WIND BIAS CORRECTION GUIDE

First draft Ad

Second draft Jur

Third draft Jur

Fourth draft Jur (with input from Gerrit Burgers and John Eyre)

General

Within the Satellite Application Facility for Numerical Weather Prediction (NWP SAF) software is made for processing scatterometer data over the open ocean to ocean vector winds. This software is freely available upon registration, and is also used in the Ocean and Sra Ice SAF (OSI SAF) to produce near-real-time ocean vector wind products.

It has been demonstrated that the SAF scatterometer winds are accurate and reliable. Yet, as every measured quantity, these products have their own error characteristics. Long term monitoring is needed to reveal these characteristics, and this is part of the tasks of the NWP SAF and OSI SAF project teams. Correction for biases in scatterometer winds is considered to be the responsibility of the user. This document is written for all users of NWP SAF scatterometer wind processors or OSI SAF wind products. It gives the state of the art concerning scatterometer wind error characteristics in terms of resolution and accuracy, and contains recommendations how to correct for biases. The authors hope that this will help the user community to exploit the potential of scatterometer wind data as much as possible.

Introduction

The purpose of data assimilation is to find a model state that gives the best match between the most recent model prediction and the observations that became available since. This state is called the analysis. Modern assimilation techniques as Optimal Interpolation, 3DVar, and 4DVar require as good as possible estimates for the random error characteristics of both model and observations, since the error variances determine the relative weight of each information source in the analysis. These techniques are based on BLUE, Best Linear Unbiased Estimates, and therefore do not deal with variable biases. This guidance document addresses how systematic differences between NWP models and scatterometer wind observations, further referred to as biases, may be estimated and corrected.

Biases can be detrimental for NWP impact, e.g., by decelerating or accelerating flows and thereby filling in or intensifying atmospheric disturbances or lows. It is therefore important to correct for biases. In practice best results are obtained when the observations are corrected to fit the model, even when the biases are caused by model imperfections: consistency appears to be more important.

Biases in scatterometer observations are studied in detail (*Stoffelen*, 1998; *Vogelzang et al*., 2011). Moored buoys are generally taken as calibration target to establish “surface truth”. This does not mean that biases of scatterometer winds against all NWP models will be minimized in this way. In the next sections we discuss what NWP winds and scatterometer winds represent and how these different representations may lead to biases w.r.t. the buoys. Moreover, biases may change with wind speed, time, atmospheric stratification, etc.

Some data assimilation systems are able to correct for biases. See *Dee* (2005) and references therein or *Dee and Uppala* (2008).

What does a NWP surface model wind represent?

A NWP model calculates meteorological quantities like wind on a regular grid. The equations use derivatives in space and time and only structures defined over several grid points are propagated well. In NWP model resolution is commonly referred to as grid distance, but spatially resolved structures over the open oceans are usually about 5 times larger (Skamarock, YEAR); finer resolution is obtained only when orographic effects are taken into account. Since only the open ocean is of interest here, one can think of the model values as representative for 5 times the grid cell. NWP model fields are propagated in discrete time steps and the model values are also representative for a time window of several time steps. This poses, of course, limits to the deterministic spatial and temporal resolution of the model fields. The size of these limits depend on the model characteristics, e.g., horizontal and vertical diffusion schemes and closure of the dynamical equations.

The NWP surface wind vector depends on how the boundary layer processes are described in the model. Important aspects are:

- *Friction. Turbulent transport? Turbulence closure? Explain*
- Stability. The NWP SAF scatterometer winds are processed assuming neutral stability, meaning that the ocean and the air are assumed to have equal temperature. When the air is much warmer than the ocean, the situation is called stable. Under such conditions the wind profile over the ocean surface changes, leading to reduced surface wind. When the ocean is warmer than the overlying air the situation is called unstable. Instability has less effect on the surface wind speed than stability. Several different parameterizations for the wind profile exist.
- Sea state. *Explain*

What does a Scatterometer wind represent ?

A Scatterometer is a radar instrument that measures the radar cross section of a portion of the Earth's surface (for spaceborne scatterometers typically of size 25 km × 25 km) from a number of incidence and/or azimuth angles and/or polarizations. The radar cross section of a, σ_0, is a surface property and a measure for the fraction of incident radar radiation scattered back under given azimuth and incidence angle. It is measured by a scatterometer antenna with known antenna gain pattern and distance between radar and surface.

The radar cross section is a property of the surface itself. It is a measure of the surface roughness and therefore directly related to the wind stress. This is directly related to the friction wind velocity, u_*. The surface wind depends on u_* and the temperature difference between the ocean and the overlying air (stability, see previous paragraph). NWP SAF scatterometer winds are processed assuming neutral stability, i.e., equal temperature of air and sea.

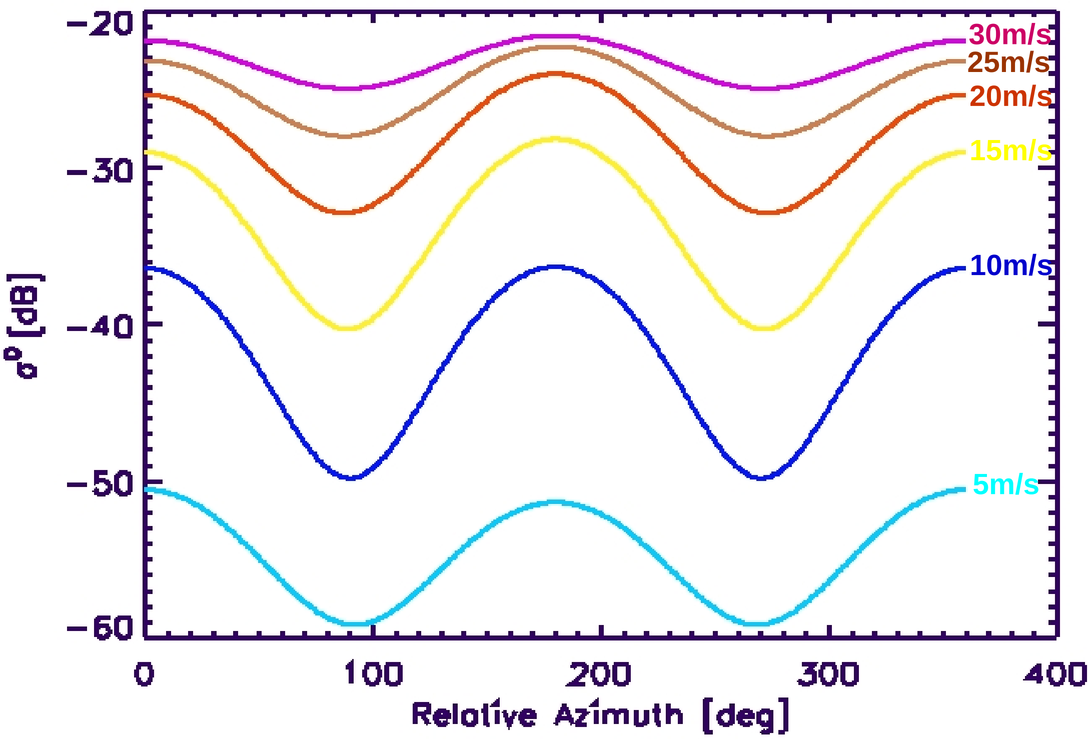
Over water, the radar cross section depends on the following geophysical parameters:

- wind speed;
- wind direction;
- wind variability;
- radar incidence angle;
- radar azimuth angle;
- radar frequency and polarization.

The following effects may also play a role;

- presence and intensity of rain. Microwave radiation is scattered into all directions by raindrops in the atmosphere and therefore less signal is received back than in the absence of rain, leading to an underestimation of the wind speed. On the other hand, splashing rain on the ocean surface disturbs the radar cross section.
- presence of land and/or sea ice. Land and sea ice have a much larger radar cross section than the ocean surface, so land or sea ice contamination of a cell may lead to overestimation of the wind speed.
- wave age. *explain*;
- ocean currents. The wind retrieval algorithms assume that the ocean surface is at rest w.r.t. the Earth, so a scatterometer measured the wind vector relative to the ocean surface. Other measurement systems (buoys, NWP models) measure the wind vector relative to the Earth, so a discrepancy occurs when the ocean surface moves due to currents like the Gulf Stream or the Kuroshio current. The discrepancy may be as large as 1 m/s in speed.

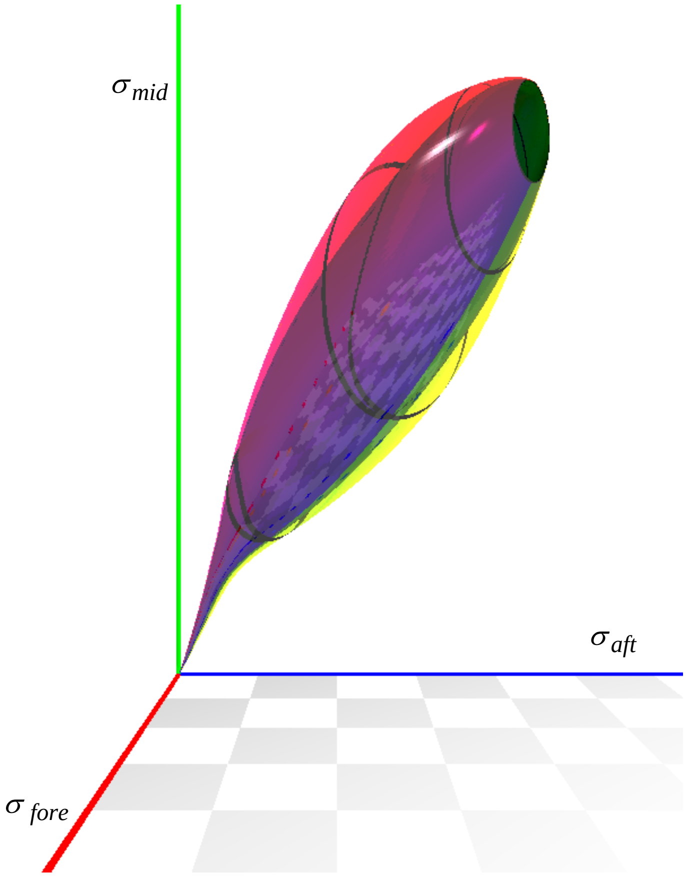
Generally, the radar cross section as function of azimuth angle has a minimum value when the radar look direction is perpendicular to the wind direction (radar looking crosswind). The radar cross section reaches its maximum value when the radar look direction is opposite to the wind direction (radar looking upwind) and a second, generally slightly lower maximum when the radar look direction is the same as the wind direction (radar looking downwind). The radar cross section decreases with increasing incidence angle (leaving all other geophysical variables the same). Furthermore, the radar cross section increases with wind speed (again leaving all other geophysical variables the same), but at high wind speeds the increase in σ_0 becomes smaller and smaller, until it saturates at very high winds as shown in the figure below.



Radar cross section as a function of the angle between wind and radar look direction for various wind speeds at an incidence angle of 40° (*courtesy Z. Jelenak*).

There are two ways of modeling σ_0 as a function of the other parameters: empirical and fundamental. In the fundamental approach wave generation by wind and radar backscatter from the ocean surface are modeled to yield σ_0. The empirical approach fits some form of σ_0 as a function of the other parameters with a number of coefficients that are fitted to the observations. The outcome of the two approaches is the same: a prescription of how to calculate σ_0 as a function of wind speed and direction, measurement geometry, radar properties, etc. This function is called the Geophysical Model Function (GMF). The empirical approach has two main advantages over the more fundamental approaches (given the present state of the fundamental algorithms): the radar cross section is calculated faster and it is calculated more accurate. This makes the empirical approach better suited for applications.

The GMF for ASCAT is called CMOD. The current version is CMOD-5, but CMOD-6 is under development. The figure below gives a an impression of CMOD-5. The incidence angle of the mid beam is 25°. The fore and aft beams make an angle of 45° in azimuth with the mid beam.



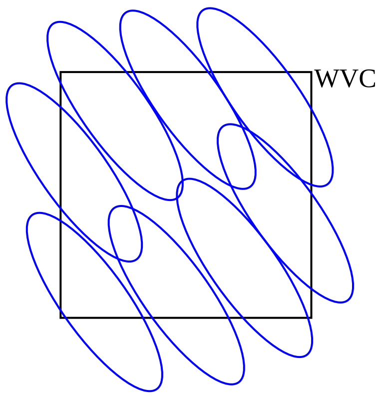
CMOD5 visualized in measurement space. The red axis gives the cross section of the forward-looking beam, the green axis that of the mid beam, and the blue axis that of the aft beam. CMOD5 shows up as a double-folded cone. The colors along the cone indicate the wind direction. The black bands along the cone designate wind speeds of 10 m/s, 20 m/s, and 30 m/s. The cone ends at 40 m/s wind speed. The details of the cone change with incidence angle.

Animation of CMOD-5?

A scatterometer's radar parameters are, of course, well known, while its measurement geometry can be determined from position and attitude measurements using standard techniques. If σ_0 is measured only once, its value gives some indication of the wind speed. In this case the minimum wind speed can be found from the GMF as the upwind wind speed that yields σ_0, and the maximum wind speed as the crosswind wind speed that yields σ_0. Note that a single measurement gives no information on the wind direction. For that two or more measurements are needed. Nevertheless, in most cases numerical inversion of the GMF yields two or more possible wind vectors that fit the measured σ_0 values, because the GMF is a nonlinear function and because the σ_0 values inevitably contain measurement errors.

The inversion residual, i.e., the difference between the measured σ_0 values and those obtained from the GMF using an estimated wind vector as input, can be used to detect the presence of wind variability, rain, land, or sea ice. This detection process is referred to as Quality Control (QC) and is an important step in scatterometer processing. The inversion residual can be visualized using the figure of the CMOD5 cone above: a measurement is represented by a point in measurement space. When the inversion residual is small the measurement lies close to the cone surface; if it is large the measurement point lies far away.

Returning to the real world, each radar measurement yields a σ_0 value for a specific area. The shape of the area is determined by the antenna pattern and the measurement geometry. Scatterometer processing starts with defining a regular grid on the Earth's surface. The area of a grid cell is larger than the area over which a single radar measurement is performed. Next, for each measurement geometry all individual radar measurements centered within a grid cell are averaged. This results in a gridded σ_0 product in which each grid cell contains exactly one σ_0 value per antenna view. The averaging process reduces the speckle noise (measurement error) that is inherent in radar observations.



Averaging the radar views (blue ellipses) in the WVC (black square).

Scatterometer wind processing starts with the gridded σ_0 product. The retrieved wind is therefore representative for the grid cell, further referred to as wind vector cell (WVC). The WVC size determines the spatial resolution of the wind field, i,e, the size of the smallest wind feature visible. In reality the individual radar measurements do not cover the WVC exactly, nor are they spread homogeneously. Such effects are found to be small and are generally neglected.

Multiple views in varying antenna geometry are needed to resolve the wind vector. Due to the varying antenna orientation, the area sampled in a given WVC is not identical in the different views. Wind variability in the WVC area may this cause noise in the wind retrieval, known as geophysical noise.

- references

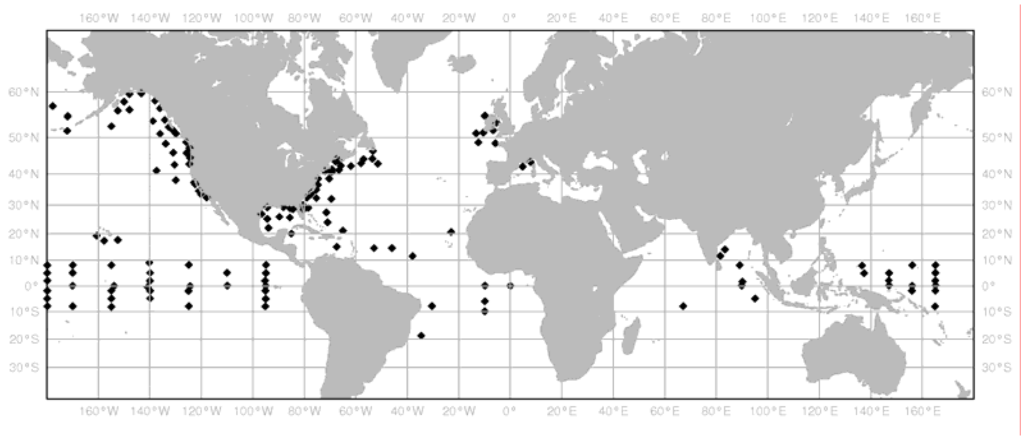
What are the main differences with buoy winds ?

A number of moored buoys measure the wind speed and direction, together with a number of other parameters. If these include air and sea temperatures it is possible to convert the measured wind vector to an equivalent neutral wind vector at 10 m anemometer height. Buoy winds are commonly given as averages over 10 minutes. Note that buoys give time averaged winds at a fixed location, while scatterometers give a spatially averaged wind at a certain time. A typical wind speed of 7 m/s averaged over 10 minutes (600 s) corresponds to a track in one dimension of about 4 km length and a spatial scale of about 2 km. This is about one order of magnitude smaller than the typical scatterometer resolution.

What causes biases?

Biases can originate from various causes:

- Scatterometer. Scatterometer biases originate from effects that are averaged out in the GMF. Examples are:
    - Ocean currents. Buoys are moored and measure the wind w.r.t. the Earth, while scatterometers winds are w.r.t. the ocean surface. In case of large-scale ocean currents this may cause a local bias up to 1 m/s.
    - Calibration errors. Errors in the calibration of the scatterometer will cause global biases.
    - Sea state.
- Model. The model description of the boundary layer processes may be incorrect.
- Sampling. Biases may occur when the dataset used is not representative for the global wind climate. High quality buoy measurements, for instance, are concentrated in the tropical oceans and along the coasts of North America and Europe (see figure below). If one fixes to the coastal buoys only, one may find biases that would be different if the tropical buoys were considered.



Location of buoys measuring high-quality winds.

How to detect biases?

Biases show up when plotting the difference between scatterometer wind and model wind. A number of such plots is made available on the web. The NWP SAF web page at www.nwpsaf.org provides links to the monitoring pages which link to the sites of ECMWF, UKMO, and KNMI that give monitoring information on scatterometers and models. Also many studies are published in the scientific literature (Hersbach, Chelton, …)

For estimating biases, two methods are available:

- Triple collocation. This is the most general method, but also the most elaborate method. It yields (linear) calibration coefficients and error variances for three collocated data sets.
- O-B regression. Under some assumptions discussed below, also O-B regression may give useful results

We will now give an example of each of the two methods.

Triple collocation example

Method:

The triple collocation method assumes that three systems (buoys, scatterometer, and model background in the case considered here) all give information on the true value t . The buoy is chosen as reference relative to which the other systems are calibrated. Assuming that linear calibration suffices and that the buoy is free of bias (i.e., free of systematic errors), the values w measured by the different systems satisfy

$$
\begin{aligned}
w_{buoy} &= t + \delta_{buoy} \\
w_{scat} &= a_{scat} t + b_{scat} + \delta_{scat} \\
w_{back} &= a_{back} t + b_{back} + \delta_{back}
\end{aligned}
$$

with a and b the calibration coefficients and δ the random measurement error. Note that the triple collocation calibration procedure is not part of the NWP SAF wind processors: their output (and, hence, the OSI SAF wind products) contain the values w_{scat} and w_{back} but no buoy measurements.

Forming all possible first and second statistical moments results in a set of equations that is simplified by the following assumptions on the error characteristics:

1. Linear calibration is sufficient over the whole range of measurement values considered;
2. The reference measurement values are unbiased;
3. All measurement errors are random and unbiased;
4. The measurement errors have constant variance over the whole range of measurement values;
5. The measurement errors are uncorrelated with each other;
6. The measurement errors are uncorrelated with the measurement values.

The error variances $<\delta^2>$ and the calibration coefficients can then be solved from the equations. Some subtleties are involved in handling the representation error, see *Stoffelen* (1998),

The following example uses representation errors calculated from wind spectra, see *Vogelzang et al.* (2011).

Data used:

- Buoy measurements not blacklisted by ECMWF (see figure above)
- ECMWF forecasts
- Scatterometer data (from OSI SAF):

  - ASCAT-12.5, October 1, 2008 – November 30, 2009

  - ASCAT-25, November 1, 2007 – November 30, 2009

  - SeaWinds-KNMI, November 1, 2007 – November 30, 2009

Results

Let $u_{cal} = a_u u + b_u$ and $v_{cal} = a_v v + b_v$ with (u,v) the wind components from the OSI SAF wind product and (u_{cal}, v_{cal}) the linearly calibrated wind. The calibration constants a and b are given in the table below for the various scatterometer wind products and for the collocated ECMWF forecast

	Scatterometer				ECMWF			
Dataset	a_u	b_u (ms^{-1})	a_v	b_v (ms^{-1})	a_u	b_u (ms^{-1})	a_v	b_v (ms^{-1})
ASCAT-12.5	1.012	0.19	1.008	-0.01	1.032	0.32	1.043	0.09
ASCAT-25	1.021	0.18	1.009	0.01	1.020	0.29	1.039	0.10

SeaWinds-KNMI	1.048	0.28	1.030	0.01	1.011	0.35	1.039	0.07

Calibration coefficients

The error standard deviations are given in the table below. The figures are valid for the calibrated wind components (using the calibration coefficients given above). See *Vogelzang et al.* [2011] for a discussion of these values.

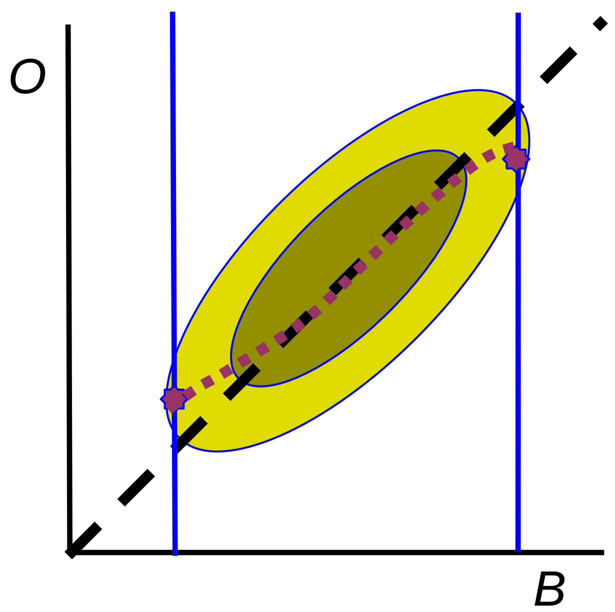
Dataset	Buoy		ECMWF		Scatterometer	
	ε_u (ms^{-1})	ε_v (ms^{-1})	ε_u (ms^{-1})	ε_v (ms^{-1})	ε_u (ms^{-1})	ε_v (ms^{-1})
ASCAT-12.5	1.21	1.23	1.54	1.55	0.69	0.82
ASCAT-25	1.24	1.30	1.42	1.45	0.65	0.74
SeaWinds-KNMI	1.40	1.44	1.19	1.27	0.79	0.63

Error standard deviations

O-B regression example

Method

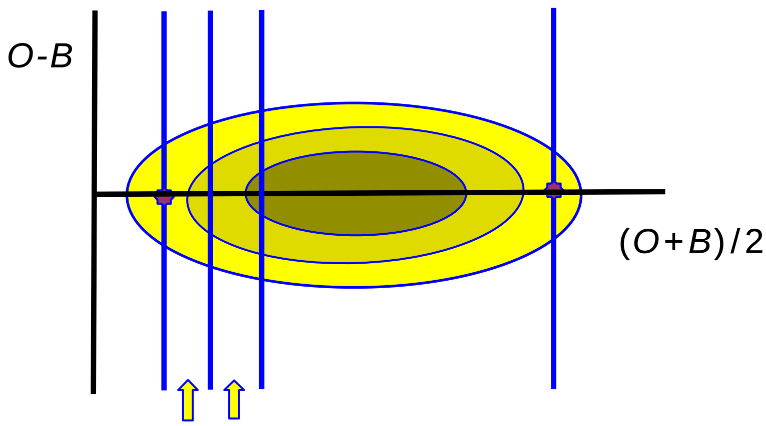
When applying standard regression methods on differences between observed (scatterometer) and model winds, one must be cautious to how the errors are handles. Most regression methods assume that all errors are contained in the dependent variable, but this will cause errors as depicted in the figure below:



In the figure above the observations are perfectly calibrated (dashed black curve). However, when a regression routine assumes all errors to be contained in O, the average for low values of B (red dot on the left hand side blue line) will lie above the true calibration curve. Similarly, the calculated average at high values of B (red dot on right hand side blue line) will be too low. As a result, regression would yield something like the red dotted curve.

More sophisticated regression methods take the error in both variables into account. The average values are now calculated along skewed lines with a slope determined by the ratio or the errors.

If, however, one can safely assume that O and B have the same error distribution, which in most cases is a reasonable assumption, one can also apply standard regression to $O-B$ versus $\frac{1}{2}(O+B)$, as depicted below.



Now standard regression will not introduce spurious biases. One may also bin the data in $(O+B)$ values, as indicated by the blue lines and the yellow arrows, and obtain a nonlinear calibration curve by calculating the average in each bin. In this way, calibration issues for low and/or high winds will become visible.

How to correct biases?

The output of NWP SAF wind data processors (including the OSI SAF wind products) are not calibrated against other wind data using triple collocation or O-B regression. If a bias is encountered that affects assimilation quality, one can take the following measures:

- Recalibrate the scatterometer winds using triple collocation or O-B regression techniques described above. It is advised to calibrate the observations w.r.t. to the model, even when the model is known to be incorrect, to ensure model consistency.
- Improve model physics in order to better describe the reality as it is measured.
- Select the data. If the problems occur at certain wind speed ranges, in certain geographical area's, or in certain times of the year, one may consider to leave out those data that cause problems.
- Discard the data. Since scatterometer winds are known to be accurate and reliable, this is not a recommended strategy.

References

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- Vogelzang, J., A. Stoffelen, A. Verhoef, and J. Figa-Saldaña, 2011. On the quality of high resolution scatterometer winds, *submitted to J. Geophys. Res.*

Useful web sites

- NWP SAF monitoring pages:
  http://research.metoffice.gov.uk/research/interproj/nwpsaf/monitoring
  Under "Scatterometer reports" links are given to the web pages of ECMWF, Meteo France, and UKMO.
- OSI SAF monitoring pages at KNMI:
  www.knmi.nl/scatterometer
  Select a wind product on the right hand side of the screen and then "Monitoring information", again on the right hand side of the screen.

Old remaining points

Refer to Hersbach, Chelton, etc.

- Statistical effects; when compared winds are not mutually calibrated biases will show up depending on the underlying wind distribution, which geographically highly variable
- Stability
- Currents
- Sea state
- Wind direction (friction bias)
- ...

How to correct NWP biases

- Use equivalent neutral winds
- Plot scat-NWP versus (scat+NWP)/2 and regress to provide calibration

Improve geophysical description:

- Wind direction ?
- Currents ?
- Sea state ?
- ..