BMT ARGOSS

# Validation of the BMTA 35-year Hindcast Database v361

Prepared for: *BMT ARGOSS*
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# Document Status Sheet

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# 1. Introduction

## 1.1. Scope and Objectives of the Validation

The purpose of this validation document is to check that the new 35-year hindcast (v361)

1. Performs as can be expected
2. Performs at least as well as the previous 22-year hindcast (v352)
3. Has been improved (*according to buoys*) by means of calibration with satellites

The quality of the hindcast is evaluated both over the years and per region. This report focuses on the normal wind and wave climate but higher and extreme hindcast values have also been validated.

## 1.2. Grids of Interest

The hindcast has been validated for the global grid and for the regional EU-shelf grid.
Table 1 characterizes the available model grids; the model grids validated in this report are highlighted in the table. Note that the global grid used for the new hindcast (v361) has finer resolution than the global grid used previously (v352).

| Model Grid | Resolution | Area S-N | Area W-E | Period Validated |
|---|---|---|---|---|
| **Global (v361)** | **30' x 30'** | **78°S-78°N** | **180°W-180°E** | **1979-2013** |
| **EU-Shelf** | **10' x 10'** | **40°N-66°N** | **15°W-31°E** | **1992-2013** |
| Mediterranean | 15' x 15' | 13°N-47°N | 5°W-56°E | 1992-2013 |
| NW Australia | 10' x 10' | 24°S-8°S | 111°E-131°E | 1992-2013 |
| Indonesia | 5' x 5' | 9°S-3°N | 98°E-122°E | 1992-2013 |
| Thailand | 5' x 5' | 2°N-14°N | 99°E-121°E | 1992-2013 |
| **Global (v352)** | **1°x 1¼°** | **78°S-78°N** | **180°W-180°E** | **1992-2013** |

**Table 1: Characteristics of available hindcast grids**

The regional model grids are outlined in Figure 1.

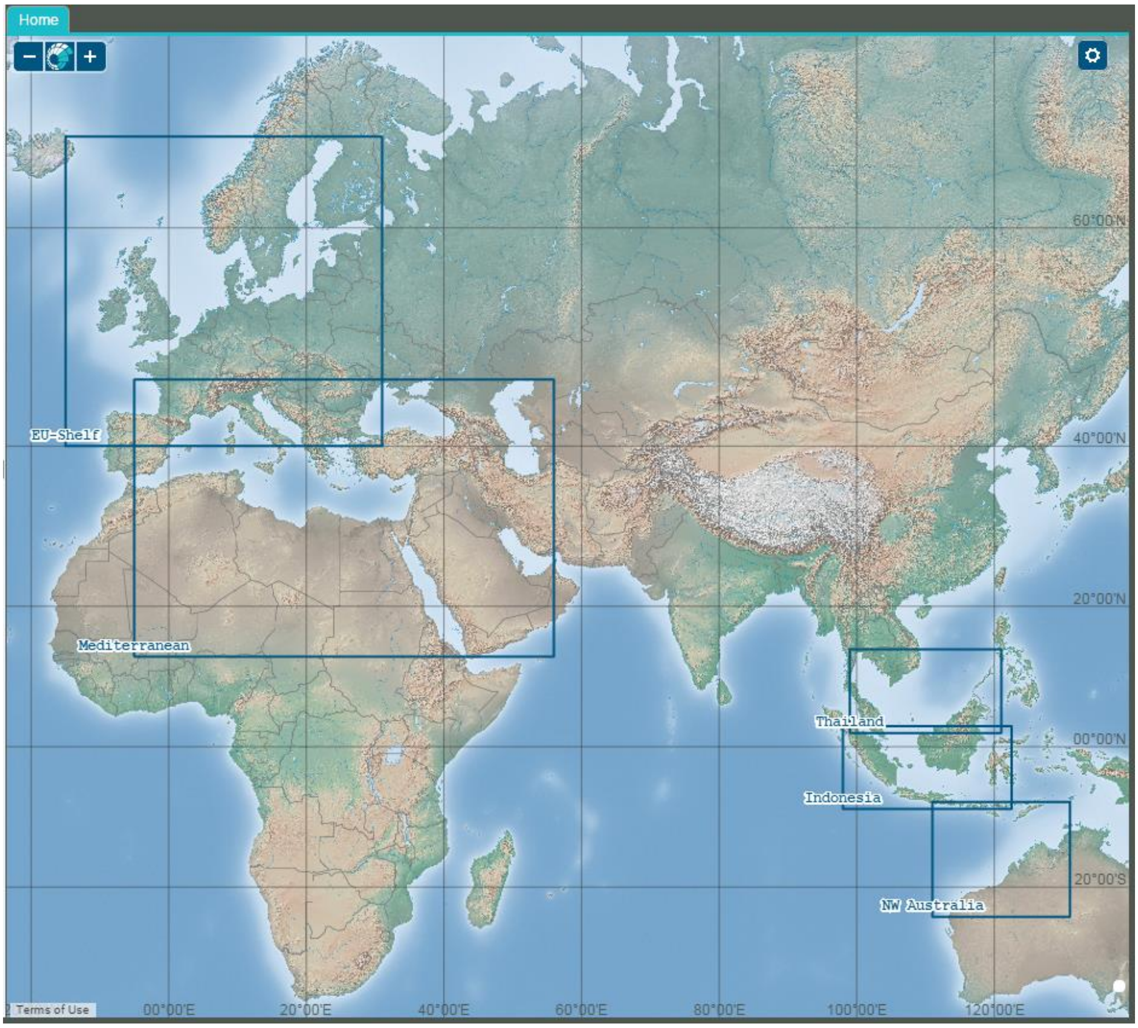


**Figure 1 Extension of the available hindcast grids**

## 1.3. Fitness for Purpose

Calibration of hindcast wind and waves with satellites as described in this report aims to remove the systematic error in wind and wave parameters for the ambient offshore climate. The calibration was done in an automated way, applying grid point specific corrections based on the bulk of the model data.

Extreme conditions, effects of tropical storms, vicinity of land or shallow water need special attention and cannot be dealt with by means of automated calibration. For these cases, manual calibration by an expert is required.

**The above means that for consultancy projects the distributions of auto-calibrated higher and extremes values presented in this report would normally be further improved by means of manual calibration of the tail of the distributions.**

## 1.4. Executive Summary

We validated BMTA's new 35-year hindcast wind and wave database (v361; 1979-2013) and we compared it to the previous 22-year version (v352; 1992-2013) with reference to nearly 100 buoys, spread over 13 different regions with a more or less homogenous climate. We also checked the effect of basic, automated calibration with satellites meant to remove any systematic model error for the ambient climate.

**The quality of the hindcast is consistently high over the years, also before 1992, and the quality has improved: wind speed is clearly better and height, period and direction of the waves are equally good or better, provided that we calibrate with satellites.**

The work done and the above claim are elaborated on in the remainder of this summary starting on the next page.

We validated the new hindcast (1979-2013) against 94 buoys and we compared it to the previous hindcast (1992-2013), for the global grid and for the regional EU-shelf grid. We used 57 buoys spread over 6 regions for the global grid and 37 buoys in 7 distinct regions for the regional grid. We also compared the quality of the new global hindcast before and after 1-jan-1992 based on a subset of 28 NOAA buoys. Focus is on 'best' hindcast, i.e. auto-calibrated with satellites. Apart from wind speed and wave height, we also looked at wave period and wave direction. We investigated both ambient and extreme conditions. In this summary the quality of ambient model data relative to buoys is expressed in terms of relative error and correlation coefficient. The relative error incorporates both mean and standard deviation of the model error. Higher values and extremes are checked by means of plots. The conclusions, related to the three main questions (section 1.1), are formulated below.

### 1-The quality of the new database is high for all years 1979-2013

Overall error in 'best' model wind speed is 17-18% and the error in 'best' wave height is 15-16%. Correlation between buoy and model samples is high, i.e. linear correlation coefficients are 0.92 for wind and 0.96 for waves. Please refer to Table 2. *For comparison: based on the validation of satellites vs. buoys for the period 1992-2013, the overall error in altimeter wind is 17% and 10-11% for wave height. Correlation is 0.92 for wind and 0.98 for waves. See Table 7.*

Over the years, quality of model wind and waves is consistently high, although model variability is a bit higher before 1992 and wind quality suddenly reduces in 2010. Performance of the global model is reflected by the red lines in Figure 2-Figure 5 (1992-2013) and by Figure 13-Figure 18 (1979-2013). See Figure 29-Figure 32 for the regional model. As might be expected, model performance varies over regions; see Table 3 and Table 4. Newfoundland statistics might suffer a bit from lesser buoy quality; results in the English Channel are quite deviant. Despite the fact that we only applied basic satellite calibration for the ambient climate, the higher values of 'best' model winds and waves differ no more than say 10% from buoy data, as illustrated by the red lines in Figure 9-Figure 12 and Figure 36-Figure 39. The appendices show that quality of hindcast wave periods and directions is consistent over the years with good correlation and small biases; see for example Figure 140-Figure 143 and Figure 148.

### 2-The new database is better than the previous one

Mainly thanks to less variability, but also through less bias, the error in 'best' model wind has been reduced by 2-4%. Thanks to calibration, 'best' model waves improved by 1-2% ('raw' model waves are worse though). The new database is better for practically all regions. Please refer to Table 3 and Table 4. Improvement over the years is seen from the red and yellow lines in Figure 2-Figure 3 and Figure 29-Figure 32. From Table 5 and Table 6 and the associated plots, it is found that high and extreme winds improved for the global grid. For some regions however, particularly in the North Sea but also in areas affected by cyclones, higher and extreme wind and waves did not improve. In the appendices it is shown that 'best' wave periods and wave directions of both models are comparable.

### 3-Calibration with satellites significantly improves the hindcast

Calibration with satellites reduces the error in model wave height by about 2% and the error is reduced for almost all regions (11/13) as indicated in Table 3 and Table 4. Over the years, calibration consistently improves model waves as illustrated in Figure 6-Figure 7 and Figure 33-Figure 34. Calibration also significantly improves the more energetic model waves in most regions (11/13). Strongest impact is seen off Newfoundland (Figure 96), in the southern North Sea (Figure 126) and in the Irish Sea (Figure 120). Exception is the English Channel, where both model versions and altimeter clearly disagree with local buoys on the above average waves. Please refer to Table 5 and Table 6. In the appendices it is demonstrated that calibration also improves model wave periods as seen from e.g. Figure 136 and Figure 146.

The next table summarizes the overall error statistics of 'best' wind and waves produced by the global and by the regional model. The term 'overall' means taken over the years 1992-2013 and all buoys, i.e. 57 different buoys for the global model and 37 buoys for the regional model.

| Model | Hourly Mean Wind speed u10 | | | | | Significant Wave height Hs | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Mean (m/s) | Bias (m/s) | Std (m/s) | Rrmse (%) | Corr (-) | Mean (m) | Bias (m) | Std (m) | Rrmse (%) | Corr (-) |
| Global | **6.78** | **-0.08** | **1.29** | **17.0** | **0.92** | **1.99** | **-0.01** | **0.35** | **15.2** | **0.96** |
| EU-shelf | **7.89** | **0.06** | **1.54** | **17.7** | **0.92** | **2.01** | **0.05** | **0.39** | **16.4** | **0.96** |

**Table 2: Overall error statistics of model version v361 rel. to buoys per grid**

The following pair of tables provides the model-buoy error (%) and the impact of calibration with satellites per region and per grid, both for the old and for the new model. Errors are based on validation of the model against all buoy data in a particular region over the years 1992-2013. Comparison of the model errors leads to the best model ('best model' follows from comparison of 'v361-cal' to 'v352-cal') and to the effect of satellite calibration ('Sat Effect' is based on comparing 'v361-raw' and 'v361-cal').

| Global Model | Hourly Mean Wind speed u10 | | | | | Significant Wave height Hs | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | v361 cal (%) | v352 cal (%) | v361 raw (%) | Best Model | Sat Effect | v361 cal (%) | v352 cal (%) | v361 raw (%) | Best Model | Sat Effect |
| Gulf of Mexico | 19.4 | 22.0 | | v361 | | 17.6 | | 19.4 | | + |
| Atlantic | 18.5 | 23.7 | | v361 | | 16.9 | | 19.8 | | + |
| Newfoundland | 19.6 | 25.3 | | v361 | | 18.6 | | 21.3 | | + |
| Pacific | 15.5 | 19.1 | | v361 | | 14.4 | | 16.5 | | + |
| Hawaii | 14.7 | 17.1 | | v361 | | 12.6 | | 13.9 | | + |
| Caribbean | 16.3 | 15.5 | | v361 | | 14.6 | | 16.8 | | + |
| **Global** | **17.0** | **20.6** | | **v361** | | **15.2** | | **17.4** | | **+** |

**Table 3: Error in global model and the effect of calibration with satellites per region**

| Regional EU-shelf Model | Hourly Mean Wind speed u10 | | | | | Significant Wave height Hs | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | v361 cal (%) | v352 cal (%) | v361 raw (%) | Best Model | Sat Effect | v361 cal (%) | v352 cal (%) | v361 raw (%) | Best Model | Sat Effect |
| EU-Atlantic | 17.2 | 21.2 | | v361 | | 14.9 | 15.7 | 14.5 | v361 | - |
| Celtic Sea | 16.9 | 17.4 | | v361 | | 15.7 | 16.7 | 18.7 | v361 | + |
| Irish Sea | 20.8 | 20.5 | | v352 | | 18.2 | 20.1 | 34.8 | v361 | + |
| Channel | | | | | | 23.6 | 24.1 | 22.4 | v361 | - |
| NS-South | 17.3 | 18.7 | | v361 | | 16.5 | 18.4 | 22.6 | v361 | + |
| NS-Central | 18.3 | 19.4 | | v361 | | 16.4 | 18.4 | 18.8 | v361 | + |
| NS-North | 17.2 | 19.7 | | v361 | | 16.9 | 18.1 | 17.6 | v361 | + |
| **EU-shelf** | **17.7** | **19.7** | | v361 | | **16.4** | **17.7** | **18.3** | v361 | **+** |

**Table 4: Error in EU-shelf model and the effect of calibration with satellites per region**

The pair of tables on this page provides an overview of model behaviour with respect to above-average wind and wave conditions per region for both models over the years 1992-2013. The tables also indicate how basic, automated satellite calibration, meant to improve average model values, also affects the higher and extremes values. A questions mark means that the old and the new model perform equally well.

*Please click on the links in the tables below to see the QQ-plot and the PoE plot for a region.*

| Global Model | Hourly Mean Wind speed u10 | | | | Significant Wave height Hs | | | |
|---|---|---|---|---|---|---|---|---|
| | Best Higher values | Best Extreme values | Sat Effect | Link to Plots | Best Higher values | Best Extreme values | Sat Effect | Link to Plots |
| Gulf of Mexico | v361 | v361 | | 94 | | | + | 95 |
| Atlantic | v361 | v361 | | 96 | | | + | 97 |
| Newfoundland | v361 | v361 | | 98 | | | + | 99 |
| Pacific | v361 | v361 | | 100 | | | + | 101 |
| Hawaii | v361 | ? | | 102 | | | + | 103 |
| Caribbean | v352 | v361 | | 104 | | | + | 105 |
| **Global** | **v361** | **v361** | | **31** | | | **+** | **32** |

**Table 5: Performance global model for higher and extreme values per region**

| Regional EU-shelf Model | Hourly Mean Wind speed u10 | | | | Significant Wave height Hs | | | |
|---|---|---|---|---|---|---|---|---|
| | Best Higher values | Best Extreme values | Sat Effect | Link to Plots | Best Higher values | Best Extreme values | Sat Effect | Link to Plots |
| EU-Atlantic | v361 | v361 | | 107 | v361 | v352 | - | 108 |
| Celtic Sea | v361 | ? | | 109 | ? | ? | + | 110 |
| Irish Sea | v361 | v361 | | 111 | v361 | v361 | + | 112 |
| Channel | | | | | ? | ? | - | 113 |
| NS-South | ? | ? | | 114 | ? | v352 | + | 115 |
| NS-Central | v352 | v352 | | 116 | ? | v352 | + | 117 |
| NS-North | ? | v352 | | 118 | ? | ? | + | 119 |
| **EU-shelf** | **V361** | **v352** | | **54** | **v361** | **v352** | **+** | **55** |

**Table 6: Performance EU-shelf model for higher and extreme values per region**

*Please note that calibration of hindcast wind and waves with satellites as investigated in this report aims to remove the systematic error for the ambient offshore climate. This basic calibration was done in an automated way: based on co-located model-satellite sample pairs, grid point specific model corrections were found from fitting the bulk of the sample pairs at that point. Extreme conditions, effects of tropical storms, vicinity of land or shallow water need special attention and cannot be dealt with by means of this basic, automated calibration. For these cases, manual calibration by an expert is required, which is common practice in BMTA consultancy. The distributions of auto-calibrated higher and extremes values presented in this report would normally be further improved by means of manual calibration of the tail of the distributions.*

# 2. Frames of Reference

## 2.1. Units and Conventions

Units are expressed using the SI (*Système International d'unités*) convention unless otherwise stated.

**Wave** and **Wind** direction is expressed as '**FROM'** which the wind and waves are approaching and in nautical degrees, i.e. degrees relative to true north (°T), positive clockwise.

## 2.2. Metocean Criteria Types

BMT ARGOSS typically distinguishes 3 different levels of offshore "climate" severity:

**Ambient Climate:** Normal conditions, comprising of conditions that prevail for the majority of the time. Ambient climate is characterised by the statistical distributions of metocean parameters as they appear in the hindcasts. These include the wide range from calm to severe conditions. As statistics on ambient conditions are often used to support offshore operations, they are also referred to as operational statistics.

**Normal Climate Extremes:** More energetic conditions, comprising of relatively severe conditions that only rarely occur in a particular area but are not classified as tropical storms. Extremes are statistical extrapolations based on the severest events observed in the hindcasts. By definition, the extreme value is the estimated magnitude of a particular metocean parameter to be equalled or exceeded once during a defined period, called the return period. Various methods are applicable for extreme value analysis for metocean parameters.

**Tropical Storm Extremes:** More energetic conditions - not of relevance in this report.

## 2.3. Metocean Parameters

- **Wind speed (u10) and direction (u10d) at 10 m asl.**
  Hourly Mean Wind speed at 10 m asl and associated direction.

- **Spectral density of sea surface waves S (wave spectrum)**
  The spectral density describes how the variance of the sea surface elevation is distributed over frequency f. It is often referred to as wave spectrum.

- **Significant wave height (Hs)**
  Derived from the zeroth spectral moment ($m_0$) and defined as $4 \times m_0^{0.5}$.

- **Principle wave direction (Hsd)**
  The direction derived from the first-order directional Fourier moments (sine and cosine-weighted moments) of the directional wave spectrum.

- **Mean zero-crossing wave period – spectral estimate (Tz or Tm02)**
  Defined as $(m_0/m_2)^{0.5}$. Spectrally derived Tz are typically a few percent shorter than the deterministically derived (up-crossing) mean period.

- **Spectral peak period (Tp)**

Derived as the reciprocal of the frequency associated with the peak energy of the wave spectrum.

- **Spectral moment (*$m_p$*)**
  For any integer p, $m_p$ is the integral over frequency f of $f^p$ multiplied by the wave spectrum, with f frequency in cycles per unit time. Remark: $m_0$ is the total variance of sea surface elevation.

## 2.4. Statistical Parameters

Model (or satellite) performance with respect to the ambient climate is expressed in terms of basic model-buoy error statistics of wind and integrated wave parameters. Basic error statistics involve

- Relative root mean square error (RRMSE)
- Bias (a negative bias means that model / satellite are too low)
- Standard deviation
- Linear correlation coefficient
- Number of samples

For directions, averages are found using the corresponding magnitudes as weight factors.

The relative root mean square error can be used as an overall performance indicator as it reflects both (absolute) bias and standard deviation.

- **Relative Root Mean Square Error (RRMSE)**

The relative error is the root-mean-square error normalised by the root-mean-square value of the buoy wave height:

$$RRMSE = \sqrt{\frac{\sum_{i=1,..n} \left| H_i^{satellite} - H_i^{buoy} \right|^2}{\sum_{i=1,..n} \left| H_i^{buoy} \right|^2}}$$

The overall quality of satellite/model data can be conveniently expressed by this one measure: the relative root-mean-square error (%) which incorporates both bias (offset) and standard deviation (variability) of the differences between two data sources.

# 3. Key Data Sources

## 3.1. BMT ARGOSS Hindcast Wind and Wave Database

BMTA runs a 3rd generation wave prediction model[1] based on the WAVEWATCH III ™ (WWIII) code, further improved in-house. The model is operated both in hindcast and forecast mode, on a global grid as well as on several regional grids. The new 35-year hindcast was generated for the grids listed in Table 1 and outlined in Figure 1.

In this report, we distinguish two versions of the BMTA wind and wave database:

- The new 35-year database based on WWIII driven by CFSR wind fields covering the period 1979-2013 (v361);
- The previous 22-year database based on WWIII driven by NCEP/ECMWF wind fields covering the period 1992-2013 (v352).

Please refer to Appendix A – Wave Model for a more detailed description of the model.

## 3.2. BMT ARGOSS Buoy Database

The in-house buoy database covers the years 1992-2013. Most buoy data were downloaded from NOAA website and checked for consistency and presence of outliers. Please refer to Appendix B1 – Buoys Used for the Global Hindcast and Appendix B2 – Buoys Used for the EU-shelf Hindcast for more detail.

## 3.3. BMT ARGOSS Satellite Database

The in-house satellite database covers the years 1992-2013 and all observations are extensively calibrated and validated against wave buoy data; the calibration is re-run each time the satellite database is extended, nominally annually.

Due to their global coverage and accuracy, the satellite wind/wave data can be used to validate/calibrate hindcast wind/wave data at practically any site in the world, and also at sites where no local in-situ wave measurements are available. The systematic quality control applied to the satellite data including their calibration/validation to wind and wave buoy data by BMTA ensures that the satellite data can be used as a reliable source of reference data worldwide.

The error estimates for the altimeter data obtained from these comparisons encompass sampling errors and spatial collocation errors. Satellite measurements are generally more accurate than hindcast data.

Wind satellite measurements are provided by altimeters and by scatterometers. If available, the scatterometer data are preferably used for model/dataset wind calibration: the error in scatterometer measurements relative to wave buoy data is generally smaller, and scatterometer data do not 'saturate in the tail' as the altimeter does for high wind speeds typically above 25 m/s. In the open sea, scatterometer data are generally available and supply the best wind measurements. For coastal areas however, typically within 50 km from the shore, sufficient scatterometer data may not be available; in this case altimeter measurements can be used to supplement the analyses. Error statistics of the 'best' satellite data are provided in Table 7.

[1] A 3rd generation wave model involves the representation of the spectrum on a discrete frequency-direction grid, and explicit computation of non-linear wave-wave interaction to re-distribute energy over frequency-direction bins such that no a-priori constraints are imposed on the spectral shape.

Appendix C – Validation of Satellite Data explains how the quality of our satellite data is maintained. The appendix provides buoy-satellite error statistics per satellite mission and shows the consistent quality of our 'best' satellite data over the years.

| **Buoy-Satellite Error Statistics 1992-2013** | **Altimeter** | | **Scatterometer** |
|---|---|---|---|
| | **Hs** | **U10** | **U10** |
| Buoy Mean | 2.06 m | 6.99 m/s | 6.95 m/s |
| Bias (satellite minus buoy) | 0.00 m | 0.06 m/s | 0.06 m/s |
| Standard Deviation | 0.25 m | 1.33 m/s | 1.07 m/s |
| Linear Correlation Coefficient | 0.98 | 0.92 | 0.94 |
| Number of Samples | 51762 | 49927 | 137201 |
| **Relative Root Mean Square Error** | **10.5 %** | **17.2 %** | **14.0 %** |

**Table 7: Error statistics of calibrated satellite data relative to buoys**

# 4. Approach

This section explains our approach to obtain the objectives of this study listed in section 1.1.

## 4.1. Creation of the 35-year Hindcast Database

CFSR wind fields covering the years 1979-2013 were used to drive our in-house WAVEWATCH III wave model and wind and computed wave parameters were added to the hindcast database for the grids mentioned in Table 1. Prior to running the wave model, the CFSR winds were calibrated with satellite observations in an automated way. Wave parameters stored in the hindcast database are un-calibrated. The calibration coefficients (scale and intercept) for wind speed and significant wave height were stored per grid point for each grid. The calibration coefficients for significant wave height are used to auto-calibrate wave spectra. Integration of calibrated wave spectra then provides auto-corrected integrated wave parameters, i.e. significant wave height, wave periods and wave directions. Note that automated correction is used for online services only. For consultancy projects the distributions of auto-calibrated higher and extremes values presented in this report would normally be further improved by means of manual calibration of the tail of the distributions.

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## 4.2. Analysis of the Model Performance

To pursue the first objective of this study, the performance of the new 35-year hindcast was checked against buoys and satellites, both globally, regionally and over the years 1979-2013. In view of the second objective, the new 35-year hindcast was compared to the previous 22-year hindcast in terms of model-buoy error statistics for ambient wind speed and significant wave height (see section 4.3) as well as for the higher values and extremes (see section 4.4). Following the third objective, model-buoy error statistics for significant wave height were determined before and after calibration with satellites (see section 4.7). The consistency of the hindcast before 1992 was checked separately against the more recent years (see section 5.3. Finally, model wave periods and wave directions were validated against buoys where available.

The following buoy-related regions are distinguished for the global hindcast (the set of buoys is elaborated and visualised in Appendix B1 – Buoys Used for the Global Hindcast):

- Gulf of Mexico (GOM)
- NW Atlantic (ATL)
- Newfoundland (NFL)
- Northern Pacific (PAC)
- Hawaii (HAW)
- Caribbean (CAR)
- North Sea (NS)
- Mediterranean (MED)

And for the EU-shelf (refer to Appendix B2 – Buoys Used for the EU-shelf Hindcast for details):

- The western part of the EU-shelf grid, i.e. the NE Atlantic (EU-ATL)
- The Celtic Sea (CELTICSEA)
- The Irish Sea (IRISHSEA, buoy M2 is the only buoy)
- The English Channel (CHAN)
- North Sea northern part (NS-N)
- North Sea central part (NS-C)
- North Sea southern part (NS-N)

Parameters analysed for both the global and for the regional EU-shelf model:

- Wind speed (*1-hr u10*)
- Significant wave height (*Hs*)

Wave periods and wave directions were evaluated where buoy data were available

- Wave period (*Tz/Tp*)- evaluated for the global model
- Wave direction (*Hsd*)- evaluated for the regional EU-shelf model

*Note:*
*Many buoys report wave periods as whole numbers, in particular the peak wave period. This does not significantly influence the bias found between model and buoy data because positive and negative differences will equal out. These low resolution measurements will however weaken any linear correlation between co-located model data and buoy samples. Also bear in mind that, by definition, model peak wave period is a bit more 'jumpy' than integrated wave periods like zero-crossing wave period. Consequently, it can be expected that any correlations for peak wave period will be weaker than correlation for zero-crossing wave period.*

## 4.3. Model Performance for the Ambient Climate

The performance of the hindcast for normal conditions was checked against buoy measurements.

Model performance is expressed in terms of bias (mean of the model error), standard deviation of the error, relative error and linear correlation coefficient between co-located model data and buoy data. A negative bias means that the model values are too low in comparison to the buoy measurements. The relative error conveniently combines (absolute) bias and standard deviation of the error into one measure. Details on these statistical parameters are explained in section 2.4.

Consistency of the hindcast performance was checked over the years (1979-2013) and in space. Hindcast-buoy error statistics were evaluated per year and per region with a more or less homogeneous climate.

Global and regional model-buoy error statistics of wind speed and significant wave height were

- Plotted against the years
- Tabulated (statistics averaged over all years)

Spatial plots, both globally and regionally, of overall hindcast-satellite bias and correlation were generated for wind speed and significant wave height.

## 4.4. Model Performance for the Extreme Climate

Hindcast extreme wind and wave conditions were compared to buoys and satellites, both globally and per region.

Higher values of wind speed and significant wave height were compared to buoy data and nearby satellite observations by means of Q-Q (Quantile-Quantile) plots or PoE (Probability of Exceedance) plots. The latter focus on the extreme values, i.e. on the tail of the distributions of wind speed and significant wave height whilst not so extreme but still relatively high values are best compared by means of a Q-Q plot. In the Q-Q plots in this report, the following percentiles of wind speed and wave height are plotted against each other: 50, 60, 70, 80, 90, 95, 96, 97, 98, 99 and 99.9 %. These percentiles are marked by circles in the Q-Q plots and connected by solid lines representing the distributions of the *sorted* samples (the value of sample number n in a series of N samples sorted by increasing value relates to percentile (n-1)/N*100).

## 4.5. Selection of Processing Levels

Choices were made with respect to the model processing levels presented in this report. With two model versions (v361 and v352), at least two parameters (wind speed and wave height) and un-calibrated as well as calibrated model data one would have 8 possible versions for each statistical table and plot. Bearing in mind the major questions (section 1.1) but also seeking to limit the amount of information in this report, it seemed wise to

- Focus on 'best' model wind and waves of v361 (v352 is less relevant)
- Focus on comparison of 'best' wind and waves from v361 and v352 (comparison of un-calibrated model data is less relevant)
- Present plots on the effect of satellite calibration on model waves (no such plots for winds).

## 4.6. The Use of Terms and Colours in this Report

In the plots presented in this report, model versions and processing levels are consistently indicated by specific colours and abbreviations used in the legend of the plots.

Processing levels are abbreviated as follows (abbreviation between parentheses)

- Un-calibrated (raw)
- Model wave height calibrated with altimeter (cal-alt)
- Model wind speed calibrated with satellite, i.e. with merged scatterometer and altimeter samples (cal-sat)

Colours are used as follows:

- v361 un-calibrated (dark blue)
- v361 calibrated (red)
- v352 un-calibrated (light blue)
- v352 calibrated (yellow-green)
- Buoy or satellite (dark grey)

The term 'raw' refers to model data not yet calibrated with satellites and 'cal' refers to model data that have been calibrated with satellites. Calibration by means of satellites is done assuming a linear error model: model wind speed and wave spectra are corrected by means of a scale factor and intercept (offset). Alternatively, the term 'best' model data is used for satellite-calibrated model data.

*Note:*
*Due to the relatively large distance between model points and buoy locations in the coarse global grid of v352, error statistics of calibrated v352 model waves were left out in this report: the comparison to calibrated v361 waves would be biased as the v361 grid is much finer (see Table 1). This difference in grid resolution can be mitigated by interpolating hindcast data onto the exact buoy locations instead of using hindcast data from the grid point nearest to the buoy.*

## 4.7. Application and Validation of Buoy and Satellite Data

Merged scatterometer and altimeter wind speed samples were used to calibrate the winds driving the wave model. Altimeters were used to correct the resulting hindcast wave spectra; corrected wave parameters, i.e. height, period and direction, are found by re-integration of the corrected wave spectra. Calibration leaves the steepness of the waves unchanged. Corrections are grid point specific. For the validation and automated calibration of the hindcast data, satellite samples were co-located within 25 km of each model grid point. As satellite samples within one pass are highly correlated, only one sample from each pass was used for calibration, namely the sample nearest to the model point.

Prior to use for validation/calibration of the hindcast, all buoy and satellite data were extensively checked for consistency in space and over the years (1992-2013). See Appendix B1 – Buoys Used for the Global Hindcast, Appendix B2 – Buoys Used for the EU-shelf Hindcast and Appendix C – Validation of Satellite Data.

# 5. Results for the Global Model

The quality of wind speed and significant wave height of the global WW3 model is measured against buoys in the first three sections of this chapter (5.1.1-5.1.3). The set of buoys is elaborated in Appendix B1 – Buoys Used for the Global Hindcast. Model performance is provided for various versions and processing levels of the hindcast (see section 4.5).

The last section (5.1.4) presents charts of differences between model and satellites.

*Note:*
*The quality of global model wave periods, i.e. zero-crossing wave period and peak wave period is evaluated separately in Appendix F1 – Validation of Wave Periods (Global).*

## 5.1. Results for the Ambient Climate of the Global Model

### 5.1.1. Overall Ambient Climate Results

The next table summarizes the error statistics of various versions of the global model for the years 1992-2013 and relative to all NOAA buoys for the ambient wind and wave climate.

The numbers in Table 8 below demonstrate that, in relation to buoys

1. Overall relative error in 'best' v361 wind speed is 17% and for wave height this is about 15%. Overall linear correlation coefficient is about 0.90 for winds and 0.95 for waves.

   This is as good as can be expected. For comparison, see Appendix C – Validation of Satellite Data; Table 23-Table 25. This appendix shows that the relative error in satellite wind speed ranges from 14%-18% for altimeters (17% overall) and from 13%-15% for scatterometers (14% overall); relative error in wave height from altimeter missions ranges from 9%-13% (11% overall). Correlation for altimeter wind speed is 0.92, ranging from 0.90-0.93 over missions. Scatterometer wind correlation is 0.94. Correlation for all altimeters is 0.96 for wave height.

2. 'Best' v361 winds are better than 'best' v352 winds: the relative error is about 3% lower (mainly thanks to reduction of variability) and correlation with buoy data is higher. 'Best' v361 wave height is slightly better than v352 wave height: relative error is approximately 2% lower, again mainly by virtue of a smaller standard deviation of the error (un-calibrated v361 waves are too low and have more bias than un-calibrated v352 waves).
3. Auto-calibration with altimeter practically removes the bias from v361 wave height and slightly reduces standard deviation of the model error. As a result, the relative error in hindcast v361 wave height is reduced by about 2%.

| | Wind speed U10 | | | | | Wave height Hs | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Model Version | Mean (m/s) | Bias (m/s) | Std (m/s) | Rrmse (%) | Corr (-) | Mean (m) | Bias (m) | Std (m) | Rrmse (%) | Corr (-) |
| v361 best | **6.78** | **-0.08** | **1.29** | **17.0** | **0.92** | **1.99** | **-0.01** | **0.35** | **15.2** | **0.96** |
| v352 best | **6.96** | **0.10** | **1.56** | **20.6** | **0.89** | | | | | |
| v361 raw | | | | | | **1.84** | **-0.17** | **0.37** | **17.4** | **0.95** |
| v352 raw | | | | | | **1.99** | **-0.02** | **0.42** | **17.9** | **0.94** |

**Table 8: Error statistics of global model versions relative to all NOAA buoys**

### 5.1.2. Model Performance over Time for the Ambient Climate

In this section, model-buoy error statistics of significant wave height and wind speed are checked over the years.

Figure 2 and Figure 3 illustrate the error in 'best' model wind speed over the years, both for version v352 and v361. Similarly, Figure 4 and Figure 5 summarize error statistics of 'best' model wave height for both versions. Figure 6 and Figure 7 provide a comparison between error statistics of un-calibrated and calibrated model wave height. These figures are given for model v361 only.

**Performance of Model v361 over Time (based on ALL buoys)**

Figure 2 to Figure 5 shows that the quality of model v361 winds and waves is consistently high over all years, although there seems to be a sudden loss of quality in v361 winds as of 2010 (best seen in Figure 3 where the linear correlation coefficient drops below 0.9).

**Comparison of Model v352 and v361 over Time (based on ALL buoys)**

From Figure 2 and Figure 3 it becomes clear that calibrated v352 winds are relatively bad before 1999. This is related to the poor quality of the 'reanalysis' wind source used by NCEP for that period. Later, final analysis winds were used for v352 which are much better i.e. with less positive bias but in particular less variable. Apparently, this problem has been solved in v361.

According to Figure 4 and Figure 5 'best' v361 wave height is better than 'best' v352 wave height. Bias in v361 waves is (more) consistently low over the years and variability and correlation are better, in particular before 1997 (apparently caused by the poor quality of the winds driving v352).

**The Effect of Calibration of Model Waves with Altimeter over Time (based on ALL buoys)**

From Figure 6 and Figure 7 it is seen that un-calibrated model waves are too low on average and that calibration with altimeter practically removes the error with respect to buoy observations over the years. Calibration with altimeter also slightly but consistently reduces the standard deviation of the error in model wave height over the years.

**Model Performance over Time per Buoy Region**

Plots on the model performance over the years per region can be found in Appendix D1 – Regional Results Ambient Climate (Global). The poor quality of NCEP re-analysis winds before 1999 (v352) and the sudden decrease of wind quality in 2010 (v361) is reflected in all relevant regional plots.

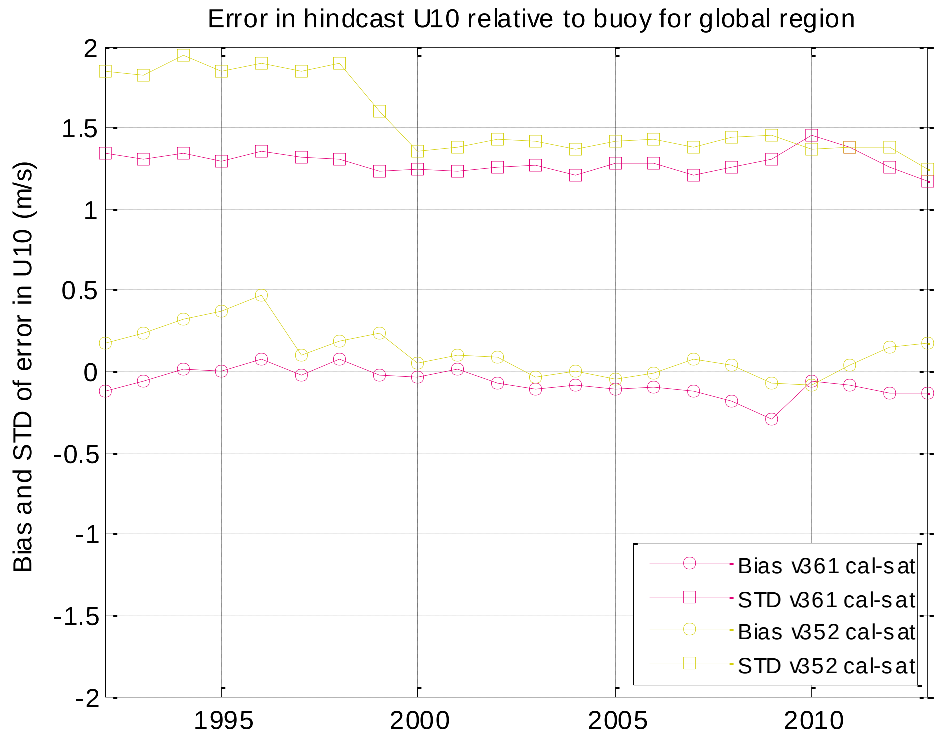


**Figure 2 Error in global hindcast wind speed relative to ALL buoys**

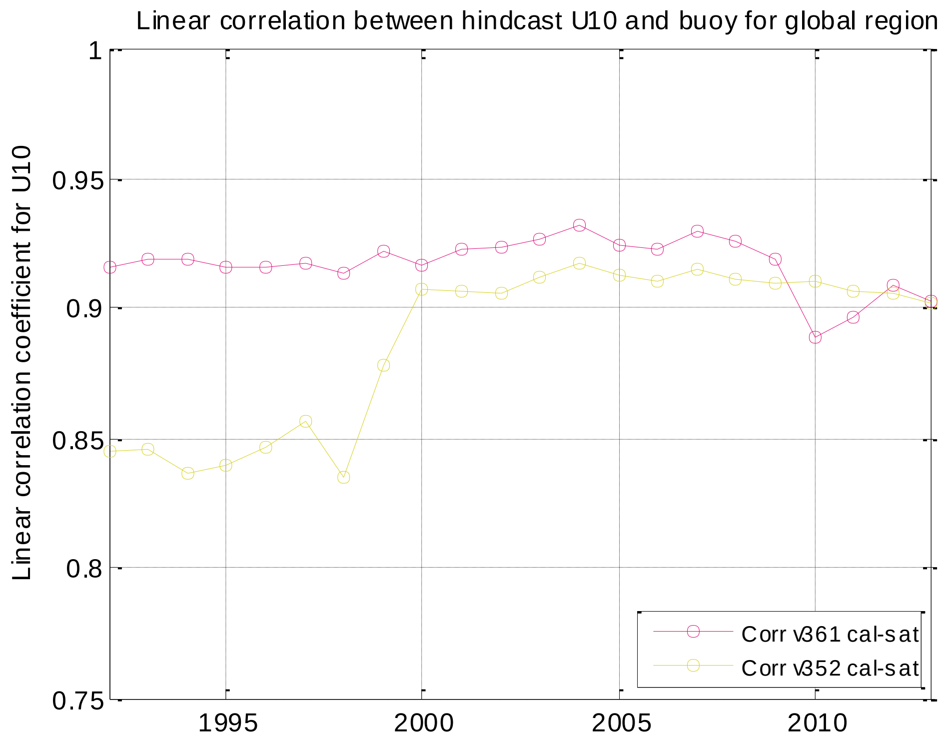


**Figure 3 Correlation wind speed global hindcast and ALL buoys**

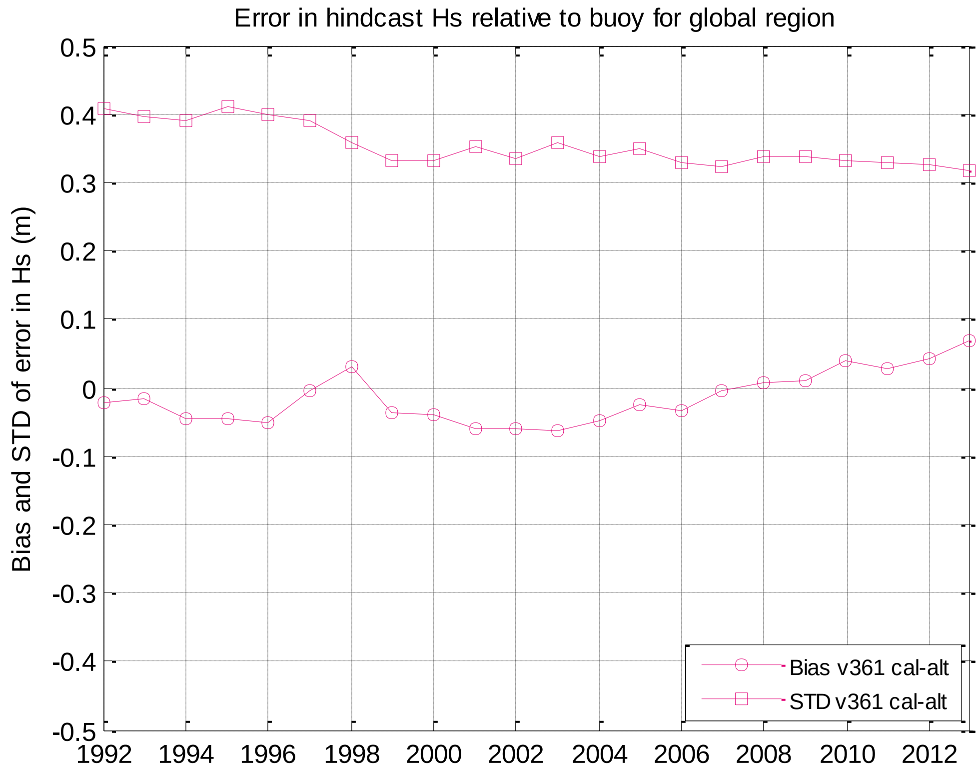


**Figure 4 Error in global hindcast wave height relative to ALL buoys**

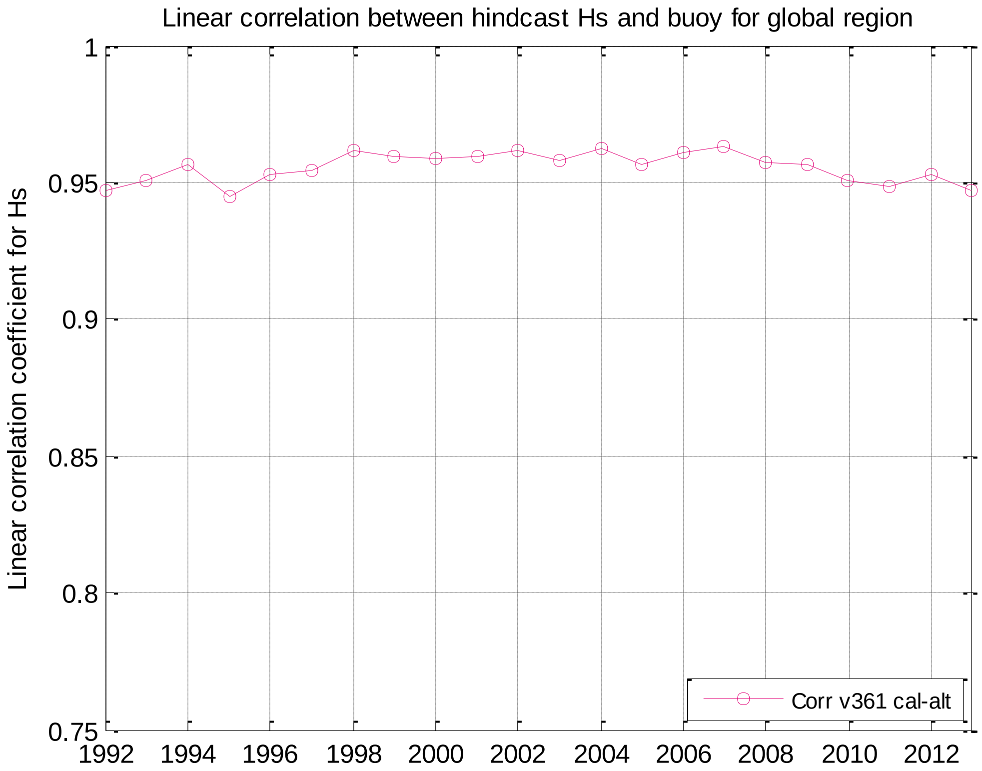


**Figure 5 Correlation global hindcast wave height and ALL buoys**

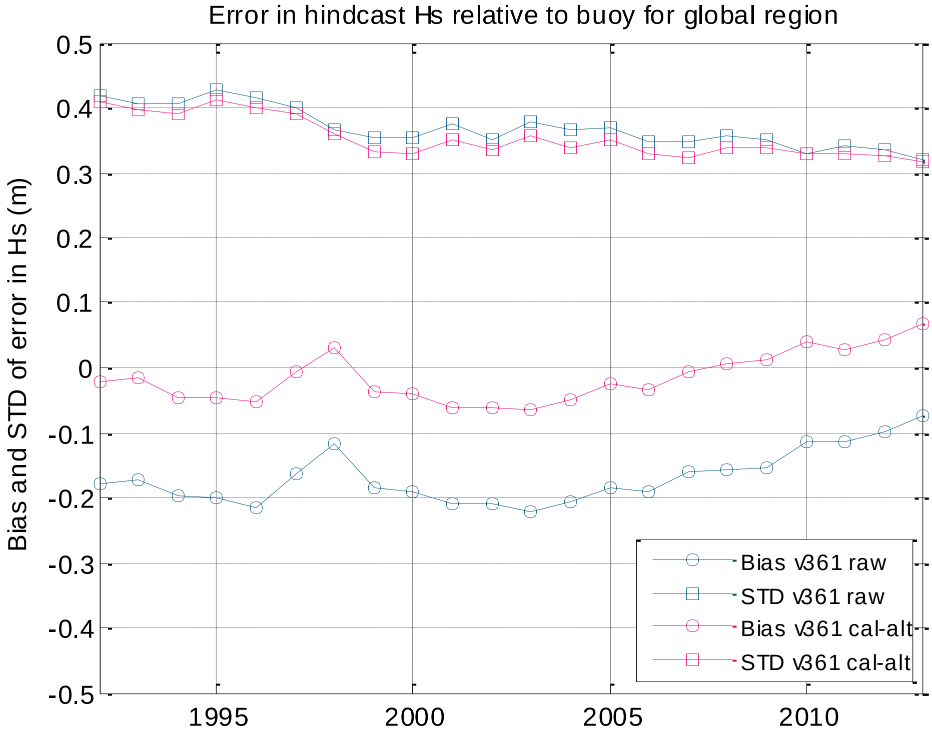


**Figure 6 Error in raw and best global v361 wave height relative to ALL buoys**

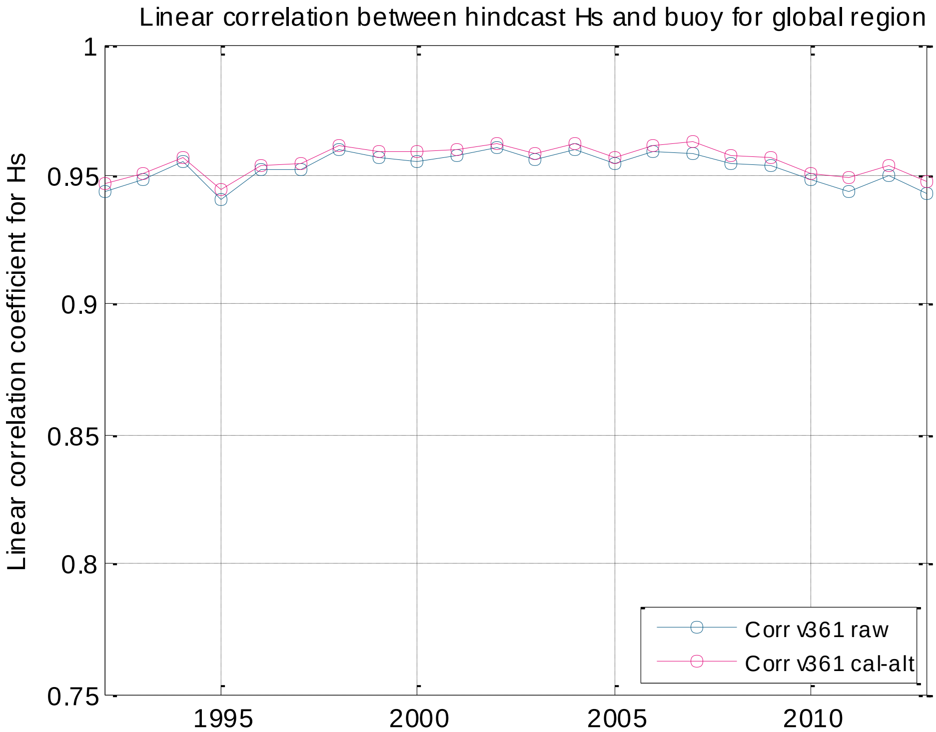


**Figure 7 Correlation raw and best global v361 wave height and ALL buoys**

### 5.1.3. Model Performance per Buoy Region for the Ambient Climate

Tables of model-buoy error statistics of wind speed and significant wave height of are presented below for all buoys (last row) and for the set of buoys per region (regions are listed in section 4.3).

Table 9 and Table 10 list the error statistics of 'best' model wind speed, both for version v352 and v361. Table 11 provides a comparison between error statistics of un-calibrated and calibrated model wave height. This comparison is done for model v361 only. Table 12 lists error statistics of un-calibrated v352 wave height.

#### Performance of Model v361 per Region

See Table 9. 'Best' winds of model v361 are slightly lower than buoy measurements: the overall bias is less than 0.1m/s. Over the regions, the bias varies from 0m/s in the Pacific to less than 0.5m/s in the Gulf of Mexico. For the Newfoundland region, variability of (the error in) hindcast winds and waves is relatively large; this is most probably also related to the lesser quality of buoy measurements for this area.

#### Comparison of Model v352 and v361 per Region

Table 9 and Table 10 show that v361 winds are considerably better than v352 winds: the relative error in v361 winds is lower for all regions. This improvement is mainly caused by less variability of the error in v361 wind speed, which is illustrated by the fact that v361 standard deviations are much lower for all regions. New v361 winds are slightly lower than buoy measurements for all regions whilst v352 winds are too high for the majority of the regions but too low for the Gulf of Mexico and the Caribbean. Correlation of v361 winds is slightly better for most regions.

#### The Effect of Calibration of Model Waves with Altimeter per Region

The numbers in Table 11 show that calibration with altimeter practically removes the bias from v361 wave height for all regions and slightly but consistently reduces standard deviation of the model error over the regions. As a result, the relative error in hindcast v361 wave height is reduced by about 2% for each region.

| Region | Un-calibrated u10 of hindcast v361 | | | | | Sat-calibrated u10 of hindcast v361 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Mean (m) | Bias (m) | Std (m) | Rrmse (%) | Corr (-) | Mean (m/s) | Bias (m/s) | Std (m/s) | Rrmse (%) | Corr (-) |
| GOM | | | | | | 5.78 | -0.19 | 1.28 | 19.4 | 0.90 |
| ATL | | | | | | 6.56 | -0.03 | 1.36 | 18.5 | 0.91 |
| NFL | | | | | | 7.66 | -0.10 | 1.70 | 19.6 | 0.91 |
| PAC | | | | | | 7.54 | 0.00 | 1.29 | 15.5 | 0.93 |
| HAW | | | | | | 6.96 | -0.05 | 1.09 | 14.7 | 0.88 |
| CAR | | | | | | 6.54 | -0.44 | 1.12 | 16.3 | 0.89 |
| **ALL** | | | | | | **6.78** | **-0.08** | **1.29** | **17.0** | **0.92** |

**Table 9: Error statistics ‘best‘ wind speed of global v361 relative to buoys per region**

| Region | Un-calibrated u10 of hindcast v352 | | | | | Sat-calibrated u10 of hindcast v352 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Mean (m) | Bias (m) | Std (m) | Rrmse (%) | Corr (-) | Mean (m/s) | Bias (m/s) | Std (m/s) | Rrmse (%) | Corr (-) |
| GOM | | | | | | 5.89 | -0.08 | 1.47 | 22.0 | 0.88 |
| ATL | | | | | | 6.84 | 0.26 | 1.73 | 23.7 | 0.88 |
| NFL | | | | | | 8.10 | 0.34 | 2.17 | 25.3 | 0.86 |
| PAC | | | | | | 7.67 | 0.14 | 1.59 | 19.1 | 0.91 |
| HAW | | | | | | 7.07 | 0.05 | 1.26 | 17.1 | 0.86 |
| CAR | | | | | | 6.86 | -0.12 | 1.14 | 15.5 | 0.90 |
| **ALL** | | | | | | **6.96** | **0.10** | **1.56** | **20.6** | **0.89** |

**Table 10: Error statistics ‘best’ wind speed of global v352 relative to buoys per region**

| Region | Un-calibrated Hs of hindcast v361 | | | | | Alt-calibrated Hs of hindcast v361 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Mean (m) | Bias (m) | Std (m) | Rrmse (%) | Corr (-) | Mean (m) | Bias (m) | Std (m) | Rrmse (%) | Corr (-) |
| GOM | 1.01 | -0.10 | 0.24 | 19.4 | 0.95 | 1.13 | 0.03 | 0.23 | 17.6 | 0.95 |
| ATL | 1.62 | -0.19 | 0.36 | 19.8 | 0.94 | 1.77 | -0.03 | 0.35 | 16.9 | 0.94 |
| NFL | 2.32 | -0.30 | 0.57 | 21.3 | 0.93 | 2.58 | -0.04 | 0.56 | 18.6 | 0.93 |
| PAC | 2.48 | -0.22 | 0.45 | 16.5 | 0.95 | 2.68 | -0.02 | 0.44 | 14.4 | 0.95 |
| HAW | 2.17 | -0.13 | 0.31 | 13.9 | 0.90 | 2.30 | 0.00 | 0.30 | 12.6 | 0.90 |
| CAR | 1.29 | -0.10 | 0.24 | 16.8 | 0.93 | 1.37 | -0.02 | 0.22 | 14.6 | 0.94 |
| **ALL** | **1.84** | **-0.17** | **0.37** | **17.4** | **0.95** | **1.99** | **-0.01** | **0.35** | **15.2** | **0.96** |

**Table 11: Error statistics wave height of global v361 relative to buoys per region**

| Region | Un-calibrated Hs of hindcast v352 | | | | | Alt-calibrated Hs of hindcast v352 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Mean (m) | Bias (m) | Std (m) | Rrmse (%) | Corr (-) | Mean (m) | Bias (m) | Std (m) | Rrmse (%) | Corr (-) |
| GOM | 1.05 | -0.05 | 0.27 | 20.7 | 0.93 | | | | | |
| ATL | 1.71 | -0.09 | 0.42 | 20.7 | 0.91 | | | | | |
| NFL | 2.53 | -0.09 | 0.61 | 20.6 | 0.91 | | | | | |
| PAC | 2.69 | 0.00 | 0.50 | 16.3 | 0.94 | | | | | |
| HAW | 2.38 | 0.08 | 0.38 | 16.3 | 0.86 | | | | | |
| CAR | 1.47 | 0.07 | 0.28 | 18.6 | 0.92 | | | | | |
| **ALL** | **1.99** | **-0.02** | **0.42** | **17.9** | **0.94** | | | | | |

**Table 12: Error statistics wave height of global v352 relative to buoys per region**

### 5.1.4. Comparison of Satellites and the Global Model

In this section, spatial plots of model-satellite bias and correlation for significant wave height are provided for the global model v361. 'Best' model waves were obtained by automated calibration with satellites, carried out per grid point and based on the years 1992-2011 (also see section 4.1). Similar plots for regional models can be found in section 6.1.4 and Appendix H – Comparison of Satellites and Regional Models.

Buoys have highest authority when it comes to judging model quality. According to Table 11, calibration with altimeter removes the systematic error in hindcast v361 relative to the buoys in each buoy region. This means that altimeter based correction 'pulls the hindcast towards truth (buoy measurements)' in regions with distinct climates, i.e. in wind-dominated semi-closed basins (Gulf of Mexico, Caribbean), swell dominated areas on open ocean (Hawaii) and areas with a mixture of wind-sea and swell (Pacific, Atlantic, Newfoundland)

The spatial plots on the next page add at least some validation for grids and areas without suitable buoy data. The plots show that, except for the polar or other regions where ice might cause problems, calibration with satellites reduces the systematic model error equally in all major oceans and seas, including the semi-closed basins. It is also seen that the model requires less correction in swell-dominated areas like the Indian Ocean, southeast Pacific and southern Atlantic.

The small remaining model bias worldwide, strongly suggests that there is no significant spatial variation in the performance of satellite based model calibration and so we may assume that the calibration of the model with satellites in regions with buoys would also be applicable to any other (ice-free) region on the globe.

*Please note that the charts on the pages below show differences between model and satellites, whereas plots and tables in previous sections 5.1.1-5.1.3 show the error between model and buoys.*

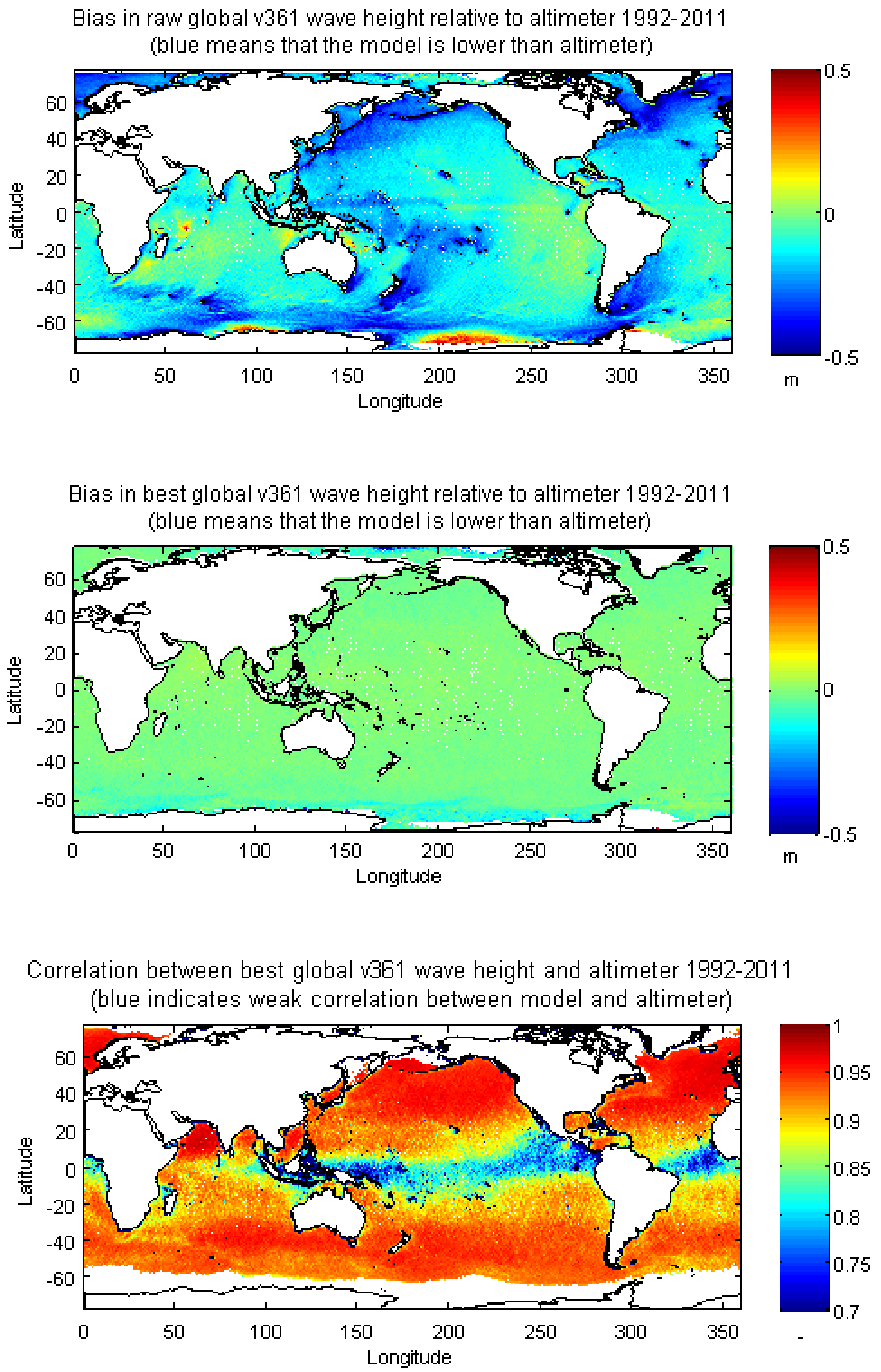


**Figure 8 Bias and correlation v361 wave height relative to altimeter for the global model**

## 5.2. Results for the Extreme Climate of the Global Model

Per buoy region and for all buoys, higher and extreme values of model wind speed and significant wave height were compared to buoy data by means of quantile-quantile (Q-Q) plots and probability of exceedance (PoE) plots. Please refer to section 4.4 for more detail.

Figure 9 compares the probability distributions of model and buoy wind speed and Figure 10 shows the corresponding Q-Q plot. Similarly, model and buoy significant wave height are compared in Figure 11 and Figure 12.

### Performance of Model v361 (based on ALL buoys)

Figure 9 and Figure 10 show that 'best' v361 high and extreme winds agree very well with buoy measurements, except perhaps for the very tail (say for wind speed above 35 m/s). From Figure 11 and Figure 12 it is seen that un-calibrated v361 higher and extreme waves are clearly too low in comparison to buoy measurements. Calibration with altimeter for the ambient climate does also improve the higher waves but, extremes remain roughly 10% too low in comparison to the buoy data.

### Comparison of Extremes of Model v352 and v361 (based on ALL buoys)

Figure 9 and Figure 10 demonstrate that

- Higher and extreme values of 'best' v352 winds are significantly higher than buoy measurements. The behaviour in the tail of the distribution, say for winds stronger than 30 m/s, is probably connected to the occurrence of cyclones. In that case, hindcast v361 apparently fails to capture these cyclonic winds.

From Figure 11 and Figure 12, one can see that

- According to buoys, un-calibrated v361 wave height is significantly worse than un-calibrated v352 wave height. After calibration with altimeter, corrected v361 wave height is practically identical to un-calibrated v352 wave height for the higher waves up to 10 m.
- In the very tail of the distribution, say for waves above 15 m, wave height from (un-calibrated) v352 exceeds v361 values and the buoy measurements by far. Apparently the excessive v352 wave heights are caused by cyclonic winds (see Figure 9),

### The Effect of Calibration of Model Waves with Altimeter on Extremes (based on ALL buoys)

According to Figure 11 and Figure 12, auto-calibration with altimeter, based on comparison of ambient wave conditions of model and altimeter, also significantly improves the higher and extreme wave heights of hindcast v361. In fact, calibration with altimeter removes more than half of the bias between un-calibrated model and buoys for the more energetic sea states.

### Extreme Climate Results per Buoy Region

Plots on regional model extremes can be found in Appendix E1 – Regional Results Extreme Climate (Global). The exceedance plots in the appendix clearly link the excessive v352 wind speeds and waves, not seen in v361, to cyclone areas, i.e. the Gulf of Mexico and the Caribbean. The Q-Q plots demonstrate that higher v361 winds (10-25 m/s) are better than v352 winds which are too high in all areas except for the Caribbean. The increased necessity to calibrate hindcast v361 waves (too low) with altimeter becomes manifest for all regions. Near Hawaii, v361 (swell) waves still remain too low according to the buoys, whilst v352 waves are too high in this region.

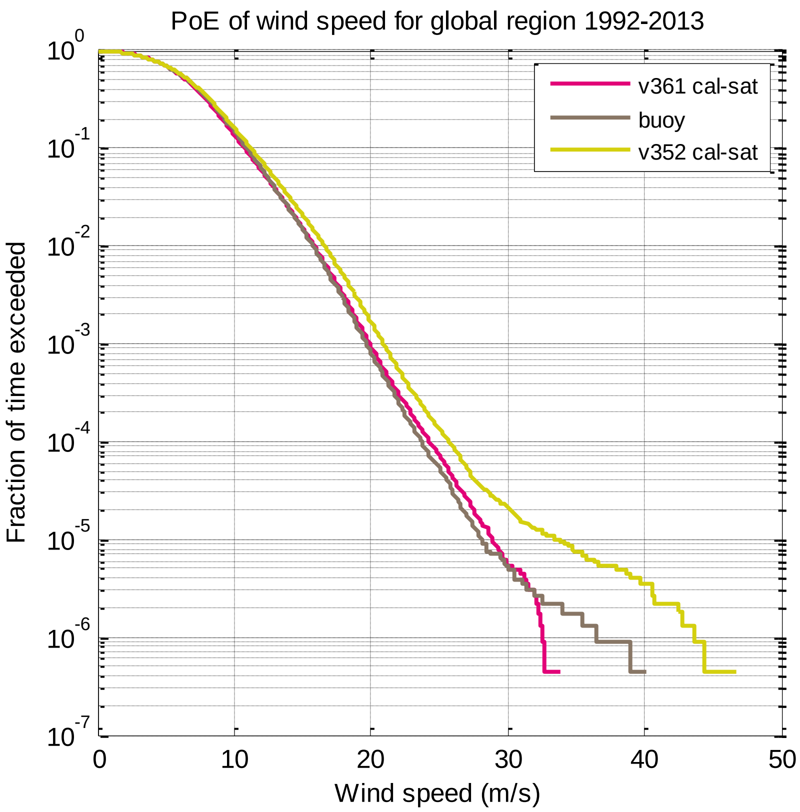


**Figure 9 PoE of global hindcast wind speed and ALL buoys**

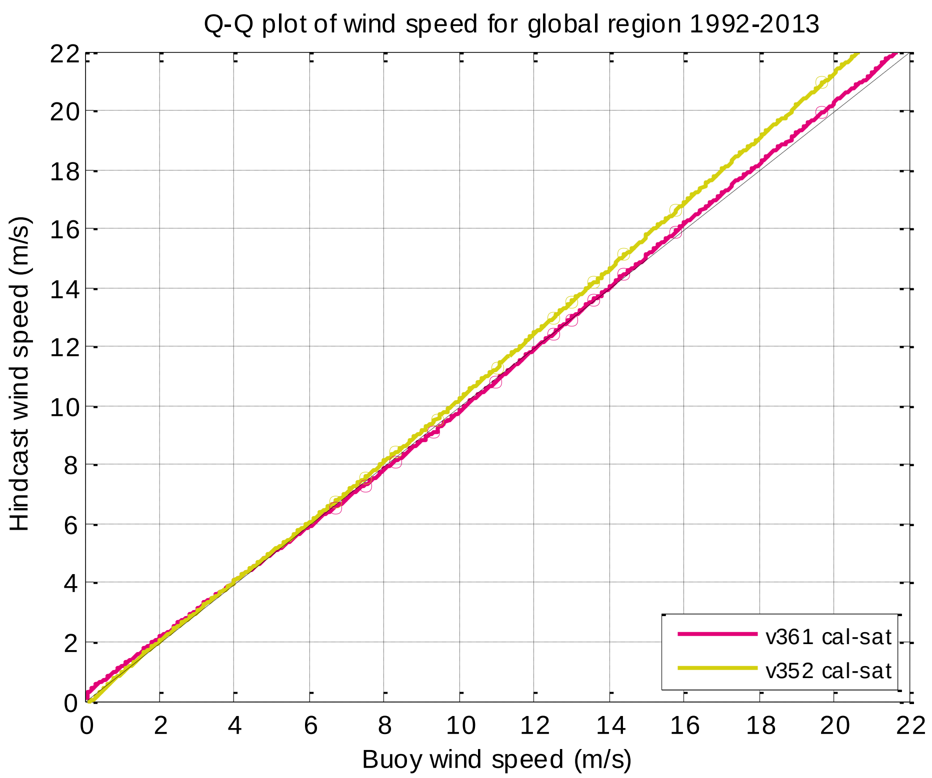


**Figure 10 Q-Q plot of global hindcast wind speed against ALL buoys**

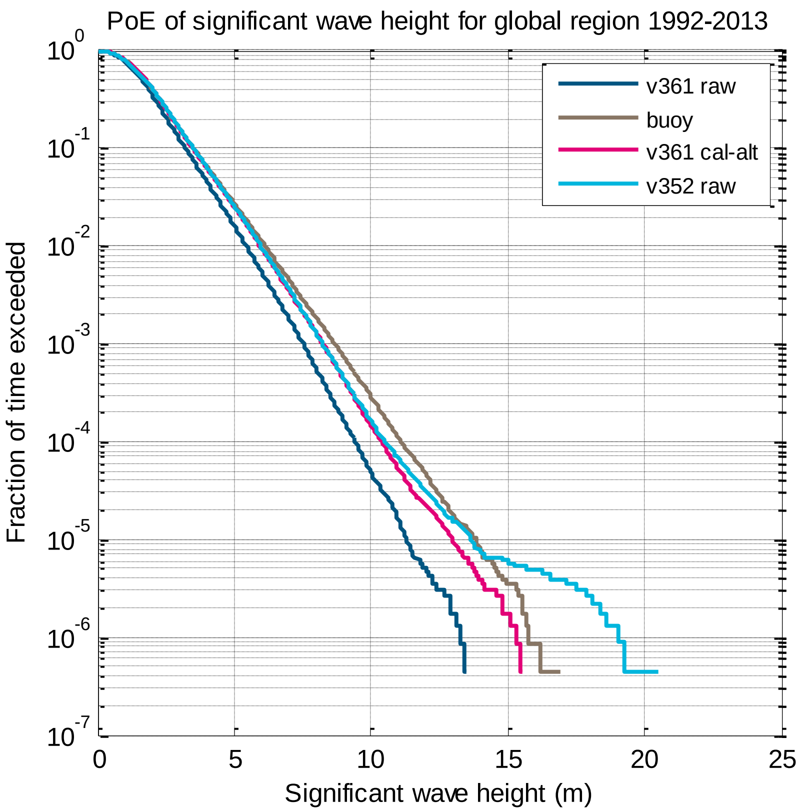


**Figure 11 PoE of global hindcast wave height and ALL buoys**

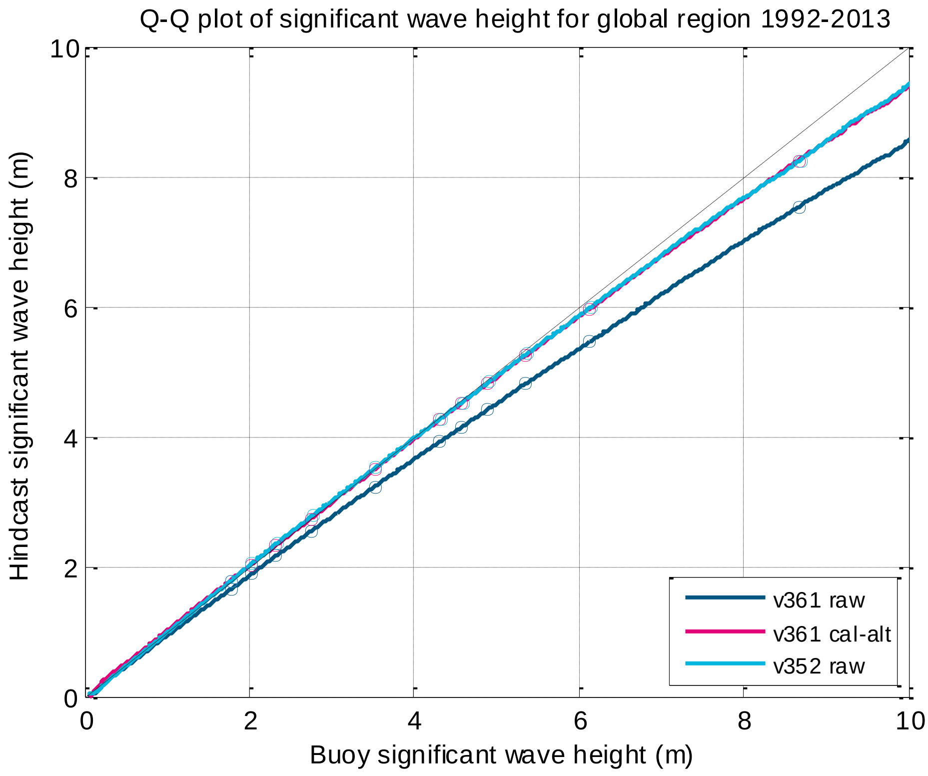


**Figure 12 Q-Q plot of global hindcast wave height against ALL buoys**

## 5.3. Validation of the Global Model before 1992

In this section, the quality of global model v361 winds and waves before 1-jan-1992 (1979-1991) is compared to the quality during more recent years 1992-2013. There are 28 NOAA buoys that provide data before as well as after 1-jan-1992. This subset, covering all regions except the Caribbean, is listed in Table 21 in Appendix B1 – Buoys Used for the Global Hindcast.

*Remark:*
*Model wind speed presented in this section has been calibrated with satellites. Due to lack of suitable satellite data before 1992, this calibration is based on the comparison between model and satellite wind over the years 1992-2013.*
*Model significant wave height presented here has* ***not*** *been calibrated by satellites. This however does not devaluate the comparison because, as for winds, calibration of waves before 1992 would also be based on the comparison of model and satellites over the years 1992-2013 and the (favourable) effect of the resulting calibration of v361 waves is known and has been quantified in the previous sections. See Figure 6 and Table 11 in section 5.1 for the effect of satellite calibration on average v361 waves: about 0.15m would be added to* ***all*** *(as in Figure 6) values of average significant wave height plotted in Figure 17 and Figure 18 below (both curves would be shifted by +0.15m). Therefore calibration would not change the conclusion below that the mean error in model wave height and the correlation with the buoy data do not change much over the years. Figure 11 and Figure 12 in section 5.2 suggest that calibration would have increased the higher and extreme v361 waves shown in Figure 25 to Figure 28 below by 10-15%. Again this would not change the comparison below.*

### Overall error in model v361 before and after 1-jan-1992 (based on 28 buoys)

Overall ambient climate error statistics of global model v361 before and after 1-jan-1992 are compared in Table 13. The model error is relative to the subset of 28 NOAA buoys that provide observations for both periods. The table demonstrates that both model winds and waves are more variable before 1992 which leads to an increase in the relative error of about 1% for winds and 0.5% for waves. Mean model error and correlation relative to buoys are comparable for the two periods.

The fact that model bias is similar for both periods means that calibration of waves, even if the corrections are based on comparing model and satellites over the years 1992-2013, will still remove most of the bias for all years 1979-2013.

| Period | Calibrated Hourly Mean Wind speed u10 | | | | | Un-calibrated Significant Wave height Hs | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Mean (m/s) | Bias (m/s) | Std (m/s) | Rrmse (%) | Corr (-) | Mean (m) | Bias (m) | Std (m) | Rrmse (%) | Corr (-) |
| 1979-1991 | **6.82** | **0.00** | **1.38** | **18.1** | **0.91** | **2.01** | **-0.13** | **0.43** | **17.7** | **0.95** |
| 1992-2013 | **6.90** | **0.01** | **1.28** | **16.9** | **0.92** | **1.96** | **-0.17** | **0.39** | **17.2** | **0.95** |

**Table 13: Error statistics of global model v361 rel. to buoys before and after 1-jan-1992**

### Error over the years in model v361 before and after 1-jan-1992 (based on 28 buoys)

The error in 'best' v361 wind speed over the years before 1992 and in later years is plotted in Figure 13 (1979-1991) and Figure 14 (1992-2013). Based on the comparison of these two figures it can be stated that the quality of model wind speed for the years before 1992 is comparable to the quality for the more recent years even though the winds before 1992 are a bit more variable. Bias in model wind speed relative to buoys is less than 0.5 m/s and standard deviation of the model error remains below 1.5 m/s for all years 1979-2013. Between 1984 and

2009 model bias remains below say 0.2 m/s and variability of the model error gradually decreases over the years to about 1.2 m/s. Figure 15 and Figure 16 show that correlation between model and buoy winds is consistently good for all years 1992-2009. Again, the sudden loss of quality in v361 model winds in 2010 is evident (also seen relative to *all* NOAA buoys in Figure 3).

For v361 model waves, similar conclusions hold over the years 1979-2013: model waves are a bit more variable before 1992 but the mean model error and the correlation with the buoy data do not change much over the years. Please compare Figure 17 to Figure 18 and Figure 19 to Figure 20.

**High and extreme values of model v361 before and after 1-jan-1992 (based on 28 buoys)**
Extreme model winds before 1992 compare very well to buoys, perhaps even better than extremes found in later years. The same is true for the above average wind speeds. Please compare Figure 21 to Figure 22 and Figure 23 to Figure 24.

Extreme and above average v361 model waves are both way too low without calibration but the difference between model and buoy extremes is larger before 1992. Compare Figure 25 to Figure 26 and Figure 27 to Figure 28.

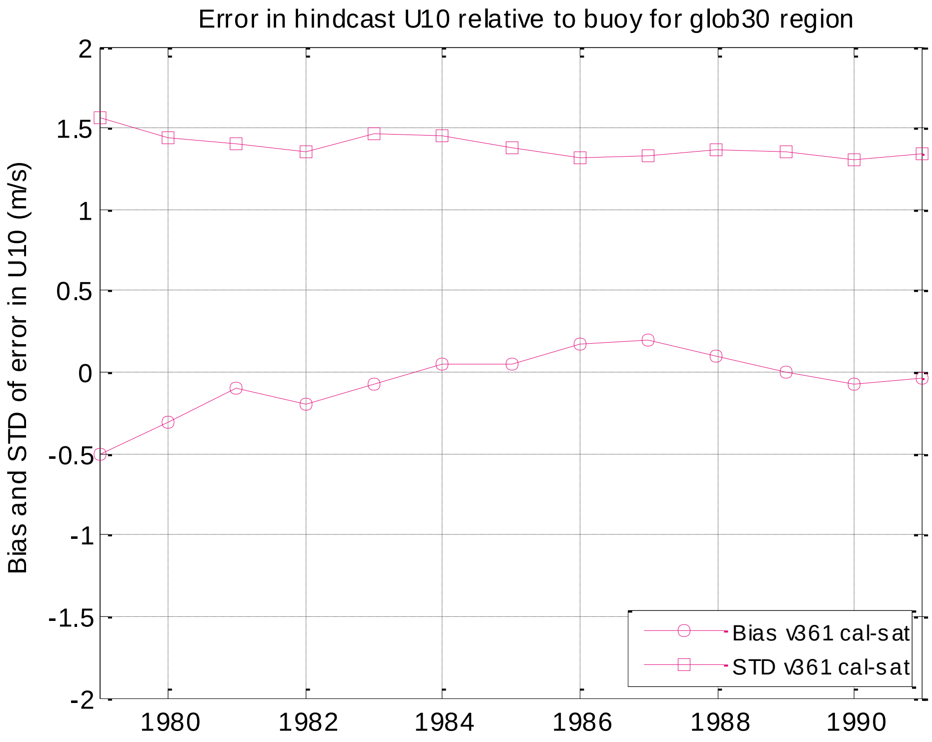


**Figure 13 Error in global hindcast wind speed relative to buoys before 1-jan-1992**

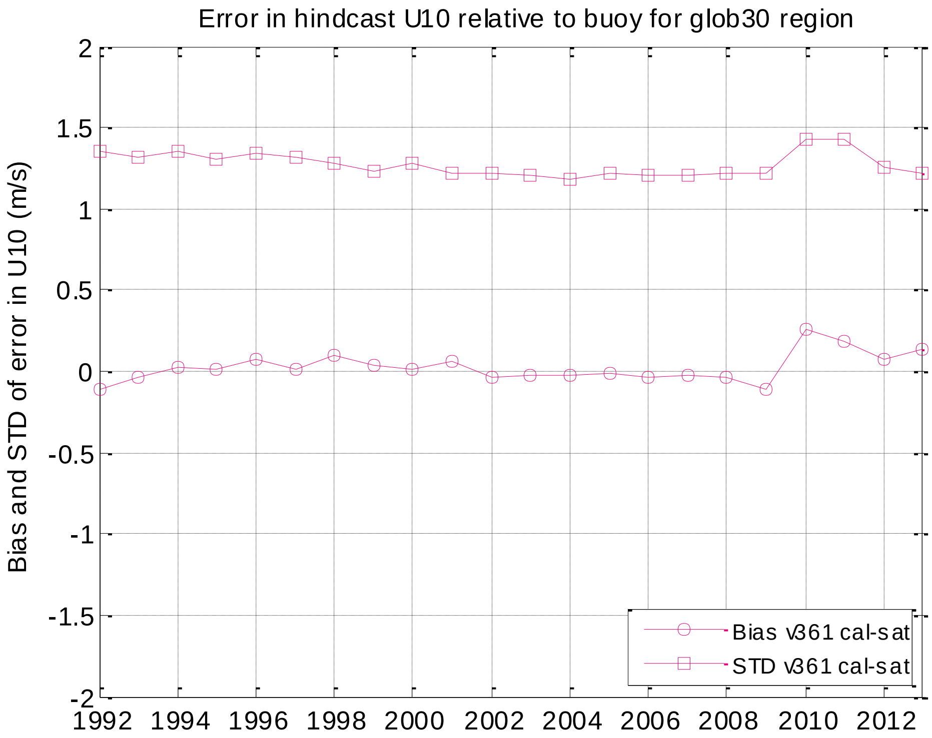


**Figure 14 Error in global hindcast wind speed relative to buoys after 1-jan-1992**

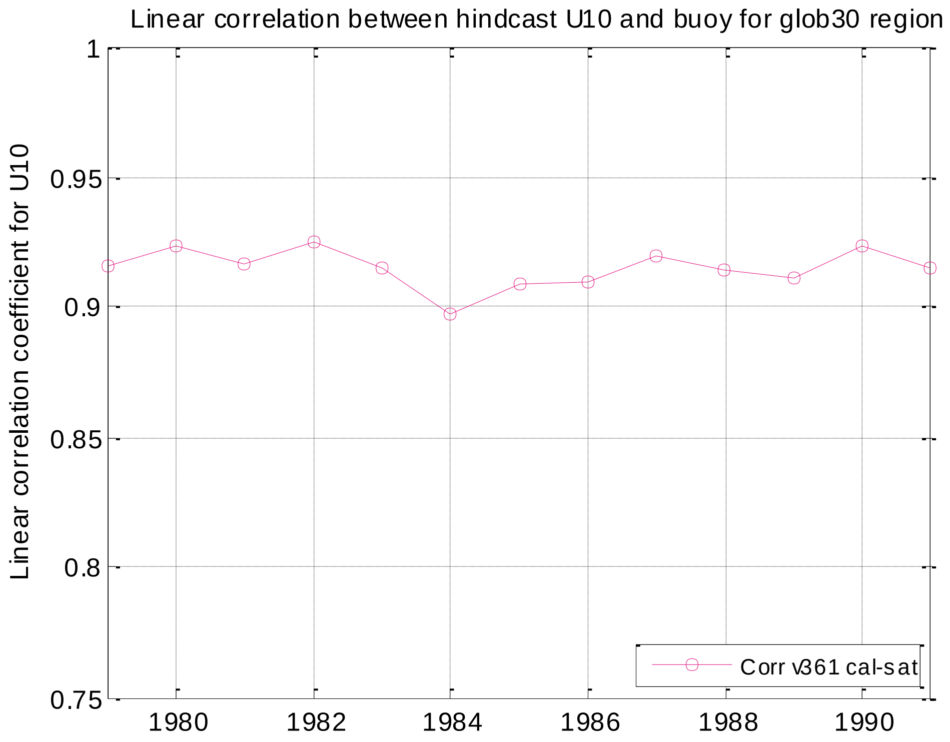


**Figure 15 Correlation wind speed global hindcast and buoys before 1-jan-1992**

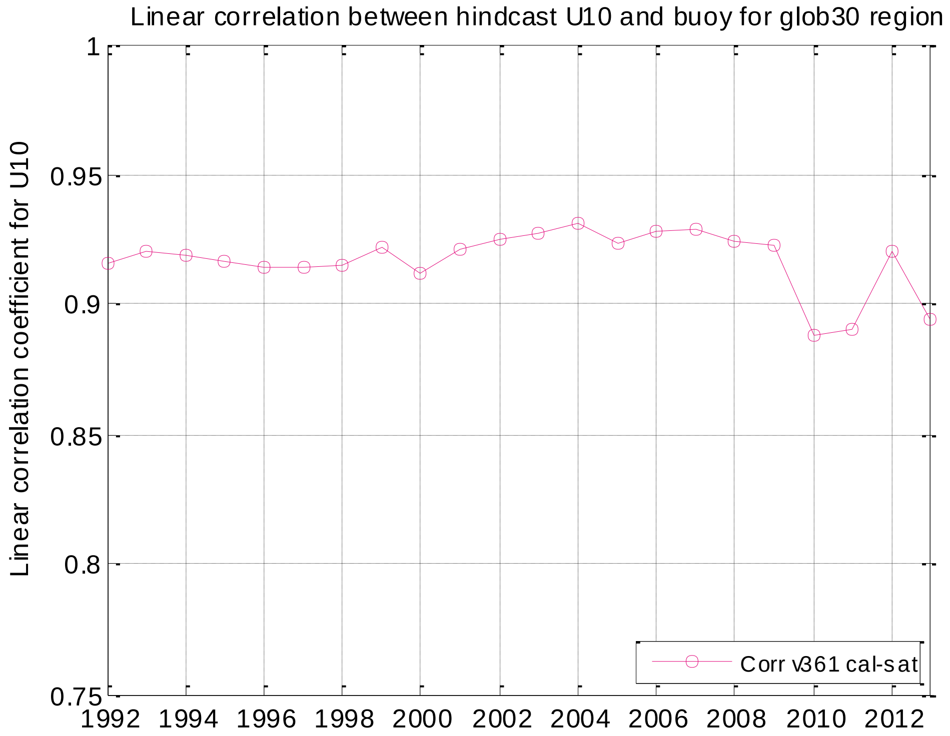


**Figure 16 Correlation wind speed global hindcast and buoys after 1-jan-1992**

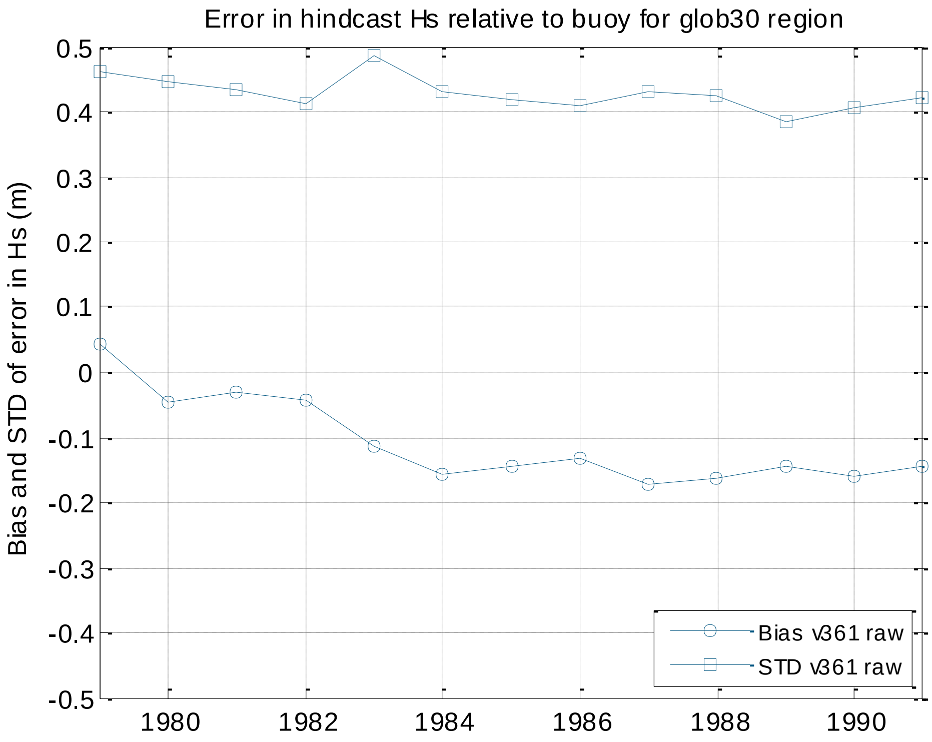


**Figure 17 Error in global hindcast wave height relative to buoys before 1-jan-1992**

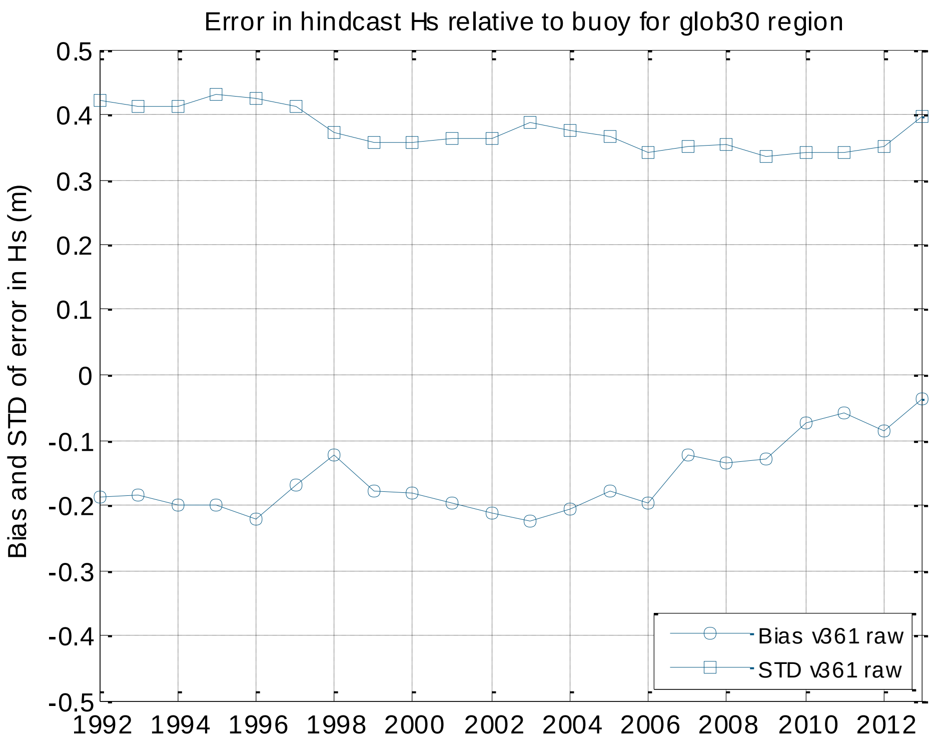


**Figure 18 Error in global hindcast wave height relative to buoys after 1-jan-1992**

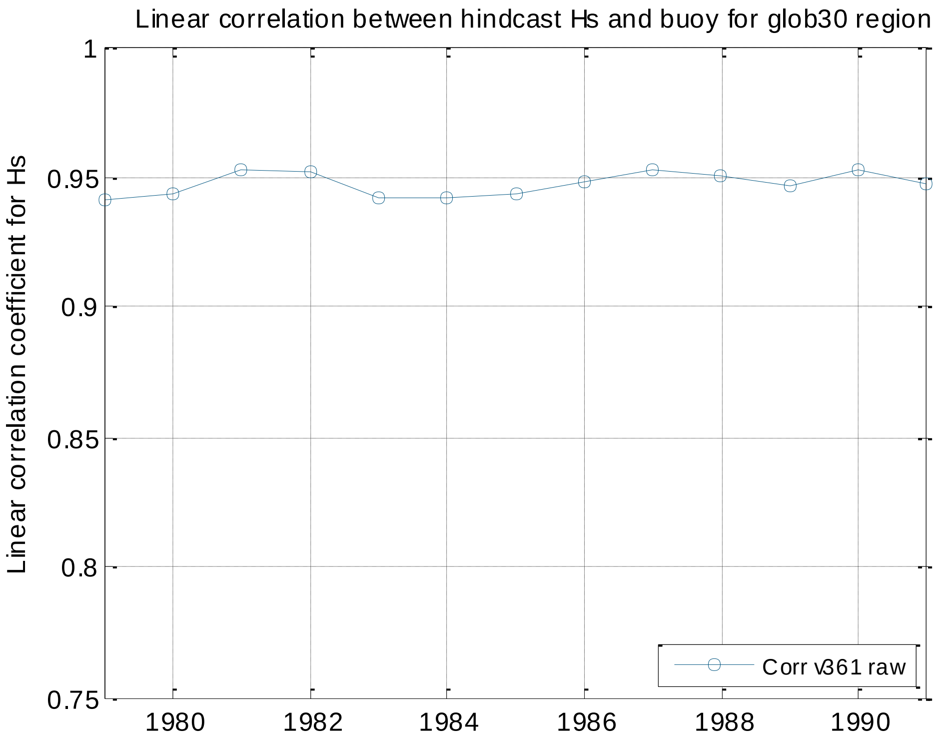


Figure 19 Correlation wave height global hindcast and buoys before 1-jan-1992

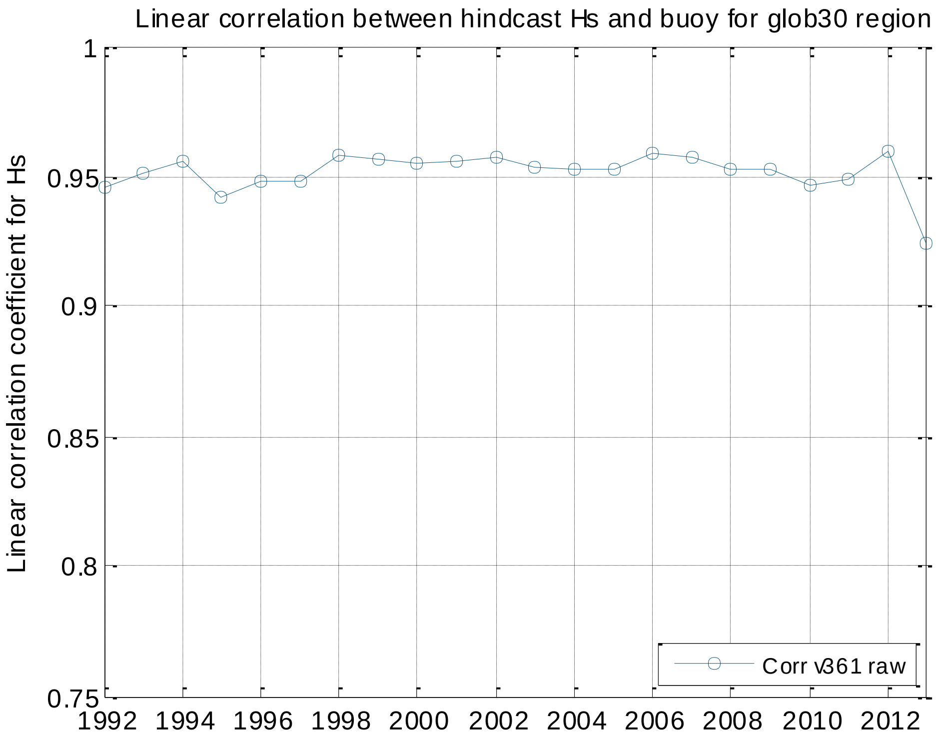


Figure 20 Correlation wave height global hindcast and buoys after 1-jan-1992

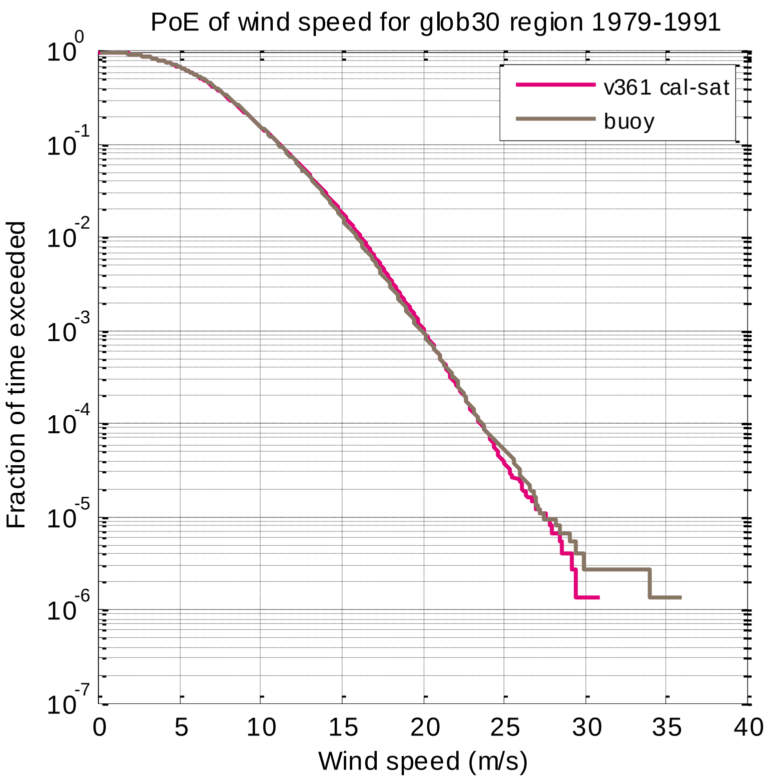


**Figure 21 PoE of global hindcast wind speed and buoys before 1-jan-1992**

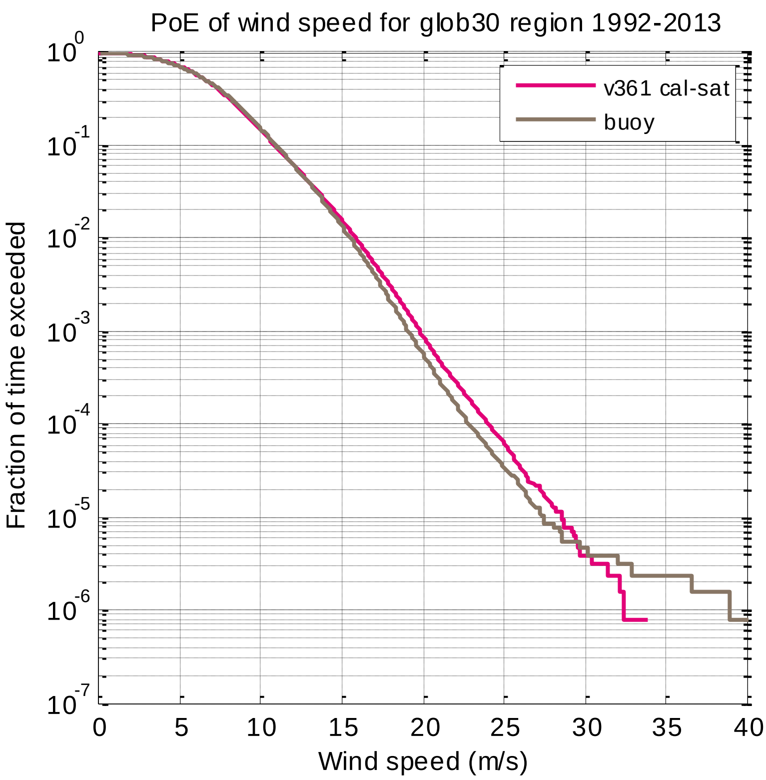


**Figure 22 PoE of global hindcast wind speed and buoys after 1-jan-1992**

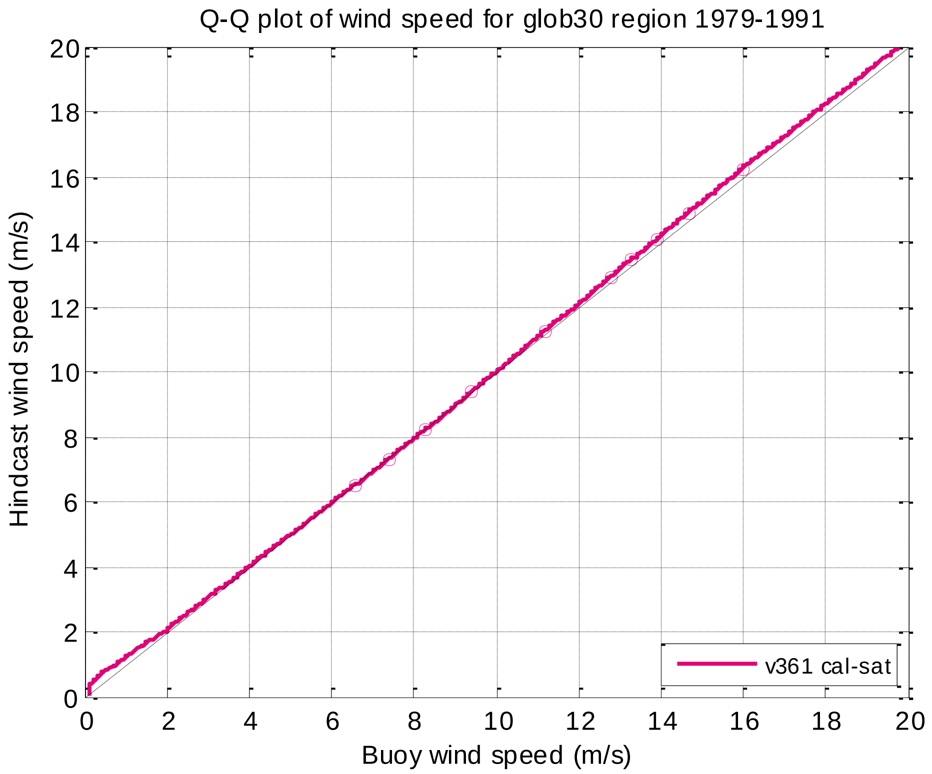


**Figure 23 Q-Q plot of global hindcast wind speed against buoys before 1-jan-1992**

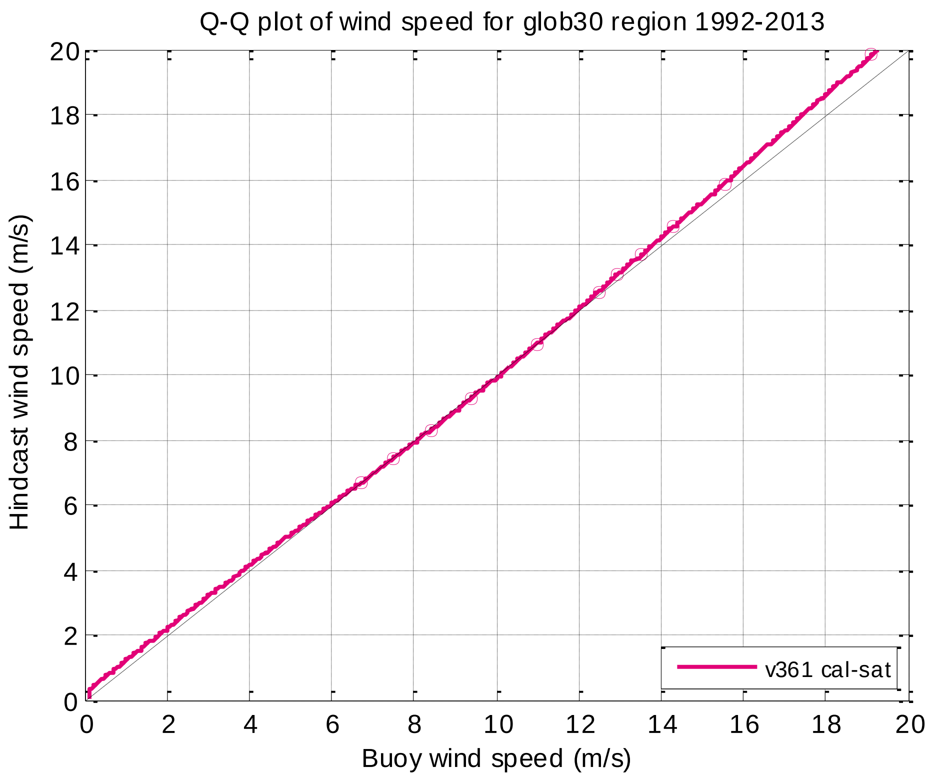


**Figure 24 Q-Q plot of global hindcast wind speed against buoys after 1-jan-1992**

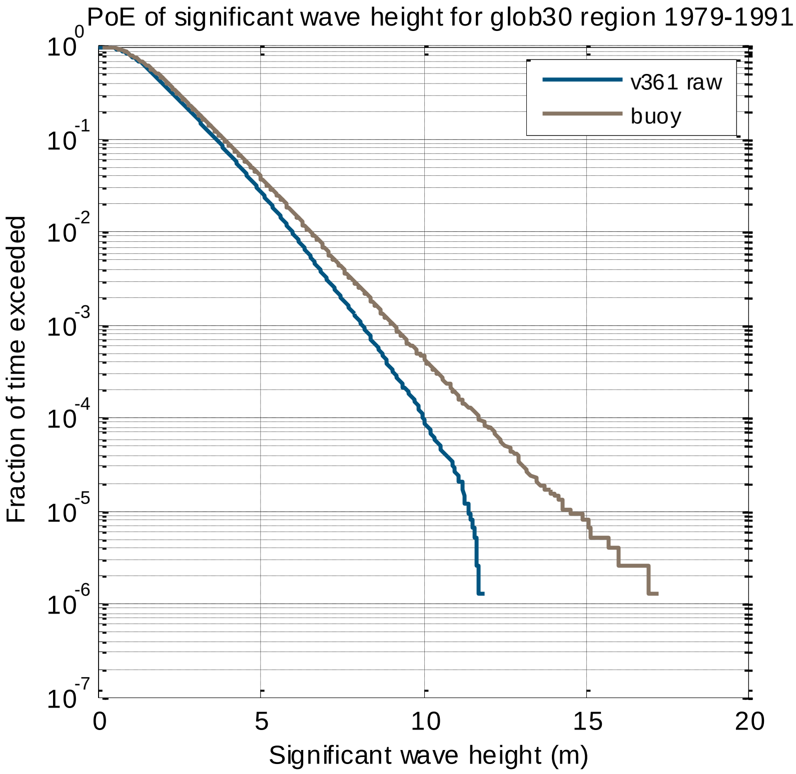


**Figure 25 PoE of global hindcast wave height and buoys before 1-jan-1992**

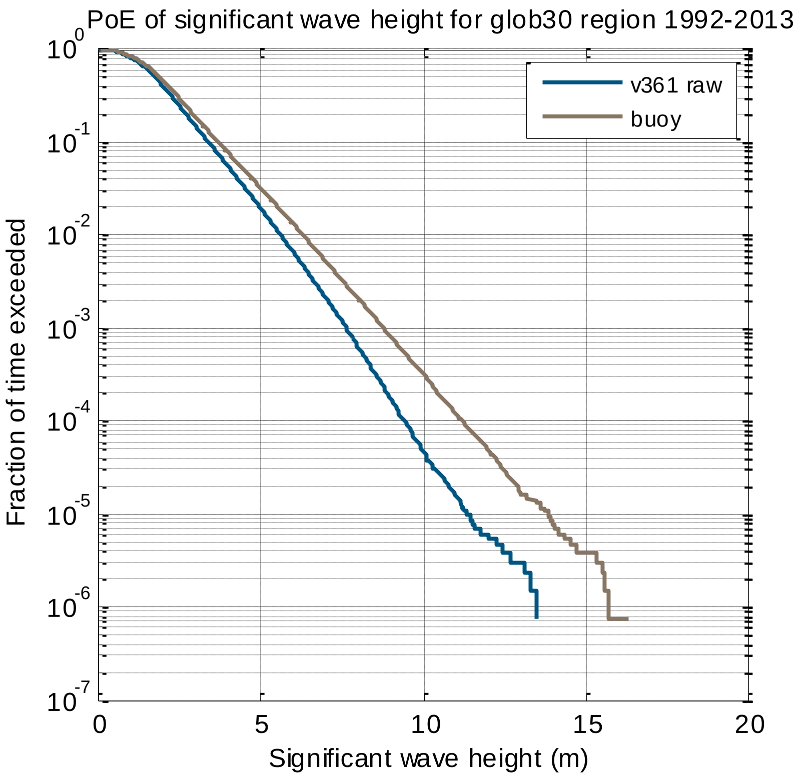


**Figure 26 PoE of global hindcast wave height and buoys after 1-jan-1992**

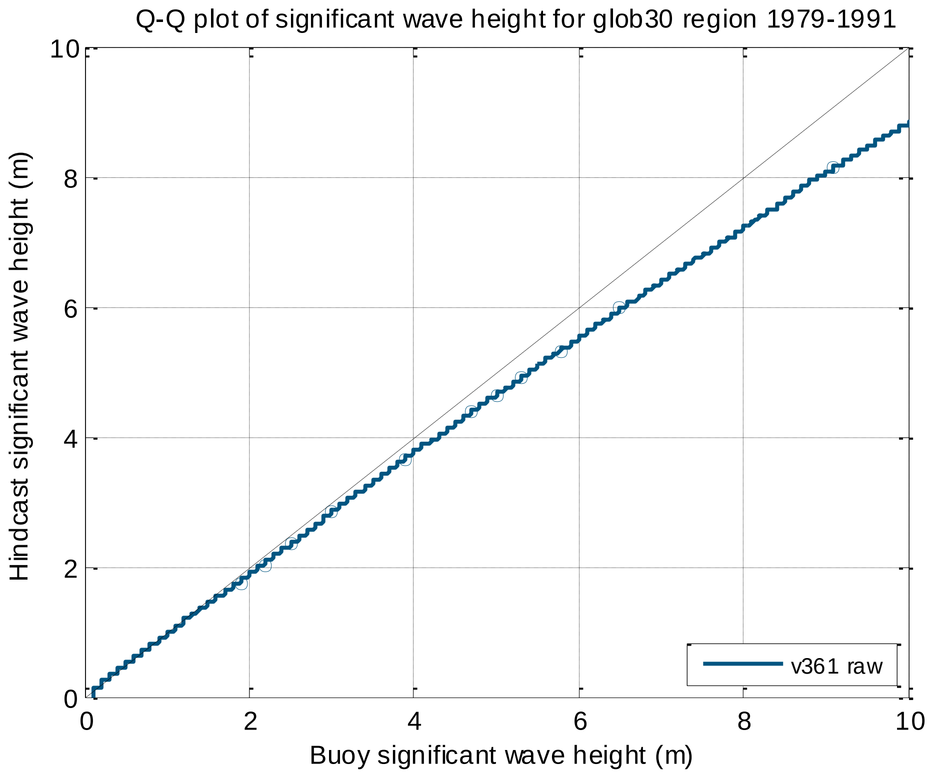


**Figure 27 Q-Q plot of global hindcast wave height against buoys before 1-jan-1992**

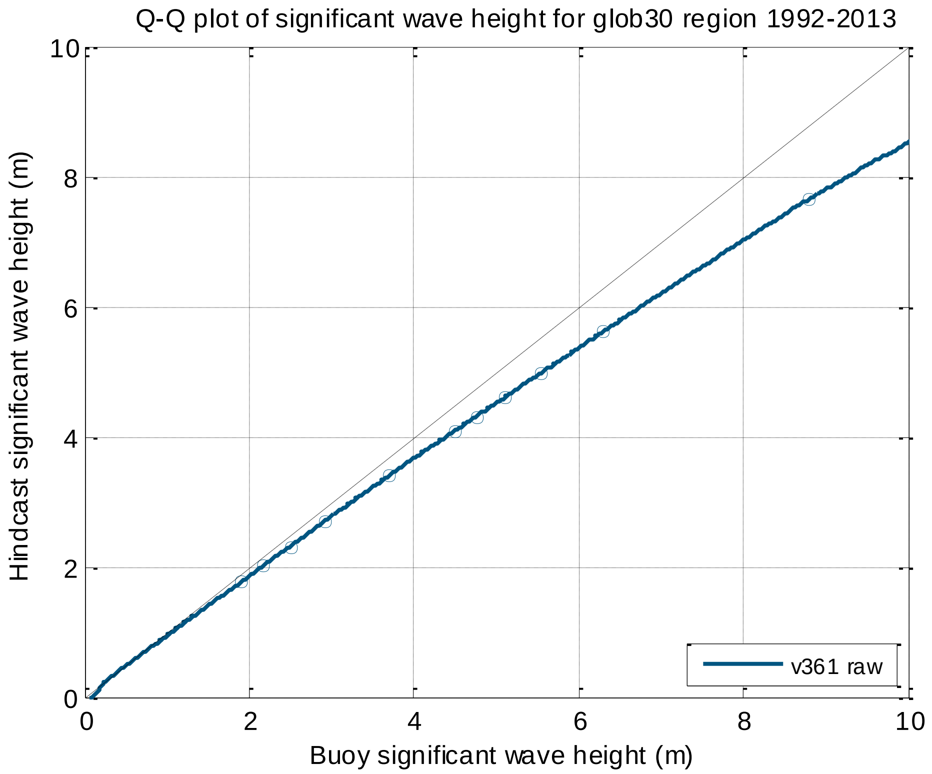


**Figure 28 Q-Q plot of global hindcast wave height against buoys after 1-jan-1992**

# 6. Results for the EU-shelf Model

The quality of wind speed and significant wave height of the regional EU-shelf model is measured against buoys in the first three sections of this chapter (6.1.1-6.1.3). The set of buoys is explained in Appendix B2 – Buoys Used for the EU-shelf Hindcast. Model performance is provided for various versions and processing levels of the hindcast (see section 4.5).

The last section (6.1.4) presents charts of differences between the model and satellites.

*Note:*
*The quality of regional model wave periods, i.e. zero-crossing wave period and peak wave period is evaluated separately in Appendix F2 – Validation of Wave Periods (EU-shelf). Model performance in terms of wave direction is addressed in Appendix G – Validation of Wave Directions (EU-shelf).*

## 6.1. Results for the Ambient Climate of the EU-shelf Model

### 6.1.1. Overall Ambient Climate Results

Table 14 below summarizes the ambient climate error statistics of various versions of the EU-shelf model relative to all buoys.

The numbers in Table 14 demonstrate that, in relation to buoys

1. Overall relative error in ‘best’ v361 wind speed is almost 18% and for wave height this is about 16%. Overall linear correlation coefficient is about 0.92 for winds and 0.96 for waves.

   This is as good as can be expected; for comparison, see Appendix C – Validation of Satellite Data; Table 23-Table 25). This appendix shows that the relative error in satellite wind speed ranges from 14%-18% for altimeters (17% overall) and from 13%-15% for scatterometers (14% overall); relative error in wave height from altimeter missions ranges from 9%-13% (11% overall). Correlation for altimeter wind speed is 0.92, ranging from 0.90-0.93 per mission. Scatterometer wind correlation is 0.94. Correlation for all altimeters is 0.96 for wave height.

2. Best’ v361 winds are better than ‘best’ v352 winds: the relative error is about 2% lower (thanks to both reduction of bias and variability) and correlation with buoy data is slightly higher. ‘Best’ v361 wave height is slightly better than v352 wave height: relative error is more than 1% lower, mainly thanks to a smaller standard deviation of the error. Note that un-calibrated v361 waves are too low and worse than un-calibrated v352 waves: calibration with altimeters is even more important for new v361.
3. Auto-calibration with altimeter removes most of the bias in v361 wave height and slightly reduces standard deviation of the model error. As a result, the relative error in hindcast v361 wave height is reduced by about 2%. Bias in un-calibrated v352 waves is less than the bias in un-calibrated v361 waves: here the reduction of the relative error of just over 1% is mainly caused by reduction of variability.

| | Wind speed U10 | | | | | Wave height Hs | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Model Version | Mean (m/s) | Bias (m/s) | Std (m/s) | Rrmse (%) | Corr (-) | Mean (m) | Bias (m) | Std (m) | Rrmse (%) | Corr (-) |
| v361 best | **7.89** | **0.06** | **1.54** | **17.7** | **0.92** | **2.01** | **0.05** | **0.39** | **16.4** | **0.96** |
| v352 best | **8.25** | **0.42** | **1.67** | **19.7** | **0.91** | **2.02** | **0.05** | **0.42** | **17.7** | **0.96** |
| v361 raw | | | | | | **1.79** | **-0.18** | **0.40** | **18.3** | **0.96** |
| v352 raw | | | | | | **1.90** | **-0.06** | **0.45** | **18.9** | **0.95** |

**Table 14: Error statistics of EU-shelf model versions relative to ALL buoys**

### 6.1.2. Model Performance over Time for the Ambient Climate

In this section, model-buoy error statistics of significant wave height and wind speed are checked over the years.

Figure 29 illustrates the error in 'best' model wind speed over the years and Figure 30 provides the correlation between 'best' model winds and buoy winds. In a similar way, Figure 31 and Figure 32 summarize error statistics of 'best' model wave height relative to buoys. Figure 33 gives the mean and deviation of the error relative to all buoys in v361 hindcast significant wave height over the years, both un-calibrated and after calibration with altimeter. Figure 34 provides the linear correlation coefficient between v361 hindcast and buoy wave height samples.

#### Performance of Model v361 over Time (based on ALL buoys)

Bias in v361 waves is consistently low over the years and correlation between model and buoy wave height is consistently high over the years.

#### Comparison of Model v352 and v361 over Time (based on ALL buoys)

From Figure 29 and Figure 30 it becomes clear that calibrated v361 wind (CFSR) is better than v352 wind (ECMWF) over the years.

Figure 31 and Figure 32 show that 'best' v361 wave height is better than 'best' v352 wave height. Bias in v361 waves is (more) consistently low over the years and variability and correlation are better.

#### The Effect of Calibration of Model Waves with Altimeter over Time (based on ALL buoys)

Figure 33 makes it clear that un-calibrated model waves are too low on average and that calibration with altimeter significantly reduces the error with respect to buoy observations for practically all years 1992-2013 (in 2010/2011 absolute bias is unchanged). Calibration with altimeter also slightly reduces the standard deviation of the error in model wave height (Figure 33) and increases correlation with buoy data (Figure 34) for practically all years.

#### Model Performance over Time per Buoy Region

Plots on the EU-shelf model performance over the years per region can be found in Appendix D2 – Regional Results Ambient Climate (EU-shelf).

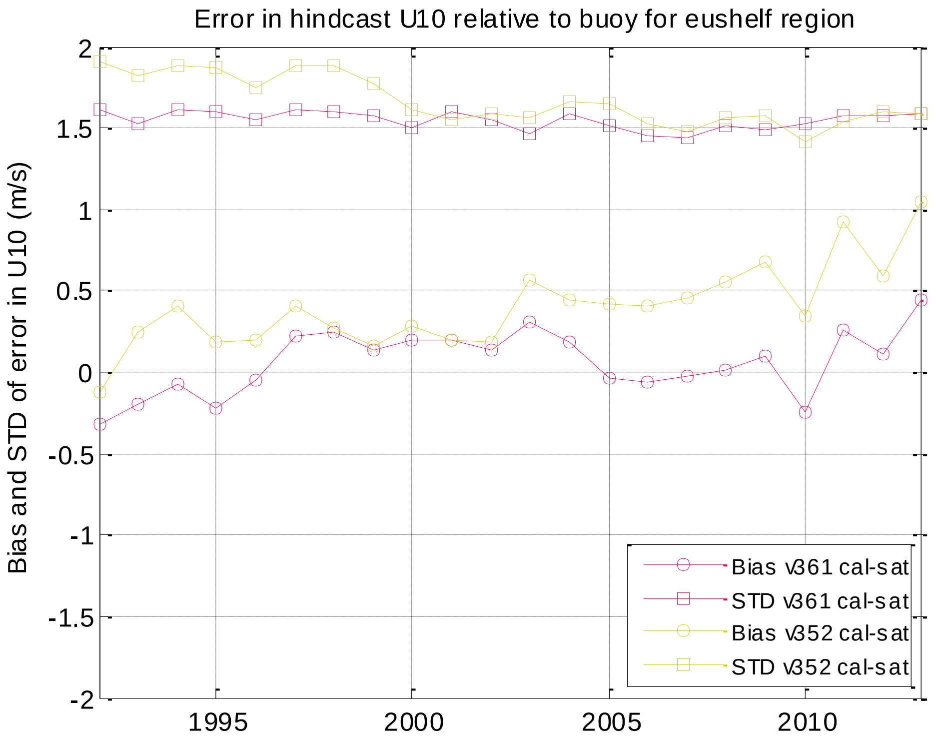


**Figure 29 Error in EU-shelf hindcast wind speed relative to ALL buoys**

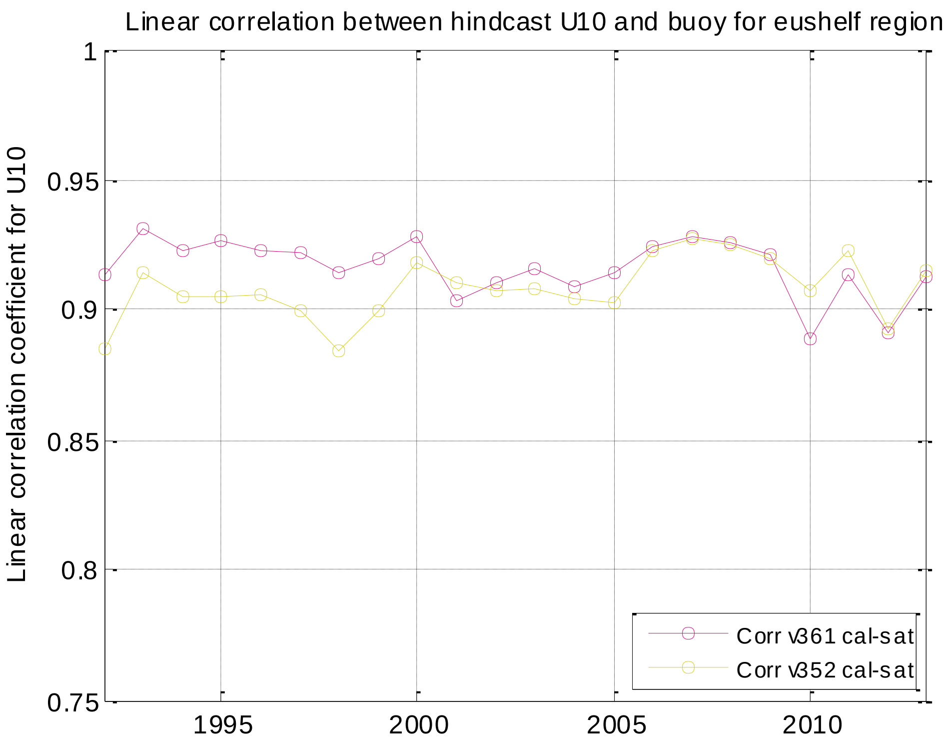


**Figure 30 Correlation wind speed EU-shelf hindcast and ALL buoys**

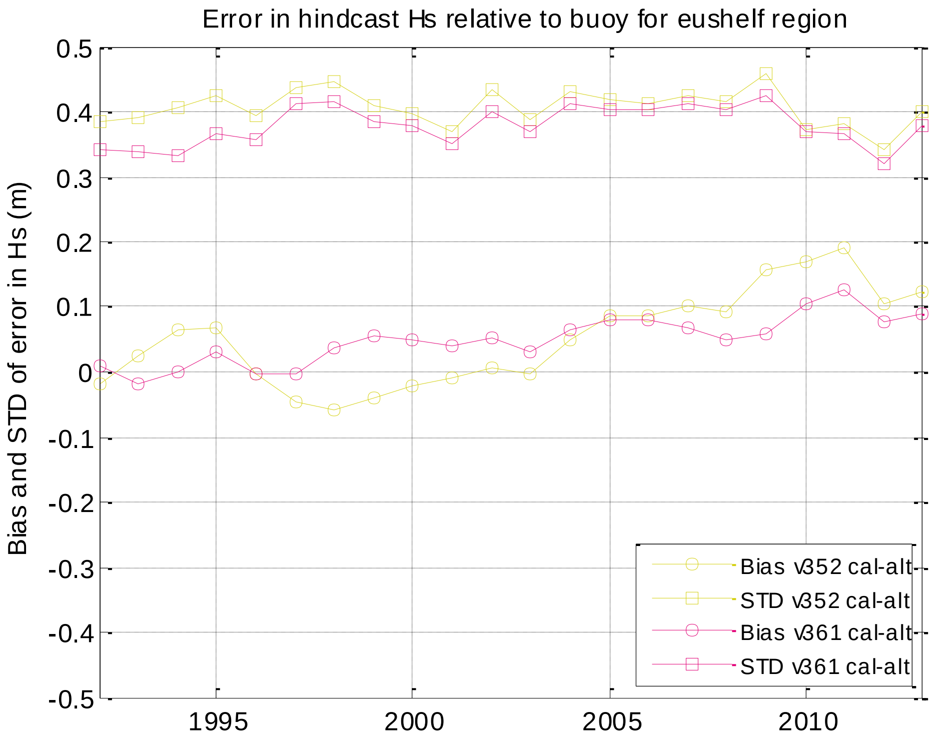


**Figure 31 Error EU-shelf hindcast wave height relative to ALL buoys**

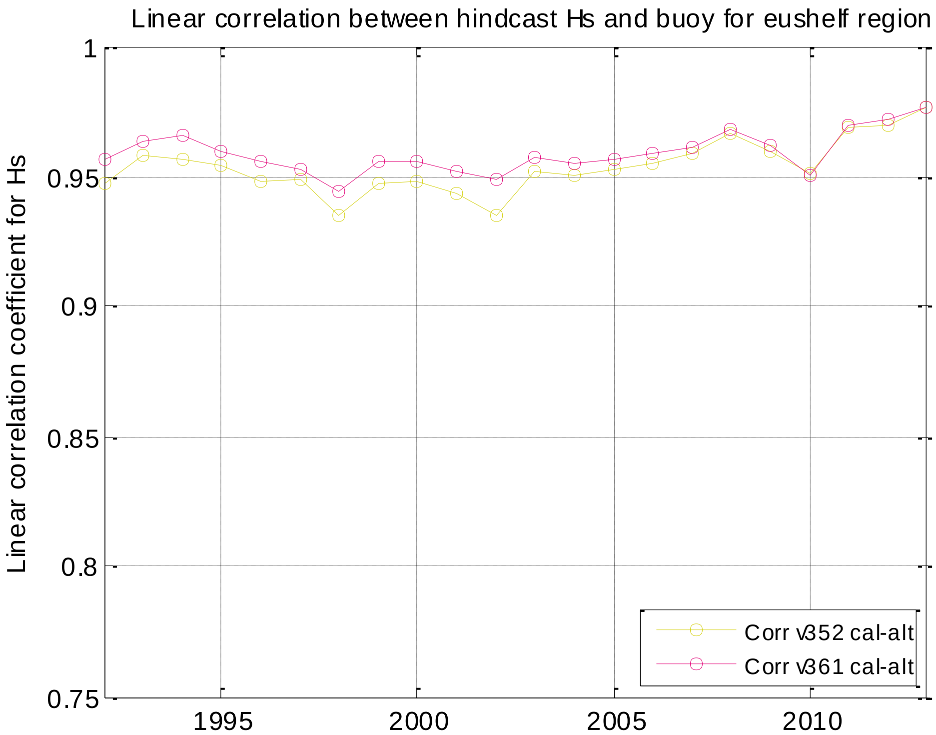


**Figure 32 Correlation wave height EU-shelf hindcast and ALL buoys**

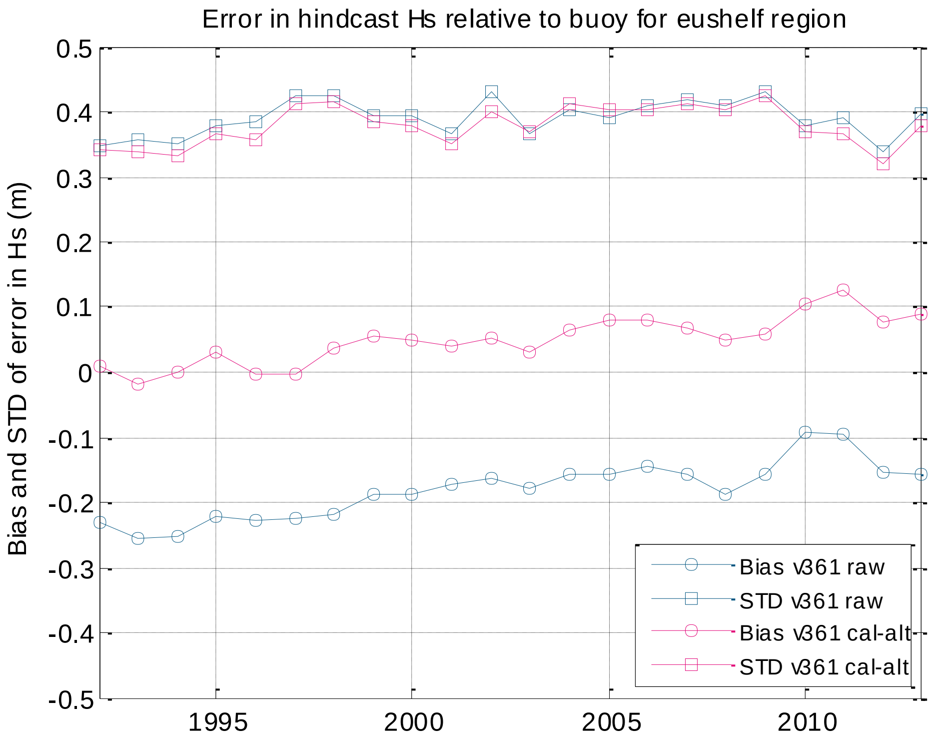


**Figure 33 Error in EU-shelf v361 wave height relative to ALL buoys**

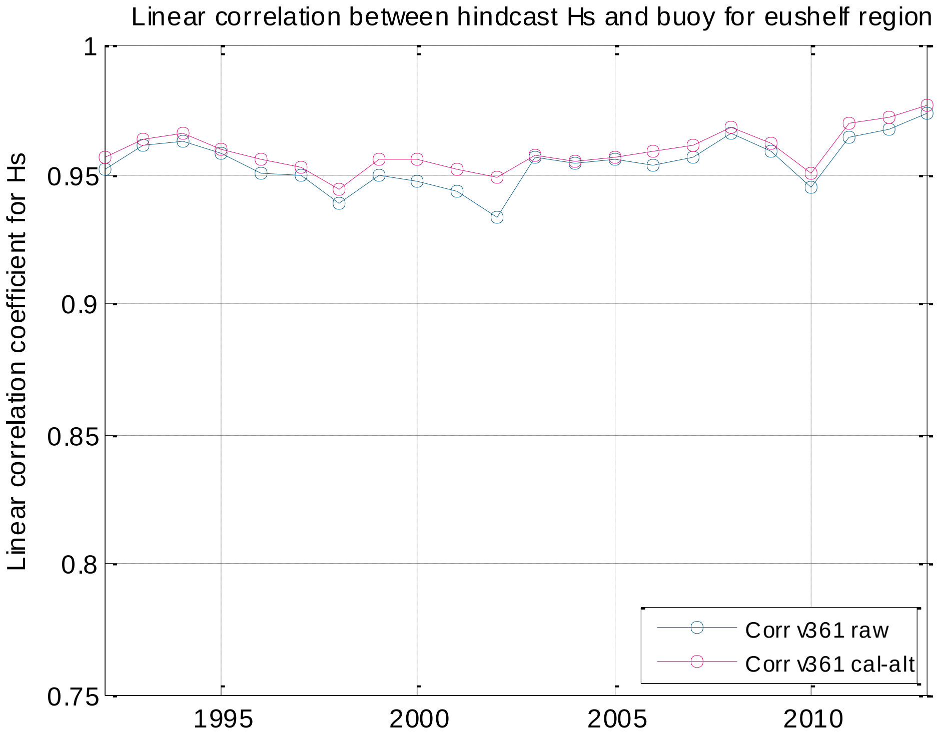


**Figure 34 Correlation wave height EU-shelf v361 and ALL buoys**

### 6.1.3. Model Performance per Buoy Region for the Ambient Climate

Tables of model-buoy error statistics of wind speed and significant wave height are presented below for all buoys and per region (regions are listed in section 4.3).

Table 15 and Table 16 list the error statistics of 'best' model wind speed. Table 17 summarizes the error statistics of v361 waves before and after calibration with altimeters. . Table 18 lists error statistics of both calibrated and un-calibrated v352 wave height.

**Performance of Model v361 per Buoy Region**

See Table 15 (winds) and Table 16 (waves). Relative to buoys, bias in 'best' v361 wind speed is less than 0.5m/s for all regions. Winds remain slightly too low in the Celtic Sea and a bit more in the Irish Sea and the southern North Sea. Winds are too high for the NE Atlantic and for the central and northern part of the North Sea.
Relative to buoys, bias in v361 waves is 0.1m or less in all regions with the exception of the English Channel where model waves are 0.17m too high (according to Table 17 this bias is introduced by calibration with altimeter).

**Comparison of Model v352 and v361 per Buoy Region**

Table 15 and Table 16 show that the quality (relative errors) of v361 winds is better than v352 winds for most regions: absolute bias in v361 wind speed is significantly lower and standard deviation of the error is less. In the Irish Sea, v361 and v352 winds are comparable but v361 wind speed is too low and v352 wind speed is too high. Winds of v352 are higher than buoy measurements for all regions except for the southern part of the North Sea; in this region v361 winds are also too low according to the buoy data.

**The Effect of Calibration of Model Waves with Altimeter per Buoy Region**

The numbers in Table 17 show that calibration with altimeter practically removes the negative bias from v361 wave height in the Celtic Sea, in the Irish Sea and in the North Sea regions. Standard deviation of the error does not change much by calibration. As a result, calibration with altimeter reduces the error in model wave height for these regions. In the NE Atlantic, calibration corrects v361 wave height too much: un-calibrated v361 waves are 0.1m lower than the average buoy observation whilst waves are 0.1m too high after calibration.

The English Channel is an exceptional area. According to the buoys in this region, calibration with altimeter makes average model wave height worse: calibration introduces a positive bias of 0.17m in v361 wave height.

| Region | Un-calibrated u10 of hindcast v361 | | | | | Sat-calibrated u10 of hindcast v361 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Mean (m) | Bias (m) | Std (m) | Rrmse (%) | Corr (-) | Mean (m/s) | Bias (m/s) | Std (m/s) | Rrmse (%) | Corr (-) |
| EU-ATL | | | | | | 8.06 | 0.27 | 1.44 | 17.2 | 0.92 |
| CELTICSEA | | | | | | 7.48 | -0.16 | 1.40 | 16.9 | 0.91 |
| IRISHSEA | | | | | | 6.94 | -0.42 | 1.64 | 20.8 | 0.89 |
| CHAN | | | | | | | | | | |
| NS-S | | | | | | 7.43 | -0.44 | 1.44 | 17.3 | 0.92 |
| NS-C | | | | | | 8.03 | 0.14 | 1.62 | 18.3 | 0.92 |
| NS-N | | | | | | 8.35 | 0.38 | 1.51 | 17.2 | 0.93 |
| **ALL** | | | | | | **7.89** | **0.06** | **1.54** | **17.7** | **0.92** |

**Table 15: Error statistics 'best' wind speed of EU-shelf v361 relative to buoys per region**

| Region | Un-calibrated u10 of hindcast v352 | | | | | Sat-calibrated u10 of hindcast v352 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Mean (m) | Bias (m) | Std (m) | Rrmse (%) | Corr (-) | Mean (m/s) | Bias (m/s) | Std (m/s) | Rrmse (%) | Corr (-) |
| EU-ATL | | | | | | 8.74 | 0.95 | 1.54 | 21.2 | 0.92 |
| CELTICSEA | | | | | | 7.97 | 0.33 | 1.41 | 17.4 | 0.92 |
| IRISHSEA | | | | | | 7.62 | 0.26 | 1.65 | 20.5 | 0.90 |
| CHAN | | | | | | | | | | |
| NS-S | | | | | | 7.53 | -0.33 | 1.59 | 18.7 | 0.91 |
| NS-C | | | | | | 8.18 | 0.28 | 1.70 | 19.4 | 0.91 |
| NS-N | | | | | | 8.73 | 0.76 | 1.61 | 19.7 | 0.93 |
| **ALL** | | | | | | **8.25** | **0.42** | **1.67** | **19.7** | **0.91** |

**Table 16: Error statistics 'best' wind speed of EU-shelf v352 relative to buoys per region**

| Region | Un-calibrated Hs of hindcast v361 | | | | | Alt-calibrated Hs of hindcast v361 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Mean (m) | Bias (m) | Std (m) | Rrmse (%) | Corr (-) | Mean (m/s) | Bias (m/s) | Std (m/s) | Rrmse (%) | Corr (-) |
| EU-ATL | 2.77 | -0.10 | 0.46 | 14.5 | 0.96 | 2.97 | 0.10 | 0.48 | 14.9 | 0.96 |
| CELTICSEA | 1.62 | -0.23 | 0.33 | 18.7 | 0.95 | 1.89 | 0.03 | 0.33 | 15.7 | 0.95 |
| IRISHSEA | 0.80 | -0.41 | 0.27 | 34.8 | 0.94 | 1.15 | -0.06 | 0.25 | 18.2 | 0.94 |
| CHAN | 1.56 | 0.00 | 0.42 | 22.4 | 0.94 | 1.73 | 0.17 | 0.41 | 23.6 | 0.95 |
| NS-S | 1.11 | -0.22 | 0.28 | 22.6 | 0.95 | 1.33 | 0.00 | 0.26 | 16.5 | 0.95 |
| NS-C | 1.95 | -0.20 | 0.43 | 18.8 | 0.95 | 2.19 | 0.03 | 0.41 | 16.4 | 0.95 |
| NS-N | 2.39 | -0.17 | 0.49 | 17.6 | 0.94 | 2.66 | 0.09 | 0.49 | 16.9 | 0.94 |
| **ALL** | **1.79** | **-0.18** | **0.40** | **18.3** | **0.96** | **2.01** | **0.05** | **0.39** | **16.4** | **0.96** |

**Table 17: Error statistics wave height of EU-shelf v361 relative to buoys per region**

| Region | Un-calibrated Hs of hindcast v352 | | | | | Alt-calibrated Hs of hindcast v352 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Mean (m) | Bias (m) | Std (m) | Rrmse (%) | Corr (-) | Mean (m/s) | Bias (m/s) | Std (m/s) | Rrmse (%) | Corr (-) |
| EU-ATL | 3.04 | 0.16 | 0.51 | 16.5 | 0.96 | 3.02 | 0.15 | 0.49 | 15.7 | 0.96 |
| CELTICSEA | 1.78 | -0.07 | 0.35 | 16.9 | 0.95 | 1.91 | 0.06 | 0.35 | 16.7 | 0.95 |
| IRISHSEA | 0.91 | -0.29 | 0.28 | 28.9 | 0.93 | 1.17 | -0.03 | 0.28 | 20.1 | 0.93 |
| CHAN | 1.70 | 0.13 | 0.50 | 27.8 | 0.93 | 1.72 | 0.16 | 0.42 | 24.1 | 0.94 |
| NS-S | 1.14 | -0.19 | 0.30 | 22.4 | 0.94 | 1.31 | -0.02 | 0.29 | 18.4 | 0.94 |
| NS-C | 2.03 | -0.13 | 0.46 | 18.9 | 0.94 | 2.18 | 0.02 | 0.46 | 18.4 | 0.94 |
| NS-N | 2.54 | -0.02 | 0.51 | 17.5 | 0.94 | 2.66 | 0.10 | 0.52 | 18.1 | 0.94 |
| **ALL** | **1.90** | **-0.06** | **0.45** | **18.9** | **0.95** | **2.02** | **0.05** | **0.42** | **17.7** | **0.96** |

**Table 18: Error statistics wave height of EU-shelf v352 relative to buoys per region**

### 6.1.4. Comparison of Satellites and the EU-shelf Model

On the next page, spatial plots of model-satellite bias and correlation for significant wave height are provided for the regional EU-shelf grid. 'Best' model waves were obtained by automated calibration with satellites, carried out per grid point and based on the years 1992-2011 (also see section 4.1). Similar spatial plots for the other regional models can be found in Appendix H – Comparison of Satellites and Regional Models.

Buoys have highest authority when it comes to judging model quality. According to Table 17, calibration with altimeter removes the systematic error in hindcast v361 relative to the buoys in most EU-shelf buoy regions. The table shows that altimeter based correction 'pulls the hindcast towards truth (buoy measurements)' in semi-closed basins like the Irish Sea and the North Sea.

It is also seen that the model requires less correction in areas on open ocean with more swell like the western part of the EU-shelf.

*Please note that the charts on the pages below show differences between model and satellites, whereas plots and tables in previous sections 6.1.1-6.1.3 show the error between model and buoys.*

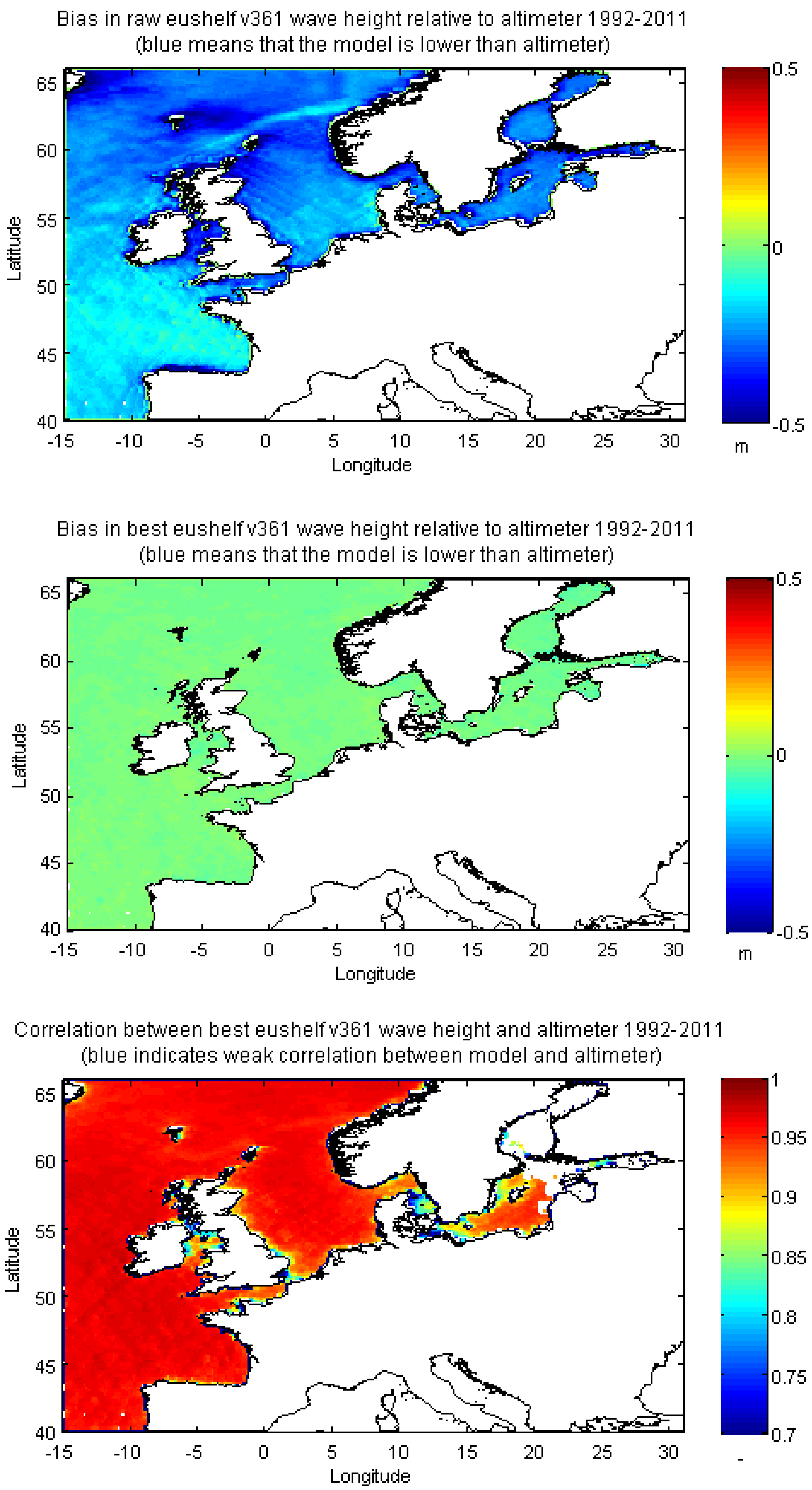


**Figure 35 Bias and correlation v361 wave height relative to altimeter for the EU-shelf**

## 6.2. Results for the Extreme Climate of the EU-shelf Model

Per buoy region and for all buoys, higher and extreme values of model wind speed and significant wave height were compared to buoy data by means of quantile-quantile (Q-Q) plots and probability of exceedance (PoE) plots. Please refer to section 4.4 for more detail.

Figure 36 compares the probability distributions of 'best' model and buoy wind speed and the corresponding Q-Q plot is shown in Figure 37. Similarly, model and buoy waves are compared in Figure 38 and Figure 39.

### Performance of Model v361 (based on ALL buoys)

Figure 36 and Figure 37 demonstrate that 'best' v361 wind speed is about right for values up to say 20m/s. For higher wind speeds, buoy observations start to exceed model values. In the uppermost tail, around 30m/s, model winds have become about 2m/s too low.
Figure 38 shows that 'best' v361 waves are slightly higher than buoy observations between 5m and 12m. For higher values, buoy wave height gets ahead of v361 wave height. Highest wave reported by a buoy is about 17m; maximum model wave height is about 15m.

### Comparison of Extremes of Model v352 and v361 (based on ALL buoys)

'Best' v361 winds are somewhat better than 'best' v352 winds up to about 20m/s (see Figure 37). For higher values, v352 wind speed is closer to the buoy observations.
Figure 38 shows that raw v361 waves are too low and increased by calibration whilst raw v352 waves are too high and decreased by calibration. In the very tail both v361 and v352 waves remain about 2m too low: maximum model wave height is near 15m whilst maximum buoy wave height is about 17m.

### The Effect of Calibration of Model Waves with Altimeter on Extremes (based on ALL buoys)

From Figure 38 it is seen that auto-calibration with altimeter based on the ambient climate also improves higher model waves above say 10m. Highest model waves remain too low.

### Extreme Climate Results per Buoy Region

Plots on regional model extremes can be found in Appendix E2 – Regional Results Extreme Climate (EU-shelf).

From the wind speed distributions in this appendix it can be seen that 'best' model wind speed extremes match quite well with buoy observations for the EU-shelf, both for v361 and v352. In general, model wind speed extremes are within 10% of the buoy data.
Apart from the very tail where models underestimate observed wave height, there is a fair match between higher values and extremes of 'best' model wave height and buoy data for the EU-shelf regions. There is one major exception however: according to the buoys in the Channel region, higher model waves are way too high (see Figure 122-Figure 123).
The crucial role of altimeter-based model calibration is best seen for waves in the Irish Sea (Figure 120-Figure 121) and in the North Sea (e.g. Figure 126). As for the global model, calibration with altimeter has become even more important as un-calibrated v361 waves are clearly too low.

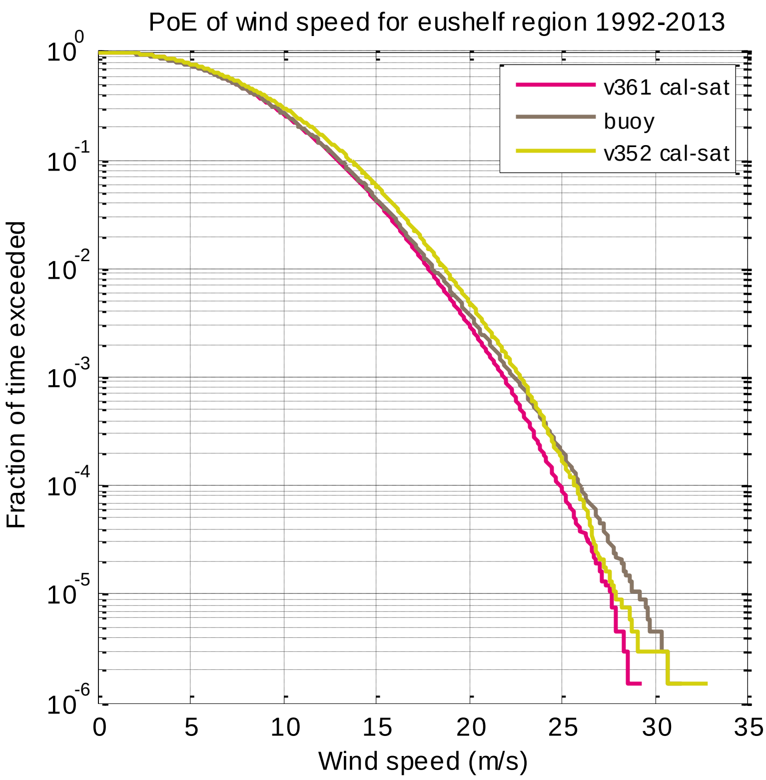


**Figure 36 PoE of EU-shelf hindcast wind speed and ALL buoys**

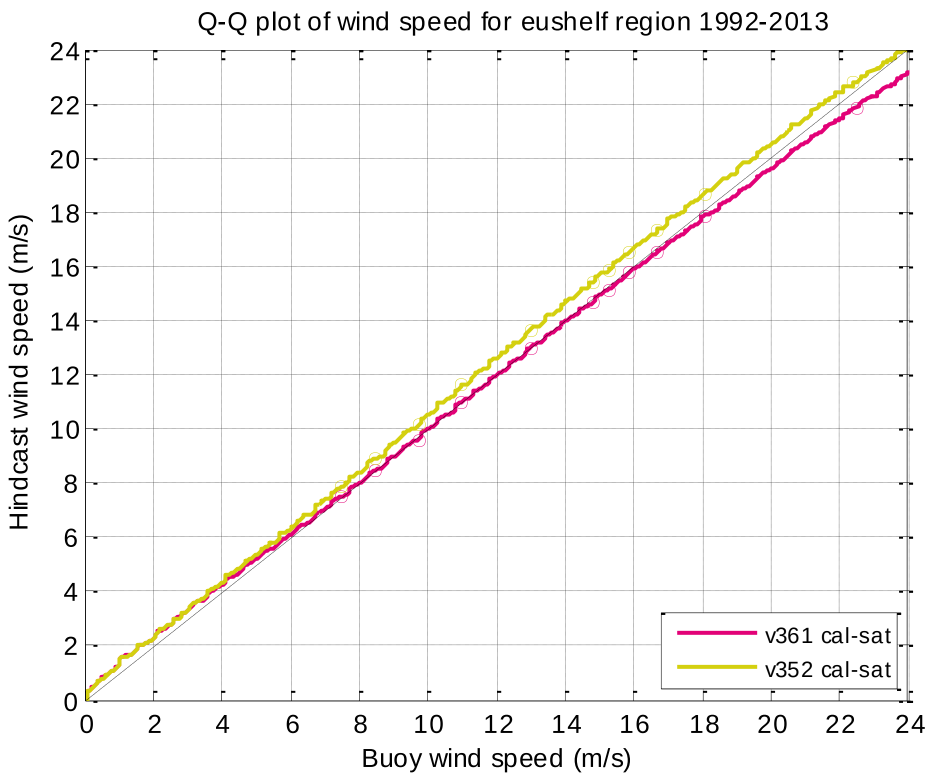


**Figure 37 Q-Q plot of EU-shelf hindcast wind speed against ALL buoys**

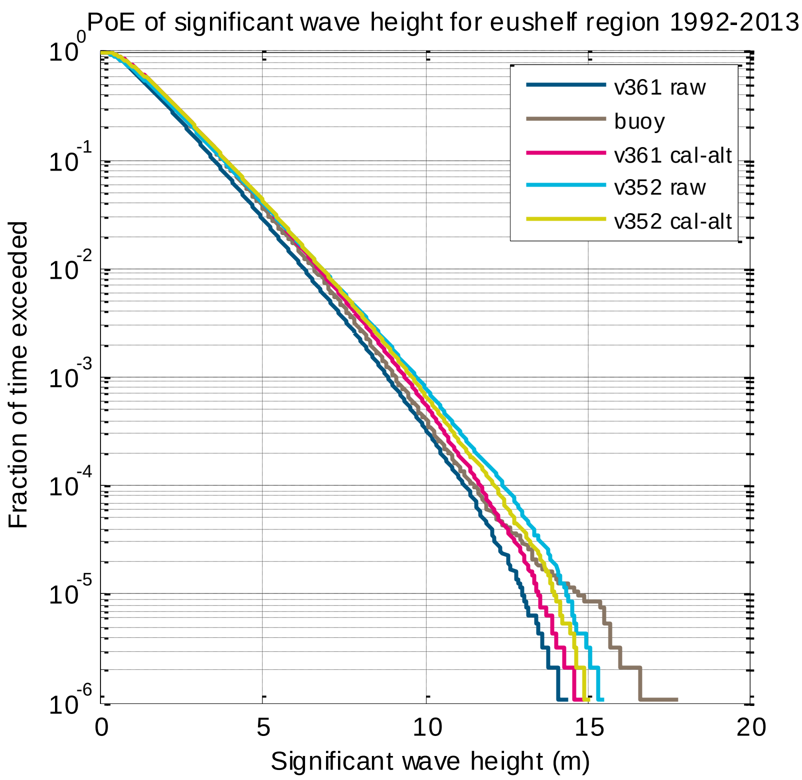


**Figure 38 PoE of EU-shelf hindcast wave height and ALL buoys**

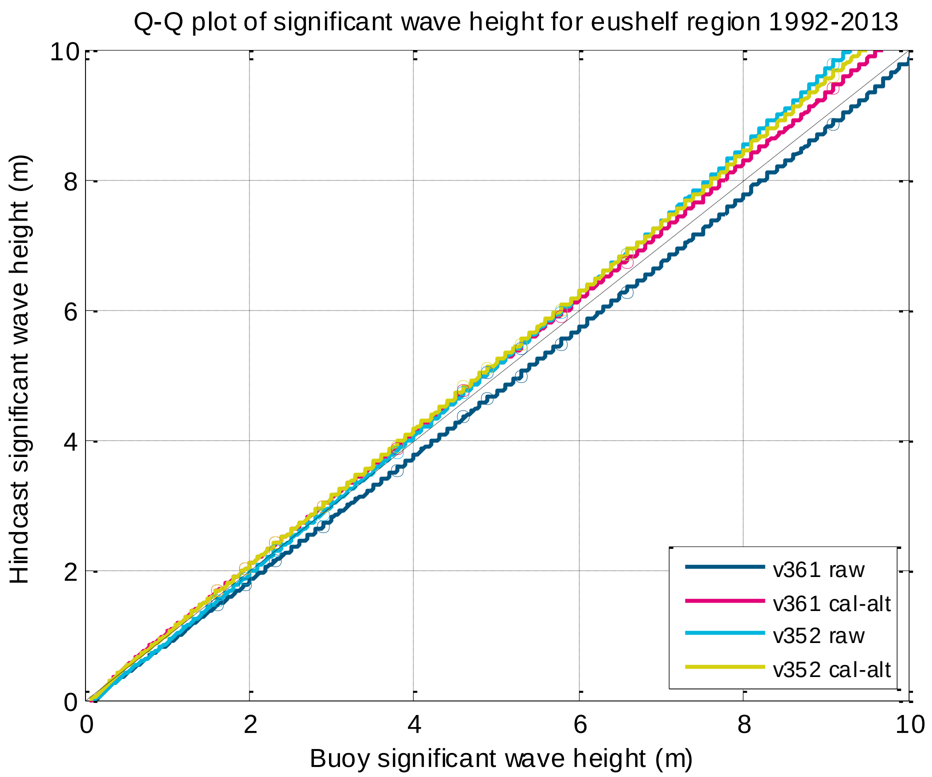


**Figure 39 Q-Q plot of EU-shelf hindcast wave height against ALL buoys**

# 7. Discussion and Conclusions

In general, the results presented in this report confirm the improved quality of the new 35-year hindcast database. According to buoys, model winds and waves are better than before, mainly thanks to less variability. At the same time, calibration with satellites has become even more important as un-calibrated v361 waves are systematically too low. Most likely, model v361 requires further tuning of the wind source term by means of the ‘drag coefficient’ which represents the roughness of the surface and hence influences wave growth. Fortunately, most of this bias in model waves can be removed by means of calibration with altimeters (reduction of variability of the model error is harder).

The results in this report demonstrate that, both over the years and in space

1. The quality of the new hindcast database is consistently high over the years 1979-2013
2. The new database is better than the previous database (v352; 1992-2013)
3. According to buoys, calibration with satellites significantly improves the hindcast data.

The conclusions are elaborated in the Executive Summary (section 1.4).

*End of Main Report*
*(Appendices to Follow)*
*BMT ARGOSS*

# Appendix A – Wave Model

WAVEWATCH III ™ (WW III) is a third generation wave model developed at NOAA/NCEP in the spirit of the WAM model (WAMDIG 1988, Komen et al. 1994). It is a further development of the model WW I, as developed at Delft University of Technology (Tolman 1989, 1991) and WW II, developed at NASA, Goddard Space Flight Center (e.g., Tolman 1992). WW III however, differs from its predecessors in many important points such as the governing equations, the model structure, the numerical methods and the physical parameterisations. The model solves the spectral action density balance equation for wavenumber-direction spectra. The implicit assumption of this equation is that properties of medium (water depth and current) as well as the wave field itself vary on time and space scales that are much larger than the variation scales of a single wave. A further constraint is that the parameterisations of physical processes included in the model do not address conditions where the waves are strongly depth-limited. These two basic assumptions imply that the model can be applied on spatial scales (grid increments) larger than 1-10 km outside the surf zone. The model is written in ANSI standard FORTRAN 90. It is fully modular and uses dynamic memory allocation. For a generic validation of the model, see the document [Tolman, 2002][2].

Physical and numerical features of the model are summarized below. The model's dataflow is depicted in Figure 40 on the next page.

### Physical features

- The governing equations include wave propagation, refraction and straining of the wave field due to temporal and spatial variations of the water depth and, if applicable, of current due to tides, surges, et cetera.
- The 'source terms' parametrize wind-driven wave growth, non-linear resonant wave-wave interactions, white-capping and bottom friction.
- The model includes several alleviation methods for the Garden Sprinkler Effect.
- Sub-grid representation of unresolved islands, referred to as obstruction.
- Option to use full non-linear wave–wave interaction (for research only).
- Dynamically updated ice coverage.

### Numerical features and compile options

- Wave propagation is considered to be linear.
- The model uses a regularly spaced longitude-latitude grid.
- Wave spectra are discretized using a constant directional increment and a spatially varying wavenumber grid that corresponds to an invariant logarithmic intrinsic frequency grid (Tolman and Booij 1998).
- Both a first order accurate and third order accurate numerical scheme is available to describe wave propagation (Tolman 1995). Selected at the compile level.
- The source terms are integrated in time using a dynamically adjusted time stepping algorithm, which concentrates computational efforts in conditions with rapid spectral changes (Tolman 1992, 1997, 1999a).
- Compile options: choose different source term package; include shared memory parallelisms; include a distributed memory environment.

[2] Tolman, H.L., 2002, Testing of WAVEWATCH III version 2.22 in NCEP's NWW3 ocean wave model suite. US Department of Commerce, NOAA, NOAA/ NWS/NCEP/OMB Technical Note Nr. 214 (http://polar.ncep.noaa.gov/waves/wavewatch/wavewatch.html)

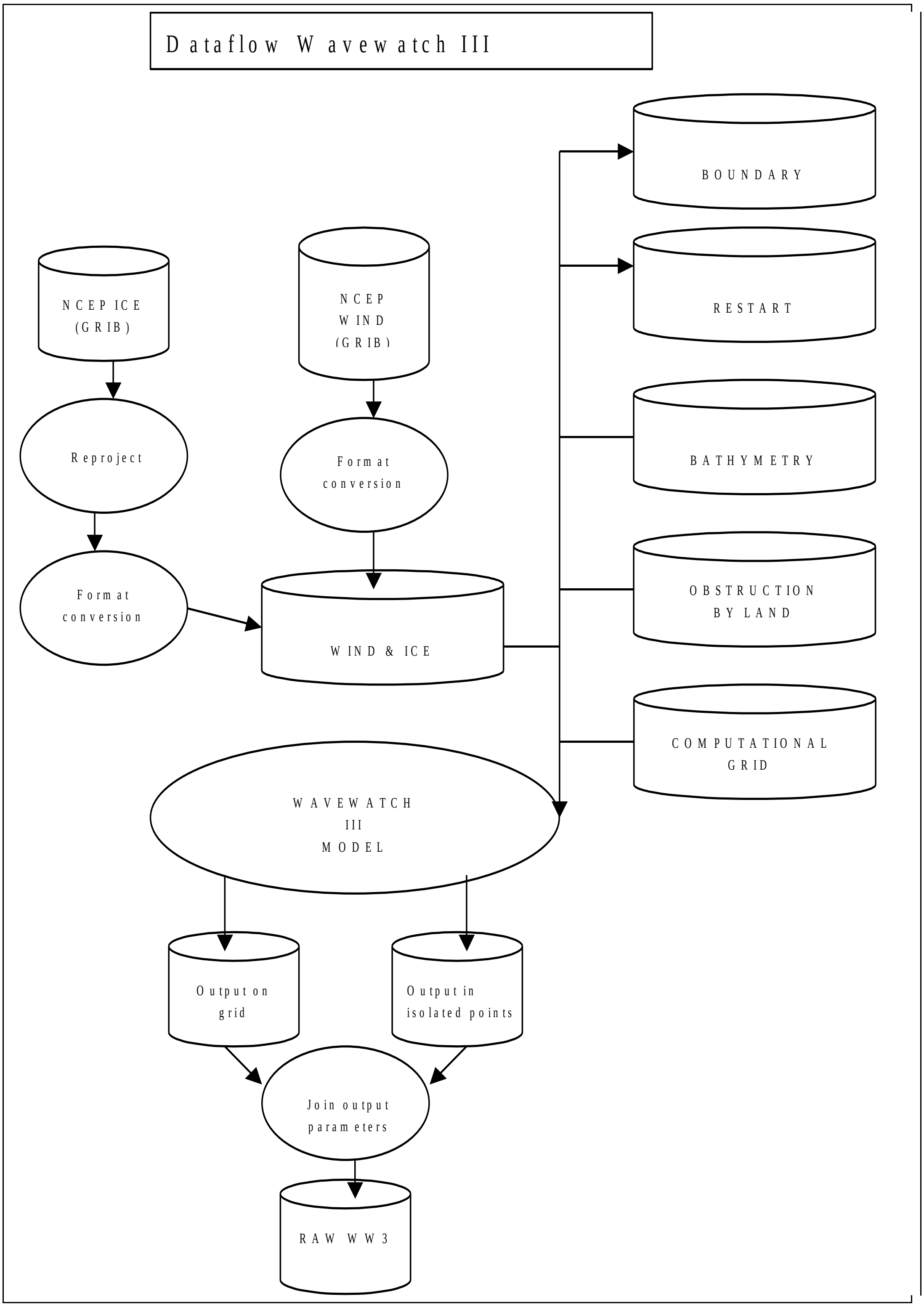


**Figure 40  Dataflow of the WAVEWATCH III wave model**

# Appendix B1 – Buoys Used for the Global Hindcast

In this appendix characteristics are supplied for the buoys used for the validation of the global hindcast. There are 57 different buoys in total. This set of buoys was also used for the calibration and validation of the satellites based on the years 1992-2013 (see Appendix C – Validation of Satellite Data). A subset of 28 buoys supply data before and after 1-jan-1992.

The buoys report hourly wind speed at 10m, wind direction, significant wave height, zero-crossing wave period and peak wave period.

First, the quality check applied to our in-house buoy data is briefly described. Next, the set of buoys used for the validation of the global hindcast is elaborated.

### Quality checks

- Apart from visual inspection of time series, buoys are compared to satellites over the years to check for sudden change in quality (of course this works both ways: both satellite and buoy can be the cause of deviant error statistics).
- Some buoys have been relocated over the years. For example, NOAA relocated buoy 41002 twice; hence the labelling 41002a, 41002b and 41002c. If a buoy label ends with ‘h’, the buoy in question has not been relocated.

The set of buoys used for the validation of the global hindcast is shown below. Colours indicate significant wave height averaged over the observation period of each buoy (a similar plot can be made for averaged wind speed). Table 19 and Table 20 list each buoy's position, region, observation period and the number of observation records.

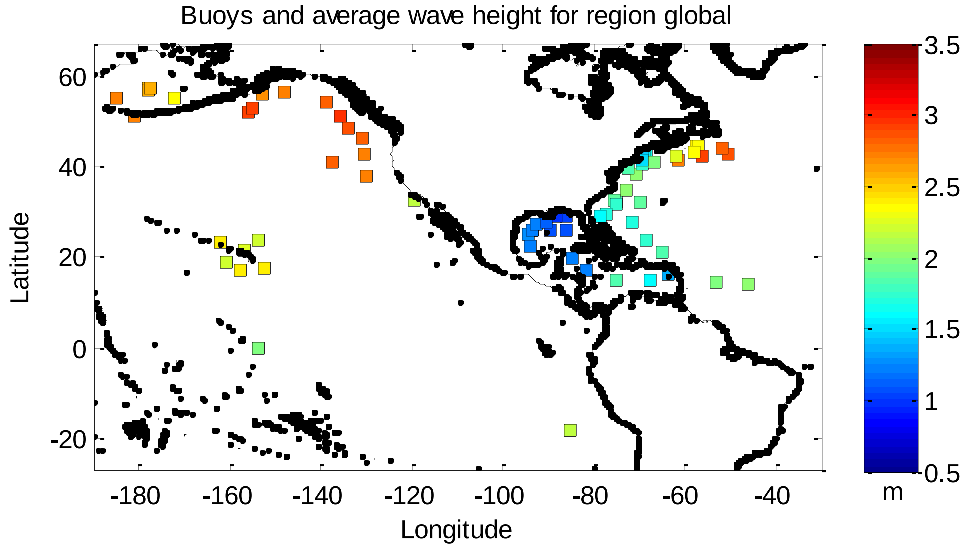


**Figure 41 NOAA buoys used for validation of the global hindcast**

The set of buoys depicted in the figure above has been divided into the following regions with a more or less uniform wave climate:

- The Gulf of Mexico (GOM, buoy numbers 42001-42041)
- The Caribbean (CAR, buoys numbers 42055-42060)
- The northern Atlantic east of Northern America (ATL, buoy numbers start with 41 or 440)
- Offshore Newfoundland (NFL, buoy numbers start with 441)
- The northern Pacific (PAC, buoy numbers start with 46)
- The region around Hawaii (HAW, buoy numbers start with 51)
- Off Chile (CHI, 32302h is the only buoy)

The figures on the next pages show the individual buoys for the various regions.

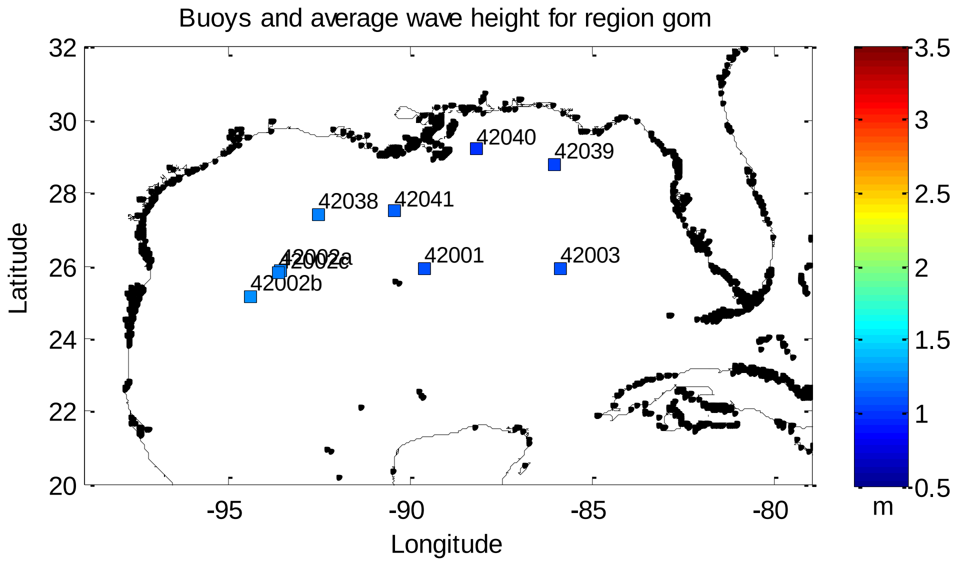


**Figure 42 NOAA buoys in the Gulf of Mexico (GOM)**

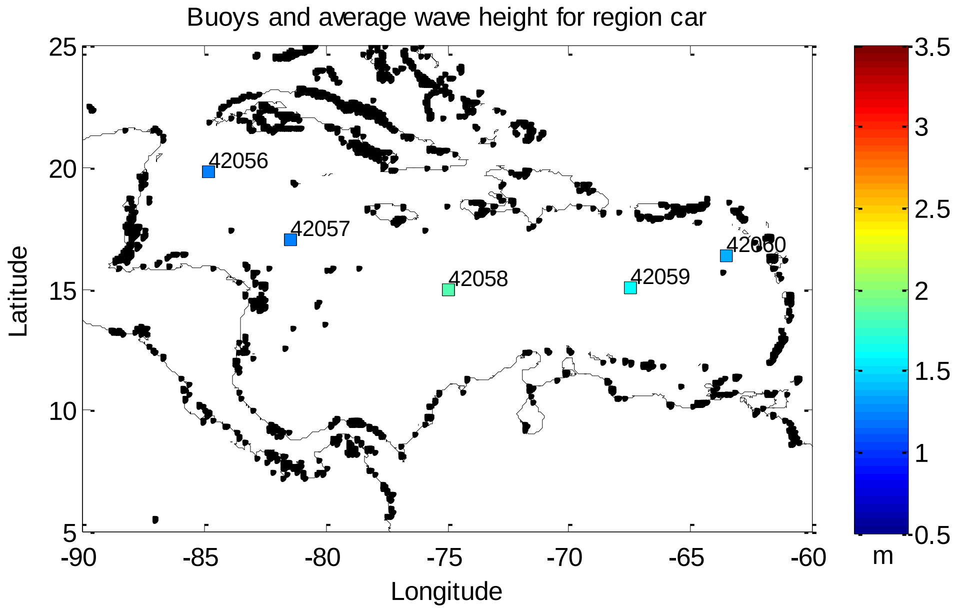


**Figure 43 NOAA buoys in the Caribbean (CAR)**

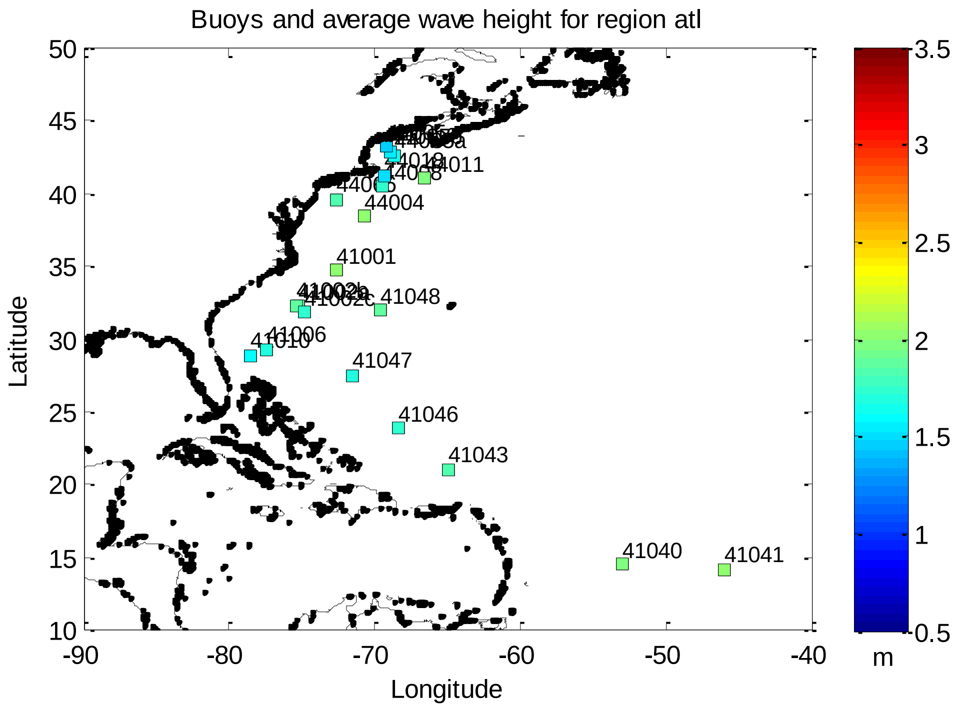


**Figure 44 NOAA buoys in the NW Atlantic (ATL)**

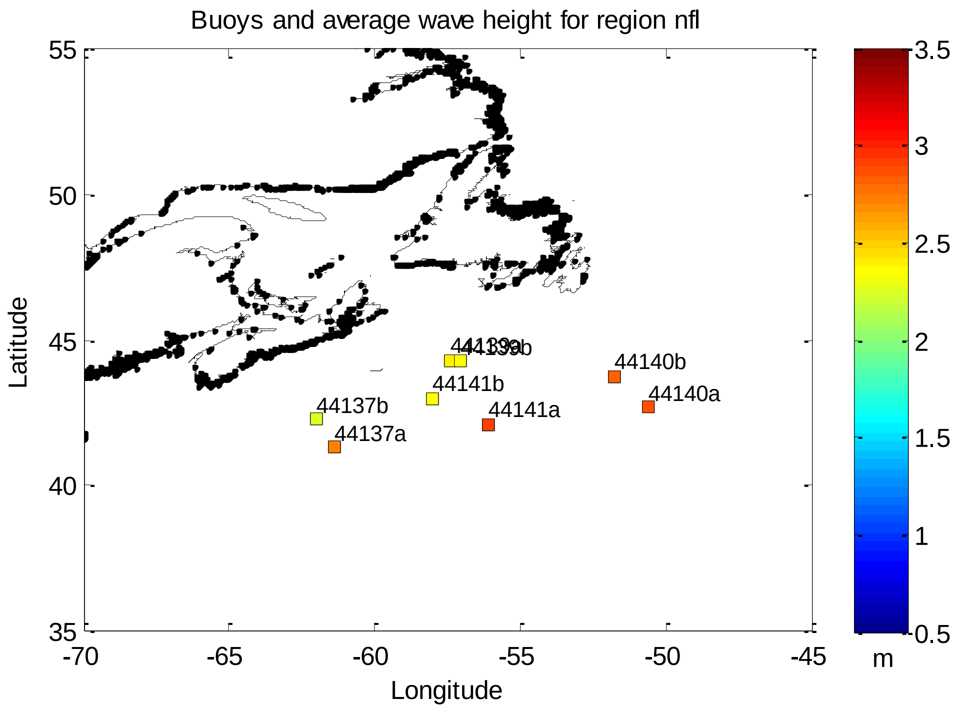


**Figure 45 NOAA buoys off Newfoundland (NFL)**

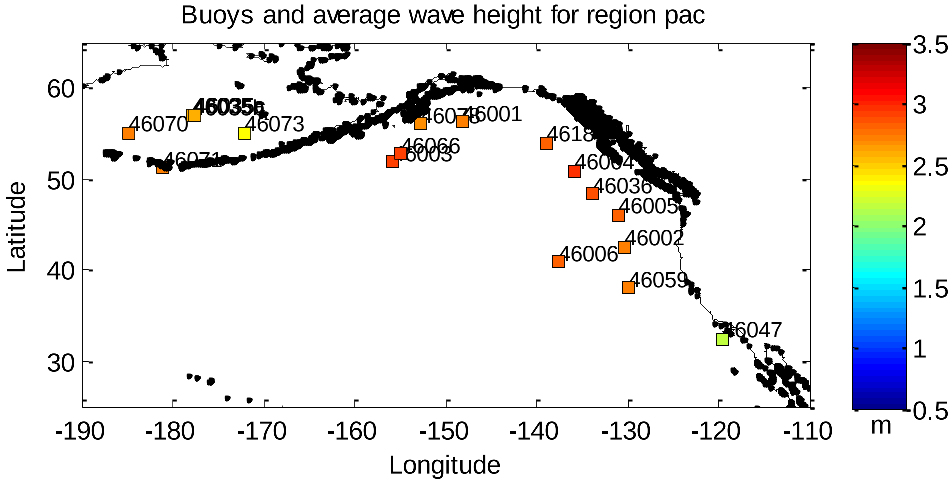


**Figure 46 NOAA buoys in the NE Pacific (PAC)**

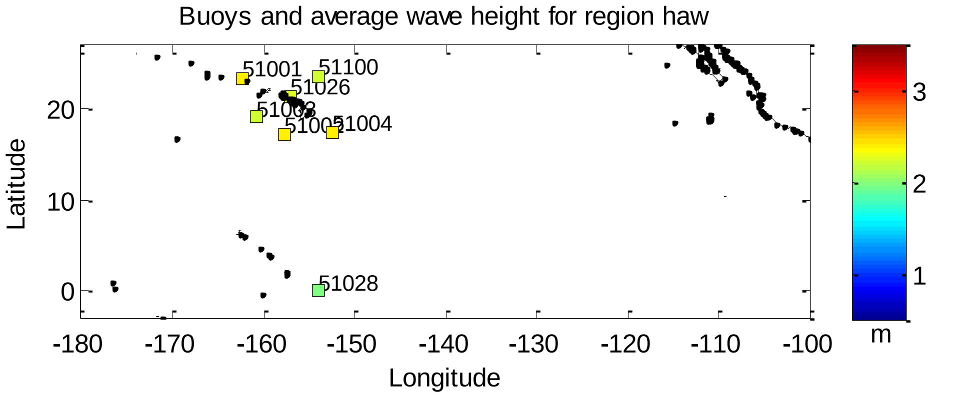


**Figure 47 NOAA buoys near Hawaii (HAW)**

| NOAA Buoy | Nobs | Latitude | Longitude | Region | Begin | End |
|---|---|---|---|---|---|---|
| **32302h** | 27466 | -18.00 | -85.10 | CHI | 01-Jan-92 | 01-Apr-95 |
| **41001h** | 121573 | 34.68 | -72.64 | ATL | 01-Jan-92 | 09-May-13 |
| **41002a** | 65499 | 32.27 | -75.19 | ATL | 01-Jan-92 | 03-Jan-02 |
| **41002b** | 45121 | 32.31 | -75.35 | ATL | 01-Feb-02 | 12-May-10 |
| **41002c** | 13472 | 31.86 | -74.84 | ATL | 17-May-12 | 31-Dec-13 |
| **41006h** | 34324 | 29.30 | -77.40 | ATL | 29-Jan-92 | 21-Apr-96 |
| **41010h** | 171253 | 28.90 | -78.53 | ATL | 01-Jan-92 | 26-Apr-13 |
| **41040h** | 59957 | 14.48 | -53.00 | ATL | 30-May-05 | 31-Dec-13 |
| **41041h** | 68384 | 14.18 | -46.00 | ATL | 28-May-05 | 31-Dec-13 |
| **41043h** | 57136 | 21.06 | -64.97 | ATL | 11-Apr-07 | 31-Dec-13 |
| **41046h** | 17141 | 23.84 | -68.33 | ATL | 31-Dec-11 | 31-Dec-13 |
| **41047h** | 43625 | 27.52 | -71.48 | ATL | 21-Sep-07 | 31-Dec-13 |
| **41048h** | 42190 | 31.98 | -69.65 | ATL | 18-Sep-07 | 31-Dec-12 |
| **42001h** | 173002 | 25.93 | -89.65 | GOM | 01-Jan-92 | 28-Dec-13 |
| **42002a** | 75712 | 25.89 | -93.57 | GOM | 01-Jan-92 | 30-Apr-02 |
| **42002b** | 52701 | 25.17 | -94.42 | GOM | 01-May-02 | 31-Jul-08 |
| **42002c** | 31268 | 25.79 | -93.67 | GOM | 01-Aug-08 | 31-Dec-13 |
| **42003h** | 160732 | 25.94 | -85.91 | GOM | 01-Jan-92 | 31-Dec-13 |
| **42038h** | 16514 | 27.42 | -92.56 | GOM | 12-May-04 | 30-Apr-06 |
| **42039h** | 142242 | 28.80 | -86.06 | GOM | 12-Dec-95 | 31-Dec-13 |
| **42040h** | 133069 | 29.21 | -88.20 | GOM | 04-Dec-95 | 31-Jan-13 |
| **42041h** | 33375 | 27.50 | -90.46 | GOM | 13-Dec-99 | 16-Mar-05 |
| **42055h** | 58244 | 22.20 | -94.10 | CAR | 10-May-05 | 31-Dec-13 |
| **42056h** | 65852 | 19.80 | -84.86 | CAR | 04-May-05 | 31-Dec-13 |
| **42057h** | 35861 | 17.00 | -81.50 | CAR | 06-Jun-05 | 31-Dec-13 |
| **42058h** | 39973 | 14.92 | -74.92 | CAR | 08-Jun-05 | 31-Dec-13 |
| **42059h** | 48688 | 15.05 | -67.47 | CAR | 17-Apr-07 | 31-Dec-13 |
| **42060h** | 37126 | 16.33 | -63.50 | CAR | 28-Apr-09 | 31-Dec-13 |
| **44004h** | 114864 | 38.46 | -70.69 | ATL | 01-Jan-92 | 08-Mar-08 |
| **44005a** | 12543 | 42.60 | -68.60 | ATL | 14-Jan-92 | 13-Jan-94 |
| **44005b** | 43614 | 42.90 | -68.94 | ATL | 12-Apr-94 | 28-Feb-01 |
| **44005c** | 80868 | 43.19 | -69.16 | ATL | 01-Mar-01 | 28-Nov-12 |
| **44008h** | 145286 | 40.50 | -69.43 | ATL | 01-Jan-92 | 26-Mar-13 |
| **44011h** | 133516 | 41.08 | -66.58 | ATL | 01-Jan-92 | 08-Jan-13 |
| **44018h** | 68794 | 41.26 | -69.31 | ATL | 31-Jul-02 | 14-Mar-12 |
| **44066h** | 20437 | 39.58 | -72.60 | ATL | 19-Jun-09 | 31-Dec-13 |

**Table 19: NOAA buoys Chile, Gulf of Mexico, North Atlantic and Caribbean 1992-2013**

| Buoy | Nobs | Latitude | Longitude | Region | Begin | End |
|---|---|---|---|---|---|---|
| **44137a** | 26625 | 41.30 | -61.40 | NFL | 01-Jan-92 | 15-Oct-97 |
| **44137b** | 16685 | 42.26 | -62.00 | NFL | 01-Jan-08 | 31-Dec-09 |
| **44139a** | 24125 | 44.30 | -57.40 | NFL | 01-Jan-92 | 21-Nov-97 |
| **44139b** | 16977 | 44.26 | -57.08 | NFL | 01-Jan-08 | 31-Dec-09 |
| **44140a** | 16117 | 42.70 | -50.60 | NFL | 01-Jan-92 | 19-Nov-96 |
| **44140b** | 12445 | 43.75 | -51.74 | NFL | 01-Jan-08 | 31-Dec-09 |
| **44141a** | 37289 | 42.10 | -56.10 | NFL | 01-Jan-92 | 08-Dec-97 |
| **44141b** | 16674 | 43.00 | -58.00 | NFL | 01-Jan-08 | 31-Dec-09 |
| **46001h** | 150084 | 56.29 | -148.18 | PAC | 01-Jan-92 | 08-Sep-13 |
| **46002h** | 129086 | 42.53 | -130.26 | PAC | 27-Feb-92 | 31-Dec-13 |
| **46003h** | 46354 | 51.85 | -155.92 | PAC | 15-Mar-92 | 11-Aug-99 |
| **46004h** | 29750 | 50.90 | -135.90 | PAC | 01-Jan-92 | 31-Dec-97 |
| **46005h** | 128930 | 46.08 | -131.00 | PAC | 01-Jan-92 | 01-Jul-12 |
| **46006h** | 116599 | 40.84 | -137.49 | PAC | 17-Jun-92 | 07-Feb-13 |
| **46035a** | 31227 | 57.00 | -177.70 | PAC | 01-Jan-92 | 29-Jun-96 |
| **46035b** | 32273 | 56.91 | -177.81 | PAC | 18-Sep-96 | 30-Jan-02 |
| **46035c** | 68475 | 57.05 | -177.58 | PAC | 16-Jul-02 | 31-Aug-12 |
| **46036h** | 38899 | 48.30 | -133.90 | PAC | 31-Dec-91 | 31-Dec-97 |
| **46047h** | 114778 | 32.43 | -119.53 | PAC | 02-Jan-92 | 05-May-13 |
| **46059h** | 126023 | 37.98 | -130.00 | PAC | 19-Oct-94 | 30-Jun-12 |
| **46066h** | 65774 | 52.70 | -155.00 | PAC | 11-May-00 | 31-Dec-13 |
| **46070h** | 34674 | 55.08 | 175.27 | PAC | 16-Sep-06 | 31-Dec-13 |
| **46071h** | 34746 | 51.16 | 179.00 | PAC | 01-Oct-04 | 13-Nov-12 |
| **46073h** | 40768 | 55.01 | -171.98 | PAC | 13-May-05 | 07-Apr-11 |
| **46078h** | 36732 | 55.99 | -152.64 | PAC | 18-May-04 | 31-Dec-13 |
| **46184h** | 38379 | 54.00 | -138.80 | PAC | 01-Jan-92 | 31-Dec-97 |
| **51001h** | 130280 | 23.40 | -162.30 | HAW | 01-Jan-92 | 24-Dec-09 |
| **51002h** | 153544 | 17.20 | -157.80 | HAW | 01-Jan-92 | 14-Jan-13 |
| **51003h** | 169960 | 19.10 | -160.80 | HAW | 01-Jan-92 | 31-Dec-13 |
| **51004h** | 150268 | 17.40 | -152.50 | HAW | 01-Jan-92 | 31-Dec-13 |
| **51026h** | 18805 | 21.40 | -157.00 | HAW | 16-Jan-93 | 05-Dec-95 |
| **51028h** | 62072 | 0.00 | -153.90 | HAW | 29-Oct-97 | 14-Apr-08 |
| **51100h** | 26822 | 23.59 | -153.90 | HAW | 23-Apr-09 | 31-Dec-13 |

**Table 20: NOAA buoys Newfoundland, northern Pacific and Hawaii 1992-2013**

| Buoy | Nobs | Latitude | Longitude | Region | Begin | End |
|---|---|---|---|---|---|---|
| **41001h** | 68251 | 34.68 | -72.64 | ATL | 01-Jan-79 | 31-Dec-91 |
| **41002a** | 40627 | 32.27 | -75.19 | ATL | 26-Feb-85 | 31-Dec-91 |
| **41006h** | 62630 | 29.30 | -77.40 | ATL | 26-May-82 | 23-Feb-91 |
| **41010h** | 25398 | 28.90 | -78.53 | ATL | 10-Nov-88 | 31-Dec-91 |
| **42001h** | 86622 | 25.93 | -89.65 | GOM | 07-Mar-79 | 31-Dec-91 |
| **42002a** | 92233 | 25.89 | -93.57 | GOM | 01-Dec-79 | 31-Dec-91 |
| **42003h** | 85085 | 25.94 | -85.91 | GOM | 01-Jan-79 | 31-Dec-91 |
| **44004h** | 71106 | 38.46 | -70.69 | ATL | 01-Jan-79 | 31-Dec-91 |
| **44005a** | 88596 | 42.60 | -68.60 | ATL | 01-Jan-79 | 19-Aug-91 |
| **44008h** | 68816 | 40.50 | -69.43 | ATL | 18-Aug-82 | 31-Dec-91 |
| **44011h** | 55932 | 41.08 | -66.58 | ATL | 23-May-84 | 31-Dec-91 |
| **44137a** | 9651 | 41.30 | -61.40 | NFL | 30-Nov-88 | 31-Dec-91 |
| **44139a** | 9200 | 44.30 | -57.40 | NFL | 02-Dec-88 | 31-Dec-91 |
| **44140a** | 9252 | 42.70 | -50.60 | NFL | 05-Sep-90 | 31-Dec-91 |
| **44141a** | 5602 | 42.10 | -56.10 | NFL | 05-Sep-90 | 31-Dec-91 |
| **46001h** | 95364 | 56.29 | -148.18 | PAC | 01-Feb-79 | 31-Dec-91 |
| **46002h** | 82031 | 42.53 | -130.26 | PAC | 01-Jan-79 | 13-Nov-91 |
| **46003h** | 78366 | 51.85 | -155.92 | PAC | 12-Nov-79 | 31-Dec-91 |
| **46004h** | 39894 | 50.90 | -135.90 | PAC | 09-Feb-85 | 31-Dec-91 |
| **46005h** | 78219 | 46.08 | -131.00 | PAC | 01-Jan-79 | 31-Dec-91 |
| **46006h** | 70353 | 40.84 | -137.49 | PAC | 18-Jan-79 | 13-Jan-91 |
| **46035a** | 46679 | 57.00 | -177.70 | PAC | 13-Sep-85 | 31-Dec-91 |
| **46036h** | 30929 | 48.30 | -133.90 | PAC | 22-Sep-87 | 31-Dec-91 |
| **46184h** | 23245 | 54.00 | -138.80 | PAC | 20-Sep-87 | 31-Dec-91 |
| **51001h** | 70214 | 23.40 | -162.30 | HAW | 11-Feb-81 | 31-Dec-91 |
| **51002h** | 45130 | 17.20 | -157.80 | HAW | 06-Sep-84 | 31-Dec-91 |
| **51003h** | 44972 | 19.10 | -160.80 | HAW | 01-Nov-84 | 31-Dec-91 |
| **51004h** | 43921 | 17.40 | -152.50 | HAW | 08-Nov-84 | 31-Dec-91 |

**Table 21: NOAA buoys used before 1992**

# Appendix B2 – Buoys Used for the EU-shelf Hindcast

In this appendix characteristics are supplied for the buoys used for the validation of the EU-shelf hindcast. There are 37 different buoys in total.

Most buoys provide hourly wind speed at 10m, wind direction, significant wave height, zero-crossing and/or peak wave period. About half of the buoys provide information on wave direction.

First, the quality check applied to our in-house buoy data is briefly described. Next, the set of buoys used for the validation of the hindcast is elaborated.

### Quality check

- Apart from visual inspection of time series, buoys are compared to satellites over the years to check for sudden change in quality (of course this works both ways: both satellite and buoy can be the cause of deviant error statistics).

Figure 48 shows the set of buoys used for the validation of the EU-shelf hindcast. Colours indicate significant wave height averaged over the observation period of each buoy. A similar plot can be made based on averaged observed wind speed. Buoys measuring wind data only are marked by blank rectangles in Figure 48. Table 22 lists each buoy's position, region, observation period and the number of observation records. There's a separate column 'Directions' indicating the presence of directional wave data.

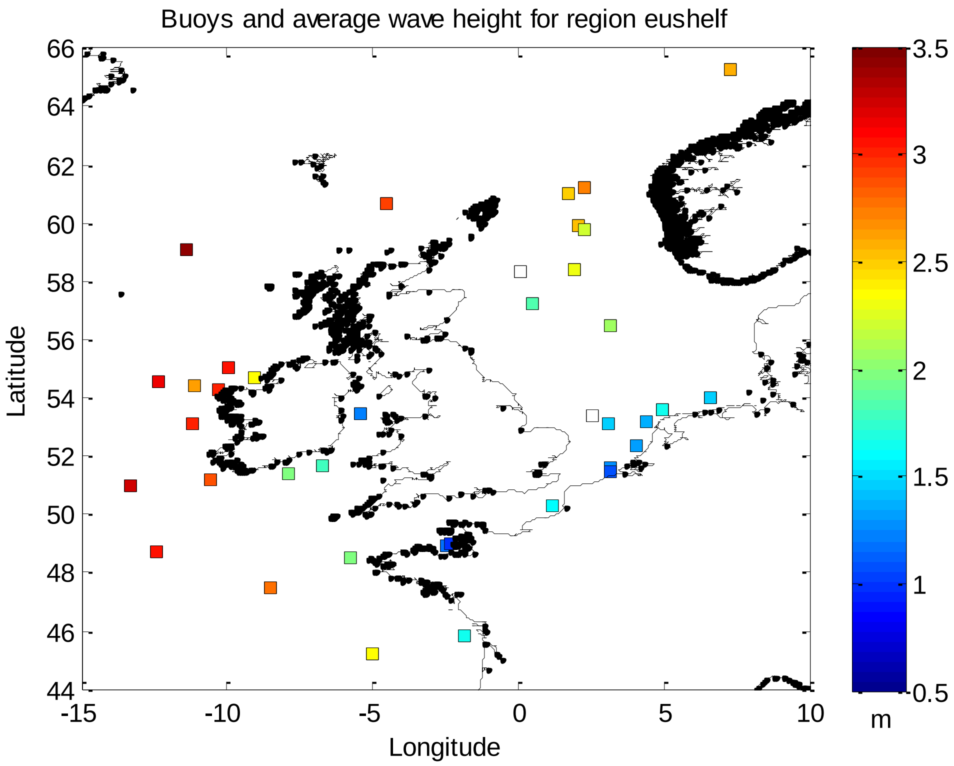


**Figure 48 Buoys used for validation of the EU-shelf hindcast**

The set of buoys depicted in the figure above has been divided into the following regions with a more or less uniform wave climate:

- The western part of the EU-shelf grid, i.e. the NE Atlantic (EU-ATL)
- The Celtic Sea (CELTICSEA)
- The Irish Sea (IRISHSEA, buoy M2 is the only buoy)
- The English Channel (CHAN)
- North Sea north part (NS-N)
- North Sea central part (NS-C)
- North Sea southern part (NS-S)

The figures on the next pages show the individual buoys for the various regions.

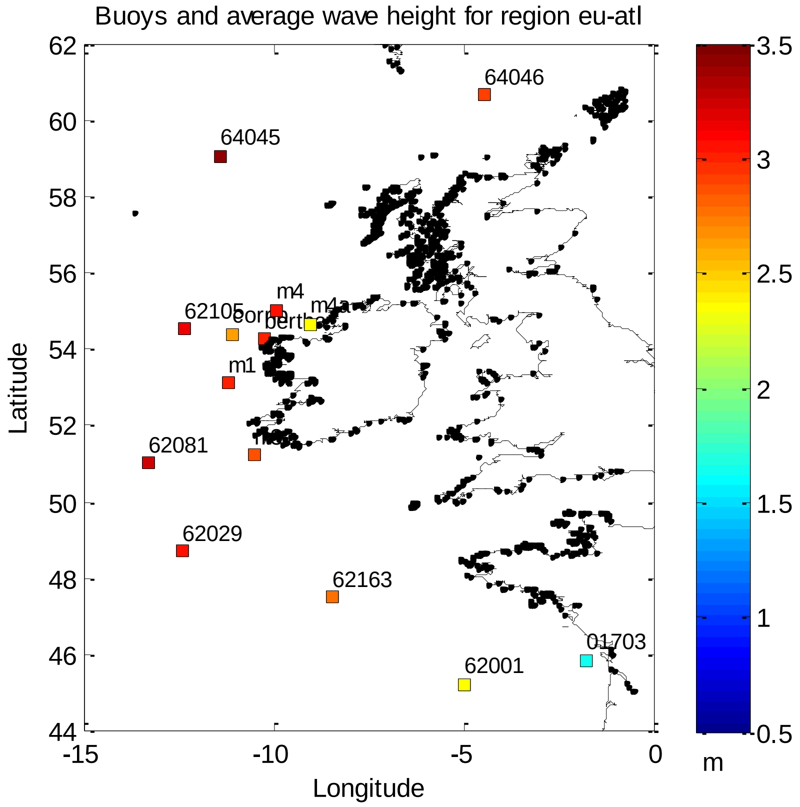


**Figure 49 Buoys off the UK and France in the NE Atlantic (EU-ATL)**

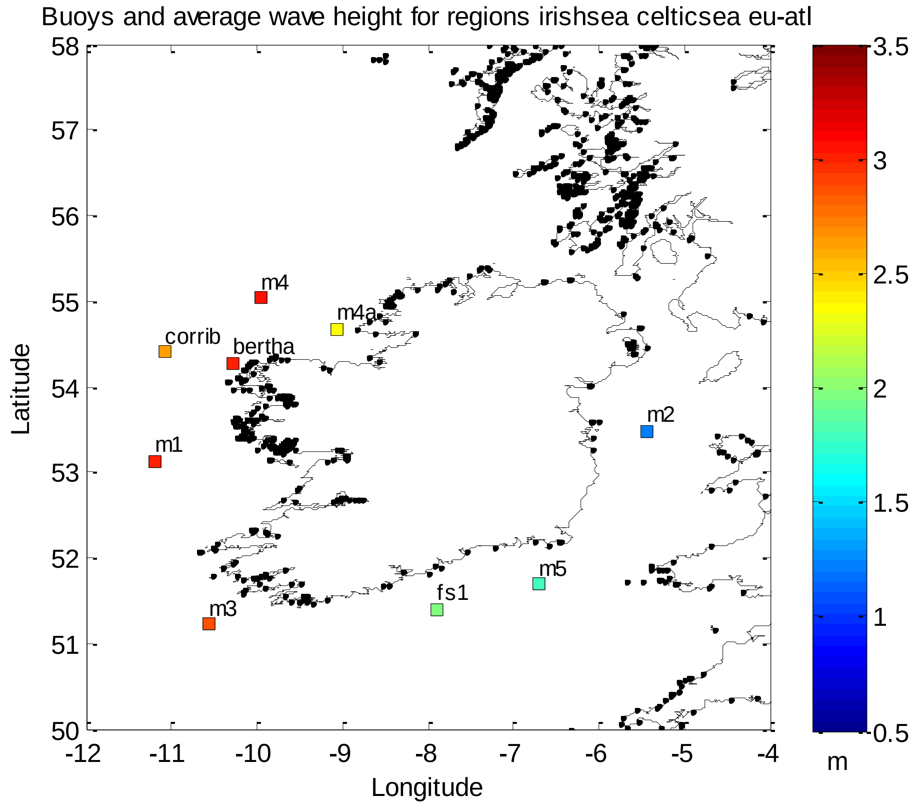


**Figure 50 Buoys around Ireland in the Irish Sea, Celtic Sea and the Atlantic**

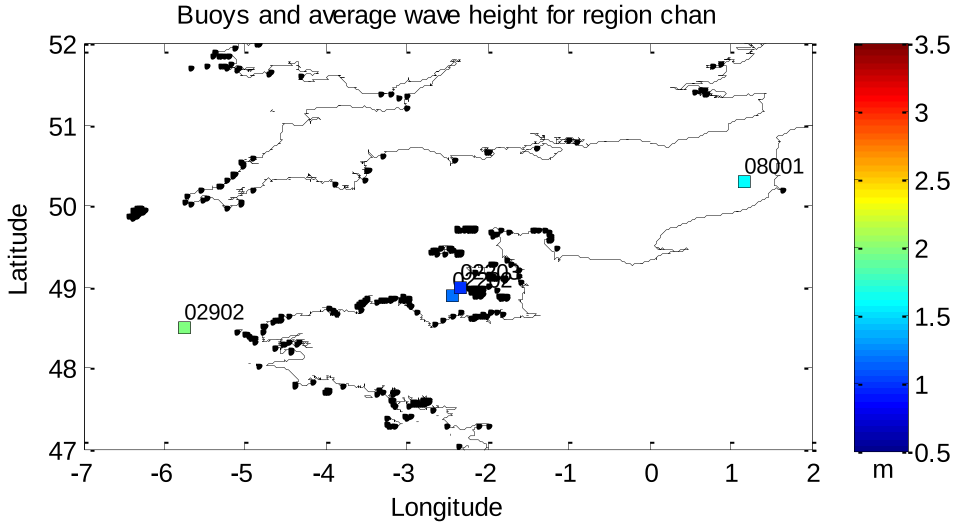


**Figure 51 Buoys in the English Channel (CHAN)**

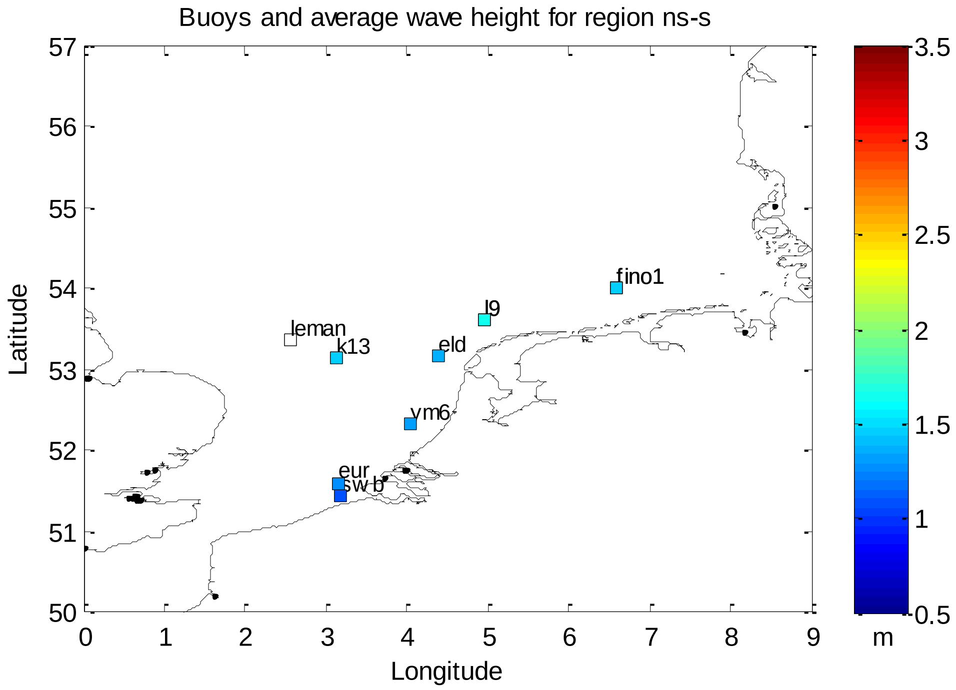


**Figure 52 Buoys in the southern part of the North Sea (NS-S)**

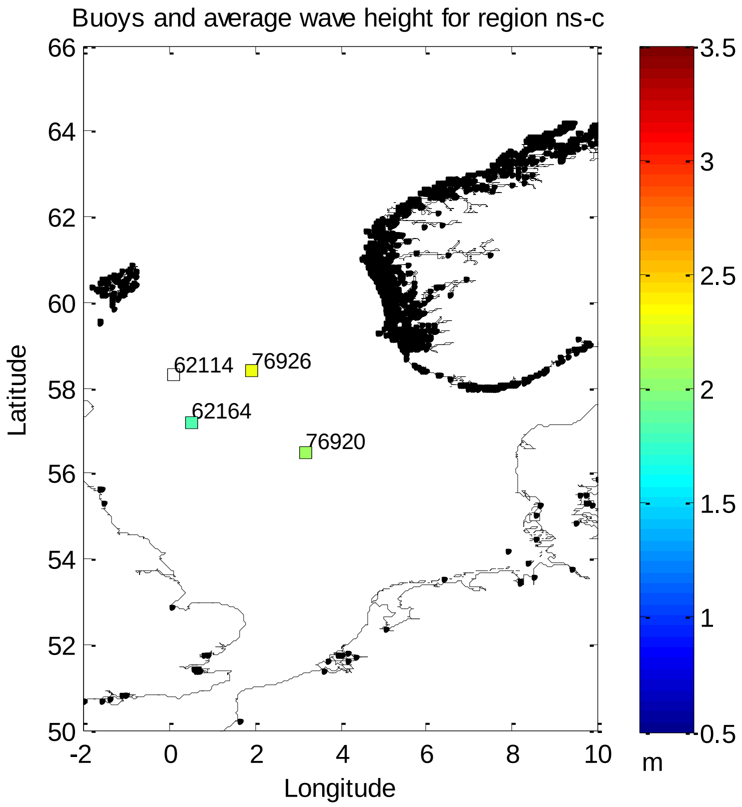


**Figure 53 Buoys in the central part of the North Sea (NS-C)**

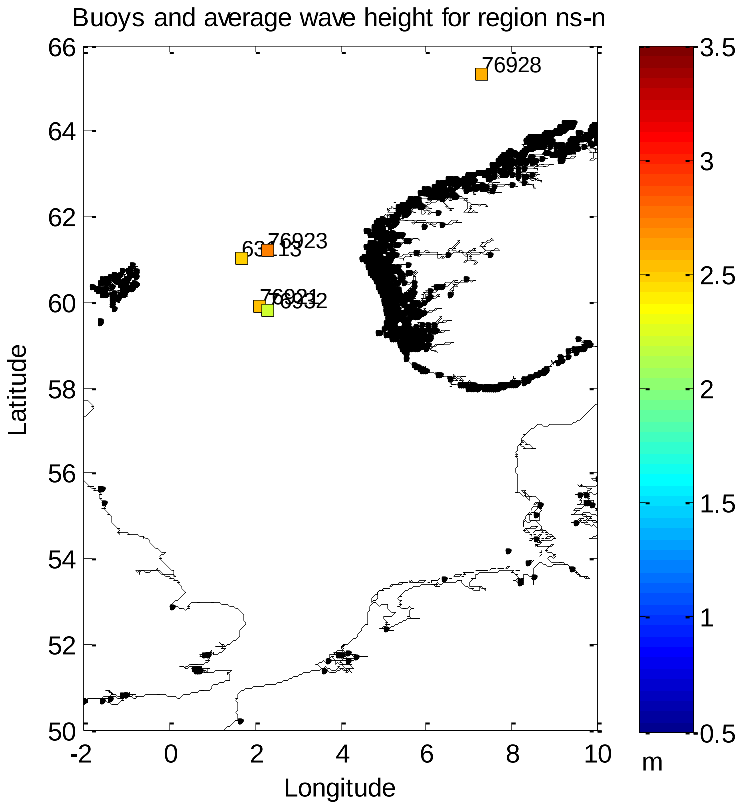


**Figure 54 Buoys in the norhern part of the North Sea (NS-N)**

| Buoy | Nobs | Latitude | Longitude | Region | Directions | Begin | End |
|---|---|---|---|---|---|---|---|
| 1703 | 11048 | 45.84 | -1.81 | EU-ATL | X | 02-Jan-10 | 08-Apr-11 |
| 62001 | 13756 | 45.20 | -5.00 | EU-ATL | | 01-Jun-07 | 31-Dec-09 |
| 62029 | 22205 | 48.70 | -12.40 | EU-ATL | | 01-Jun-07 | 31-Dec-09 |
| 62081 | 21713 | 51.00 | -13.30 | EU-ATL | | 01-Jun-07 | 31-Dec-09 |
| 62105 | 6885 | 54.54 | -12.36 | EU-ATL | | 05-Jul-07 | 31-Dec-09 |
| 62163 | 19988 | 47.50 | -8.50 | EU-ATL | | 01-Jun-07 | 31-Dec-09 |
| 64045 | 22145 | 59.10 | -11.40 | EU-ATL | | 01-Jun-07 | 31-Dec-09 |
| 64046 | 17676 | 60.70 | -4.50 | EU-ATL | | 01-Jun-07 | 31-Dec-09 |
| bertha | 12603 | 54.28 | -10.28 | EU-ATL | X | 16-May-12 | 31-Dec-13 |
| corrib | 7286 | 54.41 | -11.09 | EU-ATL | X | 10-Jun-10 | 12-Oct-11 |
| m1 | 42864 | 53.13 | -11.20 | EU-ATL | X | 06-Feb-02 | 09-Jul-07 |
| m3 | 84563 | 51.22 | -10.55 | EU-ATL | X | 22-Jul-02 | 21-Feb-13 |
| m4 | 53272 | 55.03 | -9.94 | EU-ATL | X | 03-May-07 | 31-Dec-13 |
| m4a | 31105 | 54.67 | -9.07 | EU-ATL | | 16-Apr-03 | 01-May-07 |
| fs1 | 28404 | 51.40 | -7.90 | CELTICSEA | | 23-Jan-03 | 17-Feb-08 |
| m5 | 74224 | 51.69 | -6.70 | CELTICSEA | X | 18-Oct-04 | 31-Dec-13 |
| m2 | 90340 | 53.48 | -5.43 | IRISHSEA | X | 06-Feb-02 | 31-Dec-13 |
| 2202 | 46129 | 48.89 | -2.44 | CHAN | X | 20-Aug-97 | 16-May-09 |
| 2203 | 17191 | 48.99 | -2.34 | CHAN | X | 30-Mar-11 | 24-Oct-13 |
| 2902 | 66153 | 48.50 | -5.75 | CHAN | | 22-Jul-96 | 27-Nov-11 |
| 8001 | 1826 | 50.30 | 1.17 | CHAN | | 21-Aug-99 | 05-Feb-01 |
| eld | 157777 | 53.16 | 4.39 | NS-S | X | 01-Jan-92 | 31-Dec-09 |
| eur | 96431 | 51.60 | 3.16 | NS-S | X | 01-Jan-92 | 31-Dec-02 |
| fino1-wave | 37229 | 54.01 | 6.59 | NS-S | X | 01-Jan-04 | 25-Aug-09 |
| fino1-wind | 45550 | 54.01 | 6.59 | NS-S | | 01-Jan-04 | 31-Dec-09 |
| k13 | 96431 | 53.13 | 3.13 | NS-S | X | 01-Jan-92 | 31-Dec-02 |
| l9-wave | 17863 | 53.61 | 4.96 | NS-S | | 01-Oct-06 | 31-Jan-13 |
| l9-wind | 16983 | 53.61 | 4.96 | NS-S | | 01-Oct-06 | 31-Jan-13 |
| leman-wind | 17992 | 53.37 | 2.57 | NS-S | | 01-Oct-06 | 31-Jan-13 |
| swb | 96431 | 51.44 | 3.18 | NS-S | | 01-Jan-92 | 31-Dec-02 |
| ym6 | 157791 | 52.33 | 4.03 | NS-S | X | 01-Jan-92 | 31-Dec-09 |
| 62114 | 15127 | 58.30 | 0.10 | NS-C | | 02-Jul-07 | 31-Dec-09 |
| 62164 | 20389 | 57.20 | 0.50 | NS-C | | 01-Jun-07 | 31-Dec-09 |
| 76920 | 151734 | 56.50 | 3.20 | NS-C | | 01-Jan-92 | 31-Dec-09 |
| 76926 | 129082 | 58.40 | 1.90 | NS-C | X | 01-Jan-95 | 31-Dec-09 |
| 63113 | 21094 | 61.00 | 1.70 | NS-N | | 01-Jun-07 | 31-Dec-09 |
| 76921 | 67105 | 59.90 | 2.10 | NS-N | | 01-Jan-92 | 31-Dec-99 |
| 76923 | 104143 | 61.20 | 2.30 | NS-N | X | 01-Jan-92 | 31-Dec-09 |
| 76928 | 94901 | 65.30 | 7.30 | NS-N | X | 01-Jan-96 | 31-Dec-06 |
| 76932 | 53295 | 59.80 | 2.30 | NS-N | | 01-Dec-03 | 31-Dec-09 |

**Table 22: Buoys used for the validation of the EU-shelf hindcast**

# Appendix C – Validation of Satellite Data

Satellite data have been used to validate and calibrate hindcast wind and wave parameters. For the validation and (automated) calibration of hindcast v352/v361, satellite samples were co-located within 25 km of each model grid point. Altimeters were used for calibration of hindcast wave parameters. Scatterometer and altimeter wind speed samples were merged prior to use for calibration of hindcast winds.

A summary of the quality of our 'best' satellite data is given in Table 7 in section 3.3 of the main report. This appendix describes how the 'best' satellite data were created and calibrated with buoys (for the set of buoys see Table 19 and Table 20 in Appendix B1 – Buoys Used for the Global Hindcast) and summarizes the quality of this 'best' satellite data over the years and over missions.

In a nutshell, the following procedure is used to generate the 'best' satellite data:

- Apply quality flags (based on expertise from our suppliers, e.g. indicating land, rain, ice, spatial coherency, suspicious data, et cetera) to the altimeter and scatterometer data recordsand perform range checks
- Remove spikes from altimeter data through median-filtering
- Apply mission-dependent a-priori corrections to altimeter
- To get a consistent data set over the years, calibrate each altimeter mission with a "master altimeter" and merge the resulting set of altimeter data
- Calibrate the merged altimeter data with buoy observations on a yearly basis. Co-locate buoys and satellite samples. Find satellite samples within 50km and 30 minutes and select one sample per pass. Only use the sample nearest to the buoy in order to avoid dependency between altimeter samples from a single pass. Make a linear fit based on the sample pairs to find the buoy-based corrections in terms of scale and offset.
- Calibrate scatterometer data with buoy observations per mission and per year (co-location and correction as pointed out in the previous step for altimeter)
- Merge altimeter and scatterometer wind speed samples. Based on the number of measurements available, scatterometer data will be dominant in the calibration on open sea whereas altimeter will gradually take over towards the coast.

Figure 55 pictures the consistent quality of ambient altimeter wind speed relative to all buoys over the years. The higher and extreme values are checked by comparison of probability distributions of altimeter and buoy wind speed in Figure 56. Similarly, the quality of scatterometer winds is substantiated in Figure 57 and Figure 58 and altimeter wave height is checked in Figure 59 and Figure 60.

Error statistics of altimeter wind speed per satellite mission is provided in Table 23. Quality of wind speed per scatterometer mission is listed in Table 24. Error statistics of significant wave height per altimeter mission relative to all buoys can be found in Table 25.

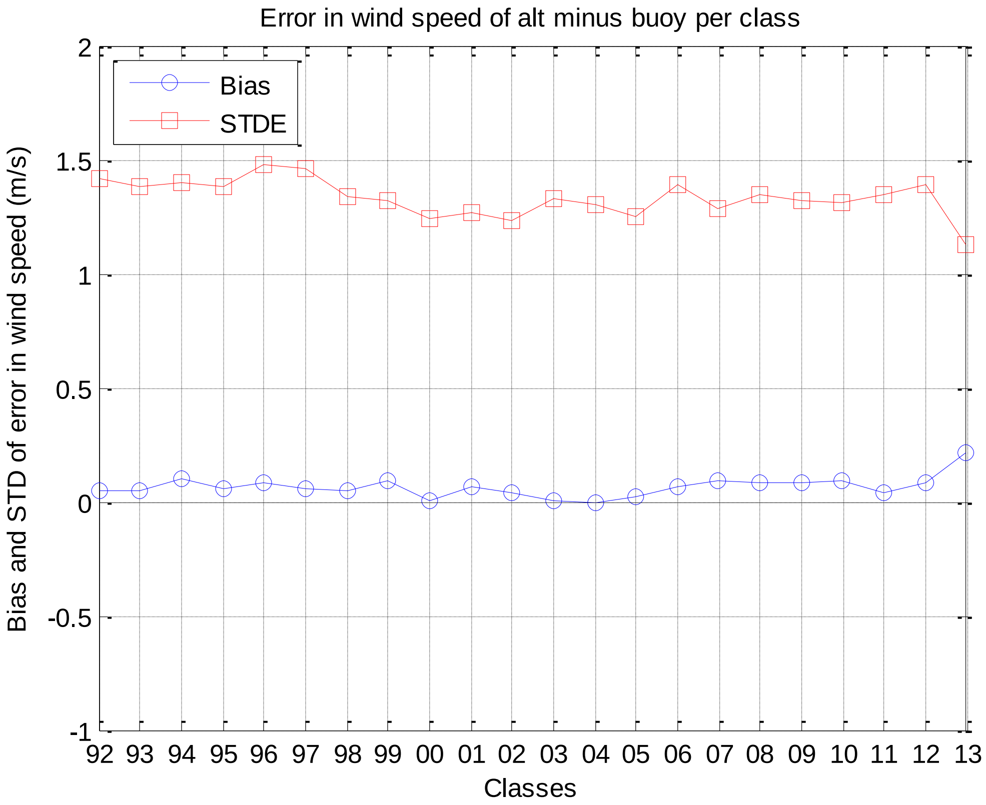


**Figure 55 Error in altimeter wind speed relative to ALL buoys over the years**

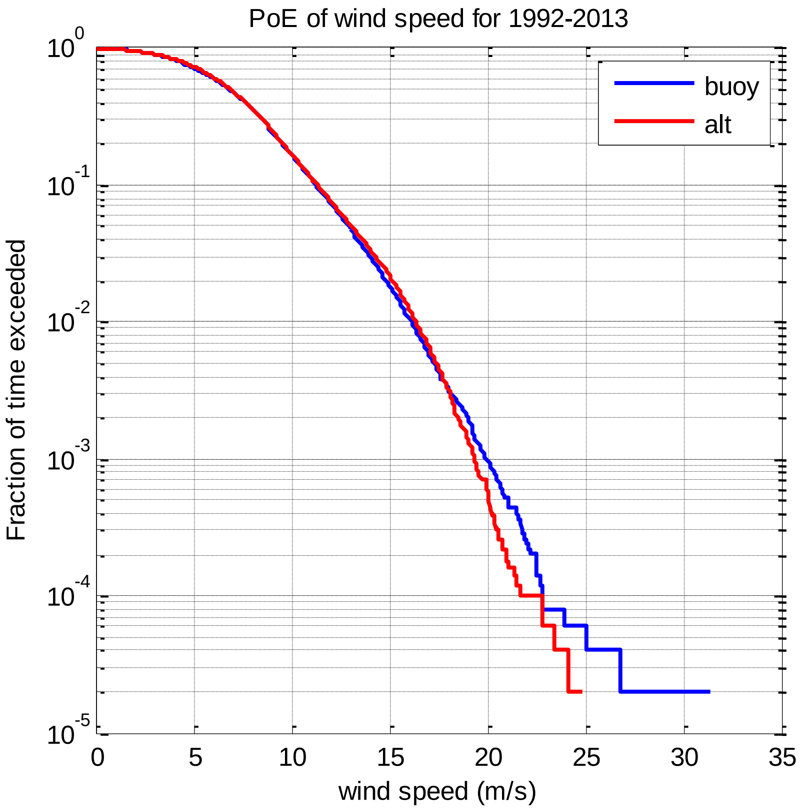


**Figure 56 PoE of altimeter wind speed and ALL buoys**

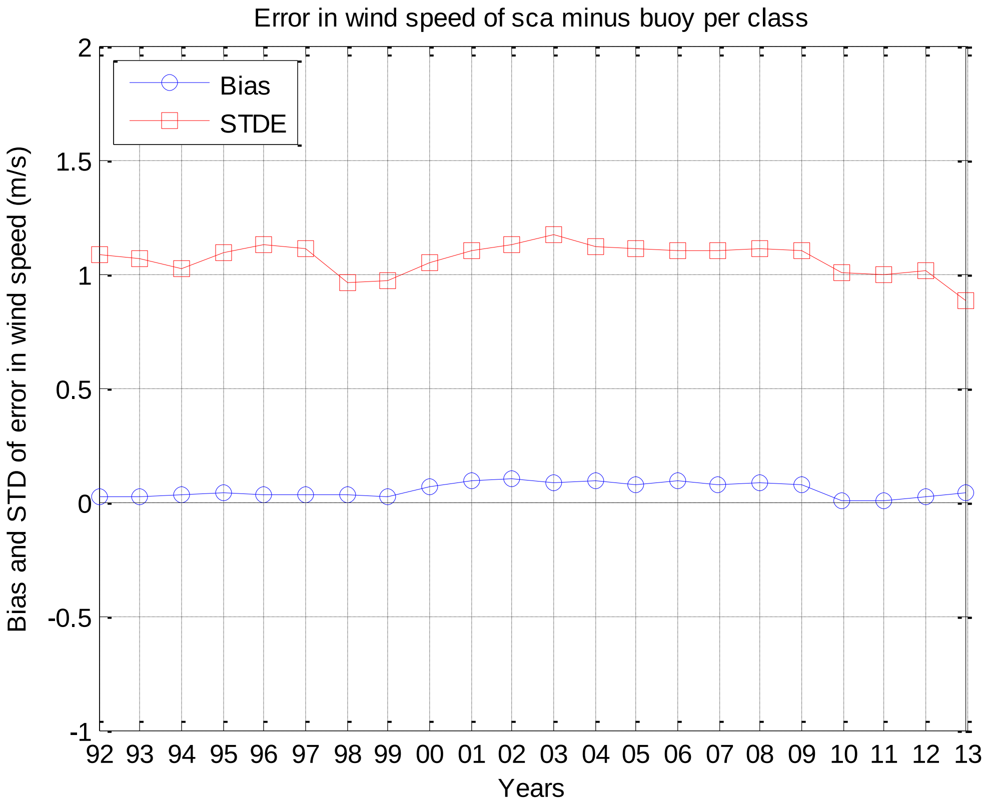


**Figure 57 Error in scatterometer wind speed relative to ALL buoys over the years**

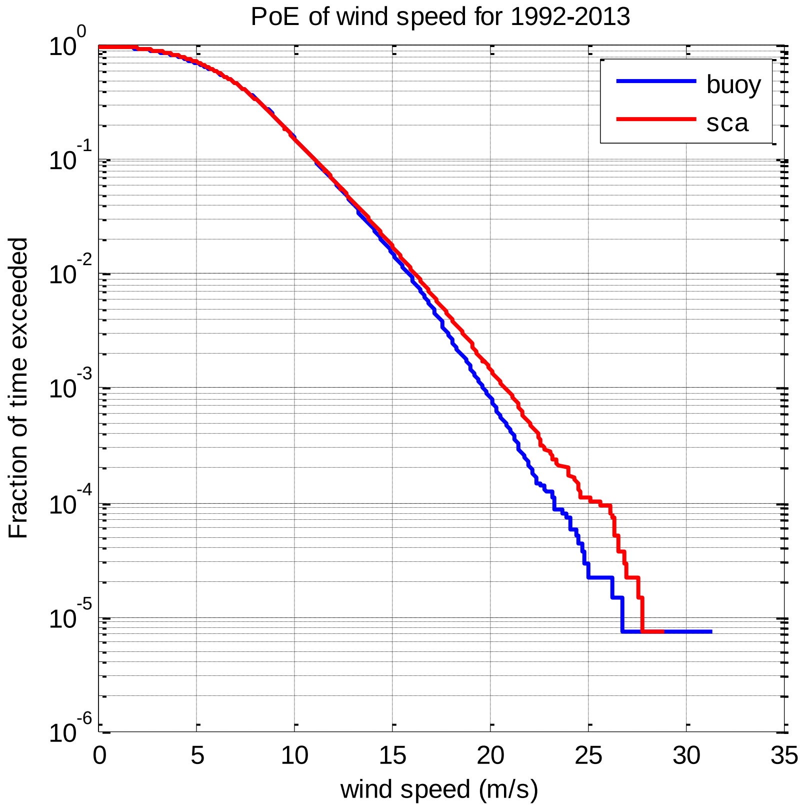


**Figure 58 PoE of scatterometer wind speed and ALL buoys**

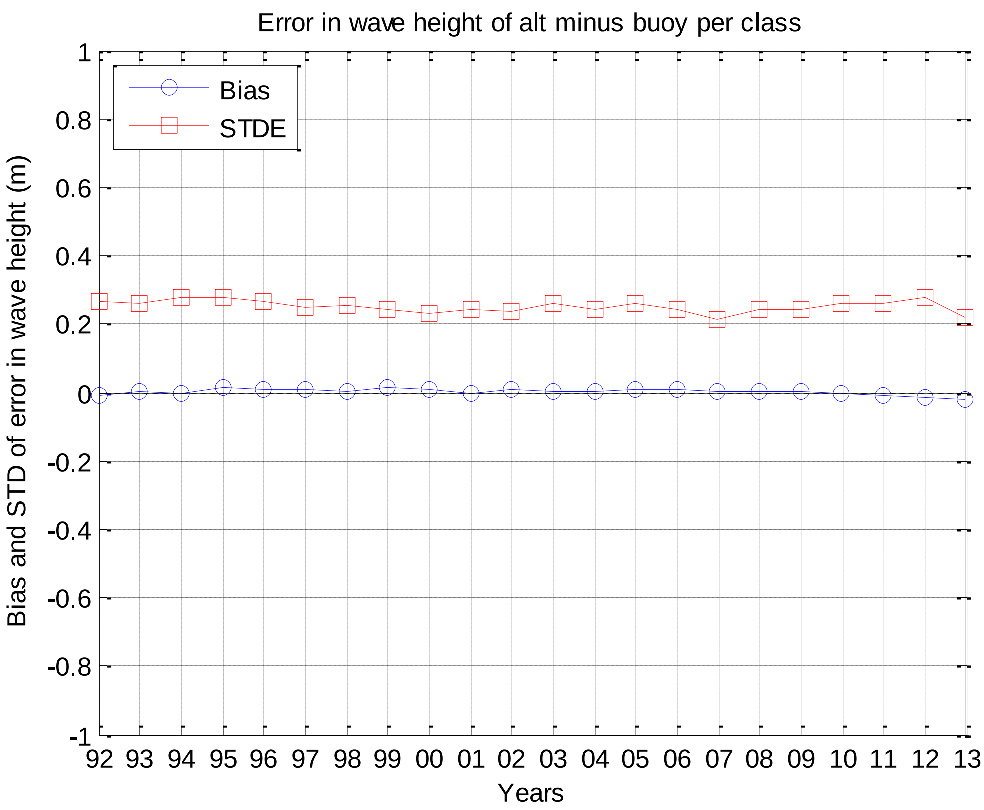


**Figure 59 Error in altimeter wave height relative to ALL buoys over the years**

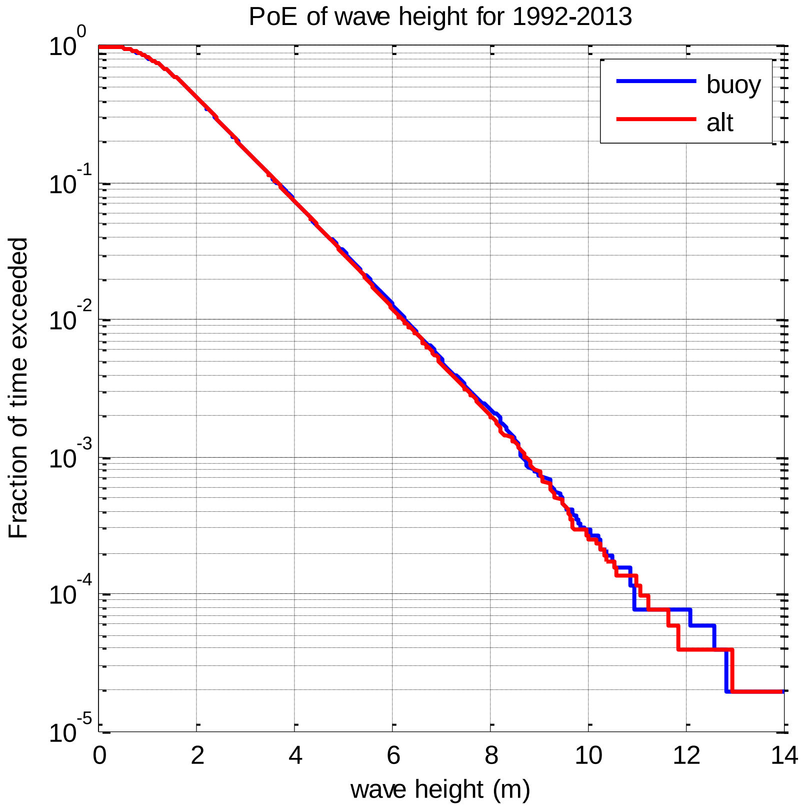


**Figure 60 PoE of altimeter wave height and ALL buoys**

| Mission | Period | Nobs | Mean (m/s) | Std (m) | Corr | Rrmse (%) | Bias (m) |
|---|---|---|---|---|---|---|---|
| ers1 | 1992-1996 | 3067 | 7.05 | 1.39 | 0.91 | 17.9 | 0.10 |
| ers2 | 1995-2011 | 9416 | 6.79 | 1.37 | 0.91 | 18.2 | 0.01 |
| topex | 1992-2005 | 8663 | 7.02 | 1.32 | 0.92 | 17.0 | -0.04 |
| poseidon | 1992-2002 | 600 | 7.19 | 1.43 | 0.91 | 18.0 | 0.13 |
| jason | 2002-2013 | 9104 | 7.02 | 1.33 | 0.92 | 17.2 | 0.12 |
| gfo | 2002-2008 | 3706 | 7.11 | 1.36 | 0.93 | 17.2 | 0.08 |
| envisat | 2003-2012 | 7646 | 7.18 | 1.28 | 0.92 | 16.3 | 0.14 |
| jason2 | 2008-2013 | 4770 | 6.93 | 1.26 | 0.92 | 16.5 | 0.07 |
| cryosat | 2010-2013 | 2447 | 6.84 | 1.34 | 0.90 | 18.0 | 0.07 |
| saral | 2013-2013 | 508 | 6.66 | 1.02 | 0.92 | 14.3 | 0.12 |
| **ALL** | **1992-2013** | **49927** | **6.99** | **1.33** | **0.92** | **17.2** | **0.06** |

**Table 23: Error statistics of altimeter wind speed per mission relative to ALL buoys**

| Mission | Period | Nobs | Mean (m/s) | Std (m) | Corr | Rrmse (%) | Bias (m) |
|---|---|---|---|---|---|---|---|
| e1 | 1992-1996 | 9875 | 7.09 | 1.08 | 0.94 | 13.8 | 0.03 |
| e2 | 1995-2009 | 10413 | 6.86 | 1.02 | 0.95 | 13.5 | 0.03 |
| qs | 2000-2009 | 82717 | 6.98 | 1.12 | 0.94 | 14.5 | 0.08 |
| as | 2010-2013 | 34196 | 6.87 | 0.98 | 0.95 | 13.0 | 0.02 |
| **ALL** | **1992-2013** | **137201** | **6.95** | **1.07** | **0.94** | **14.0** | **0.06** |

**Table 24: Error statistics of scatterometer wind speed per mission relative to ALL buoys**

| Mission | Period | Nobs | Mean (m/s) | Std (m) | Corr | Rrmse (%) | Bias (m) |
|---|---|---|---|---|---|---|---|
| ers1 | 1992-1996 | 3200 | 2.31 | 0.29 | 0.98 | 10.8 | -0.01 |
| ers2 | 1995-2011 | 9520 | 1.97 | 0.26 | 0.98 | 11.3 | 0.01 |
| topex | 1992-2005 | 8982 | 2.20 | 0.23 | 0.98 | 9.1 | 0.00 |
| poseidon | 1992-2002 | 611 | 2.19 | 0.26 | 0.98 | 10.9 | 0.09 |
| jason | 2002-2013 | 9152 | 2.04 | 0.25 | 0.98 | 10.5 | 0.01 |
| gfo | 2002-2008 | 4718 | 2.14 | 0.24 | 0.98 | 9.5 | 0.01 |
| envisat | 2003-2012 | 7660 | 2.04 | 0.24 | 0.98 | 10.2 | -0.03 |
| jason2 | 2008-2013 | 4831 | 1.93 | 0.25 | 0.98 | 11.1 | 0.02 |
| cryosat | 2010-2013 | 2501 | 1.86 | 0.28 | 0.96 | 13.3 | -0.02 |
| saral | 2013-2013 | 551 | 1.68 | 0.17 | 0.98 | 9.0 | 0.01 |
| **ALL** | **1992-2013** | **51762** | **2.06** | **0.25** | **0.98** | **10.5** | **0.00** |

**Table 25: Error statistics of altimeter wave height per mission relative to ALL buoys**

# Appendix D1 – Regional Results Ambient Climate (Global)

In this appendix global model-buoy error statistics of significant wave height and wind speed are checked over the years for each buoy region.

The model performance is expressed in terms of bias (mean of the model error) and standard deviation of the error between co-located model data and buoy data. A negative bias means that the model values are too low in comparison to the buoy measurements.

The plots in this appendix show the error in wind speed and wave height of satellite-calibrated ('best') v352 and v361 hindcast relative to buoys for the regions mentioned in section 4.2. Error statistics over the years based on all buoys can be found in the main report in section 5.1.2.

The regional plots show that the quality of 'best' v361 winds is consistently better than 'best' v352 winds over the years with only one exception: 'best' v361 wind speed is worse (too low) for the Caribbean (see Figure 71). The plots also show that the mean error and variability of the error in 'best' v361 waves are consistently low over the years.

The poor quality of NCEP re-analysis winds before 1999 (v352) and the sudden decrease of wind quality in 2010 (v361) is reflected in all relevant regional plots.

For the Newfoundland region, variability of (the error in) model winds (see Figure 65) and waves (see Figure 66) is relatively large; this is most probably also related to the lesser quality of buoy measurements for this area.

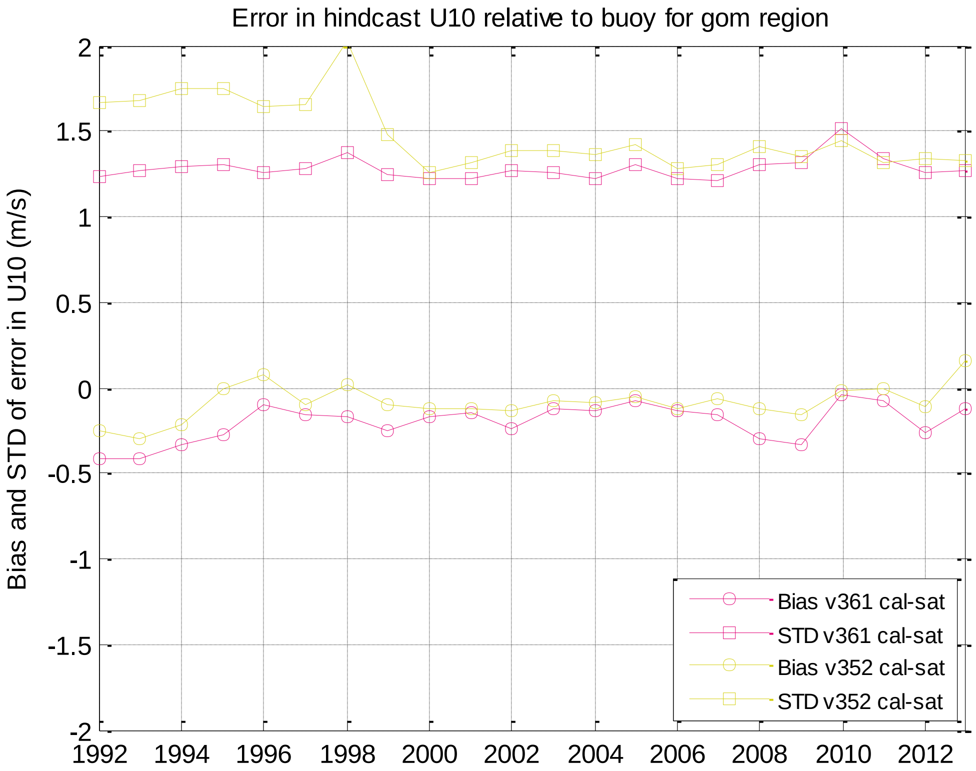


**Figure 61 Error in global hindcast wind speed relative to GOM buoys**

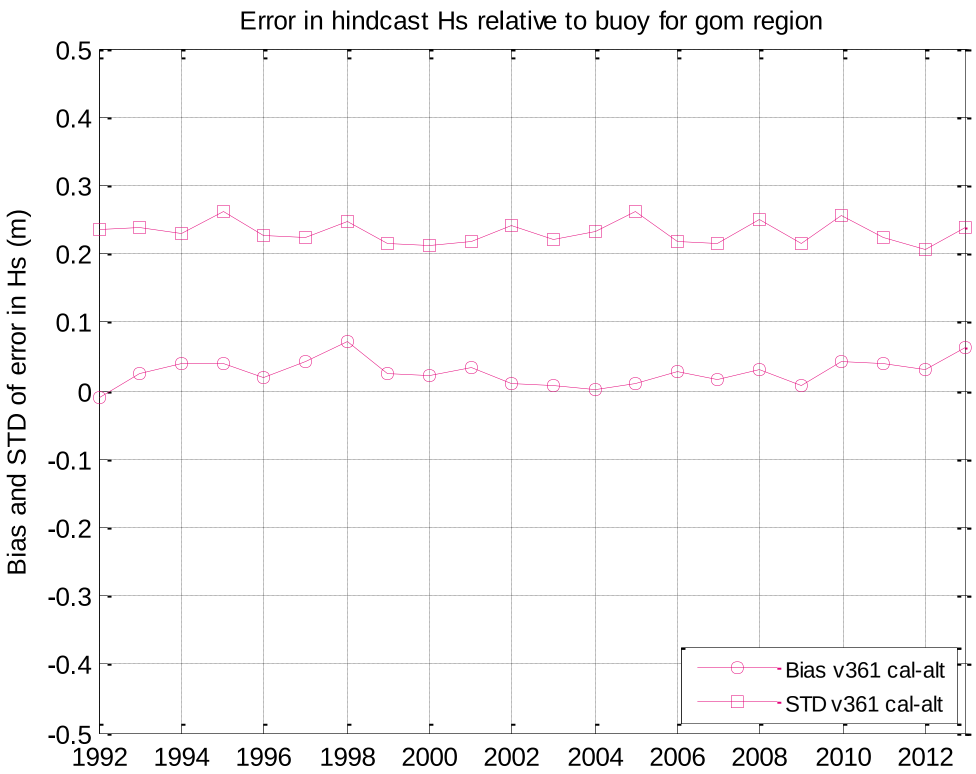


**Figure 62 Error in global hindcast wave height relative to GOM buoys**

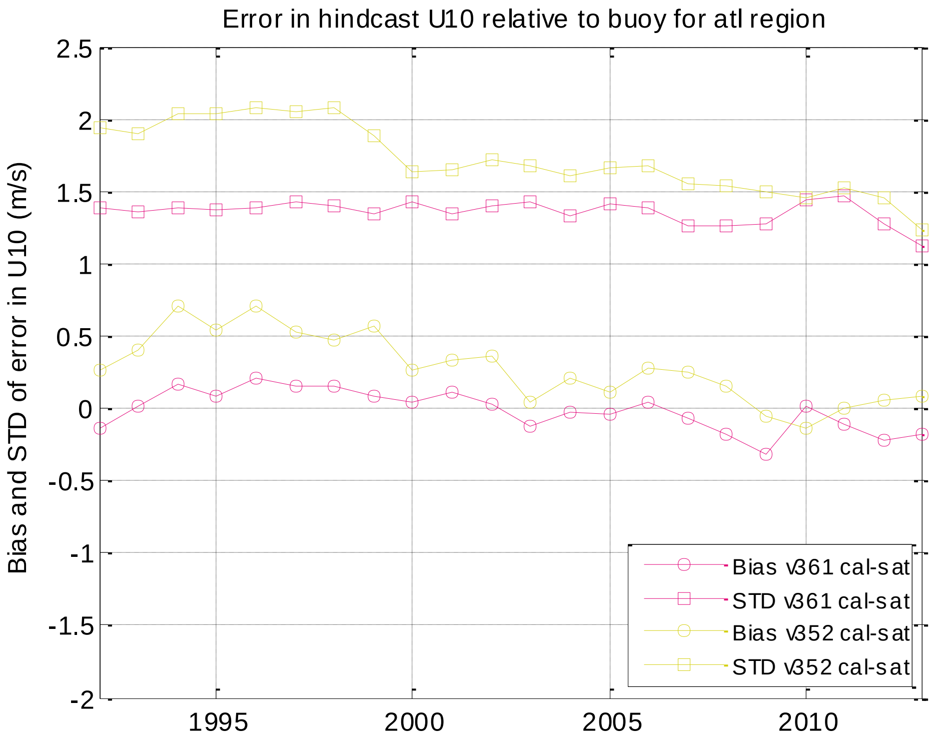


**Figure 63 Error in global hindcast wind speed relative to ATL buoys**

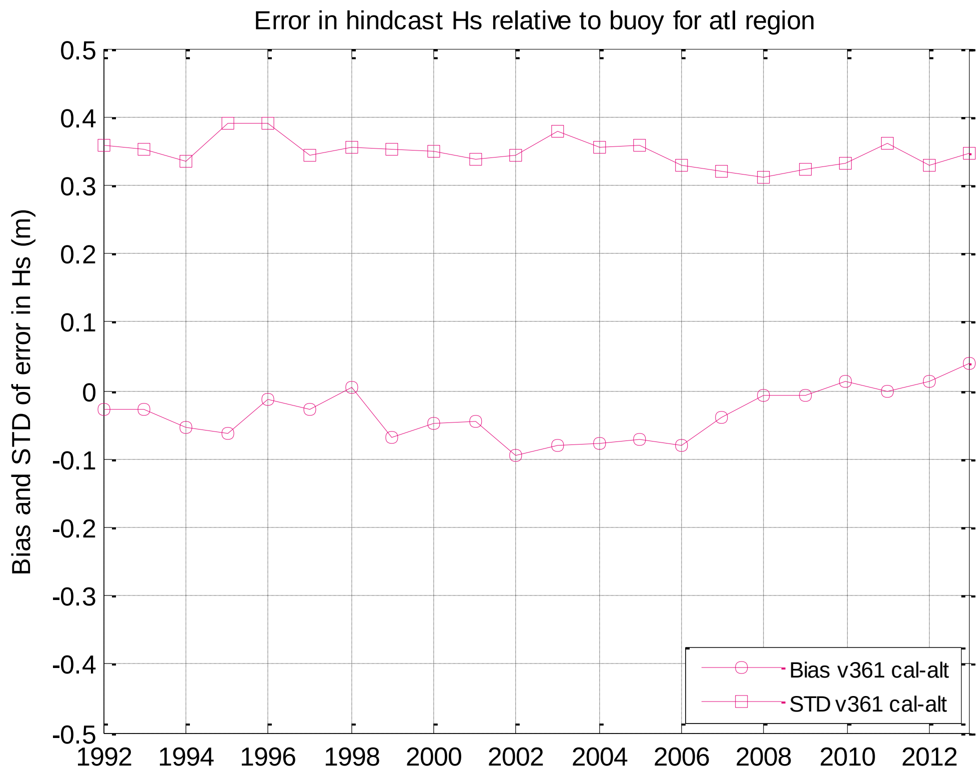


**Figure 64 Error in global hindcast wave height relative to ATL buoys**

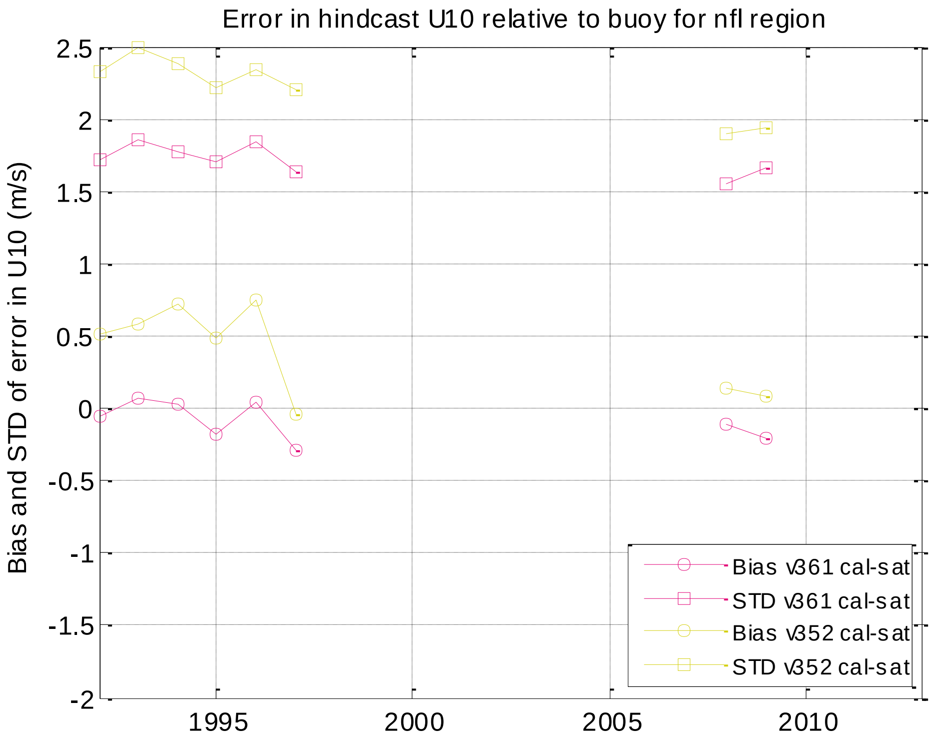


**Figure 65  Error in global hindcast wind speed relative to NFL buoys**

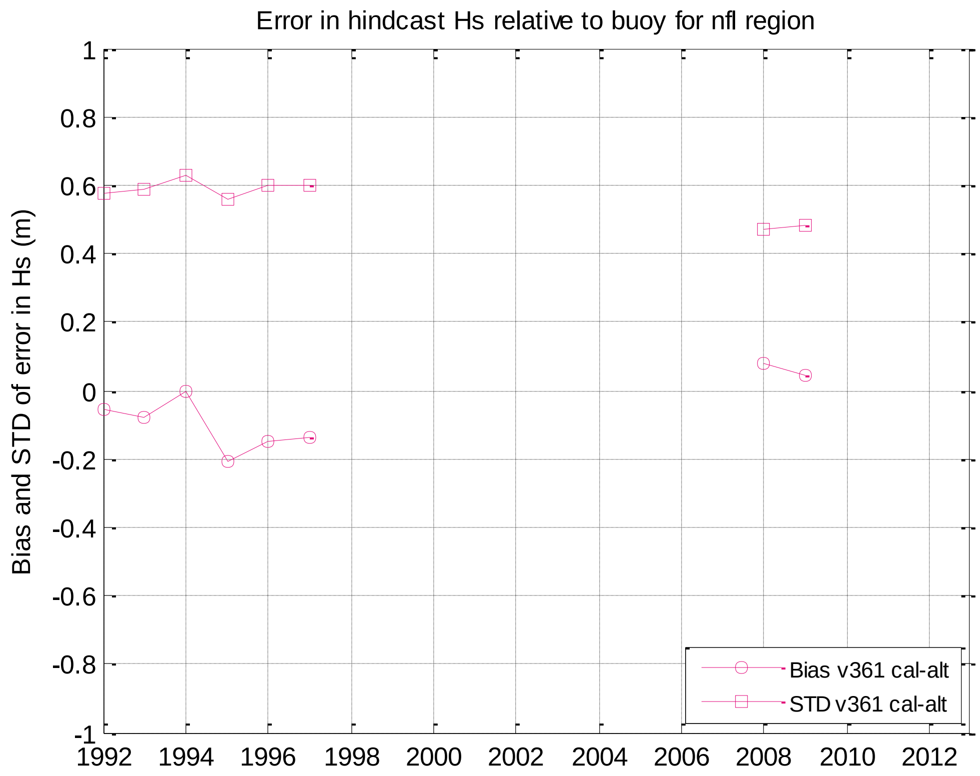


**Figure 66  Error in global hindcast wave height relative to NFL buoys**

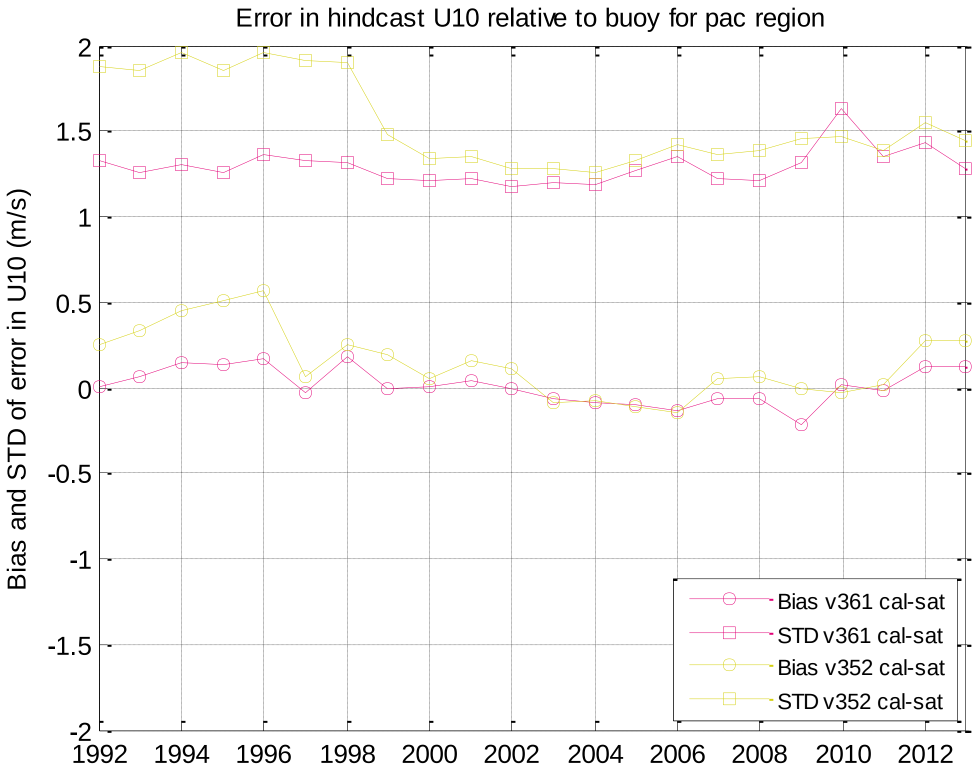


**Figure 67 Error in global hindcast wind speed relative to PAC buoys**

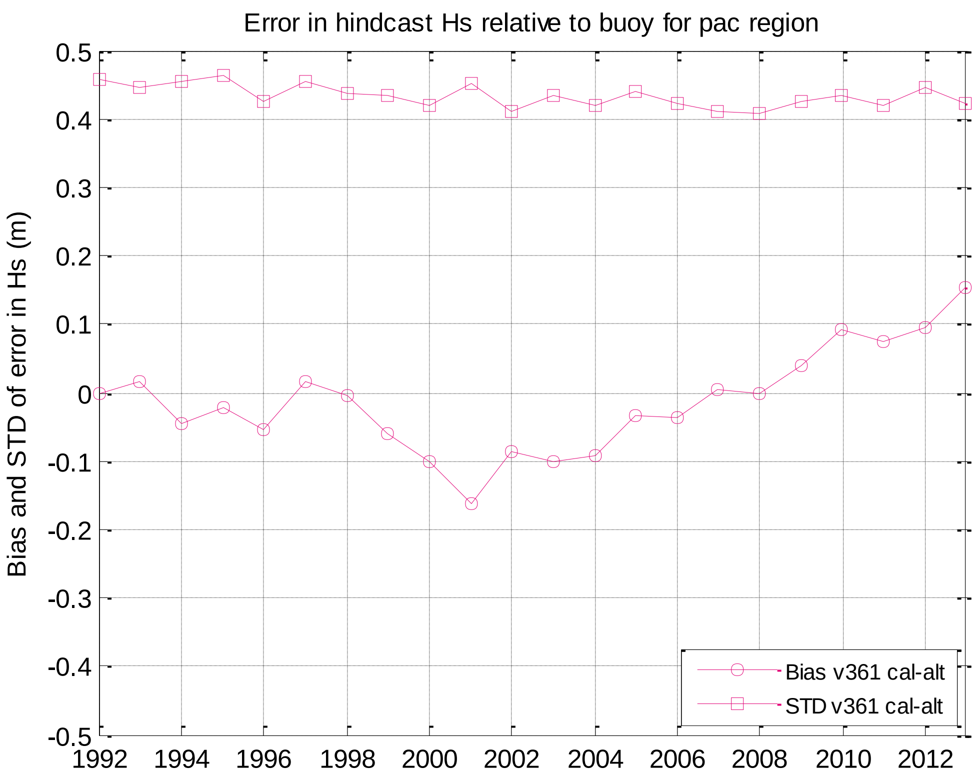


**Figure 68 Error in global hindcast wave height relative to PAC buoys**

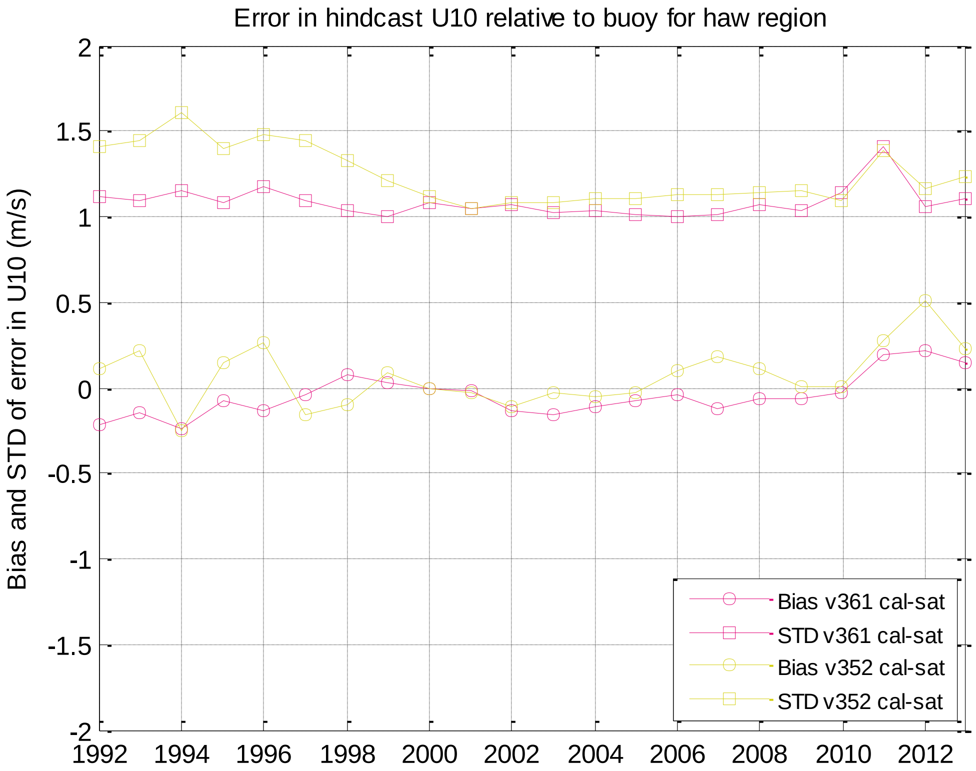


**Figure 69  Error in global hindcast wind speed relative to HAW buoys**

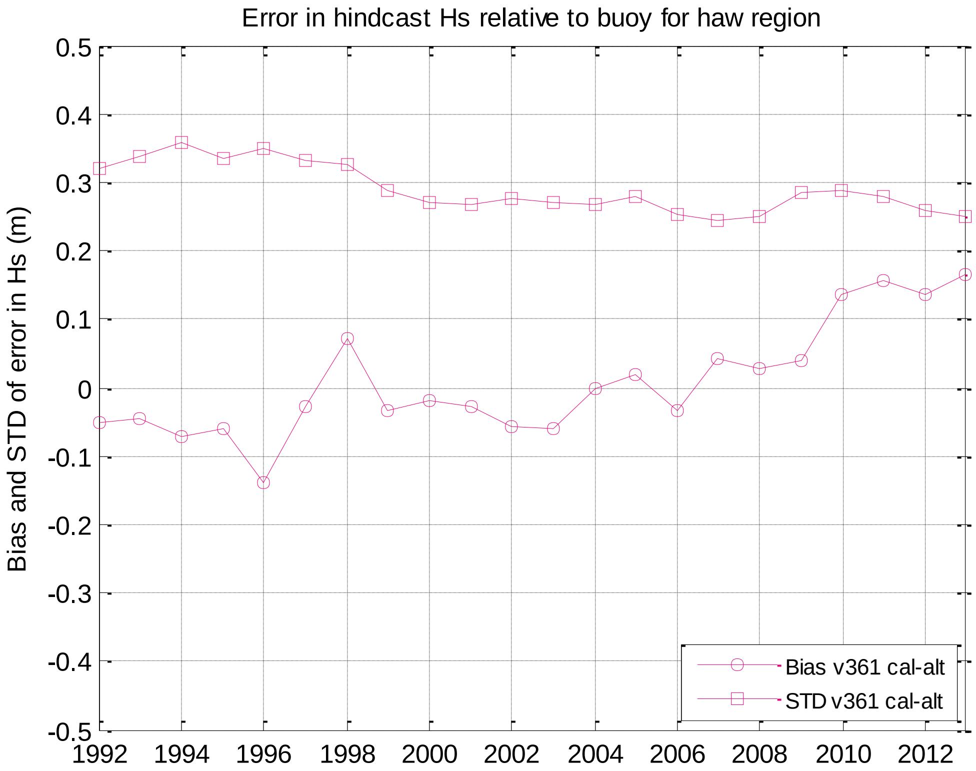


**Figure 70  Error in global hindcast wave height relative to HAW buoys**

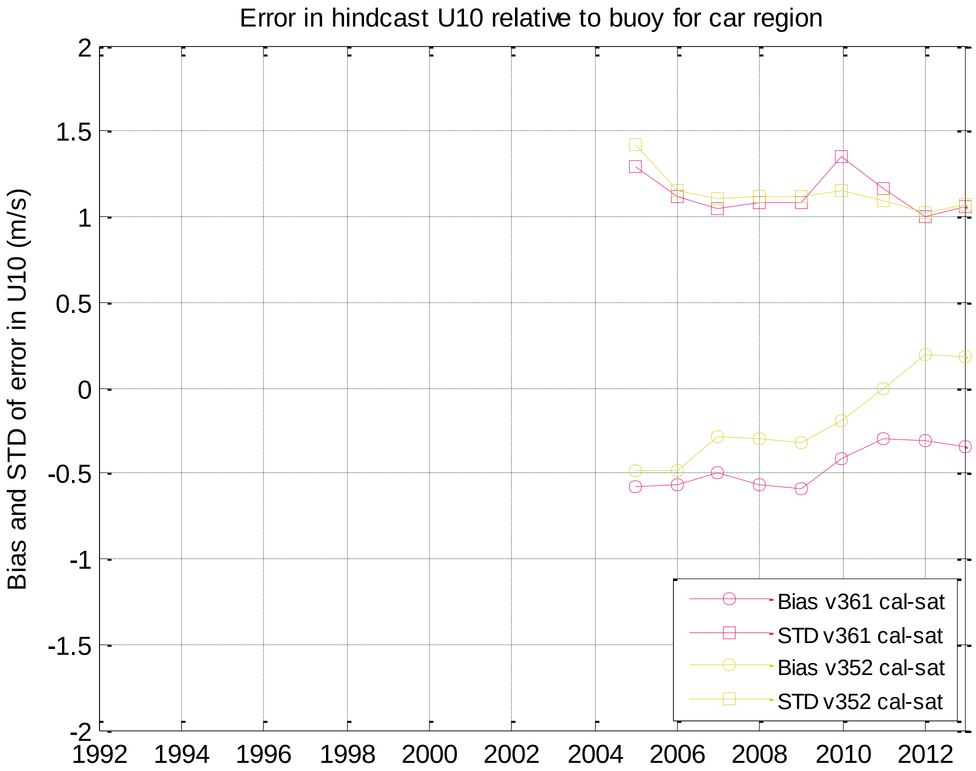


**Figure 71 Error in global hindcast wind speed relative to CAR buoys**

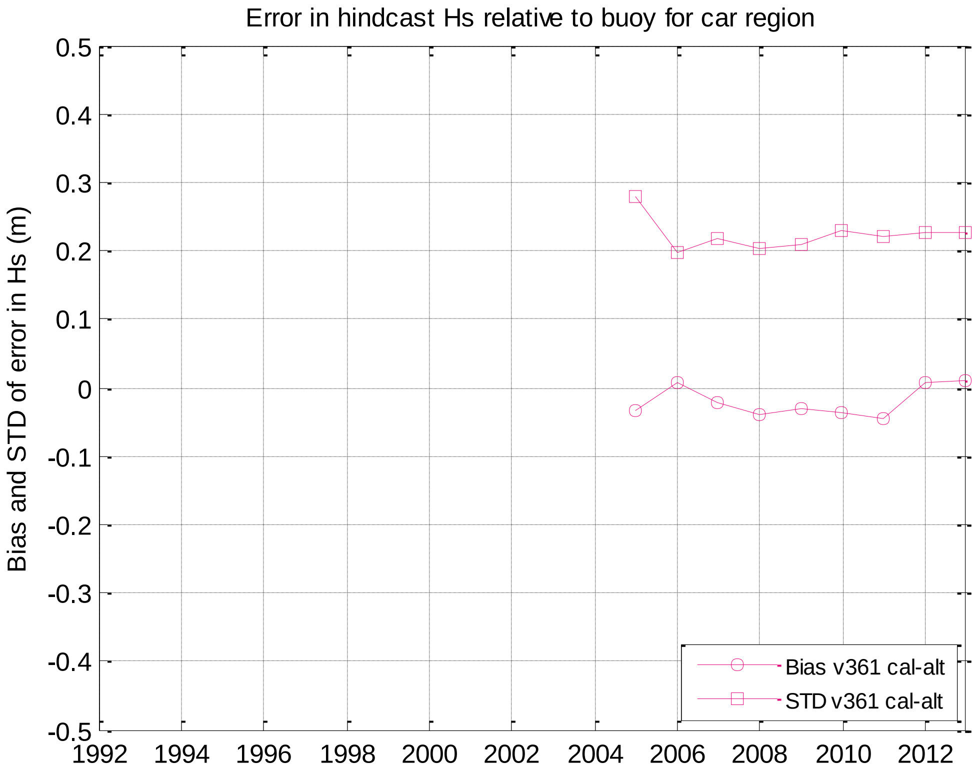


**Figure 72 Error in global hindcast wave height relative to CAR buoys**

# Appendix D2 – Regional Results Ambient Climate (EU-shelf)

In this appendix EU-shelf model-buoy error statistics of significant wave height and wind speed are checked over the years for each buoy region.

The model performance is expressed in terms of bias (mean of the model error) and standard deviation of the error between co-located model data and buoy data. A negative bias means that the model values are too low in comparison to the buoy measurements.

The plots in this appendix show the error in wind speed and wave height of satellite-calibrated ('best') v352 and v361 hindcast relative to buoys for the regions mentioned in section 4.2. Error statistics over the years based on all buoys can be found in the main report in section 6.1.2.

Most regional plots show that the quality of 'best' v361 wind and waves are consistently as good as or better than 'best' v352 wind and waves over the years.

In the NE Atlantic (see Figure 73) and in the northern part of the North Sea (see Figure 84), wind speed from both models is too high over the years. In the Irish Sea, v361 winds are too low whereas v352 winds are too high relative too buoys (see Figure 77). For the North Sea regions, v352 winds (ECMWF) appear to be relative bad (more variable) before 2000 (see for example winds for the northern North Sea in Figure 84).

In the English Channel, waves of both model versions are too high (see Figure 79).

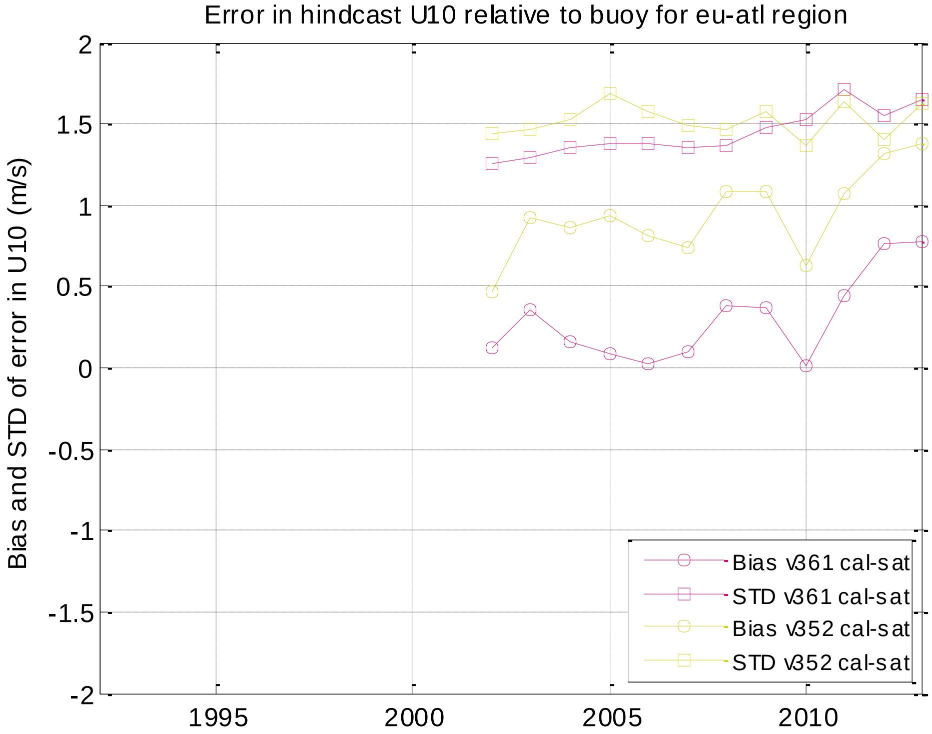


**Figure 73 Error in EU-shelf hindcast wind speed relative to EU-ATL buoys**

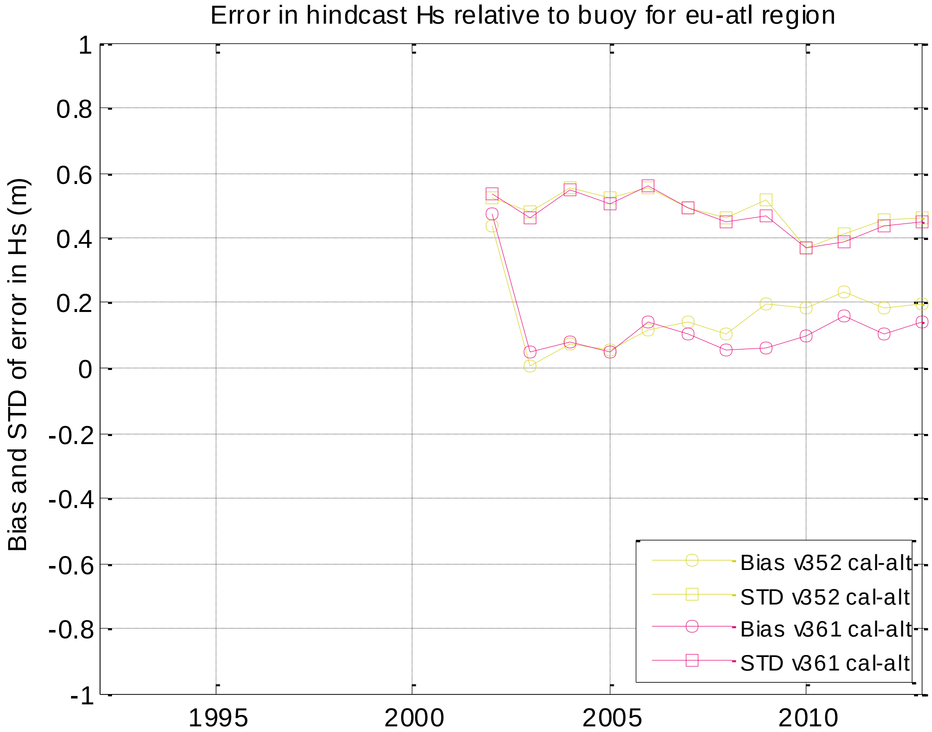


**Figure 74 Error in EU-shelf hindcast wave height relative to EU-ATL buoys**

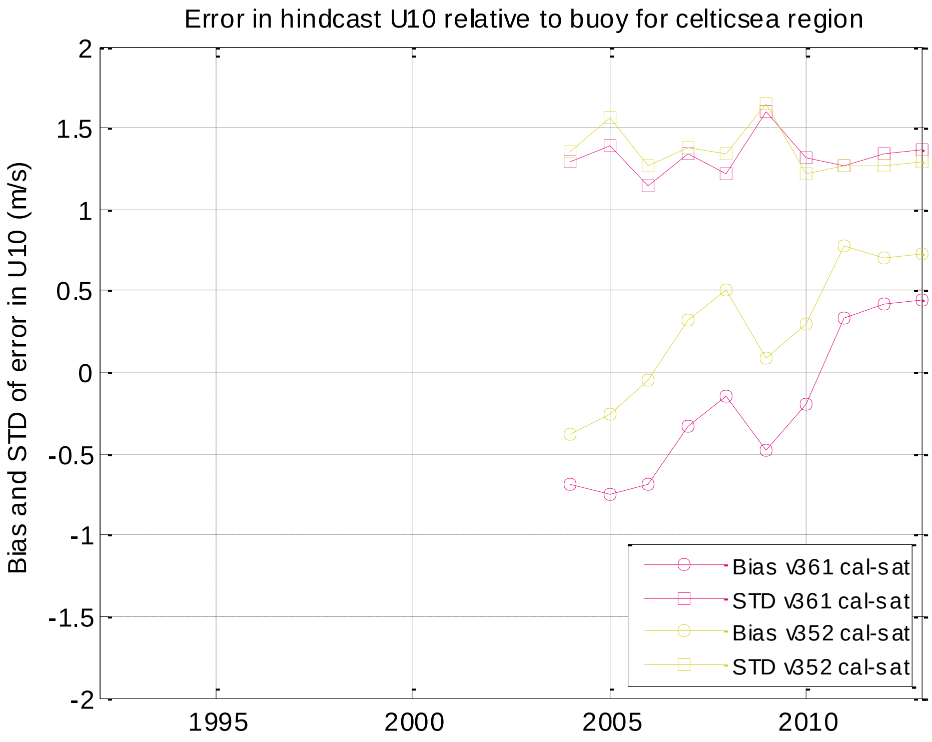


**Figure 75 Error in EU-shelf hindcast wind speed relative to CELTICSEA buoys**


**Figure 76 Error in EU-shelf hindcast wave height relative to CELTICSEA buoys**

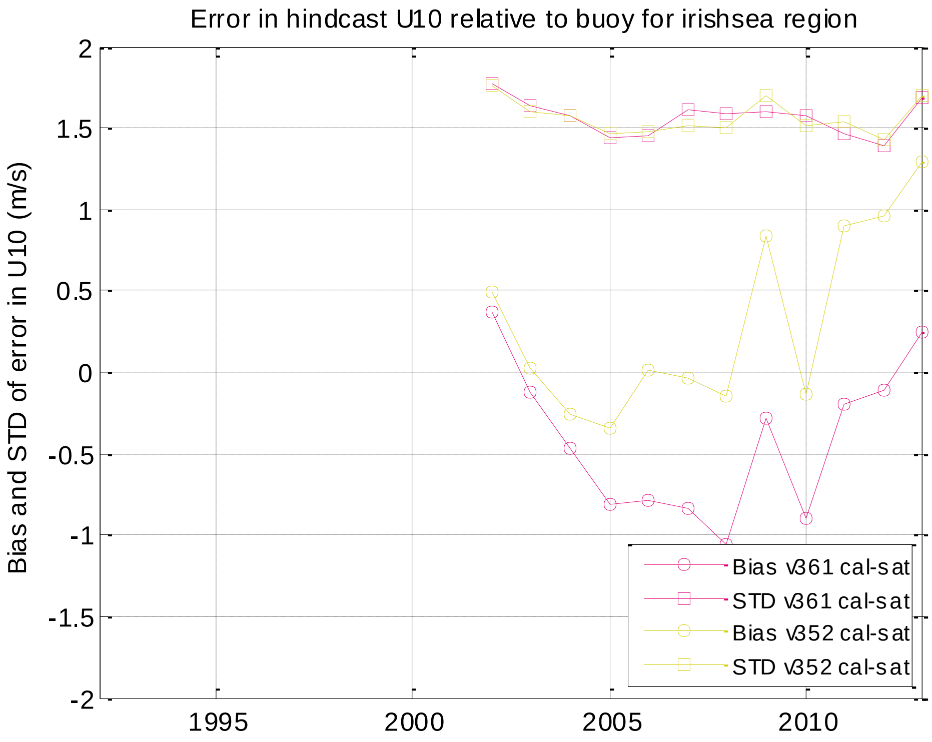


**Figure 77 Error in EU-shelf hindcast wind speed relative to IRISHSEA buoy**


**Figure 78 Error in EU-shelf hindcast wave height relative to IRISHSEA buoy**

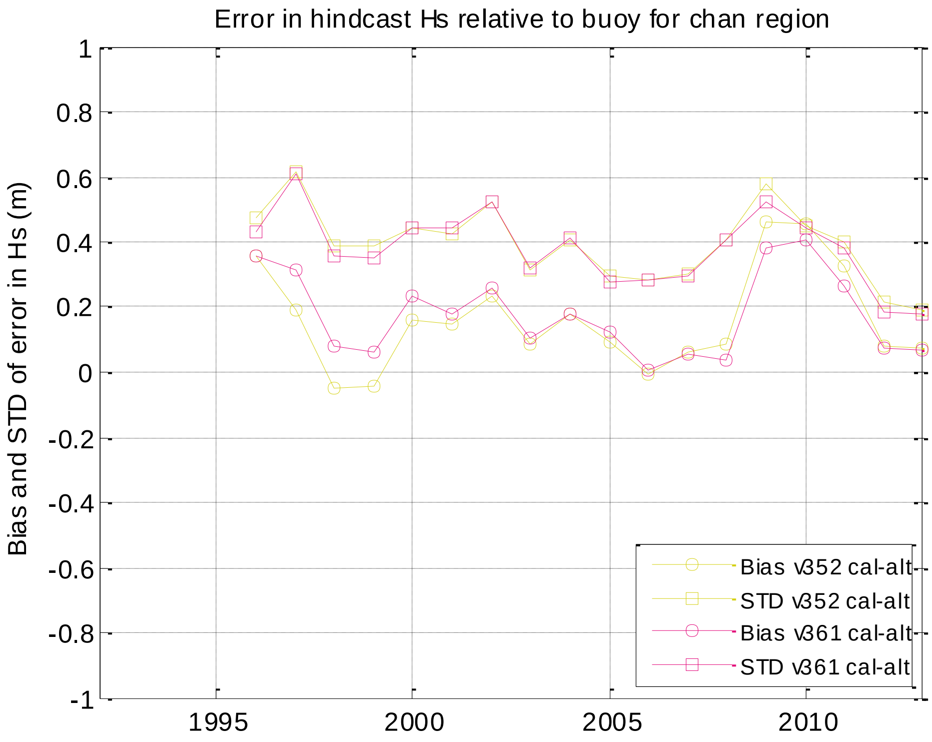


**Figure 79  Error in EU-shelf hindcast wave height relative to CHAN buoys**

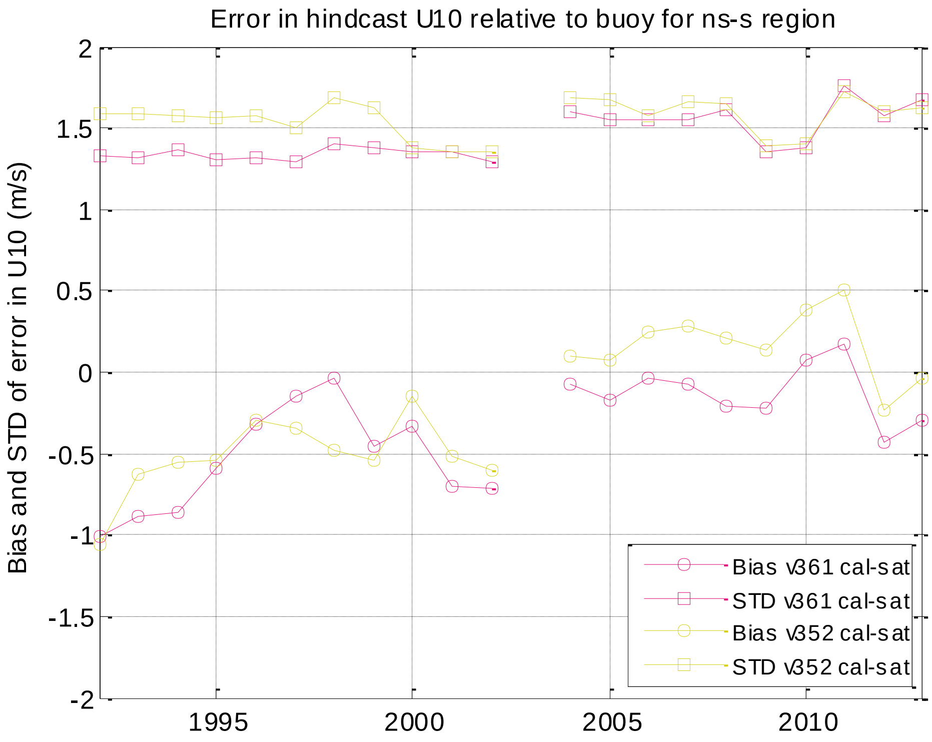


**Figure 80 Error in EU-shelf hindcast wind speed relative to NS-S buoys**

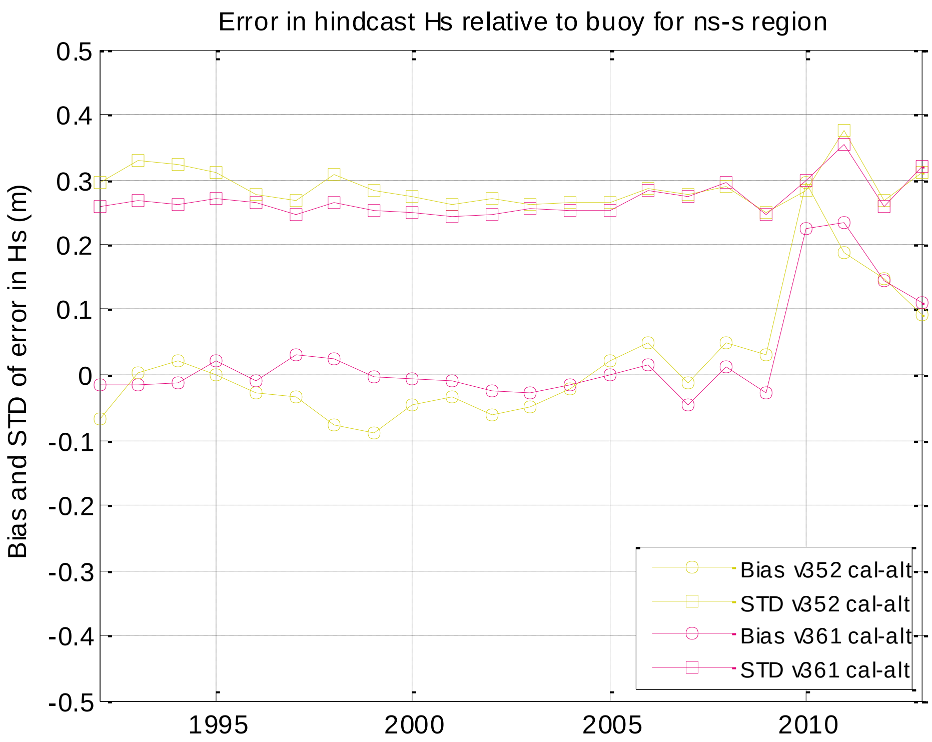


**Figure 81 Error in EU-shelf hindcast wave height relative to NS-S buoys**

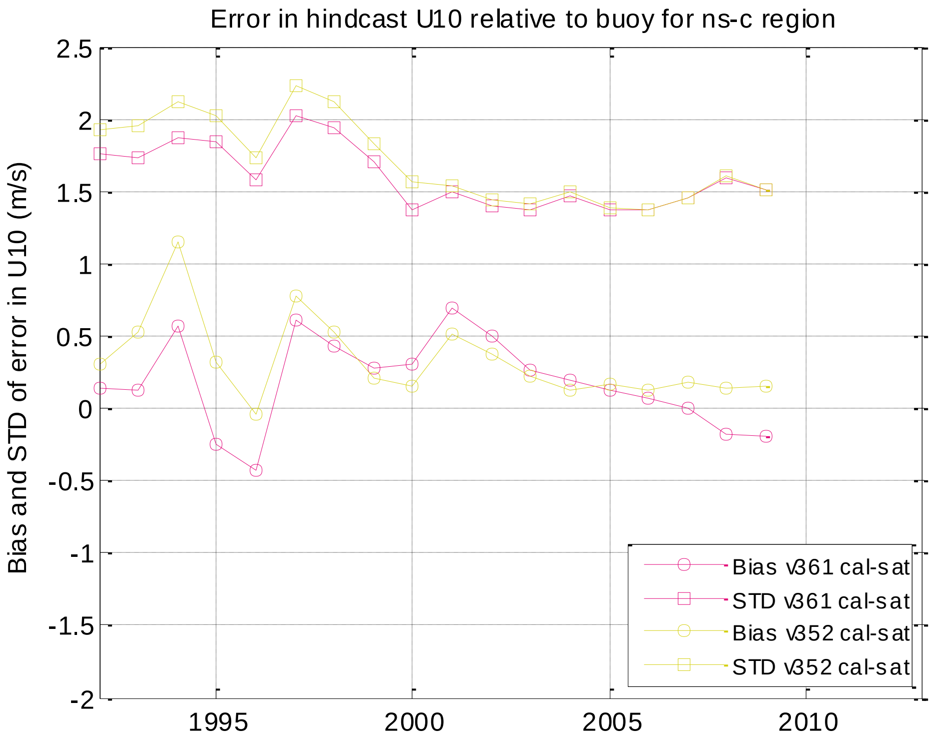


**Figure 82  Error in EU-shelf hindcast wind speed relative to NS-C buoys**

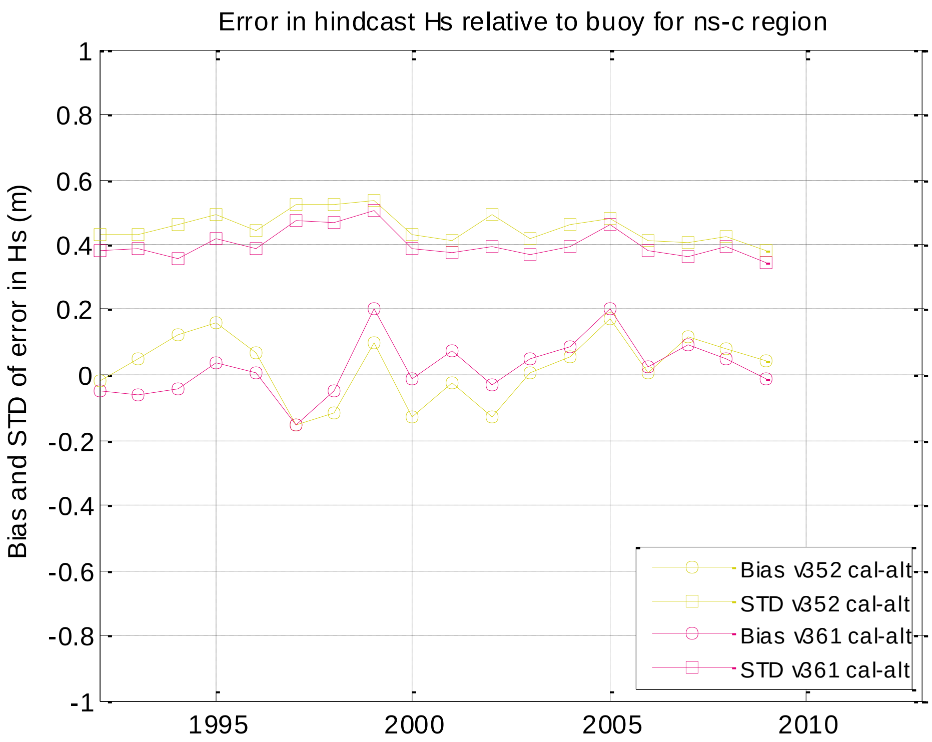


**Figure 83  Error in EU-shelf hindcast wave height relative to NS-C buoys**

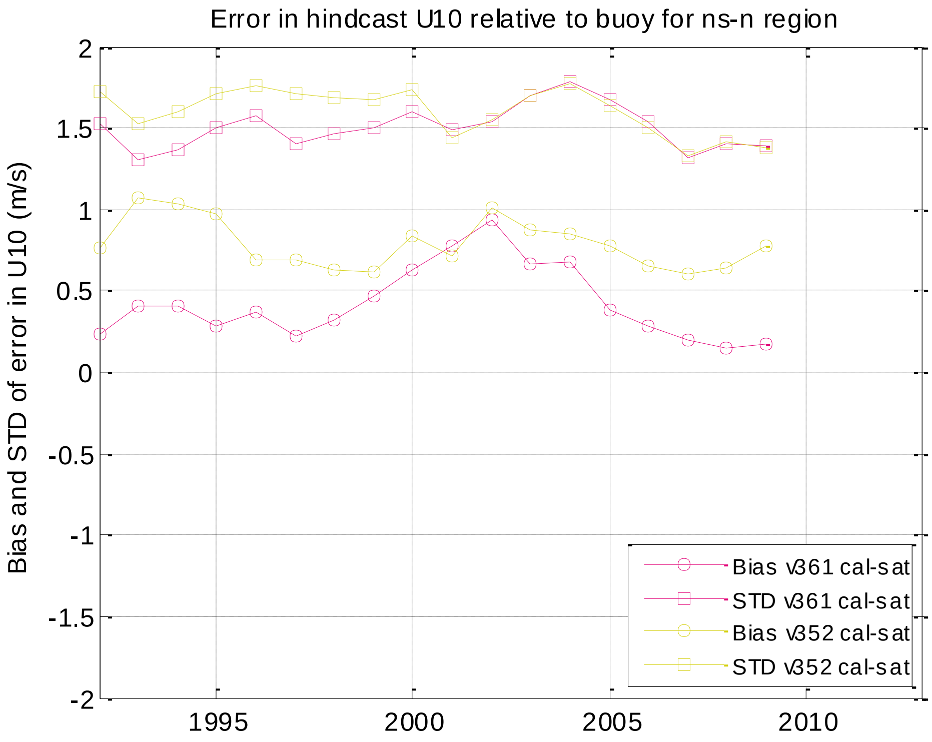


**Figure 84 Error in EU-shelf hindcast wind speed relative to NS-N buoys**

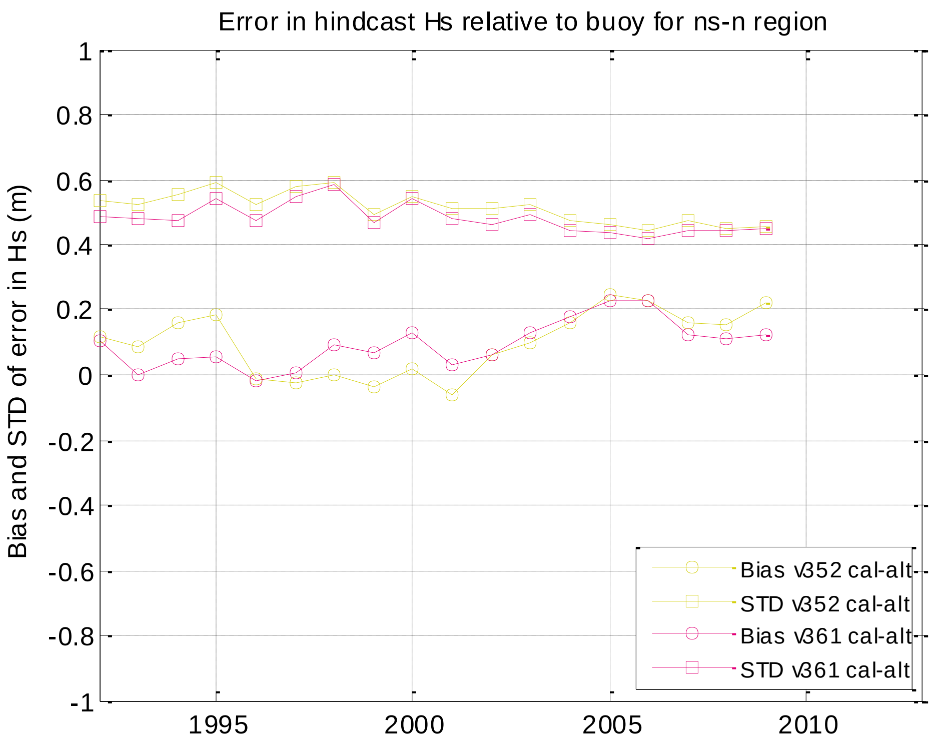


**Figure 85 Error in EU-shelf hindcast wave height relative to NS-N buoys**

# Appendix E1 – Regional Results Extreme Climate (Global)

Per buoy region and for all buoys, higher and extreme values of global model wind speed and significant wave height were compared to buoy data by means of quantile-quantile (Q-Q) plots and probability of exceedance (PoE) plots. Please refer to section 4.4 for more detail.

Plots comparing hindcast distributions against all buoys can be found in the main report in section 5.2.

For the Gulf of Mexico (GOM), the probability distributions of 'best' model and buoy wind speed are provided in Figure 86 and Figure 87 holds the corresponding Q-Q plot. Similarly, distributions of model and buoy wave height are compared in Figure 88 and Figure 89. The rest of this appendix shows similar plots for the other regions mentioned in section 4.2.

The excessive wind speeds (say above 30 m/s) and extreme waves (say above 15 m) of hindcast v352, not seen in v361, are clearly linked to cyclone areas, i.e. the Gulf of Mexico (Figure 86 and Figure 88) and the Caribbean (Figure 106 and Figure 108). The Q-Q plots demonstrate that hindcast v361 winds in the range 10-25 m/s are much closer to the buoy measurements than v352 winds: the latter are too high in all areas except the Caribbean. The shortcoming in un-calibrated hindcast v361 waves (too low) becomes manifest in all regions. However, calibration with altimeter (based on the ambient climate) does also raise the quality of v361 higher and extreme waves up to or beyond the level of (un-calibrated) v352 wave height. The region around Hawaii is a bit exceptional with respect to this behaviour: here, v352 (swell) waves are too high and v361 (swell) waves remain too low according to the buoy data (see Figure 104 and Figure 105).

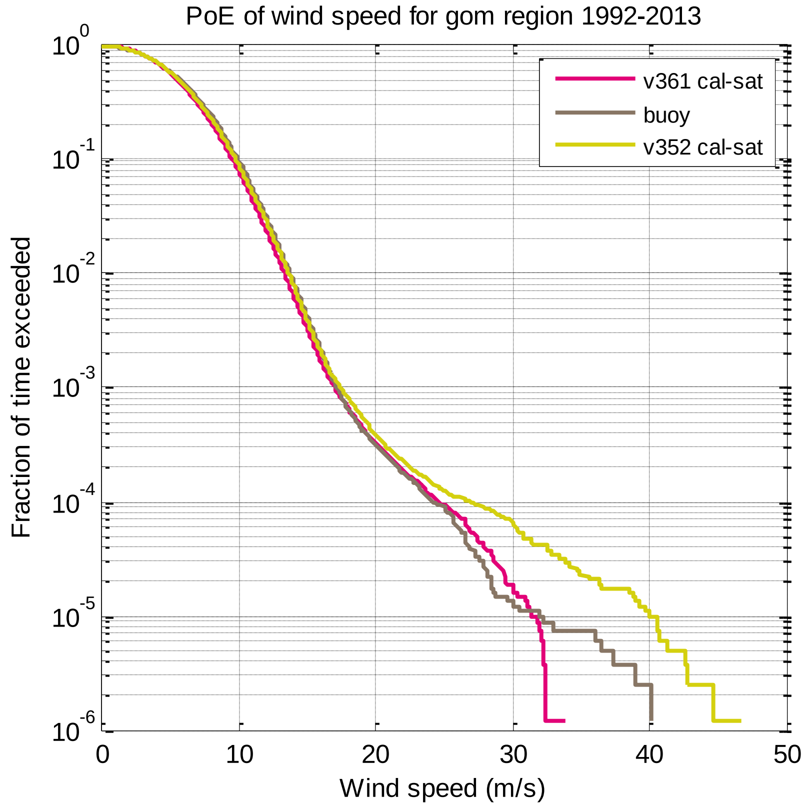


**Figure 86 PoE of global hindcast wind speed and GOM buoys**

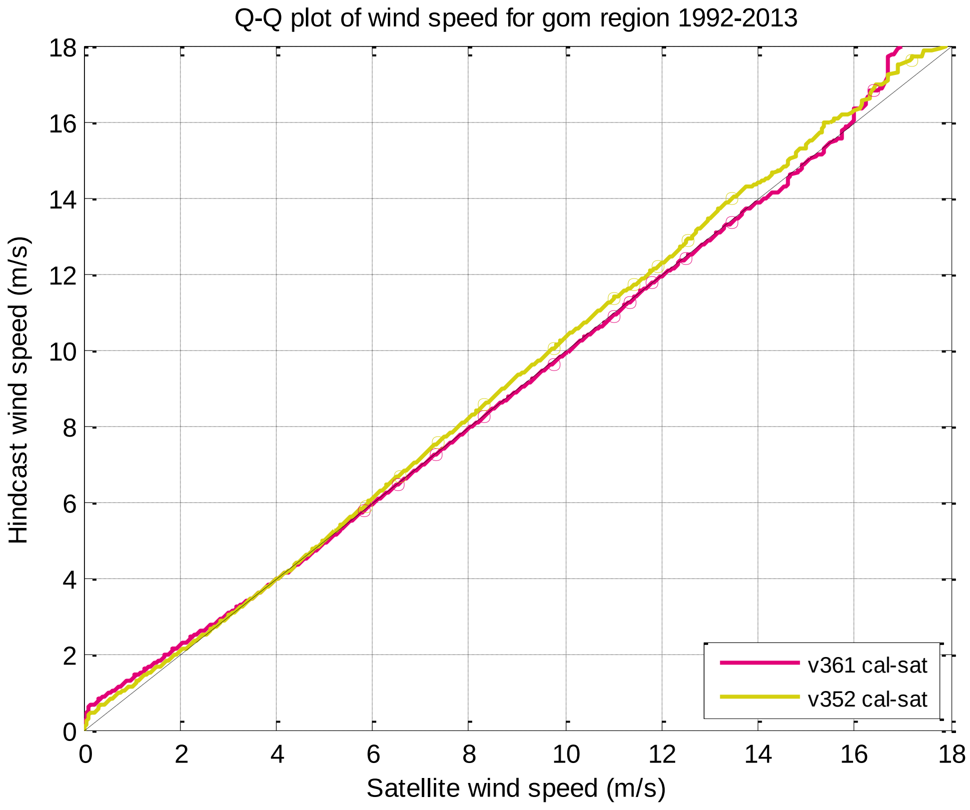


**Figure 87 Q-Q plot of global hindcast wind speed against GOM buoys**

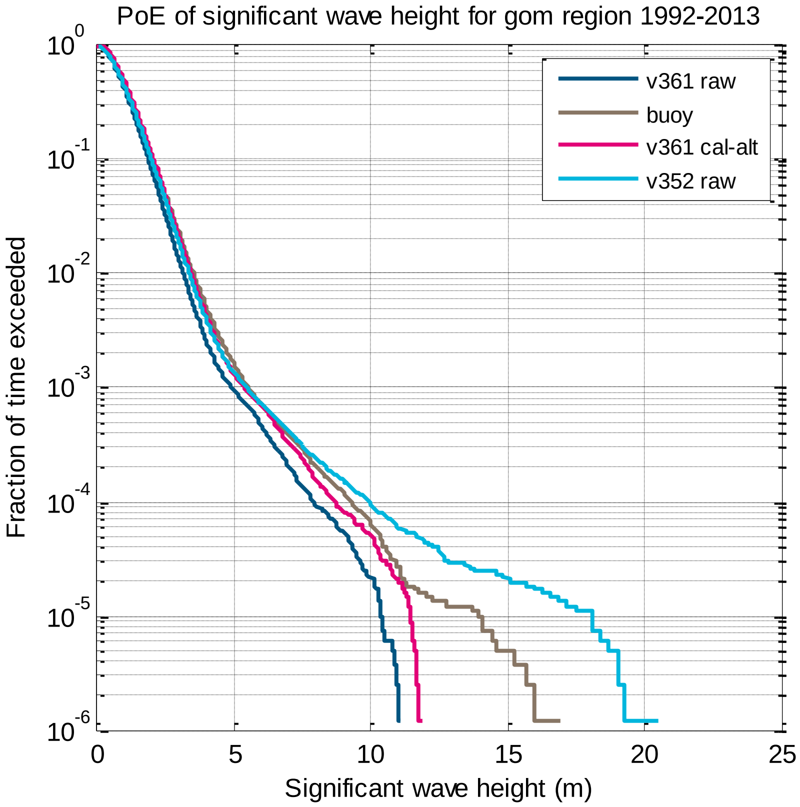


**Figure 88 PoE of global hindcast wave height and GOM buoys**

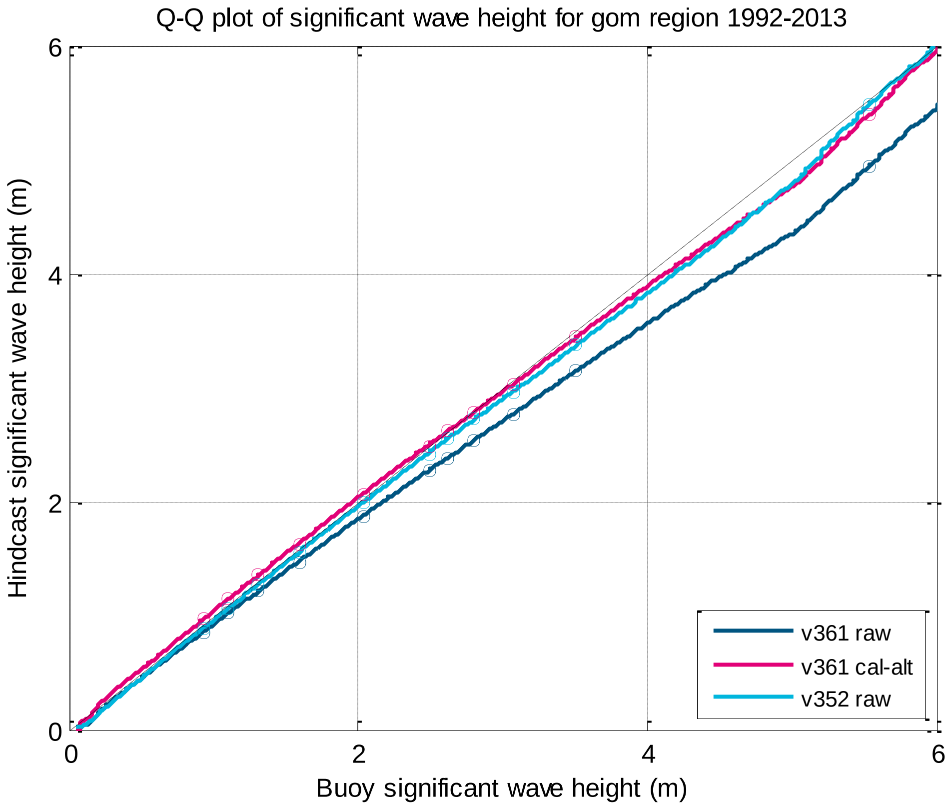


**Figure 89 Q-Q plot of global hindcast wave height against GOM buoys**

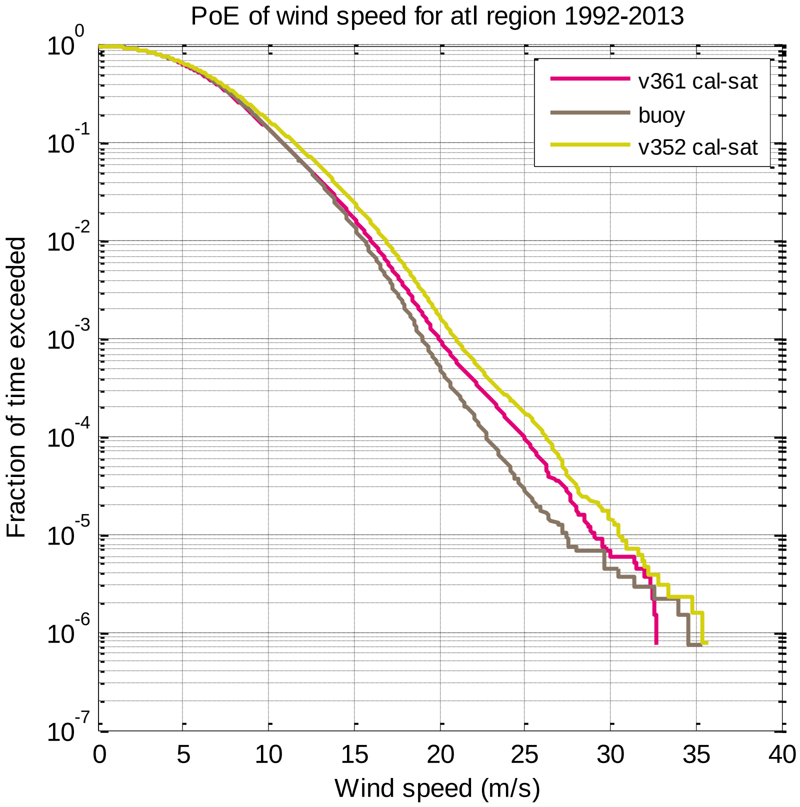


**Figure 90 PoE of global hindcast wind speed and ATL buoys**

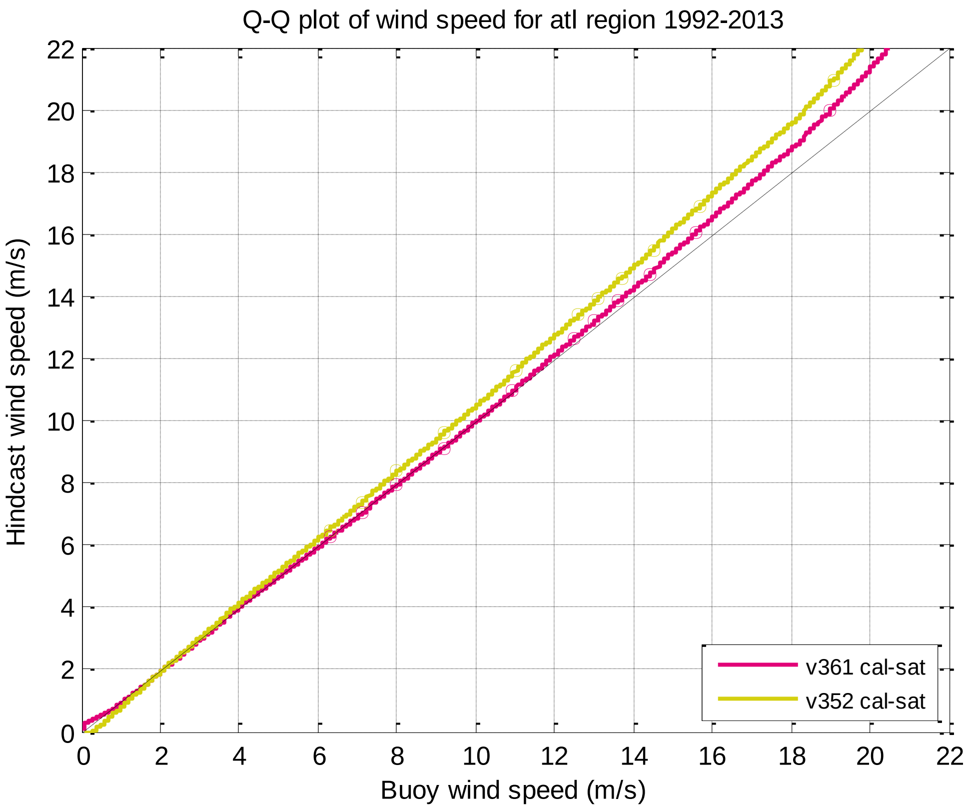


**Figure 91 Q-Q plot of global hindcast wind speed against ATL buoys**

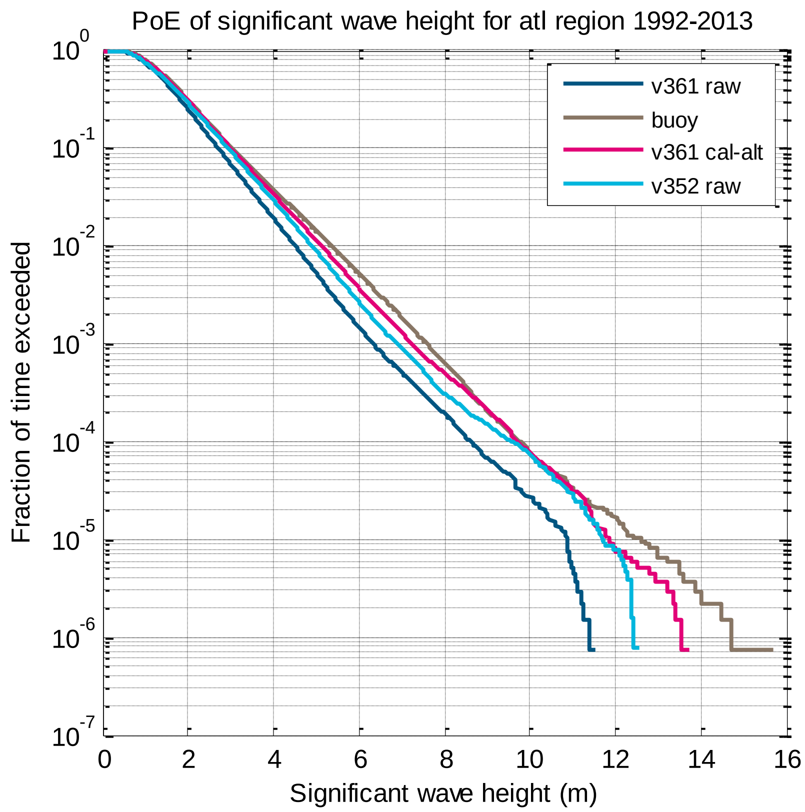


**Figure 92 PoE of global hindcast wave height and ATL buoys**

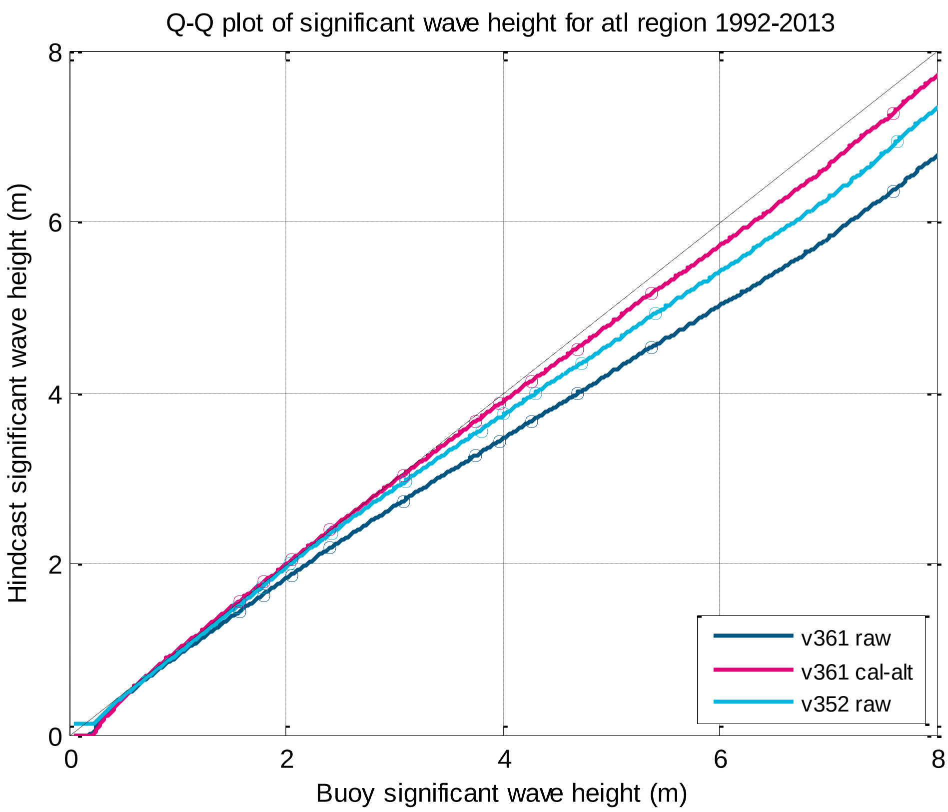


**Figure 93 Q-Q plot of global hindcast wave height against ATL buoys**

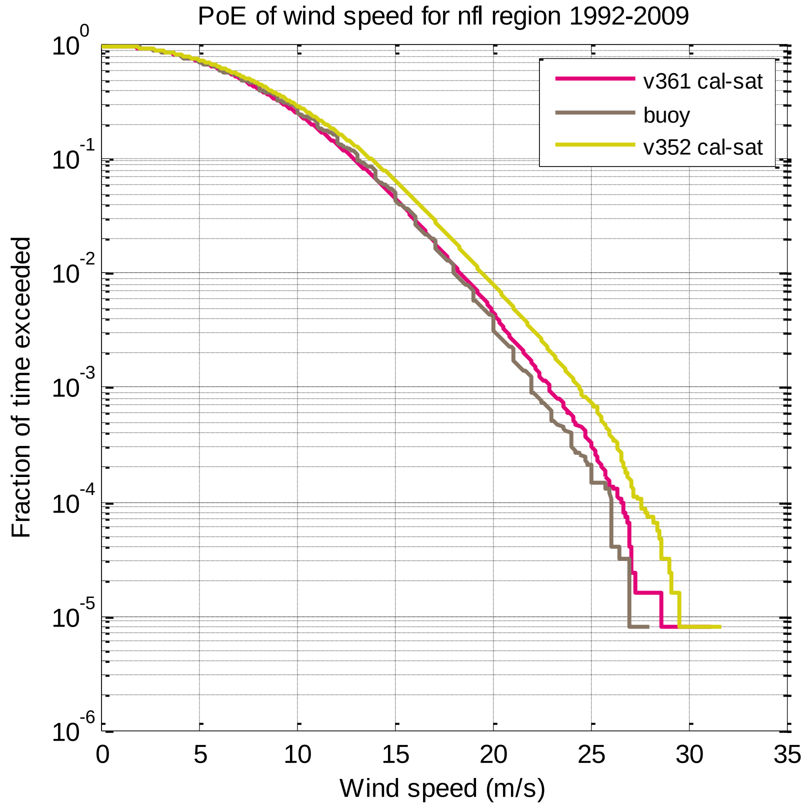


**Figure 94 PoE of global hindcast wind speed and NFL buoys**

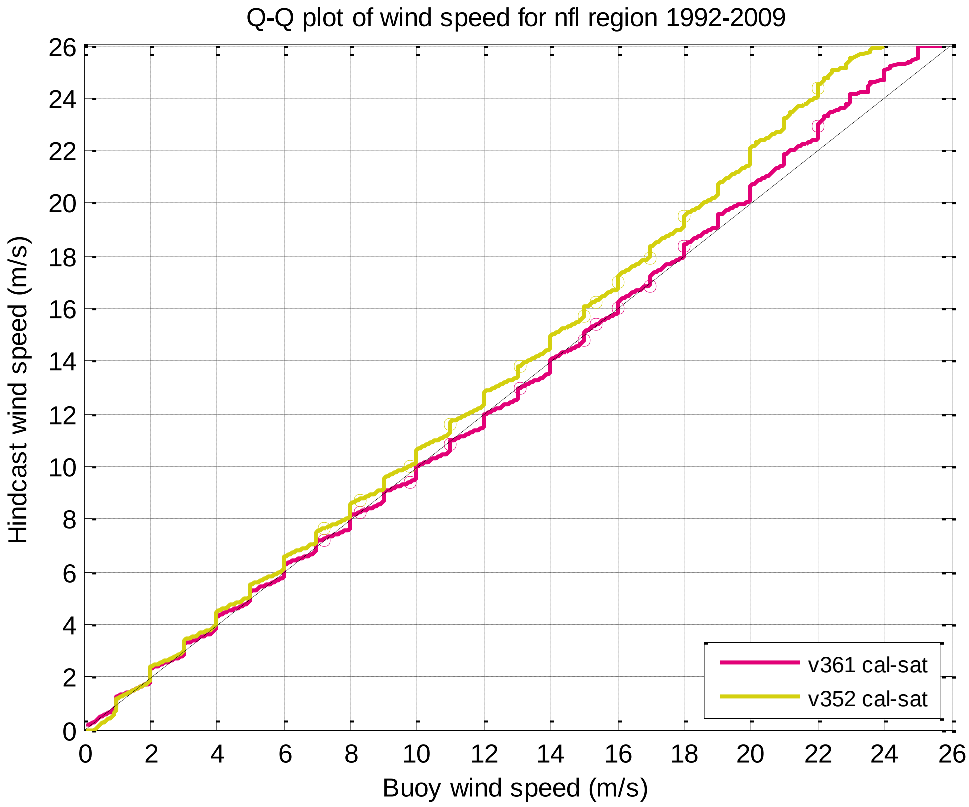


**Figure 95 Q-Q plot of global hindcast wind speed against NFL buoys**

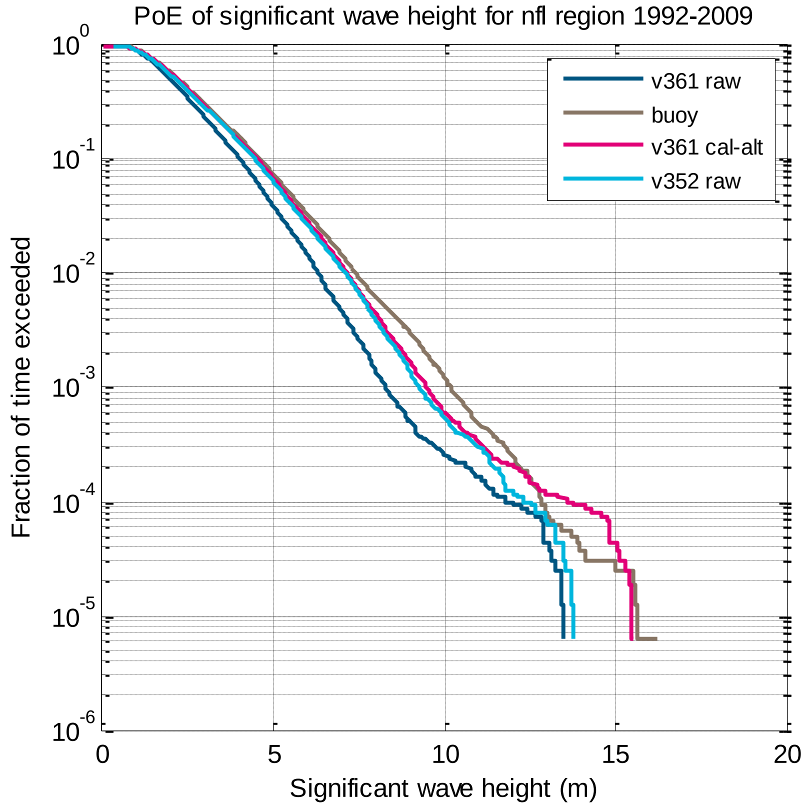


**Figure 96  PoE of global hindcast wave height and NFL buoys**

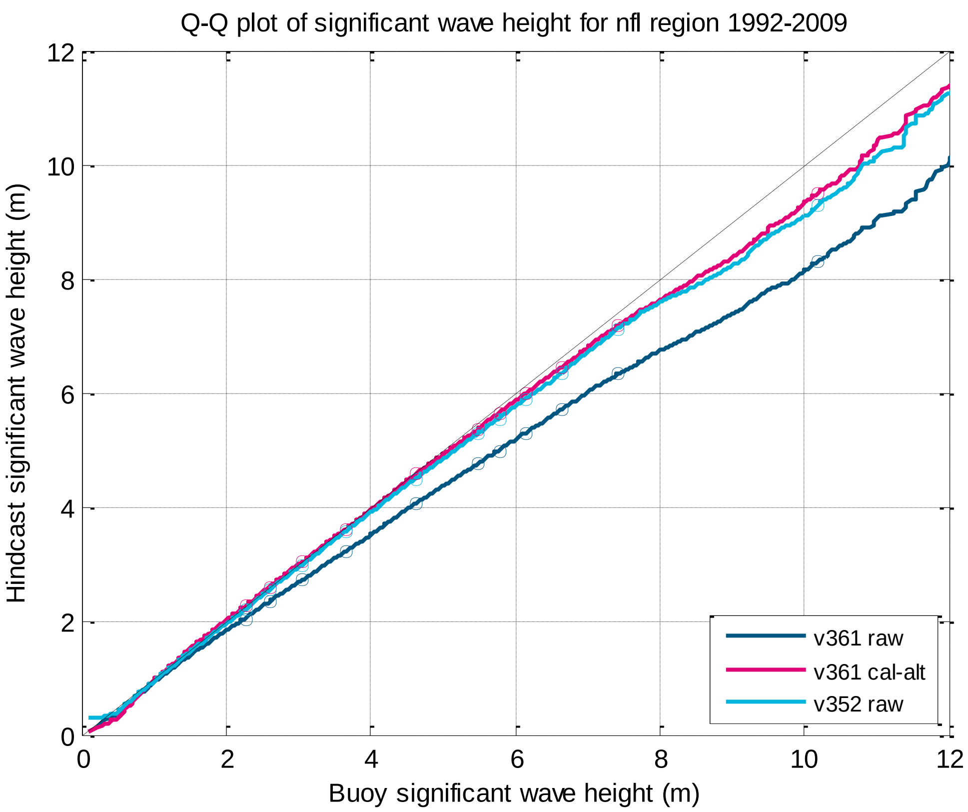


**Figure 97  Q-Q plot of global hindcast wave height against NFL buoys**

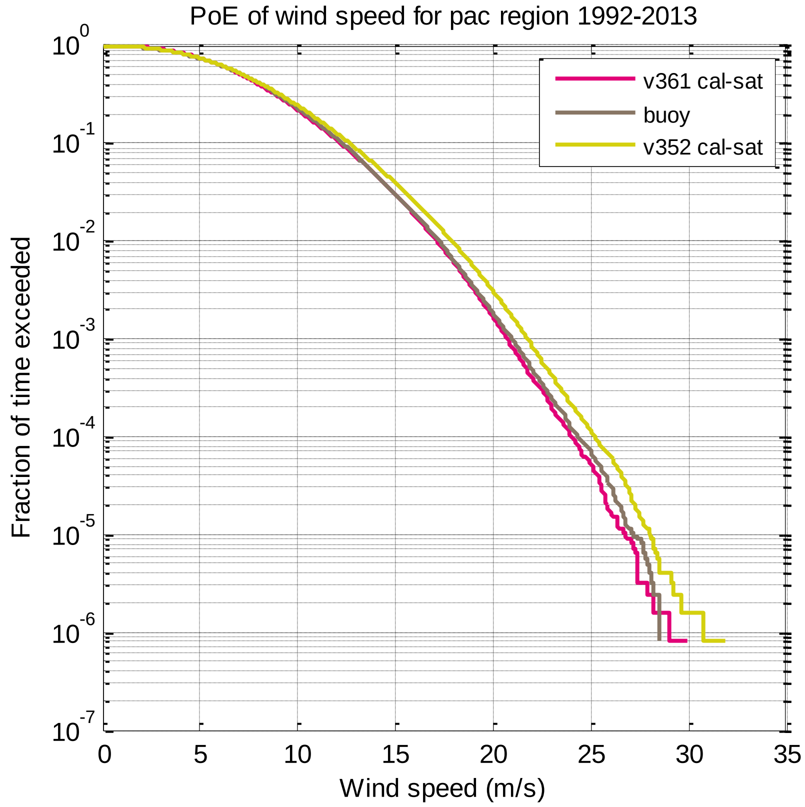


**Figure 98 PoE of global hindcast wind speed and PAC buoys**

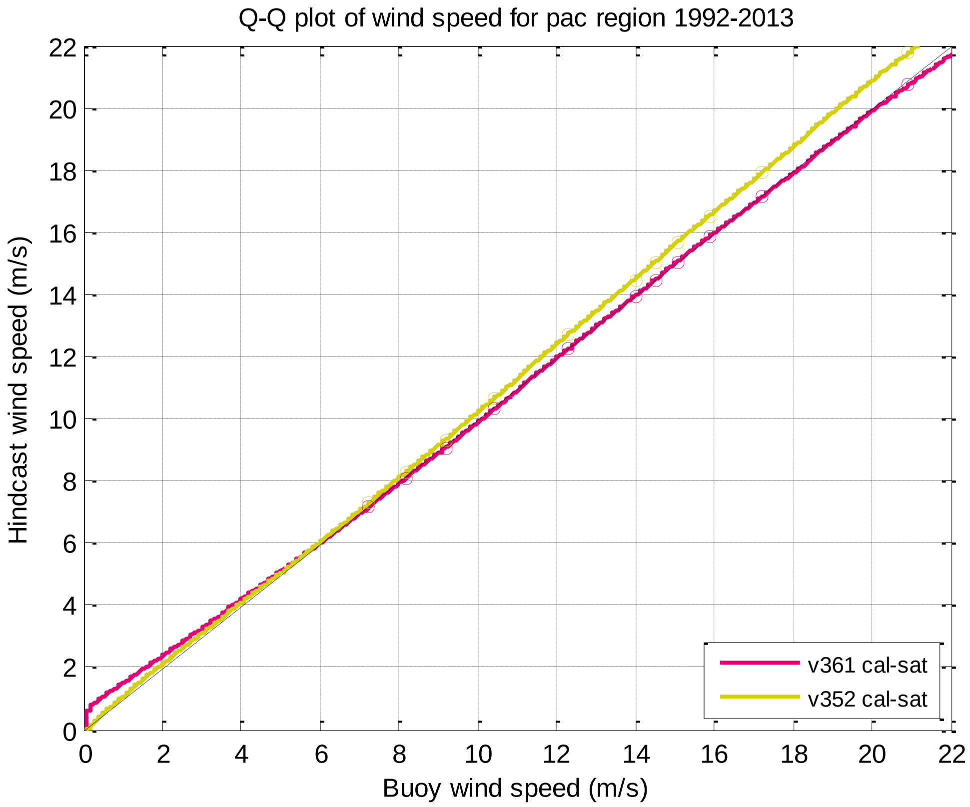


**Figure 99 Q-Q plot of global hindcast wind speed against PAC buoys**

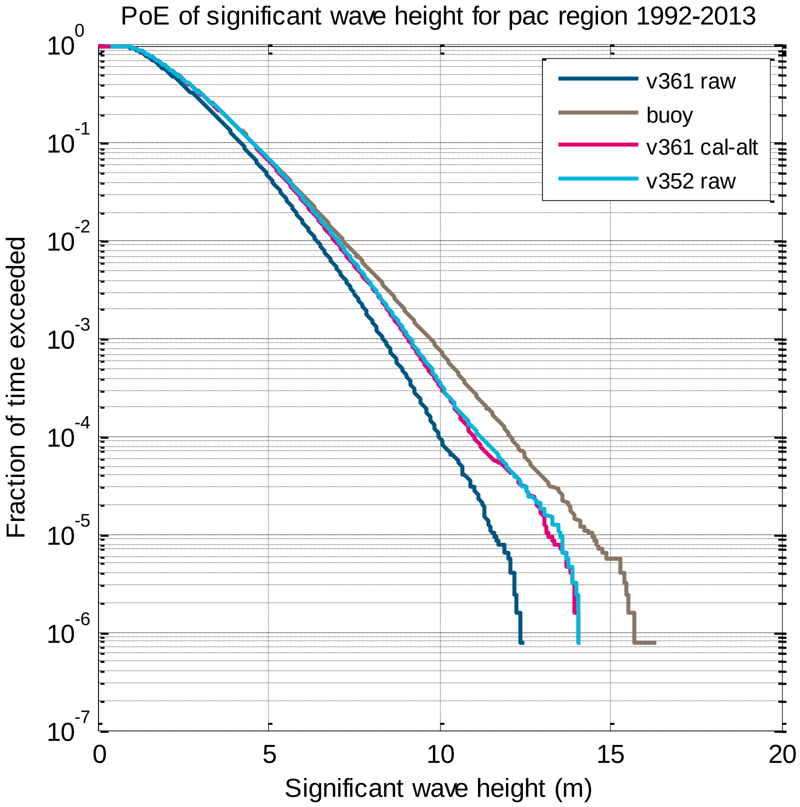


**Figure 100 PoE of global hindcast wave height and PAC buoys**

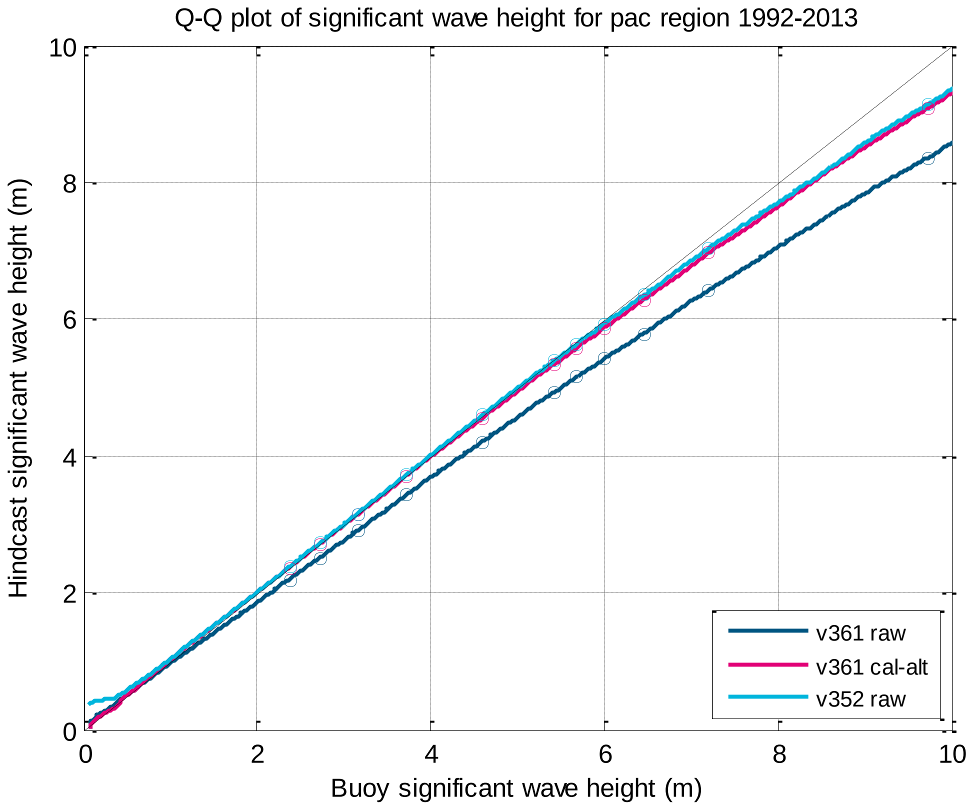


**Figure 101 Q-Q plot of global hindcast wave height against PAC buoys**

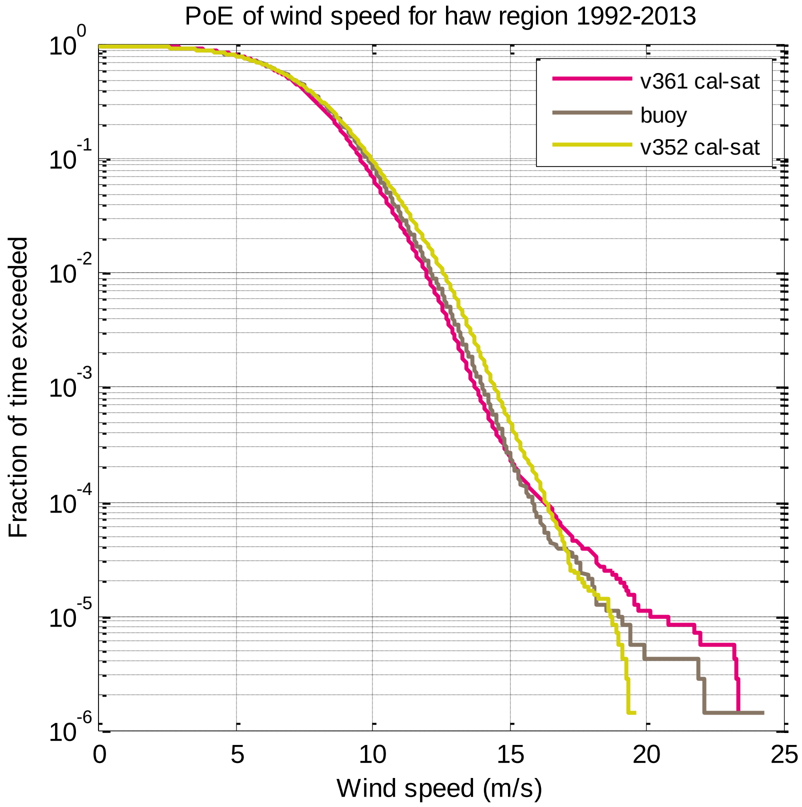


**Figure 102 PoE of global hindcast wind speed and HAW buoys**

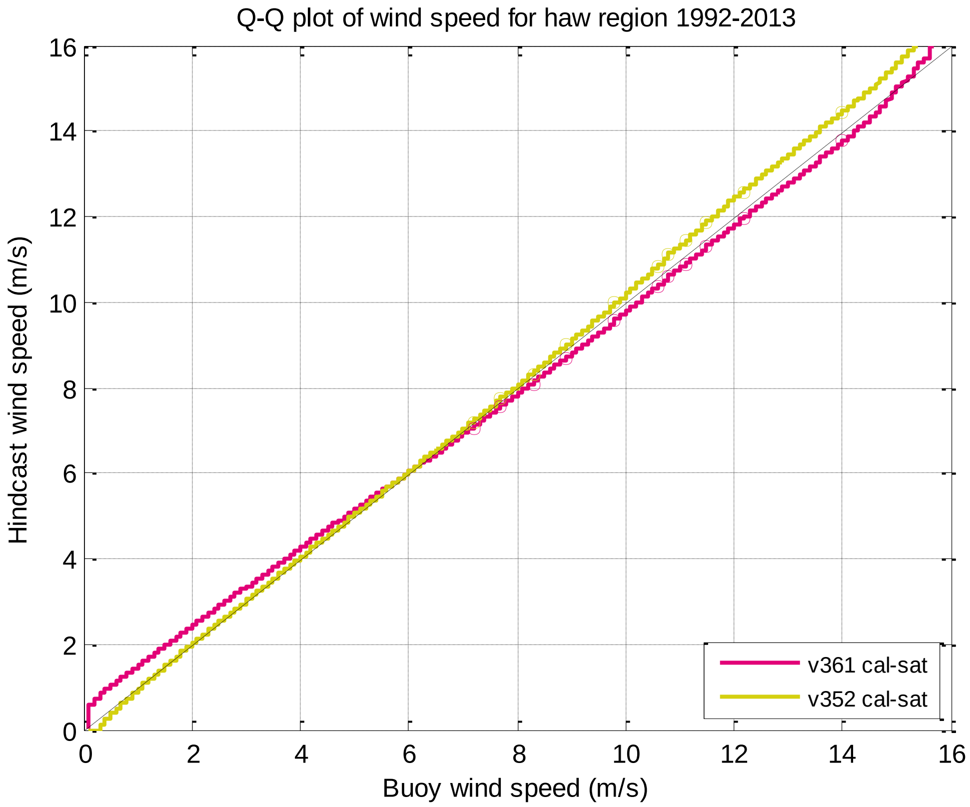


**Figure 103 Q-Q plot of global hindcast wind speed against HAW buoys**

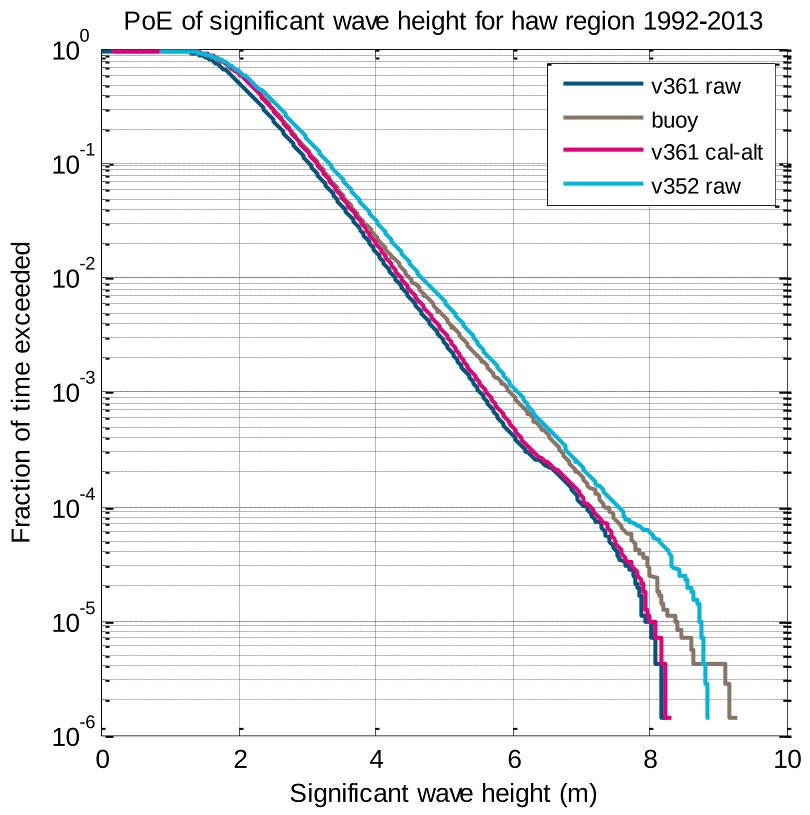


Figure 104 PoE of global hindcast wave height and HAW buoys

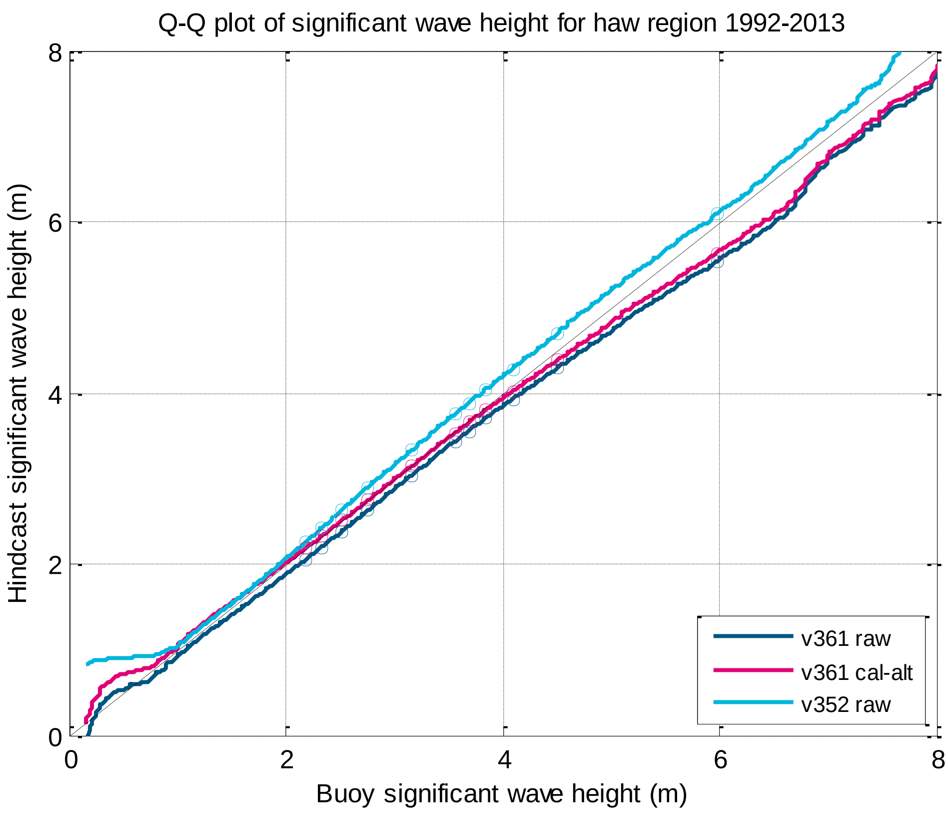


Figure 105 Q-Q plot of global hindcast wave height against HAW buoys

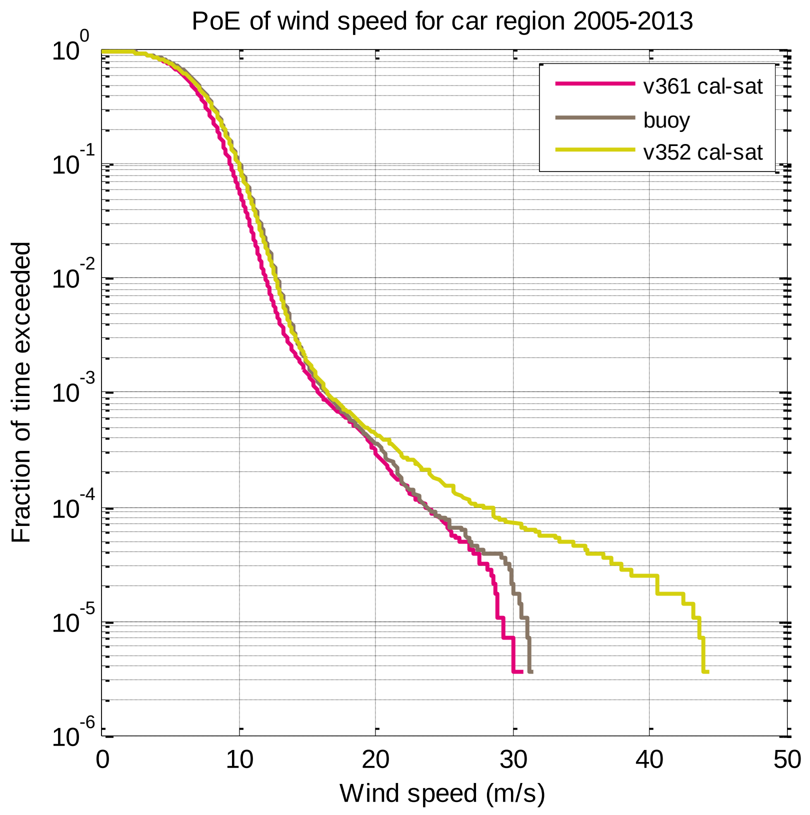


**Figure 106 PoE of global hindcast wind speed and CAR buoys**


**Figure 107 Q-Q plot of global hindcast wind speed against CAR buoys**

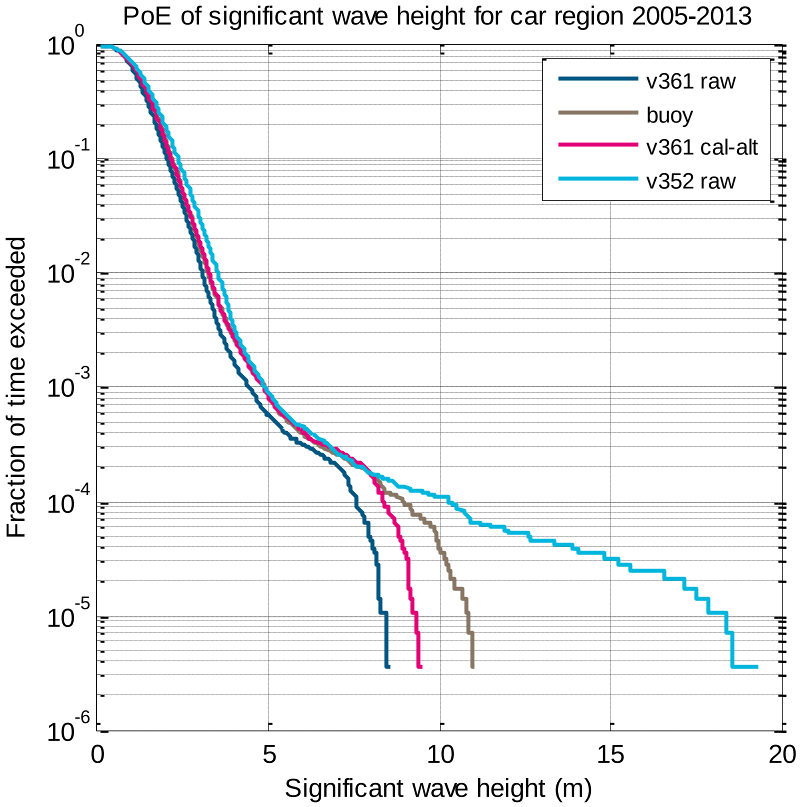


**Figure 108 PoE of global hindcast wave height and CAR buoys**

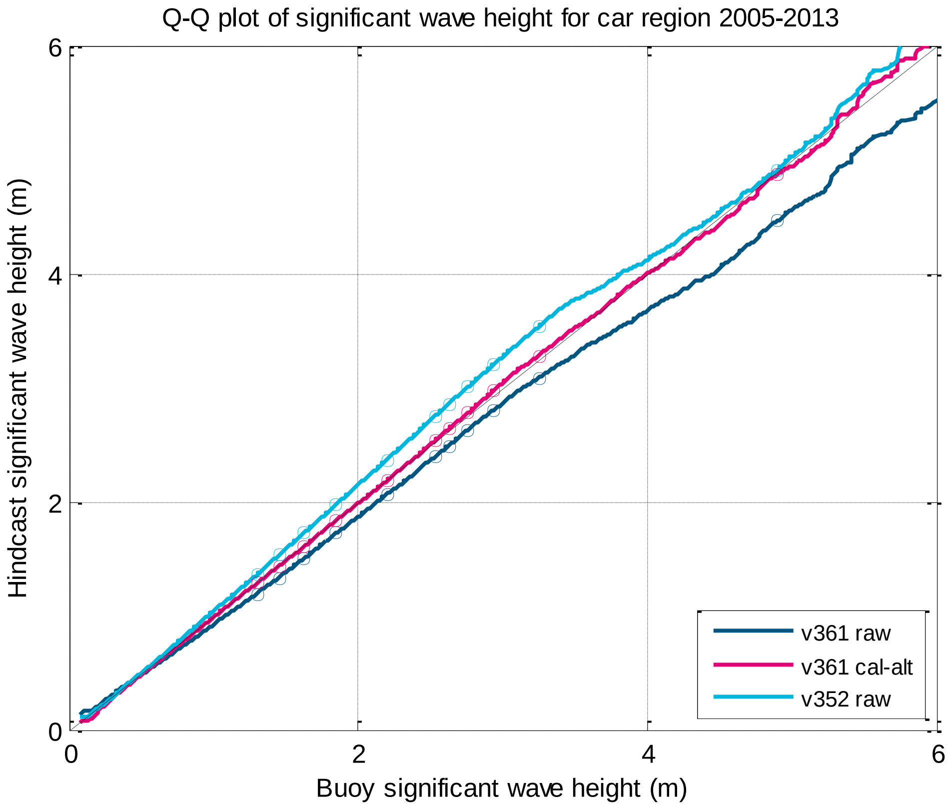


**Figure 109 Q-Q plot of global hindcast wave height against CAR buoys**

# Appendix E2 – Regional Results Extreme Climate (EU-shelf)

Per buoy region and for all buoys, higher and extreme values of the EU-shelf model wind speed and significant wave height were compared to buoy data by means of quantile-quantile (Q-Q) plots and probability of exceedance (PoE) plots. Please refer to section 4.4 for more detail.

For the NE Atlantic (EU-ATL), the probability distributions of 'best' model and buoy wind speed are provided in Figure 110 and Figure 111 holds the corresponding Q-Q plot. Similarly, distributions of model and buoy wave height are compared in Figure 112 and Figure 113. The rest of this appendix shows similar plots for the other EU-shelf regions mentioned in section 4.2.

From the wind speed distributions in this appendix it can be seen that 'best' model wind speed extremes match quite well with buoy observations for the EU-shelf, both for v361 and v352. In general, model wind speed extremes are within 10% of the buoy data. For the NE Atlantic the higher and extreme values of model wind speed exceed the buoy observations, especially v352 winds (see Figure 110 and Figure 111). In the Celtic Sea, model winds are also a bit ahead of the buoy measurements except for the uppermost tail where extreme buoy observations up to say 27 m/s are not seen in the model data (see Figure 114). In the North Sea higher values of model wind speed, in particular for v361, are a bit too low: up to about 10% (see for example Figure 128).

Apart from the very tail where models underestimate observed wave height, there is also a fair match between higher values and extremes of 'best' model wave height and buoy data for the EU-shelf regions. There is one major exception however: according to the buoys in the Channel region, higher model waves are way too high (although model and buoys do agree that maximum wave height is about 10m; see Figure 122-Figure 123). Divergence in the tail of the model and buoy wave height distributions become most apparent for the NE Atlantic (Figure 112), the Celtic Sea (Figure 116) and the northern part of the North Sea (Figure 134). In the North Sea areas, 'best' higher model waves remain roughly 10% too low, in particular v361 waves ('best' v352 waves are a bit better here). See for example Figure 126 and Figure 127.

The crucial role of altimeter-based model calibration is best seen for waves in the Irish Sea (Figure 120-Figure 121) and in the North Sea (e.g. Figure 126). As for the global model, calibration with altimeter has become even more important as un-calibrated v361 waves are clearly too low. Also note that 'best' model winds driving the wave model are about correct for the Irish Sea and the southern North Sea.

Note that in the English Channel (Figure 122-Figure 123) calibration with altimeter increases v361 wave height and decreases v352 wave height to about the same level (which is too high according to the local buoys).

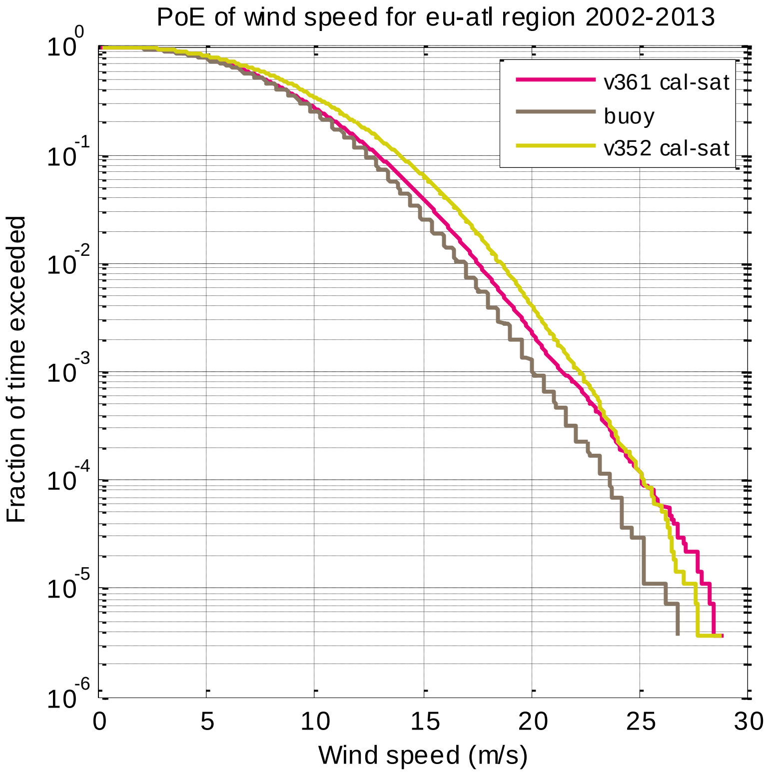


**Figure 110 PoE of EU-shelf hindcast wind speed and EU-ATL buoys**

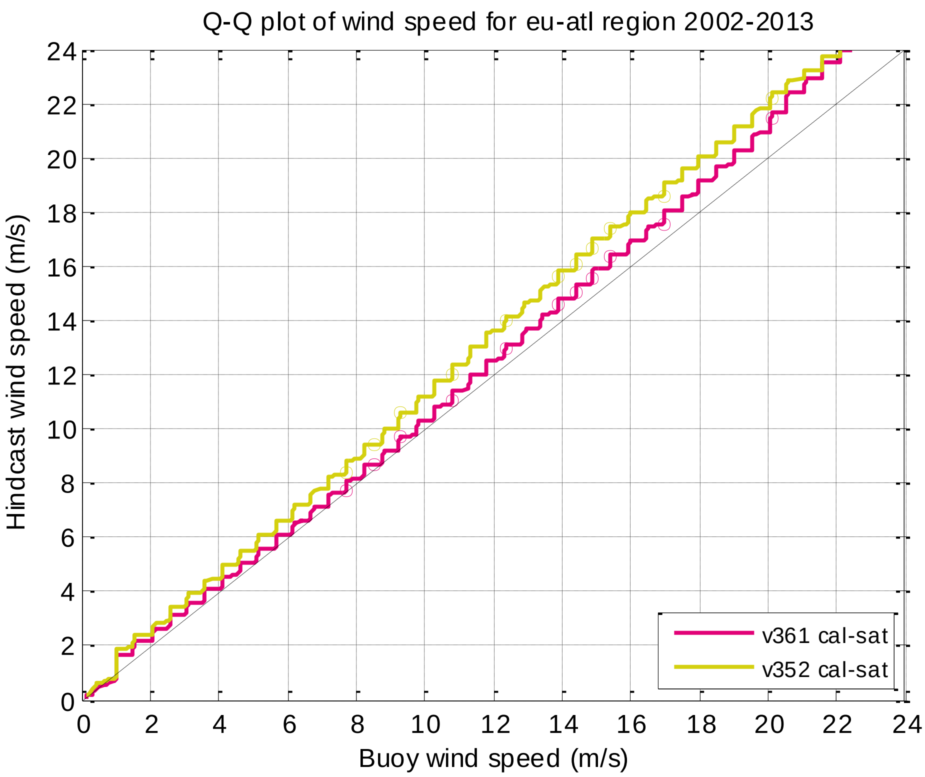


**Figure 111 Q-Q plot of EU-shelf hindcast wind speed against EU-ATL buoys**

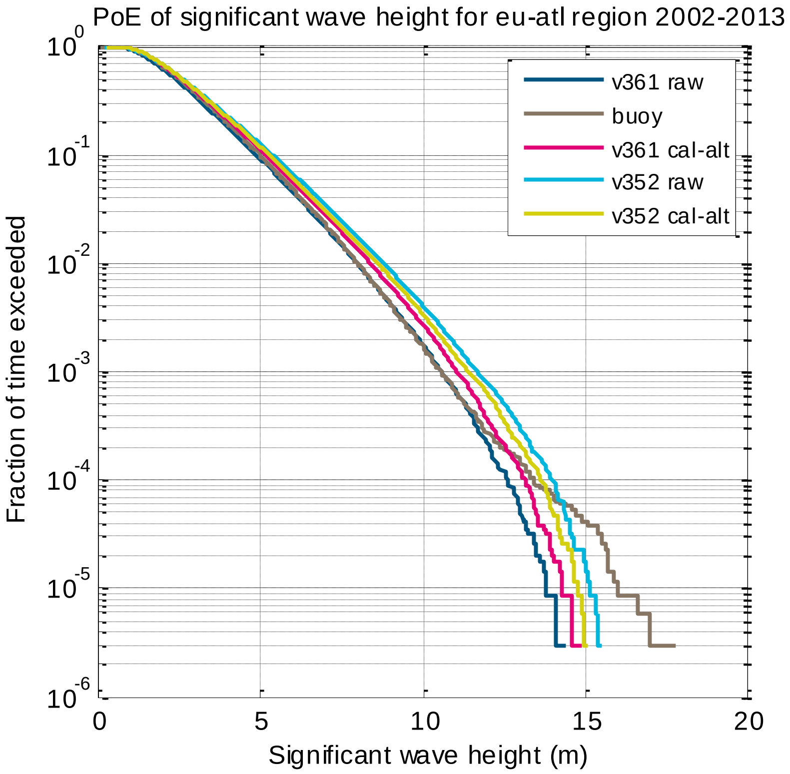


**Figure 112 PoE of EU-shelf hindcast wave height and EU-ATL buoys**

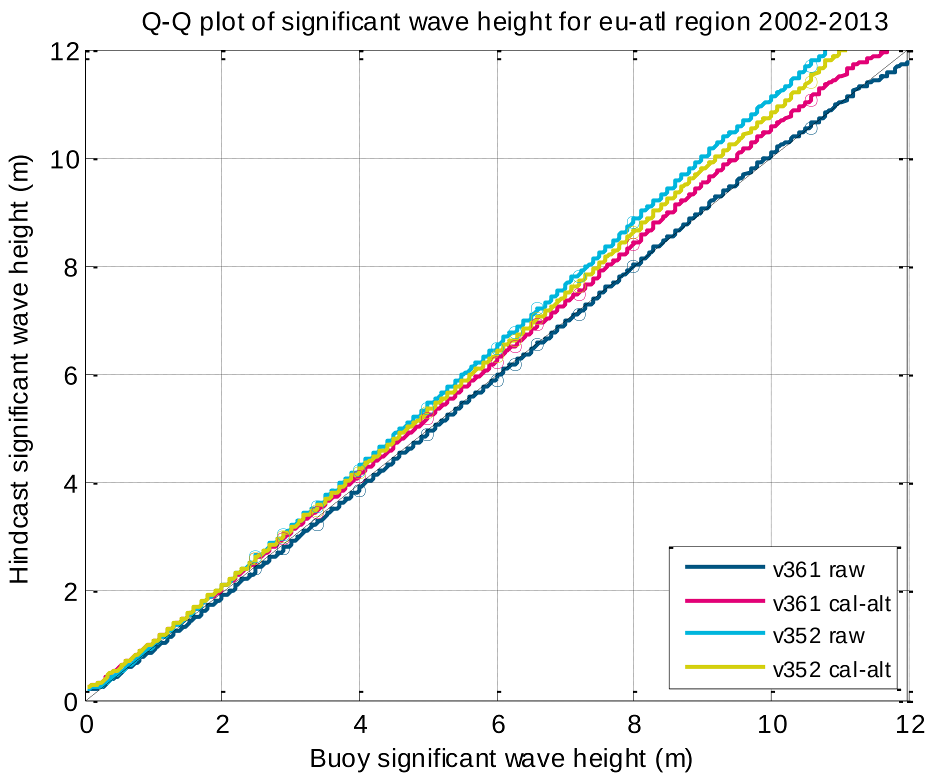


**Figure 113 Q-Q plot of EU-shelf hindcast wave height against EU-ATL buoys**

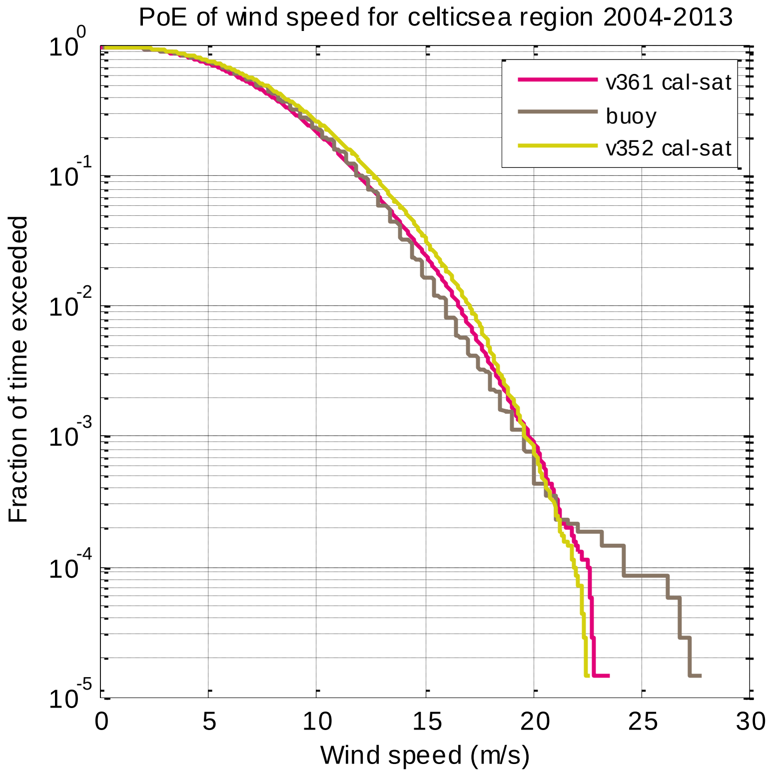


**Figure 114 PoE of EU-shelf hindcast wind speed and CELTICSEA buoys**

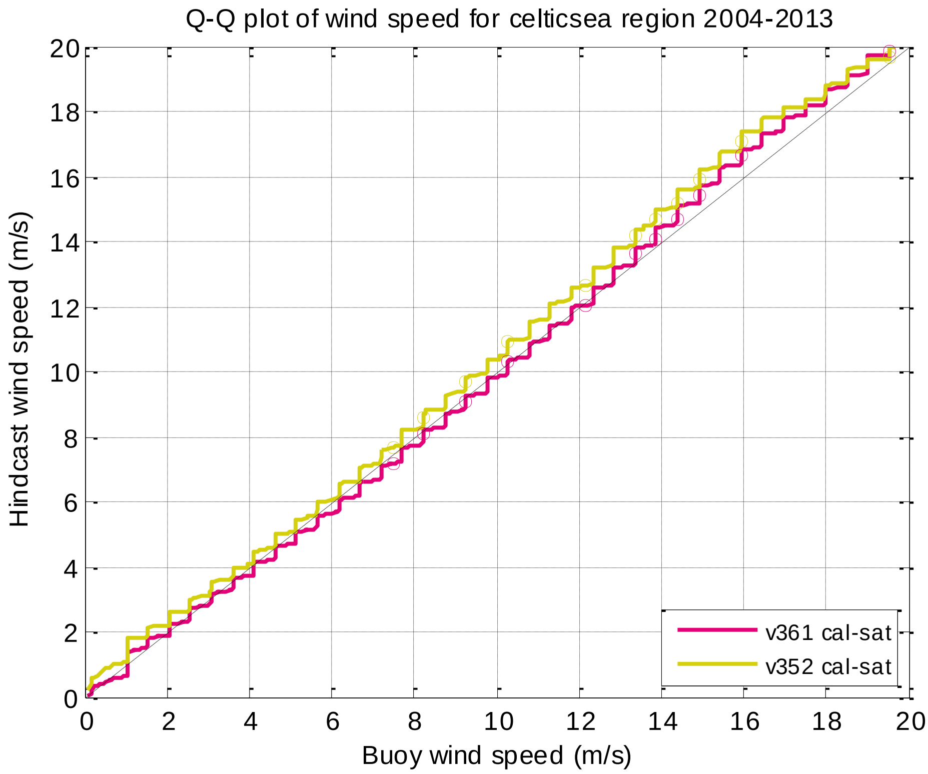


**Figure 115 Q-Q plot of EU-shelf hindcast wind speed against CELTICSEA buoys**

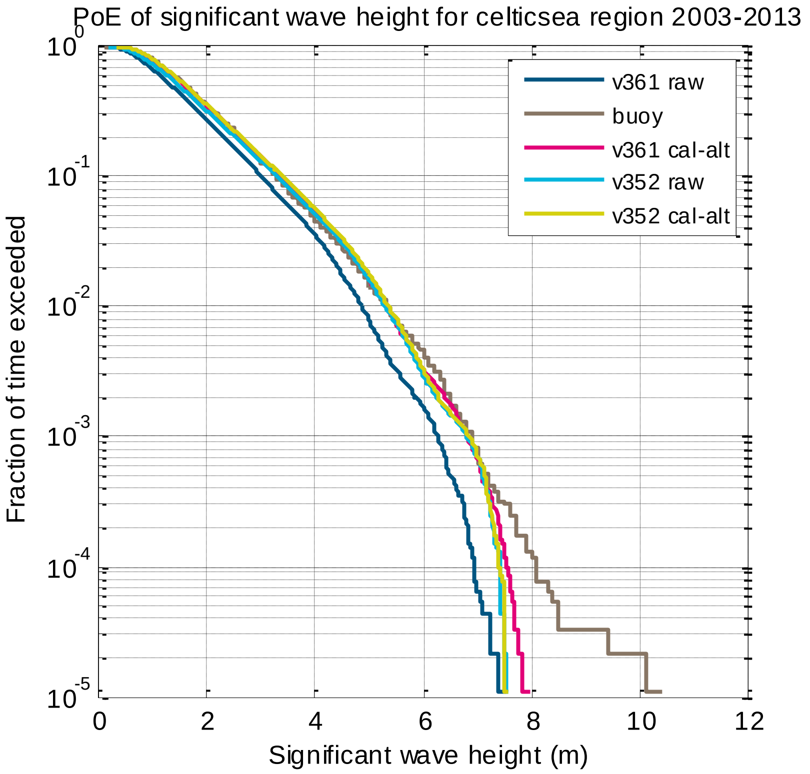


**Figure 116 PoE of EU-shelf hindcast wave height and CELTICSEA buoys**

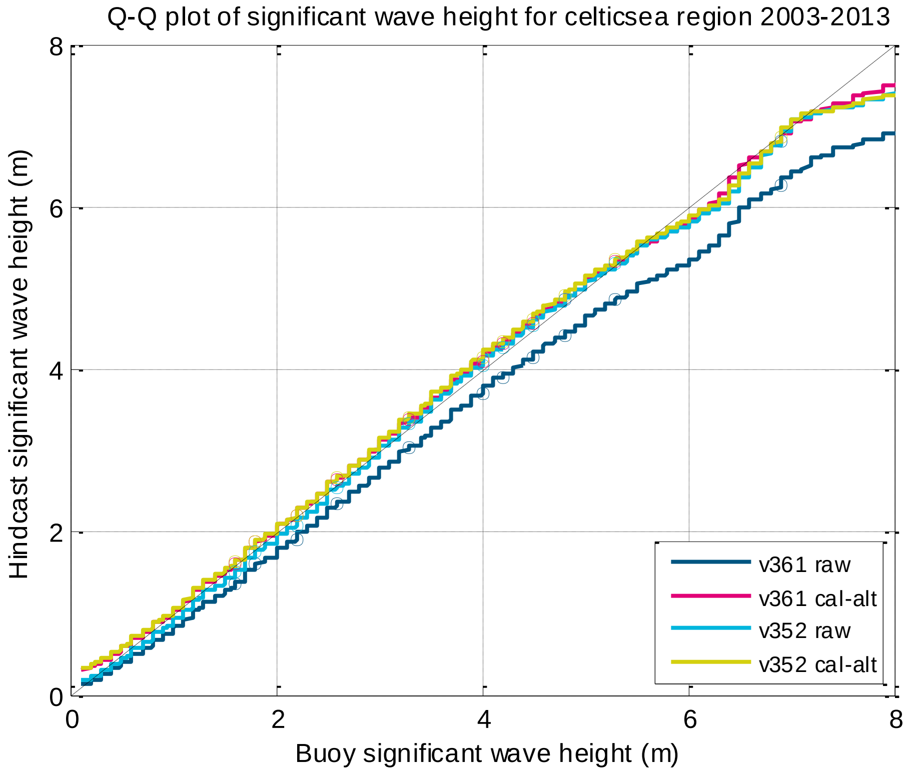


**Figure 117 Q-Q plot of EU-shelf hindcast wave height against CELTICSEA buoys**

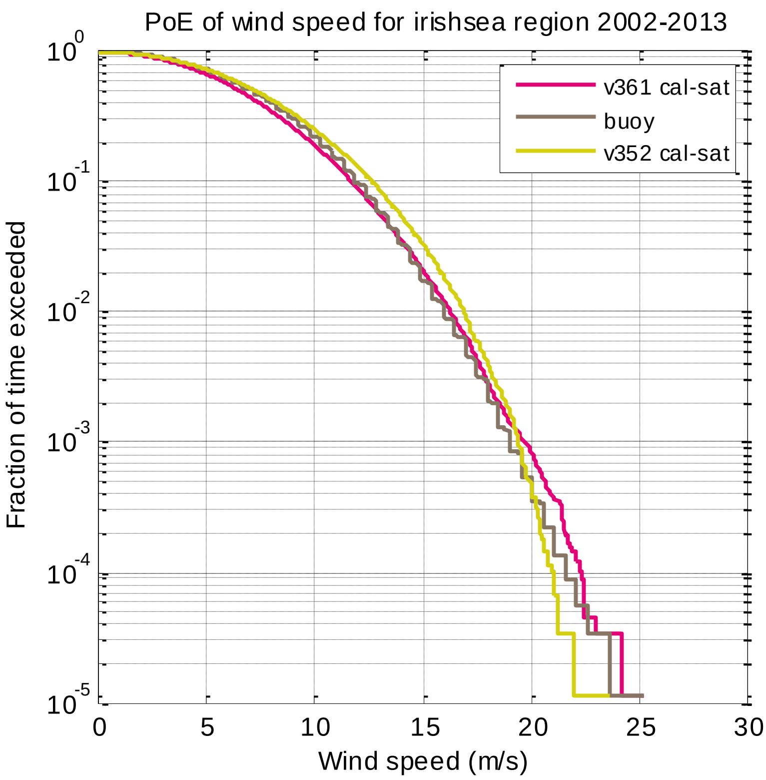


**Figure 118 PoE of EU-shelf hindcast wind speed and IRISHSEA buoy**

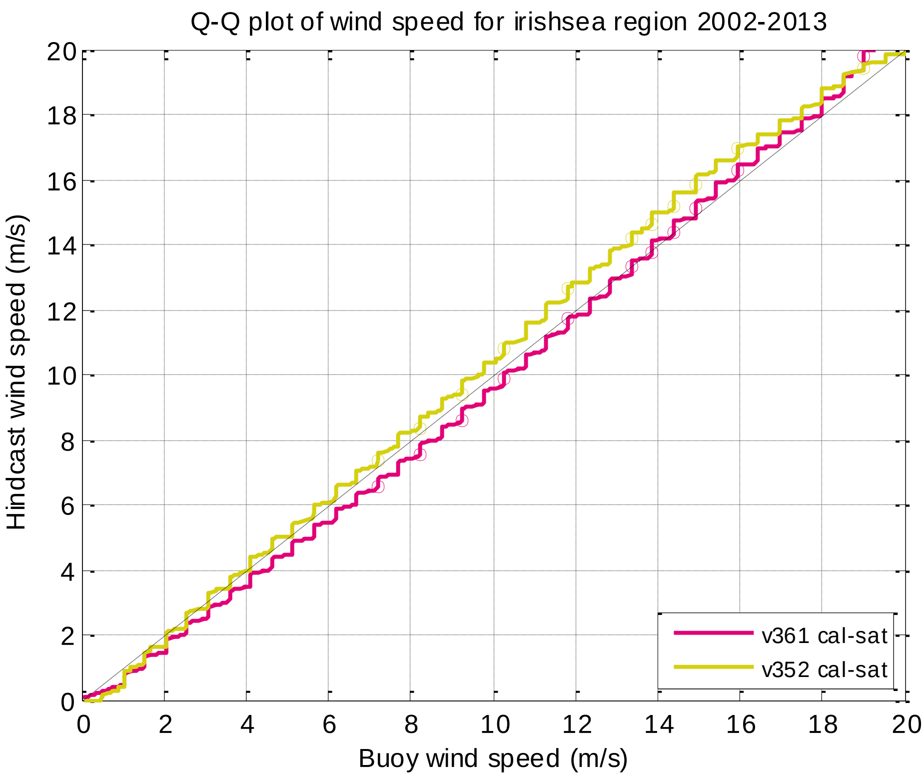


**Figure 119 Q-Q plot of EU-shelf hindcast wind speed against IRISHSEA buoy**

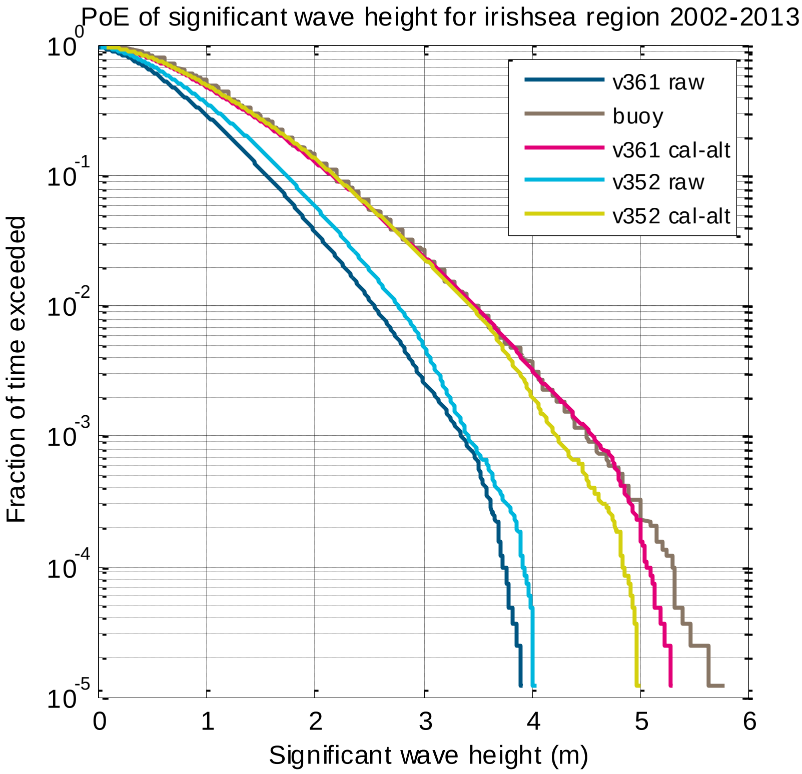


**Figure 120 PoE of EU-shelf hindcast wave height and IRISHSEA buoy**

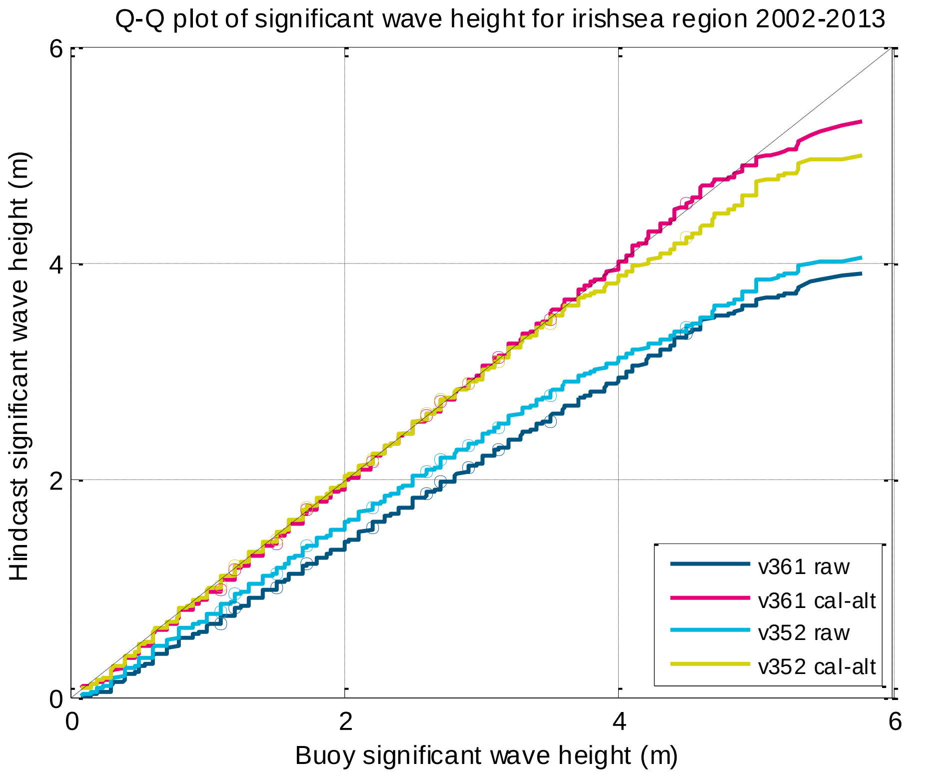


**Figure 121 Q-Q plot of EU-shelf hindcast wave height against IRISHSEA buoy**

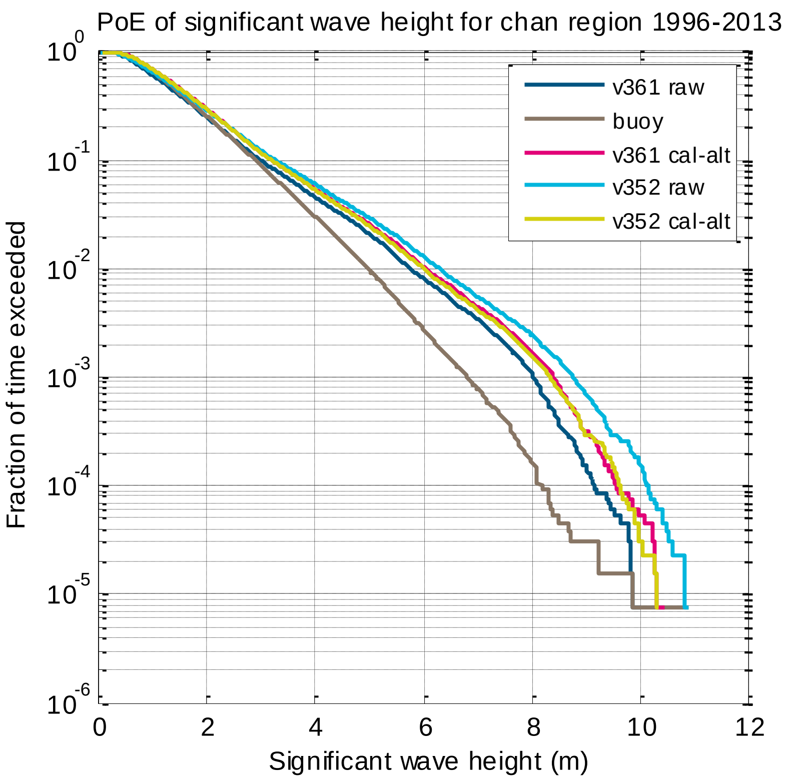


**Figure 122 PoE of EU-shelf hindcast wave height and CHAN buoys**

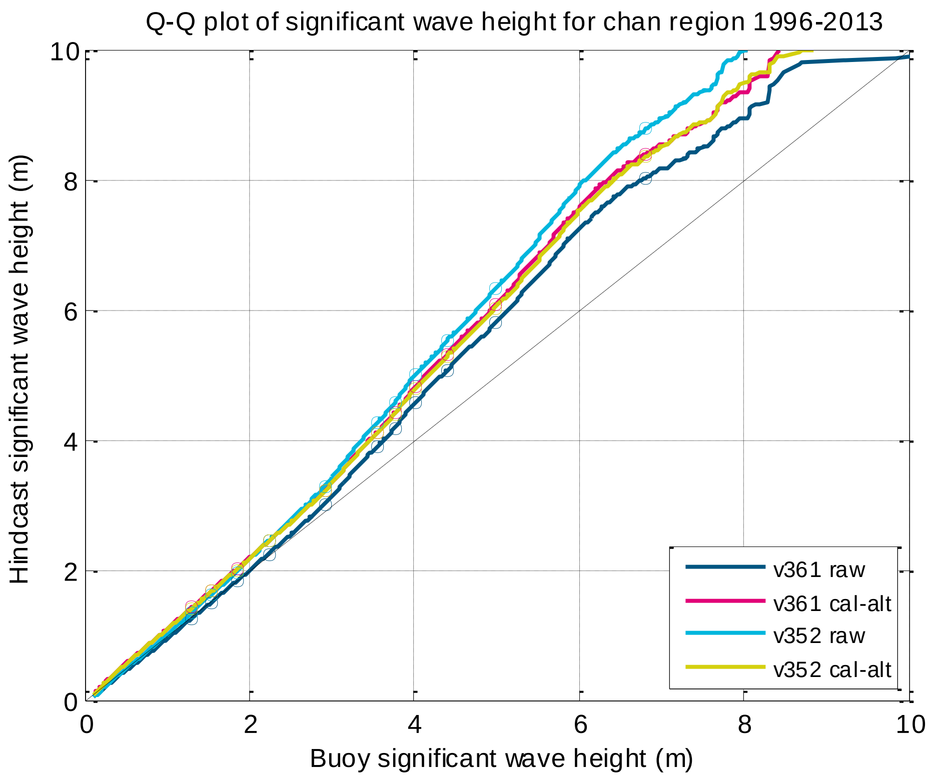


**Figure 123 Q-Q plot of EU-shelf hindcast wave height against CHAN buoys**

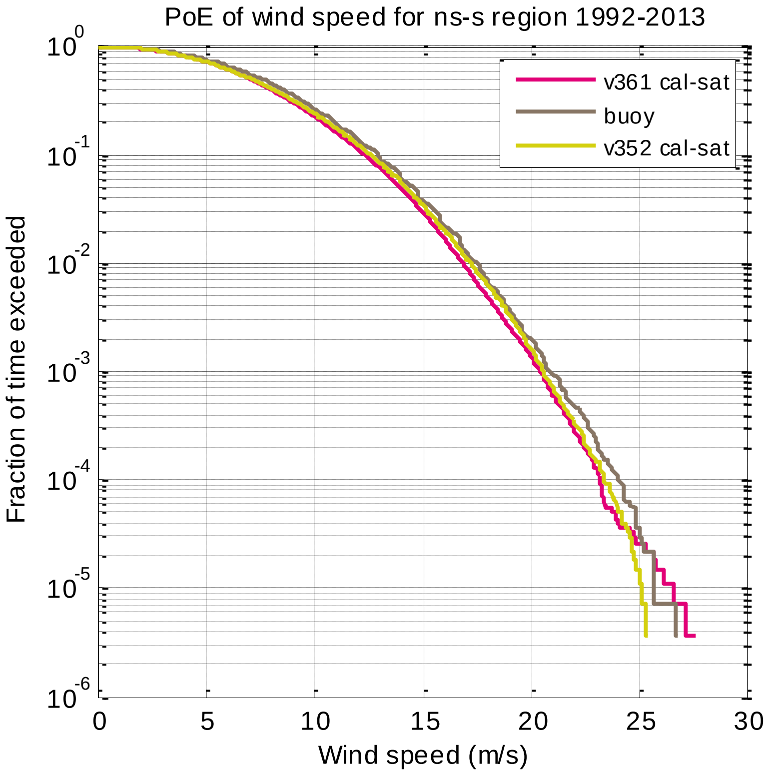


**Figure 124 PoE of EU-shelf hindcast wind speed and NS-S buoys**

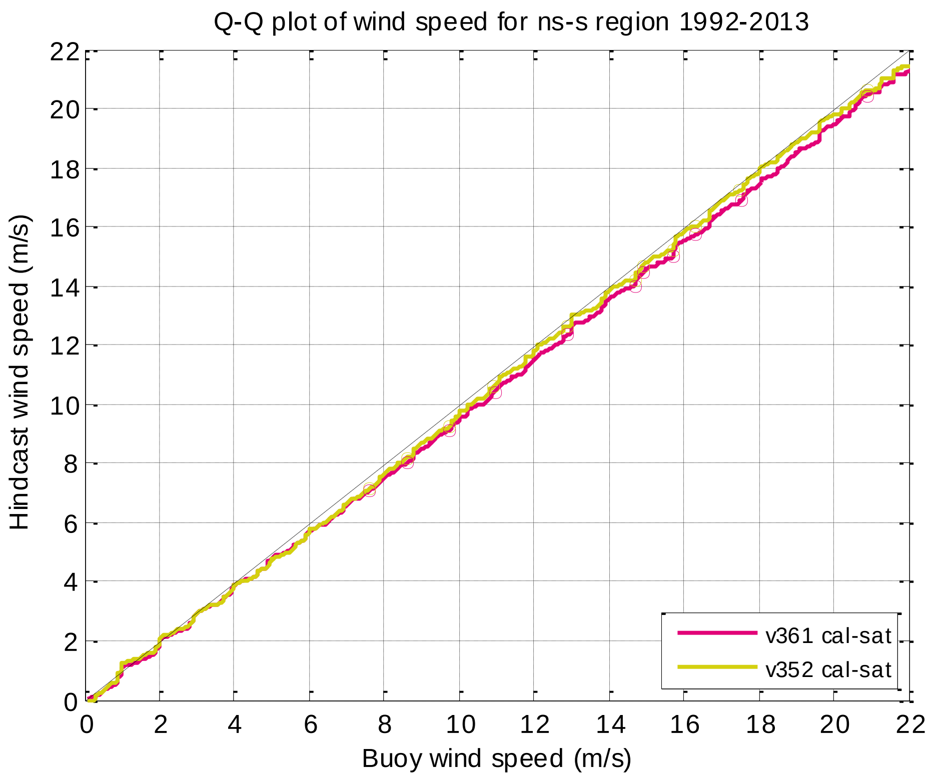


**Figure 125 Q-Q plot of EU-shelf hindcast wind speed against NS-S buoys**

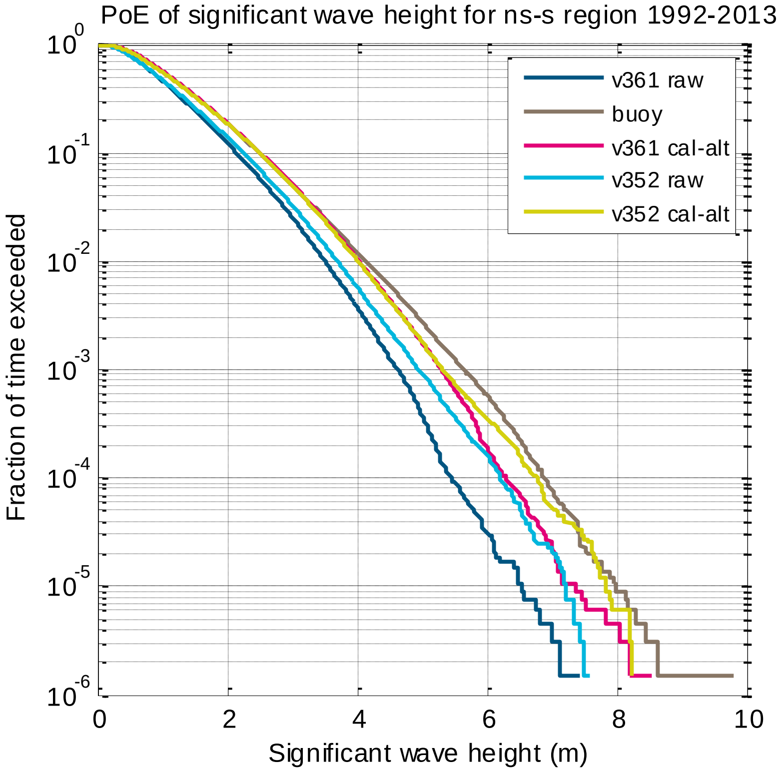


**Figure 126 PoE of EU-shelf hindcast wave height and NS-S buoys**

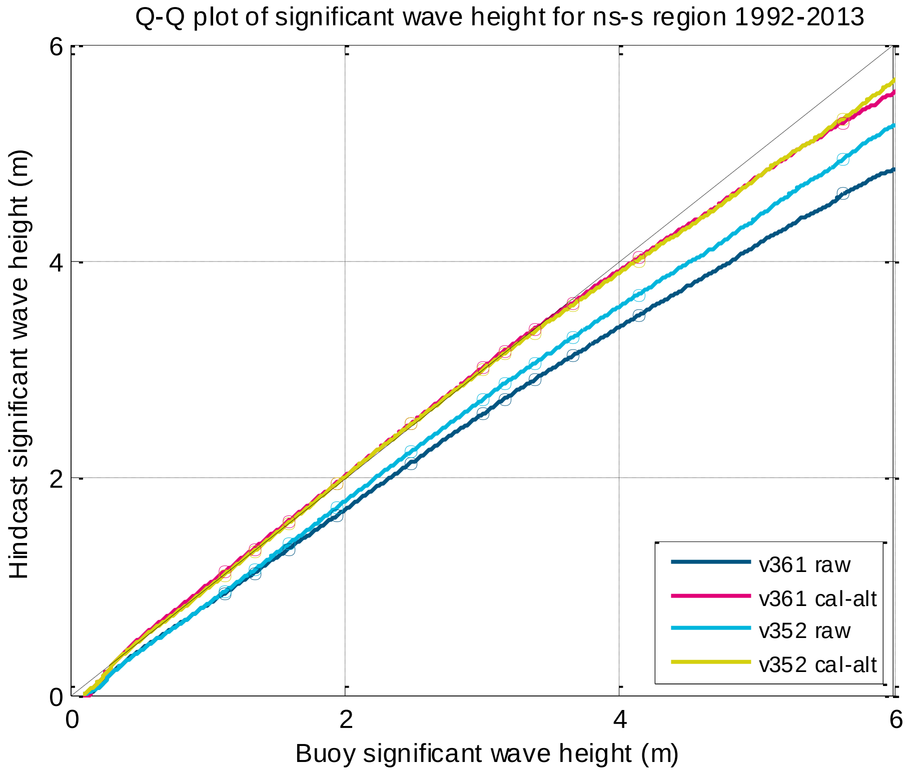


**Figure 127 Q-Q plot of EU-shelf hindcast wave height against NS-S buoys**

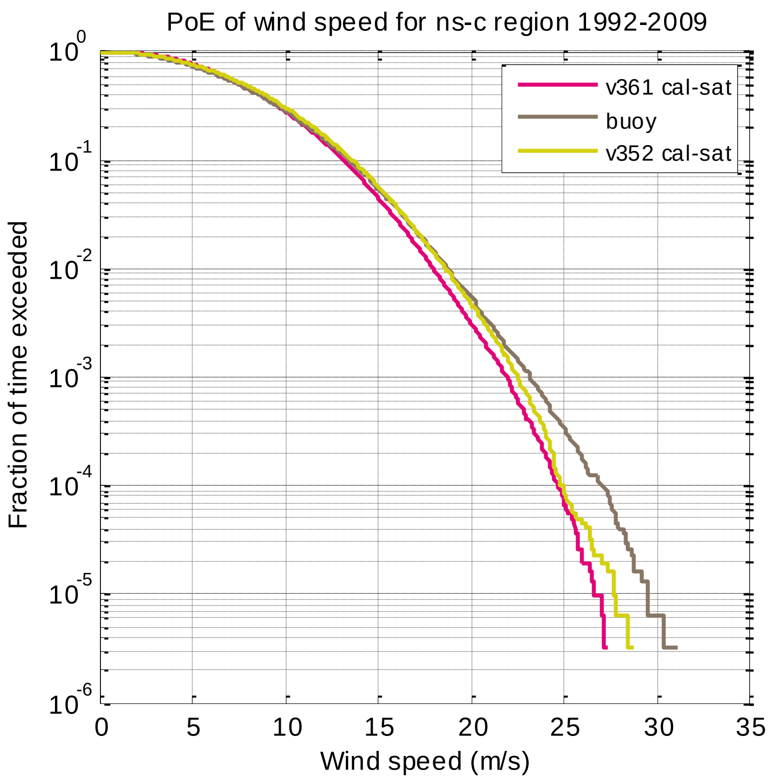


**Figure 128  PoE of EU-shelf hindcast wind speed and NS-C buoys**

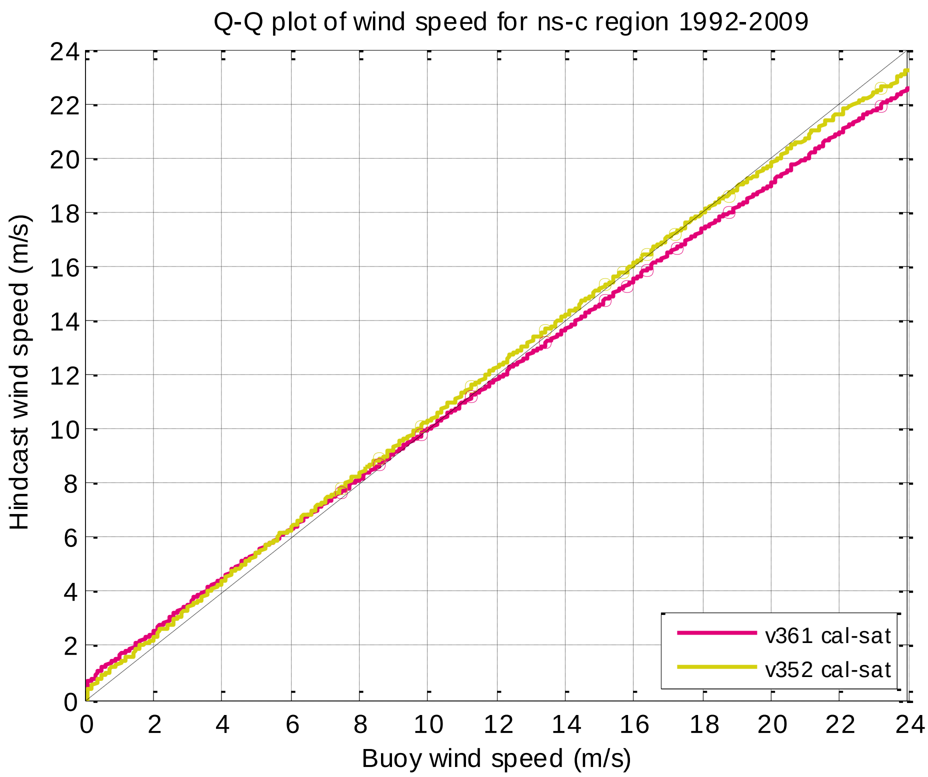


**Figure 129  Q-Q plot of EU-shelf hindcast wind speed against NS-C buoys**

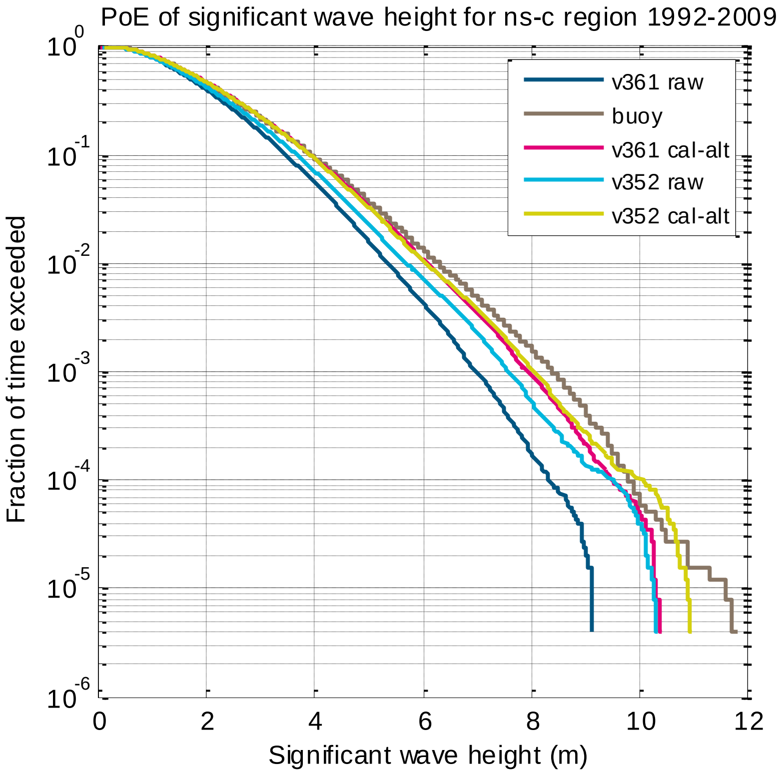


**Figure 130 PoE of EU-shelf hindcast wave height and NS-C buoys**

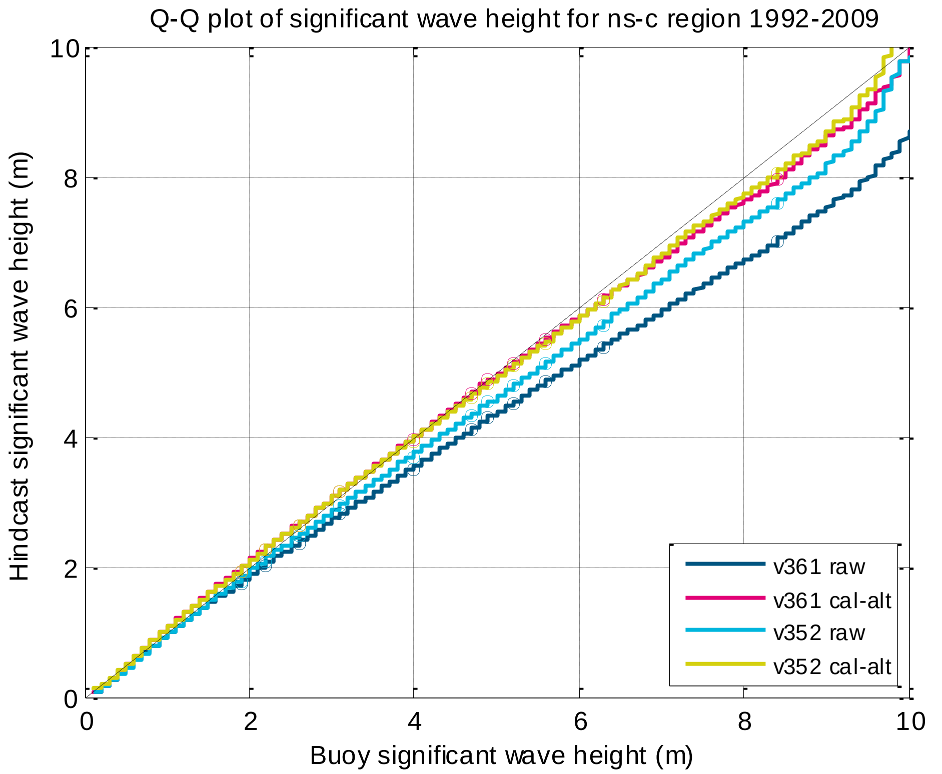


**Figure 131 Q-Q plot of EU-shelf hindcast wave height against NS-C buoys**

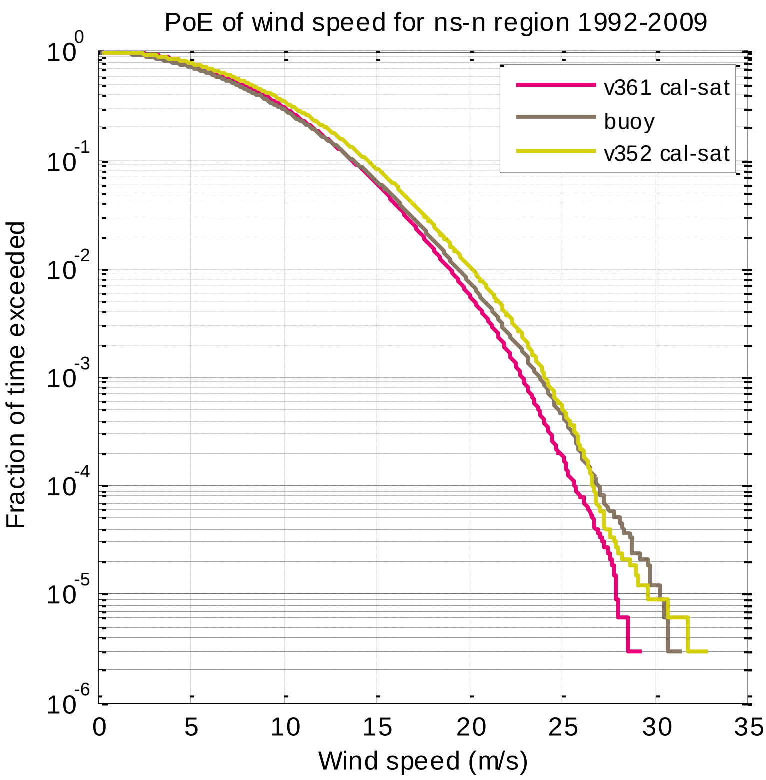


Figure 132  PoE of EU-shelf hindcast wind speed and NS-N buoys

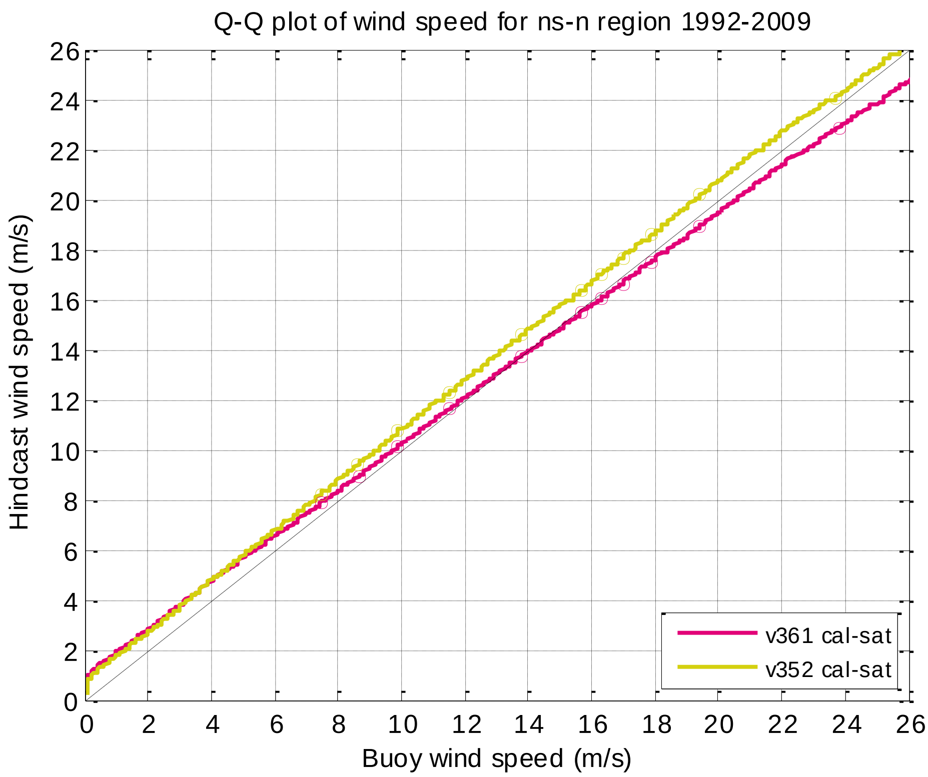


Figure 133  Q-Q plot of EU-shelf hindcast wind speed against NS-N buoys

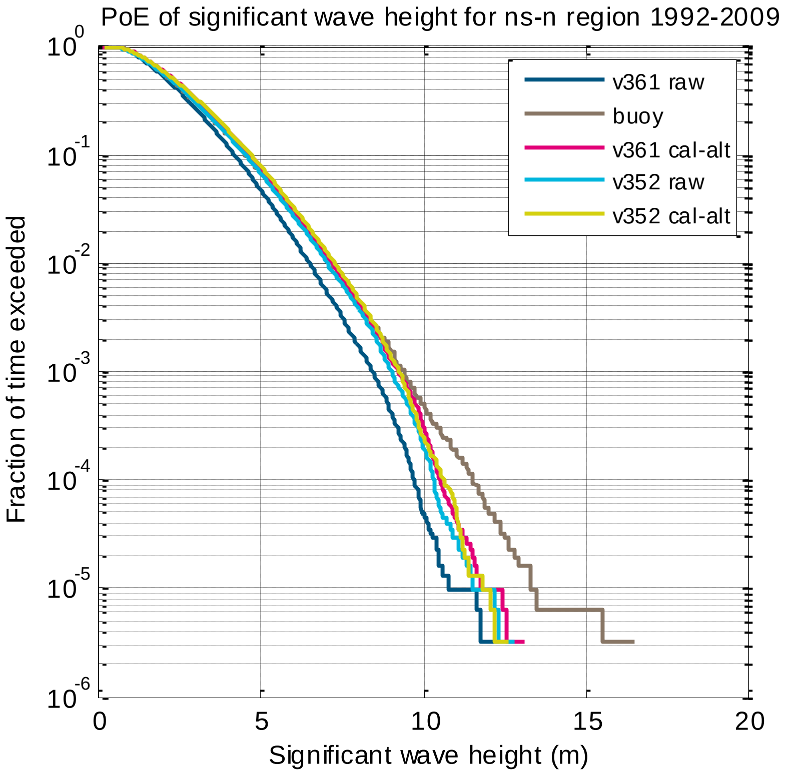


**Figure 134 PoE of EU-shelf hindcast wave height and NS-N buoys**

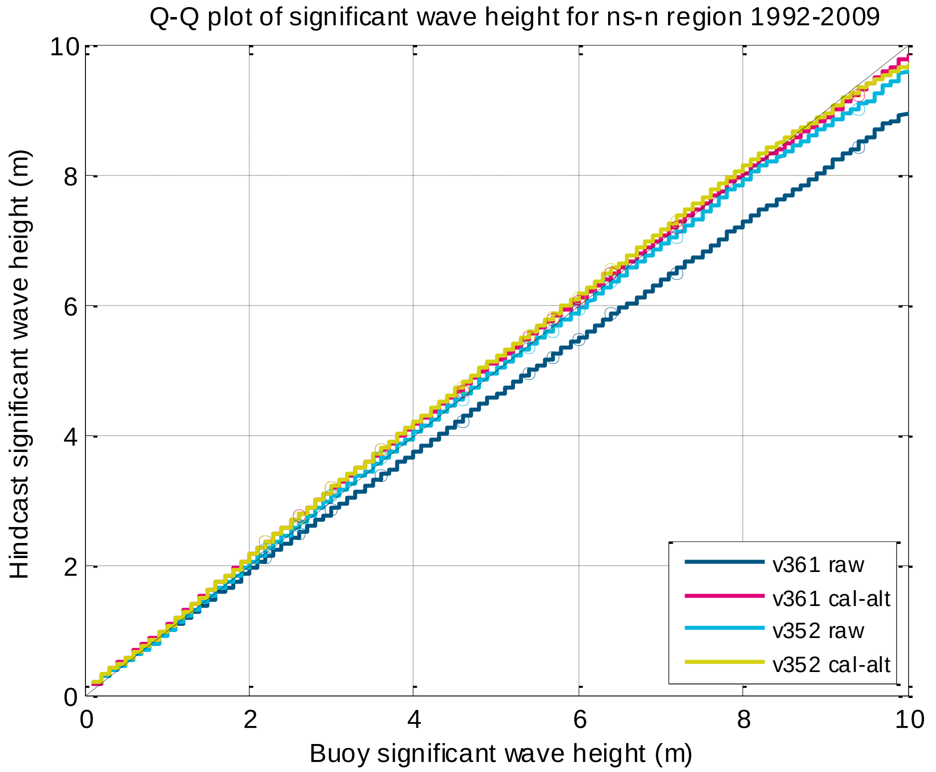


**Figure 135 Q-Q plot of EU-shelf hindcast wave height against NS-N buoys**

# Appendix F1 – Validation of Wave Periods (Global)

This appendix provides model-buoy error statistics of zero-crossing wave period and peak wave period for the global model based on the years 1992-2013. See Appendix B1 – Buoys Used for the Global Hindcast for the set of NOAA buoys. Almost all buoys provide wave period information.

The model performance is expressed in terms of bias (mean of the model error) and standard deviation of the error between co-located model data and buoy data. A negative bias means that the model values are too low in comparison to the buoy measurements.

Table 26 summarizes wave period error statistics for both global models. This table also shows the effect of satellite calibration on v361 wave periods. For 'best' v361 wave periods, results per buoy region are given in Table 27.

Table 26 and Table 27 show that

- Model wave periods are too low in comparison to buoy data
- Calibration with altimeters reduces the bias in model wave period
- v352 wave periods show less bias but they are more variable
- Model wave periods are consistently too low for all buoy regions
- 'Best' zero-crossing wave period remains 0.5-1.0 s too low; bias in peak wave period is less: about half of the bias in zero-crossing wave period.

The quality of v361 zero-crossing wave period over the years is demonstrated in Figure 136 and Figure 137, both before and after calibration with satellites. Similarly, quality of peak wave periods is seen from Figure 138 and Figure 139.

Figure 136 to Figure 139 show that the quality of model wave periods is consistent over the years. As can be expected peak wave period is much more variable than zero-crossing wave period.

| | Zero-crossing wave period Tz | | | | | Peak wave period Tp | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Model Version | Mean (s) | Bias (s) | Std (s) | Rrmse (%) | Corr (-) | Mean (s) | Bias (s) | Std (s) | Rrmse (%) | Corr (-) |
| v361 best | **5.24** | **-0.66** | **0.61** | **14.9** | **0.91** | **8.47** | **-0.29** | **2.02** | **22.0** | **0.77** |
| v352 best | | | | | | | | | | |
| v361 raw | **5.05** | **-0.86** | **0.61** | **17.3** | **0.90** | **8.20** | **-0.56** | **2.06** | **23.0** | **0.76** |
| v352 raw | **5.55** | **-0.36** | **0.67** | **12.6** | **0.89** | **8.65** | **-0.11** | **2.37** | **25.6** | **0.71** |

**Table 26: Error statistics of global hindcast wave periods relative to all buoys**

| Region | Zero-crossing wave period Tz | | | | | Peak wave period Tp | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Mean (s) | Bias (s) | Std (s) | Rrmse (%) | Corr (-) | Mean (s) | Bias (s) | Std (s) | Rrmse (%) | Corr (-) |
| GOM | 3.85 | -0.80 | 0.53 | 20.4 | 0.80 | 5.50 | -0.52 | 1.21 | 21.1 | 0.67 |
| ATL | 5.03 | -0.71 | 0.62 | 16.2 | 0.83 | 7.96 | -0.24 | 1.79 | 21.3 | 0.65 |
| NFL | | | | | | 8.68 | -0.68 | 1.74 | 19.4 | 0.66 |
| PAC | 6.19 | -0.64 | 0.68 | 13.4 | 0.88 | 10.29 | -0.21 | 2.47 | 22.7 | 0.66 |
| HAW | 6.03 | -0.51 | 0.57 | 11.5 | 0.86 | 10.25 | -0.11 | 2.45 | 22.8 | 0.62 |
| CAR | 4.27 | -0.58 | 0.49 | 15.5 | 0.79 | 6.55 | -0.16 | 1.51 | 21.9 | 0.60 |
| **ALL** | **5.24** | **-0.66** | **0.61** | **14.9** | **0.91** | **8.47** | **-0.29** | **2.02** | **22.0** | **0.77** |

**Table 27: Error statistics 'best' global v361 wave periods relative to buoys per region**

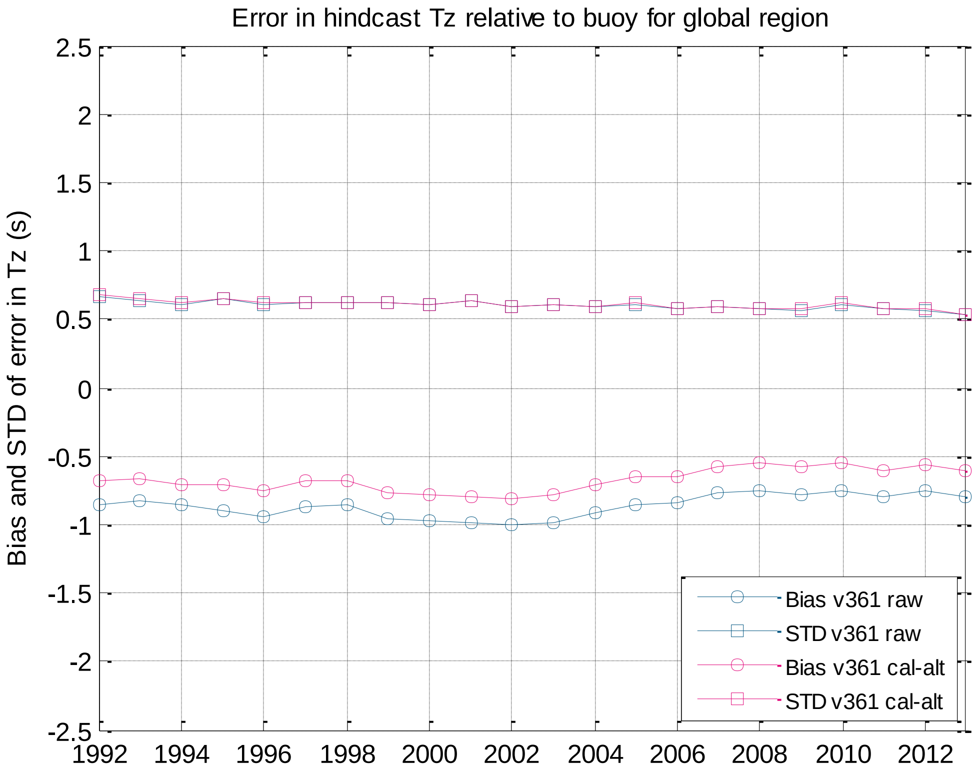


**Figure 136 Error in global v361 zero-crossing wave period against ALL buoys**

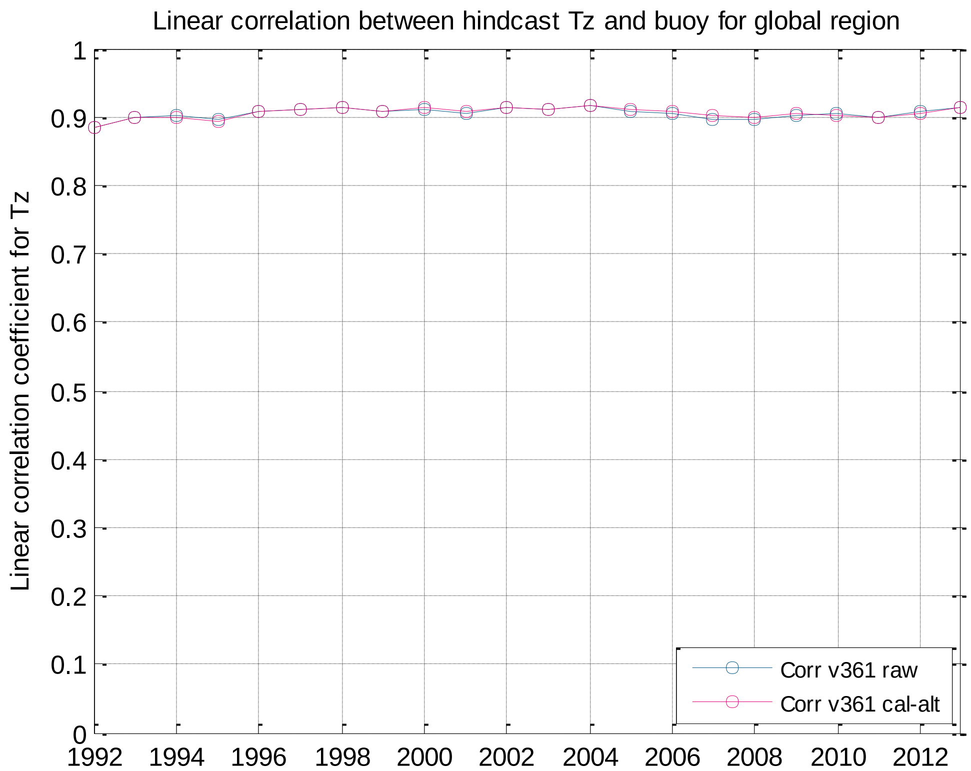


**Figure 137 Correlation global v361 zero-crossing wave period and ALL buoys**

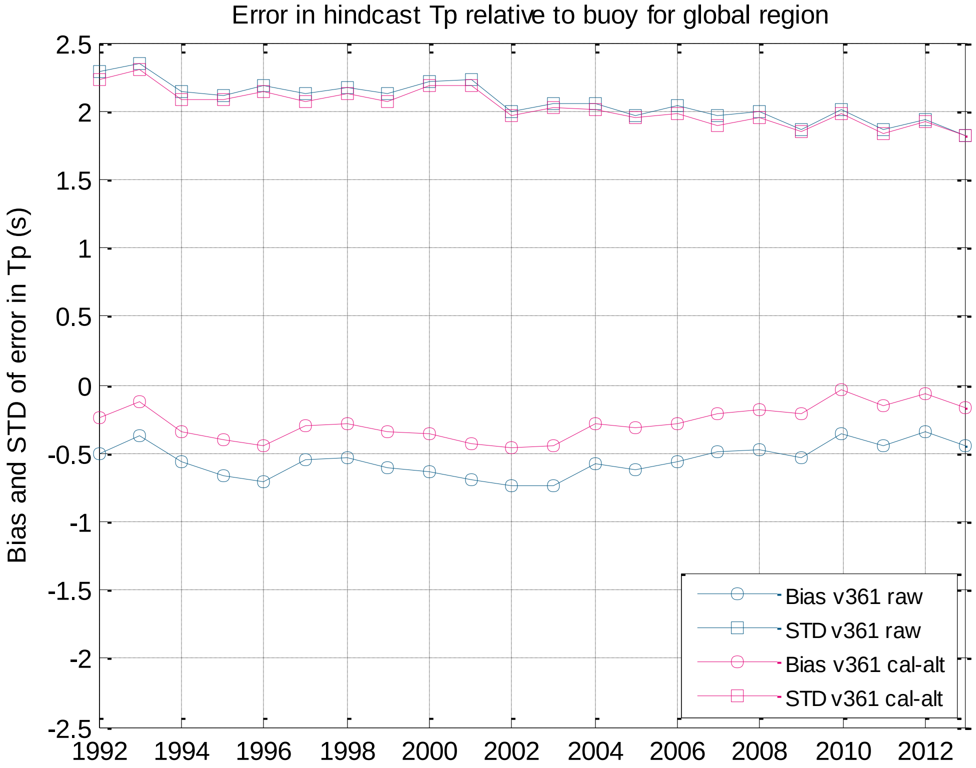


**Figure 138 Error in global v361 peak wave period against ALL buoys**

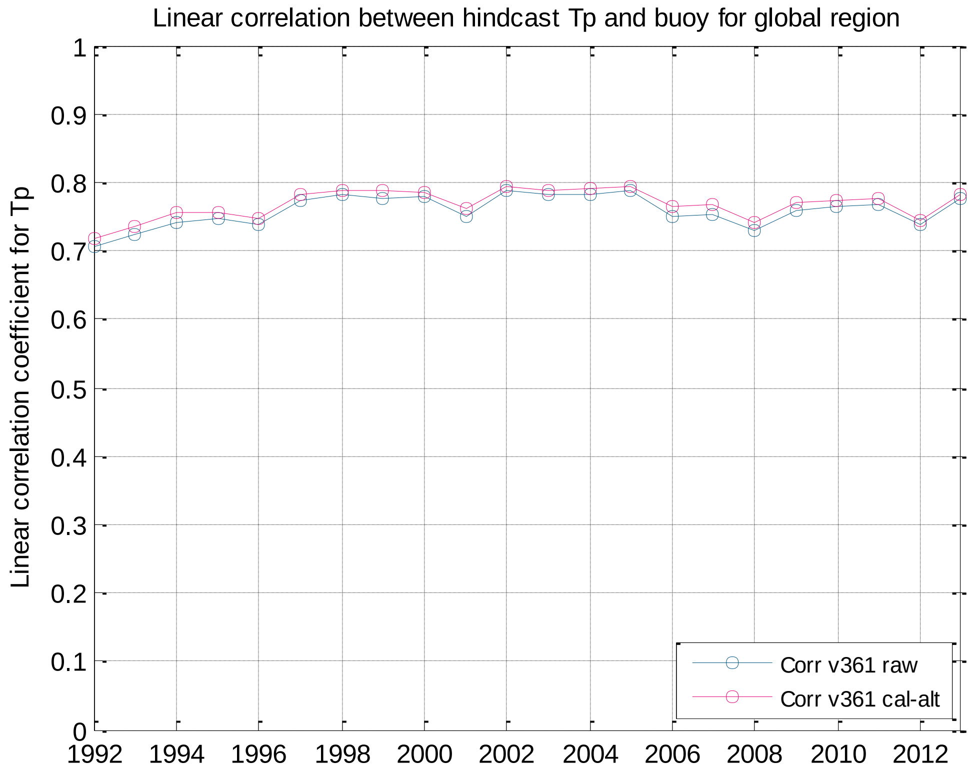


**Figure 139 Correlation global v361 peak wave period and ALL buoys**

# Appendix F2 – Validation of Wave Periods (EU-shelf)

This appendix provides model-buoy error statistics of zero-crossing wave period and peak wave period of the regional EU-shelf model based on the years 1992-2013. See Appendix B2 – Buoys Used for the EU-shelf Hindcast for the set of buoys. The majority of the buoys provide information on zero-crossing wave period. About half of the buoys reports peak wave period.

The model performance is expressed in terms of bias (mean of the model error) and standard deviation of the error between co-located model data and buoy data. A negative bias means that the model values are too low in comparison to the buoy measurements.

Table 28 summarizes wave period error statistics for both EU-shelf models. This table also shows the effect of satellite calibration on v361 wave periods. For 'best' v361 wave periods, results per buoy region are given in Table 29. 'Best' wave periods of both model versions are shown over the years in Figure 140 to Figure 143.The effect of satellite calibration on v361 wave periods over the years is demonstrated in Figure 144 to Figure 147.

Table 28 and Table 29.show that

- Model wave periods are too low in comparison to buoy data
- Calibration with altimeters reduces the bias in model wave period
- Raw v352 wave periods show less bias but they are more variable
- Model wave periods are consistently too low for all buoy regions
- Wave period buoy observations in the Irish Sea look suspicious in terms of correlation
- 'Best' zero-crossing wave period remains about 0.5s too low; bias in peak wave period is less: about half of the bias in zero-crossing wave period.

Figure 140 to Figure 143 demonstrate that the quality of 'best' wave periods of both models is consistent over the years. Bias in zero-crossing wave period varies a bit around 0.5 s; bias in peak wave period is actually quite small over the years. By nature, peak wave period is more 'jumpy' than zero-crossing wave period as reflected by higher standard deviation and less correlation.

From Figure 144 to Figure 147 it is seen that satellite calibration consistently improves the quality of hindcast wave periods over the years. Calibration removes say half of the bias in zero-crossing wave period and almost all bias in peak wave period. Note that here, as opposed to peak wave period, calibration slightly increases standard deviation of the error in zero-crossing wave period and reduces correlation with buoys.

| Model Version | Zero-crossing wave period Tz | | | | | Peak wave period Tp | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Mean (s) | Bias (s) | Std (s) | Rrmse (%) | Corr (-) | Mean (s) | Bias (s) | Std (s) | Rrmse (%) | Corr (-) |
| v361 best | 5.29 | -0.42 | 0.80 | 15.3 | 0.87 | 8.70 | -0.15 | 1.97 | 21.3 | 0.74 |
| v352 best | 5.28 | -0.43 | 0.81 | 15.5 | 0.87 | 8.69 | -0.16 | 2.02 | 21.9 | 0.73 |
| v361 raw | 4.96 | -0.75 | 0.73 | 17.7 | 0.89 | 8.24 | -0.61 | 1.93 | 21.9 | 0.74 |
| v352 raw | 5.09 | -0.62 | 0.76 | 16.6 | 0.89 | 8.47 | -0.39 | 2.00 | 22.0 | 0.73 |

**Table 28: Error statistics of wave periods of EU-shelf model relative to all buoys**

| Region | Zero-crossing wave period Tz | | | | | Peak wave period Tp | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Mean (s) | Bias (s) | Std (s) | Rrmse (%) | Corr (-) | Mean (s) | Bias (s) | Std (s) | Rrmse (%) | Corr (-) |
| EU-ATL | 6.61 | -0.36 | 0.78 | 12.0 | 0.86 | 10.64 | 0.21 | 2.19 | 20.3 | 0.67 |
| CELTICSEA | 5.37 | -0.06 | 0.83 | 15.0 | 0.80 | | | | | |
| IRISHSEA | 4.02 | -0.42 | 1.00 | 24.1 | 0.51 | | | | | |
| CHAN | 5.60 | -0.58 | 0.99 | 18.0 | 0.82 | 9.82 | 0.40 | 2.19 | 22.5 | 0.72 |
| NS-S | 4.25 | -0.33 | 0.62 | 15.1 | 0.80 | 6.65 | -0.31 | 1.89 | 26.1 | 0.66 |
| NS-C | 5.20 | -0.62 | 0.69 | 15.7 | 0.84 | 7.76 | -0.38 | 1.82 | 21.9 | 0.72 |
| NS-N | 5.91 | -0.53 | 0.94 | 16.4 | 0.76 | 9.20 | -0.28 | 1.88 | 19.4 | 0.71 |
| **ALL** | **5.29** | **-0.42** | **0.80** | **15.3** | **0.87** | **8.70** | **-0.15** | **1.97** | **21.3** | **0.74** |

**Table 29: Error statistics ‘best’ wave periods EU-shelf v361 relative to buoys per region**

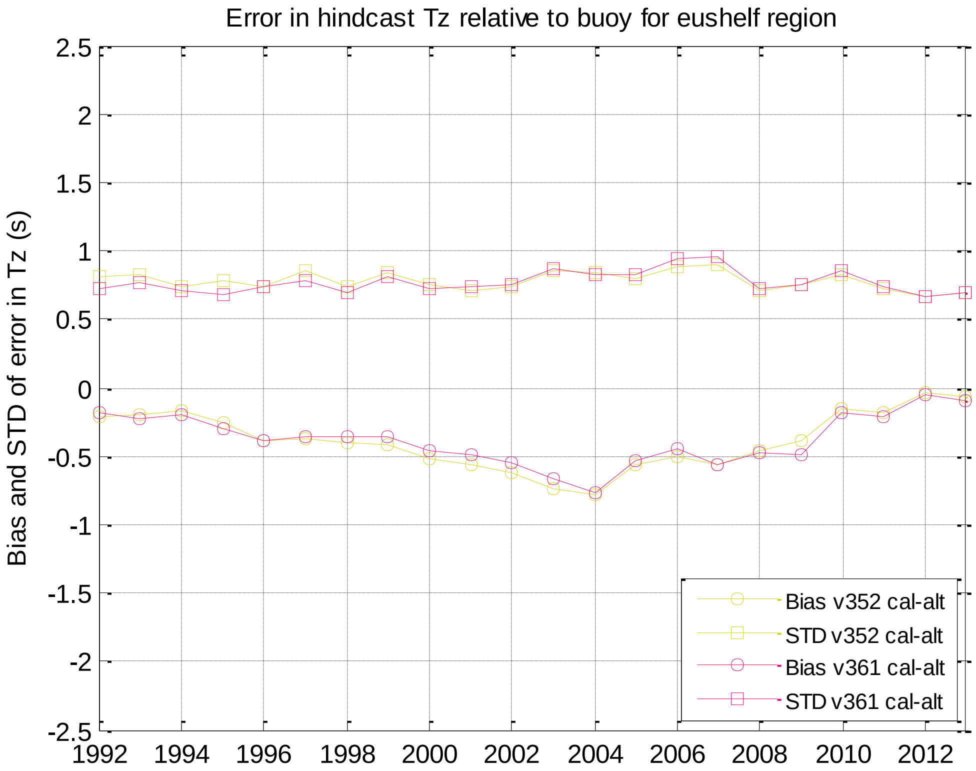


**Figure 140  Error in zero-crossing wave period EU-shelf model against ALL buoys**

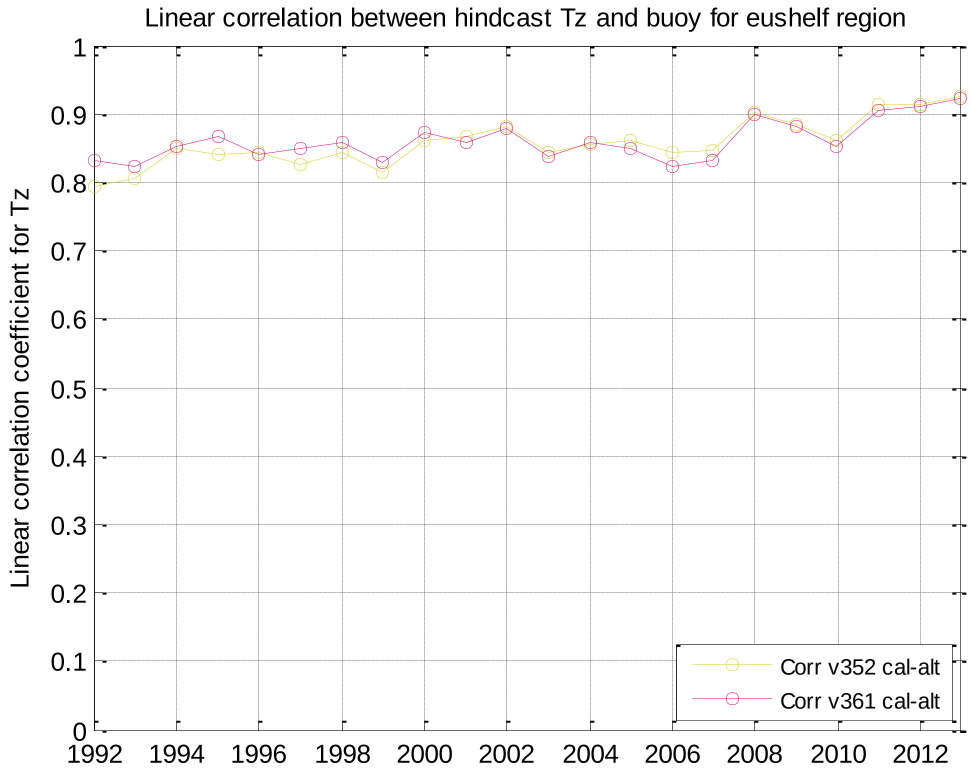


**Figure 141  Correlation zero-crossing wave period EU-shelf model and ALL buoys**

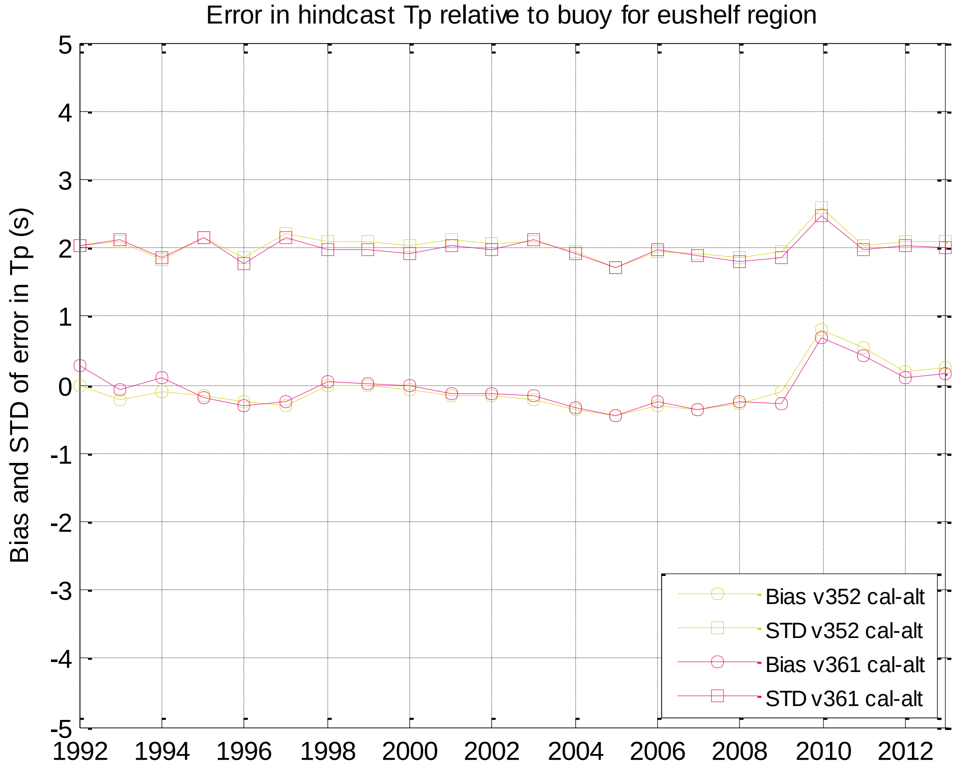


**Figure 142 Error in peak wave period EU-shelf model against ALL buoys**

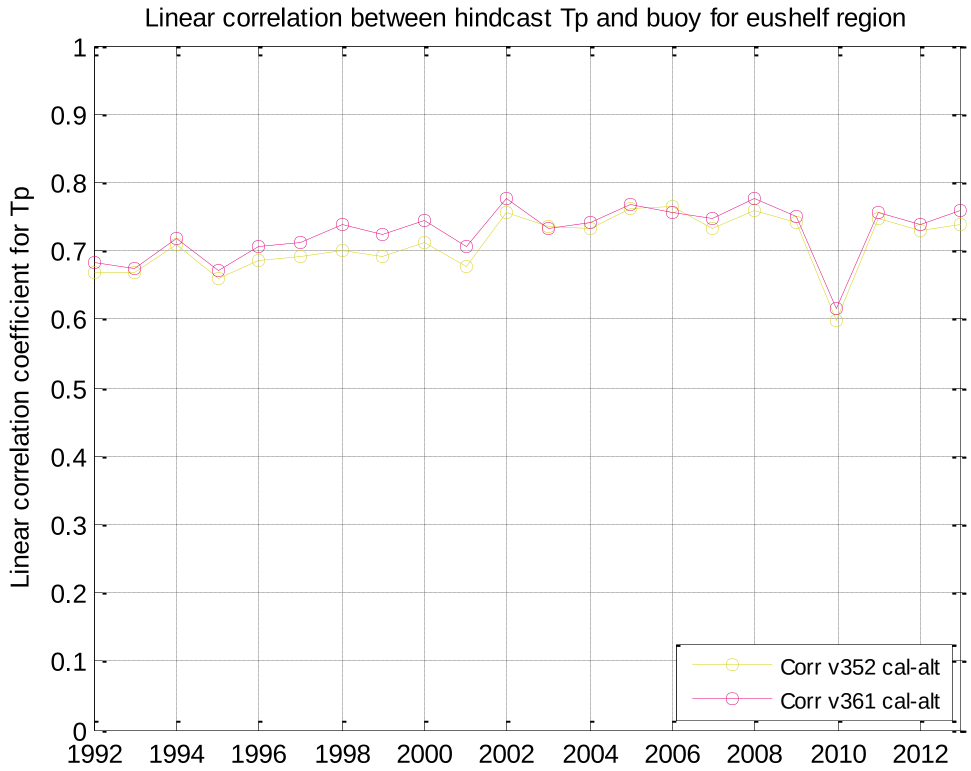


**Figure 143 Correlation peak wave period EU-shelf model and ALL buoys**

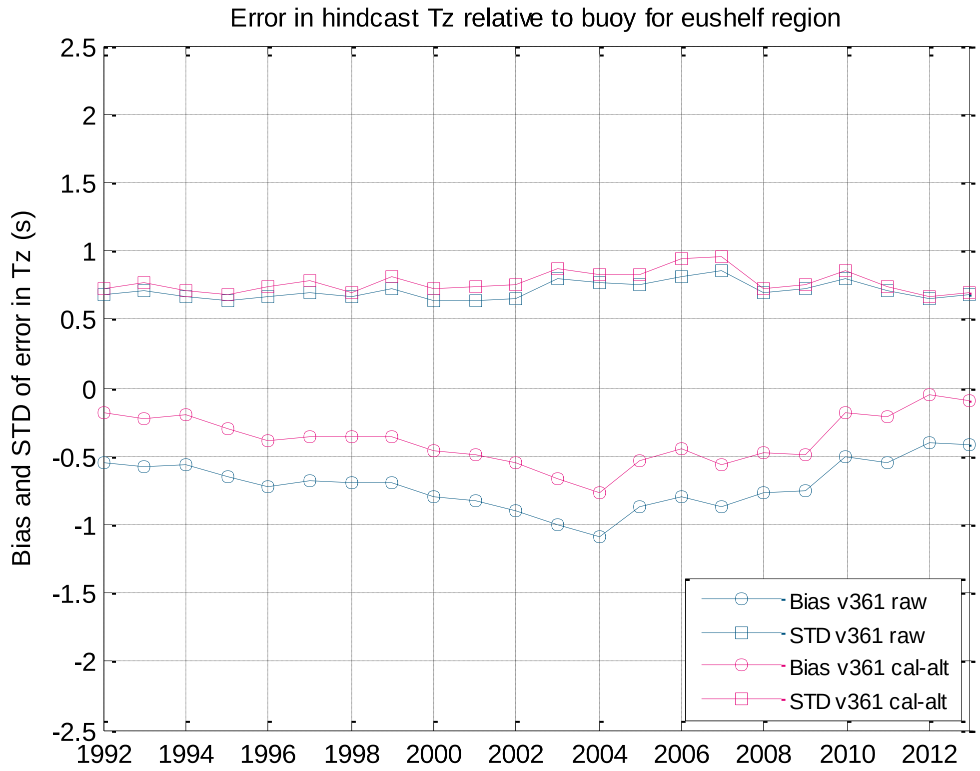


**Figure 144 Error in zero-crossing wave period EU-shelf v361 against ALL buoys**

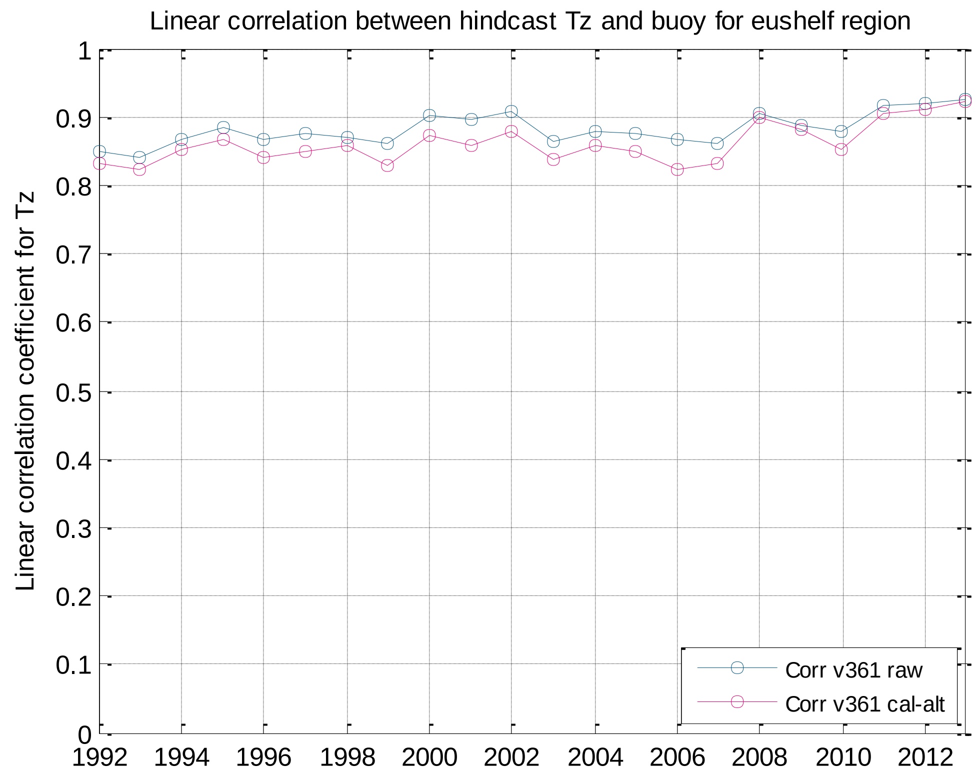


**Figure 145 Correlation zero-crossing wave period EU-shelf v361 and ALL buoys**

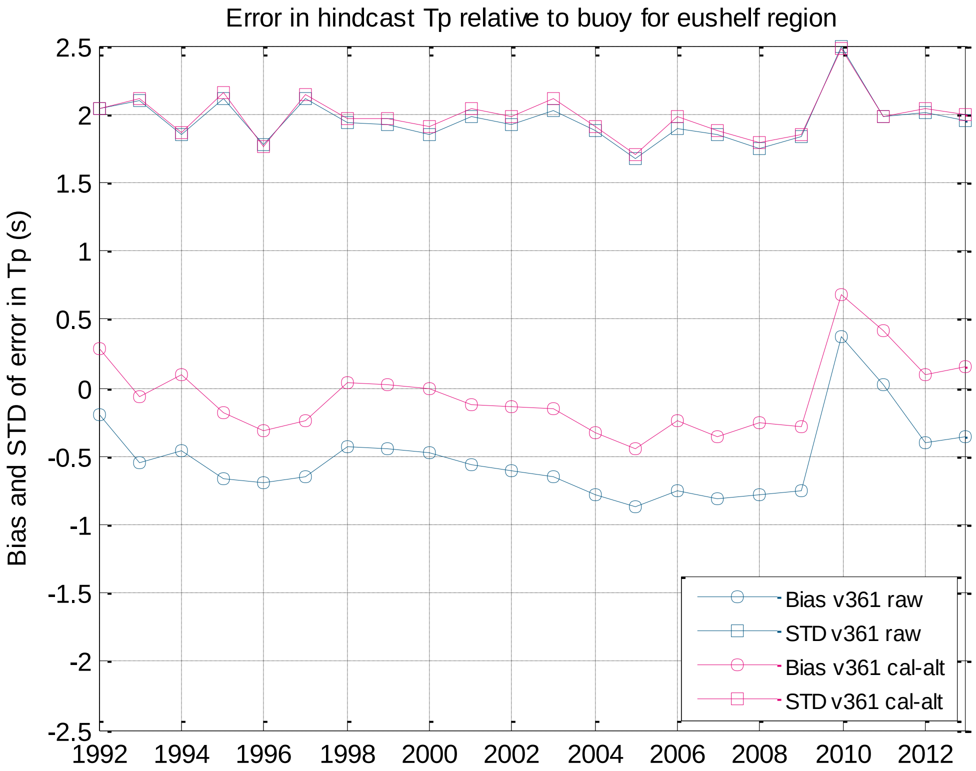


**Figure 146 Error in peak wave period EU-shelf v361 against ALL buoys**

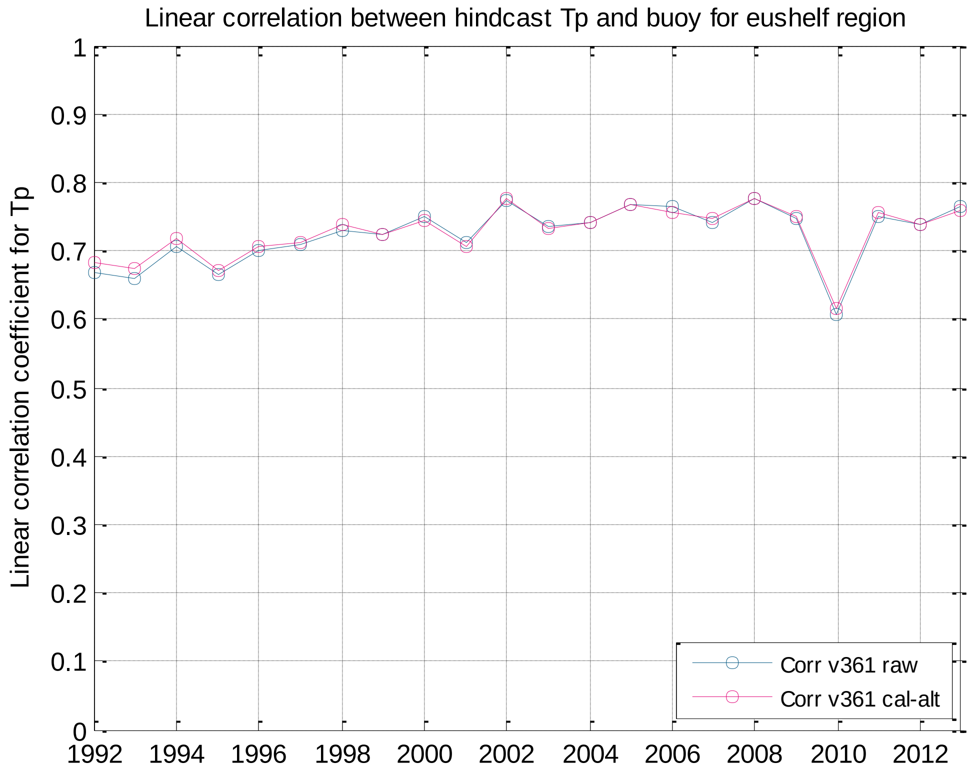


**Figure 147 Correlation peak wave period EU-shelf v361 and ALL buoys**

# Appendix G – Validation of Wave Directions (EU-shelf)

In this appendix wave directions of the regional EU-shelf wave model are validated against buoy observations over the years 1992-2013. Wave directions are observed by a subset (18) of the buoys used for validation of the regional model (the subset is marked by a cross under 'Directions' in Table 22 in Appendix B2 – Buoys Used for the EU-shelf Hindcast). All buoy regions are represented. Calibration with satellites leaves wave directions practically unchanged, hence un-calibrated model data is presented in this appendix.

The model performance is expressed in terms of bias in mean wave direction. Directions are nautical, i.e. 0° means waves come from the North and 90° means waves come from the East. A negative bias means that mean model wave direction can be found in anti-clockwise direction relative to the mean direction observed by the buoys. When computing the mean wave direction, directions are weighed by means of associated wave height.

Table 30 on the next page lists the error in mean wave direction of the EU-shelf model per buoy region. In Figure 148, bias in mean model wave direction based on all (18) buoys is plotted over the years.

From Table 30 and Figure 148 it is seen that

- Average model wave direction is less than say 10° off target for all buoy regions except for the central North Sea were deviation is about 25°.
- Bias in model wave direction relative to all buoys is less than 10° for all years
- Both models v361 and v352 perform equally well in terms of wave directions

| Region | Un-calibrated mean wave direction Hsd v361 | | | | | Un-calibrated mean wave direction Hsd v352 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Mean (°) | Bias (°) | Std (°) | Rrmse (%) | Corr (-) | Mean (°) | Bias (°) | Std (°) | Rrmse (%) | Corr (-) |
| EU-ATL | 275 | -7 | | | | 276 | -6 | | | |
| CELTICSEA | 231 | 6 | | | | 232 | 7 | | | |
| IRISHSEA | 204 | 5 | | | | 206 | 8 | | | |
| CHAN | 293 | -2 | | | | 293 | -2 | | | |
| NS-S | 293 | -2 | | | | 294 | -1 | | | |
| NS-C | 282 | 25 | | | | 285 | 28 | | | |
| NS-N | 277 | 11 | | | | 274 | 7 | | | |
| **ALL** | 284 | 0 | | | | 284 | 0 | | | |

**Table 30: Error statistics wave direction EU-shelf model relative to buoys per region**

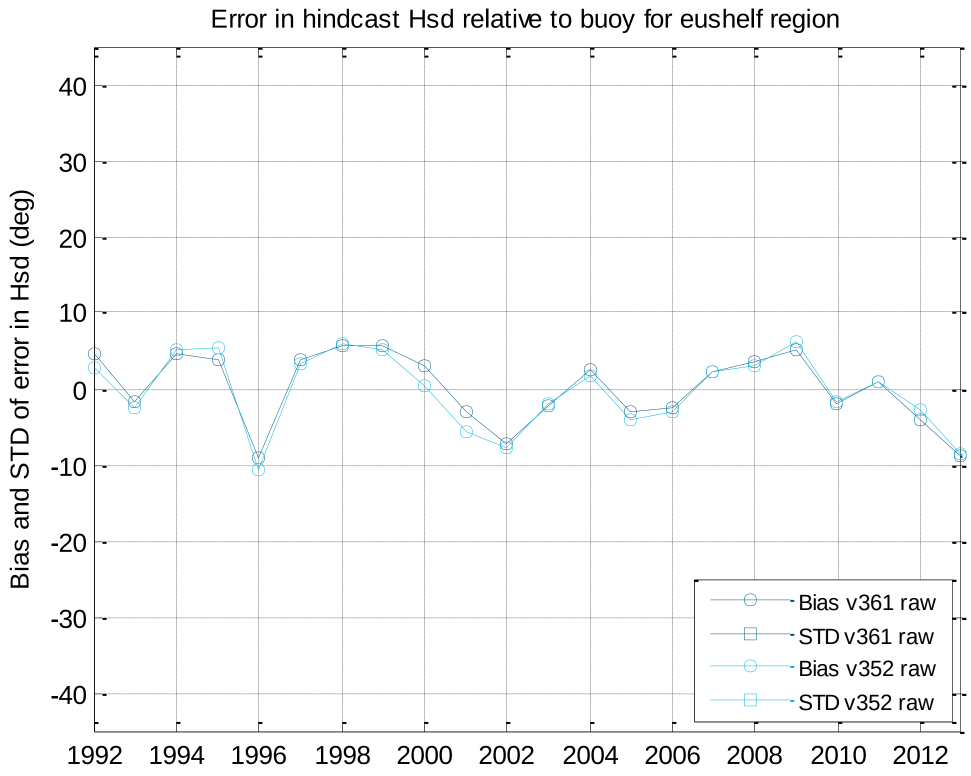


**Figure 148 Error in mean wave direction of the EU-shelf model relative to ALL buoys**

# Appendix H – Comparison of Satellites and Regional Models

On the next pages, spatial plots of model-satellite bias and correlation for significant wave height are provided for the v361 model for the following regional grids:

- Mediterranean
- NW Australia
- Indonesia
- Thailand

'Best' model waves were obtained by automated calibration with satellites, carried out per grid point and based on the years 1992-2011 (also see section 4.1).

The figures on the next pages show that calibration indeed removes most of the bias between model and satellites for all regional grids.

Again, it is seen that the model corrections in areas with long fetch and swell waves, for example in the southern parts of the Mediterranean or in the Indian Ocean south of Indonesia, differ from corrections in areas with relatively short fetch and wind-sea waves, for example the northern Mediterranean, Indonesian waters and off northwest Australia. In general, the model is a bit high in swell areas and too low in fetch-limited wind-sea areas.

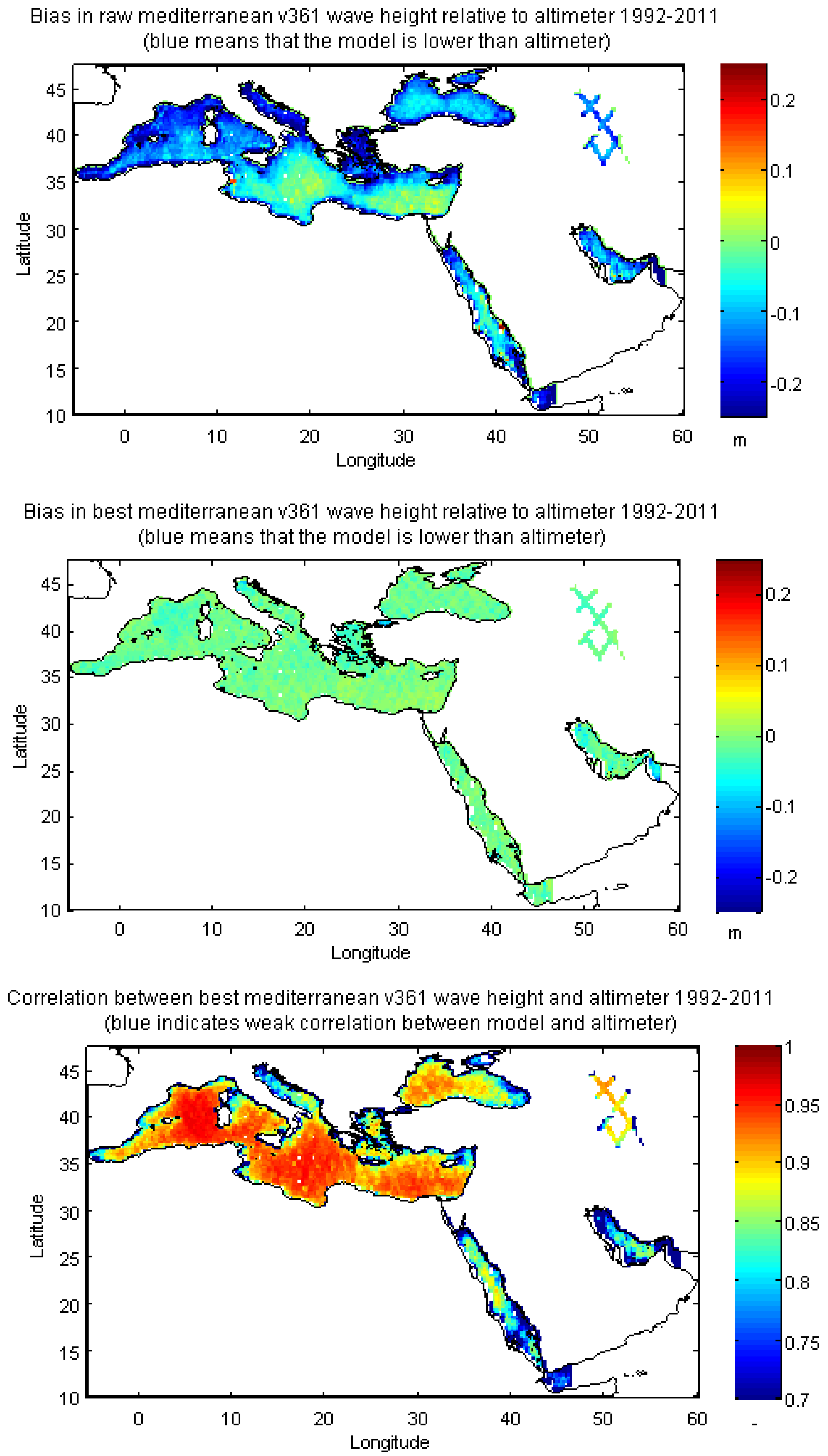


**Figure 149  Bias and correlation v361 wave height relative to altimeter for the Mediterranean**

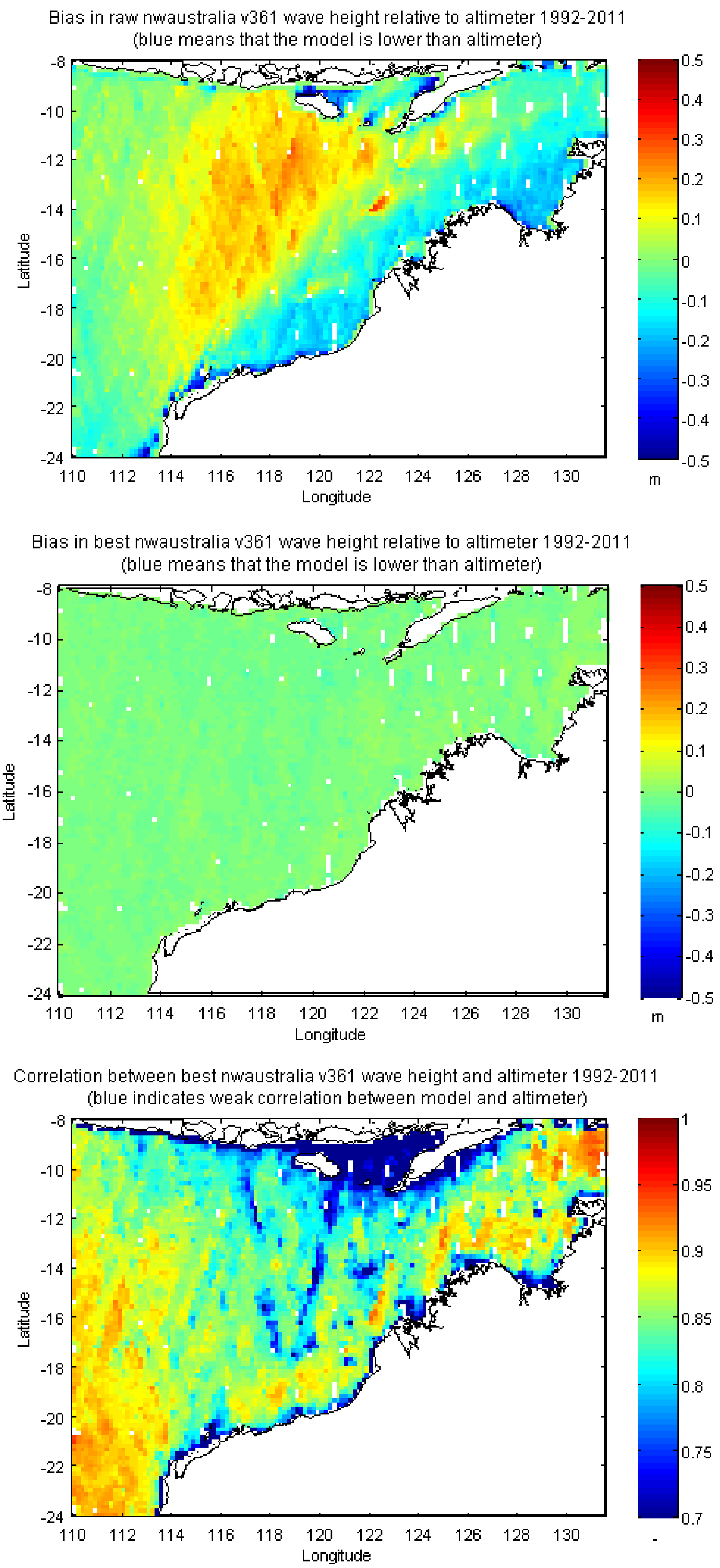


**Figure 150 Bias and correlation v361 wave height relative to altimeter for NW Australia**

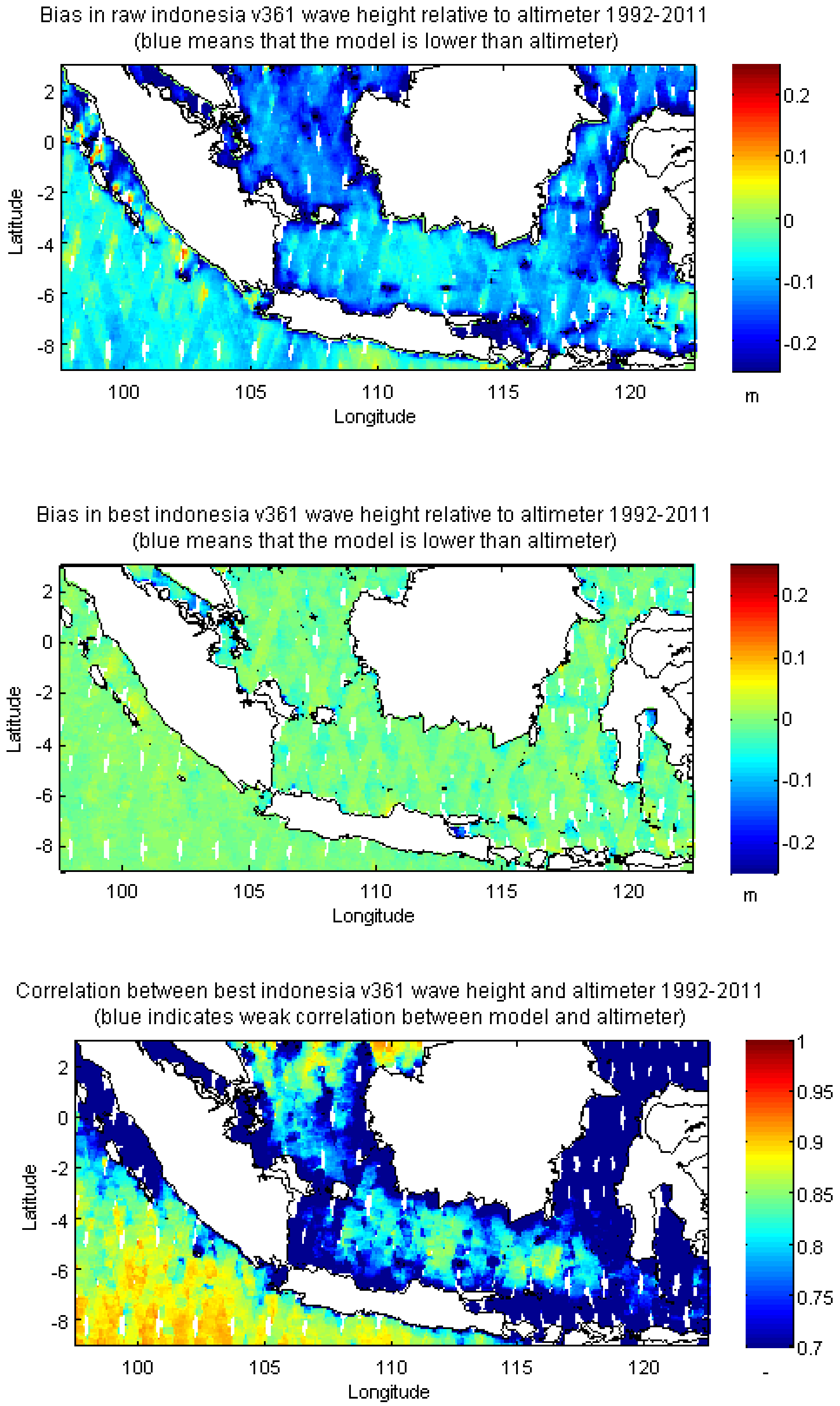


**Figure 151 Bias and correlation v361 wave height relative to altimeter for Indonesia**

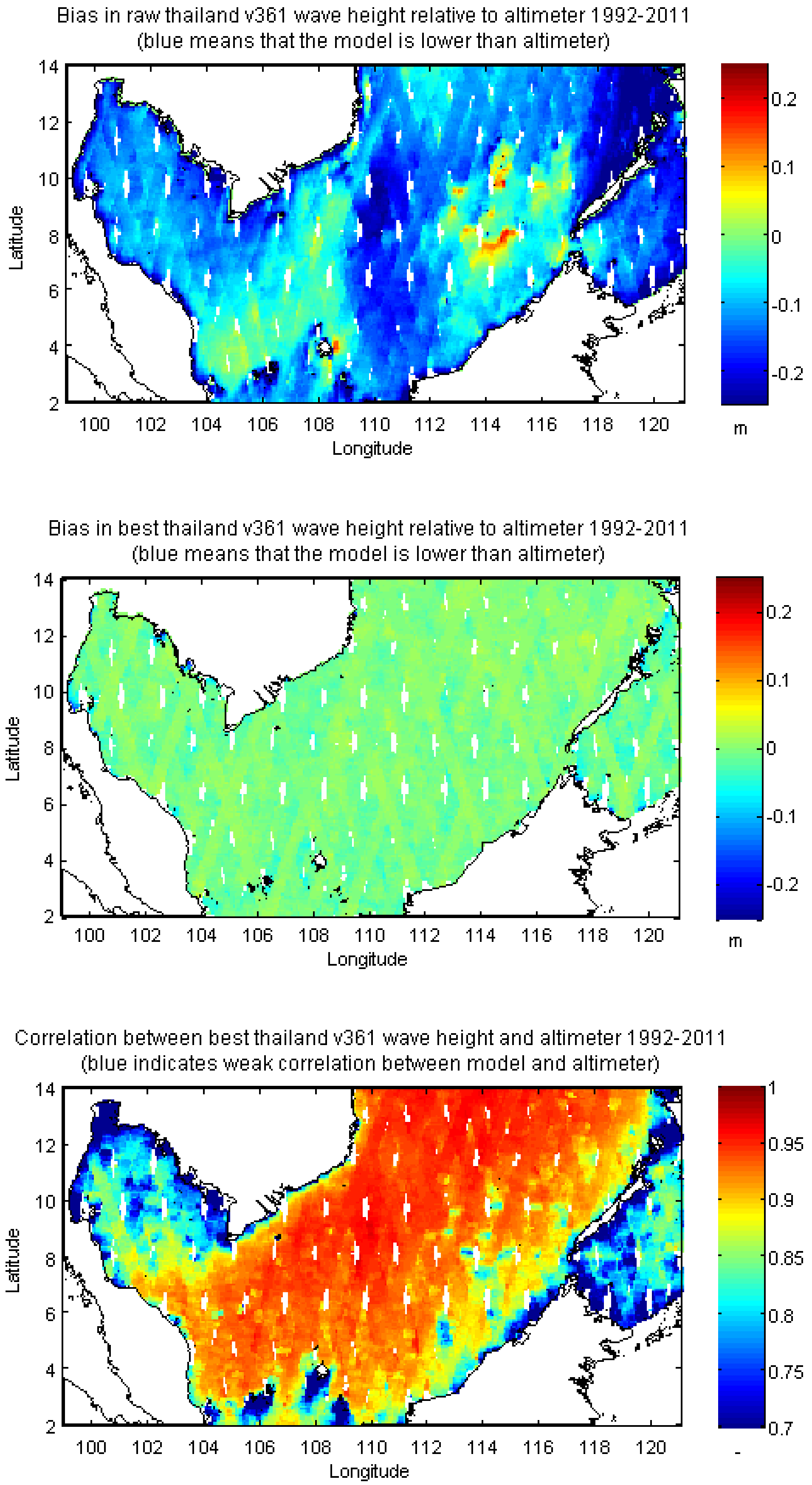


**Figure 152 Bias and correlation v361 wave height relative to altimeter for Thailand**