CFSR surface wind calibration for wave modelling purposes

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1. Introduction

Spectral wave models of the third generation are capable of predicting free-surface gravity waves based on wind fields and bathymetry alone. Where errors in the offered bathymetry generally have a local effect, errors in the wind fields tend to propagate throughout the entire model domain. It is therefore of particular importance, when wave fields are considered on a global scale, that the errors in the driving forces are minimised. Wave modellers have therefore been using state of the art reanalysis and forecast data ever since the beginning of weather climate studies and predictions. It is customary to input these wind fields into wave model “as-is”. The wave model is then calibrated against in-situ or satellite data where after a separate set of measurements is used to validate the model. However, what is calibrated during the tuning of the wave model? A homogeneous negative bias in the surface wind fields can be accounted for by increasing the surface stress factor or some other tunable parameters. However, none of the parameters in any wave model physics will correct inhomogeneous winds fields. Surface wind fields should be corrected before they are input for the wave model.

BMT ARGOSS maintains a global, spectral wave hindcast database covering 1992 - present. It is computed using the default WAVEWATCH III® 3.14 (Tolman 2009) and driven by NCEP final analysis and reanalysis 1 data (NCEP 2000; Kalnay et al. 1996). Internal quality audits showed that the database performs very well against in-situ measurements and remote sensing data, but that there are deficiencies related to: (1) the spatial and spectral resolution of the wave model grid; (2) the dissipation formulation in the applied source terms; (3) the spatial and temporal resolution and overall quality of the surface wind fields. An increase in the spatial resolution of the wave grid should benefit growth, decay and directionality of waves. The current low temporal surface wind resolution (three or six hours) is unrealistic and it causes the modelled growth of wave energy to lag. Both increasing and decreasing wind speeds occur later than in reality so wave growth and decay tend to lag behind measured surface winds. Higher resolution wind and wave grids are expected to be beneficial to a next generation wave hindcast database.

NCEP, the National Centers for Environmental Prediction, released a new Climate Forecast System Reanalysis (CFSR) with, amongst others: (1) higher horizontal and vertical resolutions of respectively $\pm$38 km and 64 layers; (2) direct coupling between the atmosphere-ocean climate system; (3) hourly output (one analysis and five forecast fields); (4) higher volumes of assimilated surface wind data (Saha et al. 2010).

In January 2014 NCEP plans to release version 4.11 of WAVEWATCH III®. It will contain new physics formulated by Ardhuin et al. (2010). Validation with remote sensed altimeter and buoy data shows that the results computed with the new source terms compare very well with measurements but some systematic errors remain (Ardhuin et al. 2010). Earlier calibration efforts of NCEP reanalysis 1 and final analysis wind fields by Groenewoud and de Valk (2011) showed that there is a strong spatial coherence in systematic errors between satellite measurements and modelled surface wind. The question arises:

Can systematic errors from surface wind speeds be removed in order to separate wind and parametrisation errors?

In view of recent progress in wave modelling technology, quality of wind fields and computer resources, BMT ARGOSS is now involved in a three-phase program to significantly improve the quality of its hindcast database. The first phase is to improve the quality of the input CFSR wind fields (i.e. the subject of this paper). The second phase is to increase the spatial and temporal resolution of our hindcast system, including an extension of 10 years backward in time to obtain a 30-year wind and wave database. The third phase is to include new parameterisations of physics (Ardhuin et al. 2010; Tolman et al. 2013).

Wang et al. (2011) studied the coherence between CFSR, Reanalysis 1 and 2, ERA-40 and several independent observation sources by comparing annual means of several derived parameters (no direct measurement assimilation). They showed that CFSR appears to perform much better than the other reanalysis sets but that some systematic errors remain. Particularly, the annual mean of the

Sea Surface Temperature (SST) parameter is expected to suffer from an excessive surface downward solar radiation. Although CFSR surface winds and remotely sensed surface winds are not independent (scatterometer data from several missions is assimilated, Saha et al. 2010), it is yet likely that surface winds will also show a correlation with the SST and the ITCZ (Intertropical Convergence Zone, sensitive to SST). This is interesting to know for the wave modelling community because it might give an indication of the quality of a wave model in certain areas. The skill of the wave model is strongly related to the skill of the driving forces. The findings of Wang et al. (2011) and the importance of surface winds for the overall skill of a wave model lead to the question:

Can any systematic errors in the surface wind be correlated to meteorological or air-sea interaction related phenomena?

This paper presents the results of phase one, the calibration of CFSR surface wind speeds using remote sensed data. Note that no effort has been made to calibrate wind directions, nor any attempt to derive calibrations per directional sector and / or season. Although applicable, these techniques are considered to be outside the scope of this paper but are planned to be investigated after completion of phases two and three.

2. Method

Within scientific and commercial communities it is customary to use satellite data to assess atmosphere and wave model skill (Ardhuin et al. 2010; Barstow et al. 2009; Groenewoud and de Valk 2011). Although it is recognised that errors are present in both recorded as well as model output (Caires and Sterl 2003; Jensen et al. 2011), measurements are considered ground truth in this study. If the contribution of each of the two datasets to the total error needs to be calculated, a third dataset is required (Caires and Sterl 2003). Even though the additional dataset is available in the form of buoy data, the limited spatial variability and inhomogeneous temporal availability of in-situ data render it impractical to estimate error contributions on a global scale. Buoy measurements are instead used to calibrate remote sensed data to create a satellite dataset where altimeter and scatterometer have errors in the same order of magnitude (Groenewoud and de Valk 2011).

Table 1 shows the missions that are included in the quality controlled satellite wind and wave measurement database. Quality controls include error flags, outlier removal and wind / wave sanity checks (Groenewoud and de Valk 2011; Schrama et al. 2000; Naeije et al. 2008). Altimeter missions, that overlap in time and derived H_s and U_{10}, are first calibrated to match the previous mission before the entire set is calibrated towards in-situ data obtained from the National Buoy Data Center (NDBC). The wind magnitude from the scatterometer platform is only calibrated toward the buoy as the missions do not overlap. Spatially, the satellite data extend from 78^o South to 78^o North. The database contains approximately 775 million altimeter and 850 million scatterometer samples over the time range between 1992 and 2012. Altimeter tends to be able to measure the backscatter closer to the coast than scatterometer, so open ocean statistics will be a combination of samples from both platforms while nearshore only altimeter remains. Refer to Groenewoud and de Valk (2011) for a full description of the calibration process and results.

Table 1. Altimeter and scatterometer missions

Id	Mission	Start	End
1	ERS1	1992-01	1996-06
2	ERS2	1995-04	2011-07
3	TOPEX	1992-09	2005-11
4	POSEIDON	1992-10	2002-09
6	JASON	2002-01	2012-01
7	GFO	2002-01	2008-09
8	ENVISAT	2003-01	2012-01
9	JASON2	2009-07	2012-01
10	CRYOSAT	2011-01	2012-01
21	ERS1	1992-03	1996-04
22	ERS2	1996-04	2003-06
22	QUICKSCAT	2000-10	2009-12
22	ASCAT	2010-01	2012-01

Collocation of the CFSR and satellite data posed a computational problem due to the size of both datasets. It was solved by extracting and parsing the data per day. Per day, each seapoint of the CFSR T382 grid was matched with satellite samples within 25 km of its location. Satellite samples are then split per pass and mission. Of the remaining candidates the nearest sample is chosen to be collocated to the model data. In order to match the time of the satellite pass, the model data is energy conserving, linearly interpolated towards the time of the pass. The collocated records are stored for the calibration step.

Two sets of statistics are derived. Firstly, during the collocation step the statistics for all globally collocated records on each day are used to determine the trend in time. Secondly, the spatial statistics are computed on each gridpoint where the number of samples between the 10% and 99% quantiles exceed 100. In this process, a slope α and intercept β are computed that allow for the calibration of CFSR towards satellite with a simple $U'_{10} = \alpha * U_{10} + \beta$.

3. Results

Three types of results are addressed. First the comparison over time between the CFSR and satellite derived surface wind speeds will be shown. Although the skill over time does not strictly answer one of the two research questions it gives confidence that, provided a trend, the collocation method worked consistently. Next, the calibration results will prove that systematic errors can be removed from surface winds using a simple calibration approach. Last, it will be shown that there exists a strong relationship between observed systematic errors in the CFSR surface wind and global phenomena like prevailing winds, sea surface temperature (SST) and the Intertropical Convergence Zone (ITCZ).

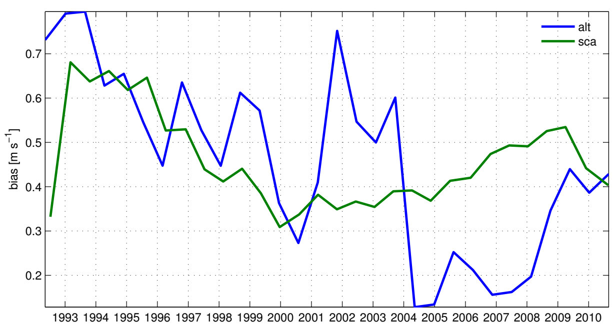

FIG. 1. bias (m s^{-1}, CFSR - satellite)

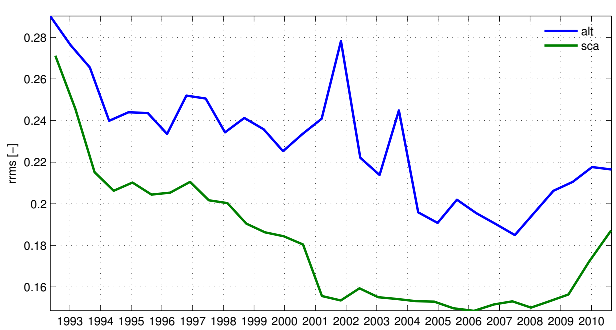

FIG. 2. Relative root mean square error

Figures 1 and 2 depict the relation between the CFSR dataset and satellite measured surface wind. The timeseries are averages of 30 day periods so that underlying trends are clearly visible. As expected, altimeter disagrees more with CFSR than scatterometer, as shown by the higher bias and relative root mean square error (RRMSE). It is partly explained by the ability of altimeter to assess backscatter closer to land where wind fields are more variable. An even more important cause is that scatterometer data is not an independent data source. Reprocessed ERS1-ERS2, Quickscat and NRL WindSat data is assimilated in the reanalysis (Saha et al. 2010). This is very clearly visible in figure 2 where the RRMSE drops over the period 2001 - 2009 because of the assimilation of Quickscat data. Altimeter data shows a sharp increase in bias in 2002 that lasts up to 2004. The cause is that the skill of GFO or JASON (or even both) changes over time. In the current database setup one α and β is computed for each mission without a yearly refinement. Even so, a general trend of decreasing bias and RRMSE can be observed in figures 1 and 2. The increase in scatterometer bias and RRMSE after 2009 occurs during the time that Quickscat is taken out of service. The CFSR switches to NRL WindSat assimilation while the BMT ARGOSS satellite database includes ASCAT data.

Figure 3 shows the average wind speed from 1992 - 2012 of the model divided by the average wind speed derived by both platforms over the same period of time. The division quickly shows where the CFSR dataset has the tendency to overestimate (red) or underestimate (blue) surface wind speeds. There is an strong spatial coherence in the observed error. A simple calibration approach with a scale and offset is capable of removing the observed systematic errors for the ambient climate as shown in figure 4.

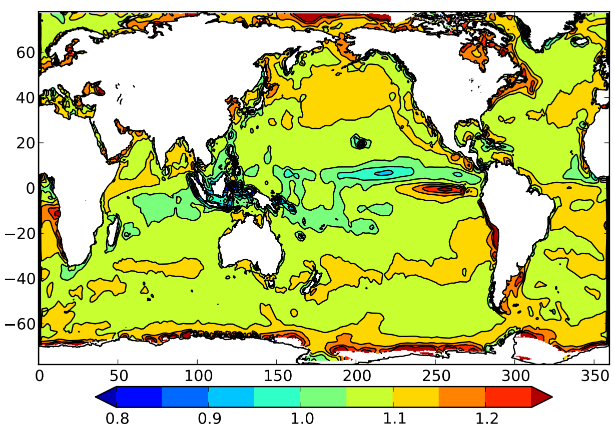

FIG. 3. Ratio uncalibrated model

Figure 3 makes it clear that errors in the surface winds are indeed related to global phenomena. The Pacific ITCZ (140^{o}E - 270^{o}E) can clearly be identified around the equator. The southern ITCZ manifests itself as an overestimation between 30^{o}S - 40^{o}S. In the Eastern Pacific ITCZ a region of highly overestimated surface winds can be identified starting at the Galapagos Islands and following the Southern Equatorial current. A similar but underestimating region can be identified North West of this area on the other side of the equator. These areas might be manifestations of a combination of underestimation of SST in the Equatorial East Pacific (Wang et al. 2011, figure 3.a)

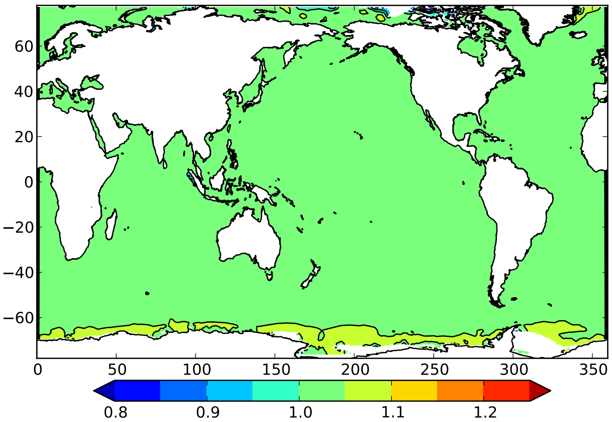

FIG. 4. Ratio calibrated model

and the Northern and Southern Equatorial currents. Similar correlations are found along the Northern Pacific and California currents and the Indonesian archipelagos. On the Atlantic a belt of overestimated surface wind speeds can be found where the Southern and Northern Equatorial current collide. The ocean currents might cause a systematic error in the sea surface temperature that causes an error in the upward vertical flux and hence disturbs the horizontal flow towards the ITCZ. Note that observed errors near the poles might well be related to a relative low number of satellite samples available and where the quality of the surface speed derivation from the backscatter is questionable.

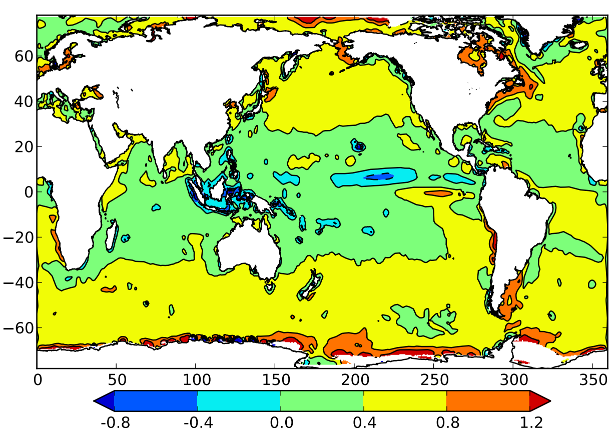

FIG. 5. Absolute bias m s^{-1} (model - measurements)

Figures 5 (and 1) show that the CFSR generally overestimates wind speeds by approximately 0.5 m s^{-1}. Furthermore, similar features are identified in the bias (figure 5) as in the ratio from figure 3, i.e. over- and underestimations in the Pacific ITCZ. Outside of the ITCZ an error in the SST does not automatically lead to a bias in the surface winds. It appears to have only an effect on lee side of the continents where a bias of around 1-2 m s^{-1} can be observed. For instance, the Southern Easterly trades cause such a positive bias near the coast of Namibia. Similar biases are found at the North of Chile (Southern Easterly trade), Argentina / Shetlands (Westerlies) and the East coast of North America and Asia (also Westerlies).

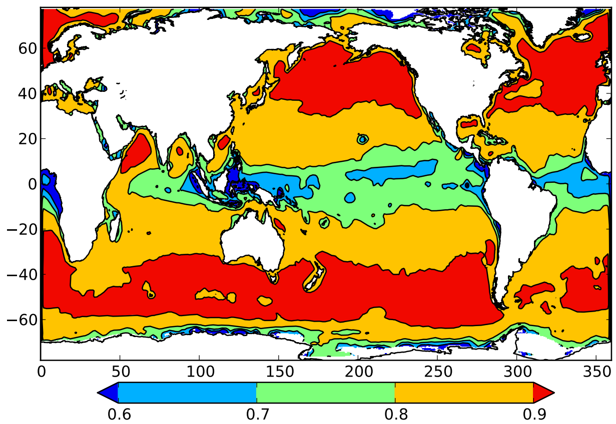

FIG. 6. Correlation

The weather in the ITCZ is known for dry, long periods of low wind speeds and short but severe storms. Figure 6 shows the correlation between the CFSR and satellite derived surface wind speeds. The correlation pattern roughly follows the global high and low pressure bands around the globe near the 30^o and 60^o latitudes. The turbid weather on the equator (long periods of low wind speeds and short, violent storms) and the squalls near Africa result in a very low correlation. Possibly, the CFSR and other atmospheric exercises have difficulties in getting the timing and magnitude of the short storm event right.

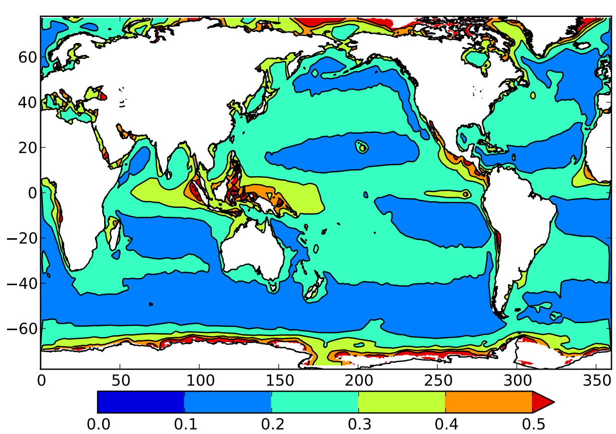

FIG. 7. RRMSE

The low correlation between the surface winds and observation in the tropics is a major concern for wave modelling in this area; while wave model results are generally in better agreement with measurements,0 this low correlation means that wave model performance will degrade. The same goes for the scatter in the model that is expressed here as the relative root mean square error in figure 7. Wave models of areas in the Indonesia archipelagos, the Pacific side of Middle-America and the West coast of Africa from South Africa up to Sierra Leone, will suffer a quality loss from the low correlation and RRMSE.

4. Conclusion

The CFSR dataset generally compares very well with satellite measurements. Its high resolution in space and time should counter some of the lag in growth and decay of modelled waves. Results are excellent above and below the 30^o latitudes. When surface winds within the 30^o latitudes are used, some consideration should be given to the propagation of errors into the wave model results.

The simple $\alpha * U_{10} + \beta$ point-by-point calibration will work much better than modifying, for instance, the C_0 tunable parameter in the Chalikov-Tolman source terms that would effect input wind over the entire domain. Furthermore, calibration of the wind field separates the systematic errors of wind and waves. This is essential for calibration of wave model parameterisations. For instance, it enables an objective comparison of the Tolman and Chalikov (1996) and Ardhuin et al. (2010) that will finally lead to a high resolution, state of the art spectral hindcast database.

Global processes like the ITCZ, ocean currents, SST and prevailing winds have a very strong impact on the quality of any surface wind dataset. Erroneous estimations of timing or the magnitude of storms in the tropics result in a low correlation and high relative root mean square error between modelled and observed data. This will have a direct impact on wave modelling performance in these areas. The presented RRMSE and correlation maps should assist a modeller in judging the regional quality of wave model results.

Future work will include a recalibration of the altimeter data per year. It will remove the spikes in 2002-2004 as found in figure 1. Furthermore, the simple calibration method can be replaced by a more sophisticated method. A tail fitting approach could be adopted in order to get the extremes better represented in the CFSR data set. An alternative method calibrates the surface wind per season in order to capture the oscillation of the ITCZ.

Acknowledgments.

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