reference.

This specific report gives the assessment of Level 2 S3A_SR_2_WAT wind and wave products made available by ESA/EUMETSAT through EUMETSAT ODA System covering Cycle No. 022 (from 04/09/2017 to **28/09/2017 which is 2 day short of the end of the cycle on 30/09/2017**).

4 Radar Backscatter and Surface Wind Speed

4.1 Backscatter

Backscatter coefficient (σ° or Sigma-0) from Sentinel-3A S3A_SR_2_WAT product seems to be reasonable and compares well with that from other altimeters. The backscatter global histogram (or the probability density function, PDF) of Sentinel-3A SRAL for the whole of Cycle 022 (except the last two days) is shown in Figure 1. The shape of the PDF for this cycle is similar to that of all previous cycles since Cycle 012. Sentinel-3 PDF compares quite well with those of other altimeters (after adjusting Jason-2/3 by about 2.5 dB; not shown).

The time series of the global (ice-free ocean only) mean and standard deviation (SD) of backscatter coefficients from SRAL of Sentinel-3A are shown in Figure 2. The temporal change in the mean and the SD of backscatter is not much different than the other altimeters (not shown). The plot shows the average of a moving window of 7 days moved by one day at a time to produce smooth plots. Both the mean and the SD of the backscatter are stable over the last few cycles.
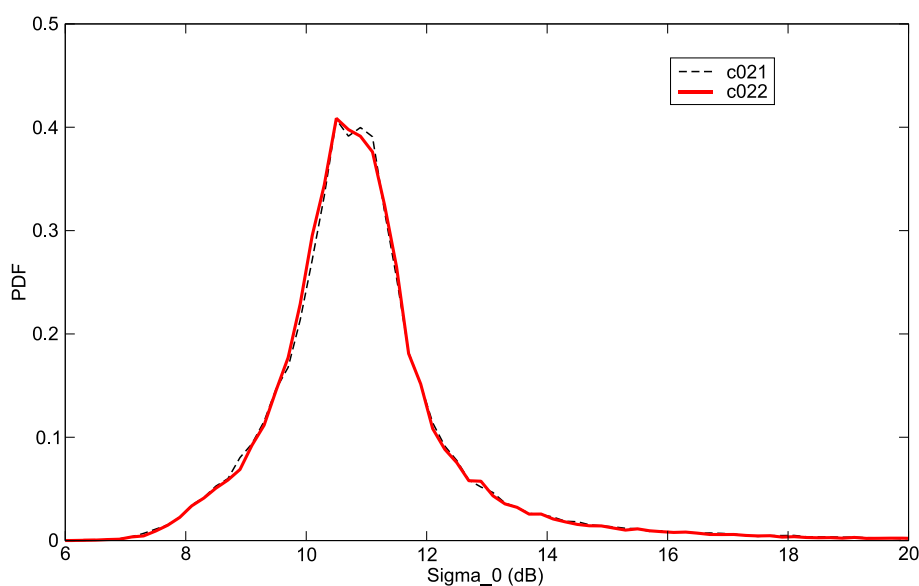
Figure 1: Sentinel-3A SRAL ocean Ku-band backscatter histogram (PDF) over the whole globe and for the period of Cycle 022. For comparison, the same plot from the previous cycle is shown as dashed black line.

4.2 SAR Mode Surface Wind Speed

Figure 3 shows the global SAR wind speed PDF of Sentinel-3A for Cycle 022. The PDF of the previous cycle is shown for comparison. The PDF's of the ECMWF Integrated Forecast System (IFS) model wind speed collocated with Sentinel-3 during the two cycles are also shown. It is clear that the PDF of Sentinel-3 wind speed is close to that of the model as well as the other altimeters (not shown). However, there are some deviations mainly around the peak of the PDF.
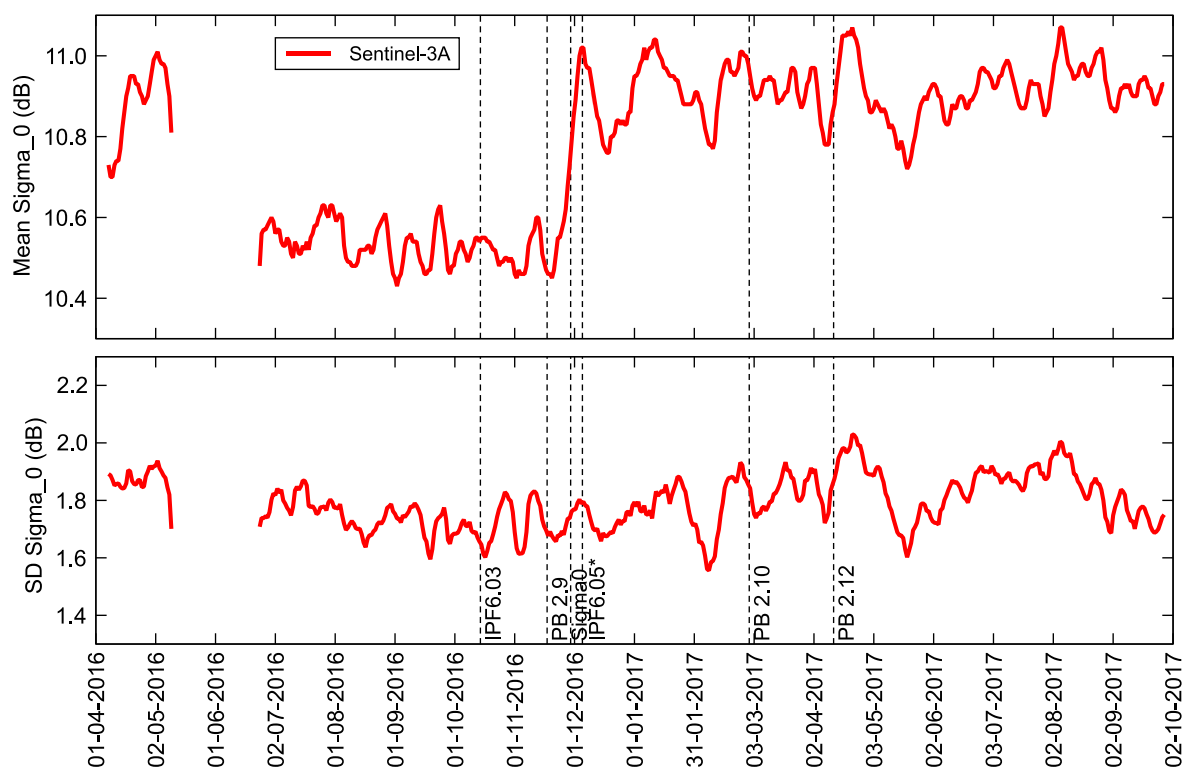
Figure 2: Time series of global mean (top) and standard deviation (bottom) of backscatter coefficient of SRAL Ku-band after quality control. Mean and SD are computed over a moving time window of 7 days.

Collocated pairs of altimeter super-observation and the analysed (AN) ECMWF model wind speeds are plotted in a form of a density scatter plot in Figure 4 for the whole global ocean over the whole Cycle 022 (except the last two days). The scatter plots in Figure 4 and other similar wind speed scatter plots that appear hereafter represent two-dimensional (2-D) histograms showing the number of observations in each 2-D bin of 0.5 m/s × 0.5 m/s of wind speed. It is clear that the agreement between Sentinel-3 winds and their model counterpart is very good with virtually no bias (except for slight bias at high wind speed values). Sentinel-3A wind speed is as good as that of the other altimeters. The standard deviation of the difference (SDD) with respect to the model, which can be used as a proxy for the random error, is less than 1.1 m/s (about 14% of the mean) which is similar to that of other altimeters. The other fitting statistics are shown in the offset of Figure 4. The scatter plots for Sentinel-3 versus the model collocations discriminated based on their geographical locations whether in the Northern Hemisphere (north of latitude 20°N; NH), the Tropics (between latitudes 20°S and 20°N) or the Southern Hemisphere (south of latitude 20°S; SH) are shown in panels (a), (b) and (c) of Figure 5, respectively. **The contradicting bias behaviour of SRAL SAR mode compared to the model within the range from 7 to 15 m/s in the last few cycles before Cycle 017 (slight overestimation in NH versus slight underestimation in the SH) seems to be reversed during the last few cycles with an evident underestimation in the NH**

but not as evident increase in the SH. This reversed behaviour is a strong indication of a seasonal signal. Further monitoring during the coming cycles is still needed to confirm this observation.
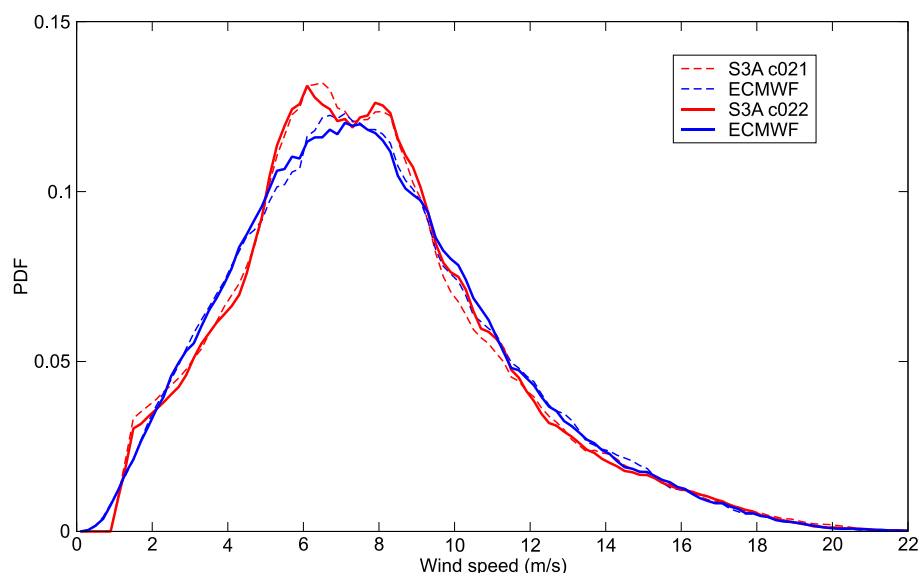
Figure 3: Sentinel-3A SRAL SAR surface wind speed PDF over the whole global ocean and for the period of Cycle 022. The corresponding ECMWF (collocated with Sentinel-3) PDF is also shown for comparison. The corresponding PDF's (SRAL and model) from the previous cycle are also shown as dashed lines.
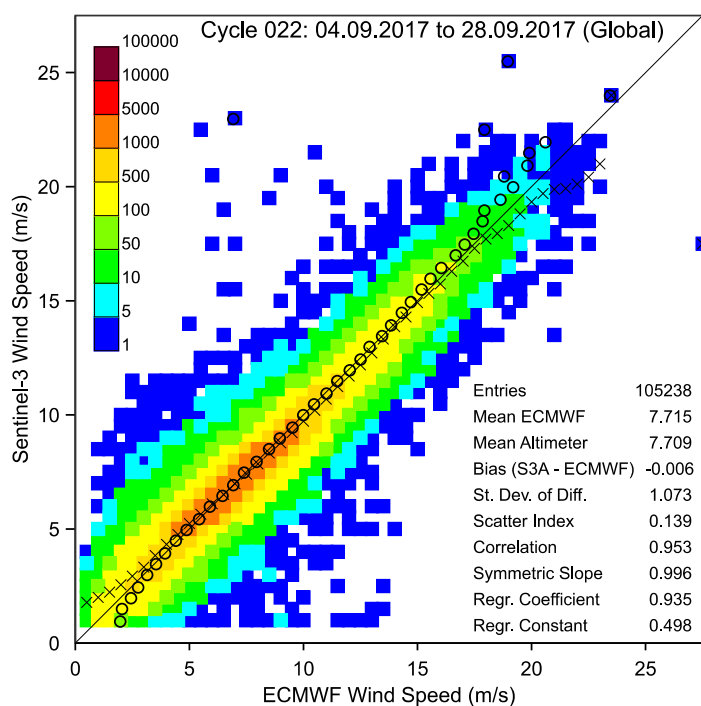
Figure 4: Global comparison between Sentinel-3A SRAL and ECMWF model analysis surface wind speed values over the period of Cycle 022. The number of collocations in each 0.5 m/s x 0.5 m/s 2D bin is color-coded as in the legend. The "x" symbols are the means of the bins for given x-axis values (model) while the "o" symbols are the means for given y-axis values (Sentinel-3).
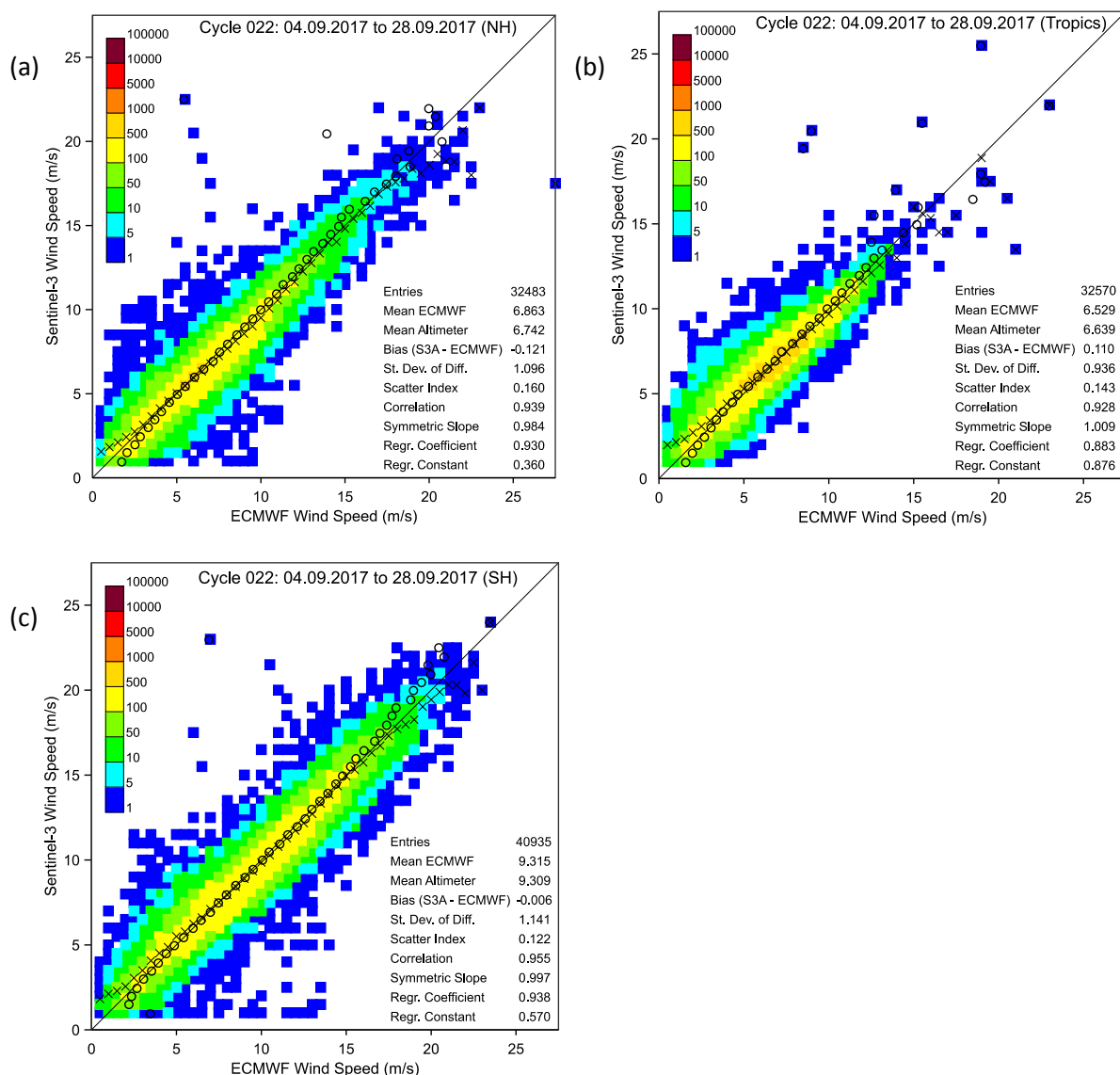
Figure 5: Same as Figure 4 but for Northern Hemisphere (latitudes to the north of 20° N), Tropics (latitudes between 20° S and 20° N) and Southern Hemisphere (latitudes to the south of 20° S), respectively.

The time series of the global mean and standard deviation (SD) of the wind speed from Sentinel-3 over a 7-day time window moving by 1 day at a time are shown in the upper and lower panels, respectively, of Figure 6. The corresponding time series of the model are also shown for comparison. It is clear that since early December 2016 Sentinel-3 mean wind speed is very close to that of the model. The global standard deviation of the altimeter measurements was almost the same as that of the model for a period of two months. However, **between early February and early July 2017 and the last two weeks of September 2017 the standard deviation of the altimeter measurements was slightly lower than that of the model. This could not be correlated to any of the processing or model changes (see Section 2). During the period from early July till mid-September 2017, the global standard deviations of the altimeter and the model winds are almost equal with a tendency for the model values to be lower than those of SRAL. The last two weeks witnessed higher SRAL SD values again.** This will be kept under monitoring and investigation during the coming few cycles.
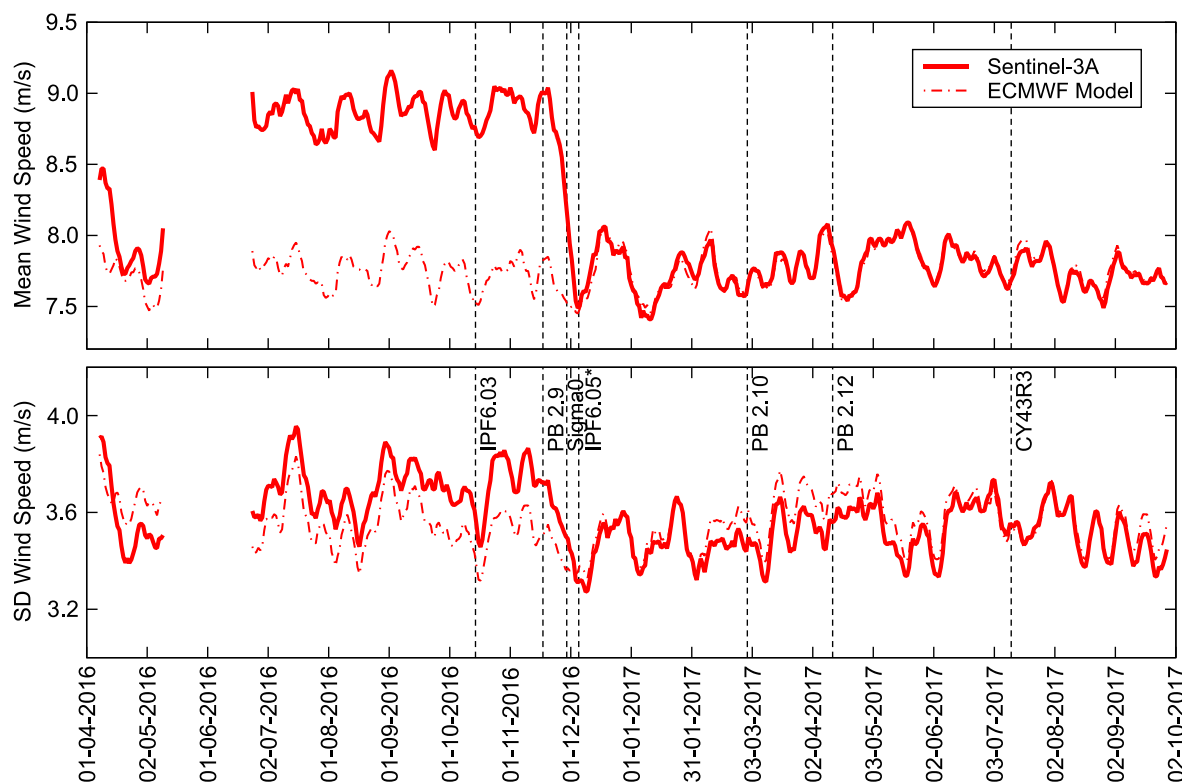
Figure 6: Time series of global mean (top) and standard deviation (bottom) of wind speed from SRAL Ku-band after quality control. The collocated model wind speed mean and SD are also shown. Mean and SD are computed over a moving time window of 7 days.

The time series of the wind speed weekly bias (defined as the altimeter – model) and standard deviation of the difference (SDD) of SRAL compared to the ECMWF model AN are shown in the upper and lower panels, respectively, of Figure 7. Before the end of November 2016, the global wind speed bias was stable at about 1 m/s. The impact of IPF change (change of sigma_0 as part of PB 2.9) in late November is very evident in Figure 7. The bias in all areas collapsed to very small values (well within ±0.4 m/s). **There are signs of bias seasonality in each hemisphere as their bias curves (with respect to the model) changed sign towards the end of April 2017 (became negative in the NH and positive in the SH).**

Until the middle of December 2016 (start of implementation of PB 2.9), the wind speed SDD values were rather high compared to those of other altimeters (Sentinel-3 SDD of 1.2-1.3 m/s versus 1.0-1.2 m/s for the other altimeters). The values decreased with the implementation of PB 2.9 and the increase of backscatter value and apparently they are now in line with other altimeters. **The SDD seems to follow a seasonal cycle in the NH and the SH as well.**

Figure 6 and Figure 7 do not show any impact as a result of implementation of PB 2.10 which was introduced on 28 February 2017. However, the positive impact is clear when the SDD between SRAL and ECMWF model is compared to SDD values of other altimeters. This is well demonstrated in Figure 20 in Appendix B.

Figure 7: Time series of weekly wind speed bias defined as altimeter - model (top) and standard deviation of the difference (bottom) between SRAL Ku-band and ECMWF model analysis.

The geographical distribution of the mean Sentinel-3 wind speed and the wind speed bias, SDD and scatter index (SI, defined as the SDD divided by the model mean and expressed in percentage in the last panel) with respect to the ECMWF model averaged over the period of Cycle 022 are shown in Figure 8. While the mean wind speed, the SDD and SI distributions all look similar to their counterparts from other altimeters (not shown), the bias in panel (b) is rather low almost everywhere.

The comparison against in-situ (mainly buoys located in the Northern Hemisphere around the American and European coasts) measurements is shown in Figure 9. The overall bias against in-situ observation for this cycle is rather small (~ 0.2 m/s). The SDD (a proxy to the random error) is about 1.33 m/s which is ~18% of the mean. These figures are comparable to same statistics emerging from the comparison of other altimeters against in-situ observations (not shown). **Within the scatter, it is possible to notice that SRAL underestimates wind speeds above 7 m/s compared to the in-situ measurements. This is consistent with the model comparison in the NH (Figure 5a).**

(a)

Satellite: Sentinel-3
Sat. Mean Wind Speed [m/s]
For period between 21:00:05UTC on 03.09.2017 and 08:47:16UTC on 28.09.2017

(b)

Satellite: Sentinel-3
Wind Speed Bias (Sat-Mod) [m/s]
For period between 21:00:05UTC on 03.09.2017 and 08:47:16UTC on 28.09.2017
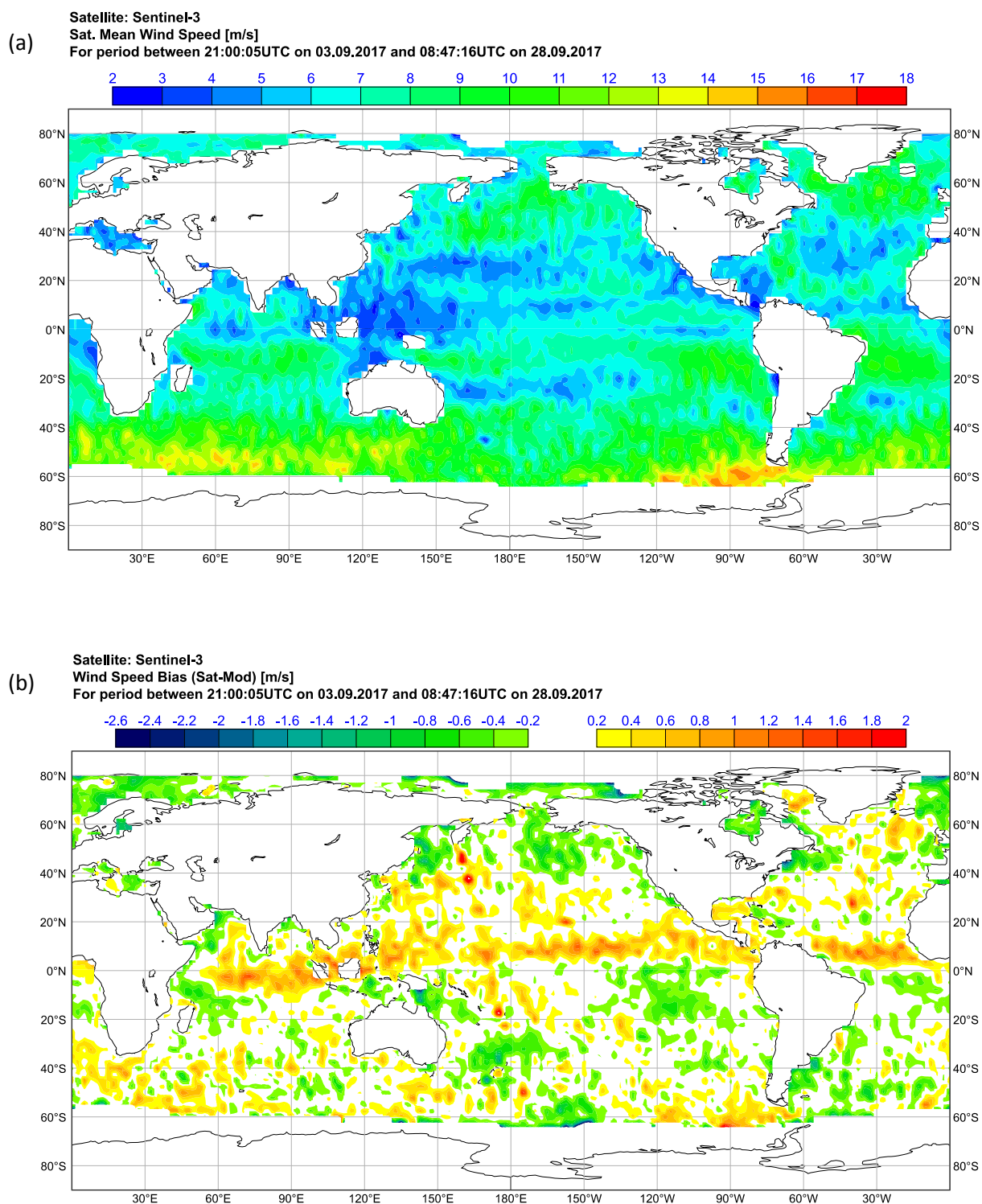
Figure 8: Geographical distribution of mean Sentinel-3 wind speed (a) as well as the bias (b); the SDD (c) and the SI (d) between Sentinel-3 and ECMWF model AN during Cycle 022. Bias is defined as altimeter – model.

(c)

Satellite: Sentinel-3
Wind Speed SDD (Sat-Mod) [m/s]
For period between 21:00:05UTC on 03.09.2017 and 08:47:16UTC on 28.09.2017

(d)

Satellite: Sentinel-3
Wind Speed SI (Sat-Mod) [%]
For period between 21:00:05UTC on 03.09.2017 and 08:47:16UTC on 28.09.2017
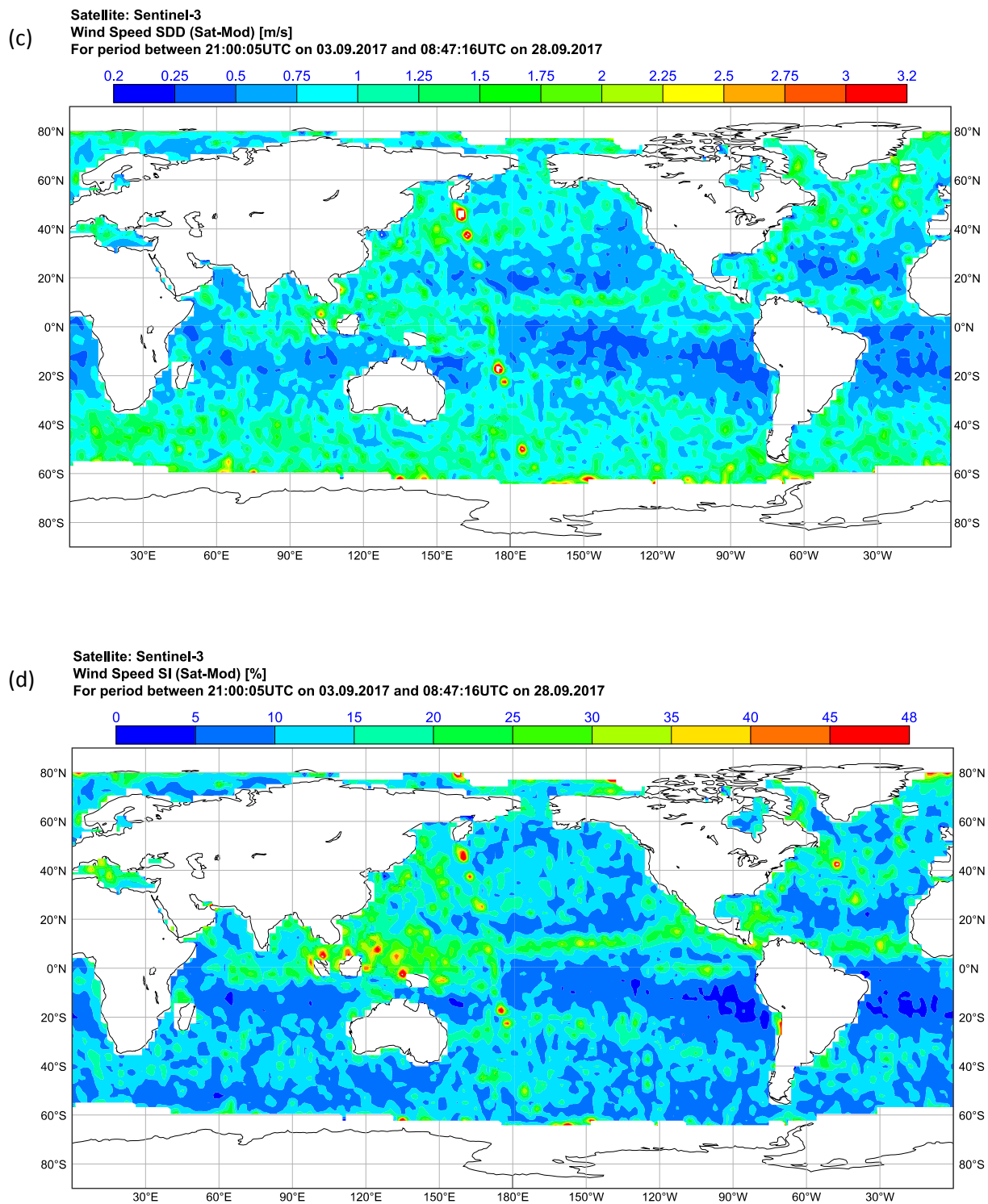
Figure 8: Continued.
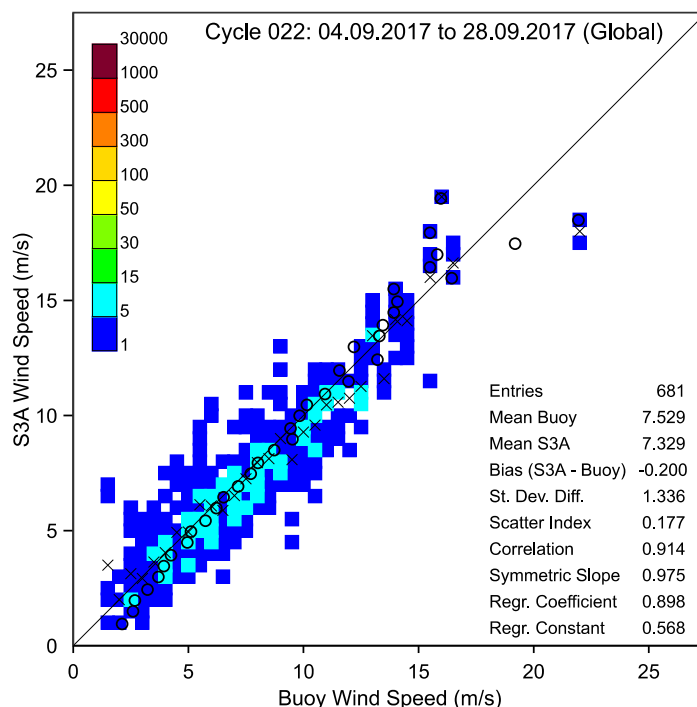
Figure 9: Same as Figure 4 but the comparison is done against in-situ observations (mainly in the NH).

4.3 PLRM Surface Wind Speed

Collocated pairs of SRAL Pseudo Low Rate Mode (PLRM) wind speed super-observation and the analysed (AN) ECMWF model wind speeds are plotted in a form of a density scatter plot in Figure 10 for the whole globe over the whole of Cycle 022 (except for the last two days). It is clear that the agreement between PLRM winds and their model counterpart is fairly good. The significant improvement noticed for Cycle 012 and lost during Cycle 013 was recovered during the last few cycles but with a noticeable minor degradation during the last three cycles. In order to remove the distraction of the obviously wrong outliers which could not be filtered out, those outliers where removed using the deviation from the model. The statistics, and in particular SDD and scatter index, are different from previous reports. The PLRM is still globally unbiased when compared to the model. The scatter plots for Sentinel-3 versus the model collocations discriminated based on their geographical locations whether they are in the Northern Hemisphere (north of latitude 20°N), the Tropics (between latitudes 20°S and 20°N) or the Southern Hemisphere (south of latitude 20°S) are shown in Figure 11. Note that the zero-valued PLRM wind speeds (see, for example, the cyclic report of Cycle 012) were eliminated from Figure 10 and Figure 11. **There are signs of bias seasonality in both hemispheres as was noticed for the SAR wind speed.**

The time series of the weekly bias and the SDD between PLRM wind speed and that of the model are shown in Figure 12. It is clear that there was a change in the PLRM wind speed statistics in the middle of November 2016 coinciding with the start of implementation of PB 2.9. This change, which is associated by an increase of PLRM backscatter, resulted in almost zero bias between the altimeter and the model.

The SDD between SRAL and the model has plateaued at about 1.2-1.3 m/s. However, there was some instants with high SDD values that exceeded 1.4 m/s during the last few cycles.
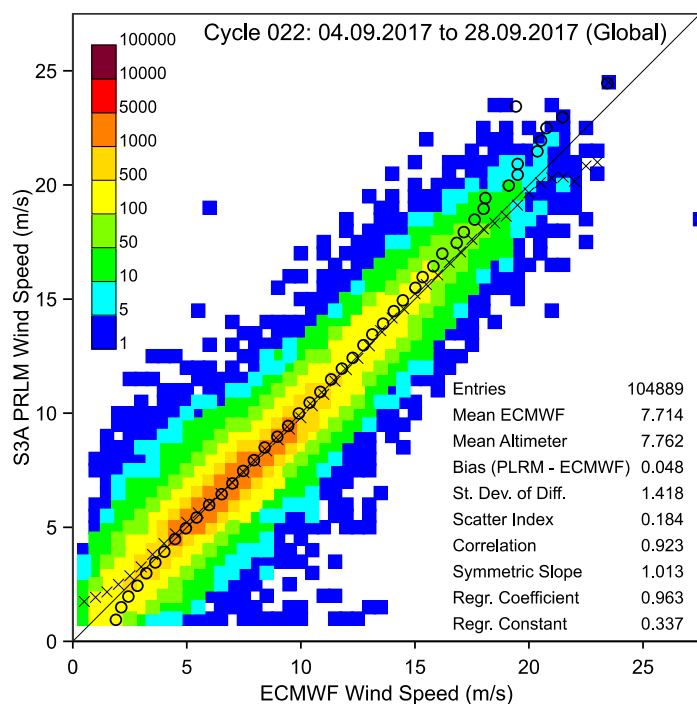
Figure 10: Global comparison between Sentinel-3A PLRM and ECMWF model analysis wind speed values over the period of Cycle 022. Refer to Figure 4 for the meaning of the "x" and "o" symbols as well as the colour coding.

Figure 11: Same as Figure 10 but for (a) Northern Hemisphere (latitudes to the north of 20° N), (b) Tropics (latitudes between 20°S and 20°N) and (c) Southern Hemisphere (latitudes to the south of 20°S), respectively.
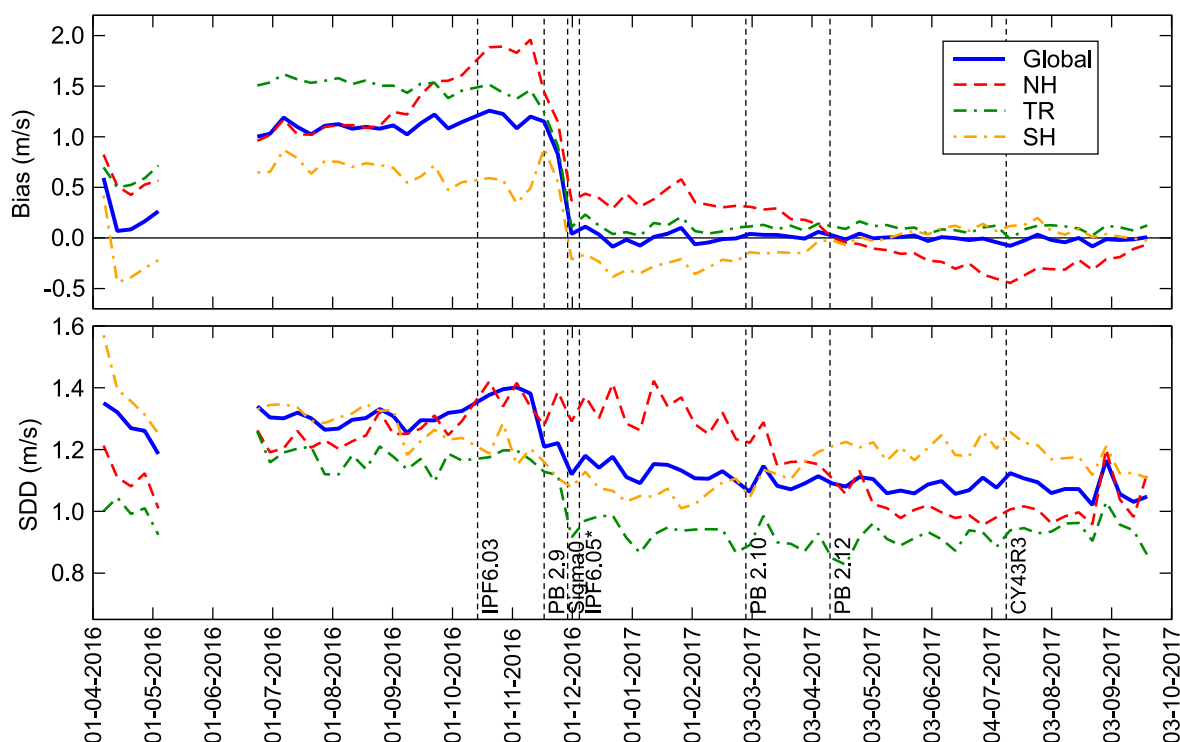
(c)

Figure 11 Continued.
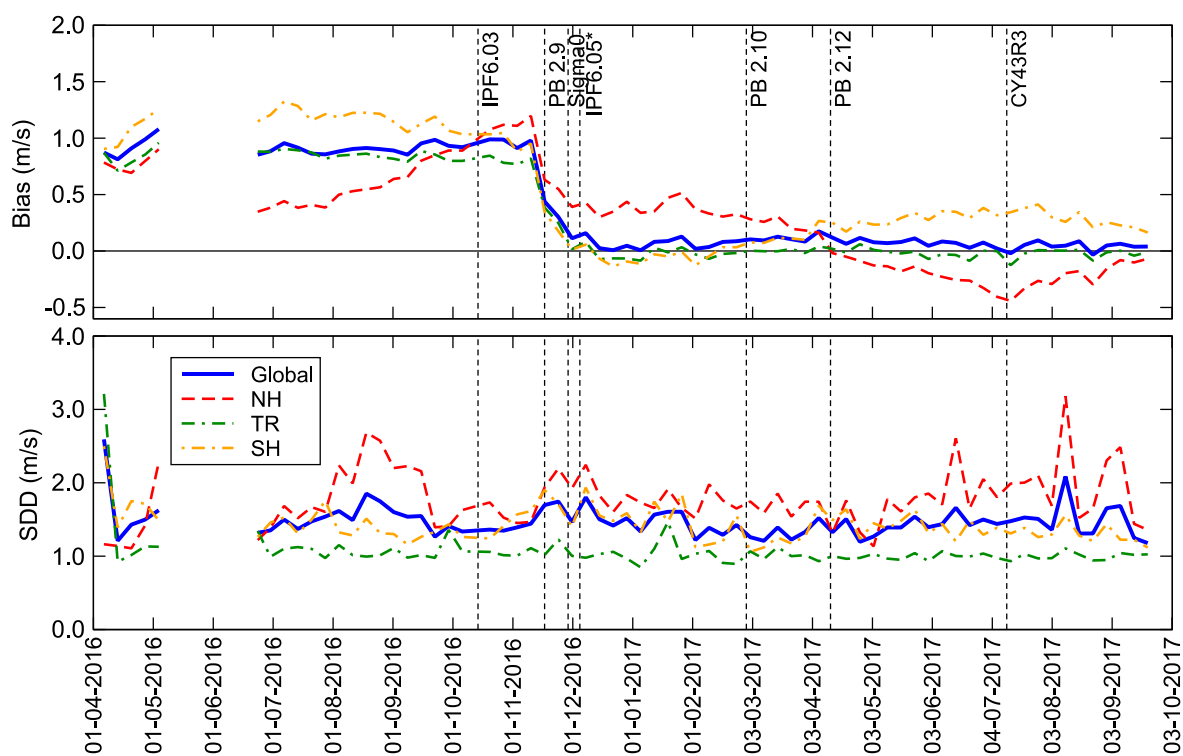
Figure 12: Time series of weekly PLRM wind speed bias defined as altimeter - model (top) and standard deviation of the difference (bottom) between SRAL PLRM and ECMWF model analysis.

5 Significant Wave Height

Altimeter significant wave height (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. At the time of writing, the altimeter SWH from Cryosat-2, Jason-2, and SARAL/AltiKa are assimilated in the ECMWF model. Therefore, the model first-guess (which is practically a short model forecast) is used for the verification to reduce the impact of error correlation between the model and Sentinel-3 SRAL that may be conveyed through sharing the same principle of measurement with the altimeters whose SWH products are being assimilated.

Figure 13 shows the global SWH PDF of Sentinel-3A for the period of Cycle 022. The PDF of the previous cycle is shown for comparison. The PDF's of the ECMWF Integrated Forecast System (IFS) model SWH collocated with Sentinel-3 during the two cycles are also shown. It is clear that PDF of Sentinel-3 SWH deviates slightly from that of the model as well as those of other altimeters (not shown). Although, the IPF changes in late November and early December 2016 (PB 2.9) improved the agreement between the PDF's from Sentinel-3 and the model, there still some differences especially around the peak of the PDF (~ 2 m).
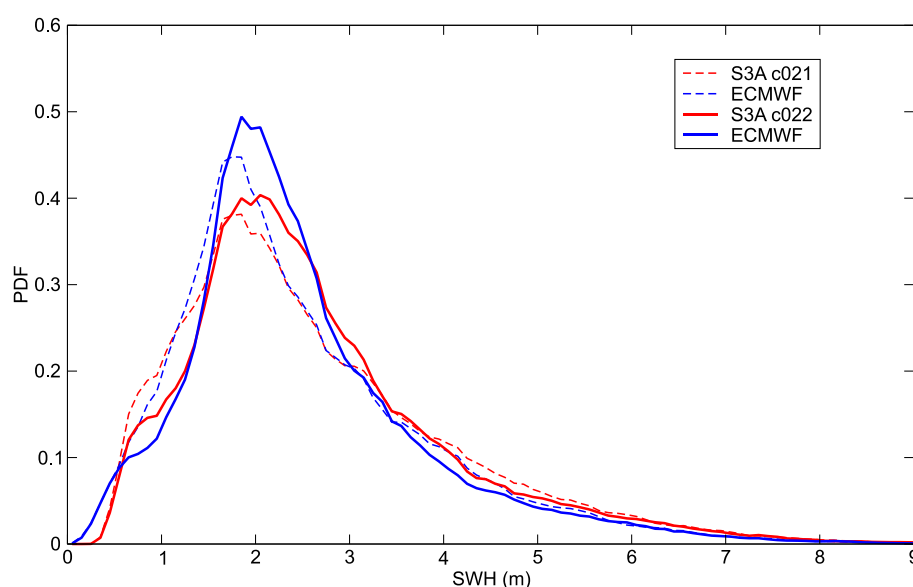
Figure 13: Sentinel-3A SRAL SWH PDF over the whole global ocean and for the period of Cycle 022. The corresponding ECMWF (collocated with Sentinel-3) PDF is also shown for comparison. The corresponding PDF's from the previous cycle are also shown as thin dashed lines.

Collocated pairs of altimeter super-observation and the ECMWF model SWH FG are plotted in a form of a density scatter plot in Figure 14 for the whole globe over the whole period of Cycle 022 (except for the last two days). The SWH scatter plots (Figure 14 and later) are plotted similar to those of wind speed (e.g. Figure 4) except for the size of the 2-D bin which is 0.25 m × 0.25 m in the case of SWH. It is clear from Figure 14 that the agreement between Sentinel-3 SWH and its model counterpart is very good

except for a slight overestimation at moderate to high SWH's (above ~4 m). This suggests that although Sentinel-3 provides practically very good SWH product, **it is still in need of fine tuning at SWH values above ~4 m**.

The scatter plots for Sentinel-3 versus the model collocations discriminated based on their geographical locations whether in the Northern hemisphere (north of latitude 20°N), the Tropics (between latitudes 20°S and 20°N) or the Southern hemisphere (south of latitude 20°S) are shown in Figure 15. The slight overestimation at higher wave heights can be clearly seen at all hemispheres (although not many SWH observations exceeding 4 m in the Tropics).

The time series of the global mean and standard deviation (SD) of the SWH from Sentinel-3 averaged over a 7-day time window moved by 1 day at a time are shown in the upper and lower panels, respectively, of Figure 16. The corresponding time series of the model as collocated with Sentinel-3 are also shown for comparison. Sentinel-3 mean and standard deviation are not much different than those of the model (and the other altimeters). The slightly higher Sentinel-3 SWH standard deviation than the model and the other altimeters (not shown) can be thought of as a result of the fact that SAR mode has higher resolution compared to the conventional altimetry (LRM). However, at the scale of the super-observations (~75 km), this cannot be correct. Therefore, this enhanced Sentinel-3 SWH variability needs to be monitored closely to see if SWH fine tuning is needed to compensate for this enhanced variability. Figure 16 suggests that the SRAL SWH statistics compared to the model have changed in mid-November 2016 (start of the implementation of PB 2.9). Sentinel-3 SWH mean value started to be higher than that of the model.
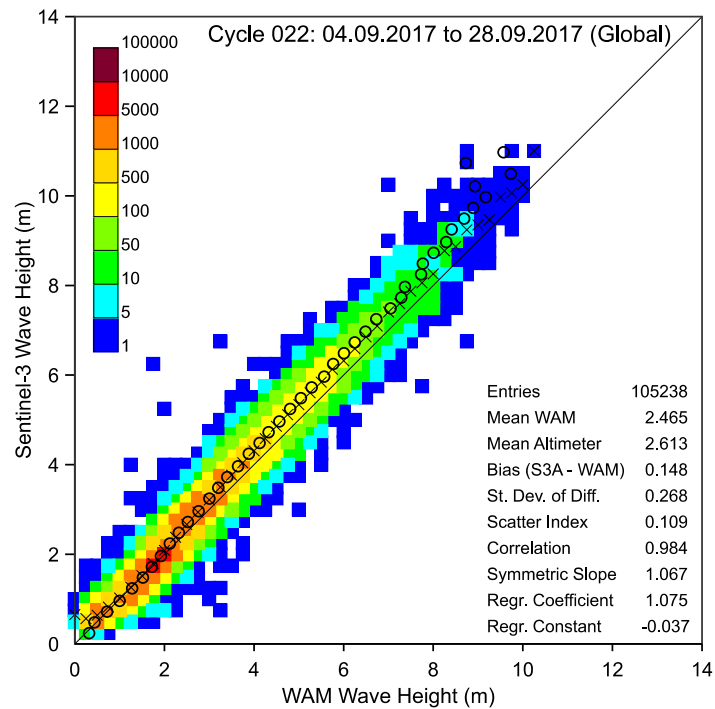
Figure 14: Global comparison between Sentinel-3A and ECMWF model first-guess significant wave height values over the period of Cycle 022. The number of colocations in each 0.25 m x 0.25 m 2D bin is coded as in the legend. Refer to Figure 4 for the meaning of the "x" and "o" symbols.
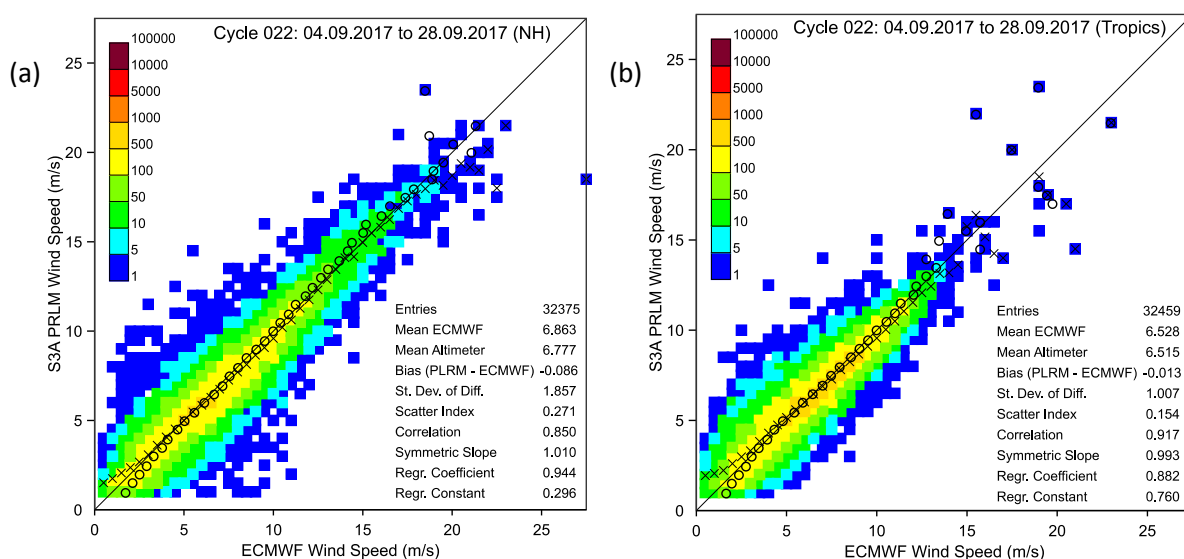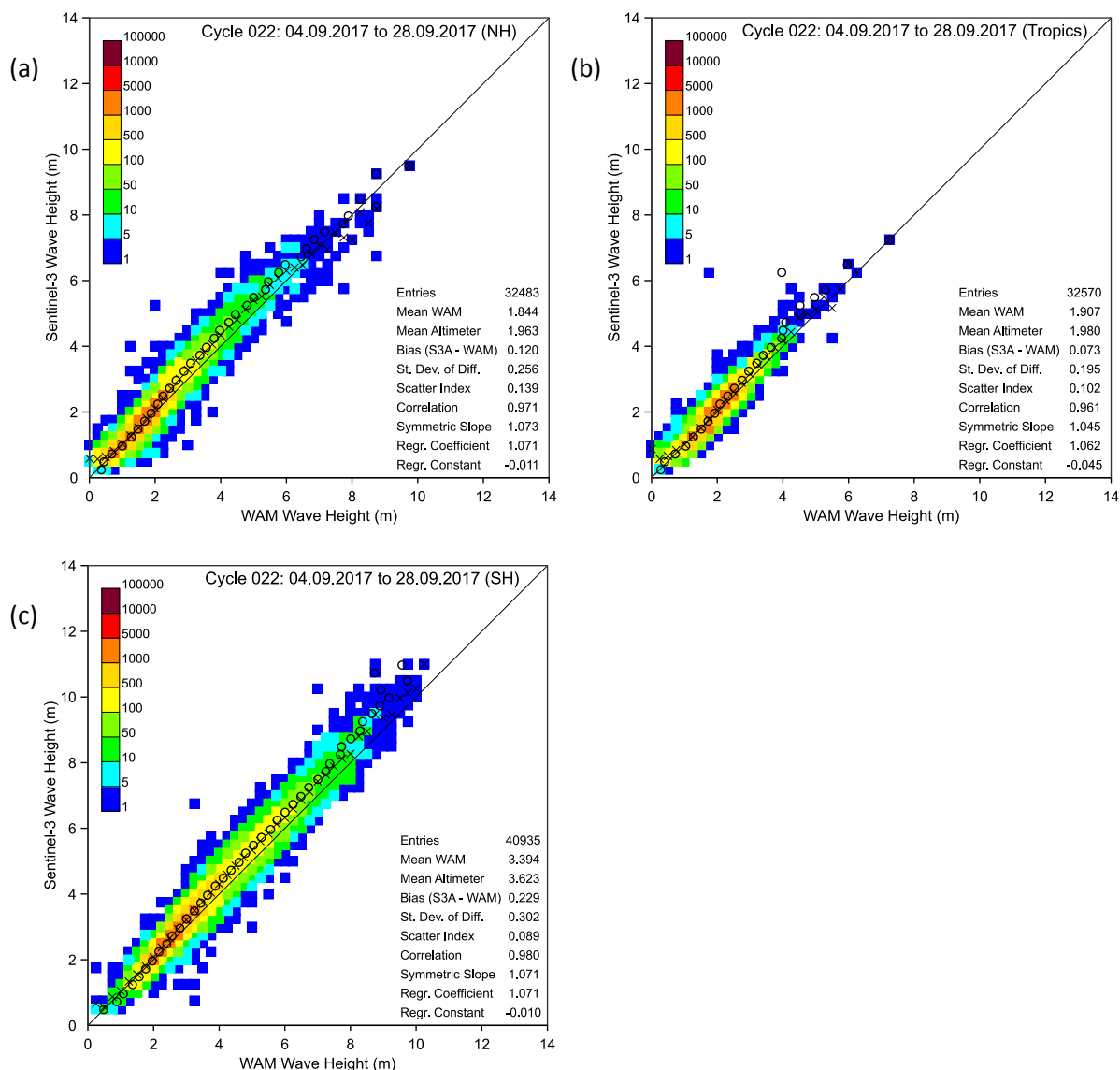
Figure 15: Same as Figure 14 but for Northern Hemisphere (latitudes to the north of 20°N), Tropics (latitudes between 20°S and 20°N) and Southern Hemisphere (latitudes to the south of 20°S), respectively.
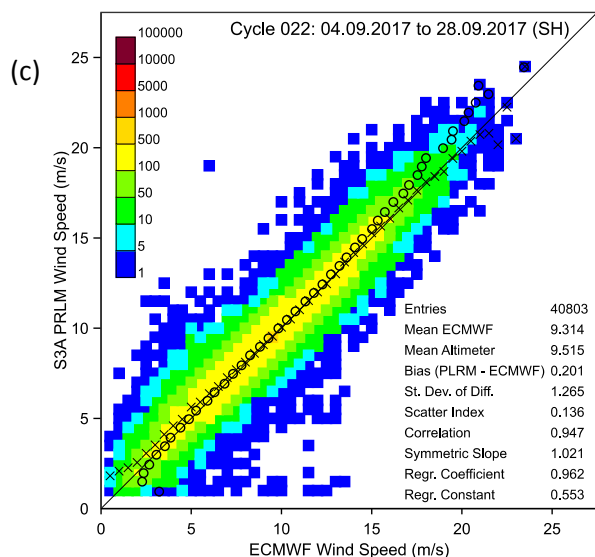
The time series of the SWH bias (altimeter – model) and SDD of Sentinel-3 compared to the ECMWF model FG are shown in the upper and lower panels, respectively, of Figure 17. Until the first week of November 2016, Sentinel-3 used to underestimate (negative bias) SWH by about 0.05 m globally, ~0.15 m for Northern Hemisphere and the Tropics while it used to overestimate SWH in the Southern Hemisphere. A change in statistics happened in mid-November 2016 which is the time of the start of PB 2.9 implementation. This led to an increase in Sentinel-3 SWH and resulted in positive bias (SRAL higher than the model) almost everywhere. However, this change had minor impact on the SDD.

Later changes associated to PB 2.9 which were implemented late in November and December 2016 do not seem to have any impact on SWH statistics. This is the case for other changes since then.
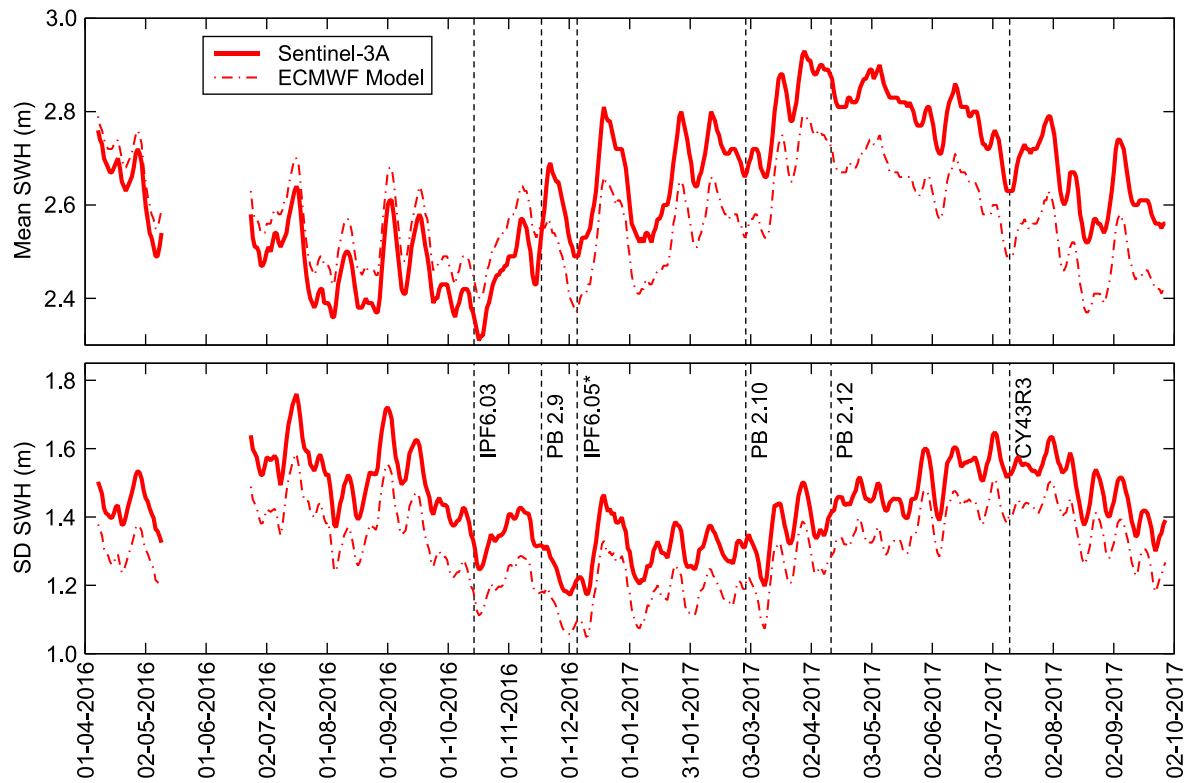
Figure 16: Time series of global mean (top) and standard deviation (bottom) of significant wave height from SRAL Ku-band after quality control. The collocated ECMWF model SWH mean and SD are also shown. The mean and SD are computed over a moving time window of 7 days.
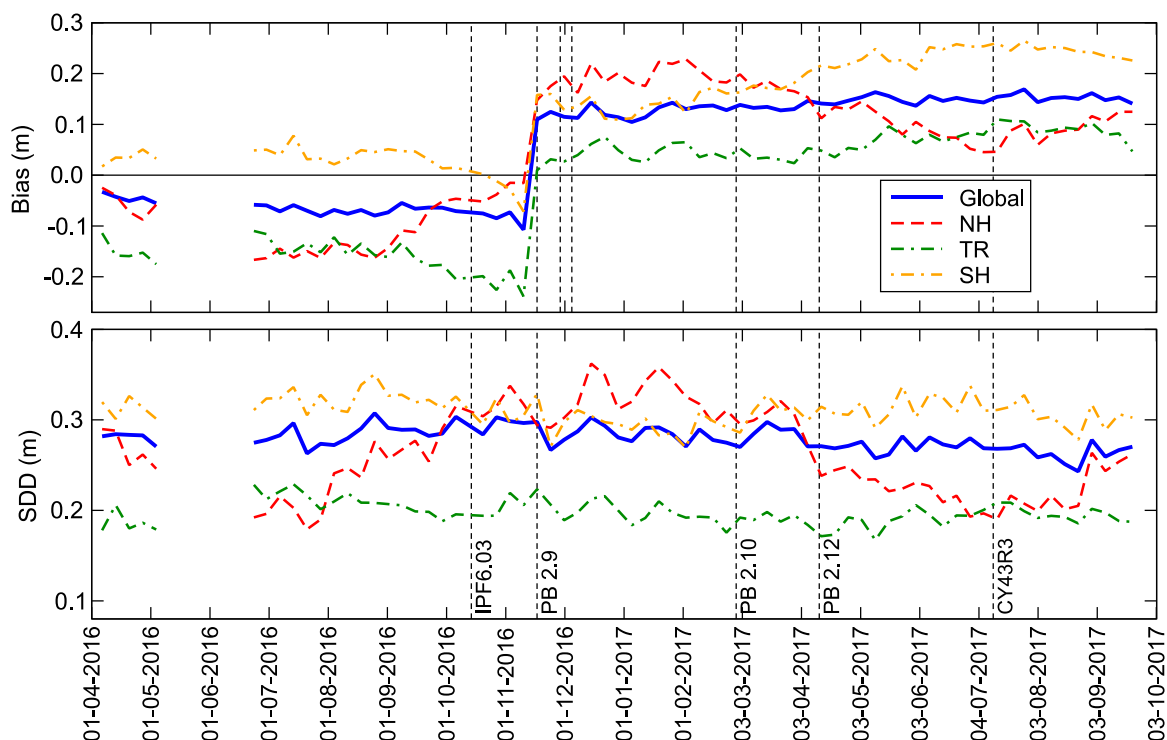
Figure 17: Time series of weekly global significant wave height bias defined as altimeter - model (top) and standard deviation of the difference (bottom) between SRAL and ECMWF model first-guess.

The geographical distribution of the mean Sentinel-3 SWH and the SWH bias, SDD and SI with respect to the ECMWF model averaged over the period of Cycle 022 are shown in Figure 18. All the four plots look similar to their counterparts from other altimeters (not shown). The overestimation of SRAL with respect to the model dominates the whole globe.

(a)

Satellite: Sentinel-3
Sat. Mean Wave Height [m]
For period between 21:00:05UTC on 03.09.2017 and 08:47:16UTC on 28.09.2017

(b)

Satellite: Sentinel-3
Wave Height Bias (Sat-Mod) [m]
For period between 21:00:05UTC on 03.09.2017 and 08:47:16UTC on 28.09.2017
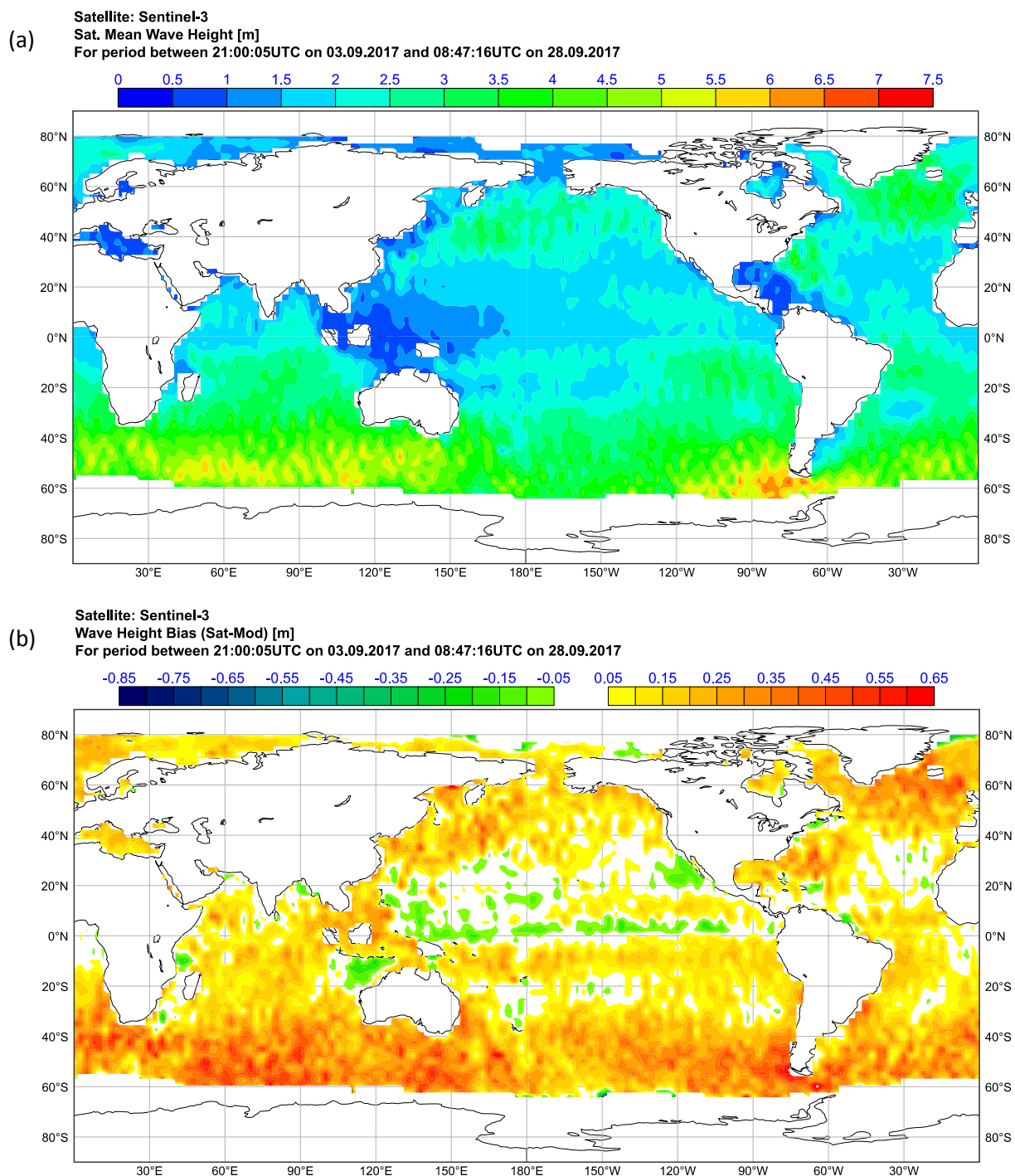
Figure 18: Geographical distribution of mean Sentinel-3 SWH (a) as well as the bias (b); the SDD (c) and the SI (d) between Sentinel-3 and ECMWF model FG during Cycle 022. Bias is defined as altimeter – model.

(c)

Satellite: Sentinel-3
Wave Height SDD (Sat-Mod) [m]
For period between 21:00:05UTC on 03.09.2017 and 08:47:16UTC on 28.09.2017

(d)

Satellite: Sentinel-3
Wave Height SI (Sat-Mod) [%]
For period between 21:00:05UTC on 03.09.2017 and 08:47:16UTC on 28.09.2017
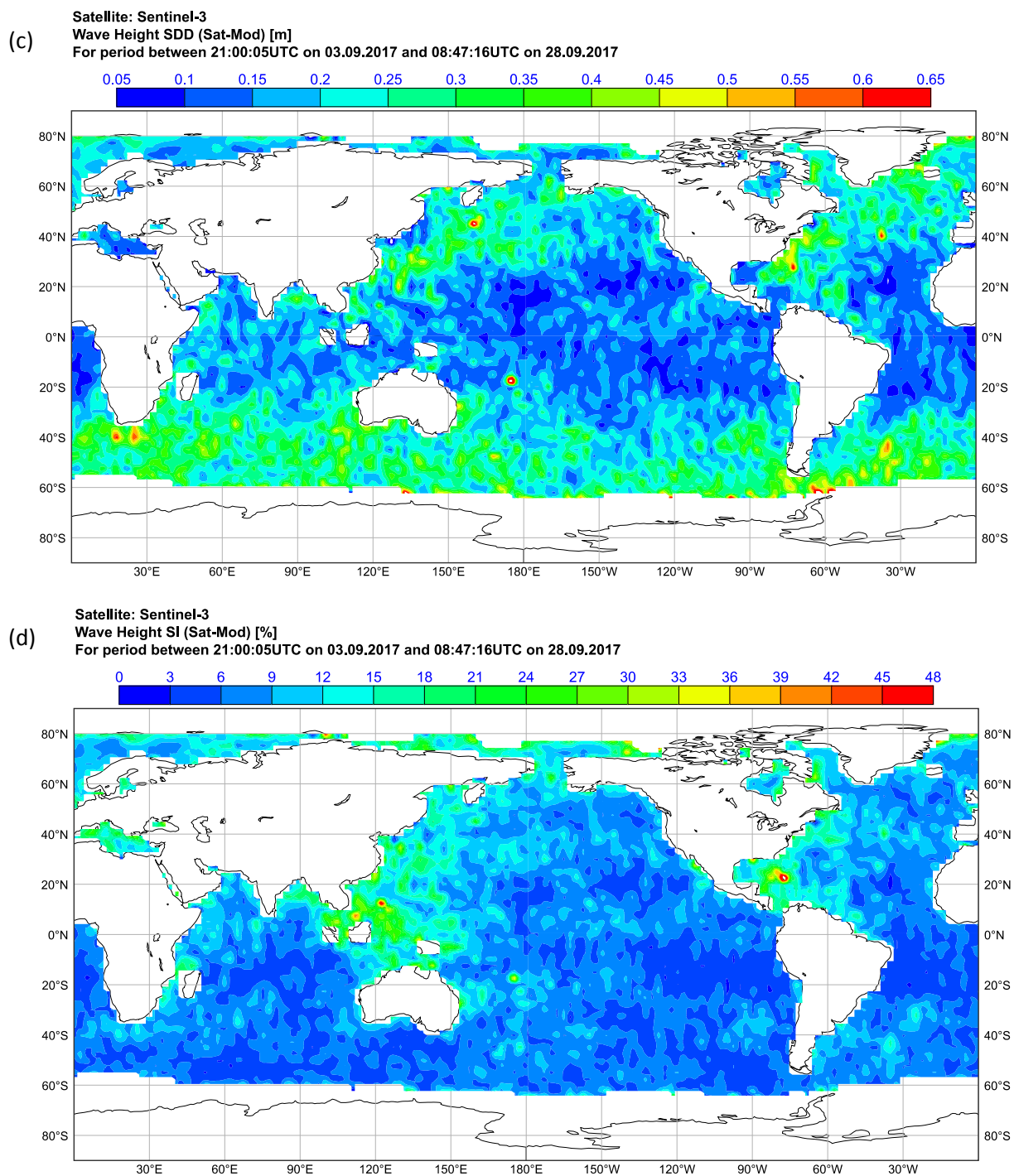
Figure 18: Continued.

The comparison against in-situ (mainly buoy) observations is shown in Figure 19. SRAL SWH is 0.17 m higher than the in-situ observations for this cycle. The SDD (a proxy to the random error) is 0.31 m which is ~15% of the mean. The slight overestimation of SRAL SWH compared to in-situ observations for waves with SWH values in excess of 3-4 m can be seen by tracing the "x" and "o" symbols in Figure 19, which represent the mean of the collocations. In general, SWH product from Sentinel-3A is as good as those from other altimeters and in-situ observations (not shown). It is important to state that most of in-situ observations are located in the Northern Hemisphere around the American and European coasts.
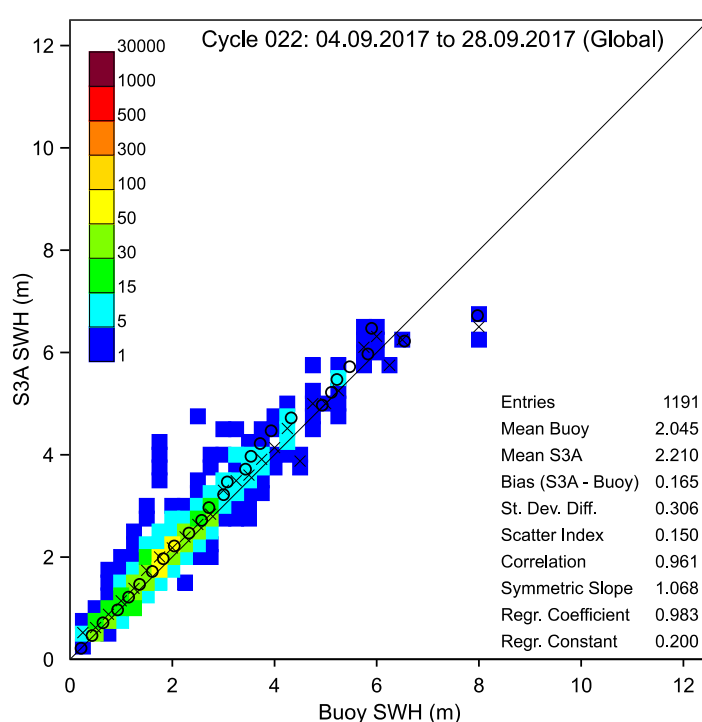
Figure 19: Same as Figure 14 but the comparison is done against in-situ observations (mainly in the NH).

6 Conclusions

Surface wind speed, PLRM wind speed and significant wave height (SWH), which are part of Level 2 Marine Ocean and Sea Ice Areas (SRAL-L2MA) also referred to as S3A_SR_2_WAT product of Sentinel-3A Radar Altimeter (SRAL) have been monitored and validated against the corresponding parameters from ECMWF Integrated Forecast System (IFS) and other altimeters. The period covers Cycle 022 (except for the last two days). The data were obtained from the Copernicus Online Data Access (ODA) service of EUMETSAT.

The impact of the processing chain IPF 6.03 which was implemented on October the 14th seems to be very small. However, the statistics show clearly that the IPF changes during November and December 2016 (processing baseline PB 2.9) have more impact. The first happened in middle of November, another one at the end of November and the last is at the beginning of December 2016. The processing baseline PB 2.10 has a positive impact on wind speed. Later processing change of PB 2.12 does not seem to have any significant impact.

The current quality of SAR wind speed, PLRM wind speed and SWH from Sentinel-3 SRAL can be summarised as being very good and they can be used for practical applications. However, some fine tuning of these products may still be needed to alleviate some of their imperfections:

❖ The SAR wind speed is now globally unbiased compared the wind speeds from the model and the other altimeters. The standard deviation of the difference (SDD) between SAR and model wind speeds is as good as that of other altimeters.

❖ The PLRM wind speed has also improved and it is now globally unbiased. The SDD with respect to the model reduced considerably during Cycle 012. However, gradual increase (mainly in the Southern Hemisphere) was witnessed during Cycle 013 but has plateaued at about 1.2 m/s until it started to increase again recently (from Cycle 018 onward).

❖ Sentinel-3 slightly overestimates high wave heights (especially those in excess of ~ 4 m) with respect to the model and the in-situ measurements. A fine tune may be needed to alleviate the overestimation at high wave heights.

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8   Appendix A: Verification Approach

8.1   Introduction

The wind and wave data collected by Sentinel-3 Radar Altimeter (SRAL) are downloaded in netCDF format which is converted into ASCII format. (In the future BUFR format will be received through the Global Telecommunication System, GTS, in near real time, NRT, and will be used directly). This product is monitored daily. The product passes through the quality control procedure described below. The data then are collocated with and verified against the model fields produced by the ECMWF integrated forecasting system (IFS) which includes an atmospheric model and a wave model (WAM) and runs operationally twice a day.

In general, the altimeter significant wave height values that pass the quality control (QC) are assimilated into the operational ECMWF wave model. This assimilation is important to improve the "nowcast" of the model and to provide more accurate initial condition for the medium-range wave forecast (up to 15 days). The altimeter wind speed data are not assimilated into the ECMWF atmospheric model. Therefore, the wind speed information is used as a diagnostic tool for the model output and the model wind speed can be used as an independent verification for the altimeter data.

The best estimate of the weather conditions (which is the model analysis) is used to verify the altimeter wind speed as it is not assimilated in the model. On the other hand, SWH which is usually assimilated in the model are verified against the model first guess (the model state just before the assimilation process). Even if the altimeter SWH product to be verified is not assimilated, the assimilation of SWH from other altimeters still cause error correlation as all altimeter products share the same principle of measurement (Janssen et al., 2007).

Furthermore, the altimeter data are collocated with and verified against available in-situ wave buoys and platform wind and wave measurements which are received at ECMWF through the GTS on weekly and monthly bases. The results of this performance monitoring and geophysical validation are summarised in this monthly report series.

Table A.1: QC Parameters for Altimeter Data from Various Satellites

Satellite	RAW	FLG	1-Hz Δ	N_{max}	N_{min}
ERS-1/2	URA	RFL	7 km	30 (=210 km)	20
ENVISAT	WWV	RF2	7 km	11 (= 77 km)	7
Jason-1	JAS	RFJ	6 km	13 (= 78 km)	8
Jason-2	JA2	RJ2	6 km	13 (= 78 km)	8
Jason-3	JA3	RJ3	6 km	13 (= 78 km)	8
Cryosat-2	CSE	RFC	7 km	11 (= 77 km)	7

SRAL/AltiKa	KAB	RFS	7 km	11 (= 77 km)	7
Sentinel-3A	S3A	RFA	7 km	11 (= 77 km)	7

8.2 Quality Control Procedure

The altimeter wave height and wind speed data are subject to a quality control (QC) procedure to eliminate all suspicious measurements. The procedure was first suggested by Janssen et al. (1989) and Bauer et al. (1992) for the SeaSat altimeter data. The procedure was enhanced later and used for ERS-1, ERS-2 (see Abdalla and Hersbach, 2004), ENVISAT (Abdalla, 2005 and 2011), Jason-1, Jason-2 (Abdalla et al., 2010 and 2011), Cryosat-2 and SARAL/AltiKa (Abdalla, 2015) altimeter data.

The daily altimeter data stream is collected for time windows of 6 hours centred at the 4 major synoptic times. Currently monitoring suites are run after the end of day "yyyymmdd", where yyyy is the year, mm is the month, dd is the day, considering time windows centred at 18:00 UTC of previous day and 00:00, 06:00 and 12:00 UTC on that specific day. This configuration is implemented to go in parallel with the ECMWF operational system. The raw data are stored in a file with the internal naming convention of "RAWyyyymmddhhnn", where RAW is a 3-letter prefix identifying the satellite or product (see Table A.1) while hh and nn are the hour and the minute, respectively, of the centre of the time window. This file is nothing but the original product (usually in in BUFR format) for the whole time window starting 3 hours before the time of the centre of the window (i.e. time "yyyymmddhhnn") and ending 3 hours afterwards.

The quality control (QC) procedure is divided into two processes:

1. A basic process: to ensure that each individual observation is within the logical range and is collected over water, during the correct time window.
2. A secondary process: to ensure that observations within any given sequence are consistent with each other. This process is only applied on observations passing the first process.

It is important to mention that this classification is just for clarification purposes and has no consequence on the quality control procedure itself.

8.3 Basic Quality Control

The RAW product is first decoded. Any record with missing value of any key parameter (i.e. time, location, backscatter, significant wave height, ... etc.) is considered as a corrupt record and is discarded (as if it does not exist). The records belong to the current time window but found in the files of the previous windows (see below), are read in (if any). All the observation records are then sorted according to the acquisition time. The records are checked to detect any duplicated observation. One of those duplicates is retained while the other(s) is/are rejected by setting the "*double-observation flag*" which is the general quality flag number 4 (Table A.2).

If the peakiness factor, which is a measure of the degree of peakiness in the return echo and is supplied as part of the RAW product, is very high, the record should be rejected as this is an indication of the existence of sea ice contaminating the observation. The threshold value for the peakiness factor is selected as 200 based on some empirical numerical tests for ERS-2. The peakiness factor in this context is defined as:

Table A.2: The Standard Quality Flags used in the Quality Control Procedure. A flags is raised (i.e. set to 1) to indicate an issue. An observation record passes QC if all general flags except flag 6 are not raised (i.e. set to zero). SWH and wind speed have their own specific flags.

General Flags

Flag #	Quality Flag Name	Meaning
1	Time window	Record belongs to another time window
2	Land point	Record over land (model land-sea mask)
3	Grid area	Record outside the WAM model grid
4	Double observation	Duplicate observation
5	Peakiness/ Range SD	Std. dev. of main band range > threshold or peakiness[*] > threshold or ice flagged
6	As above for band2[*]	Std. dev. of 2nd band range[*] > threshold
7	Rain flag[*]	Rain contamination[*] (if applicable)
8	Data gap	Jump before or after a gap (e.g. island)
9	Short sequence	Too few of accepted records in a sequence

Wave & Wind Flags

Flag #	Quality Flag Name	Meaning
1	SWH range	SWH out of range (< 0.1 m or > 20 m)
2	Noisy SWH	SWH variance too large in the sequence.
3	SWH confidence	SWH outside the 95% confidence interval.
4	Wind speed range	Wind speed out of range (< 0.1 m/s or > 30 m/s)
5	Noisy wind speed	Wind speed variance too large in the sequence.
6	w. speed confid.	Wind speed outside the 95% confidence interval.
7	Band2[*] SWH range	2nd band[*] SWH out of range (< 0.1 m or > 20 m)
8	Noisy band2[*] SWH	2nd band[*] SWH variance too large in sequence.
9	Band2[*] SWH confid.	2nd band[*] SWH outside 95% confidence interval.
10	Band2[*] short seq.	Short sequence of the 2nd band[*] SWH.

[*] *if applicable*

$$\text{Peakiness Factor} = 100\, P(t)_{max} / [2 <P(t)>] \qquad\qquad (A.1)$$

where $P(t)$ is the echo power as a function of time t, $P(t)_{max}$ and $<P(t)>$ denote the maximum and mean values of the echo power. Therefore, if the peakiness factor exceeds the threshold value (=200), the record is rejected by setting the "*peakiness/range SD flag*" which is the general quality flag number 5 (Table A.2).

The "*peakiness/range SD flag*" which is the general quality flag number 5 (Table A.2) is also raised (set to 1) if the 1-Hz range standard deviation (from the main band which is usually the Ku-band if the altimeter has more than one band) exceeds a given threshold. The threshold was set originally as 0.2 m. This caused high rejection rates at extreme sea states and therefore was adjusted later based on careful comparison with the model and buoys to be 0.20 m + 0.015 * SWH. The same flag is also raised if an ice flag is present and raised in the RAW product.

In the case that the altimeter has a secondary channel (e.g. S-band for ENVISAT and C-band for Jason-1/2/3 and Sentinel-3), if the 1-Hz range standard deviation from the secondary channel exceeds the same threshold above, the "*band-2 peakiness/range SD flag*" which is the general quality flag number 6 (Table A.2) is raised.

If the observation is found to belong to any of the previous time windows, it is assumed that it is too late to process this observation and the record is rejected by setting the "*time window flag*" (flag number 1 in Table A.2). If the observation belongs to a later time window, the record is removed from the observation stream and written into a file that will be read while processing observations of that time window.

The observation is then mapped on the land-sea mask of the wave model (WAM) model. The used land-sea mask is an irregular (reduced) latitude-longitude grid with resolution of 0.25°(around 28 km in both directions). If the observation is mapped on a land point, the record is rejected by raising the general quality flag number 2; namely "*land point flag*" (Table A.2).

If the observation is mapped on a grid point outside the grid area (e.g. over permanent sea ice which used to be north of 81°N but not the case anymore), the record is rejected by raising the "*grid area*" flag (general flag number 3 in Table A.2).

If a "*rain contamination flag*" is available in the RAW product, this information is used to set the general quality flag number 7 which is "*rain flag* (Table A.2).

The value of the altimeter significant wave height (SWH) is checked to make sure it is within the accepted logical range. If the SWH value is found to be below the accepted minimum (a value of 0.10 m is used) or above the accepted maximum (a value of 20.0 m is used), then the record is rejected by raising the "*SWH range flag*" which is flag number 1 of the group "wave and wind flags" (Table A.2).

Similar checks are done for the wind speed and the SWH of the secondary band (if available). The corresponding flags are the "*wind speed range*" (wave and wind flag number 4) and "*band2 SWH range*" (wave and wind flag number 7) of Table (A.2). Note that both flags are raised if the SWH is rejected (e.g. "*SWH range flag*" is raised).

8.4   Consistency Quality Control

The observations that pass the basic quality control go through the second stage of quality control, which includes several consistency tests. The altimeter observations are grouped as sequences of neighbouring observations. The maximum number of individual observations within each sequence, N_{max}, is selected to form altimeter "super-observations" of the same scale as that of the model. Table (A.1) lists the values on N_{max} for various satellites. Note that N_{max} value for ERS-1 and ERS-2 is 30. This selection was made in the early days of the ERS missions when the grid resolution of the ECMWF WAM model was 3 degrees (about 330 km) and later reduced to 1.5 degrees (more than 150 km). The value of 30 was never changed to maintain comparability. For reprocessing, it is suggested to change that value to 11.

The sequence construction starts by selecting the first record that passes the basic quality control in the time window under consideration as a possible candidate to be the first member in the new sequence. The time and the SWH observation of the next record is compared with that of the last selected record in the sequence. If the time difference between both records is more than an allowed maximum duration (3 s is used) or if the absolute difference between both SWH values exceeds an allowed maximum value (2.0 m is used), then it is assumed that there is a jump over a gap (e.g. land or sea ice). The previous record is removed from the sequence and is rejected by setting the "*data gap flag*" (the general quality flag number 8) to 1. The current record then becomes the first record in the sequence. The same procedure is repeated until there are two records accumulated in the sequence.

More records are recruited to the sequence in the same manner until either a gap is detected (exceeding either the maximum allowed time difference or the maximum allowed SWH difference) or until the maximum number of observations N_{max} in the sequence is reached. If a gap is detected and the number of the records accumulated in the sequence is less than a predefined minimum, N_{min}, (see Table A.1), all of the already selected records are rejected by raising the general "*short sequence flag*" (general flag 9 in Table A.2) to indicate a "*short sequence*" condition. If the number of observations in the sequence exceeds the predefined minimum (including the case that the maximum number has been reached), then the sequence goes through further quality control checks. The mean and the standard deviation of the observations accumulated in the sequence are computed.

The next step is to eliminate spikes by rejecting observations with SWH outside the 95% confidence interval. To accomplish this, we compute the SWH confidence limits of the sequence as:

$$\text{Confidence Interval} = \min \{ \alpha, \zeta \cdot \sigma \} \tag{A.2}$$

where α is a maximum value of the confidence interval (used as 2.0 m in the first iteration and as 1.0 m in the second iteration), ζ is a factor for the spike test (a value of 3 is used), and σ is the standard deviation of SWH. If the absolute value of the difference between the SWH of the individual record and the mean SWH of the sequence exceeds the confidence interval computed by Eq. (A.2), then that individual record is rejected by raising the "*SWH range flag* (Wave & Wind flag number 3 in Table A.2). The flagged records are removed from the sequence and another spikes-removal iteration is carried out using the modified sequence and a rather stricter confidence interval condition (in Eq. (A.2), the value of 1.0 m for α is used in the second iteration).

If the number of individual records passed the spikes test in the sequence is less than the minimum allowed (N_{min} records), all the records in the sequence are rejected by raising the "*short sequence flag* (general flag number 9 in Table A.2) to indicate a "*short sequence*" condition. If there are enough records, the mean and the standard deviation of SWH, backscatter, wind speed, ... etc. are computed. Also, the mean geographical coordinates and the mean time of the sequence with the records passed the spikes test are also computed. The average value of the sequence is called "super-observation".

After that, the variance of the SWH values in the sequence is tested. The maximum allowed SWH variability within the sequence is given by:

$$\text{Maximum SD} = \max \{ \beta, \gamma \cdot \mu \} \tag{A.3}$$

where β is the minimum allowed standard deviation (0.5 m is used), γ is a factor for the variance test (0.5 is used) and µ is mean value of SWH in the sequence. If the standard deviation of the SWH exceeds the maximum value computed by (A.3), all records in the sequence are rejected by raising "*Noisy SWH flag*" which is Wave & Wind Flag number 2 in Table A.2) to indicate a "*noisy observation-sequence*" condition.

The same last action is repeated on the surface wind speed (instead of SWH) and the corresponding flags (Wave & Wind flags 4 to 6 in Table A.2) are raised if needed. Similar action is done on the SWH (or wind speed) from the secondary band if one is available. The corresponding Wave & Wind flags 7 to 10 in Table A.2) are raised if needed.

The same whole procedure is repeated by selecting a new sequence until all the observations within the current time window are processed.

8.5   Output Files

The quality control procedure described above generates two types of files: "Radar flagged" (RFL) file, and "Radar averaged" (RAV) file. Furthermore, it appends a record in an "extended statistics file" (ESF) for each time window representing the statistics of quality control procedure for that specific window. The ESF file is used to plot the time series of data received, data rejections and data acceptance.

All records processed are written together with their corresponding flags in the "Radar flagged" file with the following naming convention: "FLGyyyymmddhhnn", where FLG is replaced by the 3-letter prefix

corresponding to the altimeter under consideration as given in Table (A.1). This file contains the complete information included in the RAW product with the values of the quality flags listed in Table (A.2) and described above. This file covers the 6-hour time period centred at time yyyymmddhhnn. This file is an important product that can be used instead of the original RAW product. For example, this file is used as the input to the data assimilation procedure where only observations passed the quality control are used in assimilation.

The super-observations (i.e. the means and standard deviations of the sequences with records passed the quality control) are written to the "Radar averaged" file with the following naming convention: "RAVyyyymmddhhnn". This file contains the sequence means and standard deviations for the whole time window extending from time yyyymmddhhnn-3 hours to yyyymmddhhnn+3. This file is not of much practical interest as it is considered as an intermediate medium to pass the averages needed in the next step which is the altimeter-model collocation.

8.6 Altimeter Model Collocation

After the quality control and averaging process, the individual altimeter SWH observations that pass the quality control are prepared for the data assimilation. To be specific, the FLG file is used for this procedure. The individual observations within the catchment area of a grid point (i.e. within a box with dimensions of grid increment and centred on the grid point) are averaged and assigned as the SWH observation corresponding to that grid point. The model is run to produce the first-guess fields. The data assimilation procedure is then used to blend the first guess fields with the RA observations to produce the analysed fields.

The ECMWF analysis wind velocity fields and the various WAM first-guess wave (SWH, mean wave direction, mean wave period, peak wave period, ... etc.) fields are interpolated over a regular grid (e.g. 0.5° by 0.5°) at all analysis times (00:00, 06:00, 12:00, and 18:00 UTC). Each RA super-observation represented by the mean time and position of the corresponding sequence in the RAV file is collocated with the nearest model grid point. The values of the model parameters at the corresponding grid point and at the previous and next analysis times are interpolated at the mean time of the super-observation. The super-observation record and the time-interpolated model parameters are all written in the altimeter-model collocation (RAC) file. The name convention of this file is: "RACyyyymmddhhnn" covering the 6-hour time period centred at time yyyymmddhhnn.

8.7 Altimeter Buoy Collocation

In-situ wind and wave observations, which are collected by ships, buoys and platforms (for simplicity, all will be called hereafter: "buoy data"), are routinely received at ECMWF through the GTS and archived. Significant portion of the buoy data arrives with some delay. In general, most of the buoy data arrives within 48 hours of the acquisition time.

Most of the buoy observations are collected on hourly basis. The remaining part may be collected at lower frequencies (e.g. 3 hours). The buoy observations collected 2 hours earlier and later than an

analysis time (5 observations) are averaged and assigned to be the buoy observation at that analysis time. This buoy observation is collocated with the nearest model grid. The averaged buoy observations and the model analysis parameters (namely: SWH, mean wave direction, peak wave period, wind speed and direction, MSL pressure, air and seawater temperatures) are written to a collocation buoy-model (CBM) file. This task is run operationally every day with a lag of two days to ensure the arrival of most of the buoy data.

The triple-collocation (RA-model-buoy collocation) exercise is done at the beginning of each month (on the 4th of the month) for the whole of the previous month. The contents of the RAC (described above) and the CBM files are used. A RAC record is collocated with a CBM record if the following two conditions are satisfied:

1. both the RA super-observation and the buoy observation are assigned to the same analysis cycle; and

2. the distance between the RA super-observation and the buoy is within a given distance (200 km is used).

Each collocated pair of records are merged as one record and written to a collocation altimeter-buoy (CAB) file. The name convention of this file is: "CAByyyymm010000" covering the whole month mm of year yyyy.

The maximum acceptable collocation distance and time interval between the collocated altimeter and buoy observation pair are rather relaxed (200 km and 2 hours; respectively). This criteria is selected to gather enough number of collocations for meaningful statistics. To reduce the risk that the collocated altimeter and buoy SWH observation pair do not represent the same ground truth, their model counterparts are required not to be different by more than 5%. Furthermore, the mean direction of wave propagation in the model at the two locations should not differ by more than 45°. This ensures the homogeneity of the sea-state conditions at least from the model point of view. The same criteria cannot be used for wind speed. For the results presented here, wind speed collocations are accepted whenever the SWH collocation is accepted. For more detailed analyses (e.g. triple collocation error estimates of wind speed), a relaxed SWH (not wind speed) maximum difference of 50% is used. The maximum allowed difference in model wind direction at the altimeter and buoy locations is set as 20°. The background of this selection for both SWH and wind speed is based on the physics of wind and wave generation and propagation. However, the specific values used here are based on experience (see, for example, Abdalla et al., 2011).

9 Appendix B: Wind Speed Improvement since March 2017

On 28 February 2017, processing baseline (PB) 2.10 was introduced operationally. PB 2.10 includes the following changes:

- ❍ Level-1 IPF version 06.10,

- ❍ MWR IPF version 06.03,

- ❍ Level-2 IPF version 06.06, and

- ❍ updated calibrations.

The impact of such change on wind speed is not clear from Figure 6 and Figure 7. The natural variability masked that impact.

Figure 20 shows the global wind speed bias and standard deviation of the difference (SDD) between various altimeters, including Sentinel-3A SRAL, and the ECMWF model. The positive impact of SRAL PB 2.10 can be clearly seen when comparing Sentinel-3A SDD curve with those of other altimeters. SRAL started to have one of the lowest SDD (which is a proxy for random error) values since early March 2017.
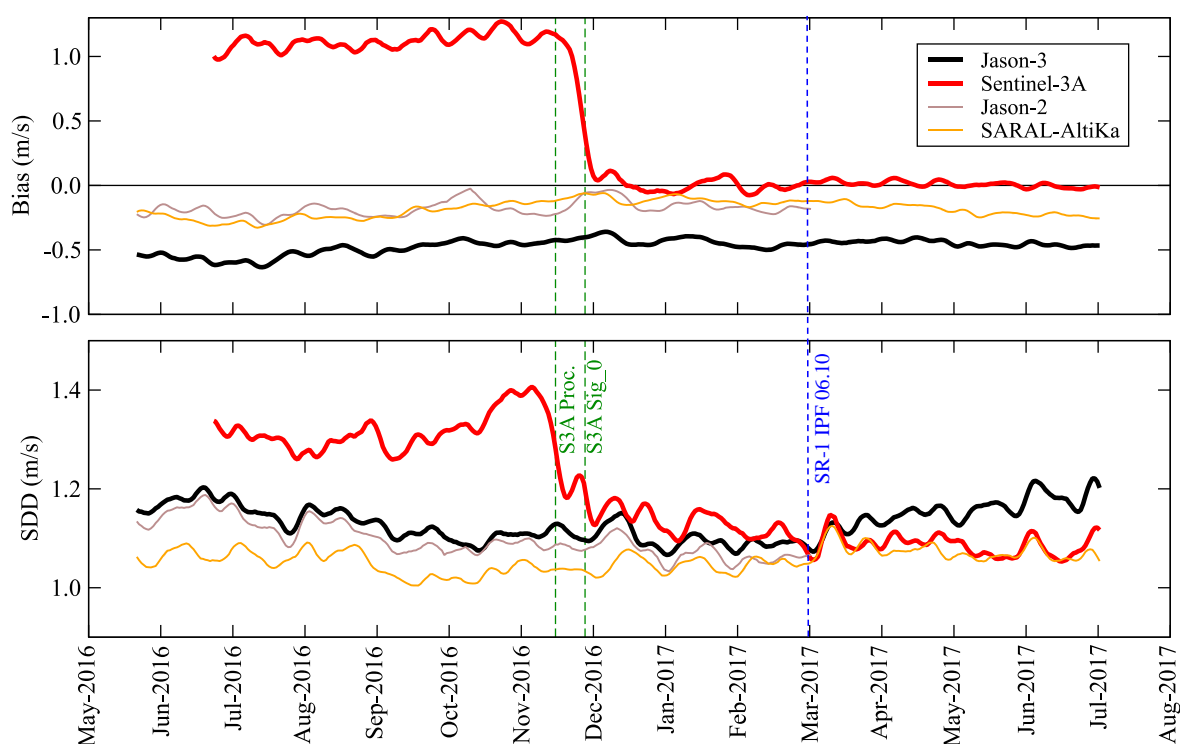

Figure 20: Time series of weekly wind speed bias defined as altimeter - model (top) and standard deviation of the difference (bottom) between various altimeters and ECMWF model analysis for the whole globe.

10 Appendix C: Related Reports

Other reports related to the STM mission are:

❖ S3-A SRAL Cyclic Performance Report, Cycle No. 022 (ref. S3MPC.ISR.PR.04-022)

❖ S3-A MWR Cyclic Performance Report, Cycle No. 022 (ref. S3MPC.CLS.PR.05-022)

❖ S3-A Ocean Validation Cyclic Performance Report, Cycle No. 022 (ref. S3MPC.CLS.PR.06-022)

❖ S3-A Land and Sea Ice Cyclic Performance Report, Cycle No. 022 (ref. S3MPC.UCL.PR.08-022)

All Cyclic Performance Reports are available on MPC pages in Sentinel Online website, at: https://sentinel.esa.int

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