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On buoys, scatterometers and reanalyses for globally representative winds

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Introduction

The global observing system is composed of various capabilities as documented, for example, in the WMO OSCAR data base (OSCAR 2015). OSCAR differentiates the Observation Requirements, Satellite Capabilities and Surface-based Capabilities. Obviously, a link exists between these three items and a main question is, given the requirements, how to build effective and synergetic surface-based and satellite capabilities. Here, we focus on ocean surface vector winds (OSVWs), where a space-based capability exists in the CEOS virtual constellation (CEOS, 2015) and a high-quality ground based capability in a moored buoy network. Both ground-based and satellite measurements are assimilated in Numerical Weather Prediction systems, which additional capability is eventually used to produce long-term climatological data sets, for example in ERA-interim (2015). A main question in the development of these capabilities remains how much and what ground truth is needed to serve the diverse meteorological and oceanographic application areas in the satellite era.

Moored buoys are deployed in the tropical Pacific, Atlantic and at higher latitudes mainly in the coastal areas. These moored buoy programs serve several application areas and community strategies are being developed for supported evolution, e.g., TPOS (2014). Note that climate monitoring requirements on global trends in principle require a global spatial representation, which is provided by satellites, but not by the buoy network.

Some questions thus pertain to the moored buoy winds in relation to how they support satellite and reanalysis OSVWs:

- How are buoy winds used to produce/evaluate the various levels of satellite and modelled wind products, up to the gridded fields used by scientists for application development?
- What degradation in these applications could be expected and at what implication, if the moored buoy network was reduced or reshaped?
- Does it matter where the satellite calibration and validation (cal/val) sites are and can adequate cal/val be done with just a few moorings?
- Would there be implications for new generations of ocean vector wind satellites if the moored buoy network were changed?

We address the question of how satellite wind calibration and the resultant accuracy will be affected if the moored buoy network is degraded, by randomly withholding some mooring winds in the cal/val process.

Second, the problem of trend analysis is addressed, based on a recent reprocessing and cal/val of the 10-year QuikScat data records at the EUMETSAT Ocean and Sea Ice Satellite Application Facility. A main question here is how representative a geographically limited measurement set, such as the moored buoy network, can be used to obtain global answers on climate change? And, what role can satellite OSVWs and model reanalyses play to obtain these answers?

Naturally, geophysical conditions vary by region, which does affect scatterometer interpretation. These are investigated, but do not lead to geographically dependent calibration. Rather, they lead the OSVW community to carry out process studies, notably in the tropics. Recent publications suggest that the observation of OSVW variability in the tropics is quite relevant, e.g., Sherwood et al. (2014), Lin et al. (2015), King et al. (2014) or Sandu et al. (2011), suggesting that spread in climate model sensitivity and model bias can be related to subtle dynamical model aspects, such as moist convection. Another question is thus how dynamical meteorological and oceanographic interaction processes, relevant for the realism of climate models should be addressed by measurement capability. The tropical buoy network has been originally deployed for this exact reason. A valid question to ask now may be whether buoys play still the same role for these process studies in the satellite era? This question is not further addressed in this report.

Satellite Calibration

We address scatterometer wind calibration, but methodologies that we discuss apply for other satellite sensors as well. First, we assume that instruments can be globally calibrated, which means that wind processing software and Geophysical Model Functions (GMFs), relating wind to radar backscatter, can be generic and rather instrument independent. Second, the imaging mechanism of the winds (essentially Bragg scattering for scatterometers) is not geographically dependent. So, we are looking for a globally representative GMF, which is used for wind retrieval anywhere. Triple collocation is part of the calibration procedure and scatterometer wind regression coefficients against buoys are indeed retrieved globally to amend the GMF to take absolutely calibrated winds as reference.

Triple collocation (TC) with moored buoys, scatterometers and General Circulation Models (GCMs) is performed to establish, at the moored buoy positions, the accuracy and calibration of the scatterometer winds and the GCMs. By physical inference, it is subsequently assumed that the spatial sample of buoys is sufficient to obtain a globally representative absolute calibration, which obviously cannot be proven, as no globally representative in situ wind network is available.

Note that scatterometers sense ocean roughness through Bragg scattering and that this can be related to OSVWs at 10m height for cal/val purposes. Ocean roughness (and stress) depend on air-mass density and atmospheric stratification, but these physical quantities are generally well known at buoy positions and in GCMs, such that the cal/val of satellite-sensed OSVWs does not much depend on them. The IOVWST community currently converges in the understanding that stress-equivalent neutral wind (U10S) is the most practical retrieval quantity for scatterometers and radiometers; this implies that for an accurate computation of U10S from buoys, we ideally need continuous buoy series of: the 10-m wind, SST, air temperature, air humidity, air pressure and ocean current; this is to respectively take out the effects of atmospheric stratification and air mass density (that the microwaves do not sense) and ocean mean motion (as the sensed ocean roughness depends on the mean relative difference between water and air motion); as less of this information would become available at the buoys, it will be harder to stay within the climate requirement of 0.1 m/s per decade in the more representative global metrics.

Triple collocation

For satellite cal/val moored buoy winds are our only absolute reference for satellite wind calibration since GCMs and satellites lack absolute calibration. We use an elaborated cal/val method by triple collocation, which involves spatial representation, error analysis and ultimately calibration (Stoffelen, 1998; Vogelzang et al., 2011; Lin et al., 2015). In order to assess the effect of buoy selection on the scatterometer calibration a series of experiments has been performed.

Collocation dataset

In this exercise a collocation dataset based on 10 minutes continuous buoy measurements has been used. Buoy measurements and ASCAT-A measurements (ASCAT coastal product, 2013) were considered to be collocated if the distance in time was less than 5 minutes and the distance in space less than 12.5 km. In case more collocations satisfied these criteria, the one with the smallest spatial distance was selected. A background ECMWF wind field interpolated in space and time to the scatterometer measurements is already present in the ASCAT wind products

The dataset was restricted to the year 2011. In that year collocations with 103 different buoys were found after blacklisting (Bidlot, 2002). Figure 1 shows the buoys with the number of collocations indicated by the color. The figure shows that most of the collocations are found for the buoys along the US coast, and that there are no buoy collocations below -10° latitude.

Triple collocation exercises

The following triple collocation exercises were done:
- All data;
- Only tropics (latitude between -20° and +20°);
- Northern Hemisphere (latitude above +20°);
- Northern Hemisphere plus Equator (latitude between -2° and +2°
- Random selection of 50 buoys (five different selections).

Table 1 gives the calibration coefficients, defined as $t = aw + b$, with w the uncalibrated wind component and t the calibrated one. Results are given for the zonal wind component u and the meridional wind component v. Also an estimate of the error in the calibration coefficient is included, based on the sample size and the assumption of Gaussian errors.

The last column in table 1 gives the number of collocations that contribute to the calibration. The triple collocation procedure is an iterative one in which points that lie more than four standard deviations from the calibration curve are omitted.

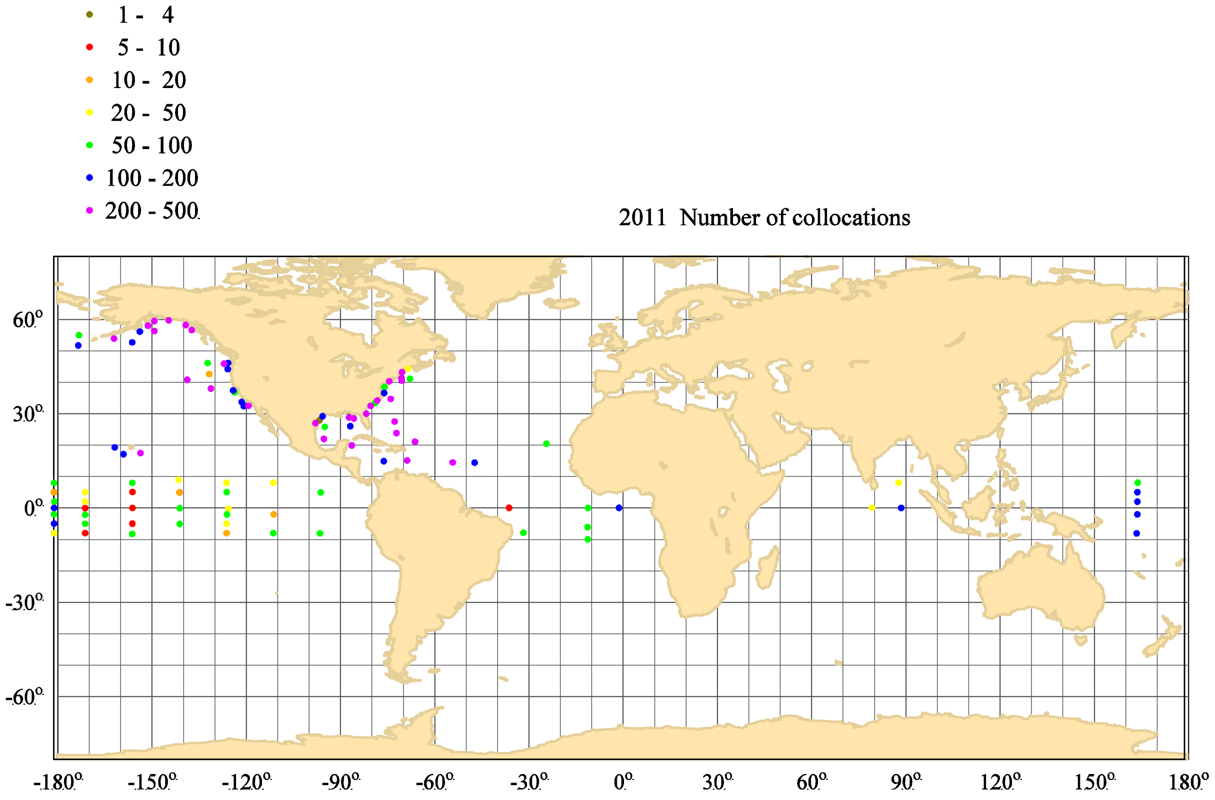

Figure 1 Buoy positions for the 2011 data set. The color indicates the number of collocations.

Exercise	a_u	b_u	a_v	b_v	N
All data	0.994 ± 0.001	-0.12 ± 0.02	1.018 ± 0.002	0.09 ± 0.02	13844
Tropics	1.018 ± 0.003	-0.07 ± 0.02	1.044 ± 0.009	0.17 ± 0.02	4288
N.H.	0.993 ± 0.002	-0.15 ± 0.02	1.014 ± 0.002	0.06 ± 0.02	9559
N.H. + Eq	0.995 ± 0.002	-0.15 ± 0.02	1.016 ± 0.002	0.09 ± 0.02	10594
Random 1	0.995 ± 0.002	-0.17 ± 0.02	1.011 ± 0.003	0.07 ± 0.02	6597
Random 2	0.998 ± 0.002	-0.19 ± 0.02	1.011 ± 0.003	0.03 ± 0.02	6575
Random 3	0.998 ± 0.002	-0.10 ± 0.02	1.018 ± 0.004	0.13 ± 0.02	6422
Random 4	0.993 ± 0.001	-0.13 ± 0.02	1.014 ± 0.003	0.06 ± 0.02	6971
Random 5	0.992 ± 0.002	-0.10 ± 0.02	1.019 ± 0.003	0.14 ± 0.02	7261

Table 1 Scatterometer calibration coefficients w.r.t. buoys.

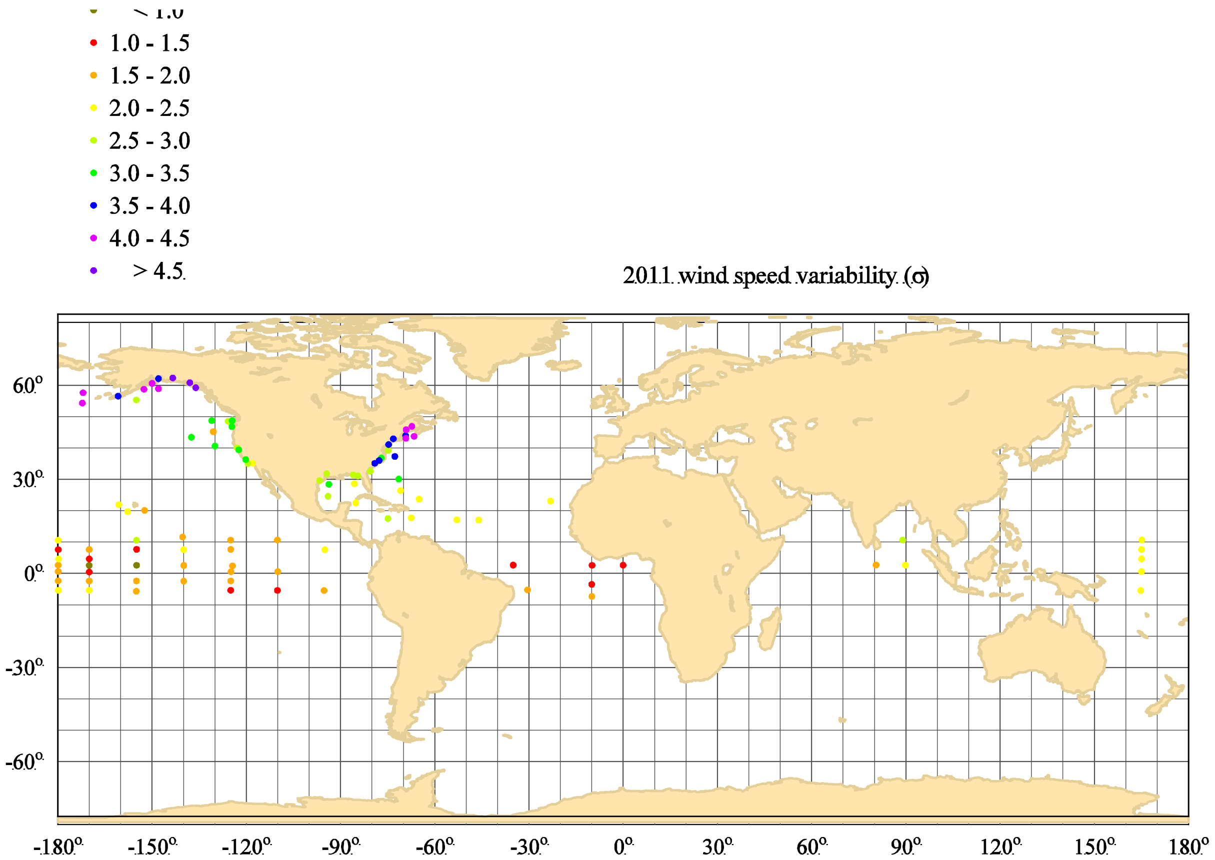

Figure 2 Wind speed variability per buoy for the 2011 data set.

The first three data rows in table 1 show that significant changes in the calibration slope occur if the calibration is limited to the Tropics. This is as expected, because the number of samples is limited in the Tropics. Moreover, the wind variability is low here, whereas it is high in the extratropics, as shown in figure 2. Therefore, the tropical calibration is based on a limited range of wind speed, resulting in a poorer calibration.

The fourth data row in table 1, labeled N.H. + Eq, shows that including the equatorial buoys (latitude between -2° and +2°) to the extratropical ones (latitude > +20°) does not affect the calibration coefficients significantly.

The calibration coefficients based on a random selection of 50 buoys show little difference for the scalings a_u and a_v. The differences found are within the expected error bars. The errors indicated in table 1 are standard deviations, so only differences beyond the 3-σ level can be considered as significant. Moreover, the error estimates are derived under the assumption of Gaussian errors. If the errors are non-Gaussian, the estimates in table 1 are too optimistic, which may occur, for example, if a relatively large proportion of the Tropical buoys were selected.

The results for the five random datasets show that the triple collocation procedure is consistent.

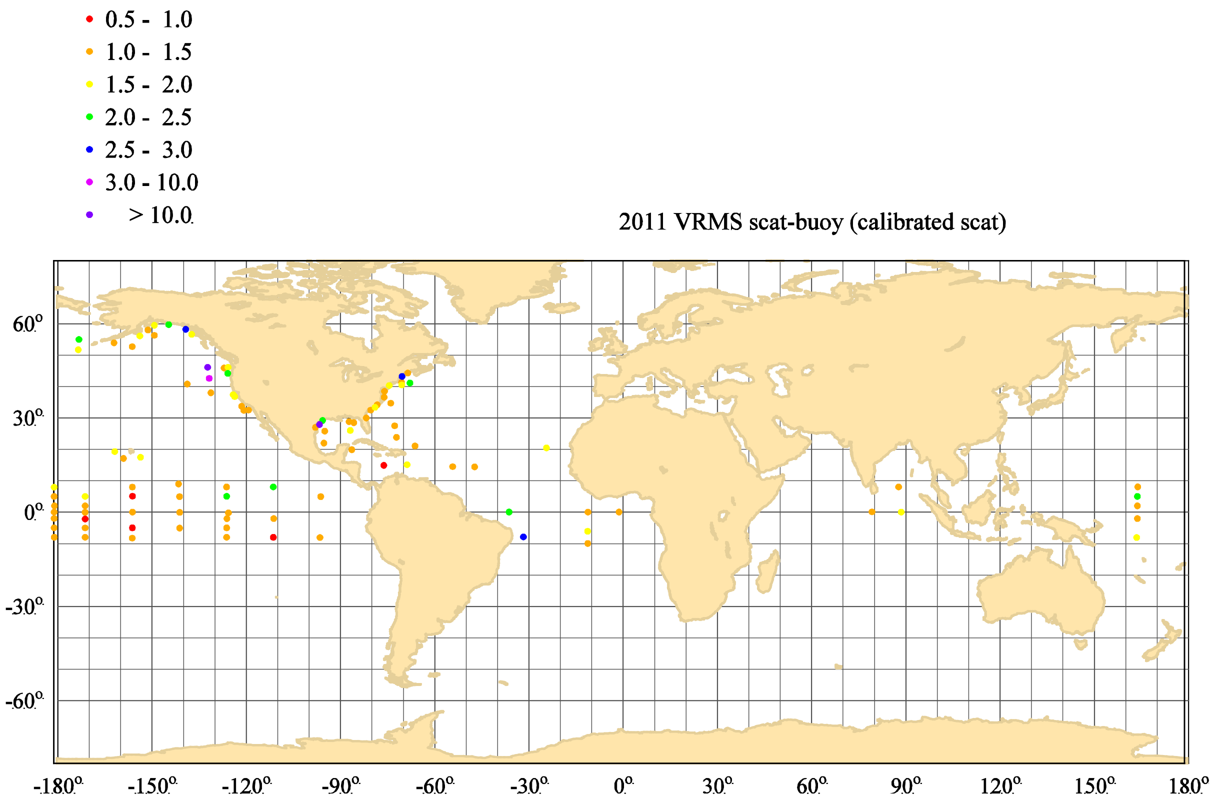

Figure 3 Average vrms difference between buoy and calibrated scatterometer winds.

Figure 3 shows the average vector root-mean-square (vrms) difference between the buoy winds and the calibrated scatterometer winds for the complete 2011 dataset. In general, the differences are small, both in the Tropics and along the US coast. There are some outliers:

- buoy 42019 at 27.9 °N, -95.4 °E (Gulf of Mexico) with vrms 15.7 (only 1 collocation)
- buoy 46005 at 46.1 °N, -131.0 °E (Gulf of Alaska) with vrms 10.6 (91 collocations)
- buoy 46002 at 42.6 °N, -130.5 °E (Gulf of Alaska) with vrms 6.3 (11 collocations)

These outliers were not further analyzed for geophysical or instrumental anomalies, but which are expected, particularly for those two in the Gulf of Alaska with substantial sampling. Note that these outliers were excluded from the triple collocation analysis by QC, so they have no influence on the calibration coefficients.

Effect of calibration in Tropical Pacific

To assess the effect of different calibrations in the Tropical Pacific, table 2 shows the standard deviations of the differences in the zonal and meridional wind components, *u* and *v*, between the calibrated scatterometer winds and the buoy winds for all data. The calibration coefficients are obtained from table 1, while the comparison was done for all buoys between 130° E and 90° W, and between 15° S and 15° N.

In total 2073 measurements contribute to the comparison, leading to a statistical accuracy of 2%, i.e. 0.02 m/s in σ_u and 0.03 m/s in σ_v. Table 2 shows that the various calibrations have no significant effect on the accuracy of the scatterometer winds in the Tropical Pacific. This is as expected, because wind are generally low in that area, and the calibration has largest effect on high winds.

Calibration set	σ_u **(m/s)**	σ_v **(m/s)**
All data	1.10	1.39
Tropics	1.10	1.40
N.H.	1.10	1.39
N.H. + Eq.	1.10	1.39

Table 2 Differences between calibrated scatterometer winds and buoy winds for the Tropical Pacific.

Main findings of triple collocation

The note the following:

- The moored buoy network appears not representative for the globe. An outstanding gap appears in the southern hemisphere extratropics, where a large part of the earth’s water surface is present, with particular conditions relevant for the earth’s climate evolution, such as momentum, moisture, heat and gas exchanges at particularly high and variable wind conditions;
- Given the geographical coverage and density of the current buoy network, randomly removing a part of it, does not alter the satellite cal/val substantially;
- The TC satellite and GCM cal/val methodology appears not particularly sensitive to outlier buoy data.

Buoy, GCM and QuikScat trends over 10 years

In this section we evaluate different global metrics to observe trends. As these metrics imply coverage of different spatio-temporal domains, e.g., at all global buoy measurement positions (as in TC), at model grid positions (either regular or uniformly spaced), or at all satellite measurement points (either strictly or loosely QC-ed) with usually poor temporal sampling of the diurnal cycle.

A recent validation of the 10-year QuikScat reprocessing at the EUMETSAT OSI SAF (Verhoef et al., 2015) discusses different global trends in different global metrics and offers consolidation. It shows different trends in GCMs, at buoy locations and at satellite locations, which latter further depend on the QC applied.

The following 10-year trends are noted in the abovementioned report:

I: Both tropical and extratropical buoys show a clear downward trend over 1999-2009:
- Global Buoy speed: **down 0.3 m/s** (Buoy sampling; figure 8);
- Lat<25 Buoy speed: **down 0.3 m/s** (Buoy sampling; figure 9);

Note that buoys poorly spatially represent a global mean ocean wind.

II: Global QuikScat data shows essentially no trend, but if samples are taken only at the buoy locations, the downward buoy trend is visible:
- Global QSCAT speed: **no trend** (QuikScat samples; figure 4);
- Global QSCAT speed: **down 0.5 m/s** (Buoy sampling; figure 8);
- Global QSCAT speed: **down 2%** (Buoy sampling; figure 12);
- Lat<25 QSCAT speed: **down 0.5 m/s** (Buoy sampling; figure 9);

Note that polar satellites have more samples near the pole than in the tropics per unit area though.

III: ERA appears to suggest a slight upward trend globally:
- Global ERA speed: **up 0.1 m/s** (QuikScat samples; figure 4);
- Global ERA speed: **down 2%** (Buoy sampling; figure 12);
- Lat<25 ERA speed: **down 0.2 m/s** (Buoy sampling; figure 9);

Note that the upward trend is sampled at QuikScat locations, which is probably similar to sampling a regular lat/lon grid (which also has more samples near the pole than in the tropics per unit area).

Sampling over a reduced Gaussian grid, with rather constant grid sampling per unit area, is the most representative of a true global ocean mean wind. It may show a slight deviation in trend from the QuikScat sampling, given the locally rather strong 10-year trends up to 1 m/s per 10 years (+ve and –ve). NB: this trend can be computed as well if needed obviously.

IV: Differences in trends at a given sampling appear almost within the GCOS requirement of 0.1 m/s per 10 years per data set:
- Global QSCAT-ERA speed: **down 0.1 m/s** (QuikScat sampling; figure 3);
- Global Buoy-QSCAT speed: **down 0.2 m/s** (Buoy sampling; figure 6);
- Lat>25 Buoy-QSCAT speed: **down 0.1 m/s** (Buoy sampling; figure 7);

Buoys are thus geophysically biased by their sampling, which might influence the differencing too. Ergo, scatterometers may be the best resort to compute globally representative trends. But scatterometers first need absolute calibration against a robust moored buoy network in order to provide reliable surface truth.

The report also notes that backscatter over Antarctica goes down by about 0.1 dB, which after wind retrieval would corresponds to about 0.1 m/s (figure 1). Other geophysical calibration targets for scatterometers reside over the rain forests, but which areal and latitude coverage is limited and declining.

Summary

Moored buoy winds are of high quality and our only absolute reference for satellite wind calibration and monitoring. General Circulation Models (GCMs) and satellites lack absolute calibration otherwise. Maintaining a long-term data record of surface wind measurements is thus critical to the cross-calibration of satellite winds from different satellite missions and different satellite sensor types (e.g., the SSM/I series microwave radiometers, Ku- vs C- vs L-band scatterometers).

The current non-uniform distribution of moored buoys makes them rather unsuitable for global change metrics. The geographical distribution of moored buoys points to a glaring hole in the southern hemisphere. With 60m of global water level stored in the southern hemisphere, scientific misjudgement may have rather drastic consequences. However, buoy monitoring in the SH extratropics is essentially missing and should be recommended in our view. It would be much appreciated if (particularly southern hemisphere governments) would take responsibility in this area.

We perform triple collocation (TC) with moored buoys, scatterometers and GCMs to establish the accuracy and calibration of the scatterometer winds and the GCMs at the moored buoy positions. By physical inference, we assume that the spatial sample of buoys is sufficient to obtain a globally representative absolute calibration. This can obviously not be proven, as no globally representative in situ wind network is available. However, given such plausible inference, it appears possible to reach the 0.1 m/s per decade stability in a representative global metric. Moreover, randomly reducing the density of the current spatial distribution of moored buoys, does not appear too harmful.

We note that different global metrics provide different trends though, as they cover different spatio-temporal domains, e.g., at all global buoy measurement positions (as in TC), at model grid positions (either regular or uniformly spaced), or at all satellite measurement points (after QC usually). The satellite or GCM representations of the global waters appear clearly the most faithful (see above).

The IOVWST community currently converges in the understanding that stress-equivalent wind (U10S) is the most practical retrieval quantity for scatterometers and radiometers, as it may be well validated by GCM and buoy data. This implies that for an accurate computation of U10S from buoys, we ideally need continuous buoy series of: the 10-m wind, SST, air temperature, air humidity, air pressure and ocean current. These variables are used to respectively take out effects of atmospheric stratification, air mass density and ocean mean motion (as the sensed ocean roughness depends on the mean relative difference between water and air motion). As less of this information would become available at the buoys, it will be harder to stay within the climate requirement of 0.1 m/s per decade in the more representative global metrics.

Recent publications suggest that observation of OSVW variability in the tropics is quite relevant, e.g., Sherwood et al. (2014), Lin et al. (2015), King et al. (2014) or Sandu et al. (2011), suggesting that spread in climate model sensitivity and model bias can be related to subtle dynamical model aspects, such as moist convection. Another question is thus how dynamical meteorological and oceanographic interaction processes, relevant for the realism of climate models should be addressed by measurement capability in the satellite era. This question is not further addressed in this report.

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