Error characterization of in situ, satellite, and synergistic sea-surface wind products under tropical cyclone conditions

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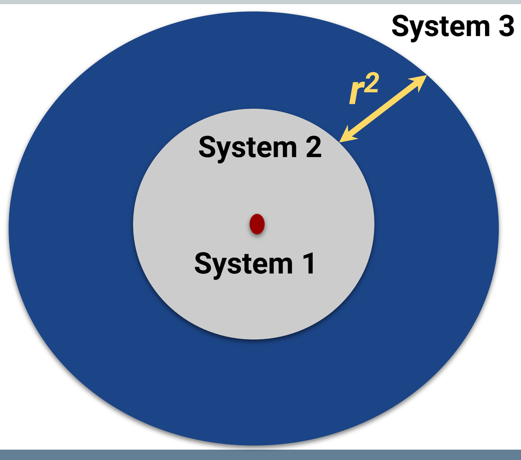
Motivation

In the framework of the ESA OCEAN+EXTREMES **MAXSS project**, a consistent, inter-calibrated extreme wind data record for satellite scatterometers (ASCAT-A, -B, -C, RapidSCAT, Oceansat-2, ScatSat-1, HY-2A, -2B) and radiometers (AMSR-2, Windsat, SMAP, SMOS) over the period 2010-2020 has been generated, using the Stepped Frequency Microwave Radiometer (SFMR) winds onboard the US National Oceanic and Atmospheric Administration (NOAA) and US Air Force Reserve Command (AFRC) "hurricane hunter" planes as reference for satellite wind data adjustment.
Then, the satellite adjusted winds have been blended using the Optical Flow Morphing technique together with the European Centre for Medium-range Weather Forecast (ECMWF) Fifth reanalysis (ERA5) winds, to produce a high spatial and temporal frequency **multimission (MM) wind product**.
An important step within the MAXSS study is to **characterize the errors** of the different MM input wind sources (i.e., scatterometers and radiometers) as well as those of the MM product itself. Note that since the MM product ingests a variety of satellite sensors with different effective spatial resolution and thus different error characteristics over different regions, it is important to fully characterize such errors and understand how these eventually impact the MM product quality.

Triple collocation analysis

A very well-established method for error assessment of different wind (and other) data sources is the **triple collocation analysis** (Stoffelen, 1998). The triple collocation was conceived as a tool for inter-calibration and individual error assessment of three different collocated sea-surface wind datasets.
The method accounts for different spatial (and/or temporal) representation of the three collocated data sources, allowing for error characterization at the scales of both the medium resolution and the lowest resolution system.
The estimation of the so-called **representativeness error** (i.e., the common true variance resolved by the two higher resolution systems but not by the lowest resolution system, $\mathbf{r^2}$) is a relevant aspect of the triple collocation analysis.



Representativeness error (r^2) estimation

Different methods to estimate r^2, i.e., either based on wind spectra, cumulative spatial variances or intercalibration constraints, have been proposed and used in the literature over the last decade. The **spatial variance analysis** is used since it is more tolerant to the presence of noise and data gaps due to quality control (e.g., because of rain contamination effects), as expected from these extreme wind datasets.
The method is applied to wind speeds in the along-track direction, within 10°x10° boxes centered on the tropical cyclones centers (see **Figure 1**), for **ASCAT 25 km** and collocated **ERA5** data, being ASCAT the satellite platform least affected by noise, and the resulting r^2 is used for the rest of the satellite products.
r^2 is given by the difference (black curve) of the two spatial variances (blue and red curves) (**Figure 2**). At the scale of 200 km, the limit below which the scatterometer reveals more structure than the model (in accordance with Vogelzang et al., 2015), the estimated $\mathbf{r^2}$ **is about 0.3 m²/s²**.

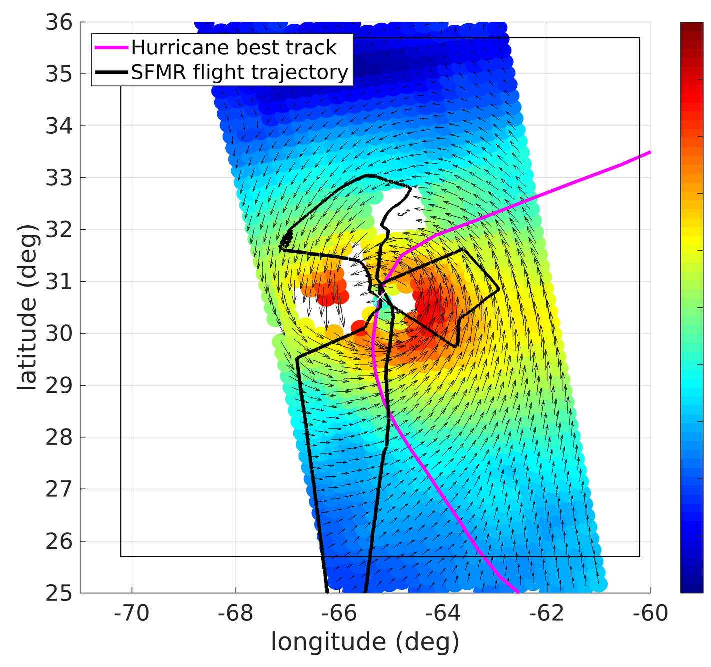


Figure 1: *Example of the satellite swath region selected for satellite and collocated ERA5 wind speed spatial variance calculations (squared box).*

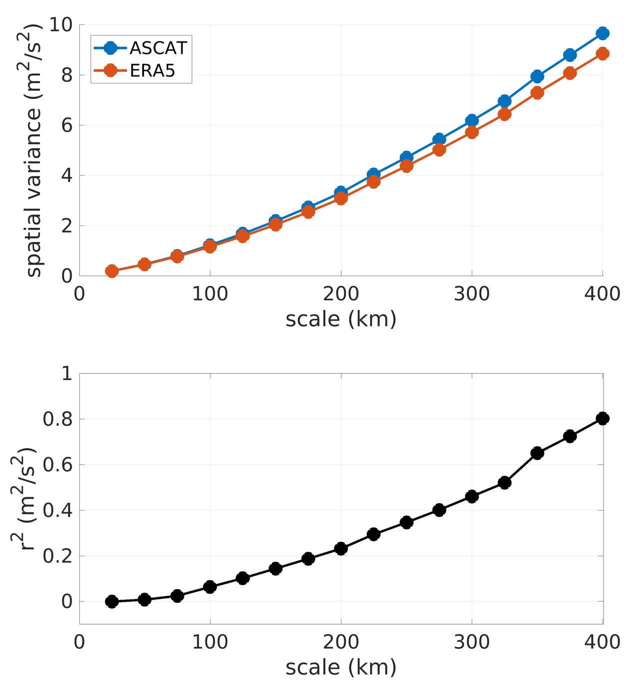
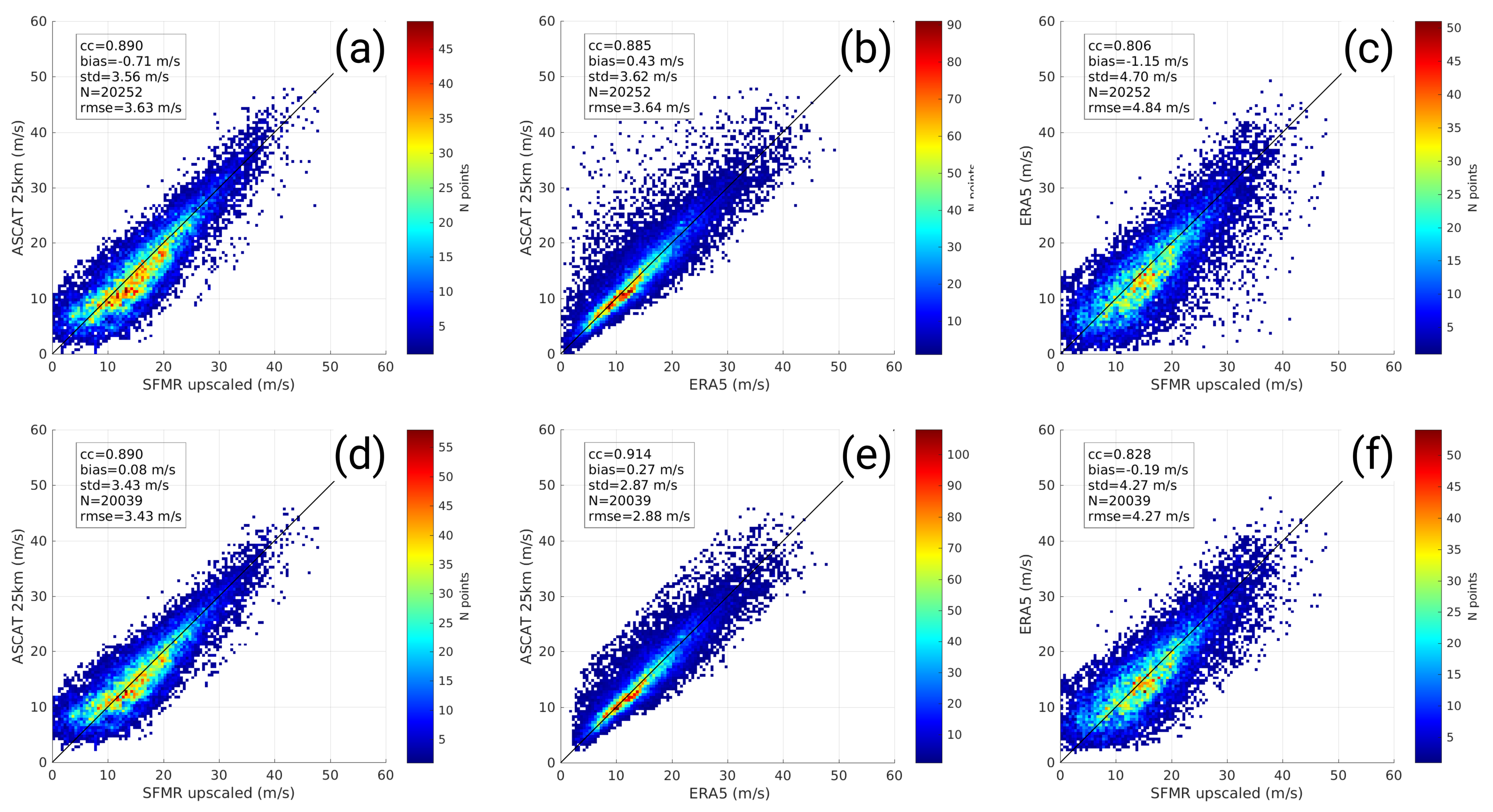


Figure 2: *Spatial variance as a function of scale for ASCAT 25 km in blue and ERA5 in red (top panel).* r^2 *, shown in black (bottom panel), is the difference of the two spatial variances.*

Triple collocation results: wind errors estimation

A thorough triple collocation analysis is carried out for the mentioned datasets under tropical cyclone conditions, using different combinations of triplets (SFMR-Satellite-ERA5 or SFMR-Satellite-MM) in order to assess consistency as well as uncertainty on the uncertainty estimates.
The top panels of the figure (**a**, **b**, **c**) show the **density plots** for the triplets SFMR-ASCAT-ERA5 **before** triple collocation, while the bottom panels (**d**, **e**, **f**) show the same density plots **after** triple collocation is performed. A 4-σ filter is applied during the process, so the triple collocation, besides recalibrating the data, also removes some outliers.
The recalibration done by the triple collocation does not seem very strong because both ASCAT and ERA5 have been previously adjusted using the same reference, i.e., SFMR winds (MAXSS Wind ATBD, 2022). The same holds for the other scatterometers and radiometers. Also note that the SFMR winds have been upscaled to match the effective resolution of scatterometer and radiometer winds.
The **estimated wind speed errors** (at model scales) are reported in **Table 1** for triplets with scatterometers and in **Table 2** for triplets with radiometers. The tables show that ASCAT winds contain the lowest errors (standard deviation of about 0.9 m/s) of all the extreme wind datasets. In order to keep extreme wind sampling, some rain contamination is allowed in the Ku-band data (by not using the KNMI_QC flag), which leads to significantly higher errors for Ku-band (ranging from 1.4 m/s to 2.1 m/s) than for C-band scatterometers. The radiometer winds show significantly larger errors than scatterometers, ranging from 2.0 m/s (SMAP) to 2.9 m/s (Windsat), in which the quality of the worst-performing scatterometer (OSCAT) is comparable to that of the best-performing radiometer (SMAP).



	Number of points	SFMR (m/s)	SCATTEROMETER (m/s)	ERA5 (m/s)
ASCAT	20039	3.30	0.93	2.75
RSCAT	1513	3.50	1.55	2.56
OSCAT	4921	3.11	2.07	2.83
OSCAT-2	10678	3.27	1.84	2.37
HSCAT-A	3041	2.99	1.44	2.73
HSCAT-B	4979	3.26	1.47	2.00

Table 1: *triple collocation errors for the SFMR-scatterometer-ERA5 triplets.*

	Number of points	SFMR (m/s)	RADIOMETER (m/s)	ERA5 (m/s)
AMSR2	9969	3.79	2.60	2.46
Windsat	7719	3.45	2.87	2.71
SMAP	6364	3.26	1.96	2.89
SMOS	14617	3.65	2.10	2.84

Table 2: *triple collocation errors for the SFMR-radiometer-ERA5 triplets.*

Multi-mission (MM) wind product

To evaluate the MM wind product, we use SFMR and RSCAT as independent data sets. All the other scatterometers and radiometers, in fact, are used in the generation of the MM wind product. **Table 3** shows the triple collocation errors from the triplets SFMR-RSCAT-MM. There is a substantial error reduction of the MM product (1.6 m/s) with respect to ERA5 (2.6 m/s, second row of **Table 1**). However, note that a relatively small sample (i.e., only about 1500 collocations) is used to assess the MM errors. This is due to the fact that the RSCAT mission only lasted 2 years. As such, it is expected that the MM error estimates are somewhat uncertain. Nevertheless, the **MM clearly outperforms ERA5** in the tropics, indicating the added value of the MM synergistic approach used. Moreover, a similar behavior of the MM product is found under extra-tropical cyclone conditions (not shown).

	Number of points	SFMR (m/s)	SCATTEROMETER (m/s)	MM (m/s)
RSCAT	1505	3.39	1.67	1.64

Table 3: *triple collocation errors for the SFMR-RSCAT-MM triplets.*

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