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

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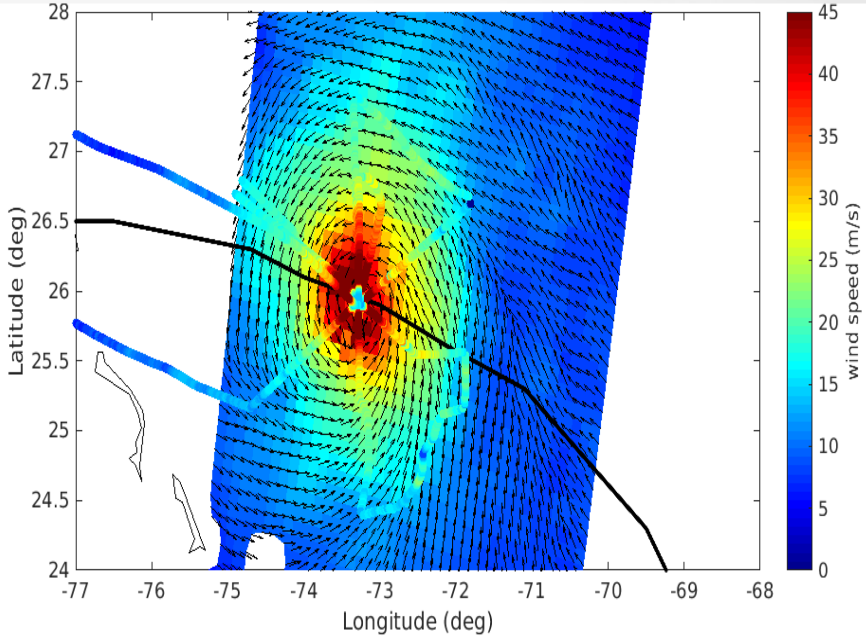

ASCAT adjusted wind field over Hurricane Dorian using SFMR winds as calibration reference

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Institut de Ciències del Mar · Norwegian Meteorological Institute · OceanDataLab · Ifremer · Koninklijk Nederlands Meteorologisch Instituut, Ministerie van Infrastructuur en Milieu · ISMAR Istituto di Scienze Marine · NOAA · esa

ESA MAXSS project: Extreme wind inter-calibration & validation

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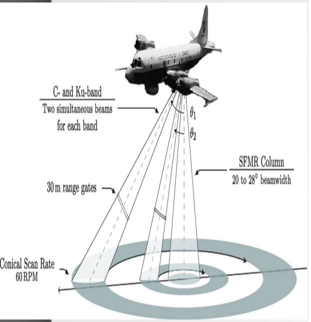
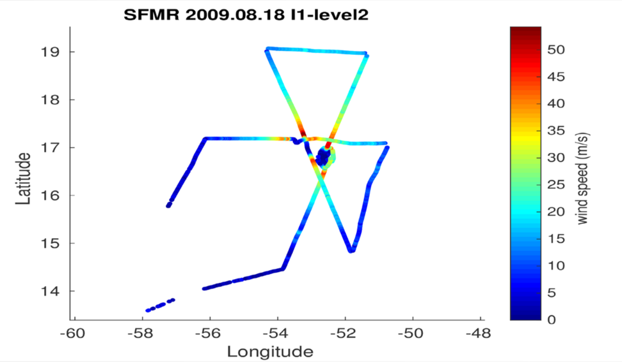
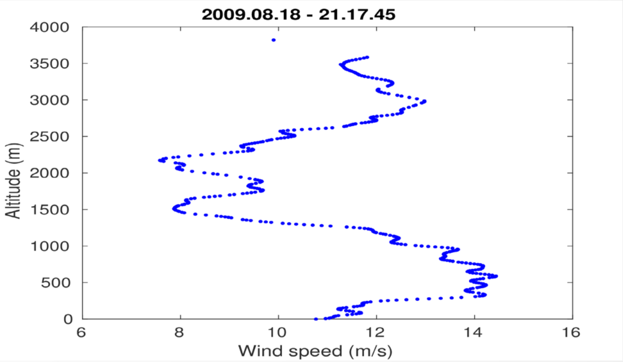
- Aim: To adjust radiometers & scatterometers high & extreme winds using SFMR (2010-2020)
  - **OSI SAF**: ASCAT-A, -B & -C, Rapidscat, OSCAT, OSCAT2, HY-2A & -2B
  - **REMSS**: Windsat (v7), AMSR-2 (v8), SMAP (v1)
  - **Ifremer**: SMOS (v2)
- Assess spatial representativeness
  - Look for suitable SFMR upscaling for each SCAT & RAD
- Analyse QC effects
- Assess SFMR calibration
- Ensure inter-calibration among all satellite systems

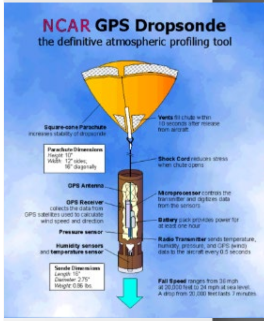
esa

SFMR & GPS Dropsonde









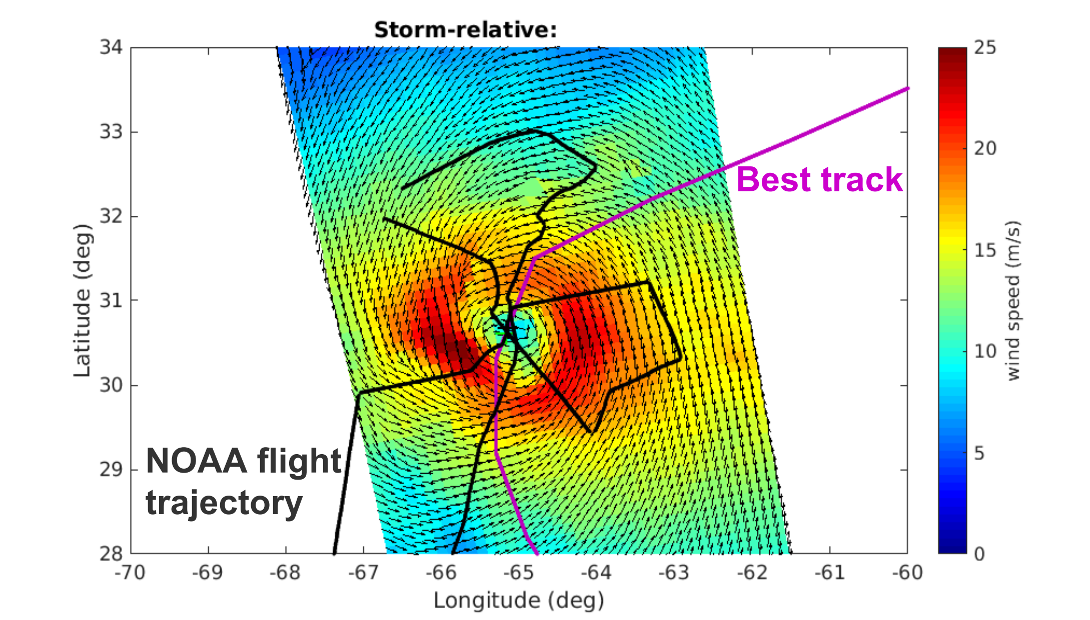
SFMR:

- Nadir-pointing radiometer at C-band.
- The equivalent neutral surface wind speed retrieved by inversion of a Geophysical Model Function.
- Surface wind retrieval are provided in **1-sec sampling** and the **aircraft position** is assigned to each wind retrieval.

Dropsondes:

- They provide the wind profile
- The 10m equivalent neutral surface wind speed and direction *empirically derived* by the **WL150 algorithm**.
- Surface wind value consists in an **height-weighted average** of the dropsonde readings available within the lowest **150m-layer** between 10m and 350m.

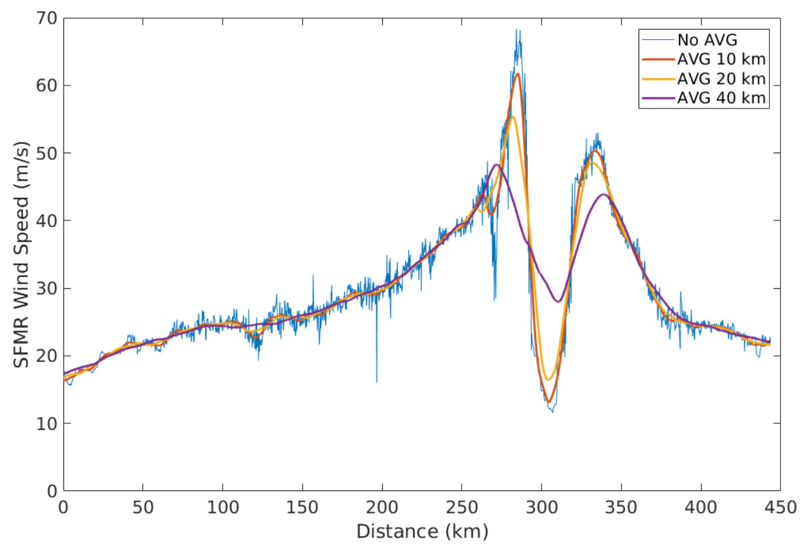
Triple collocations SFMR-SAT-Model



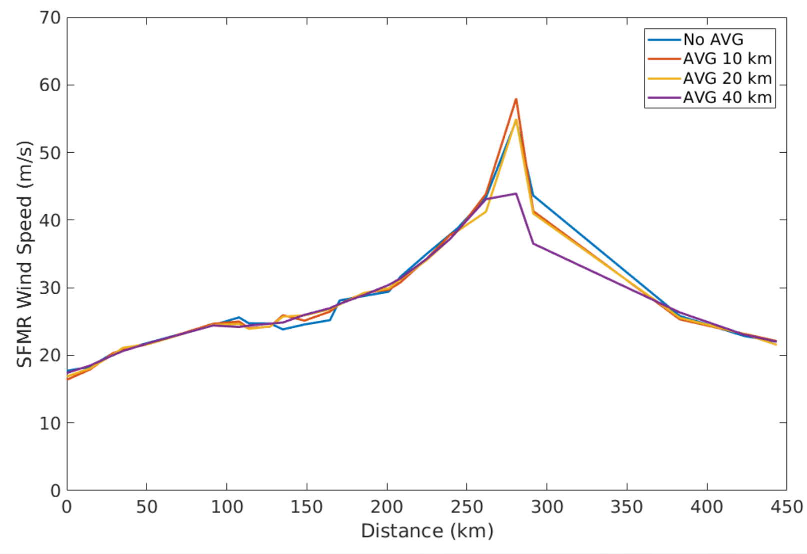
ASCAT wind field over Hurricane Karl on September 23rd, 2016

- SFMR collocations in storm-motion centric coordinates
- Model (ECMWF/MM) spatially and temporally interpolated to the Satellite wind field

SFMR upscaling effects



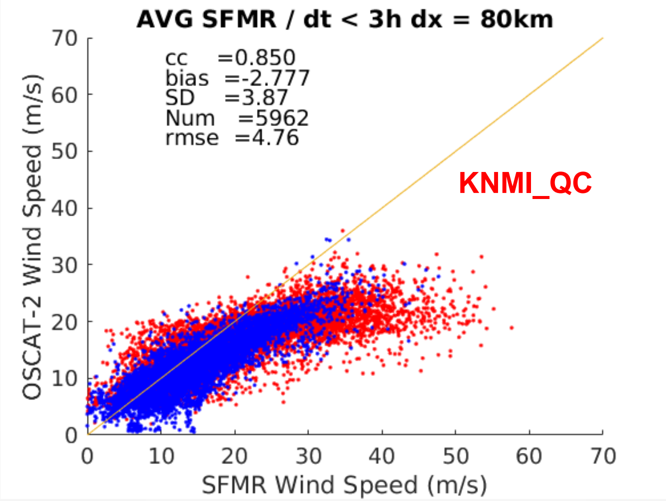
SFMR upscaling effects at SFMR 1-sec sampling



SFMR upscaling effects at 12.5 km sampling

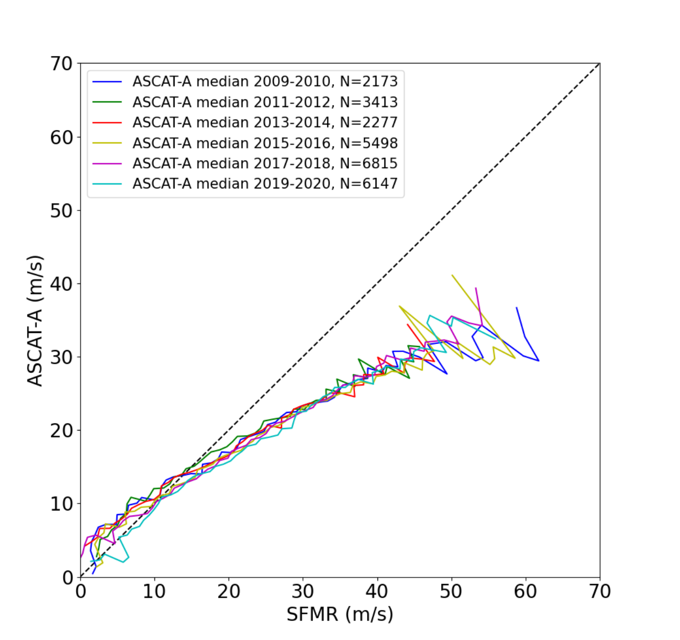
- ***SFMR upscaling effects are significantly smaller at 12.5-km (ASCAT-A) sampling***

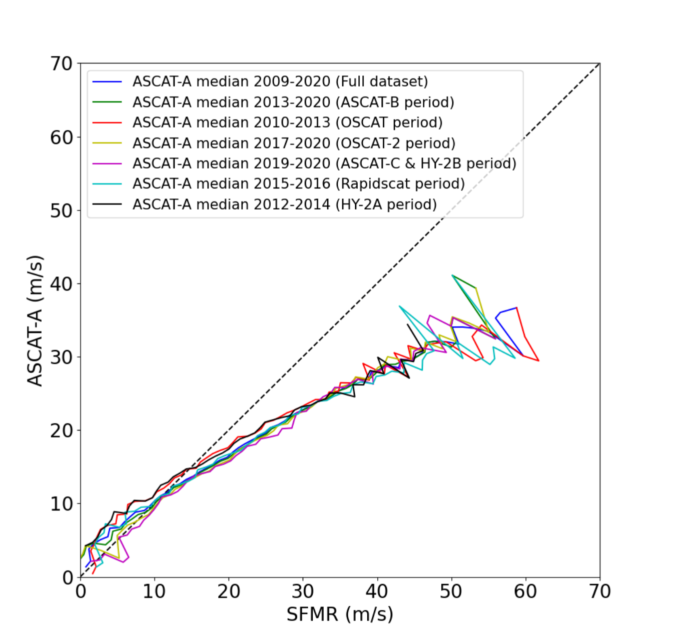
Ku-band QC effects



- ***Rain contamination filtered out by KNMI_QC; but then, only few extreme wind points left***

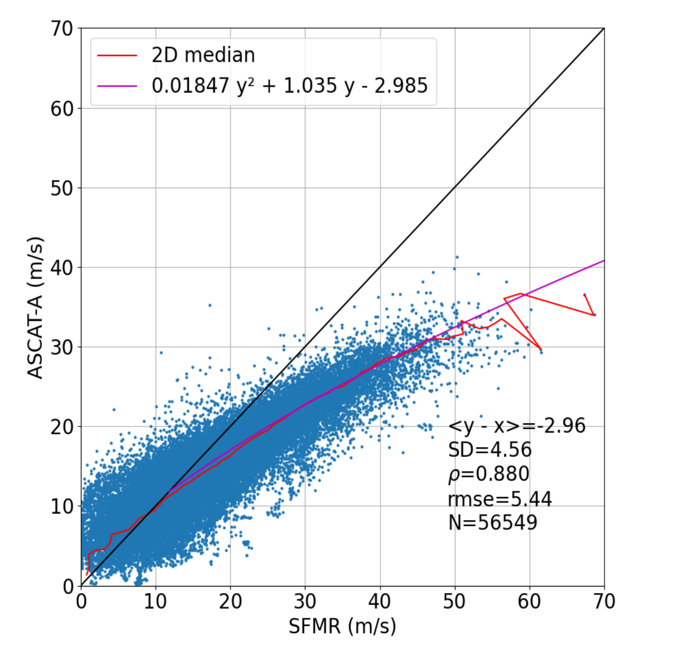
SFMR calibration effects





- ***SFMR calibration variations of up to 2 m/s between the range 15-30 m/s***

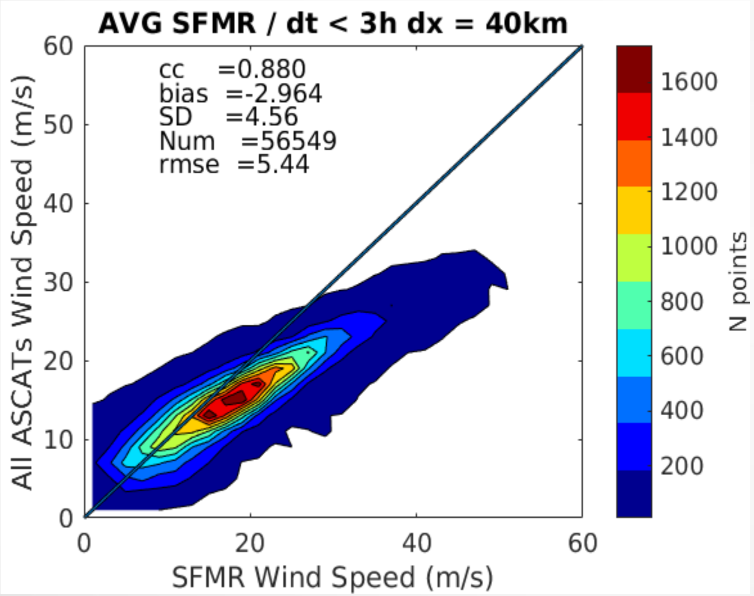
C-band scatterometer extreme wind adjustment



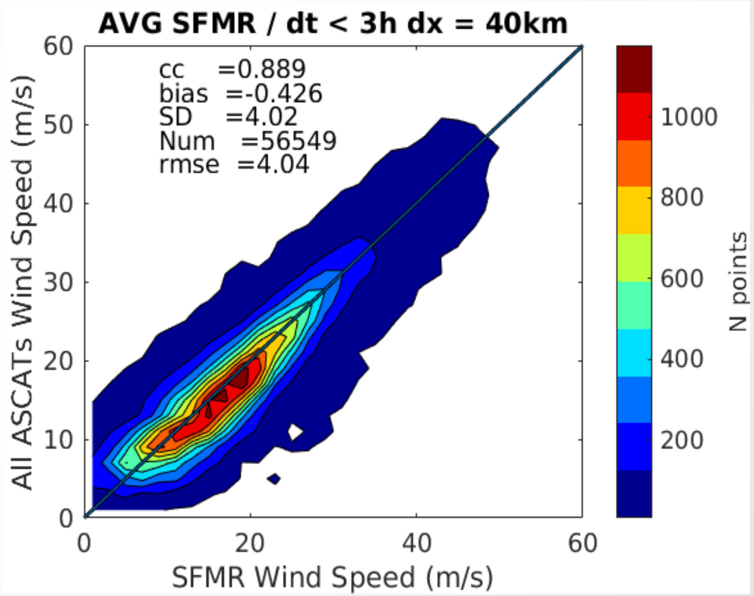
- ***Assume a mean SFMR calibration by using the full 2009-2020 period***
- ***Assume all ASCATs well intercalibrated***

Extreme wind adjustment using SFMR as reference

Original ASCAT winds

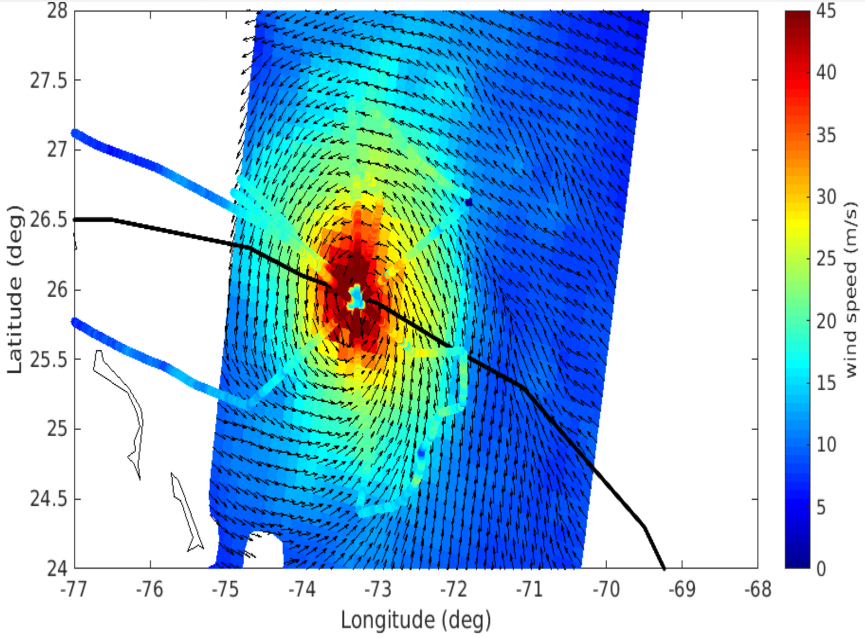


Adjusted ASCAT winds



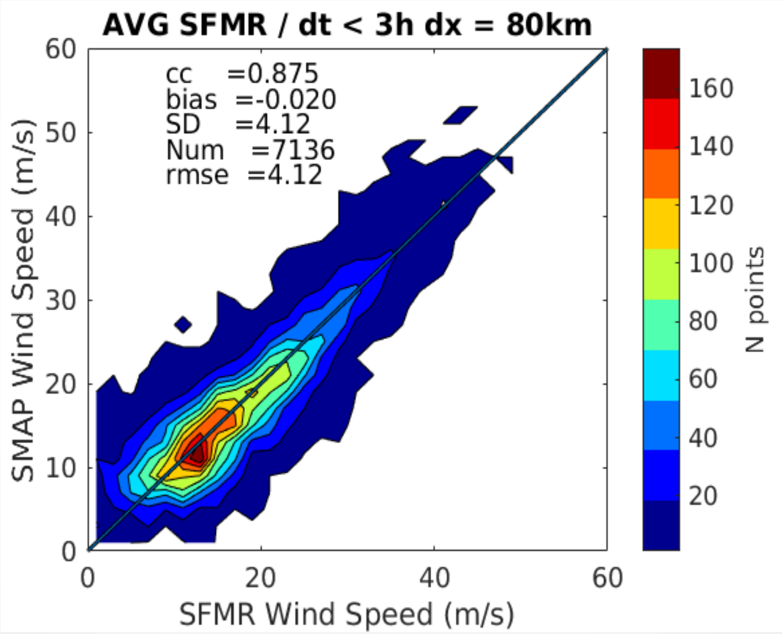
- *All scatterometer & radiometer winds adjusted using SFMR as reference*
- *A similar exercise is done with ERA5; the MM product is already adjusted by definition*

ASCAT extreme wind adjustment



ASCAT adjusted wind field over Hurricane Dorian using SFMR winds as calibration reference

Radiometer extreme wind adjustment



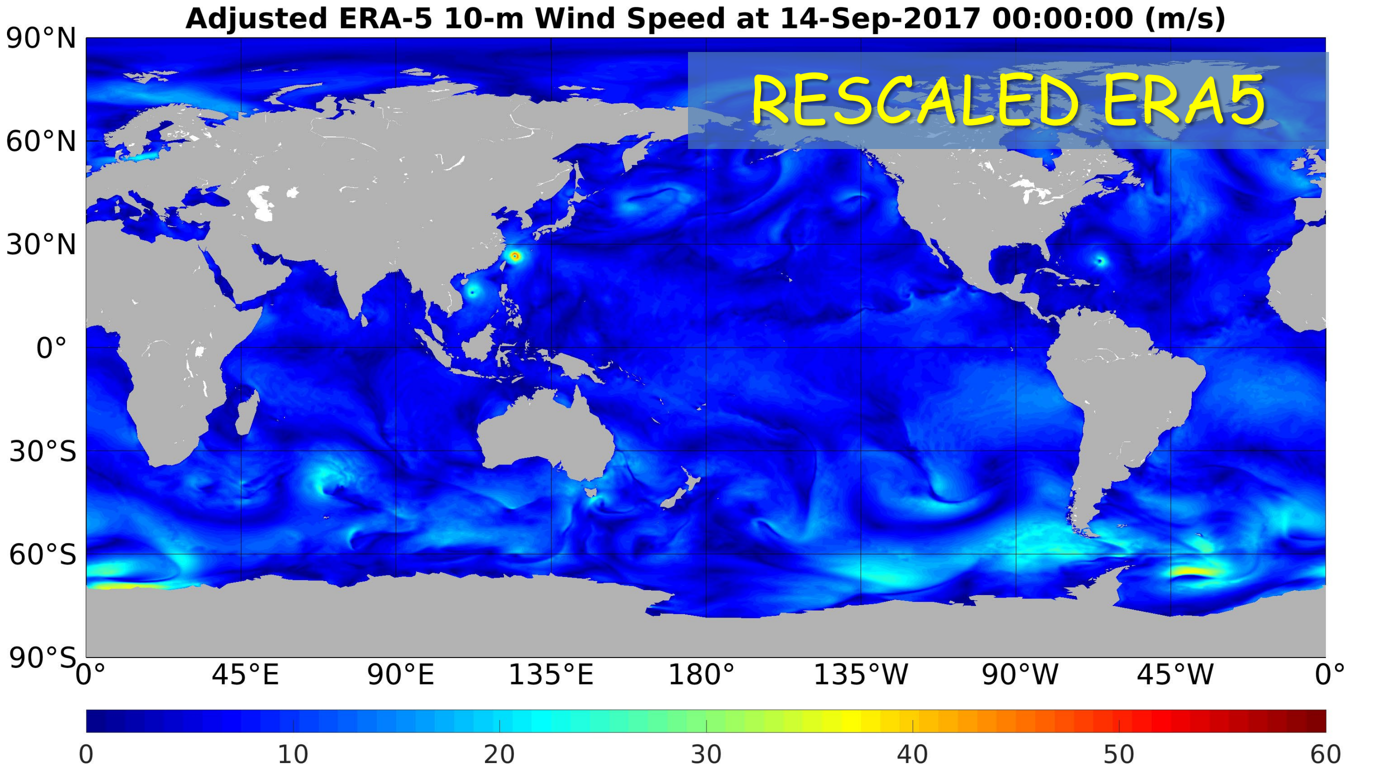
- ***SMAP winds show good correlation although a slight overestimation at extremes w.r.t. SFMR***
- ***SFMR based fitting leads to more consistent (adjusted) SMAP winds***

ESA MAXSS project:
Extreme wind inter-calibration & validation

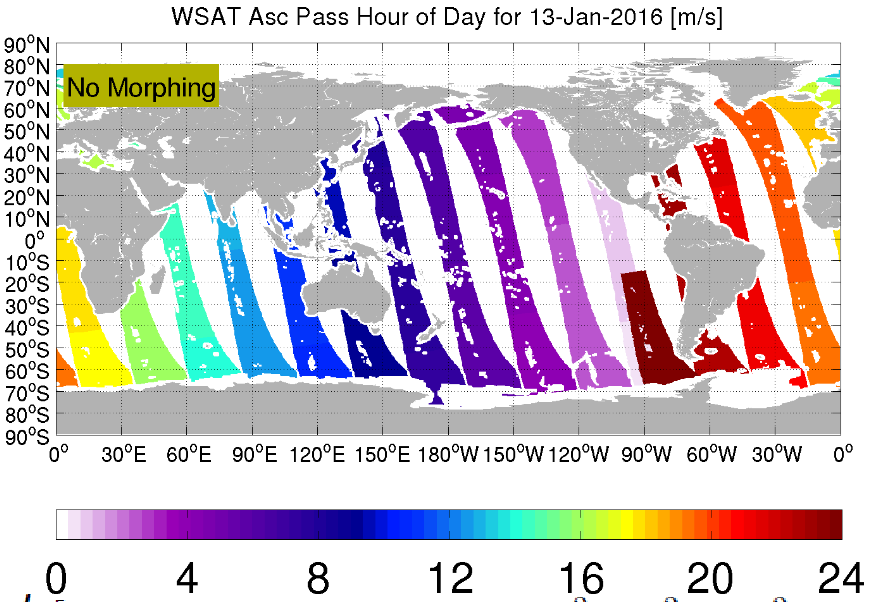
- Aim: To develop and validate the triple collocation method for extreme wind error characterization of the multi mission (MM) product
- Prior to this, to carry out triple collocation analysis to assess the quality of SCAT & RAD extreme wind data used as input to MM
- Focus on the tropical region, where triple collocation analysis is possible & wind adjustment is meaningful
- RapidSCAT (RSCAT) not used as input to MM in order to verify its quality using SFMR-RSCAT-MM triple collocations
- Intercomparison of RSCAT-MM under ETC conditions

EXAMPLE: ERA5 VS BLENDED WIND SPEED

ERA5 hourly wind fields are first rescaled and then used as the background for the blended wind field calculation:

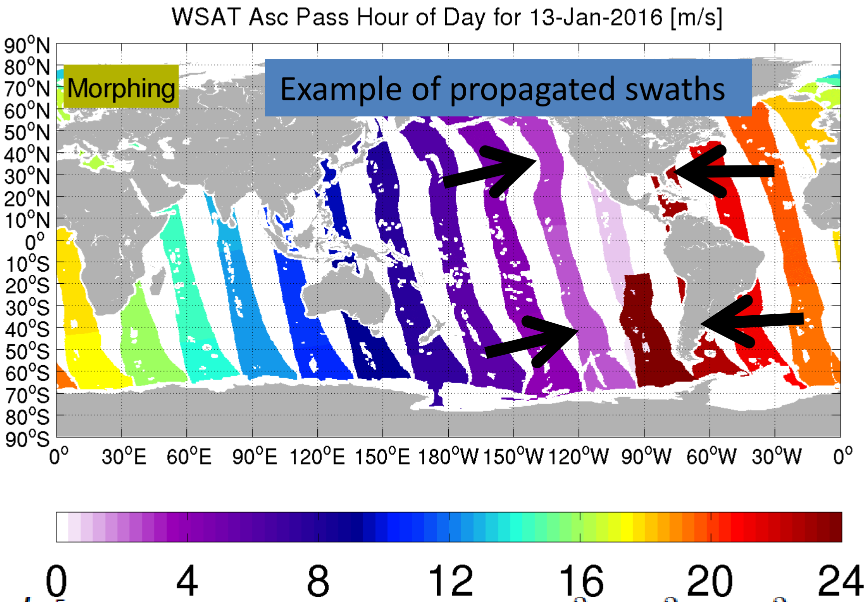


MORPHING-BASED TEMPORAL ADJUSTMENT OF SENSOR WINDS TO ANALYSIS TIME



$$J(u,v) = \int_{\Omega} \left[(I_1(x,y) - I_2(x+h_x, y+h_y))^2 + \alpha^2 (|\nabla u|^2 + \nabla v^2) \right] \, dx \, dy.$$

MORPHING-BASED TEMPORAL ADJUSTMENT OF SENSOR WINDS TO ANALYSIS TIME



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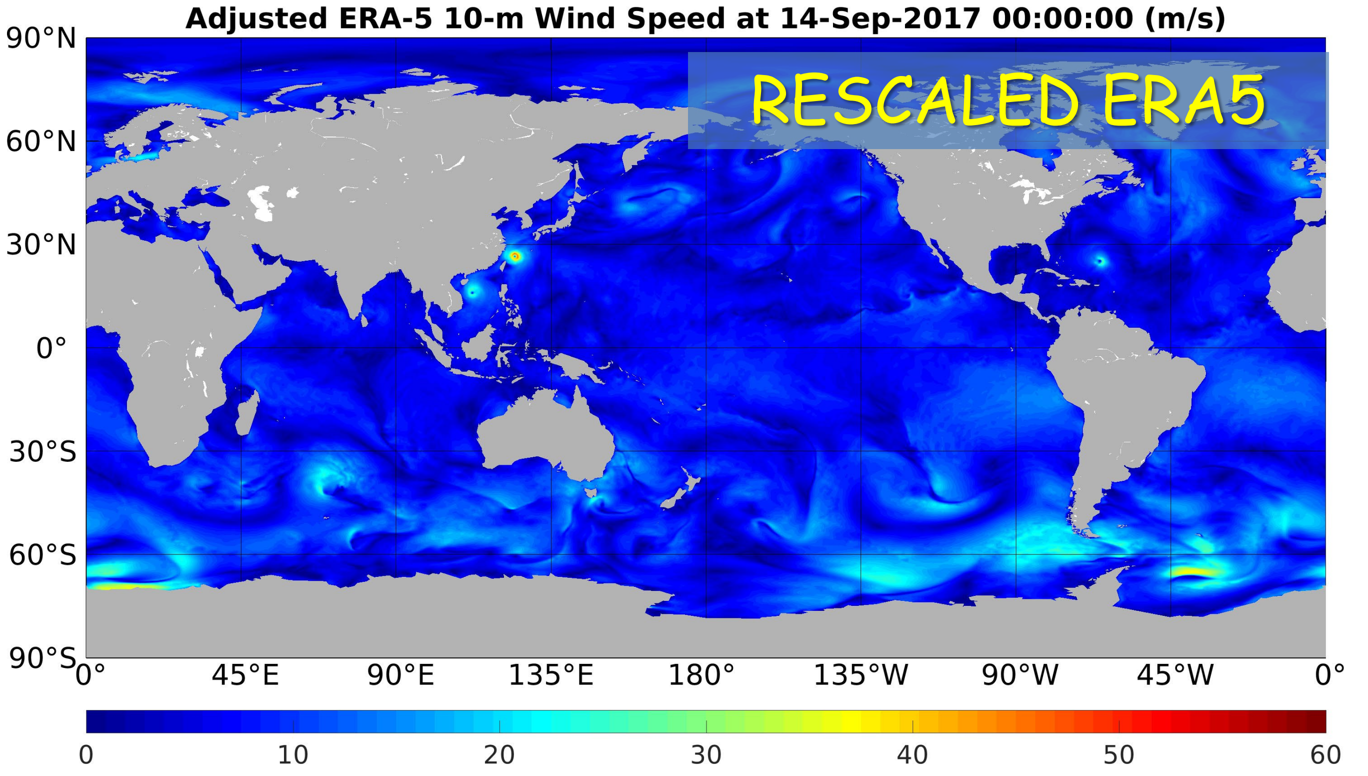

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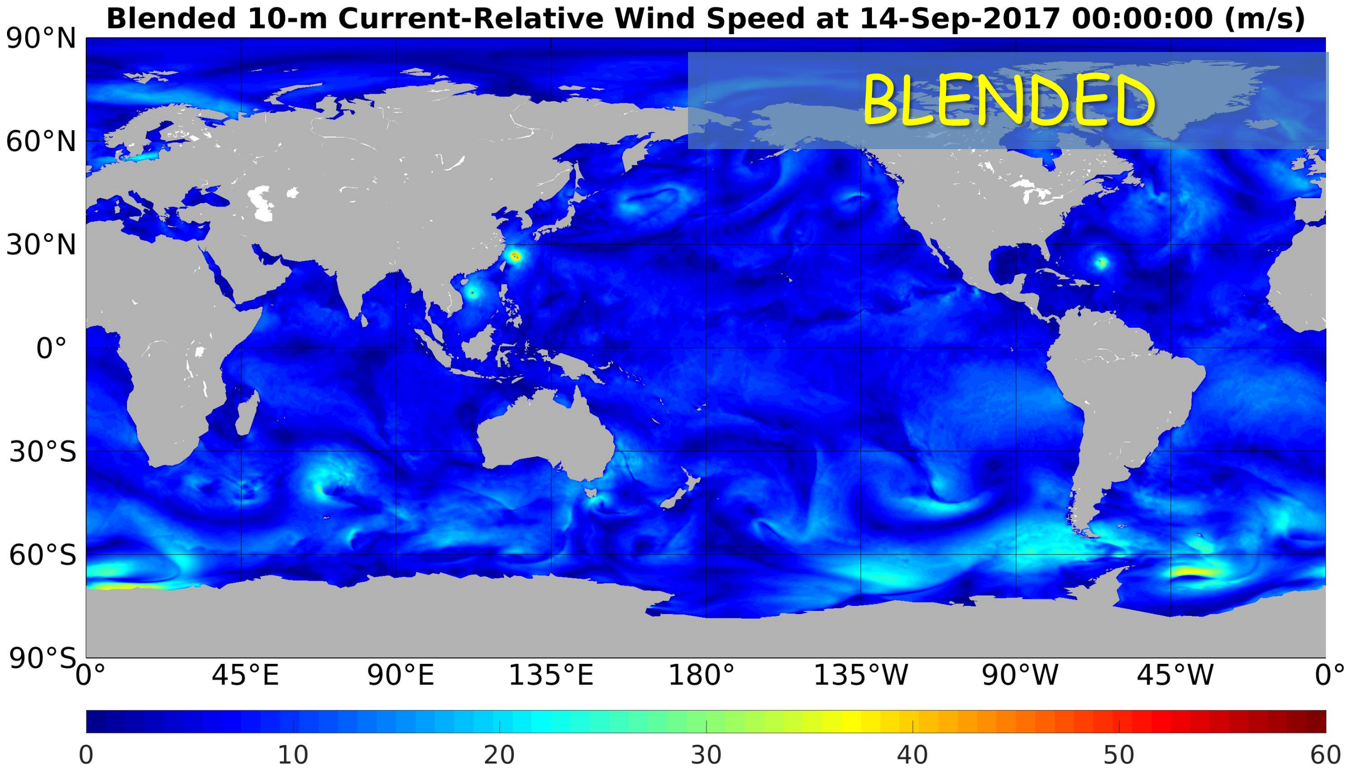


Triple collocation analysis

The three wind sources are intercalibrated and their measurement errors estimated with the triple collocation analysis:

$$x_i = a_i(t + \varepsilon_i) + b_i$$

Error model: x_i is the wind measured by system i =1,2,3; t is the true wind signal; ε_i is the measurement error for each system; a_i and b_i are the calibration coefficients.

$$M_i = \langle x_i \rangle; \quad M_{ij} = \langle x_i x_j \rangle$$
$$C_{ij} = M_{ij} - M_i M_j$$
$$T = \frac{C_{12} C_{13}}{C_{23}} - r^2$$

M_i and M_{ij} are the first and second order moments; C_{ij} are the covariances; T is the common variance; r^2 is the representativeness error.

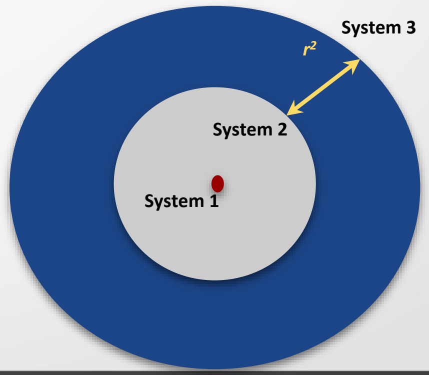
Stoffelen, 1998; Vogelzang et al., 2021

Calibration coefficients:

$$a_1 = 1; \quad b_1 = 0$$
$$a_2 = \frac{C_{23}}{C_{13}}; \quad b_2 = M_2 - a_2 M_1$$
$$a_3 = \frac{C_{13}}{T}; \quad b_3 = M_3 - a_3 M_1$$

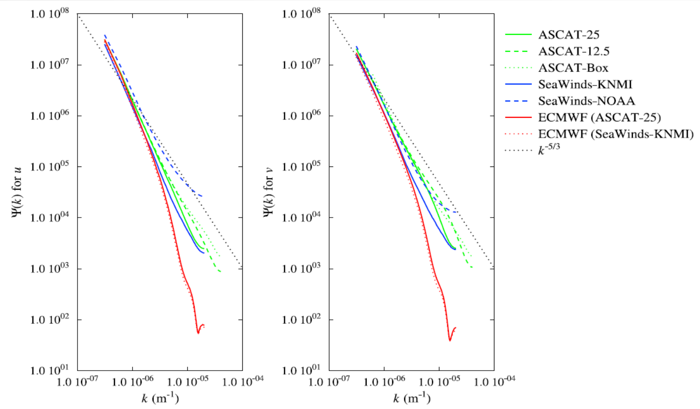
Measurement errors:

$$\sigma_1^2 = \frac{C_{11}}{a_1^2} - T - r^2$$
$$\sigma_2^2 = \frac{C_{22}}{a_2^2} - T - r^2$$
$$\sigma_3^2 = \frac{C_{33}}{a_3^2} - T$$



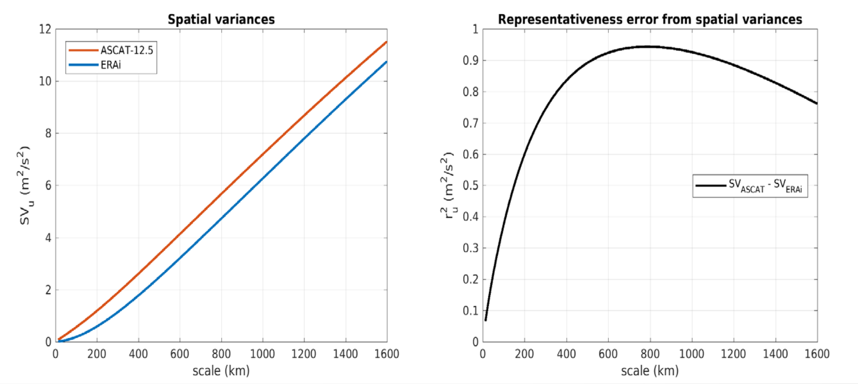
Representativeness error estimation

Power density spectra



Vogelzang et al., 2011

Spatial variances



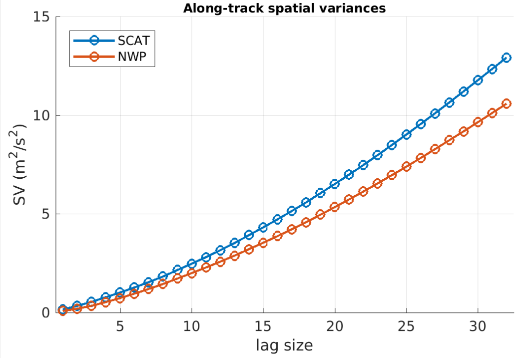
$$V_s(n) = E[M_{ss}(n) - M_s^2(n)]$$

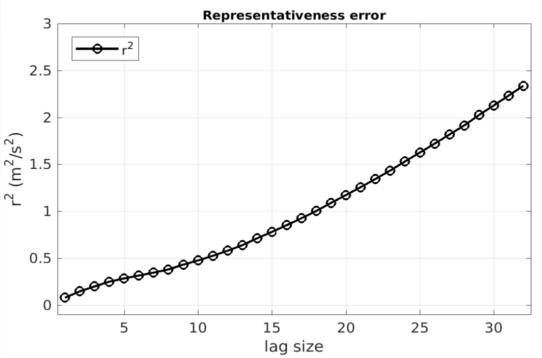
Vogelzang et al., 2015

Spatial variances are:

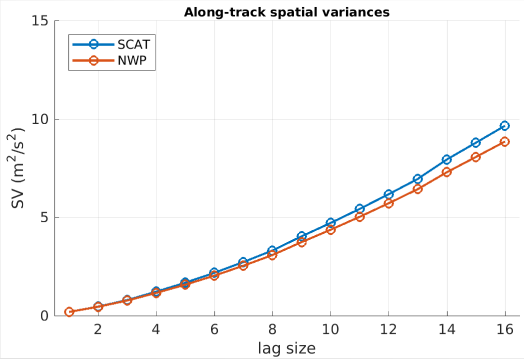
- A more reliable measure of the wind variance as a function of scale
- More tolerant to missing points (QC)

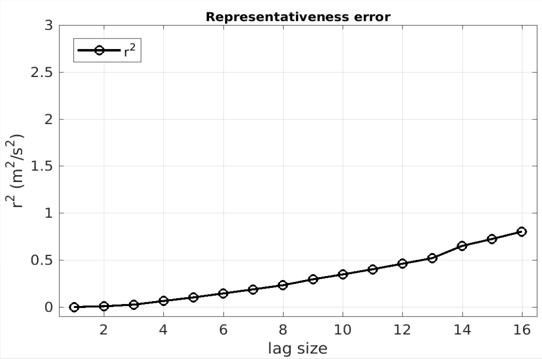
Spatial variance analysis





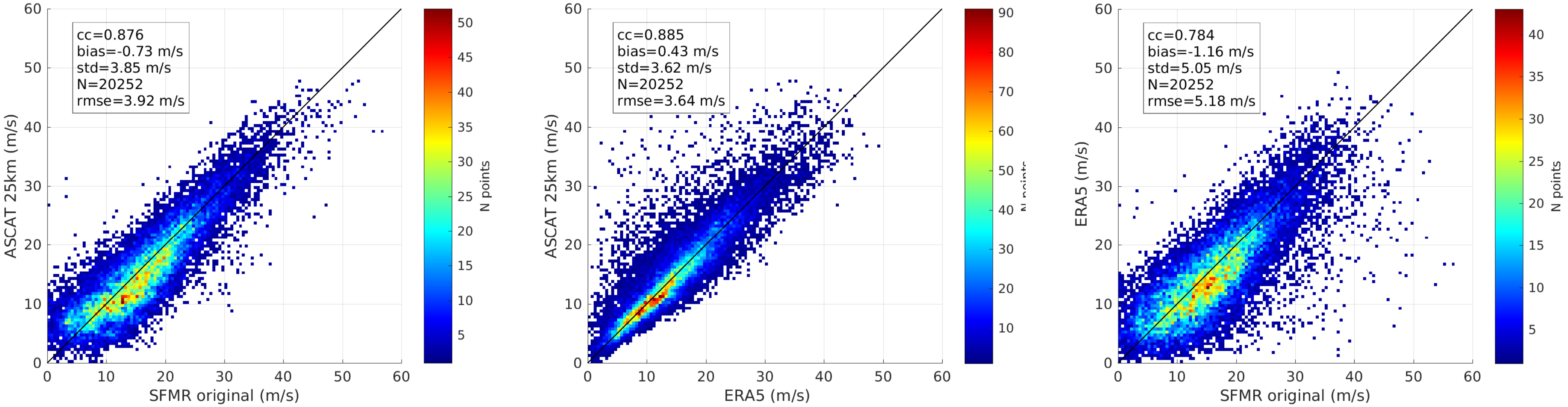
- ASCAT 12.5km – ERA5
- r^2 ~ 0.8m^2/s^2 at 200 km scales





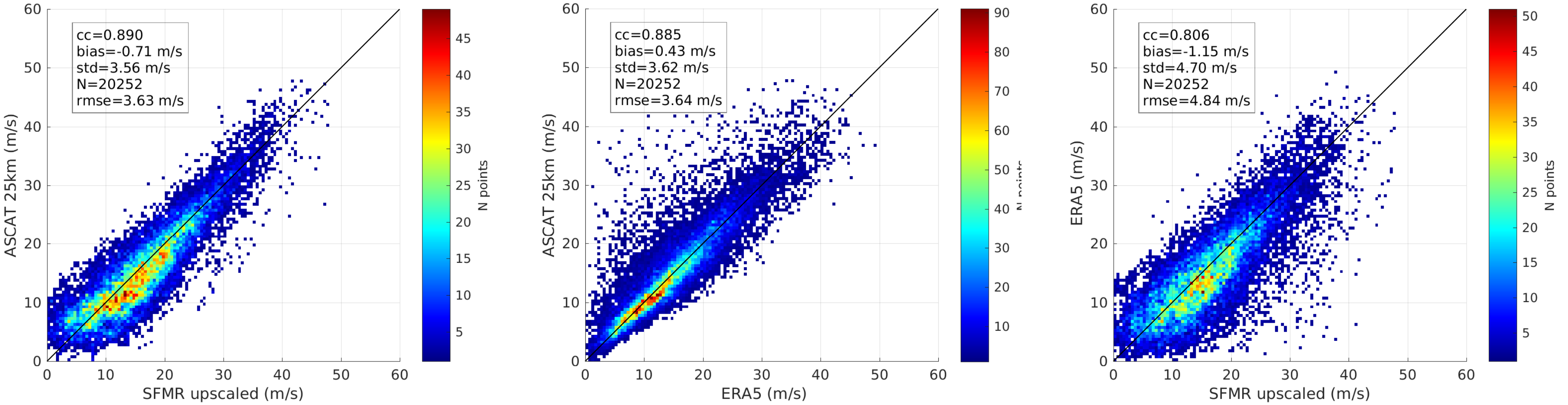
- ASCAT 25km – ERA5
- r^2 ~ 0.3m^2/s^2 at 200 km scales

Density plots triple collocation sources (SFMR-ASCATs-ERA5)



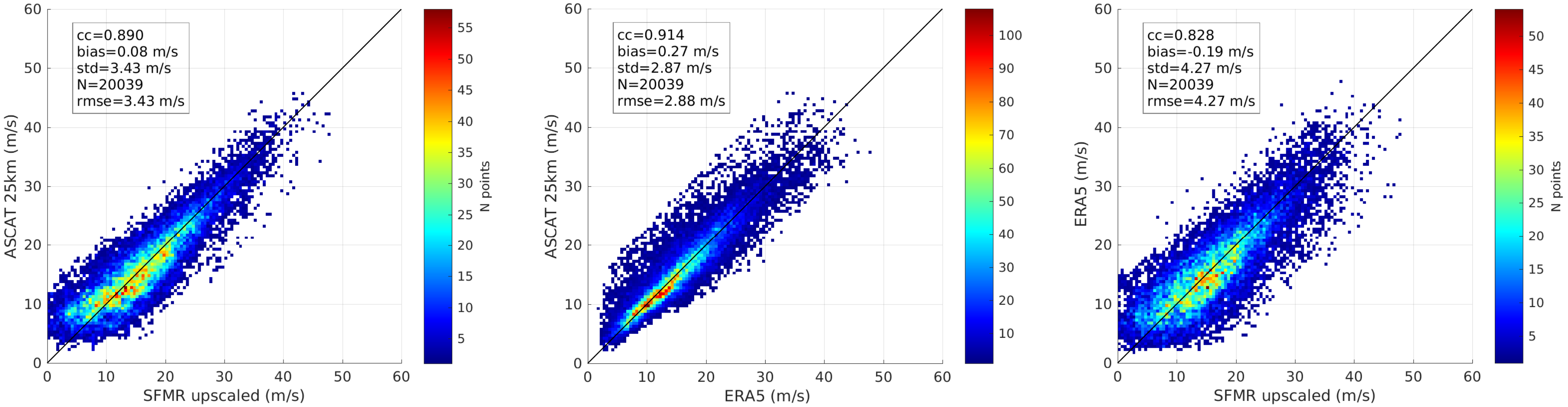
- SFMR **original** winds (100-m sampling)
- ERA5 large errors are apparent

Density plots before triple collocation analysis ($SFMR_{upscaled}$-ASCATs-ERA5)



- SFMR **upscaled** winds (80-km along-track averaging)
- Reduced scatter on left & right plots due to SFMR upscaling

Density plots triple collocation sources



- SFMR **upscaled** winds
- We take calibration coefficients from 2-sigma test and apply them to Triple collocation calibration using 4-sigma test (QC) & r^2=0.3 m^2/s^2

Triple collocation analysis

Barcelona Expert Center

Error estimates (at ERA5 spatial scales; r^2=0.3 m^2/s^2)

	SFMR (m/s)	ASCAT25 (m/s)	ERA5 (m/s)
SFMR **original**	3.60	0.85	2.77
SFMR **upscaled**	3.30	0.93	2.75

- Errors computed at **100-150 km scales**
- SFMR errors reduced when upscaled as expected

Triple collocation analysis

Error estimates (at ERA5 spatial scales; r^2=0.3 m^2/s^2)

	SFMR (m/s)	Scatterometer (m/s)	ERA5 (m/s)
RSCAT	3.50	1.55	2.56
OSCAT	3.11	2.07	2.83
OSCAT-2	3.27	1.84	2.37
HSCAT-A	2.99	1.44	2.73
HSCAT-B	3.26	1.47	2.00

Summary scatterometer errors

Number of points (after 4-sigma test) for each triple collocated SFMR-Scatterometer-ERA5 set

	ASCATs (m/s)	RSCAT (m/s)	OSCAT (m/s)	OSCAT-2 (m/s)	HSCAT-A (m/s)	HSCAT-B (m/s)
Number	20039	1513	4921	10678	3041	4979

- Each SFMR-Scatterometer-ERA5 collocated set samples different weather; some sets contain poor sampling
- Mean weighted variance and associated spread for SFMR & ERA5 errors computed
- Such spread is used to compute error bars for scatterometer uncertainty estimates

Summary scatterometer errors

Barcelona Expert Center

Error estimates (at ERA5 spatial scales; r^2=0.3 m^2/s^2)

	ASCATs (m/s)	RSCAT (m/s)	OSCAT (m/s)	OSCAT-2 (m/s)	HSCAT-A (m/s)	HSCAT-B (m/s)
Error SD	0.93 ± 0.10	1.55 ± 0.16	2.07 ± 0.22	1.84 ± 0.19	1.44 ± 0.15	1.47 ± 0.16

Summary radiometer errors

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Error estimates (at ERA5 spatial scales; r^2=0.3 m^2/s^2)

	AMSR2 (m/s)	Windsat (m/s)	SMAP (m/s)	SMOS (m/s)
Error SD	2.60 ± 0.16	2.87 ± 0.18	1.96 ± 0.12	2.10 ± 0.13

Triple collocation analysis

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Error estimates (at ERA5/MM spatial scales ; r^2=0.3 m^2/s^2)

	SFMR (m/s)	RSCAT (m/s)	ERA5 (m/s)
SFMR **upscaled**	3.50	1.55	2.56

	SFMR (m/s)	RSCAT (m/s)	MM (m/s)
SFMR **upscaled**	3.39	1.67	1.64

- Substantial reduction in error variance of MM w.r.t. that of ERA5
- Uncertainty in the uncertainty estimates non-negligible though

Triple collocation analysis

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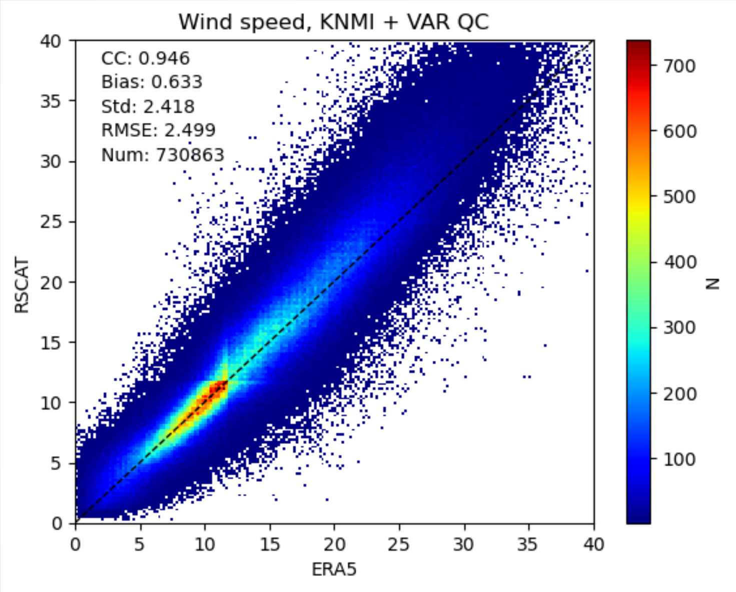
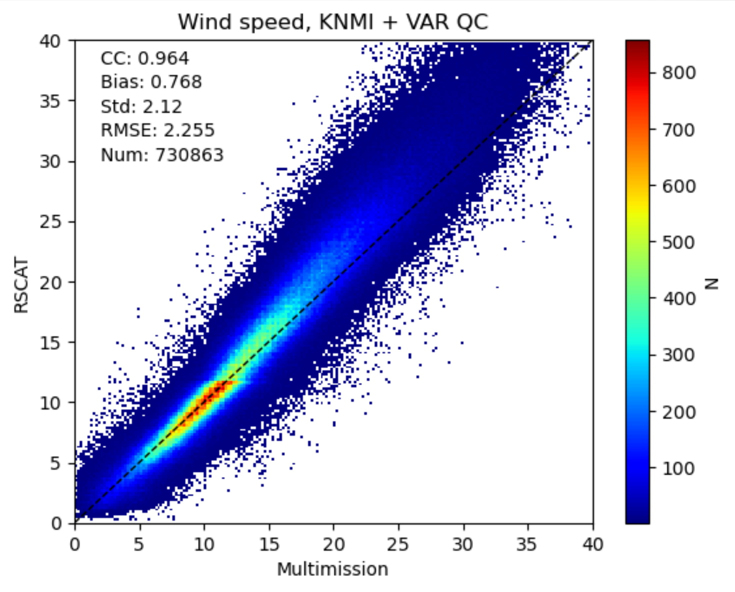
Error estimates (at ERA5/MM spatial scales)

	SFMR (m/s)	ERA5 (m/s)	Multi-Mission (m/s)
Error SD	3.41±0.23	2.66±0.23	1.64±0.17

- Errors given at **100-150 km scales**
- MM random errors **substantially smaller** than ERA5 errors

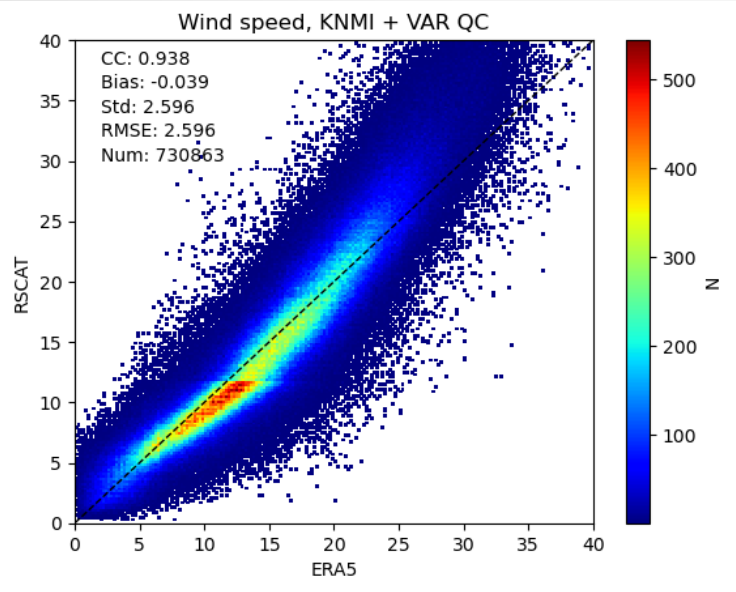
Intercomparison RSCAT-ERA5-MM
(Extra-tropical cyclone regions)

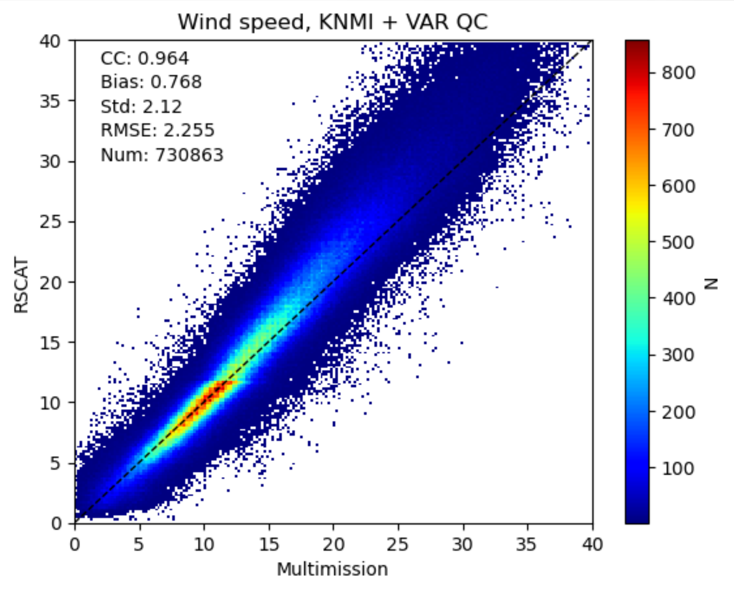




- No in-situ reference in ETCs; SFMR-based adjustment needs to be removed from all sources
- MM closer to RSCAT (independent reference in ETCs) than ERA5
- **Joint MM/RSCAT variance 23% smaller than that of ERA5/RSCAT**

Intercomparison RSCAT-ERA5-MM
(Extra-tropical cyclone regions)

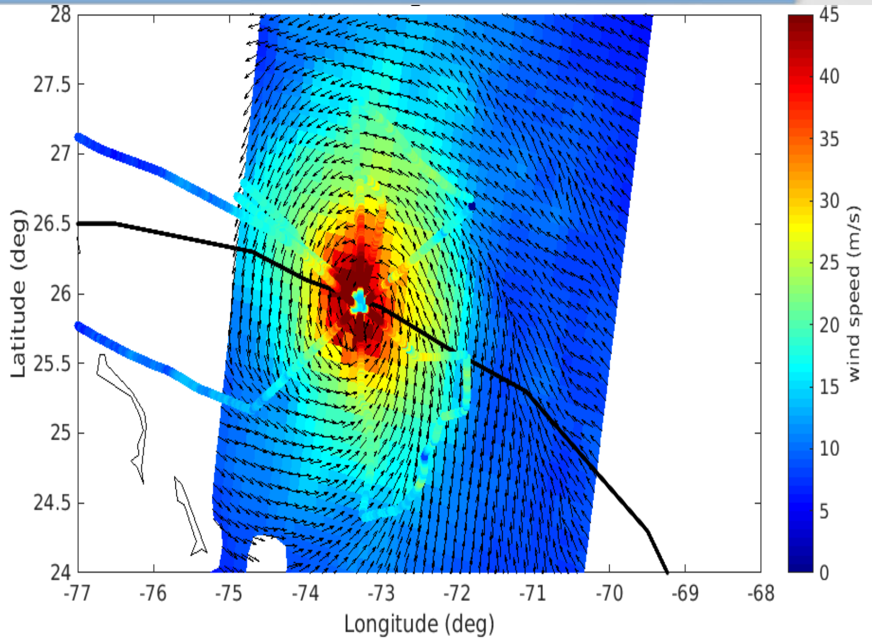




- **New ERA5 adjustment** under TC conditions shows poor agreement with RSCAT for ETC conditions
- New ERA5 adjustment based on SFMR upscaled, while old adjustment is the same as used for all scatterometer systems
- Storm phase shift effects? ERA5 poorly resolved physical processes under TC conditions?

Extreme wind inter-calibration

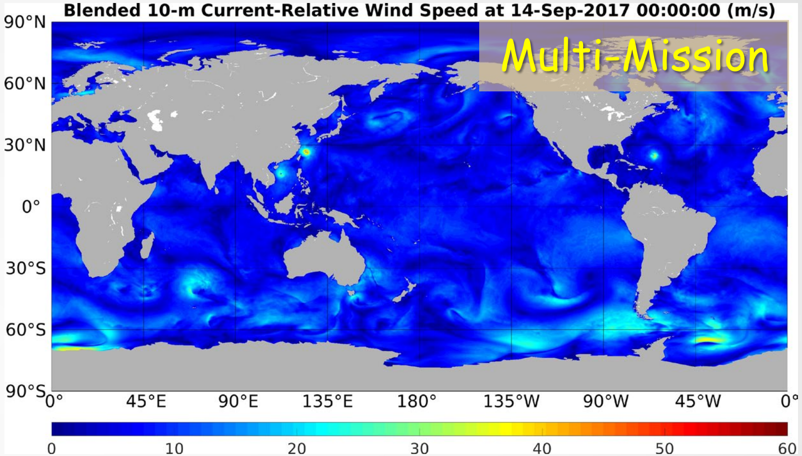
- Adjustment of scatterometers & radiometers high & extreme winds using SFMR/dropsondes (2010-2020)
  - ***OSI SAF**: ASCAT-A, -B & -C, Rapidscat, OSCAT, OSCAT2, HY-2A & HY-2B*
  - ***REMSS**: Windsat (v7), AMSR-2 (v8), SMAP (v1)*
  - ***Ifremer**: SMOS (v2)*
- Accounting for spatial representativeness and QC effects
- Addressing SFMR calibration variations
- Ensuring inter-calibration among all satellite systems
- The L2 adjusted wind products are available on the ESA MAXSS study webpage (https://www.maxss.org/Products/MAXSS-Product-Catalogue)



ASCAT adjusted wind field over Hurricane Dorian using SFMR winds as calibration reference

Extreme wind validation

- Triple collocation analysis for the following
  - *SFMR-Scatterometer-ERA5*
  - *SFMR-Radiometer-ERA5*
  - *SFMR-RapidSCAT-ERA5/MM*
- Estimation of spatial representativeness errors using spatial variance analysis
- ASCAT winds have the lowest errors
- Ku-band winds are higher, although some rain contamination is present
- Radiometer winds contain the highest errors in general, with SMAP wind quality comparable to the noisiest scatterometers (OSCATs)
- The Multi-Mission (MM) wind quality is substantially higher than that of ERA5, and comparable to that of Ku-band winds (also under ETC conditions)



	ASCATs (m/s)	RSCAT (m/s)	OSCAT (m/s)	OSCAT-2 (m/s)	HSCAT-A (m/s)	HSCAT-B (m/s)
Error	0.93±0.10	1.55±0.16	2.07±0.22	1.84±0.19	1.44±0.15	1.47±0.16

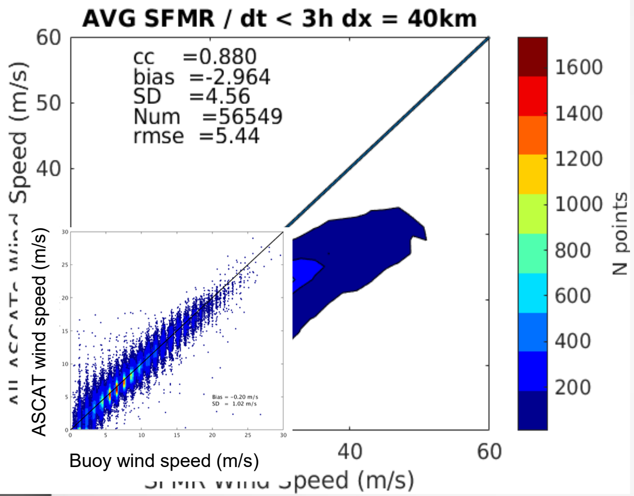
	AMSR2 (m/s)	Windsat (m/s)	SMAP (m/s)	SMOS (m/s)
Error	2.60±0.16	2.87±0.18	1.96±0.12	2.10±0.13

	SFMR (m/s)	ERA5 (m/s)	Multi-Mission (m/s)
Error	3.41±0.23	2.66±0.23	1.64±0.17

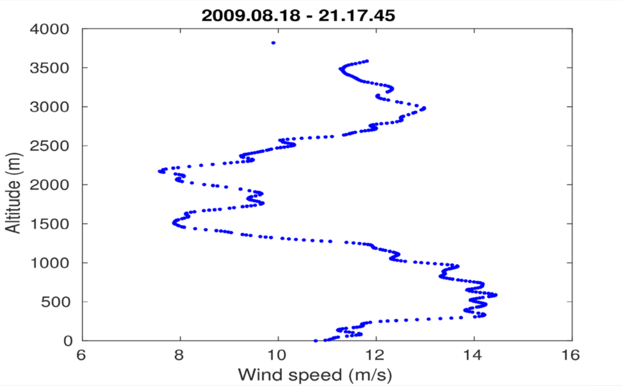
Future work

- Improve wind adjustment for Ku-band systems by revising QC effects
- Apply extreme wind adjustment to new scatterometer systems after 2020 (HY-2C, HY-2D, OSCAT3, WindRAD)
- Apply storm translation onto ERA5 to match scatterometer & radiometer storm centres
- Repeat triple collocation analysis SFMR-RSCAT-ERA5 for ERA5 used in MM generation
- Improve wind adjustment for ERA5; contribute to wind "unadjustment" of MM under ETC conditions
- Improve spatial variance analysis under TC conditions
- Spatial analysis on adjusted scatt & rad fields: wind radii, derivatives (divergence, curl)
- IWRAP data exploitation to analyze the consistency between sea surface wind fields (scatt, rad, ERA5, MM) and those aloft (IWRAP)

Can we reconcile dropsonde and buoy measurements?



Dropsondes



Dropsondes

- ASCAT nominal winds calibrated against buoys
- Dropsonde & buoy scales increasingly differ above 10 m/s
- **Which one should we trust?**

- Strong deceleration close to the Surface
- Height assignment errors
- Sampling frequency

- Work well up to 25 m/s
- Few measurements under TC conditions
- Wave effects?

Scatterometer data availability (2010-2020)

BEC
Barcelona Expert Center

Scatterometer systems	FORMAT	PERIOD	SOURCE	FREQUENCY
ASCAT-A	BUFR/NetCDF	Full period	OSI SAF	C-band
ASCAT-B	BUFR/NetCDF	11/2012 – 12/2020	OSI SAF	C-band
ASCAT-C	BUFR/NetCDF	01/2019 – 12/2020	OSI SAF	C-band
OceanSat-2	BUFR/NetCDF	01/2010 - 02/2014	OSI SAF	Ku-band
RapidScat	BUFR/NetCDF	11/2014 - 08/2016	OSI SAF	Ku-band
Scatsat-1	BUFR/NetCDF	01/2017 – 12/2020	OSI SAF	Ku-band
HY-2A	BUFR/NetCDF	06/2012 - 04/2015	OSI SAF	Ku-band
HY-2B	BUFR/NetCDF	01/2019 – 12/2020	OSI SAF	Ku-band
HY-2C	BUFR/NetCDF	11/2020 – 12/2020	OSI SAF	Ku-band
CFOSAT	BUFR/NetCDF	01/2019 – 12/2020	OSI SAF	Ku-band

Radiometer data availability (2010-2020)

Radiometers	FORMAT	PERIOD	SOURCE	FREQUENCY
SMOS	NetCDF-4	Full period	IFREMER	L-band
SMAP	Bytemap	04/2015 – 12/2020	REMSS	L-band
WindSat	Bytemap	01/2010 – 10/2020	REMSS	Channels (GHz): 6.8; 10.7; 18.7; 23.8; 37.0
AMSR2	Bytemap	07/2012 – 12/2020	REMSS	Channels (GHz): 6.93; 7.3; 10.65; 18.7; 23.8; 36.5; 89.0
SSMI / SSMIS	Bytemap	Full period	REMSS	Channels (GHz): 19.35; 23.235; 37.0; 85.5
GMI	Bytemap	03/2014 – 12/2020	REMSS	Channels (GHz): 10.65; 18.7; 23.8; 36.5; 89.0; 165.5; 183.31
TMI	Bytemap	01/2010 – 12/2014	REMSS	Channels (GHz): 10.65; 19.35; 21.3; 37.0; 85.5
AMSRE	Bytemap	01/2010 - 10/2011	REMSS	Channels (GHz): 6.93; 10.65; 18.7; 23.8; 36.5; 89.0