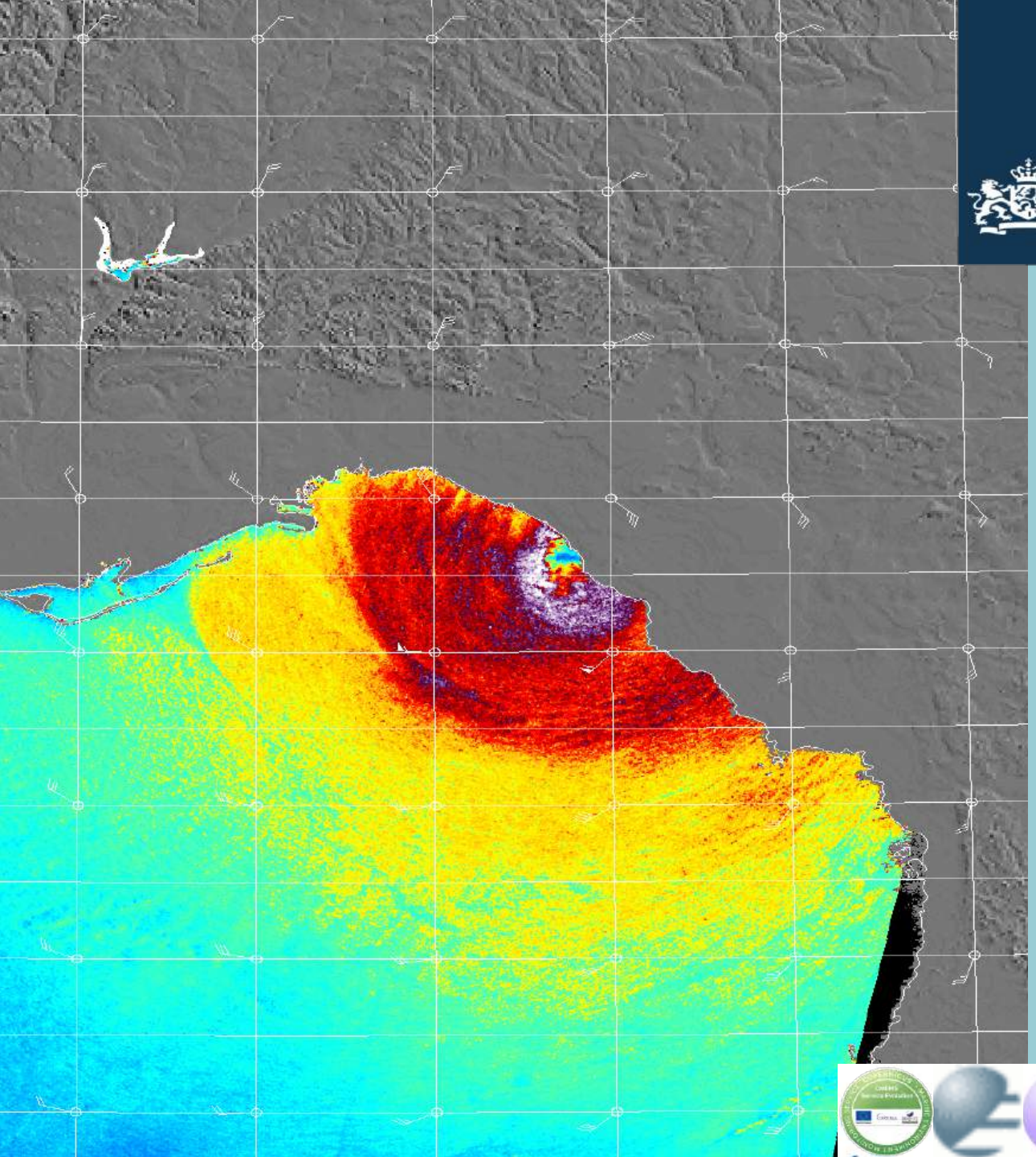


Royal Netherlands
Meteorological Institute
Ministry of Infrastructure and the Environment

SAR-learned Scatterometer Resolution Enhancement of Tropical Cyclones

Ad.Stoffelen@knmi.nl, Weicheng Ni,
Jur Vogelzang, Xingou Xu, Ke Zhao

Active Remote Sensing Group
Satellite Observations, KNMI

EUMETSAT OSI SAF
EU Copernicus Marine Services

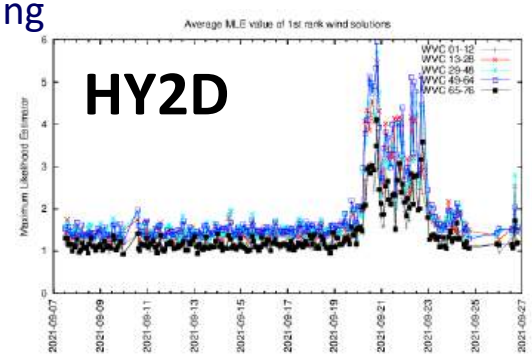
A constellation to track hurricanes

- ASCAT-A, MetOp-A : 2007- 2021 9:30 LST, End-of-service November 2021
- ASCAT-B, MetOp-B : 2012- healthy 9:30 LST
- ASCAT-C, MetOp-C : 2018- healthy 9:30 LST, Excellent for wind changes in convection
- OSCAT-2, ScatSat-1 : 2017- Feb 2021 8:45 LST, Excellent for Ku/C intercalibration
- OSCAT-3, OceanSat3 : Nov 2022 . . . 12:00 LST, in commissioning
- HSCAT-B, HY2B : 2018- healthy 6:00 LST
- HSCAT-C, HY2C : 2020- healthy Not sun-synchronous, regresses
- HSCAT-D, HY2D : 2021- healthy Regresses, development status
- CSCAT, CFOSAT : 2019- demo Stability issues, nadir issues
- WindRad, FY3E : 5/7/'21- healthy 5:30 LST, commissioning

➢ https://scatterometer.knmi.nl/proc_status/

- Vector wind CDRs for ERS (1991-1999), QuikScat (1999-2009), ASCAT (2007-), OSCAT (2014+), needed to monitor re-analyses
- Reanalyses are subject to changing inputs

➢ https://scatterometer.knmi.nl/archived_prod/



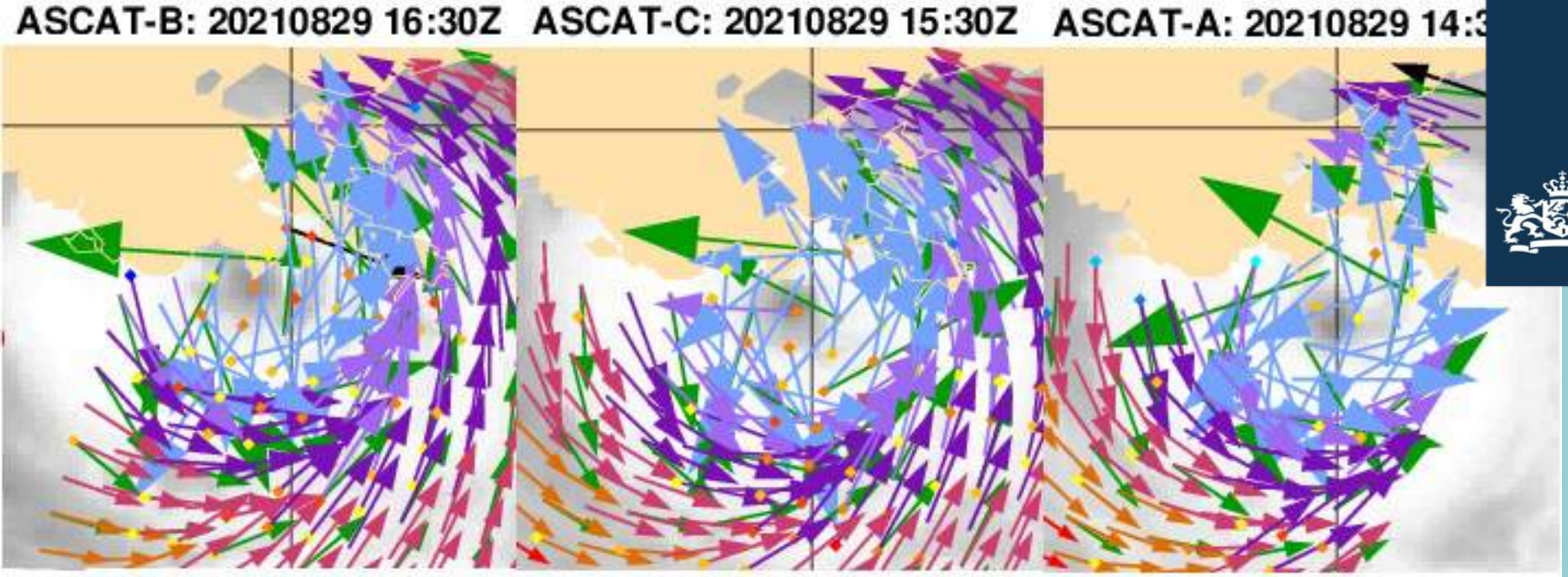
https://scatterometer.knmi.nl/hy2d_25_prod/index.php?cmd=monitoring&period=week&day=0&flag=yes

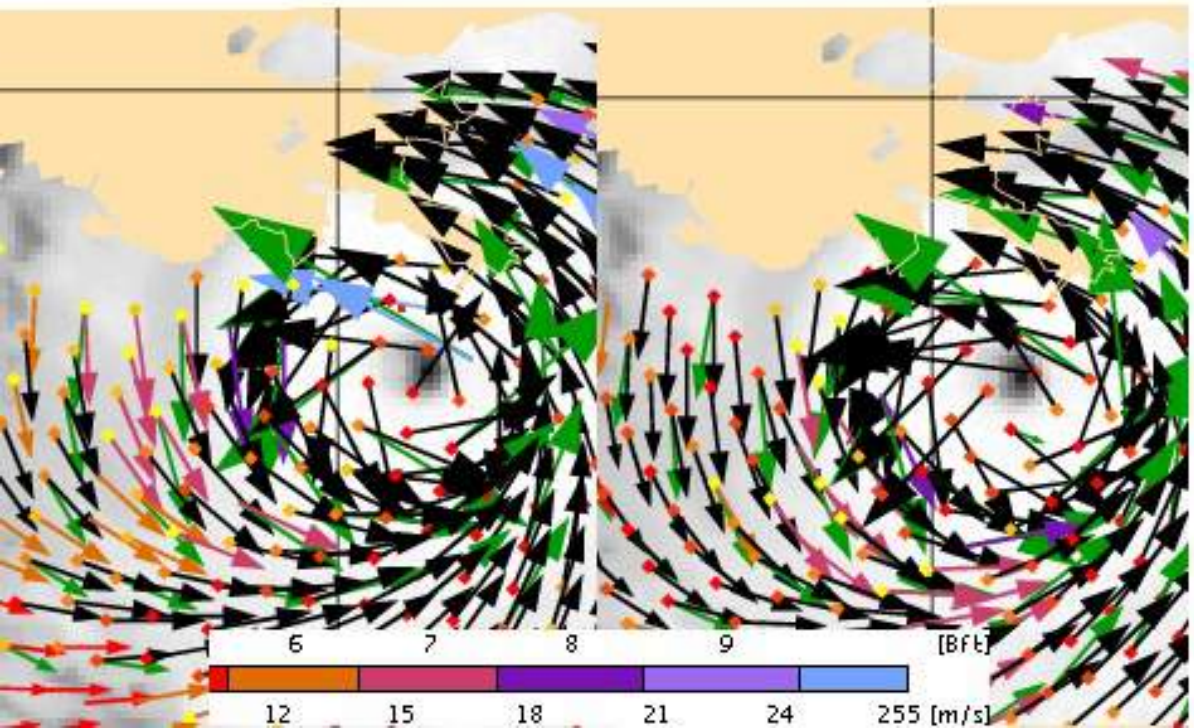
Need for accurate extreme winds

- **Nowcasting**, where **dropsondes** are the adopted wind speed reference; if the wind speed reference would change, hurricane categories change too, as everything relies on dropsonde wind speed calibration (SFMR, Dvorak, passive satellite ocean winds, ..)
- **NWP**, to formulate **drag** and air-sea interaction stresses
- **Oceanography**, to determine ocean **mixing depth** in hurricanes (see deep cold water track behind hurricane)
- **Climate** monitoring, to determine climate **change** at the extremes, i.e., recalibrate past records
- **Climate** prediction, to well describe complex extra-tropical and tropical coupled ocean-atmosphere dynamics (CO_2, heat, H_2O, …)
- Improved description of hurricane **dynamics**

➢ Satellite ocean surface wind speed calibration for active and passive microwave remote sensing

Polverari et al., 2021





Royal Netherlands Meteorological Institute
Ministry of Infrastructure and the Environment

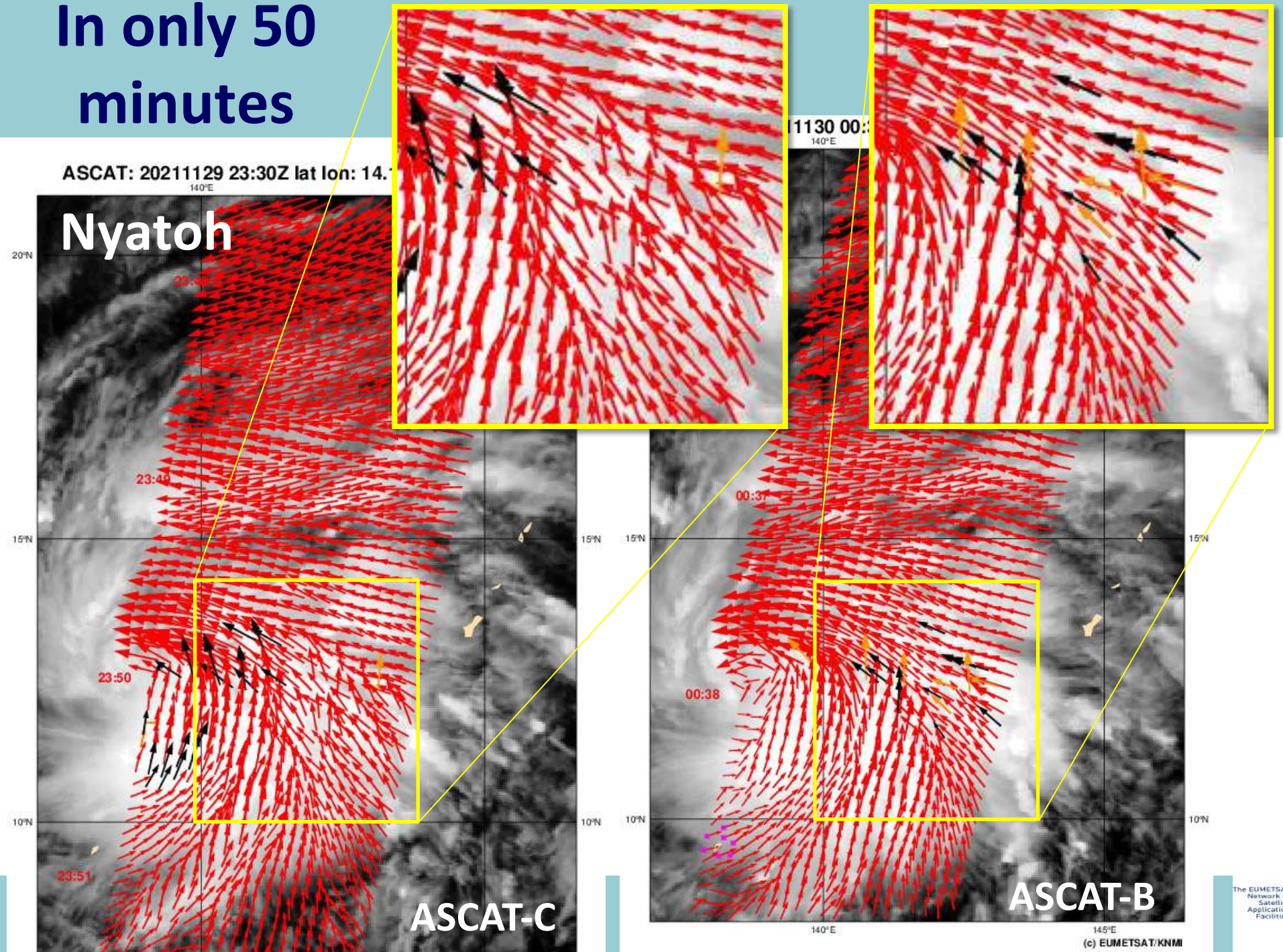
- 5 scatterometers capture landfall of Ida
- Strength consistent with NHC advisories, but . .
- Hurricane in-situ wind speed scale differs from moored buoys, our in-situ speed reference www.eumetsat.int/CHEFS, Polverari et al., ‘21
- The in-situ reference wind speed scale also determines ocean drag and fluxes, NWP u10
- Scatterometer winds do not need long waves
- SCA has VH and higher resolution, hopefully DopSCA

EUMETSAT OSI SAF, Ida land-fall news story

EU Copernicus Marine Core Services

Ni et al., 2021

In only 50 minutes



The EUMETSAT Network of Satellite Application Facilities

OSI SAF Ocean and Sea Ice

An In-situ Controversy at the Extremes

- Dropsondes are used in the operational community as reference
- SFMR, Dvorak, SMAP, SMOS, .. , depend on dropsonde speed reference
- Use CHEFS method for spatial scaling to satellite footprints, collocation, ..
- We normally use stress-equivalent 10-m ECMWF and buoy winds up to 25 m/s (at sufficient sampling) for cal/val
- Triple collocation (see table)
- Dropsondes and buoys are different =>
- **CMOD7 physically credible, CMOD7D ?**
- ➢ **CMOD7D follows SFMR speeds @25km footprint**

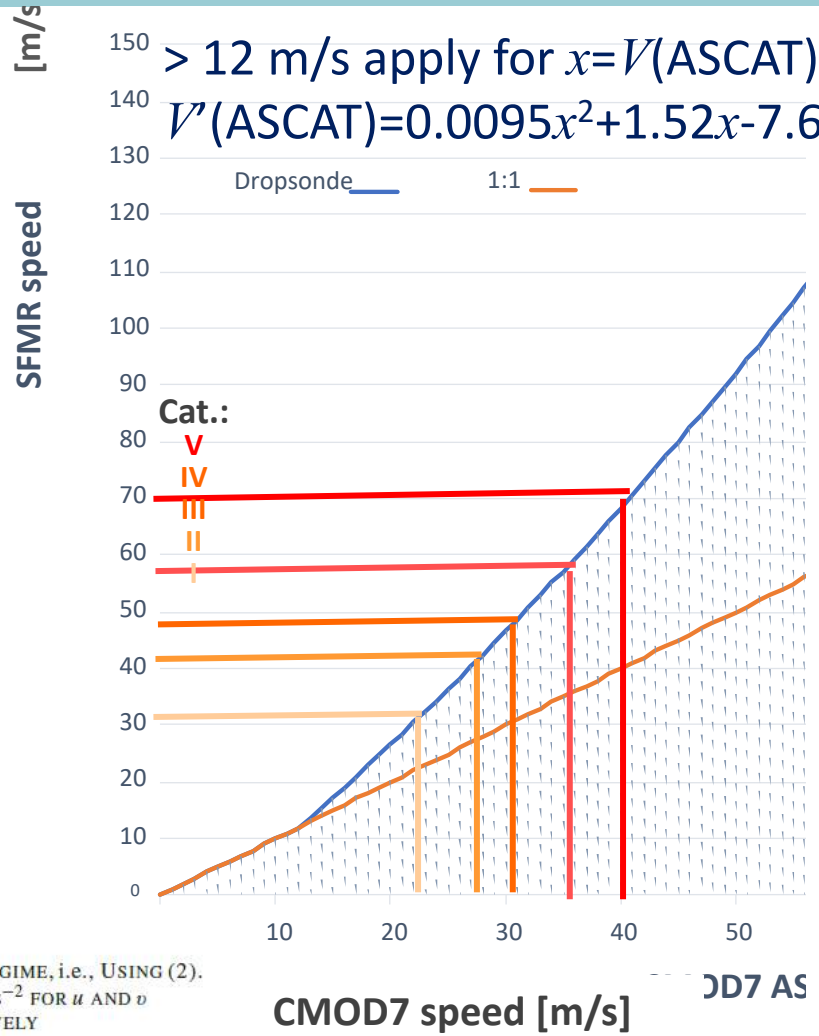


TABLE II

SAME AS TABLE I BUT FOR HIGH-WIND REGIME, i.e., USING (2). THE r^2 VALUE IS 0.63 AND 1.00 $m^{-2}s^{-2}$ FOR u AND v COMPONENTS, RESPECTIVELY

	MARS	ASCAT	ERA5
ε_u (ms^{-1})	1.90	0.60	1.60
ε_v (ms^{-1})	2.08	0.69	1.52

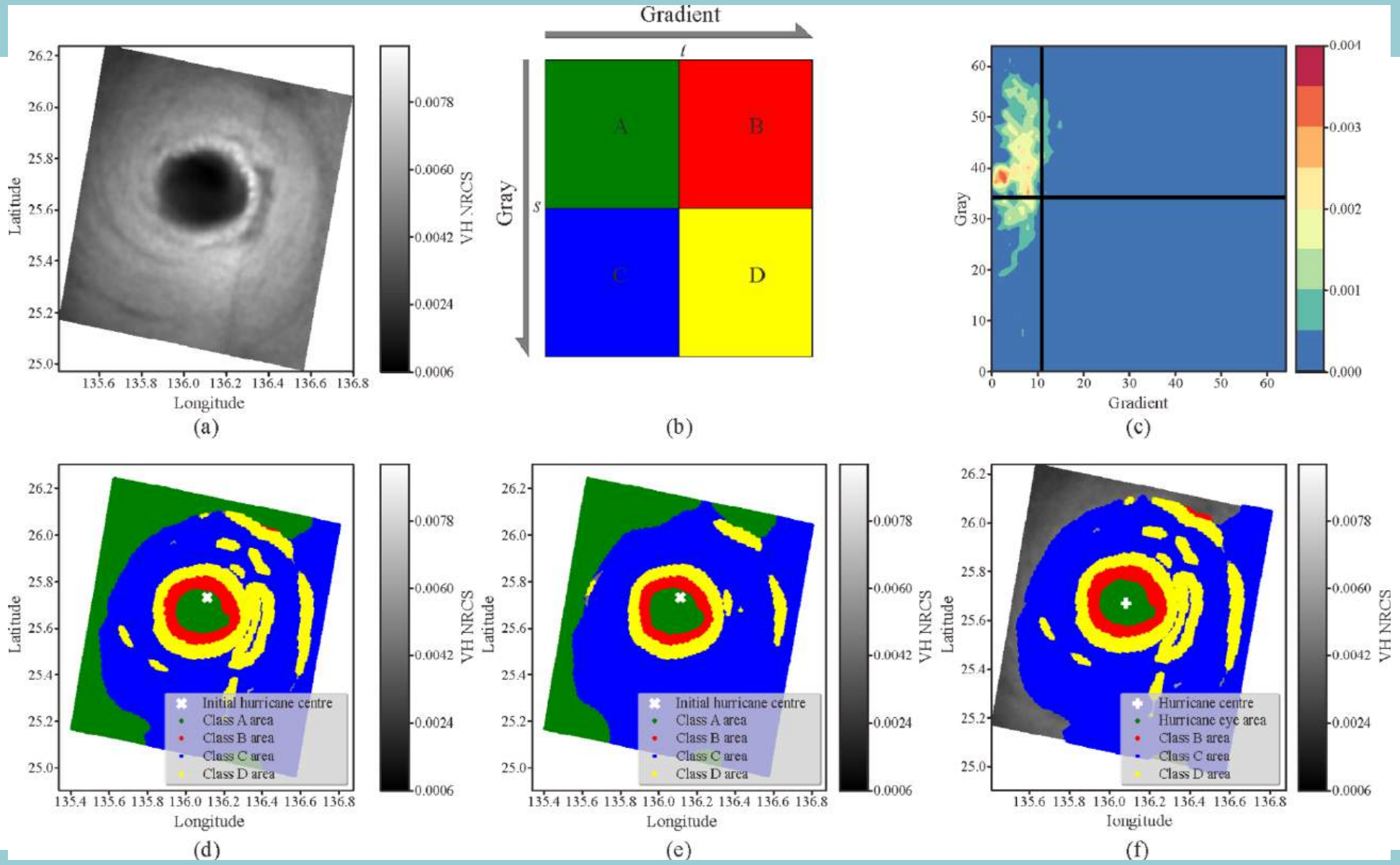
Polverari et al., 2022

Stoffelen et al., 2021

ESA MAXSS work at KNMI

- Exploiting the SAR data base
  - Hurricane morphology
  - Improve SAR wind direction (as verified by ASCAT)
  - Use SAR to train scatterometer resolution enhancement
  - Sustained wind representation 1-min (SAR) versus 10-min (Scat)
  - Wind calibration/adjustment at extremes (with ICM)
- Decadal analysis (Alexandre Payez)
- L4 validation

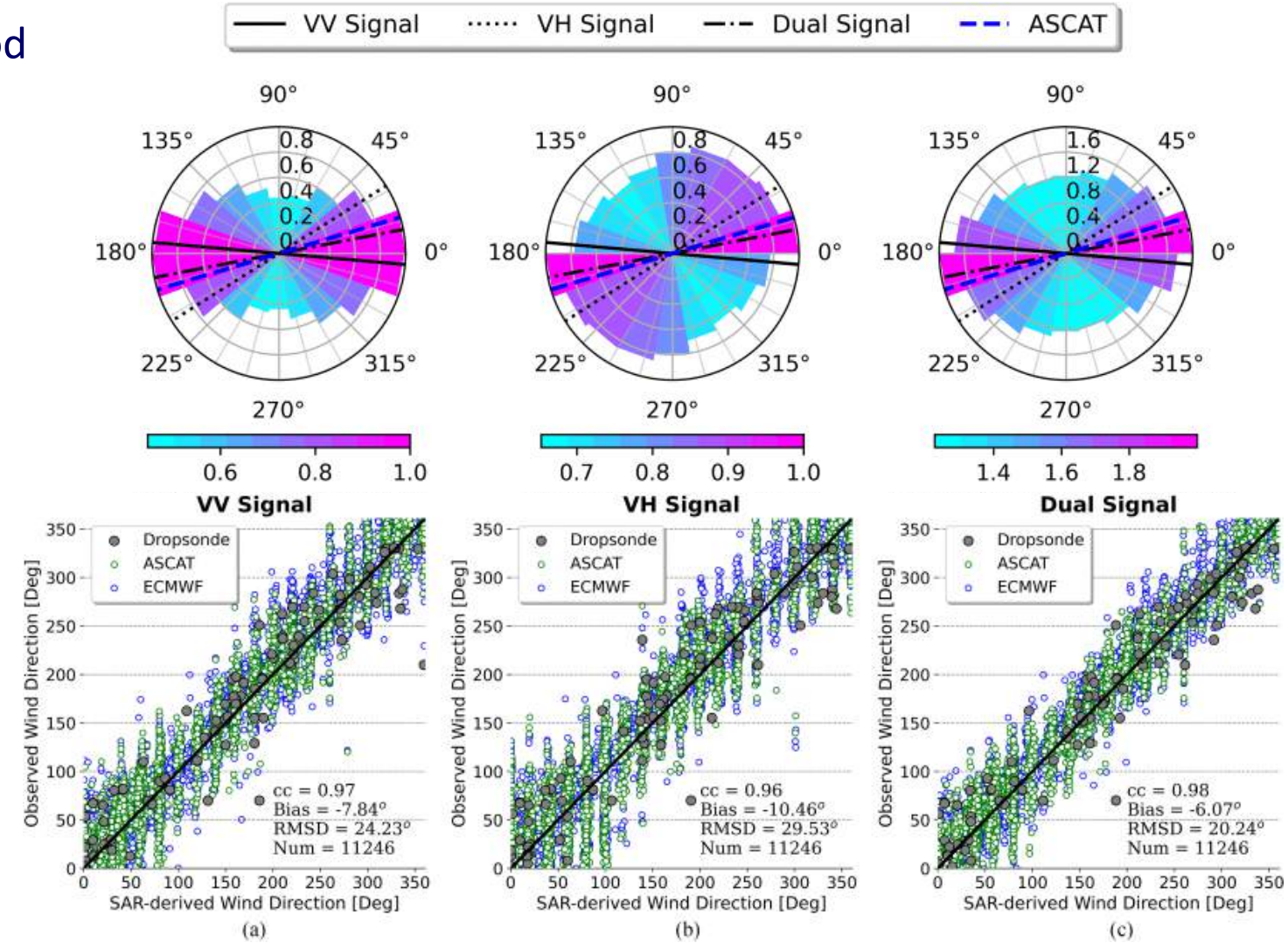
Grey gradient method for SAR



Ni et al. 2021 Hurricane eye morphology extraction from SAR images by texture analysis (MAXSS)

Improved SAR wind direction

- Gradient method
- Compare SAR VV, VH and both
- Dropsondes
- ASCAT
- ECMWF

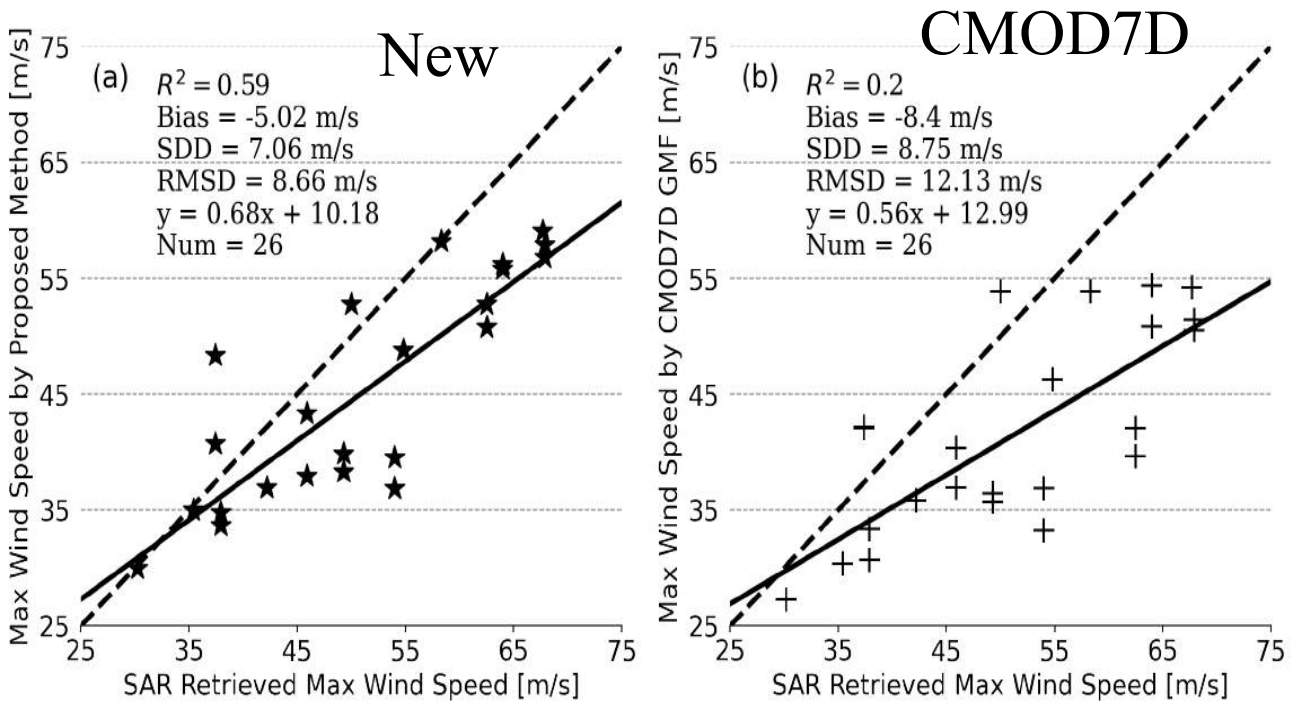


Ni et al., 2023

Tropical Cyclone Wind Direction Retrieval From Dual-Polarized SAR Imagery Using Histogram of Oriented Gradients and Hann Window Function (MAXSS)

1-min. maximum sustained winds

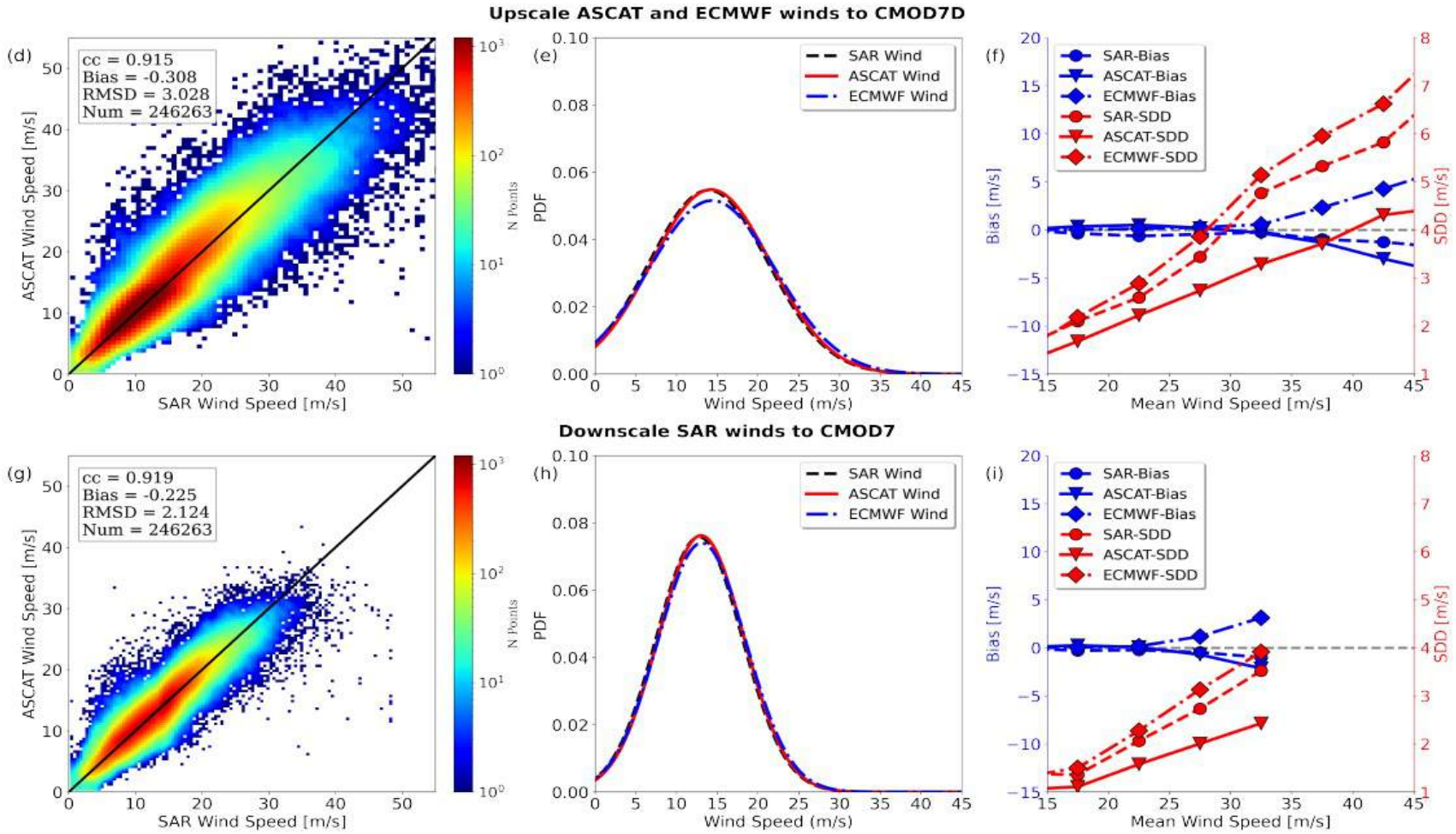
- Standard for hurricane category advisories
- Based on dropsonde wind speed scale – CMOD7D GMF for ASCAT
- Scatterometers blur the maximum eyewall winds (~10-min. value)
- Develop guidance for 1-minute maximum sustained winds for ASCAT
- Fit simple Rankine vortex to ASCAT winds:



Ni et al., 2022 Tropical Cyclone Intensity Estimation From Spaceborne Microwave Scatterometry and Parametric Wind Models (MAXSS)

ASCAT, ECMWF and SAR speed scale

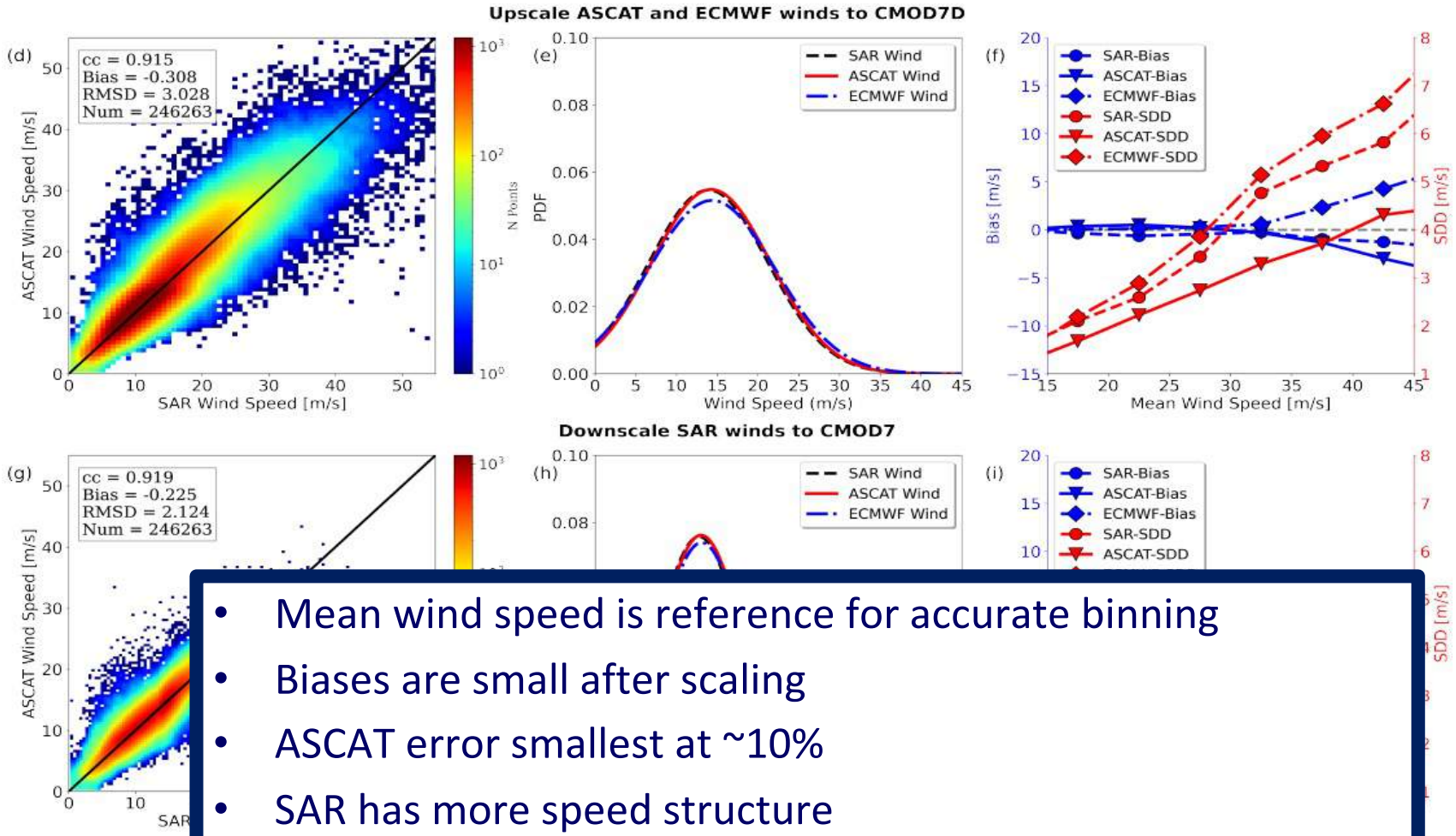
- Triple speed collocation ASCAT, SAR, ECMWF for matching



Ni et al., 2022 : SAR and ASCAT Tropical Cyclone Wind Speed Reconciliation (MAXSS)

ASCAT, ECMWF and SAR speed scale

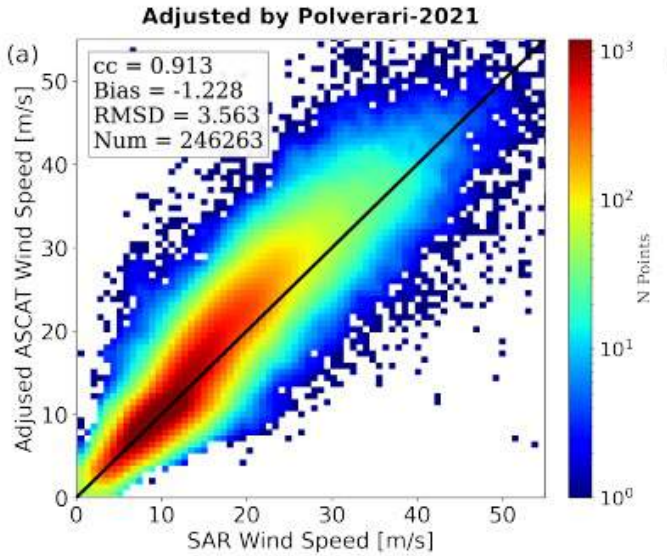
- Triple speed collocation ASCAT, SAR, ECMWF for matching

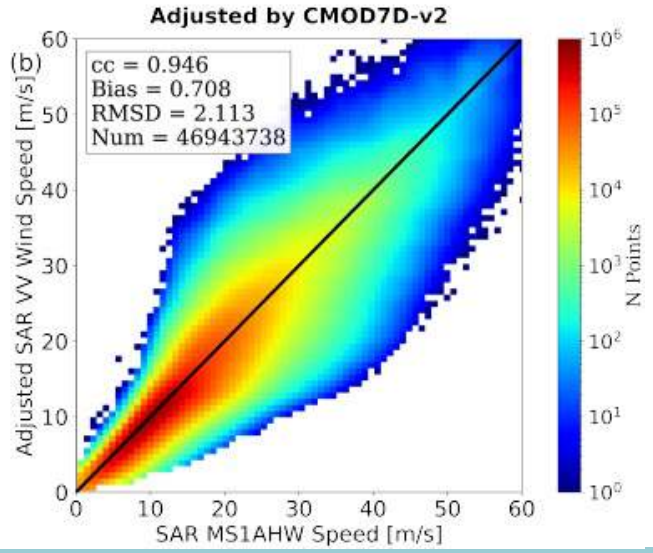


- Mean wind speed is reference for accurate binning
- Biases are small after scaling
- ASCAT error smallest at ~10%
- SAR has more speed structure
- ECMWF is smooth

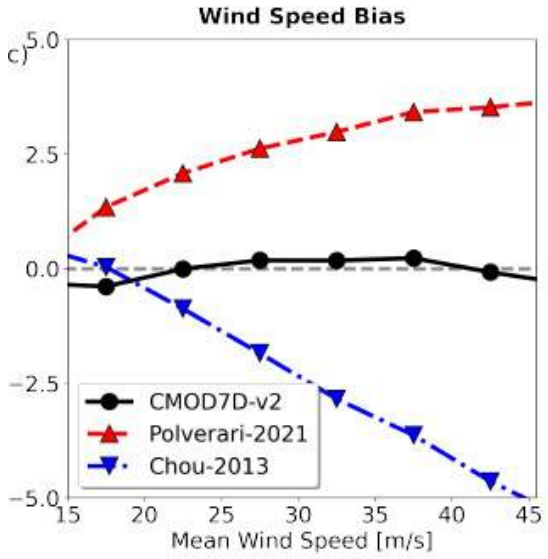
Ni et al., (MAXSS)

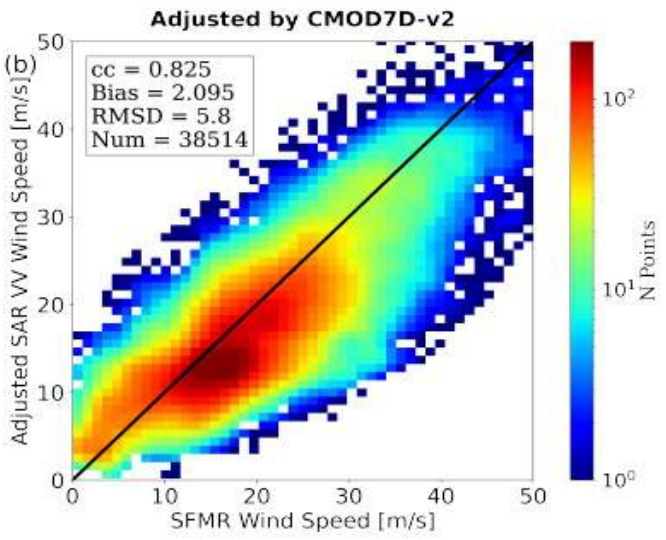
Comparing to SFMR/dropsondes





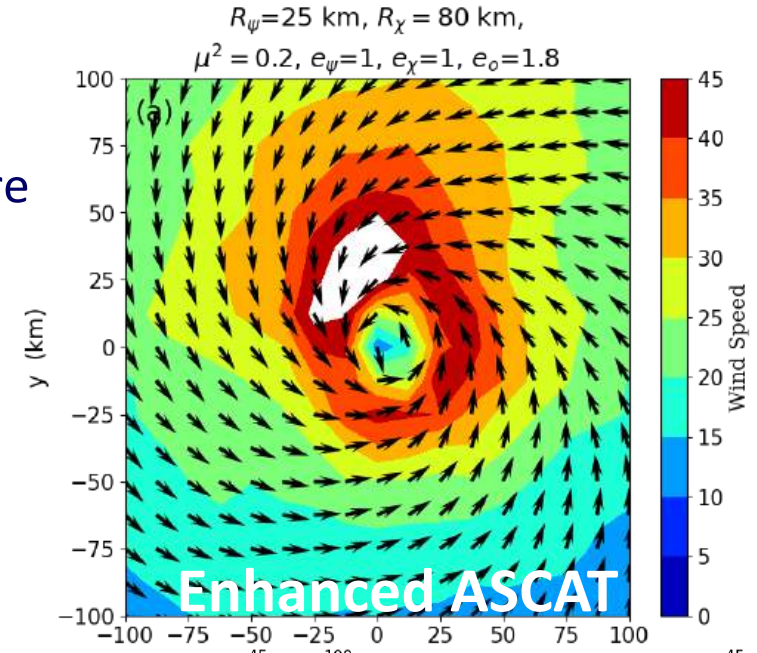
- Chou et al. adjusted to dropsondes
- Polverari et al. matched SFMR
- SAR VV and ASCAT match well with the same GMF after spatial matching
- SFMR and SAR spread substantially with RMSD of 5.8 m/s
- SFMR appears difficult to calibrate

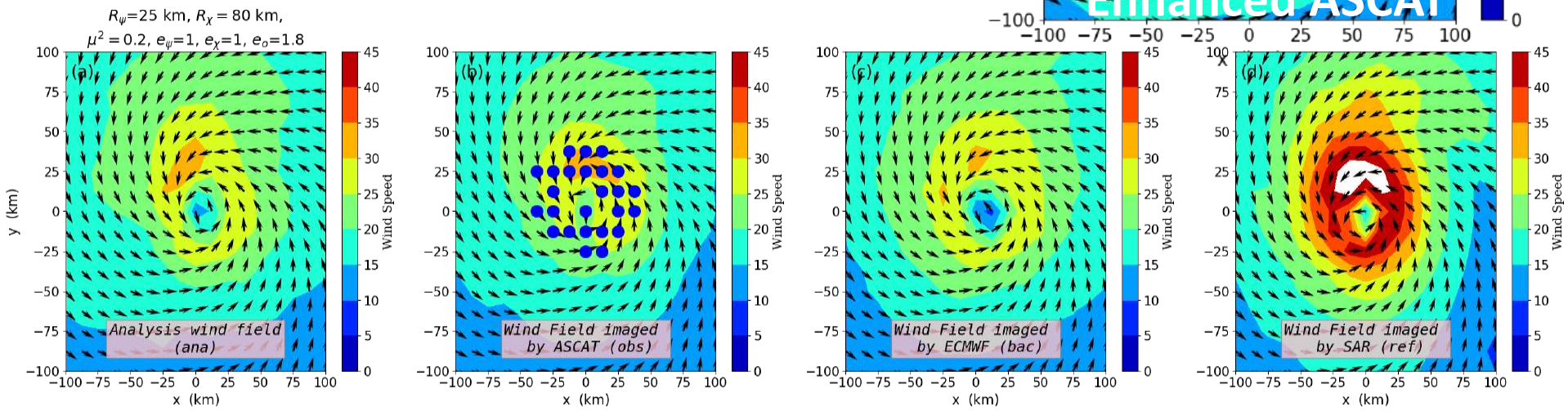




2DVAR resolution enhancement

- In development
- Storm-centered background (max. R^2 centre)
- Empiricial “hurricane” spatial B error structure functions, depending on category
- Sensitivity tests for varying radii and rot/div ratio
- Now 12.5 km product, later 5.6 km
- Wind speed scaling is last step

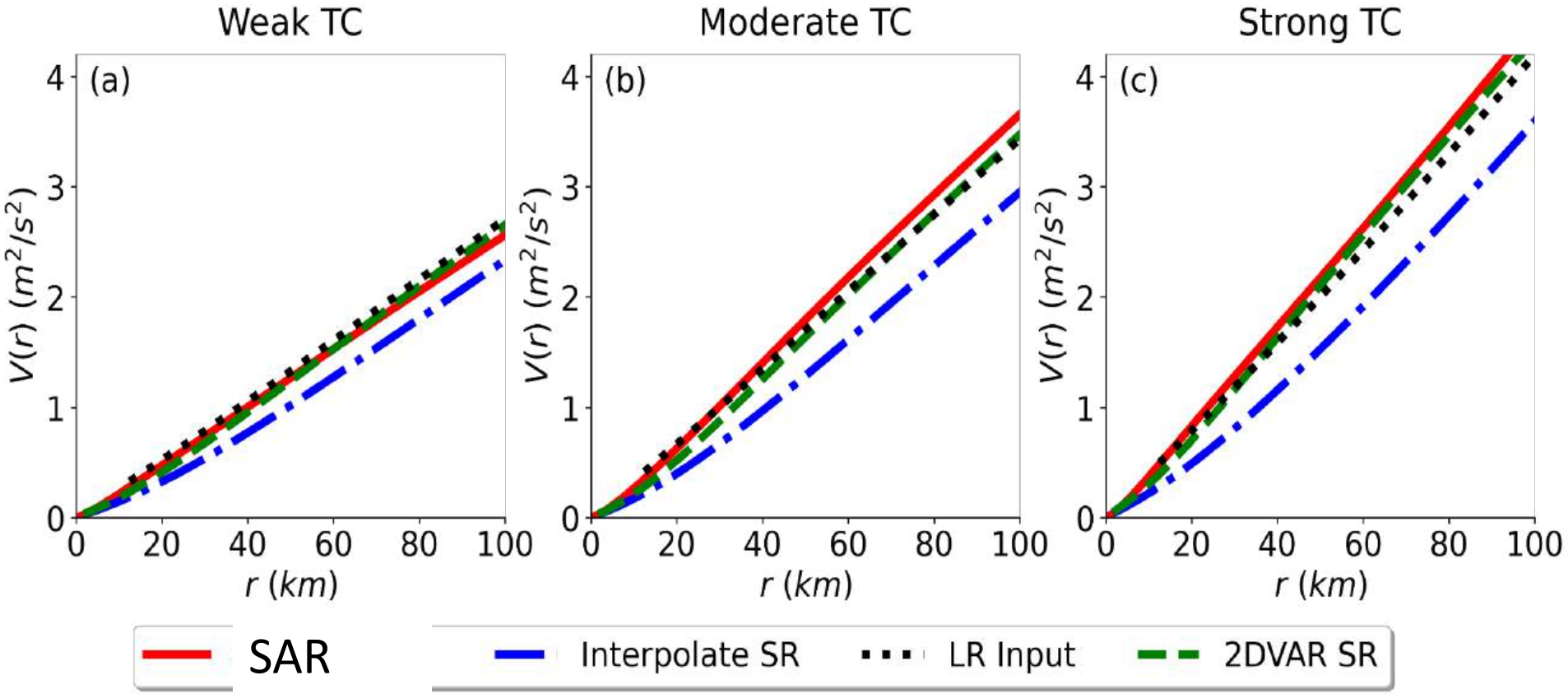




Ni et al., in preparation

2DVAR resolution enhancement

- Spatial variance in hurricane eye area well represented by 2DVAR
- ASCAT has SAR variance at low resolution (LR), but is sampled low
- Bi-linear interpolation reduces variance as expected



Ni et al., in preparation

Well Characterized Wind Quality

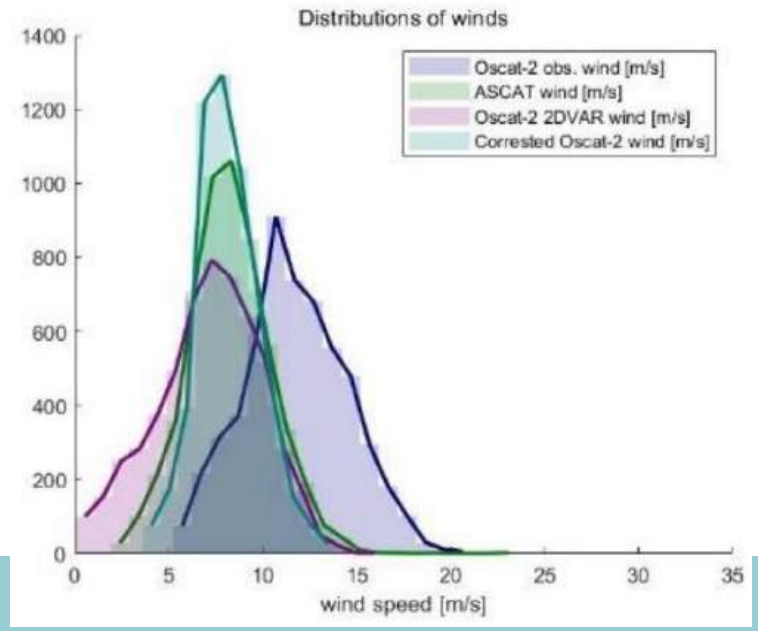
Quadruple/Quintuple Collocation Analysis of In-Situ, Scatterometer, and NWP Winds

Jur Vogelzang & Ad Stoffelen,
https://doi.org/10.1029/2021JC017189
https://doi.org/10.3390/rs14184552

Subset	Buoys		ASCAT-A		ScatSat		ECMWF	
	σ_u	σ_v	σ_u	σ_v	σ_u	σ_v	σ_u	σ_v
bAS	1.03	1.12	0.41	0.49	0.78	0.65	--	--
bAE	1.06	1.15	0.34	0.41	--	--	0.94	1.03
bSE	1.09	1.21	--	--	0.72	0.59	0.92	1.03
ASE	--	--	0.43	0.49	0.76	0.65	0.90	0.98
range	0.06	0.09	0.09	0.08	0.06	0.06	0.04	0.05

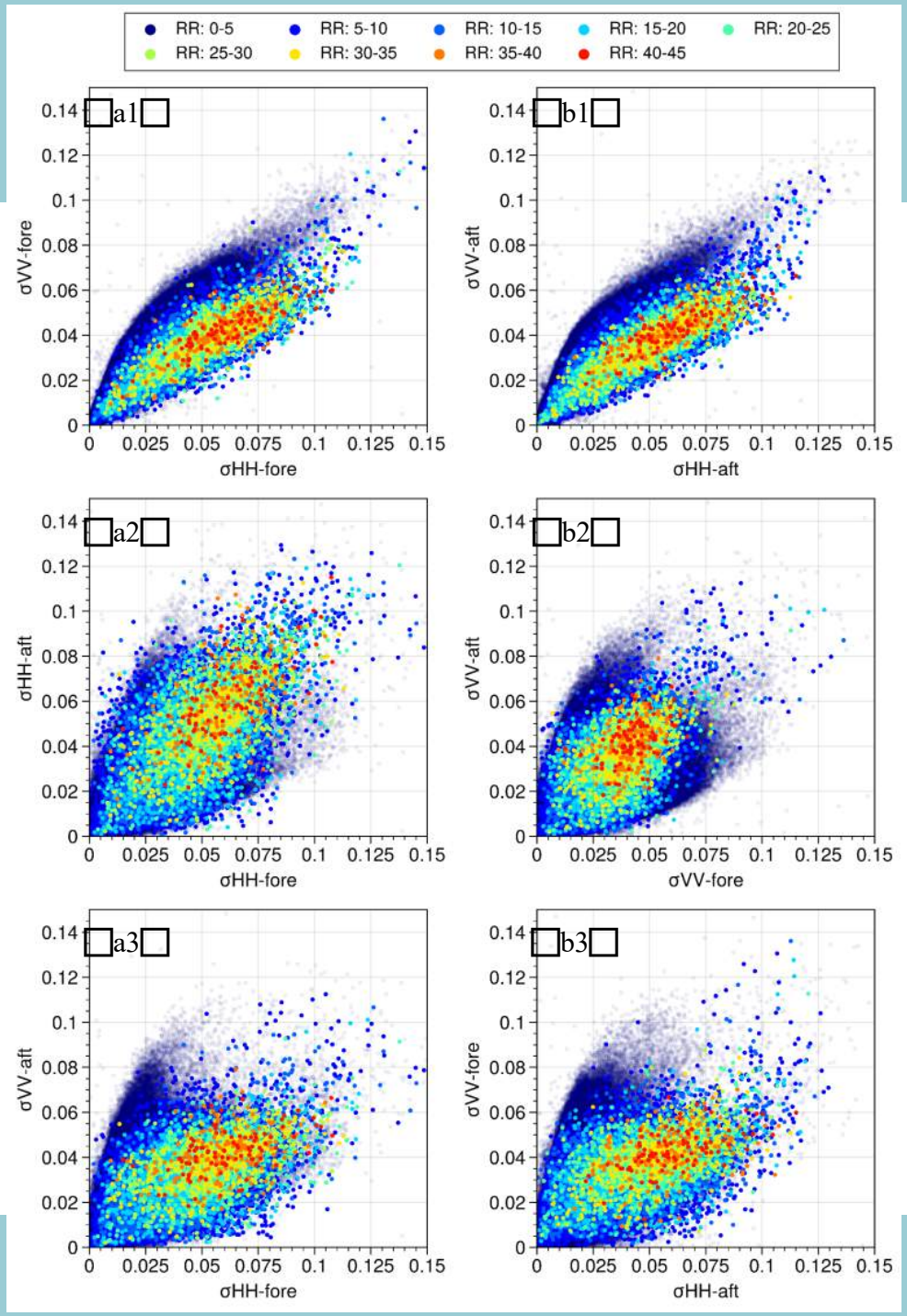
Support vector machine tropical wind speed retrieval in the presence of rain for Ku-band wind scatterometry

Xingou Xu & Ad Stoffelen
https://doi.org/10.5194/amt-2021-200



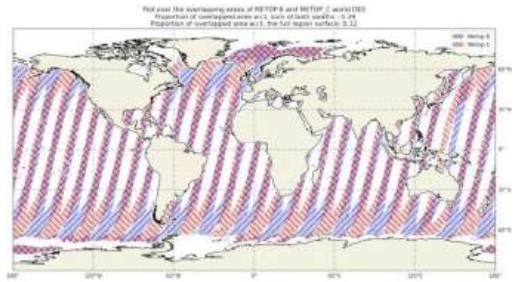
Ku-band rain

- Rain points can be separated from wind points in 4D measurement space for most WVCs
- The wind distribution is contained in the wind GMF
- Construct a VV and HH rain GMF
- Use Bayesian inference to get rain probability / rain area
- Use probability threshold for flagging
- Use probability for rain correction to retrieve corrected winds (assuming rain area for P)
- Could be promising for tropical hurricanes
- Combine with 2DVAR resolution enhancement, now developed for ASCAT in MAXSS with SAR

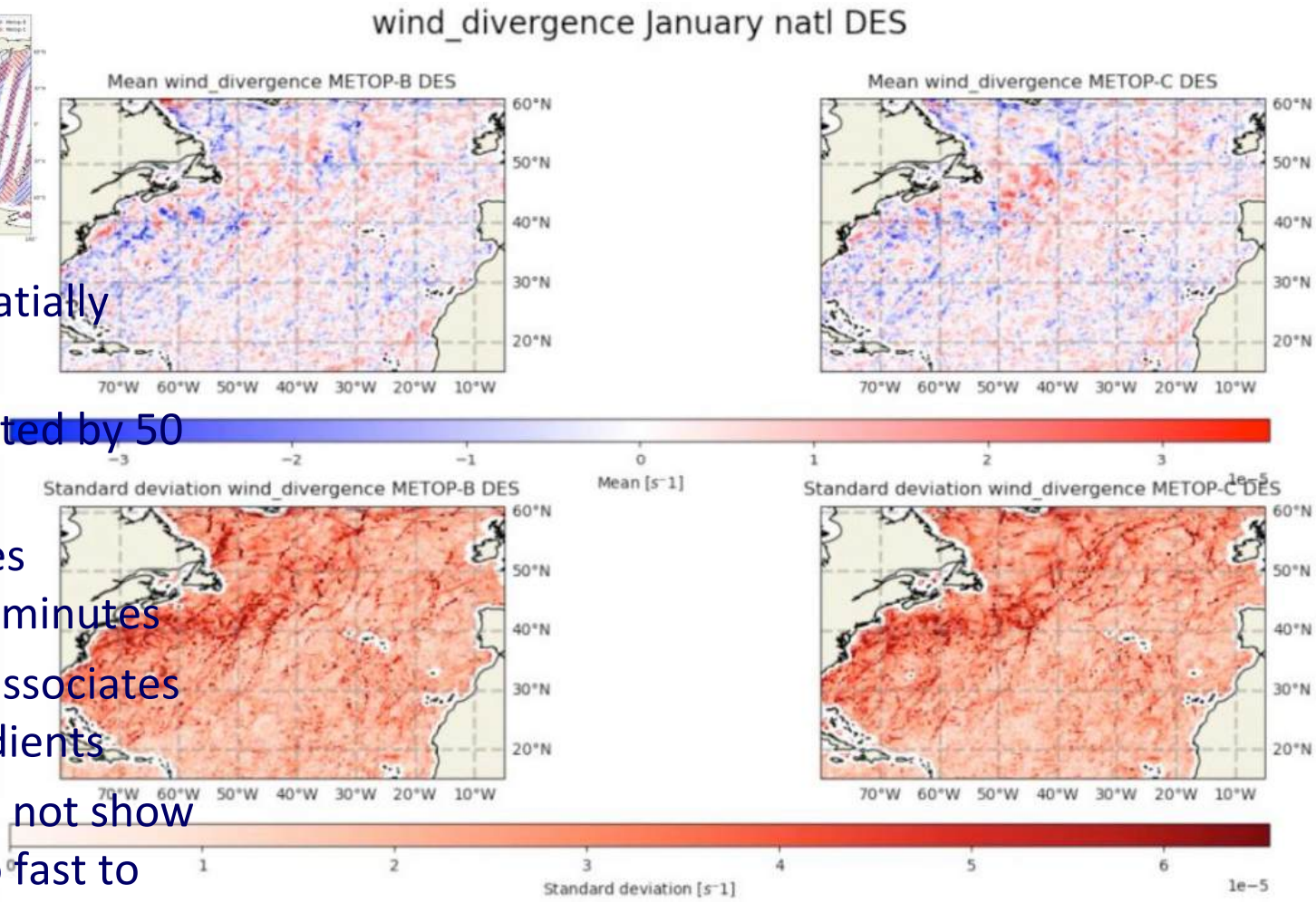


Zhoa et al., 2023, 2x accepted

L3/L4 uncertainty analysis



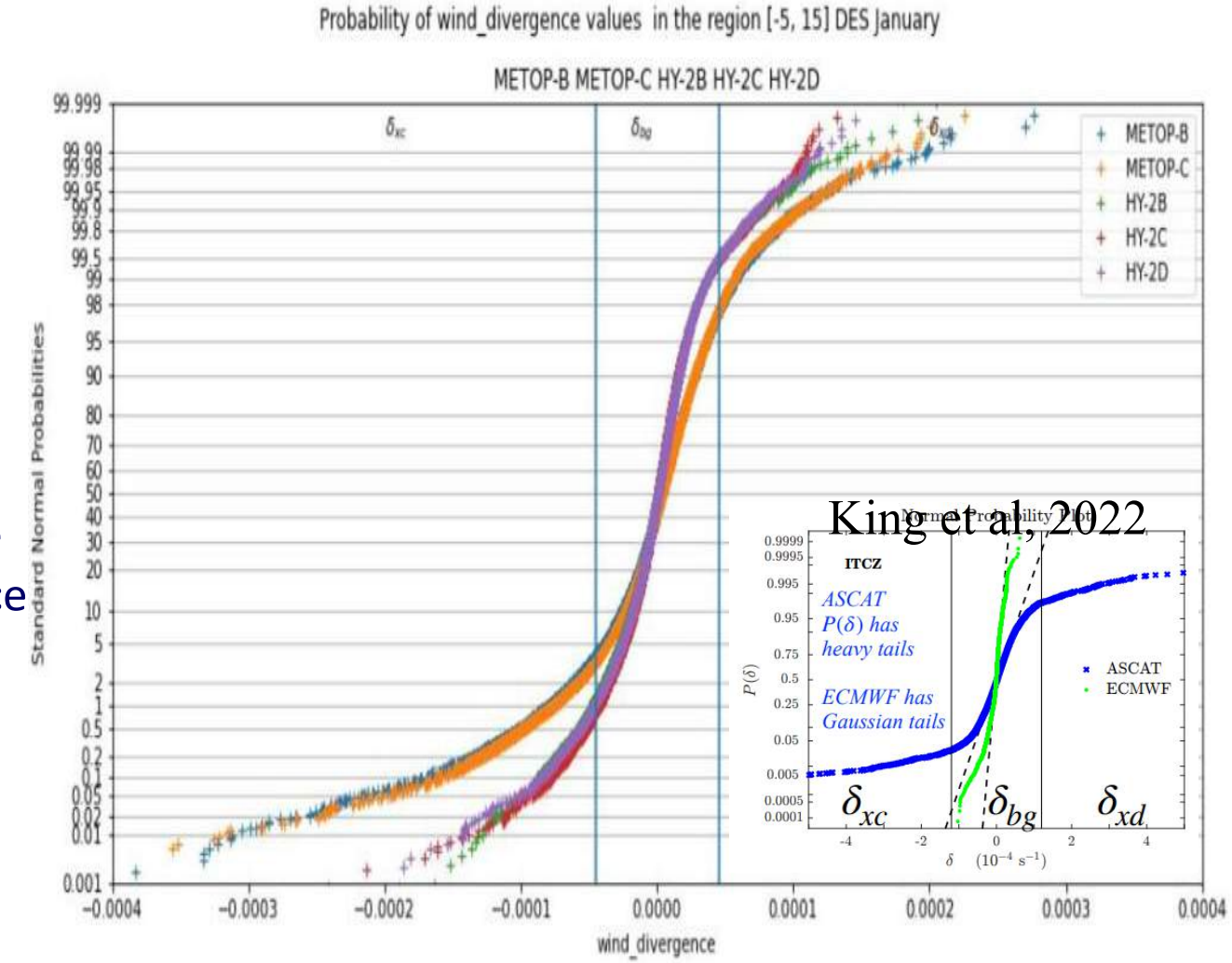
- MetOp-B and C spatially overlap
- B and C are separated by 50 minutes
- Divergence changes substantially in 50 minutes
- Large divergence associates with large SST gradients
- Global model does not show this variability (too fast to track)



Miguel Fernández et al., in preparation

L3/L4 product uncertainty analysis

- King et al. showed association of extreme ASCAT convergence and divergence to heavy rain
- ECMWF div. is close to Gaussian (straight line)
- Pencil-beam winds also show extremes, but particularly less extreme (small-scale) convergence
- How to deal with this in Copernicus L4 products?
- What about the MAXSS L4 winds?



Miguel Fernández et al., in preparation

L3/L4 product uncertainty analysis

- Scatterometers show substantial model biases
- Both in mean and variance
- How to make L4 products that maintain observed spatial characteristics?
- Ex.: IFREMER L4 product copied ERA5 model bias over time (see right)
- Verify MAXSS L4 product?

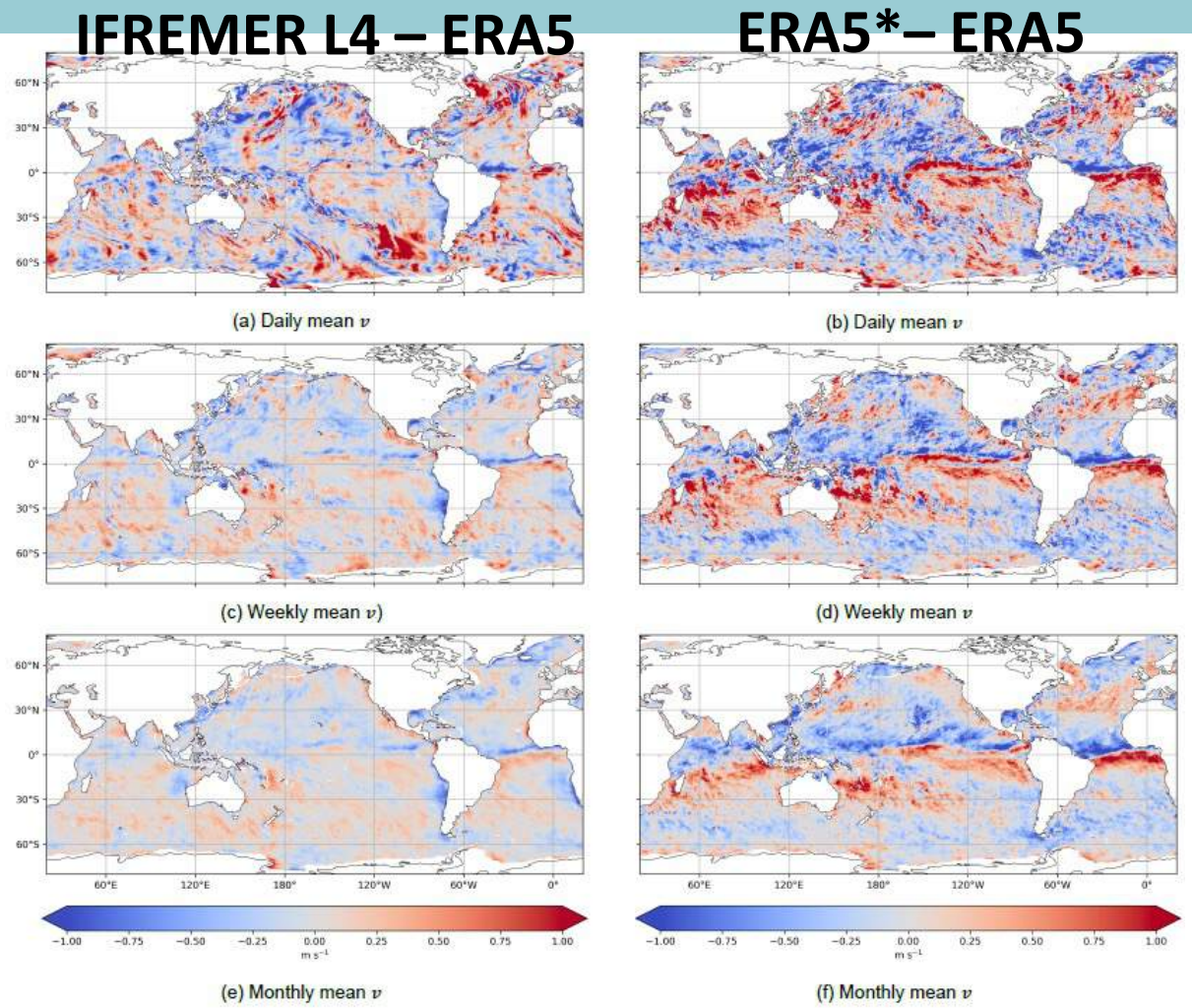


Figure 4.1: Mean meridional wind (v) differences between IFREMER and ERA5 (a, c, e) and ERA5* and ERA5 (b, d, f) averaged over a day (2 February 2019), a week (2-9 February 2019), and a month (February 2019) plotted on a 0.25°grid. Positive differences in red indicate that ERA5 is larger than either IFREMER or ERA5*.

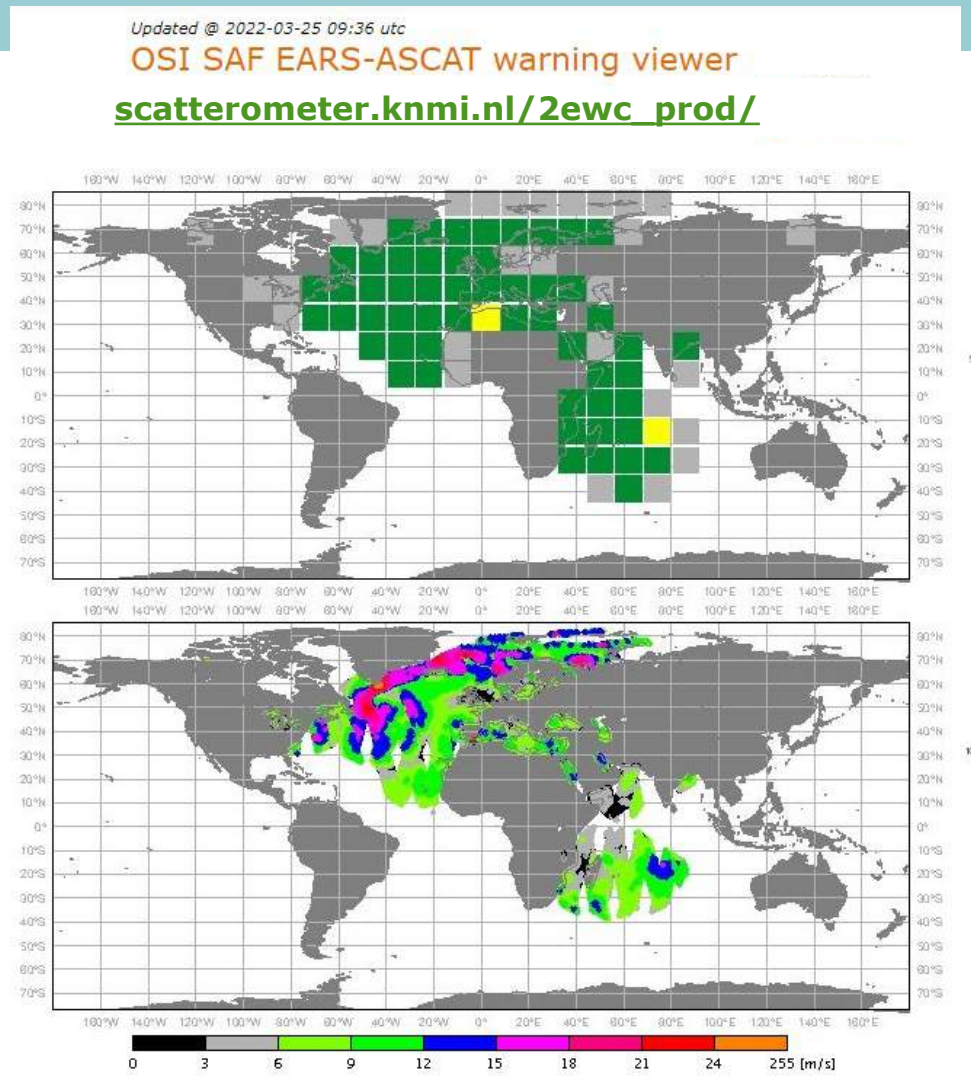
Liselotte van Cranenburgh, MSc Thesis

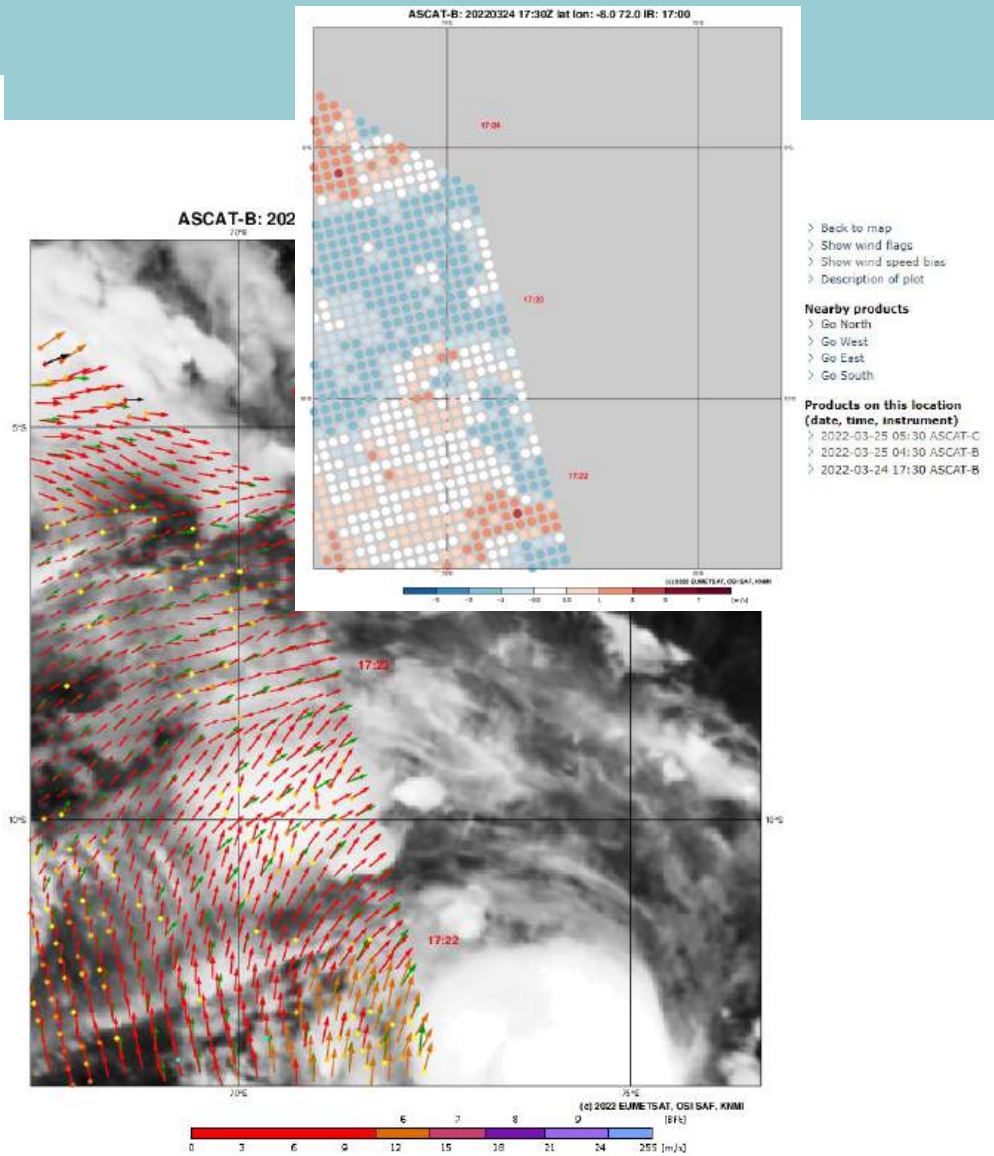
Conclusions and Outlook

- We have many scatterometers capturing tropical cyclones, showing fast changes due to moist convection
- Good science in the ESA MAXSS project on SAR and ASCAT comparisons, exploiting the SAR (thanks to ESA SHOC, CYCLOBS) to improve scatterometer winds
- Resolution enhancement ASCAT progressing well
- Resolution enhancement Ku-band scatterometers, probably after implementation rain correction
- How strong is the wind in a hurricane? (Tuesday afternoon)


GNSS Signals
of Opportunity
GPS satellite
HOW GN

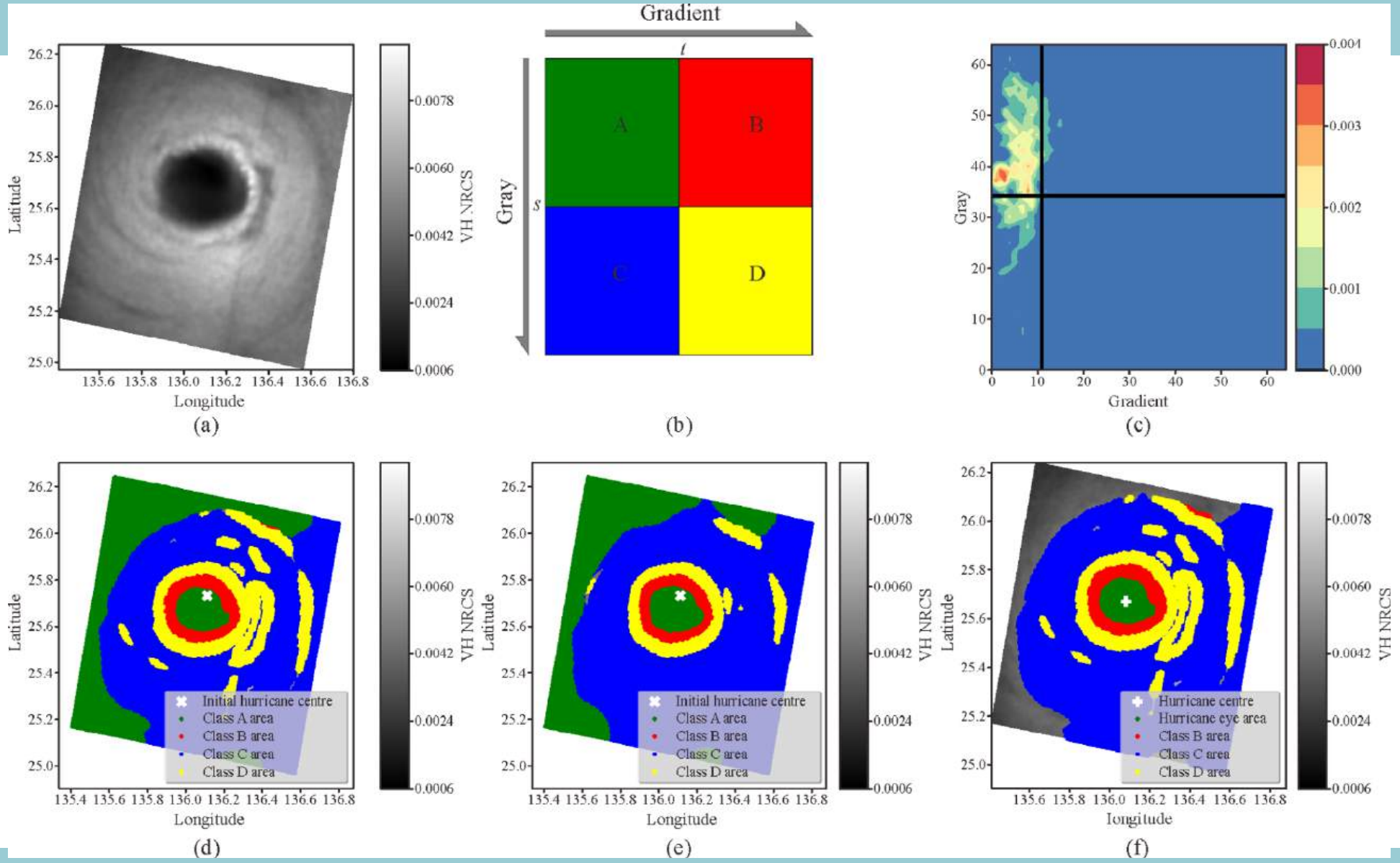
KNMI cyclone visualization and EARS Early Warning





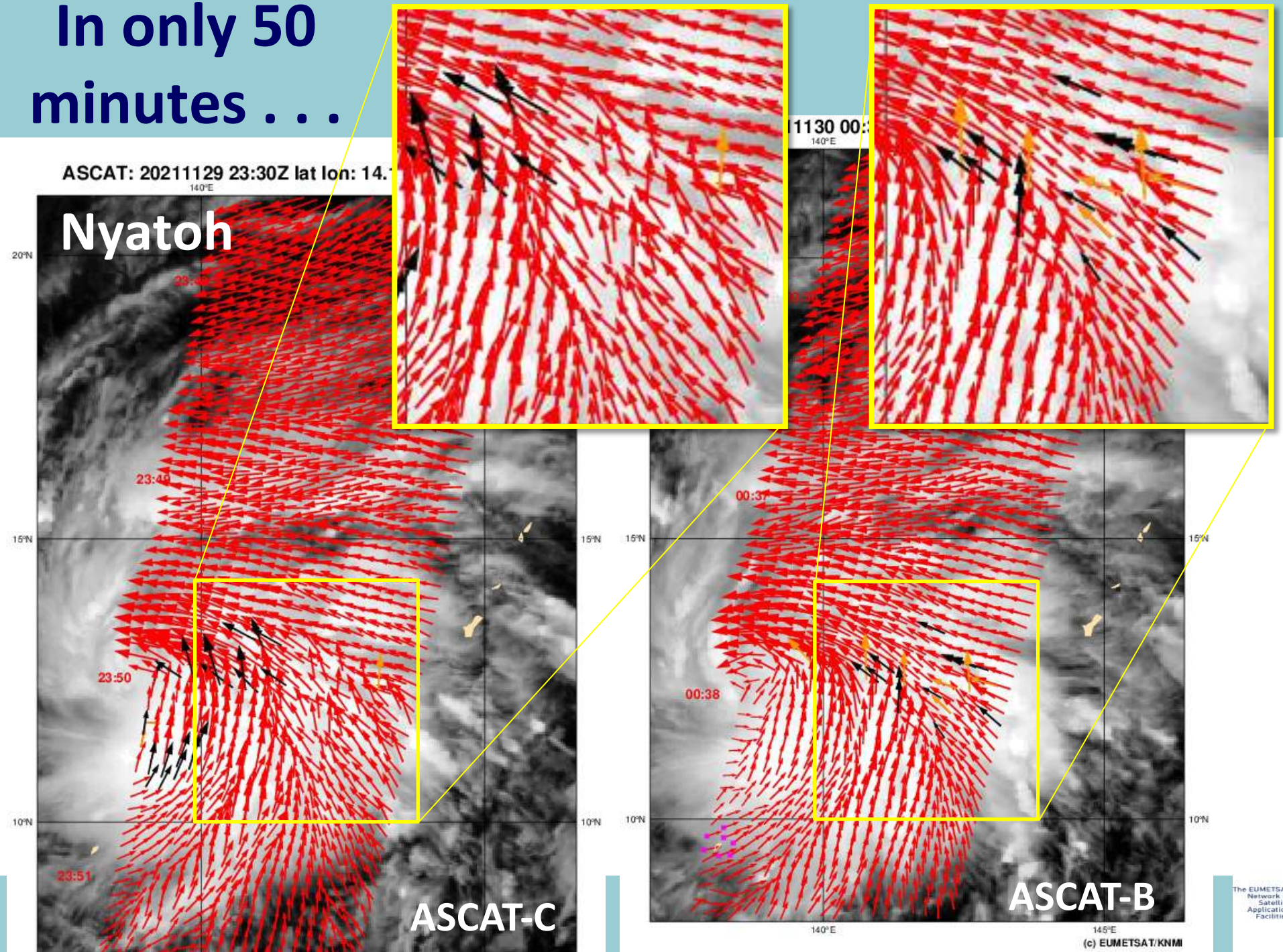
✓ Warns fast in case of climatologically large deviation between ECMWF and ASCAT

Grey gradient method for SAR



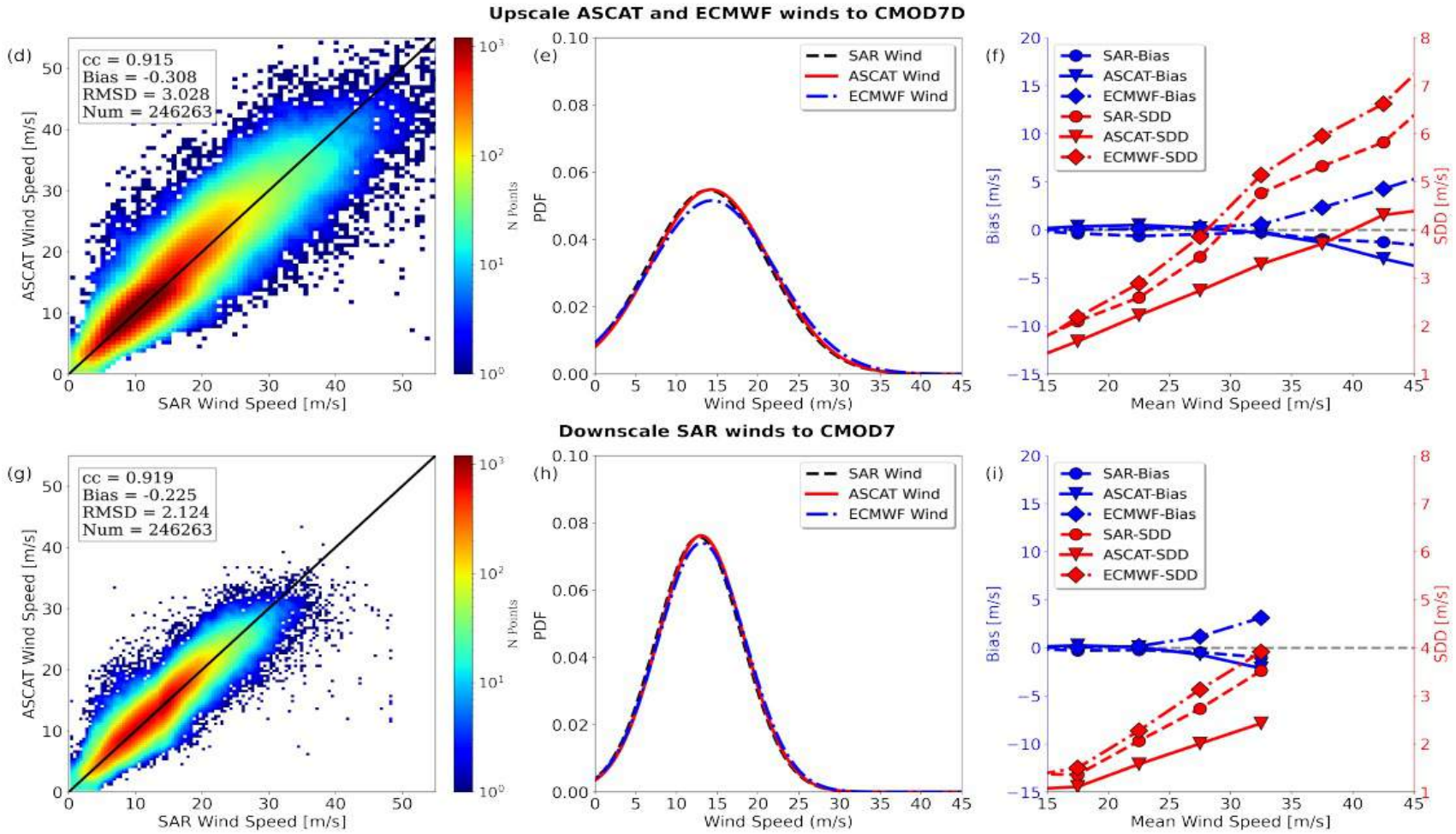
Ni et al. 2021 Hurricane eye morphology extraction from SAR images by texture analysis (ESA MAXSS project)

In only 50 minutes . . .



ASCAT, ECMWF and SAR speed scale

- Triple speed collocation ASCAT, SAR, ECMWF for matching



Ni et al., 2022 : SAR and ASCAT Tropical Cyclone Wind Speed Reconciliation (MAXSS)

ASCAT, ECMWF and SAR speed scale

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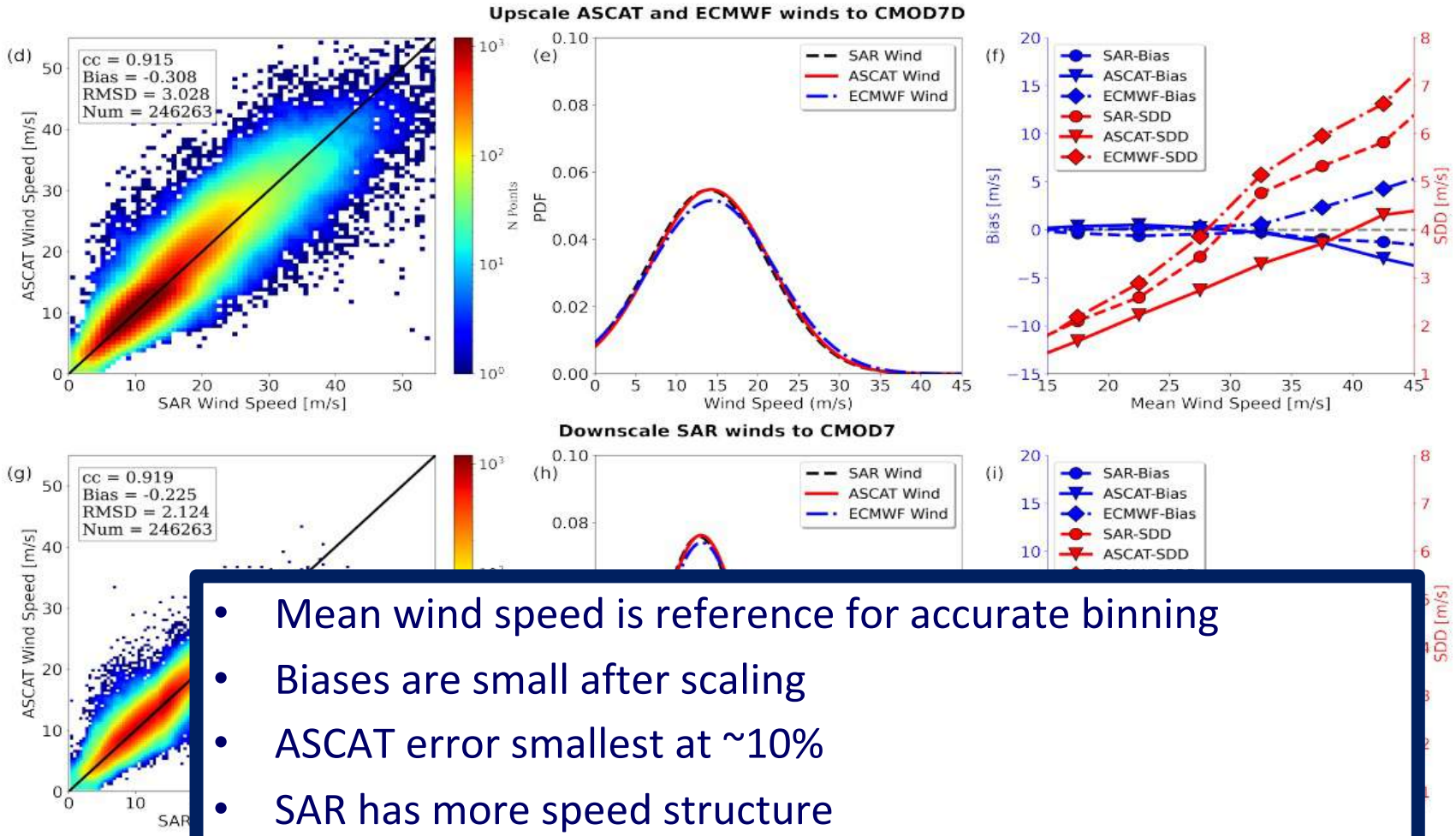
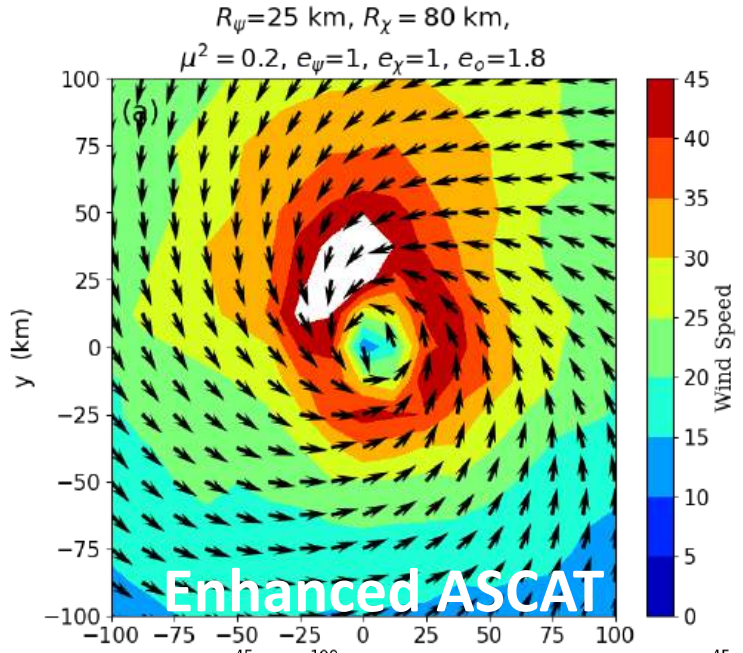


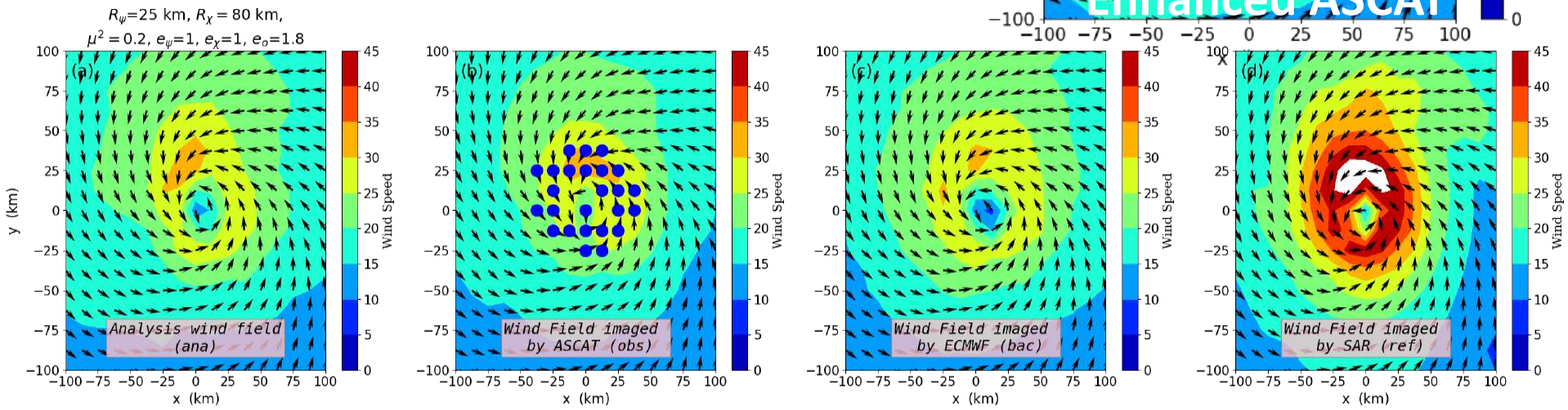
- Mean wind speed is reference for accurate binning
- Biases are small after scaling
- ASCAT error smallest at ~10%
- SAR has more speed structure
- ECMWF is smooth

Ni et al., (MAXSS)

2DVAR resolution enhancement

- PhD Weicheng Ni (NUDT)
- Storm-centered background (max. R^2 centre)
- Empiricial “hurricane” spatial B error structure functions, depending on category
- Sensitivity tests for varying radii and rot/div ratio
- Now 12.5 km product, later 5.6 km
- Wind speed scaling is last step

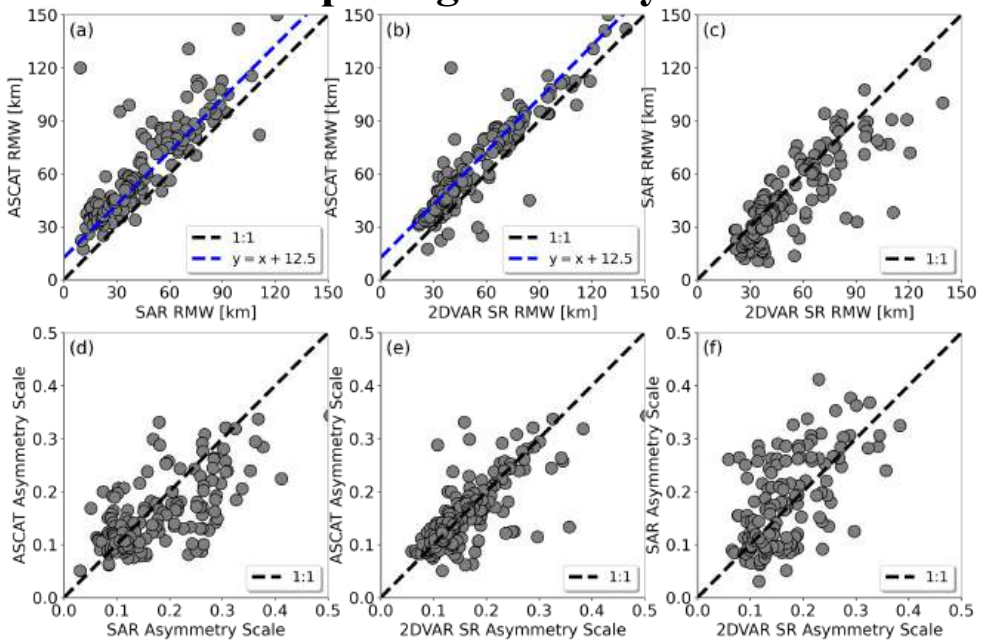




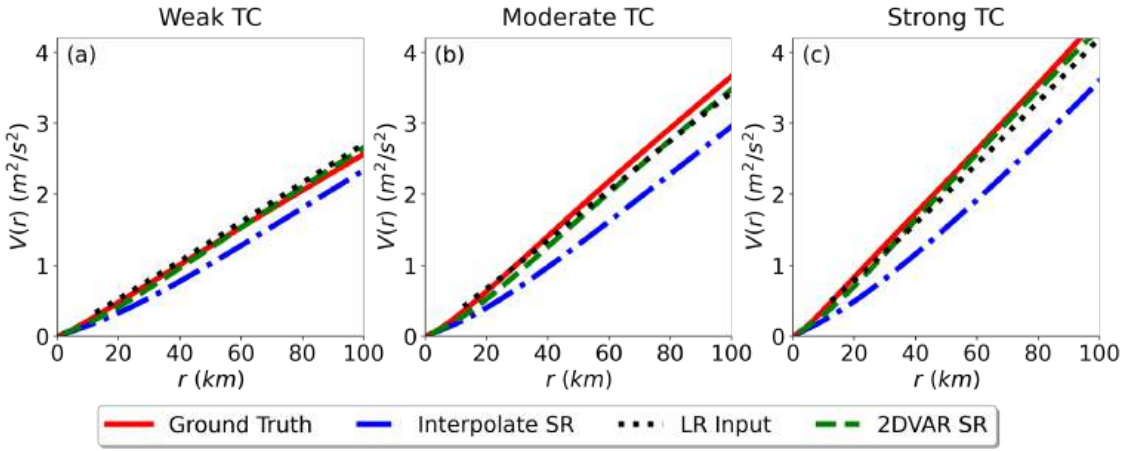
Ni et al., in preparation

Tropical Cyclone Resolution Enhancement for ASCAT Winds

Morphological Analysis



Spatial Variance Estimates



1. The proposed SR method is capable of preserving consistency at large scales with original ASCAT winds while compensating for the ASCAT footprint blurring effect of the small-scale information and enhancing TC vortex structures in a physically meaningful manner, regardless of TC strength category.
2. The obtained SR products possess the correct small-scale properties of TC inner-core structures, such as **Radius of Maximum Wind, TC asymmetry and wind variability**.

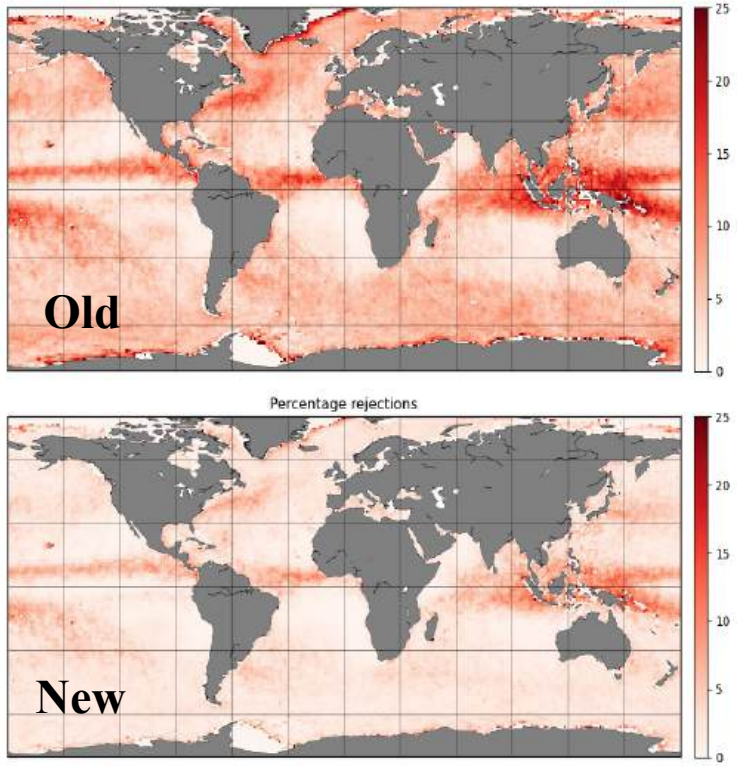
Quality Evaluation by Triple Collocation Analysis

TC Category	SR Method	SAR (m/s)	ASCAT (m/s)	ECMWF (m/s)	r_w^2 (m²/s²)	Number of Points
Weak	2DVAR SR	1.51	**0.57**	1.51	0.31	5,034,681
	Interpolate SR	1.53	**0.82**	1.53	0.06	
Moderate	2DVAR SR	1.42	**0.60**	1.43	0.35	2,891,969
	Interpolate SR	1.43	**0.95**	1.43	0.12	
Strong	2DVAR SR	1.31	**0.52**	1.31	0.43	1,418,252
	Interpolate SR	1.31	**0.77**	1.30	0.24	

Ku-band Quality Control and ocean winds

- We continuously collaborate to improve quality control (QC)
- For Ku-band scatterometers we need to control rain (=>)
- Develop algorithms to correct for remaining observational sampling biases
- We compare geographical biases between rain-insentitive (ASCAT) and rain-sensitive (Ku-band) scatterometers and collocated ECMWF winds
- Using ECMWF allows correction of satellite sampling biases
- It allows to estimate the bias due to the systematic removal of at maximum ~10% of the Ku-band winds in moist convection
- We work on Ku-band rain correction methods using Bayesian estimation

% rejections Ku-band



Zhao et al., 2023 (2x)

King et al., 2022

Xu and Stoffelen, 2021, 2019

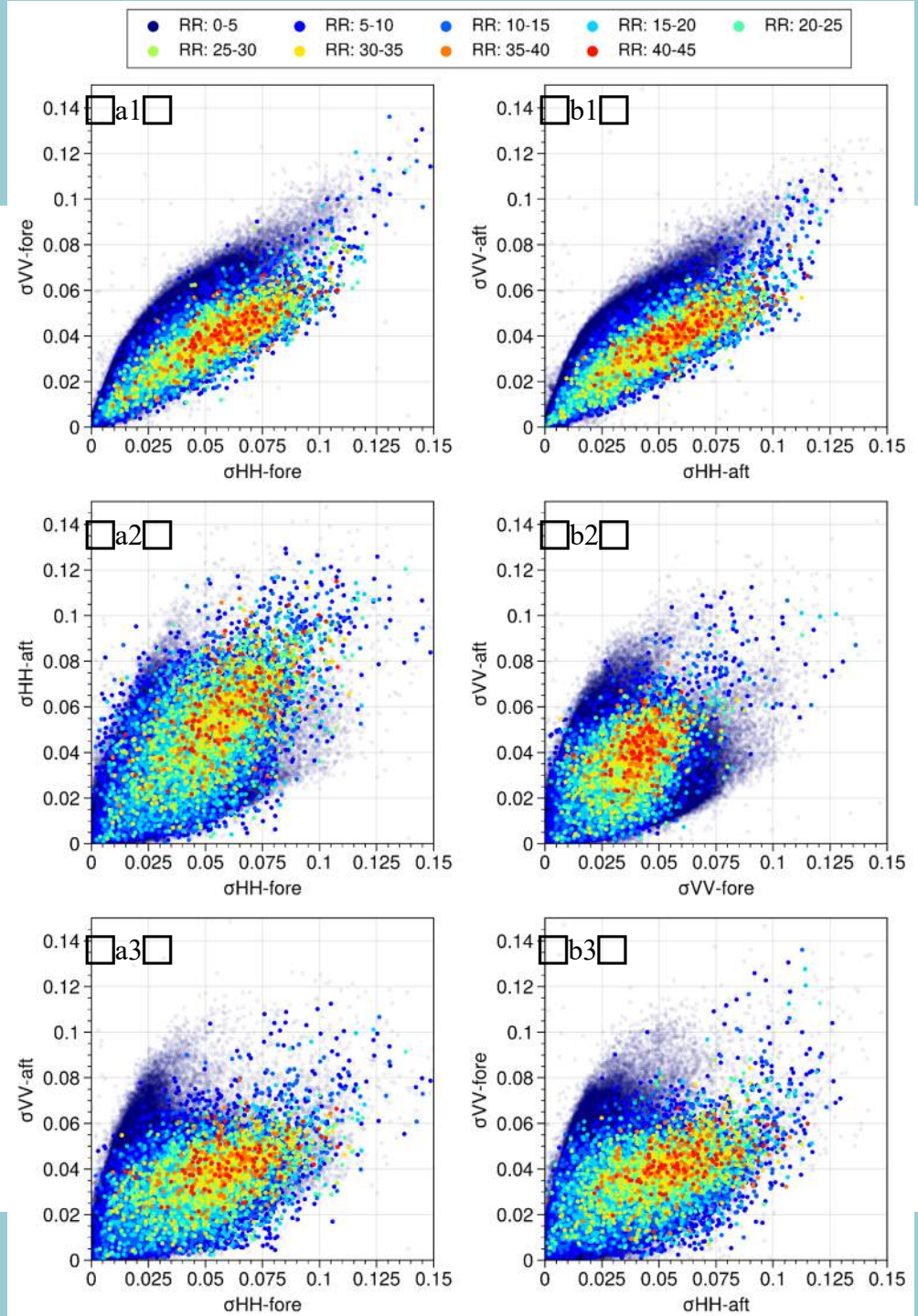
Trindade et al., 2020, 2023

Belmonte and Stoffelen, 2019

Bayesian rain estimation

- Rain points can be separated from wind points in 4D measurement space for most WVCs
- The wind distribution is contained in the wind GMF
- Construct a VV and HH rain GMF
- Use Bayesian inference to get rain probability / rain area
- Use probability threshold for flagging
- Use probability for rain correction to retrieve corrected winds (assuming rain area for P)
- Could be promising for tropical hurricanes

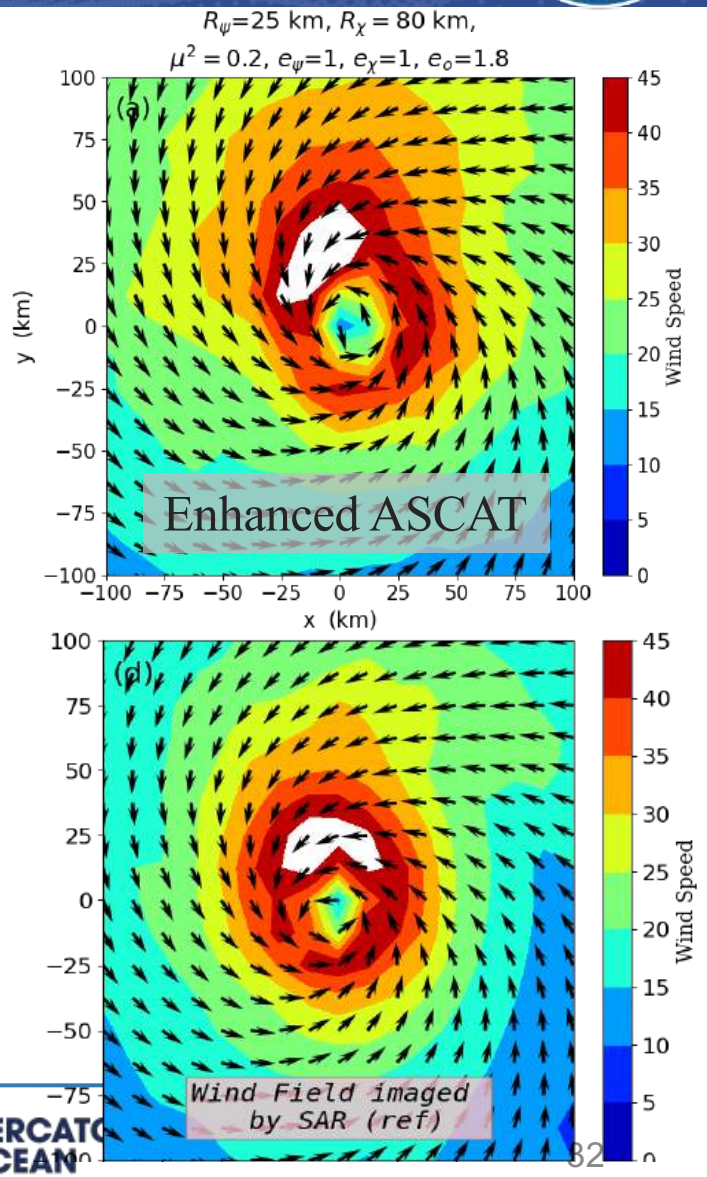
➢ Combine with 2DVAR resolution enhancement, now developed for ASCAT in MAXSS with SAR



Zhao et al., 2023, 2x accepted

New scatterometers, Passive microwaves and SAR

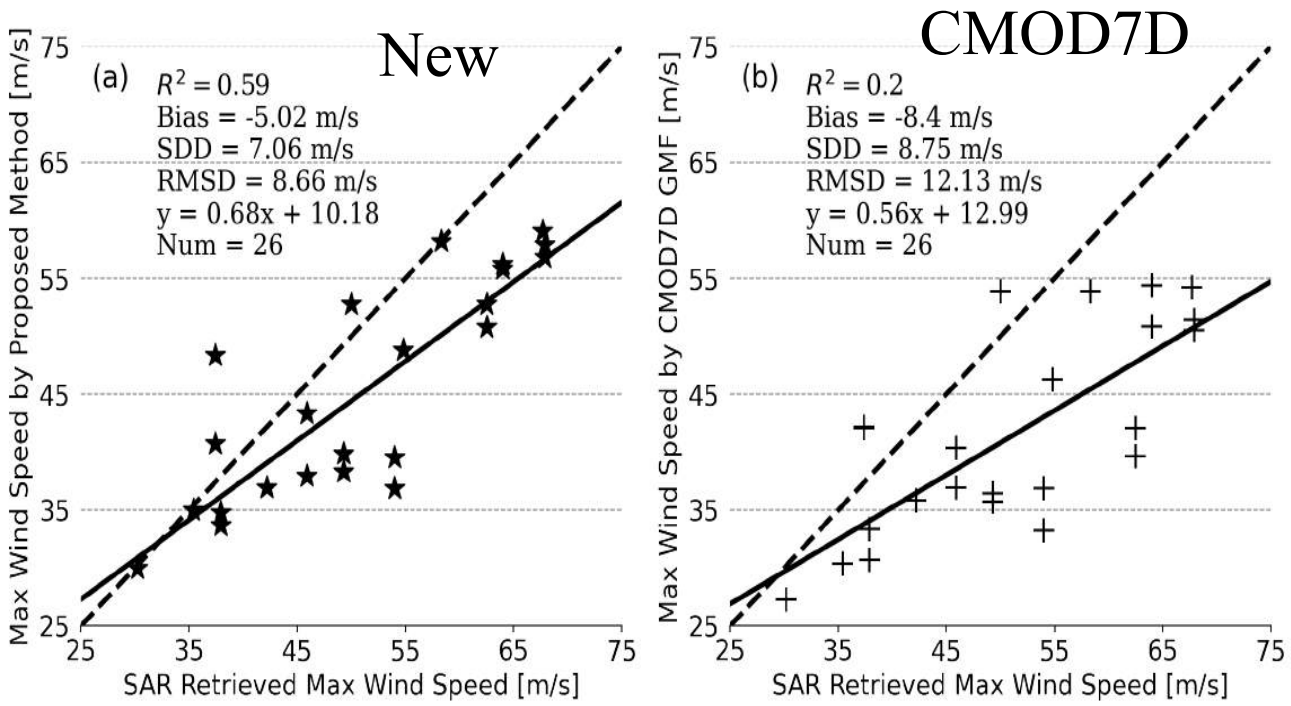
- SAR services are being developed in the Copernicus Marine Service to add value to scatterometer wind products, in particular for extremes and coastal
- Satellite B of MetOp-SG (2025) has SCA and will provide
  - 10% more swath than ASCAT
  - Double spatial resolution w.r.t. ASCAT
  - Better extremes, due to a VH channel
  - Continuous calibration by transponders
- Satellite B of MetOp-SG (2025) has a microwave radiometer MWI complementing SCA
  - “Day-2” SCA-intercalibrated MWI stress-equivalent winds
  - “Day-3” synergetic SCA and MWI stress-equivalent winds
- Copernicus Imaging Microwave Radiometer, CIMR (2025+), will provide ice and sea products, among which stress-equivalent wind speed
  - Intercalibrate with virtual scatterometer constellation



Ni et al., 2023

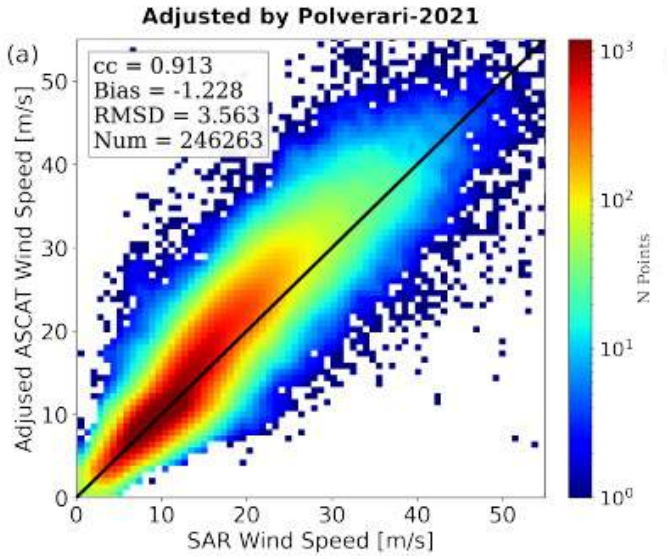
1-min. maximum sustained winds

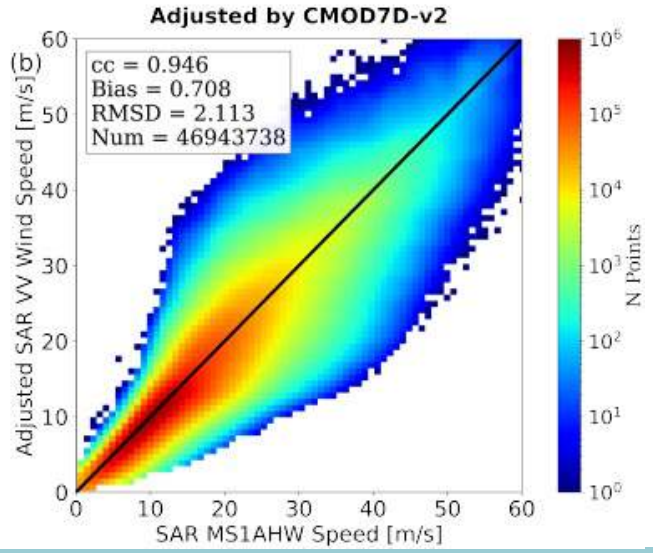
- Standard for hurricane category advisories
- Based on dropsonde wind speed scale – CMOD7D GMF for ASCAT
- Scatterometers blur the maximum eyewall winds (~10-min. value)
- Develop guidance for 1-minute maximum sustained winds for ASCAT
- Fit simple Rankine vortex to ASCAT winds:



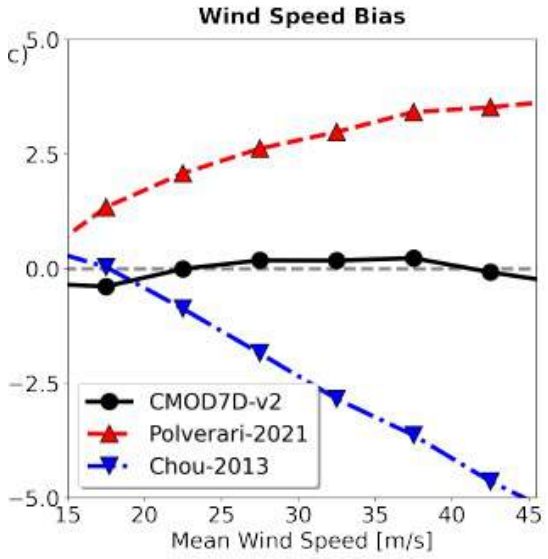
Ni et al., 2022 Tropical Cyclone Intensity Estimation From Spaceborne Microwave Scatterometry and Parametric Wind Models (MAXSS)

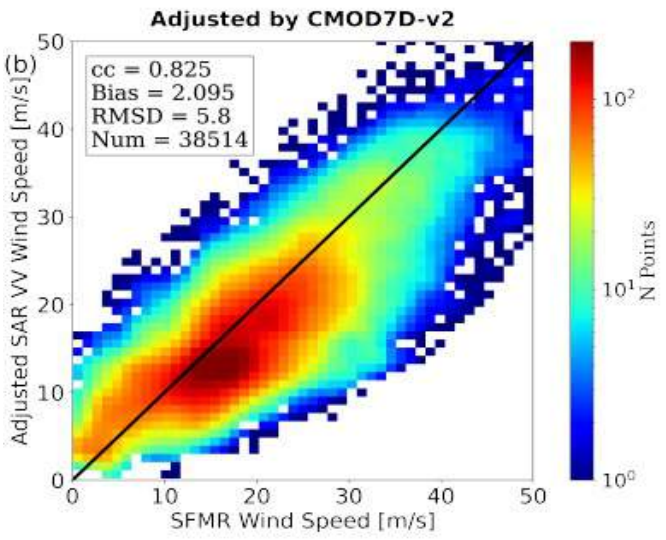
Comparing to SFMR/dropsondes





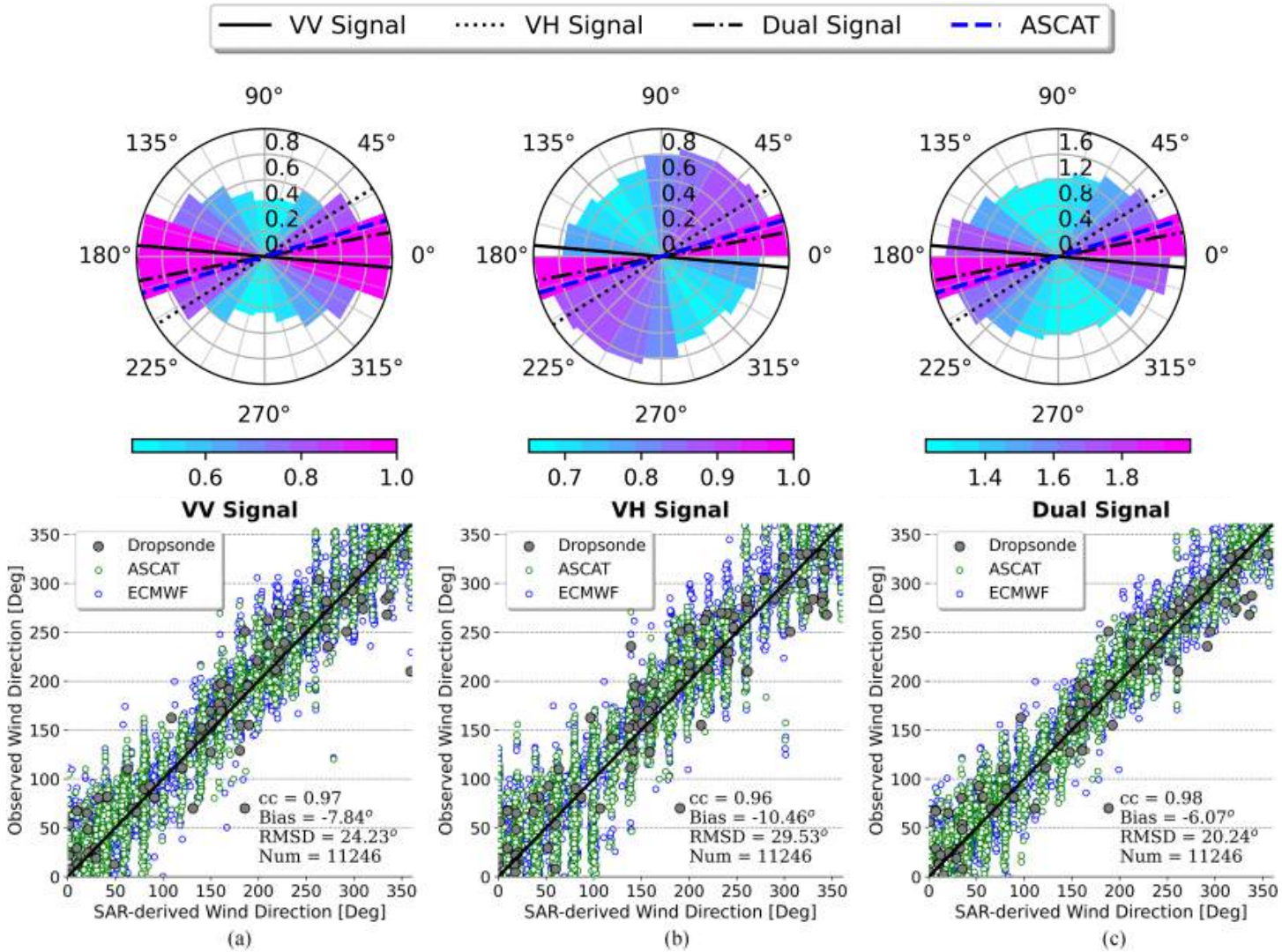
- Chou et al. adjusted to dropsondes
- Polverari et al. matched SFMR
- SAR VV and ASCAT match well with the same GMF after spatial matching
- SFMR and SAR spread substantially with RMSD of 5.8 m/s
- SFMR appears difficult to calibrate





Improved SAR wind direction

- Gradient method
- Compare SAR VV, VH and both
- Dropsondes
- ASCAT
- ECMWF



Ni et al., 2023

Tropical Cyclone Wind Direction Retrieval From Dual-Polarized SAR Imagery Using Histogram of Oriented Gradients and Hann Window Function (MAXSS)