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GlobWave Evolution: Towards a Sea-State ECV

Sea State ECV Final Report

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Approved:	Simon Pinnock	**Signature:**	

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1 EXECUTIVE SUMMARY

The objective of the original ESA-funded GlobWave project (2009-2013) was to improve the uptake of satellite-derived wind-wave and swell data by the scientific, operational and commercial user community. The main output of this was a consistently processed data set of altimeter and SAR-based wave measurements provided in a common format with additional quality and errors information together with ancillary fields from the ECMWF operational model. Another key component of GlobWave was the development of a pilot extension to the JCOMM Wave Forecast Verification Scheme to provide spatial intercomparison with satellite wave data sets to contributing meteorological offices.

The GlobWave Evolution project had two components. The first was to continue operating the Pilot Spatial Wave Forecast Verification Scheme (PS-WFVS) and making preparations for its transfer to a long-term operational framework. The second is to develop products based on the GlobWave L2P satellite wave data that target the requirements of the Global Climate Observing System (GCOS) for a Sea-State Essential Climate Variable (ECV). Three types of ECV product have been developed: a monthly gridded sea-state product for the continuous altimeter record (1991-2013); a new innovative multi-sensor high temporal resolution product; regional and global sea state change indicators. ECV products developed during the project are made freely available via the GlobWave web portal. This report summarises these ECV products, presents validation and gives recommendations and feedback as to their suitability for long-term monitoring of ocean wave climate.

2 INTRODUCTION

This report presents new products that have been developed during the ESA-funded GlobWave Evolution project as pre-cursors to a Sea State Essential Climate Variable (ECV).

Products are based on the GlobWave L2P satellite wave data and target the requirements of the Global Climate Observing System (GCOS) for a Sea-State Essential Climate Variable (ECV).

Three types of ECV product have been developed: a monthly gridded sea-state product for the continuous altimeter record (1991-2013); a new innovative multi-sensor high temporal resolution product; regional and global sea state change indicators.

ECV products developed during the project are made freely available via the GlobWave web portal. This report summarises these ECV products, presents validation and gives recommendations and feedback as to their suitability for long-term monitoring of ocean wave climate.

Further sections describe the monthly gridded sea state products for altimeter and SAR; a multi-sensor high temporal resolution product; sea state change indicators; feedback and recommendations from expert advisers.

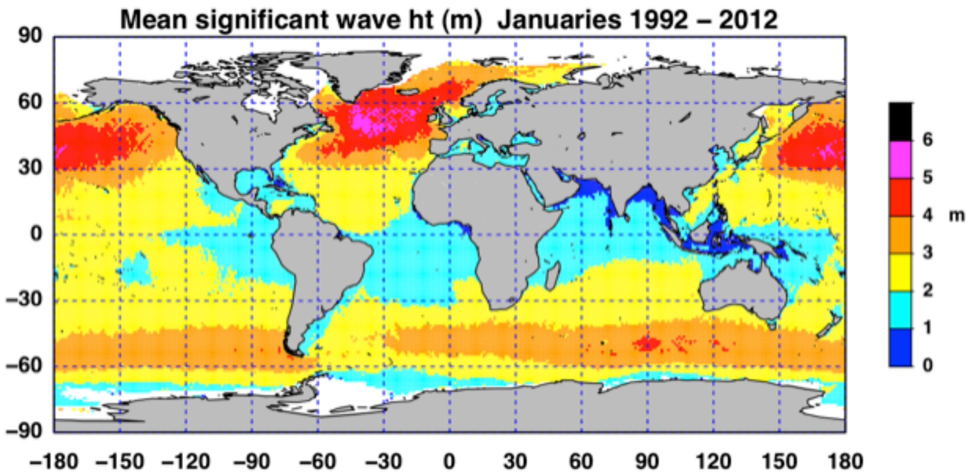
Queries and feedback are welcome and should be sent by email to Ellis Ash, e.ash@satoc.eu .

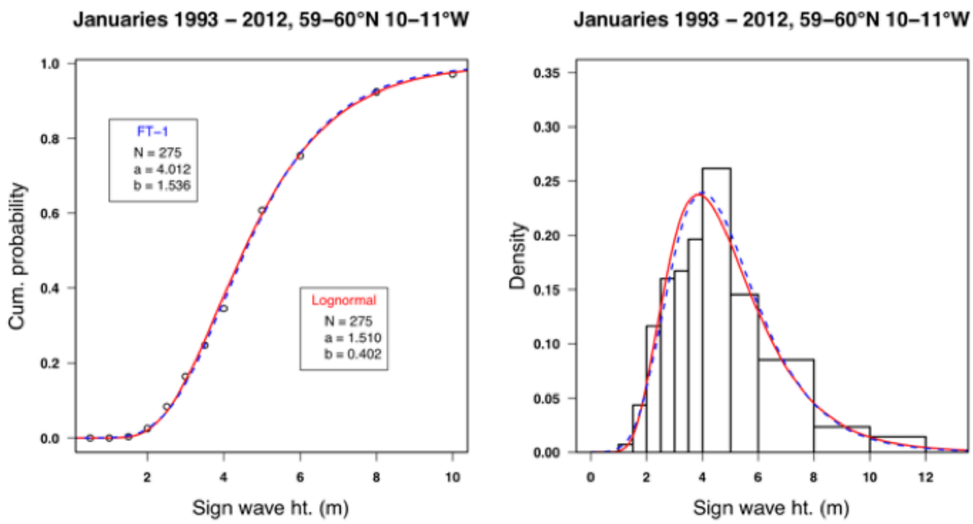
3 MONTHLY GRIDDED SEA STATE

3.1 PRODUCT OVERVIEW

3.1.1 ALTIMETRY MONTHLY GRIDDED SEA STATE

The Altimetry Monthly Gridded Sea State product provides a powerful summary dataset for rapid wave climate assessment. It is a level 4 product calculated from the GlobWave L2P data. Global 1-degree gridded products have been generated for the full continuous altimetry archive from 1991 up to 2013, with one product file per month. These gridded products allow easy calculation of several statistical parameters such as global mean significant wave height and wave height distribution curves for individual 1-degree bin areas over a time period of choice within the available time series:





Data are provided on a 1-degree grid globally (-82S to 82N) for each month, and are based on median values of satellite passes across 1x1 degree bins. The median value swh over this area is considered representative of the sea state for that area and is recommended by Carter (1990) because it is more robust against outliers than the mean. He found no evidence of skewness in the distribution of swh values across a 2° x 2° bin, with an average for the difference between the median and the mean which was not significantly different from zero. Median values are only selected where there are at least 4 good points that have a good quality level in the L2P data files. This adds a further level of quality control to the dataset.

Parameters included in the product are:

- Number of median values used to compute statistical parameters
- Sum of swh, sum of swh squared
- Sum of log swh, sum of log swh squared
- Number of medians greater than threshold values of [0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 5.0, 6.0, 8.0, 10.0]m
- Maximum measured median significant waveheight

The product size is 1.8MB per month and all products are freely available on the GlobWave Portal alongside the full L2P dataset.

Data access is by ftp, with login details obtained by contacting Ifremer by email to the CERSAT help desk, fpaf@ifremer.fr .

The ftp site is ftp://eftp.ifremer.fr/waveuser/globwave/data/ with files in a subdirectory: l4/altimeter/GW_L4_ALT_1DEG_1M_yearmonth.nc . For example GW_L4_ALT_1DEG_1M_201101.nc gives global data for January 2011.

Reference:

Carter D J T 1990, Development of procedures for the analysis of ERS-1 radar altimeter wind and wave data, using Geosat data. ESA Study Report under Contract 8315/89/HGE-I, 77pp.

3.1.2 SAR MONTHLY GRIDDED SEA STATE

The SAR monthly gridded sea state files allow easy calculation of global statistics for the long swell waves, and are calculated from Envisat SAR wave mode products from 2002 to 2012. Monthly gridded files from SAR are provided on a 2-degree grid globally (-80S to 80N) and parameters included are:

Lat and Lon values

Number of observations per bin used to compute statistical values

Percentage of occurences of detected waves and swell

Sum of swh, sum of swh squared

Sum of dominant wavelength, sum of dominant wavelength squared

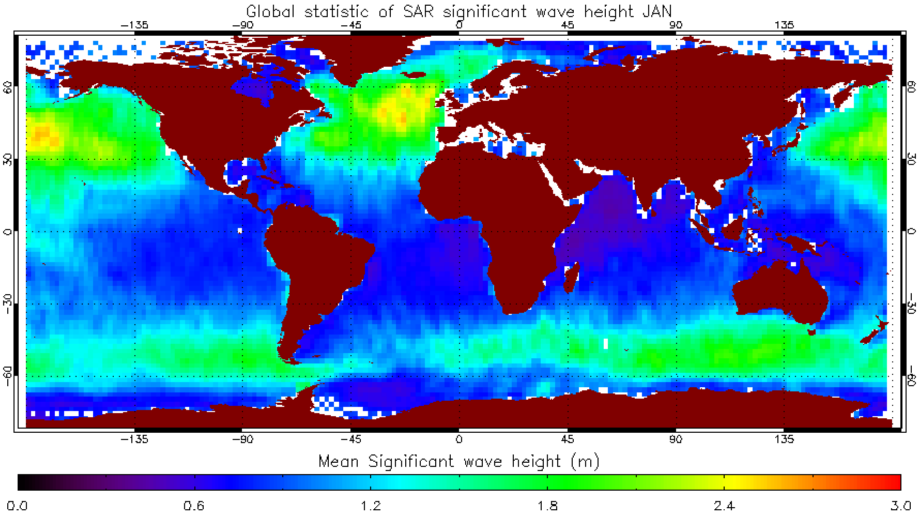
Sum of dominant direction, sum of dominant direction squared

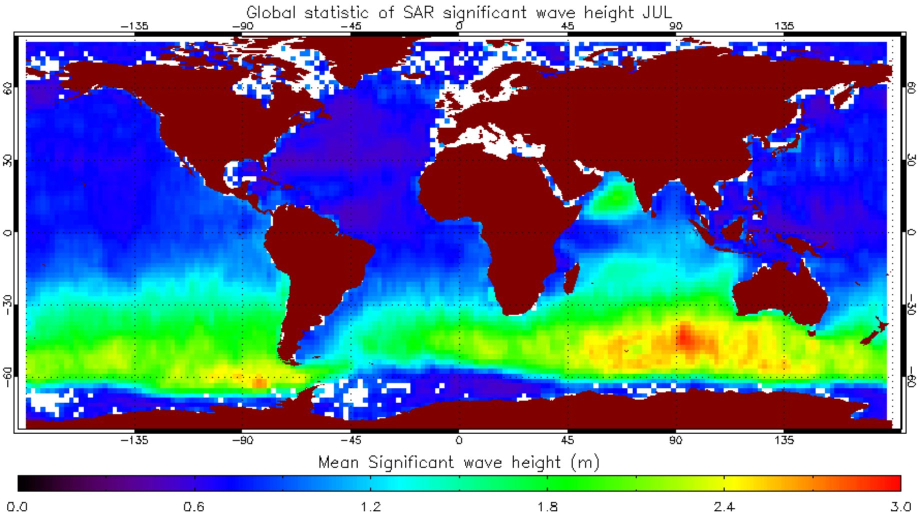
Sum of swh, sum of swh squared

Cross swell occurence with each swell swh above 0.5m, wavelength above 180m and direction difference above 45 deg.

Cross swell occurence with each swell swh above 1.0m, wavelength above 180m and direction difference above 45 deg.

Example results are shown below:





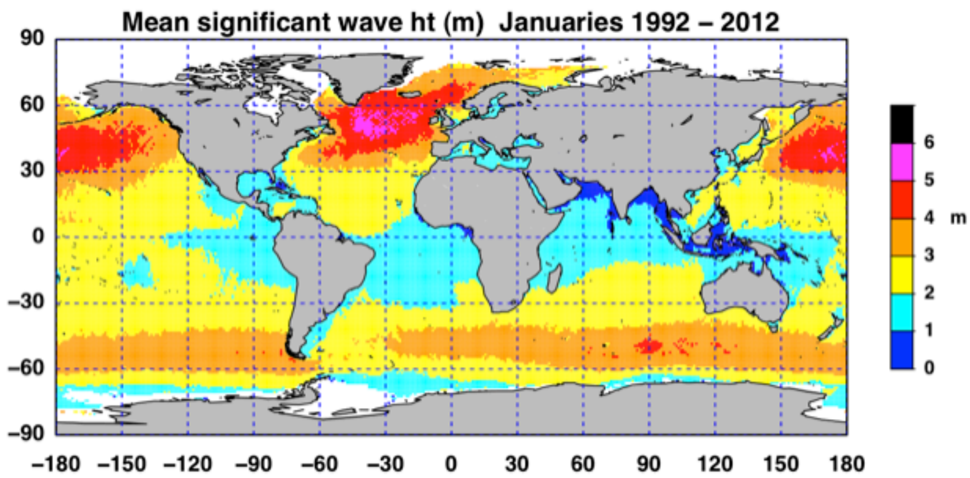
SAR long wave significant wave height monthly products as produced from SAR L2P dataset.

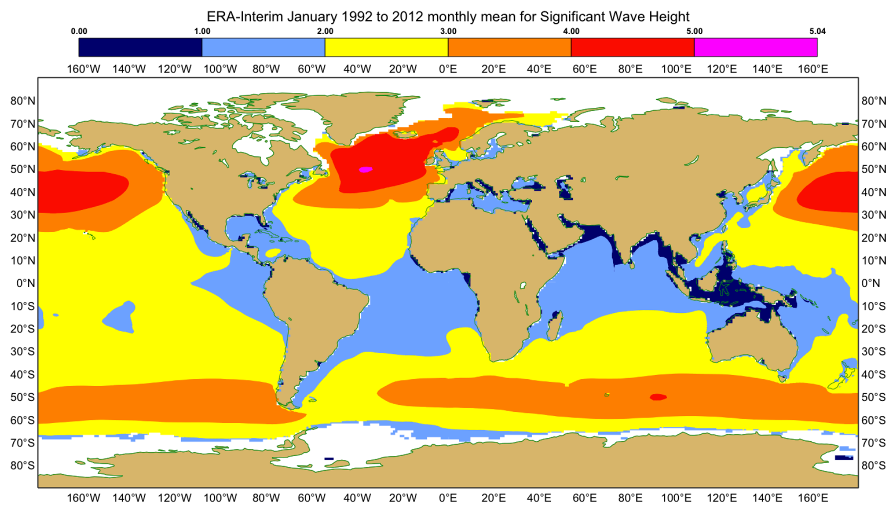
The ftp site is ftp://eftp.ifremer.fr/waveuser/globwave/data/ with files in a subdirectory: l4/sar/GW_L4_SAR_1DEG_1M_yearmonth.nc. For example GW_L4_SAR_1DEG_1M_201101.nc gives global data for January 2011

3.2 ALTIMETER PRODUCT VALIDATION

3.2.1 GLOBAL COMPARISON WITH ECMWF WAVE MODEL

The global mean significant wave height has been calculated from the ECMWF ERA Interim model for Januaries 1992 to 2012 (courtesy Jean Bidlot, ECMWF) for direct comparison with the example result from the altimeter gridded product:





The results are not entirely independent, with ERA Interim assimilating some altimeter wave data, however they show remarkable agreement and give good confidence for the altimeter products over long time scales.

3.2.2 MONTHLY MEANS BUOY COMPARISON

The climate record from selected wave buoys (Atlantic and Pacific areas) has been compared with the same quantities derived from the altimetry monthly gridded sea state product.

Comparisons of monthly mean and standard deviation are given here with comments.

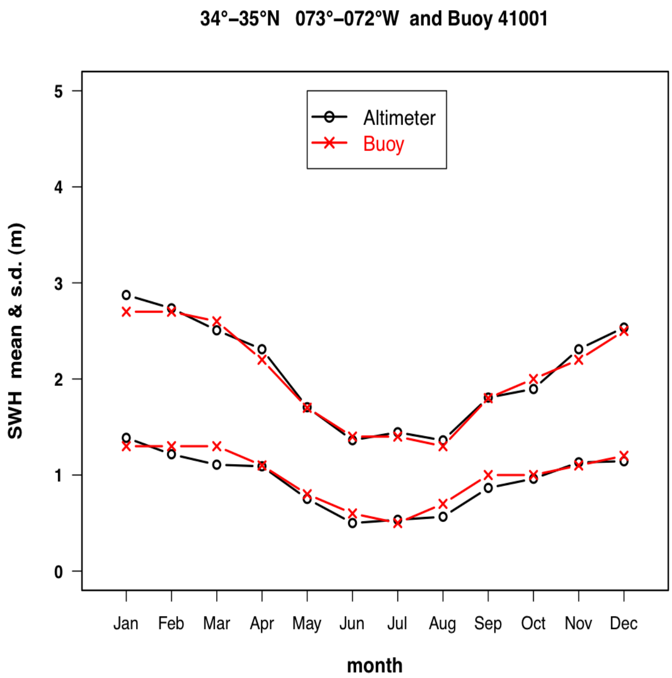


Figure 3-1: Comparison of monthly mean and standard deviation of significant wave height from altimeters, April 1992 – Dec. 2013, and Buoy 41001, June 1976 – June 2008, at 34.56°N 72.64°W, 150nm East of Cape Hatteras. (Means upper curves, s.d lower curves.)

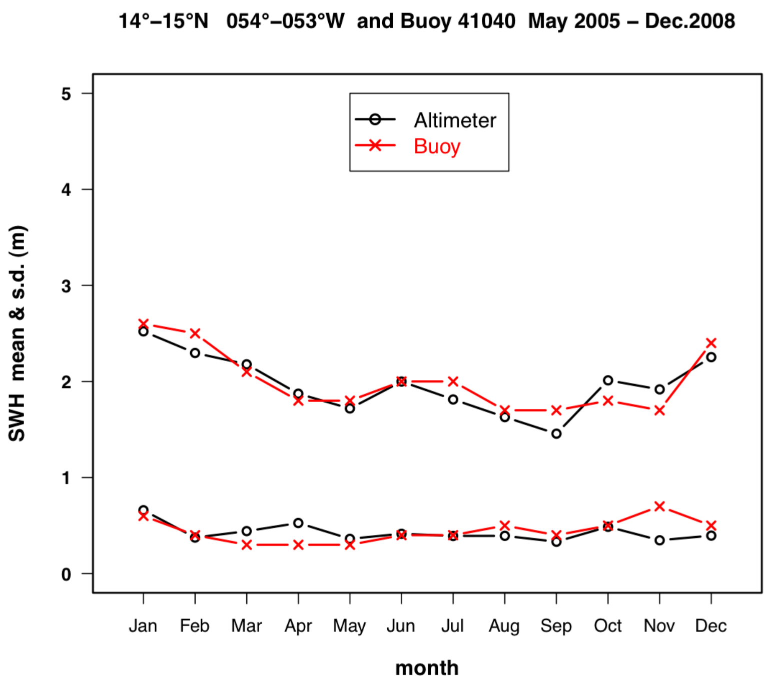


Figure 3-2: Comparison of monthly mean and standard deviation of significant wave height from altimeters and Buoy 41040, May 2005 – Dec. 2008, at 14.52°N 53.02°W. (Means upper curves, s.d lower curves.)

For buoy 41040 the time period is relatively short, and the tropical location means that Altimeter data only from about 5 passes per month. The variability between monthly means from alt and buoy is expected from so few alt records. The monthly mean from this buoy shows a secondary max in June/July, indicating a semi-annual cycle as well as a (dominant) annual cycle - as suggested from Geosat data (Carter, Foale & Webb, 1991).

Carter D J T, Foale S and Webb D J 1991 Variations in global wave climate throughout the year. Int. J.Remote Sensing, 12(8) 1687-1697.

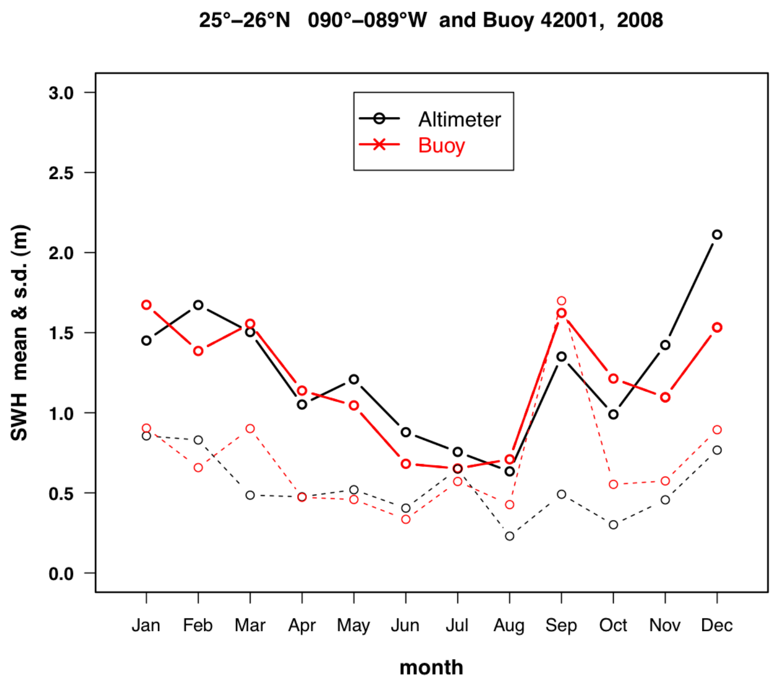


Figure 3-3: Comparison of monthly mean and standard deviation of significant wave height from altimeters, April 1992 – Dec. 2013, and Buoy 42001, Jan. 1976 – Dec. 2008, at 25,89°N 89.66°W, mid Gulf of Mexico. (Means upper curves, s.d lower curves.)

Buoy 42001 gives a comparison for a single year of data (2008). While the general agreement is good, it shows a large difference in s.d. for September. This spike is due to some high SWH during the month with a maximum of 9.25 m measured by the buoy on 18 Sept. 2008 – with a wind speed of 25.2 m/s gusting 32.4 m/s, during Hurricane IKE. The maximum of the 10 altimeter SWH measurements that month was 2.1 m. This example illustrates the inability of altimeters to accurately describe the high wave climate in areas with tropical storms.

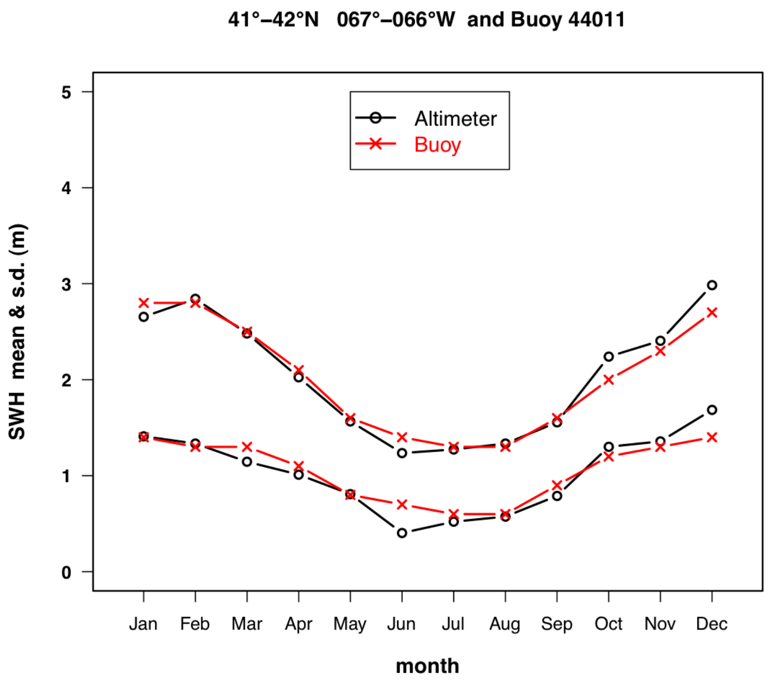


Figure 3-4: Comparison of monthly mean and standard deviation of significant wave height from altimeters, April 1992 – Dec. 2013, and Buoy 44011, May 1984 – Dec. 2008, at 41.11°N 66.60°W, 170nm East of Massachusetts in water depth of 86 m.

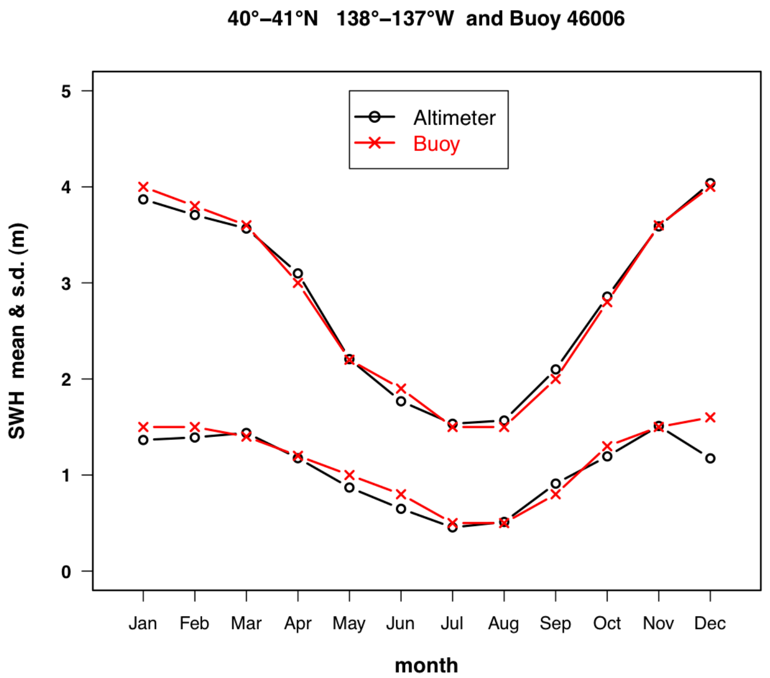


Figure 3-5: Comparison of monthly mean and standard deviation of significant wave height from altimeters, April 1992 – Dec.

2013, and Buoy 46006, April 1977 – Dec. 2008, at 40.75°N 137.46°W. (Means upper curves, s.d lower curves.)

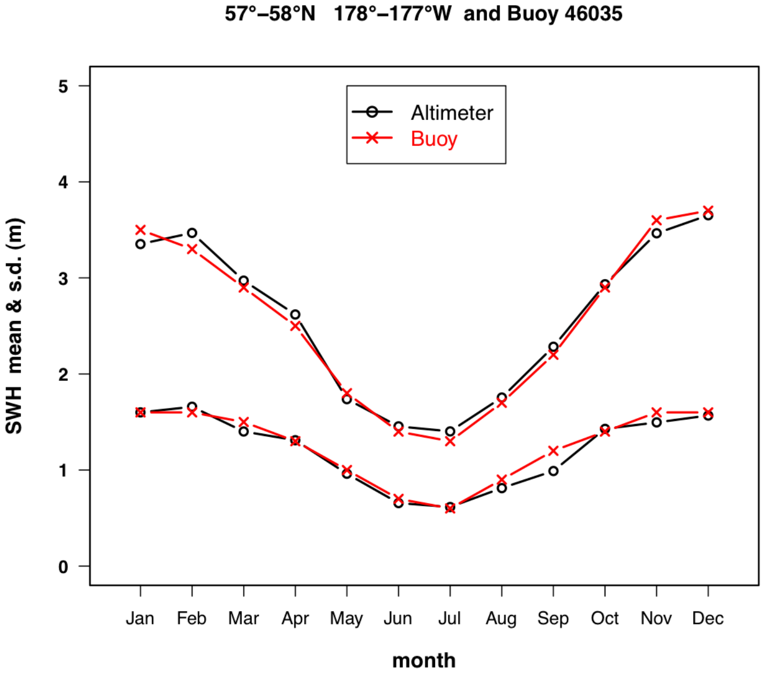


Figure 3-6: Comparison of monthly mean and standard deviation of significant wave height from altimeters, Aug. 1991 – Dec. 2013, and Buoy 46035, Sep. 1985 – Dec. 2008, at 57.07°N 177.75°W, central Bering Sea. (Means upper curves, s.d lower curves.)

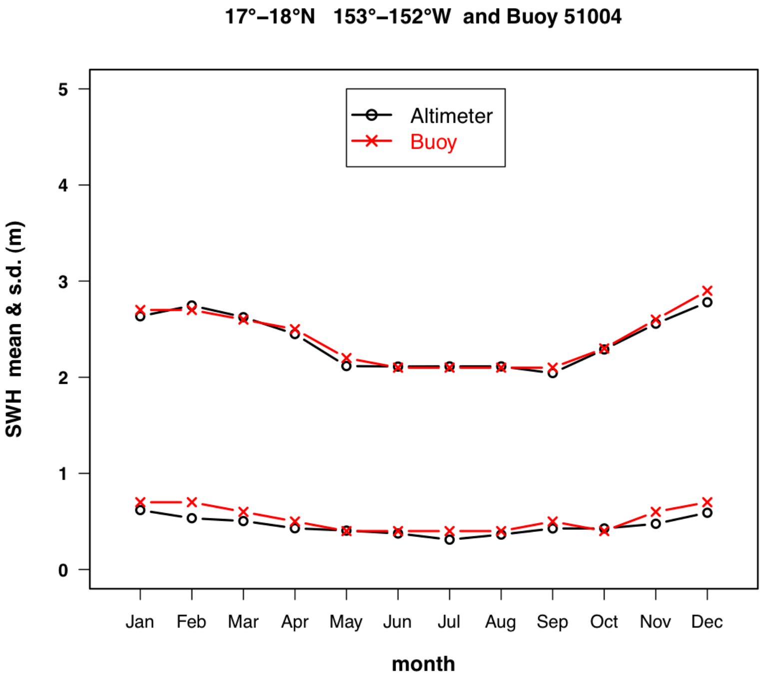
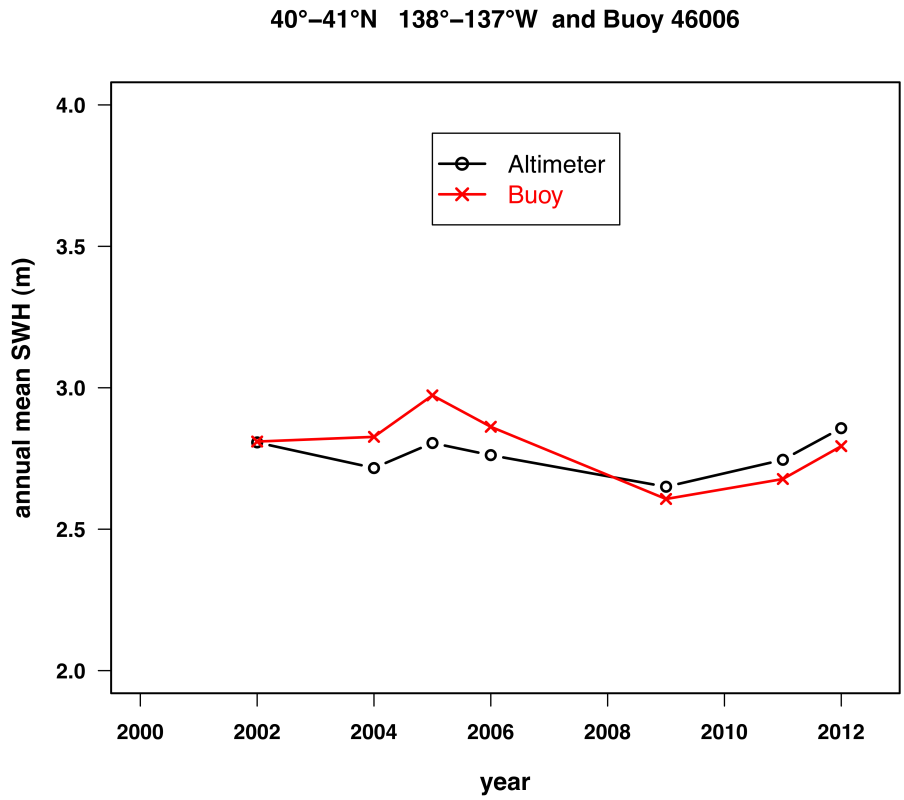


Figure 3-7: Comparison of monthly mean and standard deviation of significant wave height from altimeters, May 1992 – Dec. 2013, and Buoy 51004, Nov. 1984 – Nov. 2008, at 17.53°N 152.38°W, 205 nm SE of Hawaii. . (Means upper curves, s.d lower curves.)

3.2.3 TIME SERIES COMPARISONS

Comparisons of annual mean SWH from US NDBC buoy on Station 46006 in the Pacific, at 40.75°N 137.46°W with estimates from altimeter data in the surrounding 1° x 1° bin over the years 2000 to 2012 are shown below. Because of gaps in the buoy data, data from only 7 years are shown. Because of variations in the number of records each month, the annual means have been calculated as the mean of the 12 individual months.



There were only 147 buoy records in December 2006, for other months numbers ranged from 608 to 744. Altimeter passes per month ranged from 2 in May 2012 to 19 in December 2004, with a mean of 9 – but only of 3.25 in 2012.

The buoy annual means would appear to show a decrease over the years, but regression analysis finds this trend not to be significant, even at the 90% confidence level. Might this slight trend be caused by a small change in the calibration of the buoy after 2008?

The differences between buoy and altimeter means over these 7 years ranged from -0.068 to 0.168 m (buoy – altimeter), with a mean of 0.030 m, and s.d. of 0.096 m.

Fig. YYYY shows the buoy and altimeter estimates of the mean significant wave height in Januaries from 2001 to 2013. There were no buoy data for 2006 and 2007; the dashed line shows the altimeter means for January of those years. The variations from year to year are much larger than the variations in annual means (Fig.XXXX).

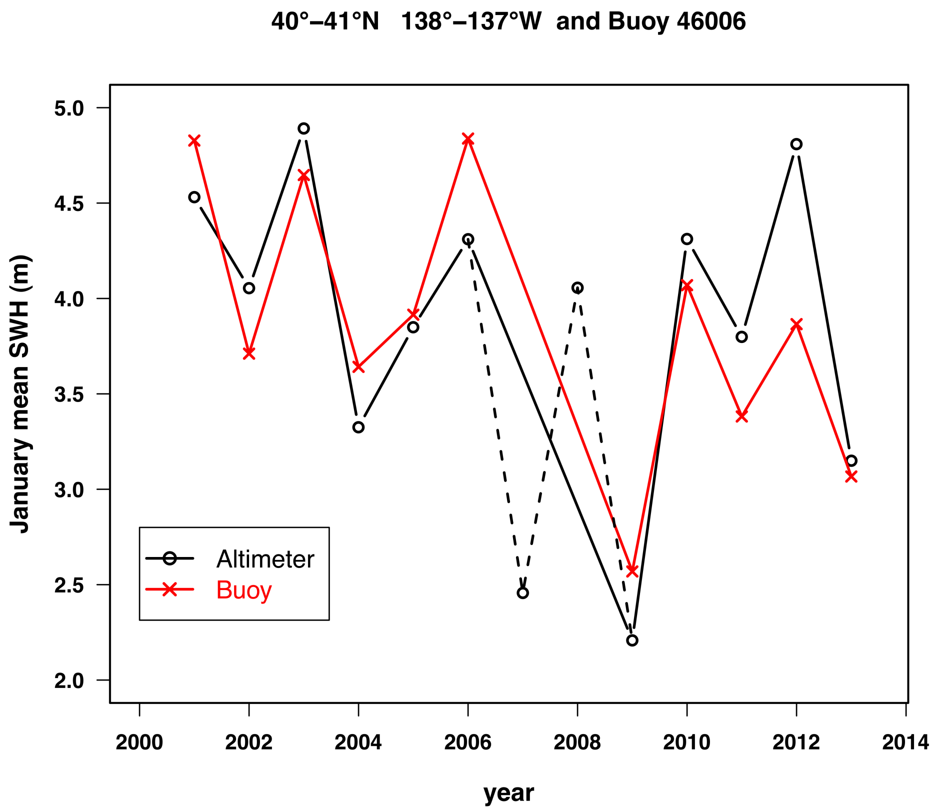


Fig. YYYY. Mean significant wave heights during Januaries 2000 -2012 from Buoy 46006 and from altimeter data.

The mean and s.d. of the difference, buoy – altimeter, omitting 2006 and 2007, are 0.064 and 0.432 m. The changes in wave height from one year to the next are remarkably similar, but the actual differences between buoy and altimeter vary quite widely, from -0.94 to +0.53 m. (Although the very close agreement for 2013 of 3.07 and 3.15 m must be luck since there were only 2 altimeter values that January.)

The buoy data suggests that there was a general decrease in January means over these years, with a slope of -0.095 m/year, significant at 93%. But the altimeter data show no significant trend.

The large variation in mean January wave heights at this location makes it difficult to determine any trend in wave climate. The s.d. of buoy means was 0.72 m (0.59 about the fitted regression line). The s.d. of the altimeter means was 0.80 m (0.84 including 2006 and 2007); larger than the buoy value presumably because of the smaller number of data (about 700 each month from the buoy except only 229 in January 2010, compare with only 2 – 17 from the altimeters).

For this open ocean site, the amount of altimeter data could be improved by combining data from say a 2° by 2° area. The product is structured to facilitate this.

4 MULTI-SENSOR HIGH TEMPORAL RESOLUTION PRODUCT

4.1 PRODUCT OVERVIEW

The main objective is to provide a merged multi-sensor synthetic swell field description on a gridded domain with high temporal resolution typically 6 hourly or better. SAR can provide a large part of the required observations using swell propagation as described in Collard & all 2009 and Ardhuin & all 2009 but the satellite orbit may irregularly observe swell propagating with the same zonal drift as the satellite orbit. The addition of propagated buoy and seismometer data is way to fill this SAR observations gap

Ardhuin Fabrice, Chapron Bertrand, Collard Fabrice (2009). **Observation of swell dissipation across oceans**. *Geophysical Research Letters (GRL)*, 36(L06607), 1-5. Publisher's official version : http://dx.doi.org/10.1029/2008GL037030 , Open Access version : http://archimer.ifremer.fr/doc/00000/6452/

Collard Fabrice, Ardhuin Fabrice, Chapron Bertrand (2009). **Monitoring and analysis of ocean swell fields from space: New methods for routine observations**. *Journal Of Geophysical Research Oceans*, 114, -. Publisher's official version : http://dx.doi.org/10.1029/2008JC005215 , Open Access version : http://archimer.ifremer.fr/doc/00000/11101/

In particular, integration of wave buoys have been implemented and the gain has been evaluated when stroboscopic satellite sampling causes all observations to be clustered in a confined area and a large part of the swell field left without observations. First results show that using wave buoy brings information not only over poorly satellite sampled area but also for large wavelength where the wave buoy cutoff wavelength is larger that the SAR L2P largest observable dominant wavelength. It was planned to include the seismometer data when they become available but the filtering of earthquake events turned to be a limiting factor to exploit the time continuity of such observations.

The methodology is described in: Tandeo et al. “Interpolated swell fields from SAR measurements”, proceedings of OCEANS conference 2013 (provided in annex)

Demonstration products are available at the following address:

http://www.boost-technologies.com/rhusson/Synthetic_swell_fields_V2/

4.2 PRODUCT VALIDATION

A product validation was performed over the Stratus deep ocean directional wave buoy offshore the Chilean Pacific coast maintained by the Woods Hole Oceanographic Institution (WMO ID. 32012). The results are given for two densities of available SAR observations: C_{High} mean high density and C_{Mid} means just above the average. And results are compared to existing wave forecasting model outputs (WW3 hindcast run at IFREMER).

The table bellow provides the performance estimation for the three main swell parameters being the Swell significant wave height (Hss), the Dominant period (Tp) and the Dominant direction (Dp).

	Config.	SAR		Model	
		C_{High}	C_{Mid}	C_{High}	C_{Mid}
any H_{ss}	RMSE [m]	0.26	0.33	0.37	0.38
	NRMSE [%]	16.6	21.6	23.9	25.3
	Bias [m]	-0.04	-0.02	0.26	0.26
	Correl.	0.87	0.82	0.86	0.87
T_p	RMSE [s]	0.46	0.49	0.62	0.66
	NRMSE [%]	3.4	3.5	4.5	4.7
	Bias [s]	-0.2	-0.2	0.43	0.43
	Correl.	0.86	0.92	0.86	0.89
D_p	RMSE [deg]	16.4	-16.2	16.9	17.4
	Bias [deg]	-2.4	-3.7	-7.3	-8.5

5 SEA STATE CHANGE INDICATORS

5.1 PRODUCT OVERVIEW

5.1.1 SAR DERIVED SEA STATE CLIMATE INDICATORS

Based on the monthly SAR products we have analysed the long term and seasonal evolution of Dominant wavelength and significant swell height (long waves imaged by SAR). The analysis has been done for each major oceans such as the southern ocean (pacific + atlantic + indian) the tropical ocean (pacific + atlantic + indian) and the northern ocean (separately North Pacific and North Atlantic).

We have used either the full ENVISAT period of SAR data (2003-2012) or the combination of this ENVISAT period and the ERS2 period (1995-1998) when the GIRO where available and therefore the quality of SAR wave mode data was nominal.

5.1.1.1 DOMINANT WAVELENGTH

The dominant wavelength is the wavelength of the most energetic peak in the SAR derived swell spectra.

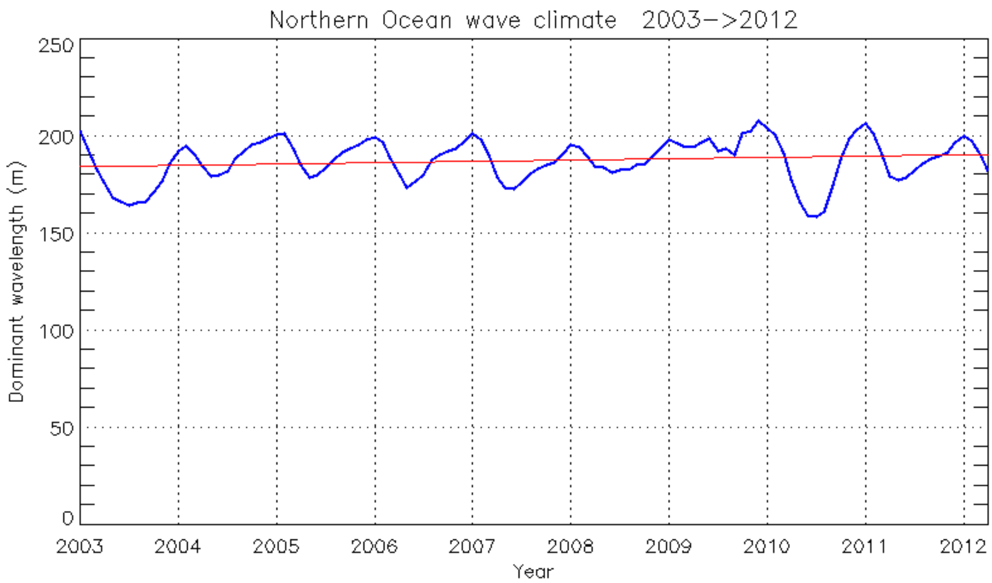


Figure 8 : Evolution of Dominant wavelength in the Northern Oceans (latitude 20° to 60°) over the ENVISAT period (blue) and linear trend (red).

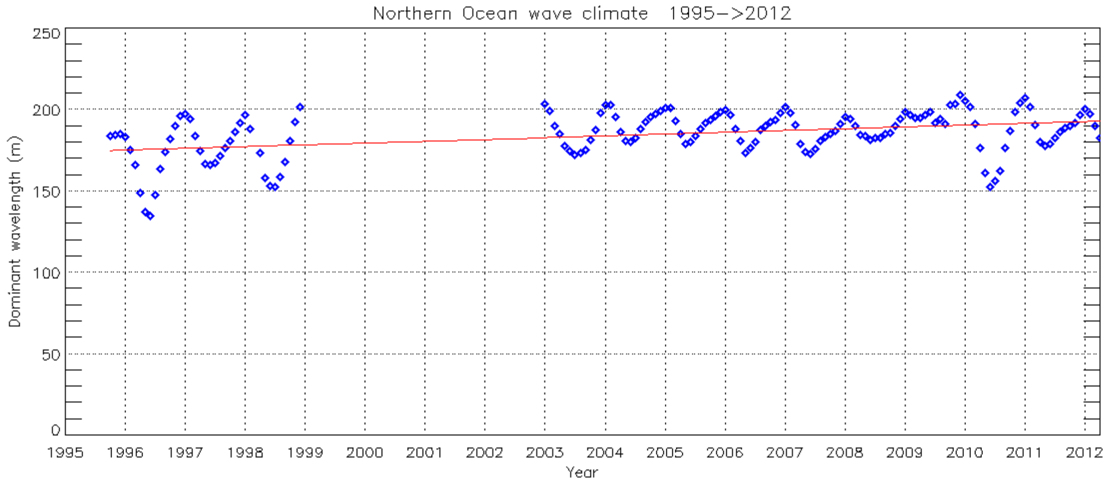


Figure 9 : Evolution of Dominant wavelength in the Northern Ocean (latitude 20° to 60°) over the combined ERS2 and ENVISAT period (blue) and linear trend (red).

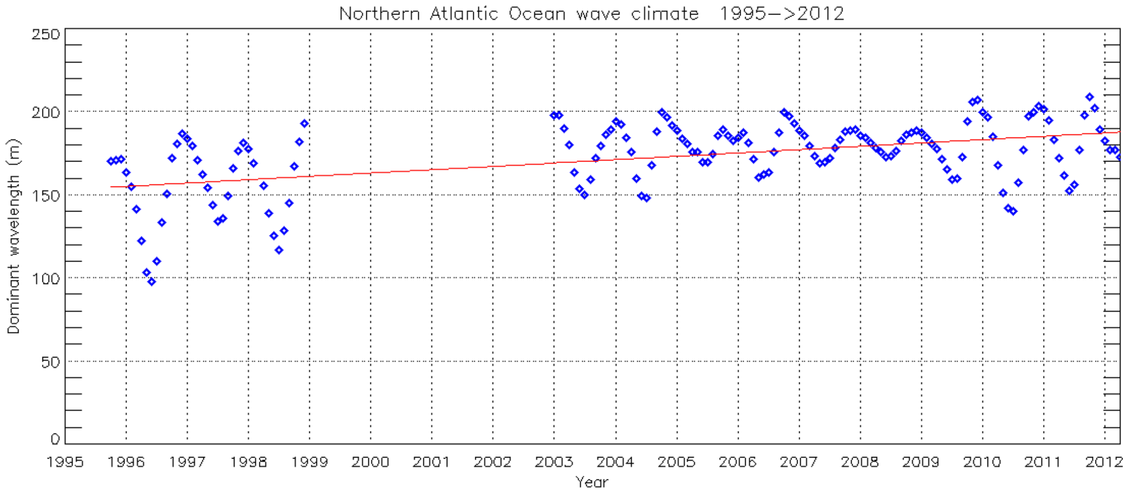


Figure 10 : Evolution of Dominant wavelength in the North Atlantic Ocean (latitude 20° to 60°) over the combined ERS2 and ENVISAT period (blue) and linear trend (red).

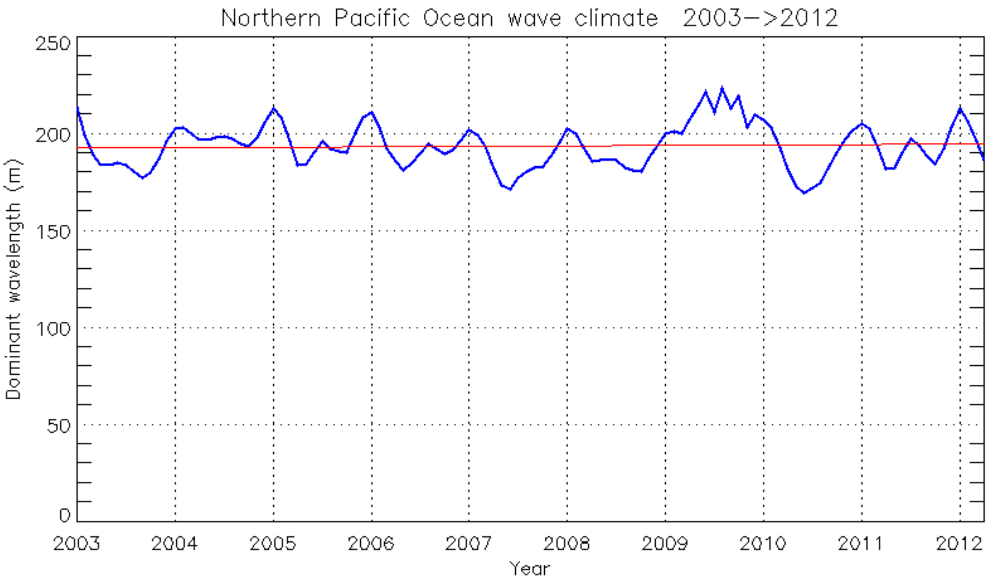


Figure 11 : Evolution of Dominant wavelength in the North Pacific Ocean (latitude 20° to 60°) over the ENVISAT period (blue) and linear trend (red).

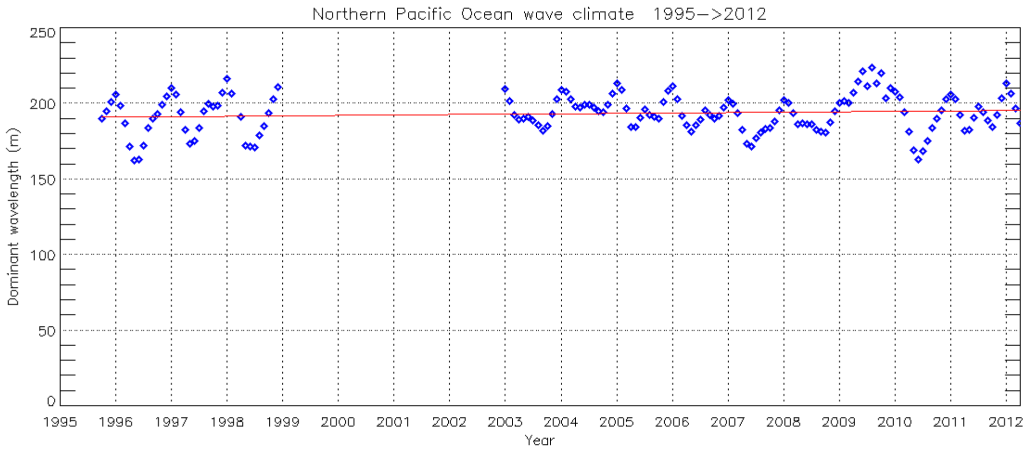


Figure 12 : Evolution of Dominant wavelength in the North Pacific Ocean (latitude 20° to 60°) over the combined ERS2 and ENVISAT period (blue) and linear trend (red).

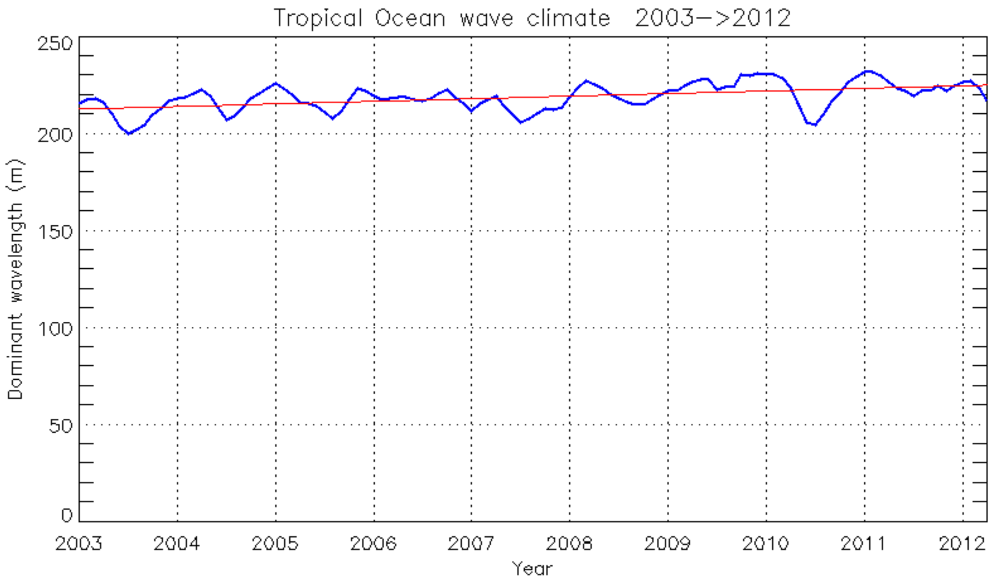


Figure 13 : Evolution of Dominant wavelength in the Tropical Oceans (latitude -20° to 20°) over the ENVISAT period (blue) and linear trend (red).

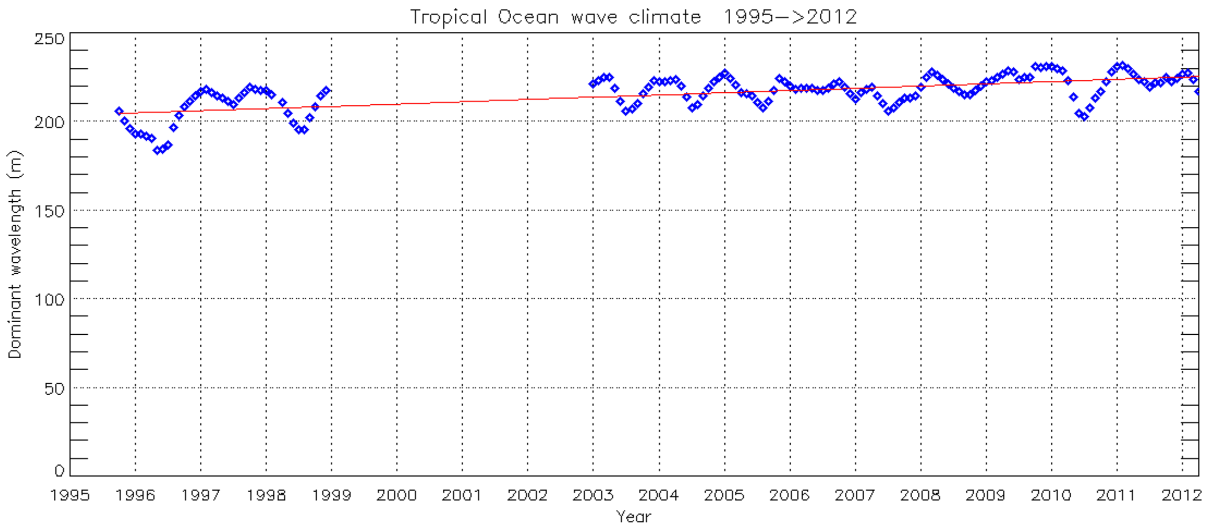


Figure 14 : Evolution of Dominant wavelength in the Tropical Oceans (latitude -20° to 20°) over the combined ERS2 and ENVISAT period (blue) and linear trend (red).

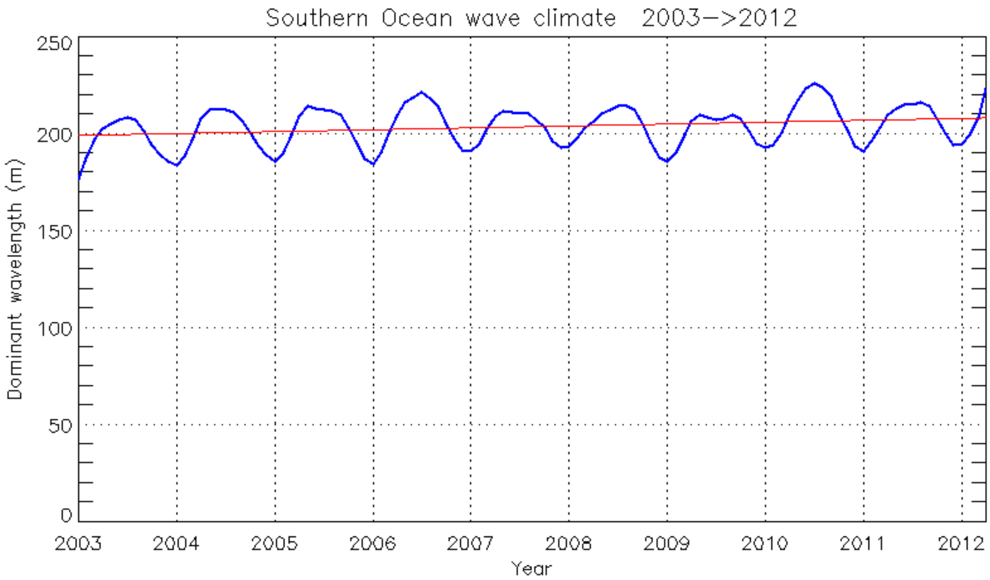


Figure 15 : Evolution of Dominant wavelength in the Southern Ocean (latitude -65° to -40°) over the ENVISAT period (blue) and linear trend (red).

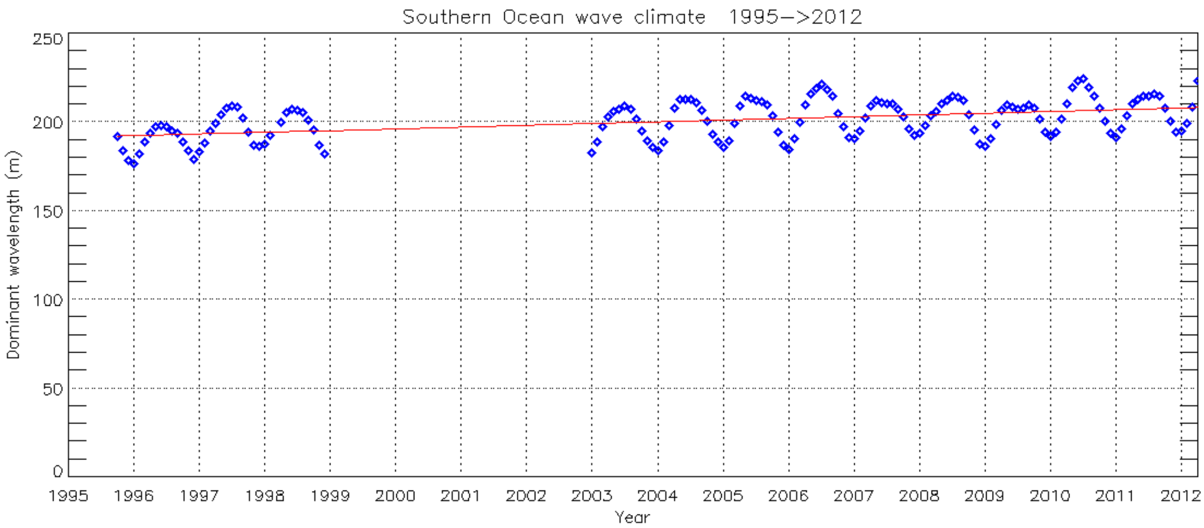


Figure 16 : Evolution of Dominant wavelength in the Southern Ocean (latitude -65° to -40°) over the combined ERS2 and ENVISAT period (blue) and linear trend (red).

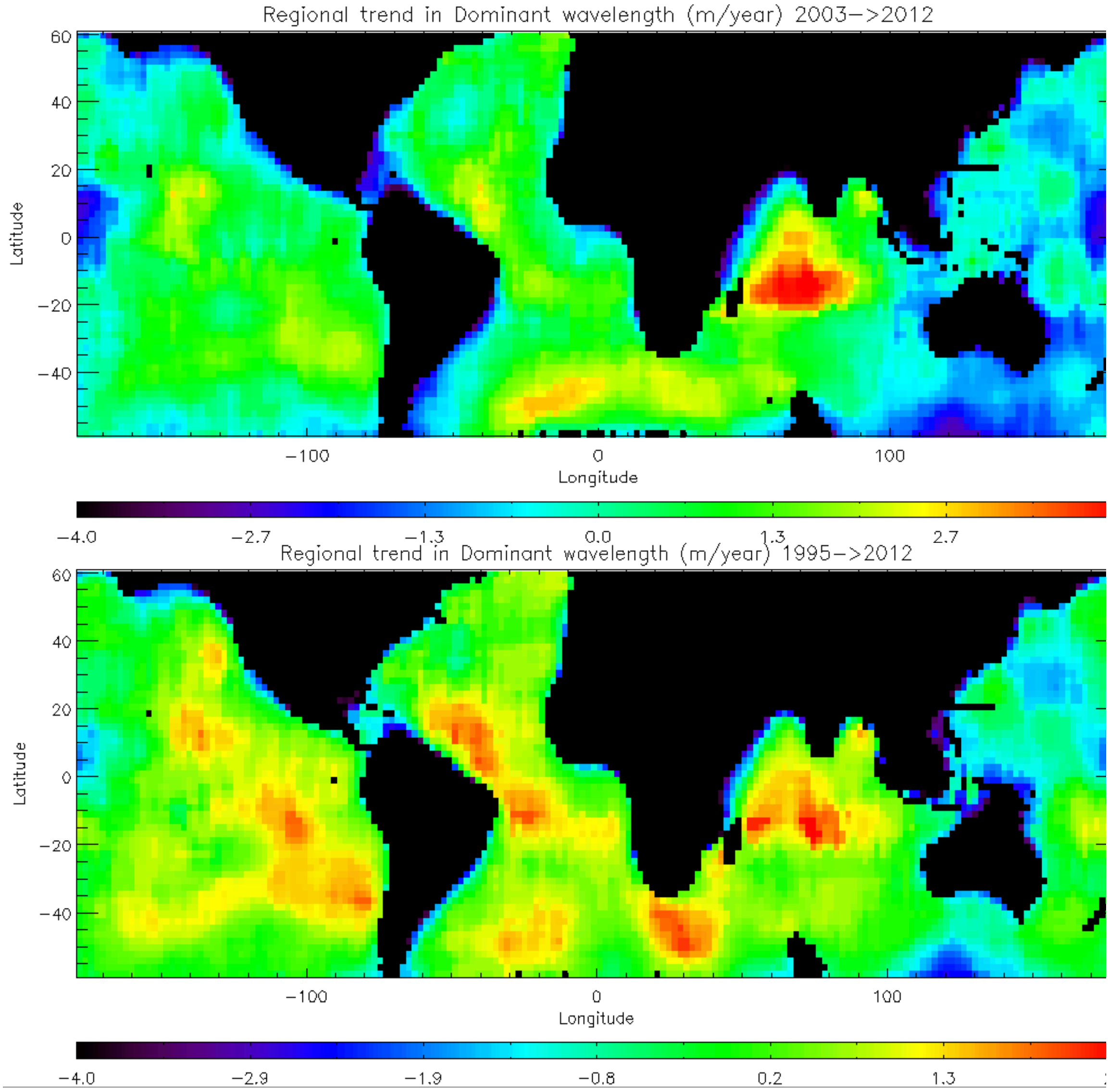


Figure 17 : Linear trend in the evolution of Dominant Wavelength over the ENVISAT period (upper map) and combined ERS2 and ENVISAT period (lower map)

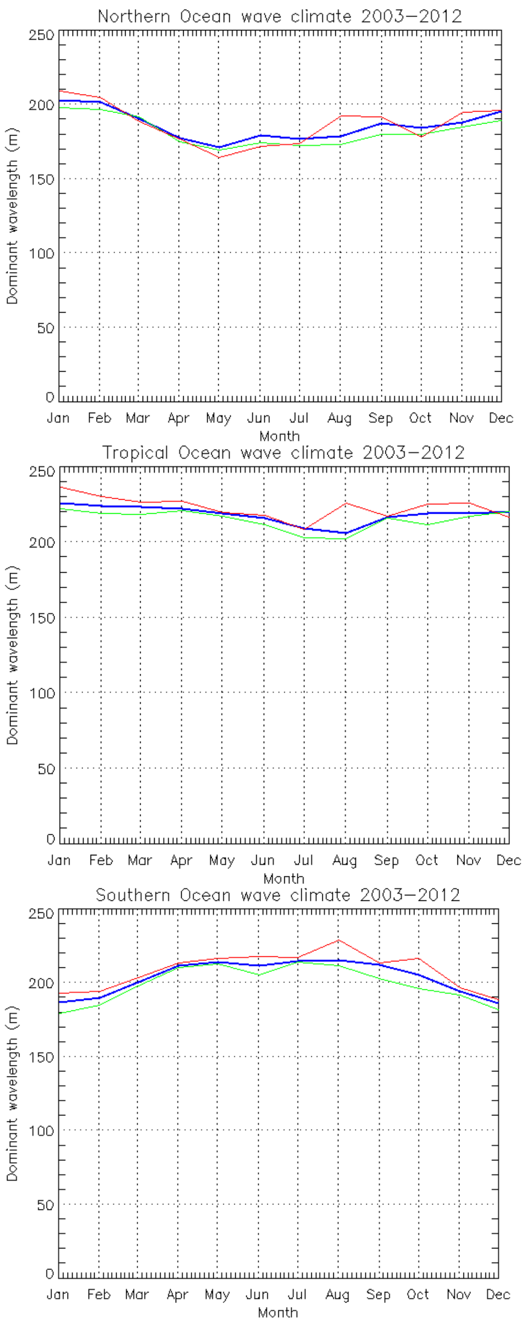


Figure 18 : Seasonal variations of Dominant Wavelength over the ENVISAT period for the Northern oceans (upper left), Tropical oceans (upper right) and Southern Oceans (lower left). Blue curve is the mean over 2003-2012 period, green line is for 2003 and 2004 only, red for 2011 and 2012.

5.1.1.2 SIGNIFICANT SWELL HEIGHT

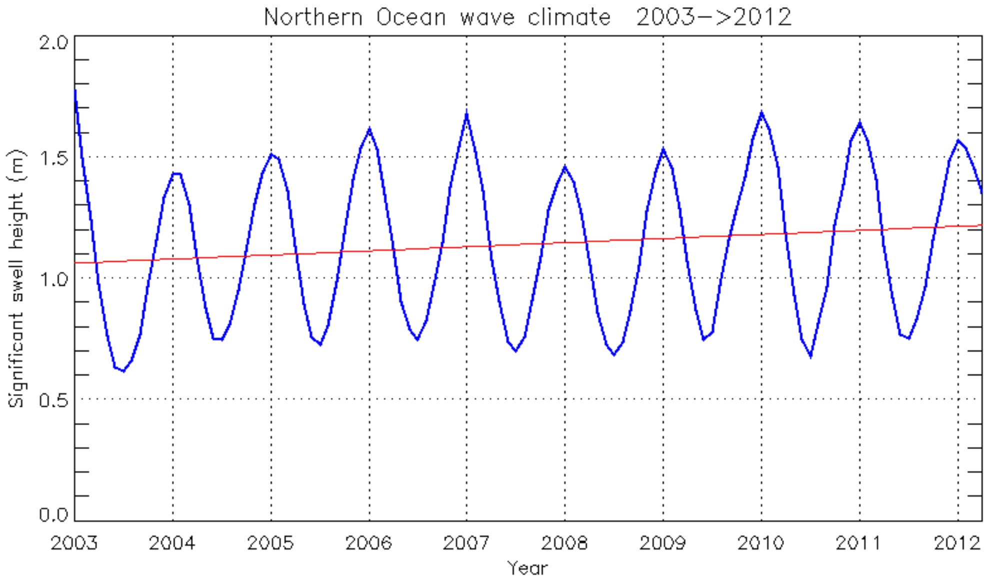


Figure 19 : Evolution of Significant swell height in the Northern Oceans (latitude 20° to 60°) over the ENVISAT period (blue) and linear trend (red).

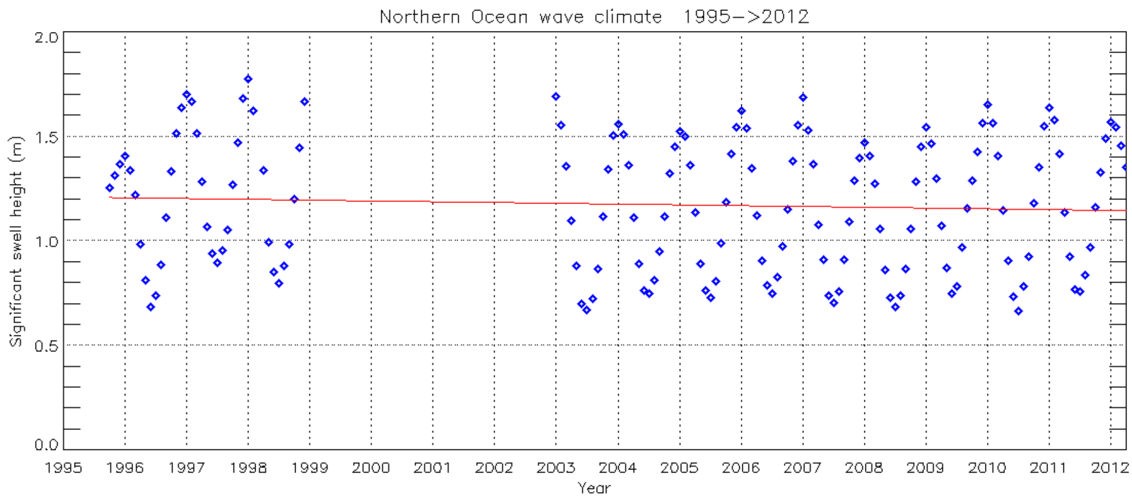


Figure 20 : Evolution of Significant swell height in the Northern Oceans (latitude 20° to 60°) over the combined ERS2 and ENVISAT period (blue) and linear trend (red).

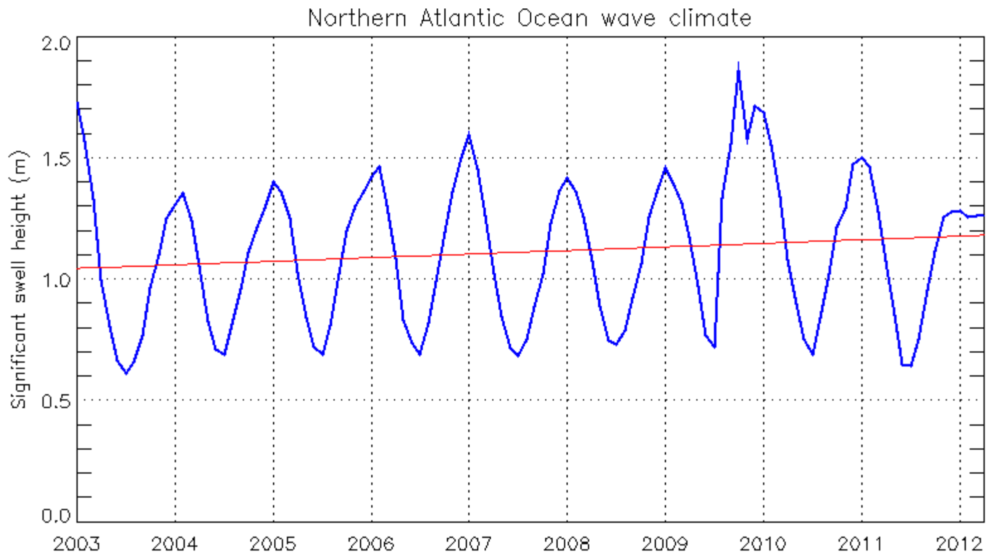


Figure 21 : Evolution of Significant swell height in the North Atlantic Ocean (latitude 20° to 60°) over the ENVISAT period (blue) and linear trend (red).

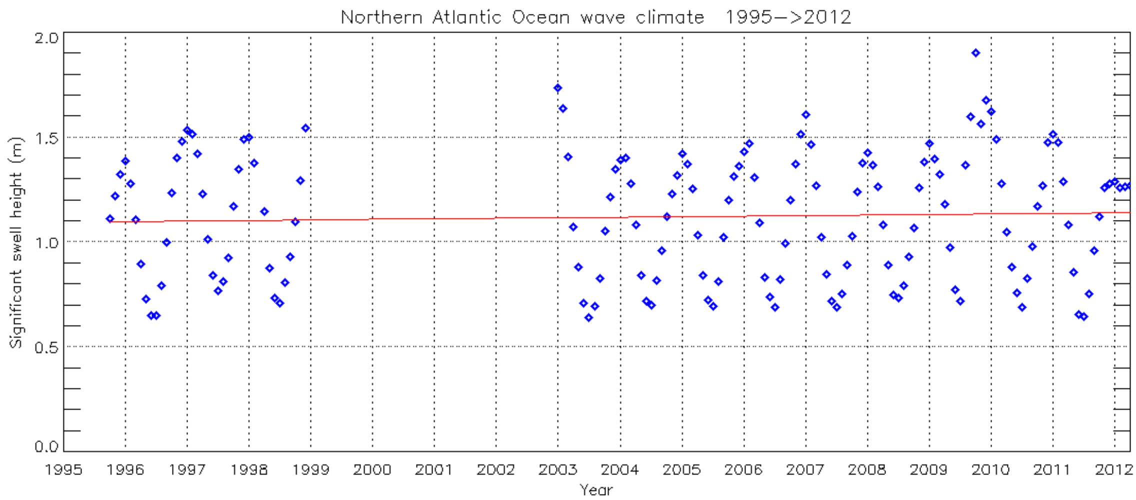


Figure 22 : Evolution of Significant swell height in the North Atlantic Ocean (latitude 20° to 60°) over the combined ERS2 and ENVISAT period (blue) and linear trend (red).

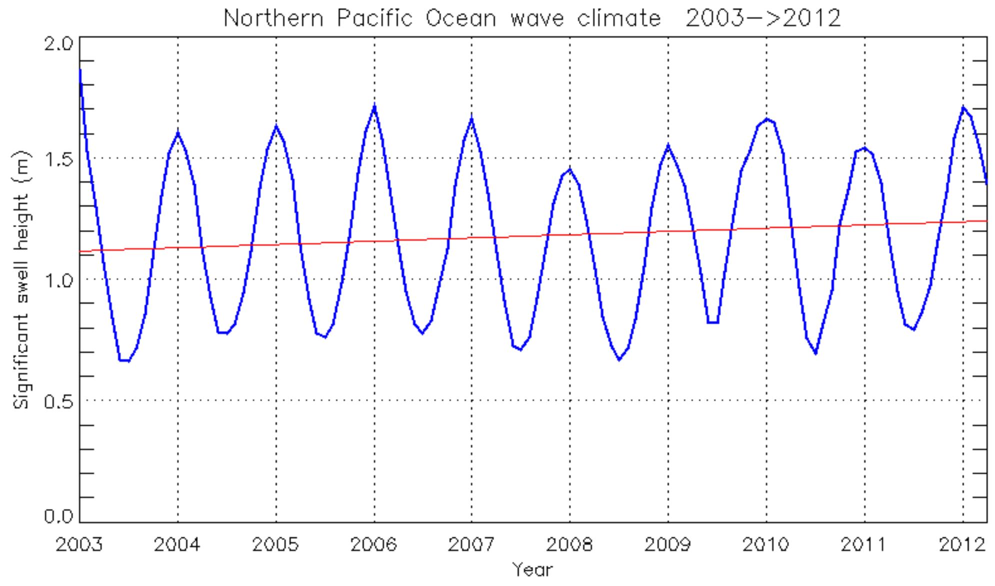


Figure 23 : Evolution of Significant swell height in the North Pacific Ocean (latitude 20° to 60°) over the ENVISAT period (blue) and linear trend (red).

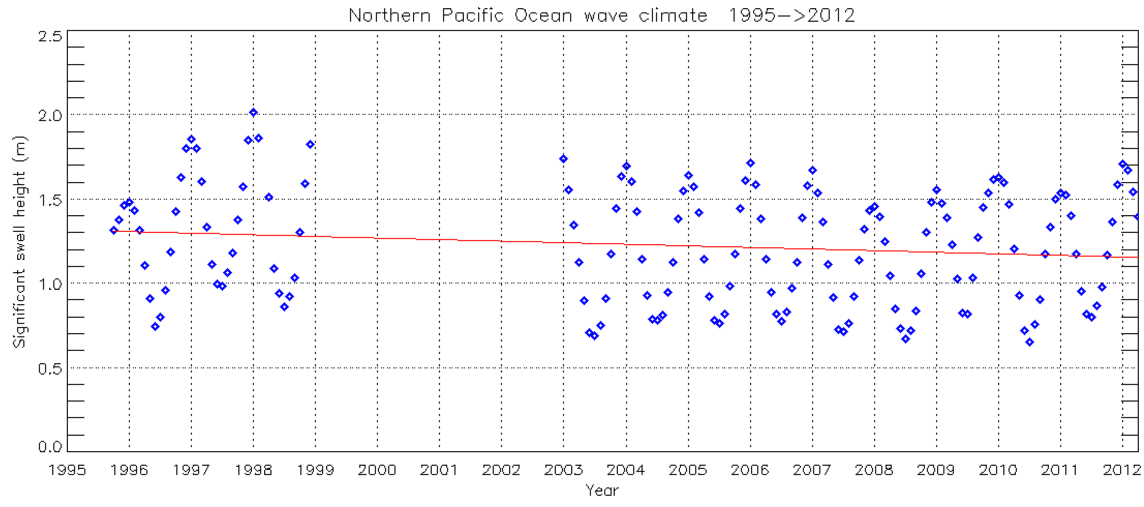


Figure 24 : Evolution of Significant swell height in the North Pacific Ocean (latitude 20° to 60°) over the combined ERS2 and ENVISAT period (blue) and linear trend (red).

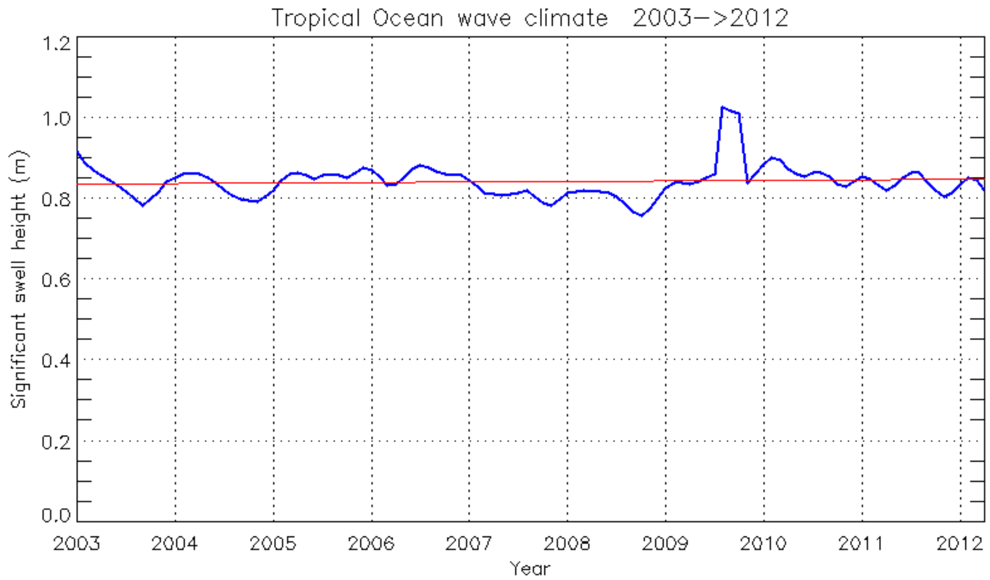


Figure 25 : Evolution of Significant swell height in the Tropical Oceans (latitude -20° to 20°) over the ENVISAT period (blue) and linear trend (red).

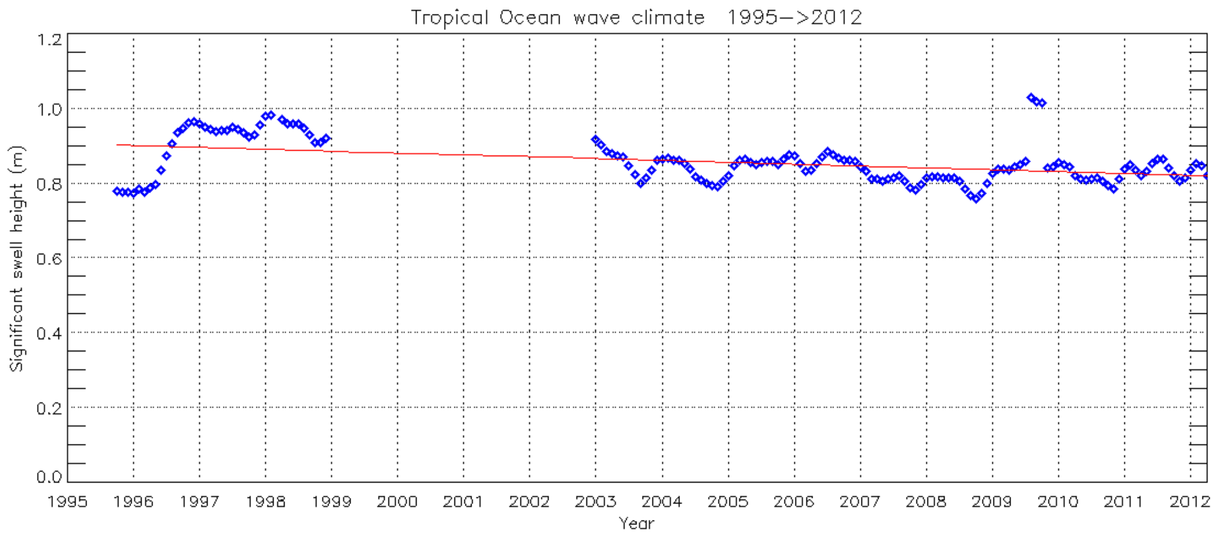


Figure 26 : Evolution of Significant swell height in the Tropical Oceans (latitude -20° to 20°) over the combined ERS2 and ENVISAT period (blue) and linear trend (red).

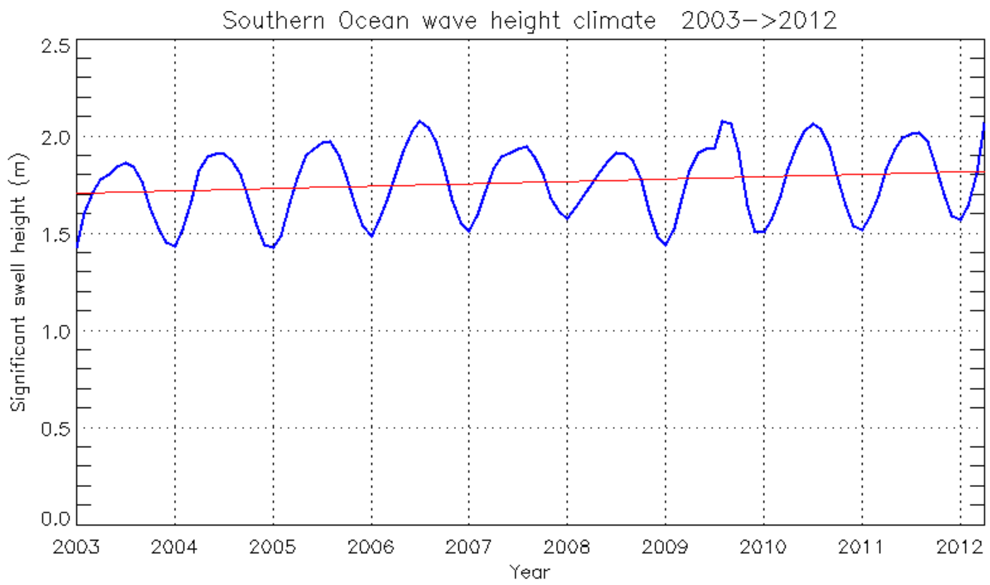


Figure 27 : Evolution of Significant swell height in the Southern Ocean (latitude -65° to -40°) over the ENVISAT period (blue) and linear trend (red).

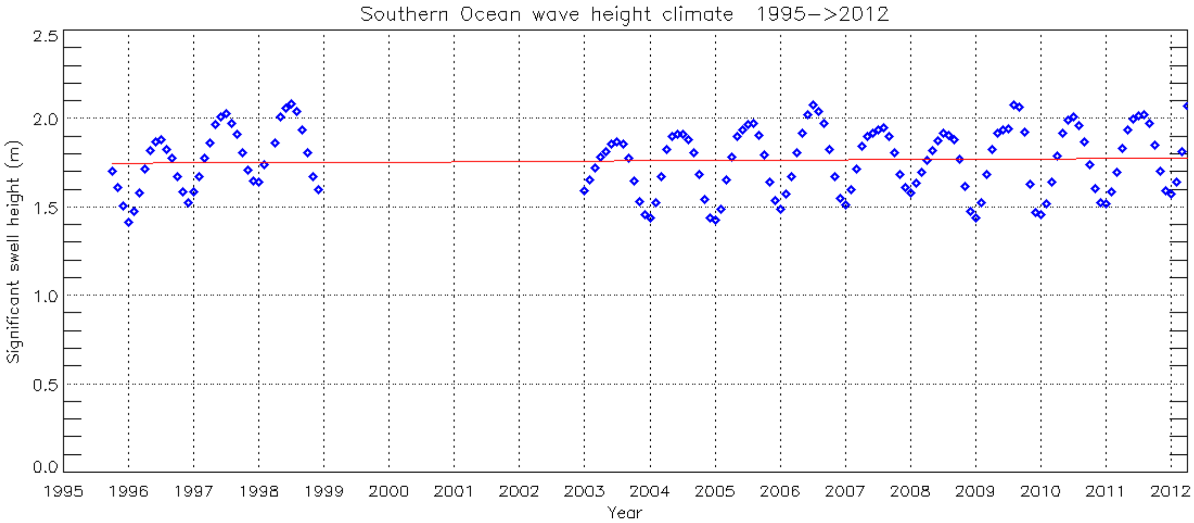


Figure 28 : Evolution of Significant swell height in the Southern Ocean (latitude -65° to -40°) over the combined ERS2 and ENVISAT period (blue) and linear trend (red).

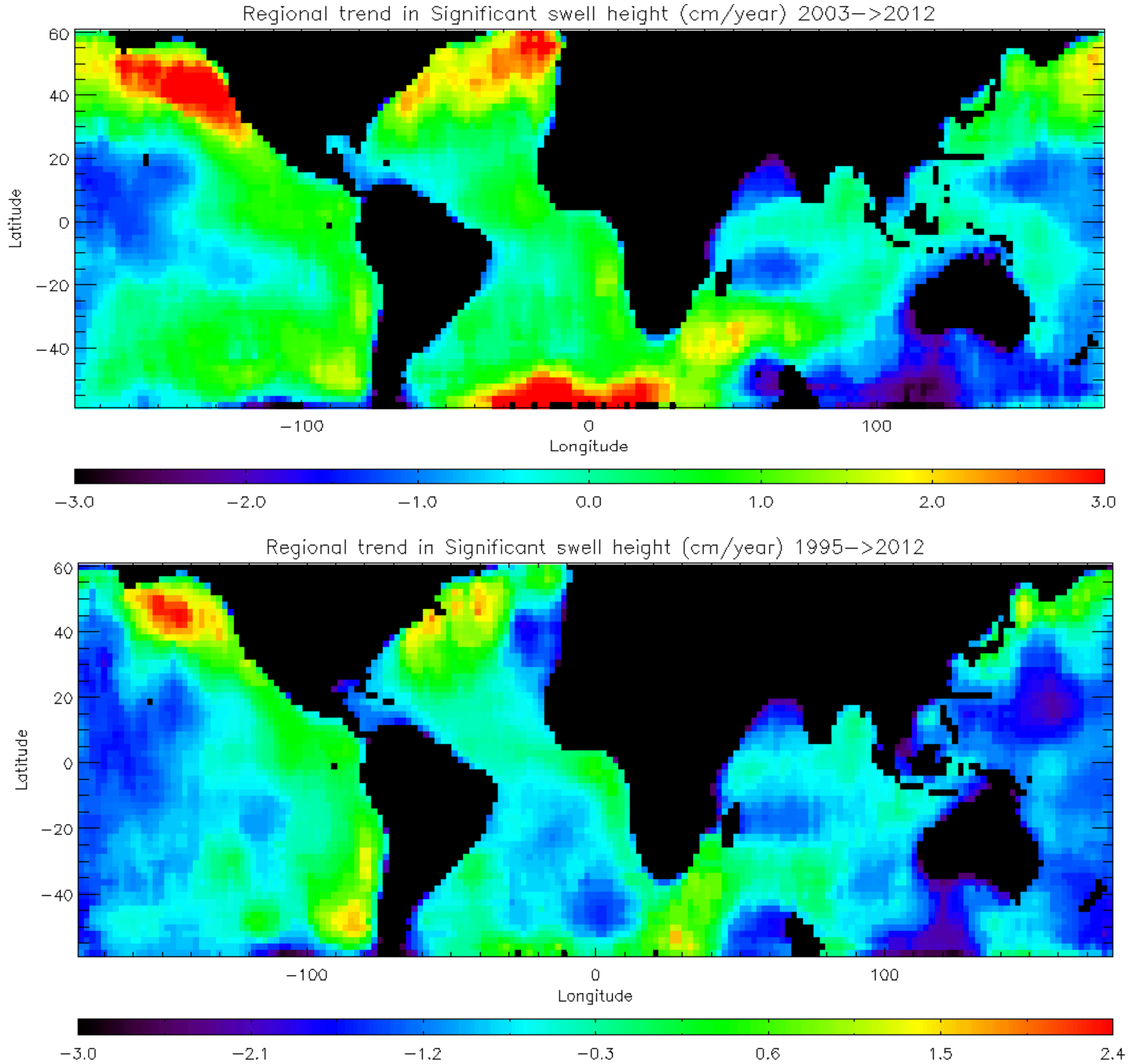


Figure 29 : Linear trend in the evolution of Significant swell height over the ENVISAT period (upper map) and combined ERS2 and ENVISAT period (Lower map)

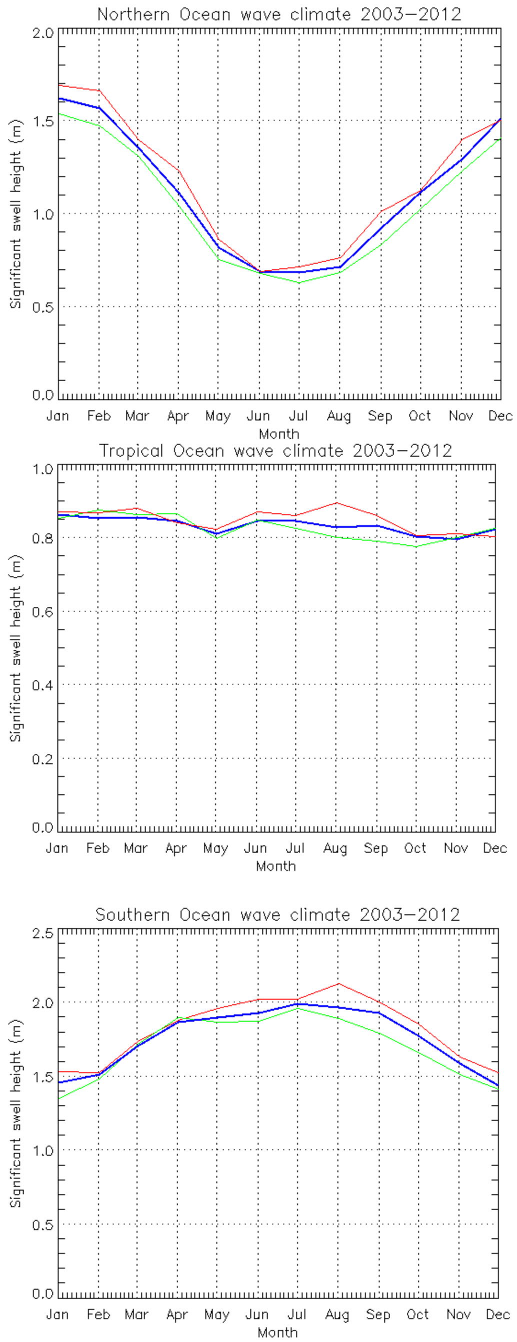


Figure 30: Seasonal variations of Significant swell height over the ENVISAT period for the Northern oceans (upper left), Tropical oceans (upper right) and Southern Oceans (lower left). Blue curve is the mean over 2003-2012 period, green line is for 2003 and 2004 only, red for 2011 and 2012.

5.2 CLIMATOLOGY ANALYSIS

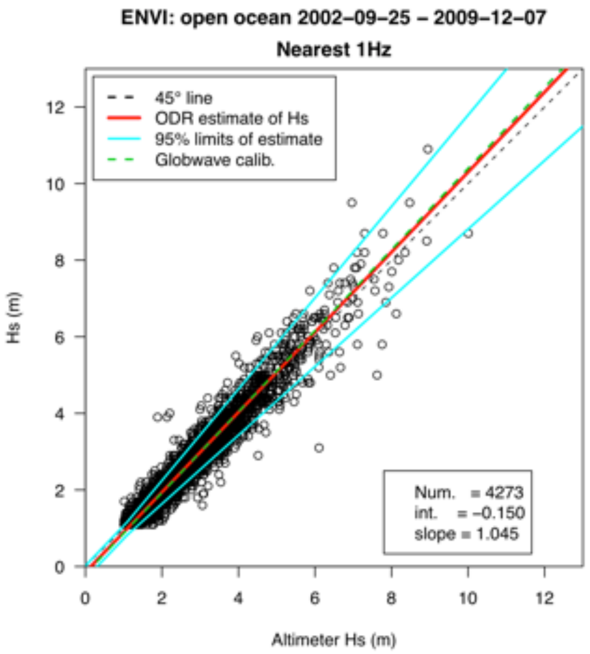
The climatologies extracted from the 3 years of ERS2 and 10 years of ENVISAT are very consistent in terms of seasonal variabilities but the long term trend in the evolution of dominant wavelength and significant swell height can be quite different if looking at the ENVISAT period only or at the combined ERS2 and ENVISAT period. The first conclusion is that, for some trend analysis, a longer time series is needed and the ENVISAT period itself is not enough. The other conclusion is that we can observe a general increase of the dominant wavelength that is much larger in the North Atlantic ocean (+15% in 17 years) and the Indian Ocean than in the Western Pacific (between 0 and -7 % over 17 years). An increase of the dominant wavelength is associated to a larger proportion of swell dominated sea states and is consistent with the general increase of significant wave height observed on the eastern side of the world oceans that are known as swell basins.

With these observations, however, it is necessary to be cautious when estimating trends across a broken time series, especially in this case when observations are from different instruments.

6 FEEDBACK AND RECOMMENDATIONS

6.1 ALTIMETRY MONTHLY GRIDDED SEA STATE

GCOS requests an accuracy of significant wave height (SWH) of 10 cm. David Carter, independent wave expert, considers that for individual estimates of SWH this is not a practical approach because standard error in estimates of SWH, from either 15 minutes of buoy measurement or 1 second of altimeter data, due to variability in these data, increases with increasing SWH. This has been shown from the altimeter error analysis work in GlobWave, for example see diverging lines of 95% limits for Envisat when comparing with buoy measurements of SWH:



The accuracy of climate parameters of SWH, such as monthly or annual means, also depends on the magnitude of individual values; also on the number of records (known but varying from month to month or year to year), on the often large within-year and between year variability, and on the correlation structure in the individual records (highly variable and very difficult to estimate). This correlation results in the accuracy of estimates of monthly means from hourly buoy data being significantly worse than expected from about the 700 records assuming they were independent, and not very much better than estimates from say 10 altimeter passes during the month. For further information on relative accuracies of buoy, altimeter and model SWH estimates see Abdalla et al. (2011).

Reference:

Saleh Abdalla, Peter A. E. M. Janssen and Jean-Raymond Bidlot (2011): Altimeter Near Real Time Wind and Wave Products: Random Error Estimation, Marine Geodesy, 34:3-4, 393-406.

The Altimetry Monthly Gridded Sea State products were presented to the Coordinated Ocean Wave Climate Project (COWCLIP) group of wave climate modellers in Paris on 1 October 2014. The products were well received and considered valuable as a comparison with model results for historical statistics. Several participants have accessed the data files and are using them in their climate comparisons.

Jean Bidlot (ECMWF) considers that comparisons with European buoys would be a useful addition to the validation of the altimeter products.

6.2 SAR PRODUCTS

Jean Bidlot suggest that care should be taken when describing significant wave height for SAR and it should always be clear that this is the significant wave height of the long swell waves. In general the term significant swell height has been used throughout the report to make this distinction.

Caution should be used when extrapolating linear trends across broken time series especially where more than one satellite instrument is used. A statistical analysis should be used to verify the robustness of the trend, and there should be careful cross-calibration between different instruments. As an example there appeared to be a trend in the significant wave height output of the ECMWF ERA Interim reanalysis over a 40-year period, but it was found that this could be attributed to a jump in the series on the introduction of altimeter data in the assimilation scheme.

In general Jean Bidlot considers the SAR and altimeter products to be a good contribution to the preparation of a Sea State ECV. He will use the products for future validation of ERA-Interim statistics results.