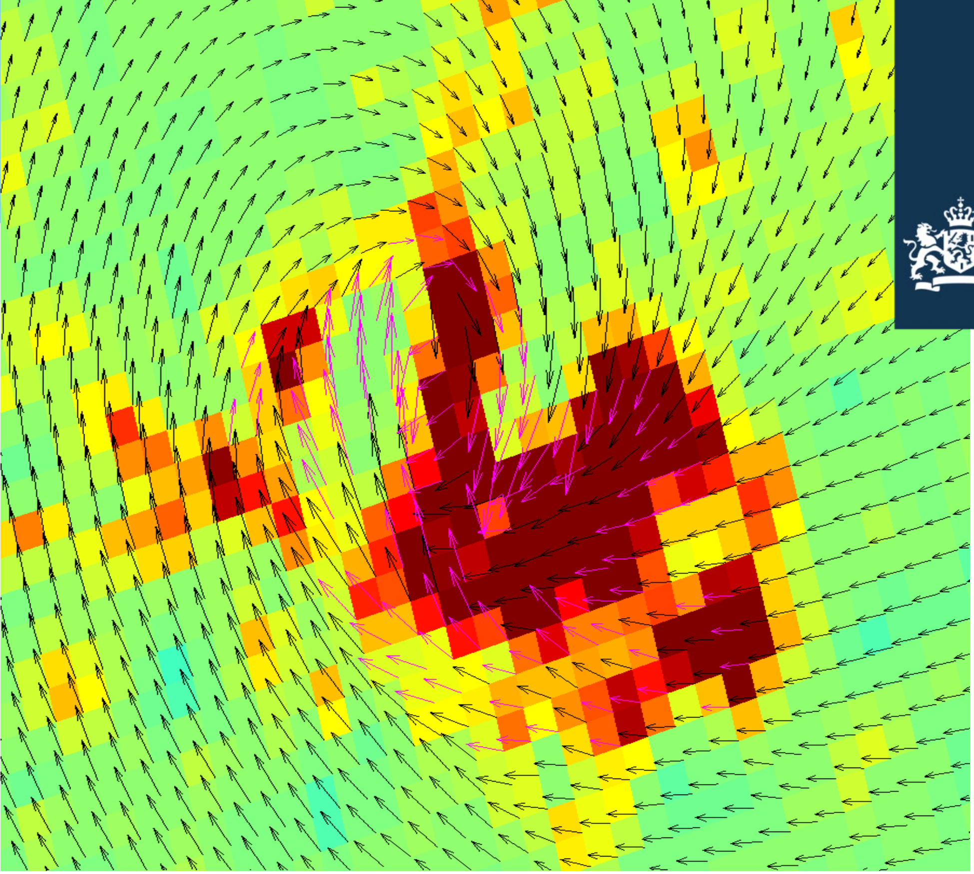
Royal Netherlands
Meteorological Institute
Ministry of Infrastructure and Waterworks

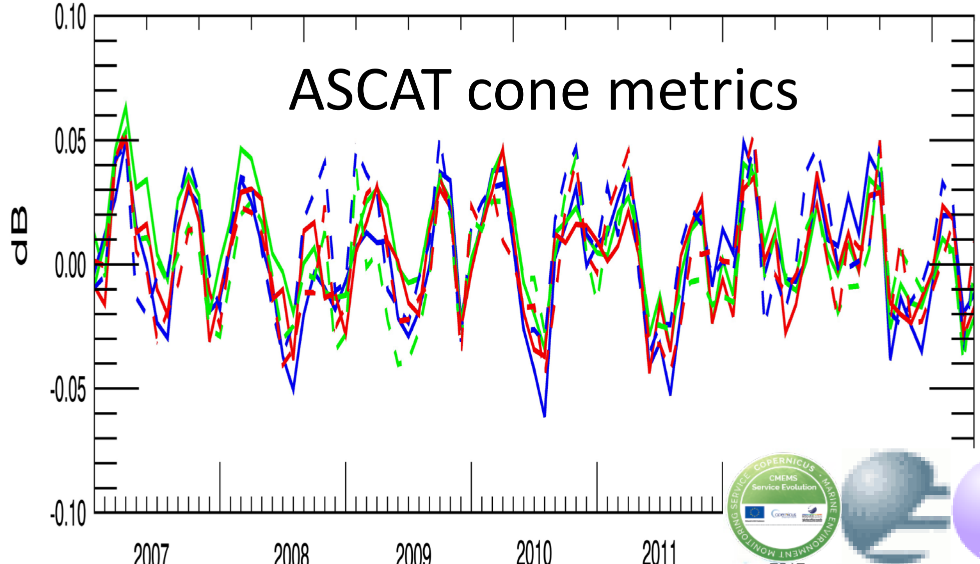


ISSI Wg Microwave Scatterometers

Ad.Stoffelen@knmi.nl

EUMETSAT OSI SAF: L2 data services
EUMETSAT NWP SAF: software
EU Copernicus Marine Core Services: L3/4

Alphen NB, 18 May 2021



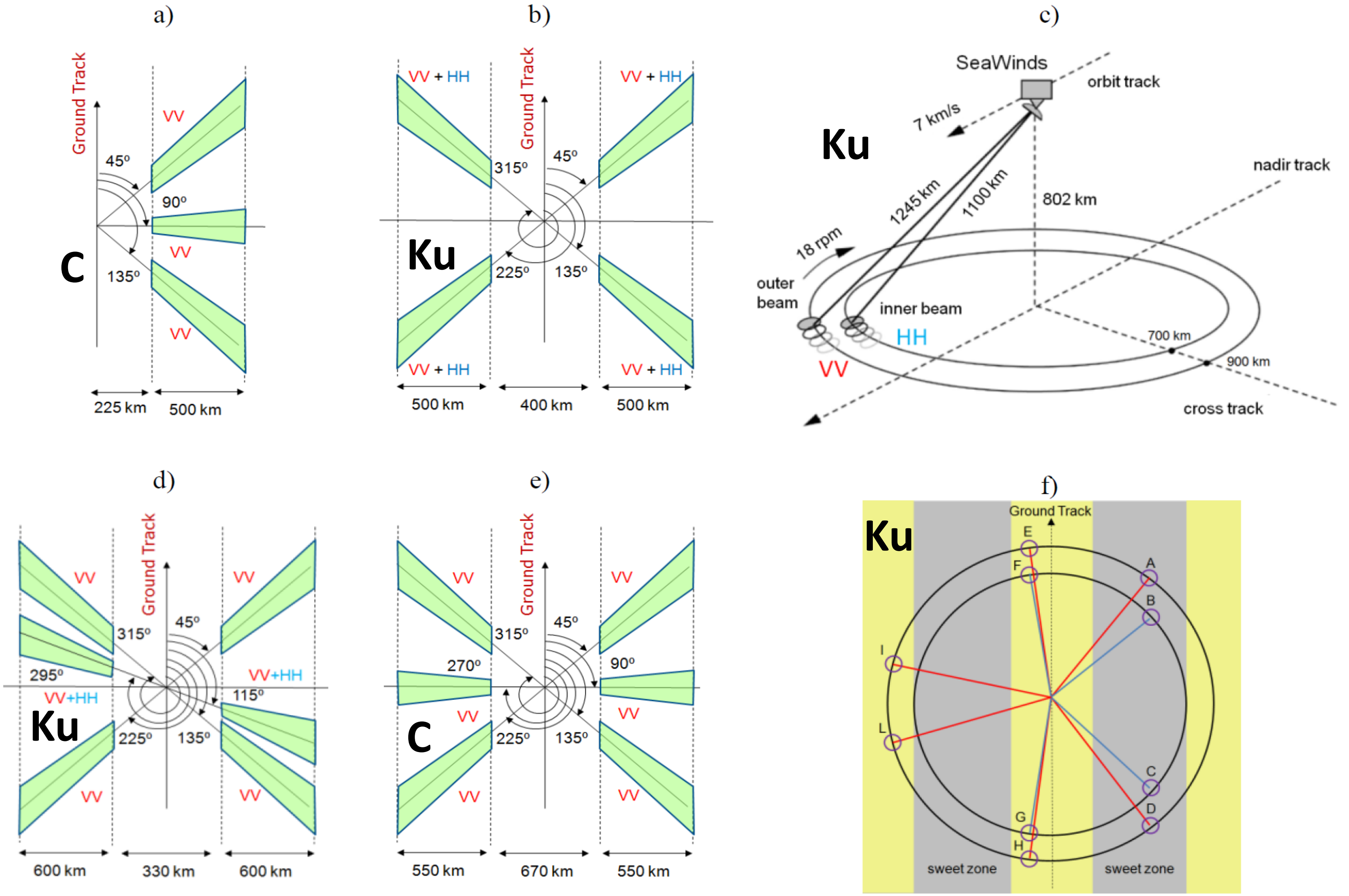


Fig. 1.4 *Sketch of the microwave illumination patterns of: a) AMI (ERS-1/2); b) SASS (SeaSat-A); c) and f) SeaWinds, Oceansat-2 SCAT and HY-2A; d) NSCAT; e) MetOp ASCAT-A and B. The case a), b), d) and e) correspond to a fan beam geometry whereas c) and f) correspond to a pencil beam geometry.*

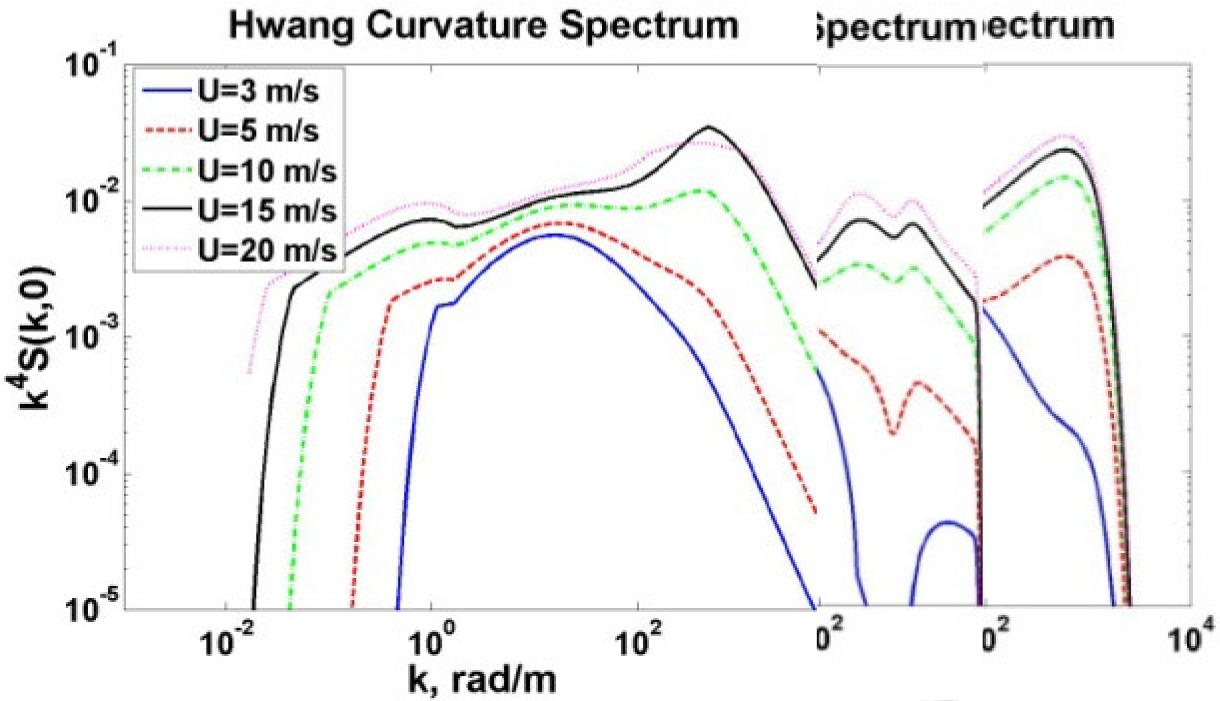
Franco Fois, PhD thesis, 2015

Satellite μw scatterometers

- Ground-based transponders are inaccurate for quality monitoring, but provide ball-park calibration for ASCAT
- The rain forest has a daily cycle of about 15% in μw backscatter; it may be used for stability monitoring at given LTAN
- Land targets are affected by moisture events (dew, rain)
- Ice/snow targets may be stable for months, years or decades, but will be affected by T>0 / rain (climate change)
- No absolute calibration, but
  - Very stable instruments within 0.1 dB (2%)
  - Cone metrics provides order 0.02 dB calibration for ASCAT (0.02 m/s)
  - Excellent relative calibration between instruments and over time
  - Non sun-synchronous satellite references for intercalibration
  - Excellent and consistent GMFs at used wavelengths, polarizations and angles
  - Many close C- and Ku-band collocations, allowing improved GMFs and consistency
  - Reasonable control on ancillary parameters: SST, stability, waves, rain, . . .
  - Well-known and controlled in situ and NWP references (except for extremes)
  - Generic C- and Ku-band processors
- Use ASCAT 2013 as calibration reference?

Satellite μw scatterometers

- Bragg scattering interference of microwaves and ocean waves
- Hydrodynamic ocean short-wave modulation, choppy wave model
- Wave-wind interaction, wave boundary layer (scatterometers see no long waves so far)
- The short wave spectrum is dominated by breaking waves and their dissipation for modal and higher winds
- Crucial to describe the short wave spectrum, but rather complex
- Use satellite data
- Wave shadowing and interference at grazing incidences
- Specular reflection dominates
  at smaller incidence angles
  (geometric optics)
- Scattering spilling breakers



Uncertainty

- Users are interested in stability and consistency of L2 geophysical products, e.g., detect 0.1 m/s trends over 10 years
  - Cone metrics provides order 0.02 dB calibration for ASCAT (0.02 m/s)
- Cone spread over ocean to provide ocean spatial variability, which is found equal to wind variability (wind downbursts, turbulence, convection)
- Related to Kp too (Kp is the σ^0 SD)
- Can be segregated into geophysical and instrument contributions

- Wind retrieval quality is in stress-equivalent wind, correcting for air stability and mass density effects
- Scatterometer wind retrievals are very consistent after intercalibration of backscatter values and GMFs

- Physically-based models are useful to describe/understand behaviour at different wavelengths and polarizations, but fed by empirical satellite data characterization to improve accuracy
  - Wavelength dependency
  - Wind azimuth and speed dependency
  - Polarization/incidence dependency

Franco Fois, PhD thesis, 2015

Scattering models

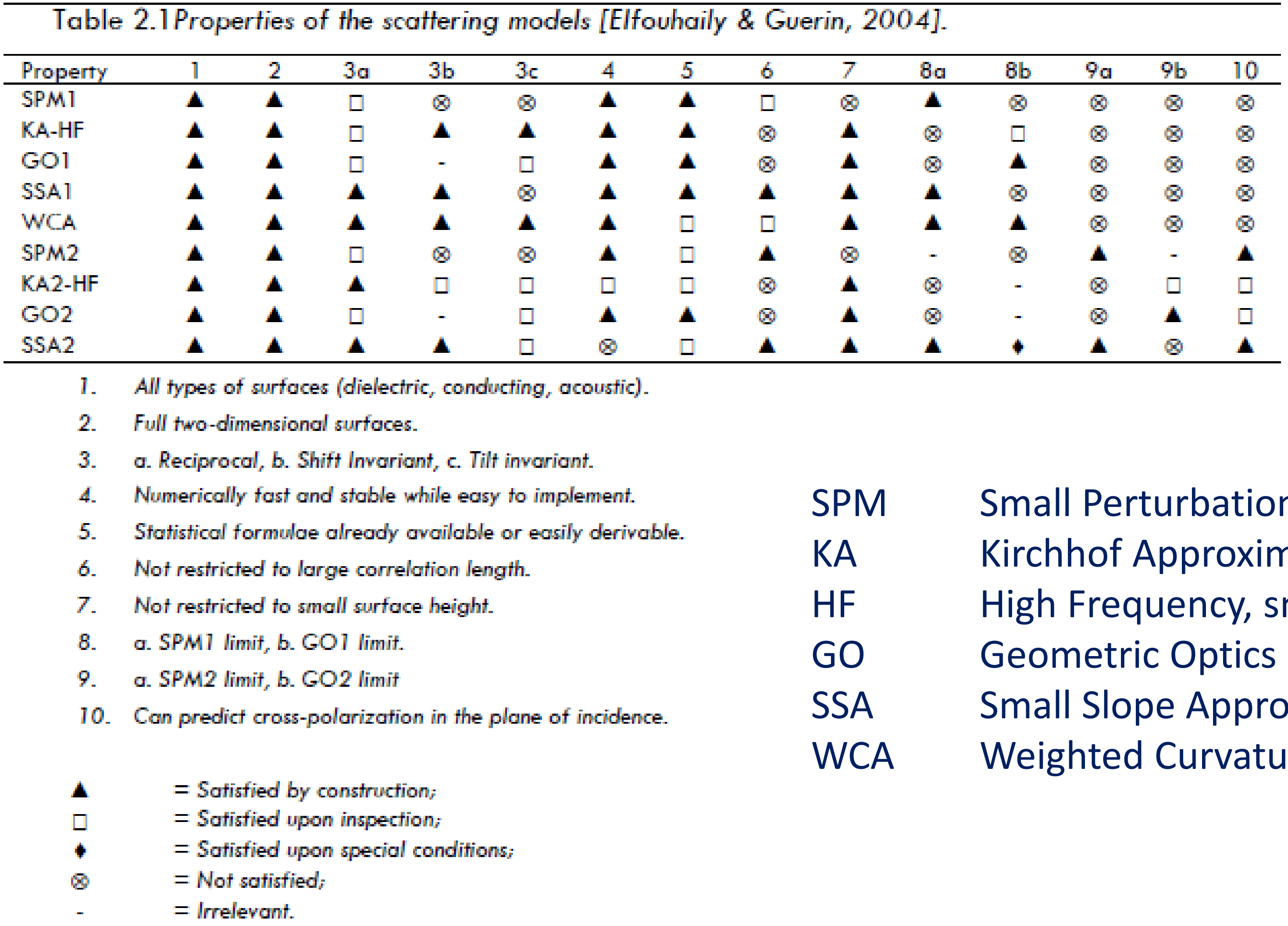


Table 2.1 *Properties of the scattering models [Elfouhaily & Guerin, 2004].*

Property	1	2	3a	3b	3c	4	5	6	7	8a	8b	9a	9b	10
SPM1	▲	▲	☐	⊗	⊗	▲	▲	☐	⊗	▲	⊗	⊗	⊗	⊗
KA-HF	▲	▲	☐	▲	▲	▲	▲	⊗	▲	⊗	☐	⊗	⊗	⊗
GO1	▲	▲	☐	-	☐	▲	▲	⊗	▲	⊗	▲	⊗	⊗	⊗
SSA1	▲	▲	▲	▲	⊗	▲	▲	▲	▲	▲	⊗	⊗	⊗	⊗
WCA	▲	▲	▲	▲	▲	▲	☐	☐	▲	▲	▲	⊗	⊗	⊗
SPM2	▲	▲	☐	⊗	⊗	▲	☐	▲	⊗	-	⊗	▲	-	▲
KA2-HF	▲	▲	▲	☐	☐	☐	☐	⊗	▲	⊗	-	⊗	☐	☐
GO2	▲	▲	☐	-	☐	▲	▲	⊗	▲	⊗	-	⊗	▲	☐
SSA2	▲	▲	▲	▲	☐	⊗	☐	▲	▲	▲	♦	▲	⊗	▲

1. *All types of surfaces (dielectric, conducting, acoustic).*
2. *Full two-dimensional surfaces.*
3. *a. Reciprocal, b. Shift Invariant, c. Tilt invariant.*
4. *Numerically fast and stable while easy to implement.*
5. *Statistical formulae already available or easily derivable.*
6. *Not restricted to large correlation length.*
7. *Not restricted to small surface height.*
8. *a. SPM1 limit, b. GO1 limit.*
9. *a. SPM2 limit, b. GO2 limit*
10. *Can predict cross-polarization in the plane of incidence.*

▲ = *Satisfied by construction;*
☐ = *Satisfied upon inspection;*
♦ = *Satisfied upon special conditions;*
⊗ = *Not satisfied;*
\- = *Irrelevant.*

SPM	Small Perturbation Method
KA	Kirchhof Approximation
HF	High Frequency, small wavelength
GO	Geometric Optics (longer sea waves)
SSA	Small Slope Approximation
WCA	Weighted Curvature Approximation

Franco Fois, PhD thesis, 2015

Franco Fois

- High Frequency: GO and Kirchhoff
- Low Frequency: SPM
- Unified models (GO and SPM), multiple scattering: SSA2
- SSA2 best fits GMF data at C, X and Ku bands
- Steep breaking waves point of concern
- Foam, small co-pol effect and large VH effect for high winds
- Mouche et al. find Tb and VH both linear with extreme winds
- Non-linear hydrodynamic coupling between long and short waves

GMF:

$\sigma^o = A_0 + A_1 \cos \phi + A_2 \cos 2\phi$

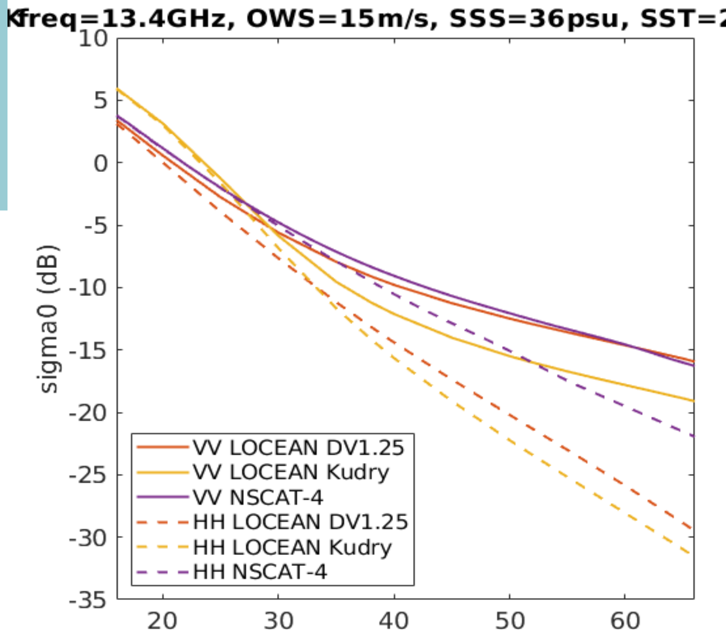
$\sigma^o = B0\,[1 + B_1 \cos \phi + B_2 \cos 2\phi]^{0.625}$ adds higher harmonic terms to fit cone

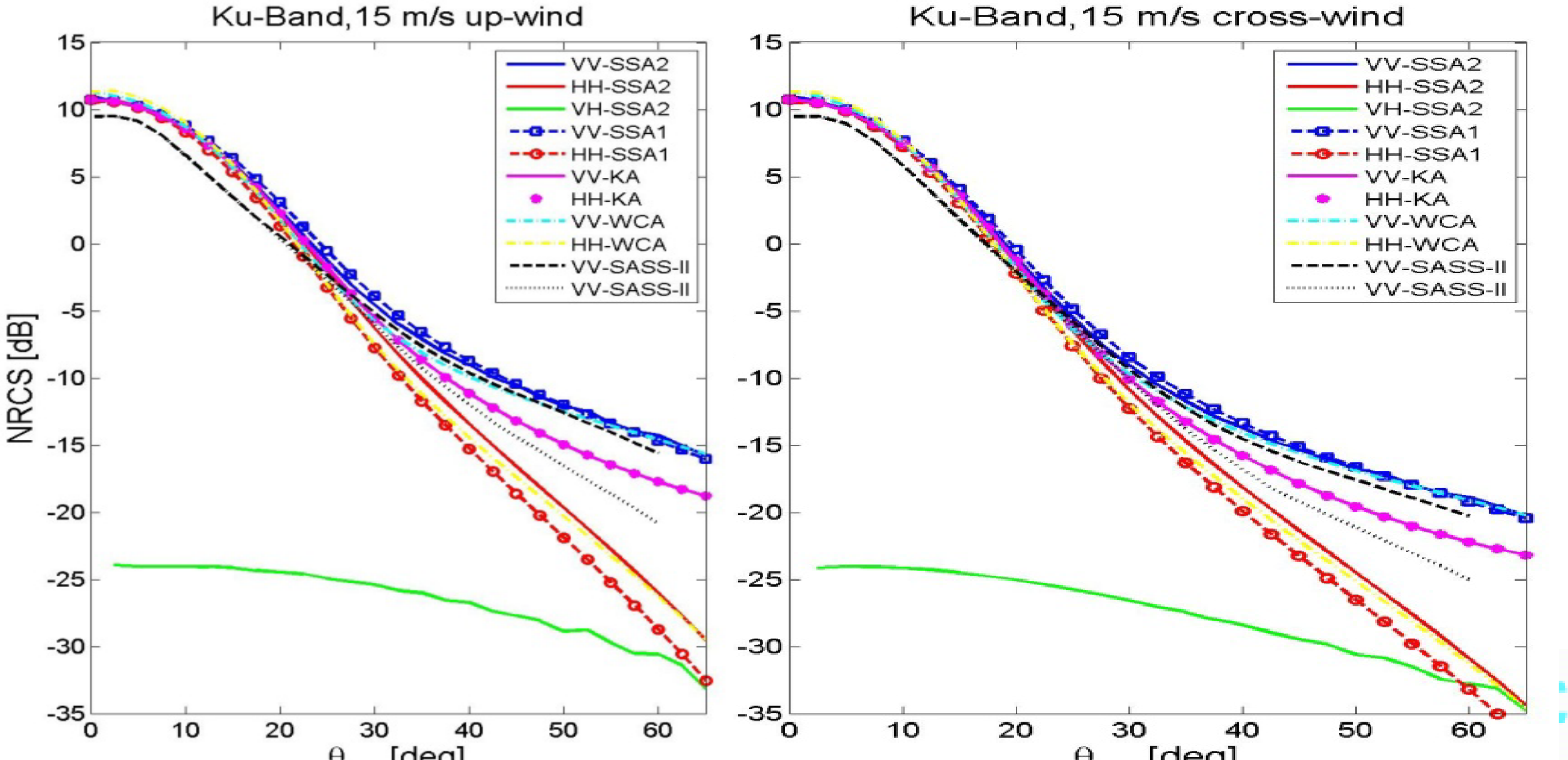
Stoffelen and Anderson (1997)

Franco Fois, PhD thesis, 2015

Ku-band vs θ

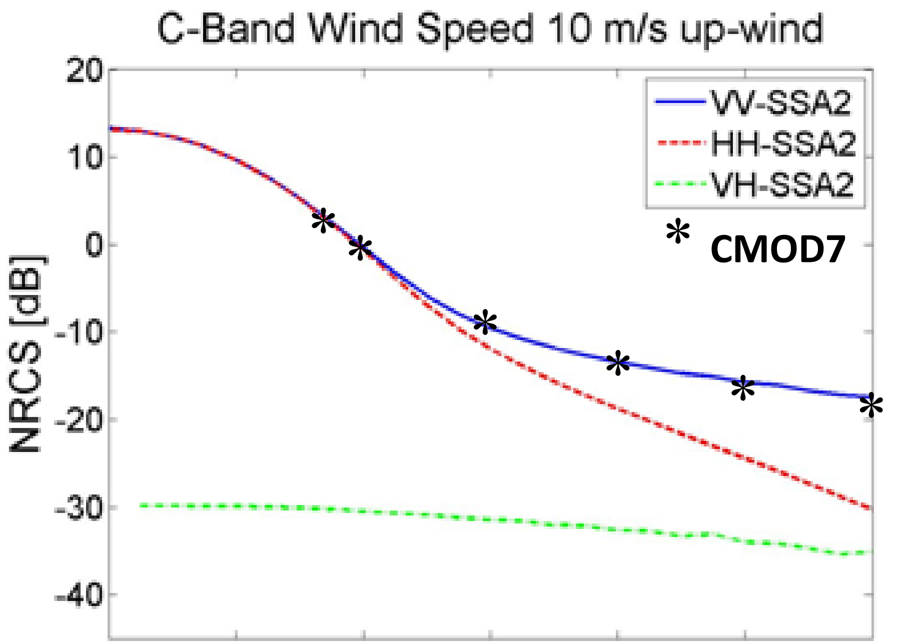
- ✓ SASS/NSCAT-4 Ku VV and DV1.25/SSA2 θ dependency match
- × Not for Kudryavtsev
- × HH DV1.25/SSA2/Kudry θ dependency too steep

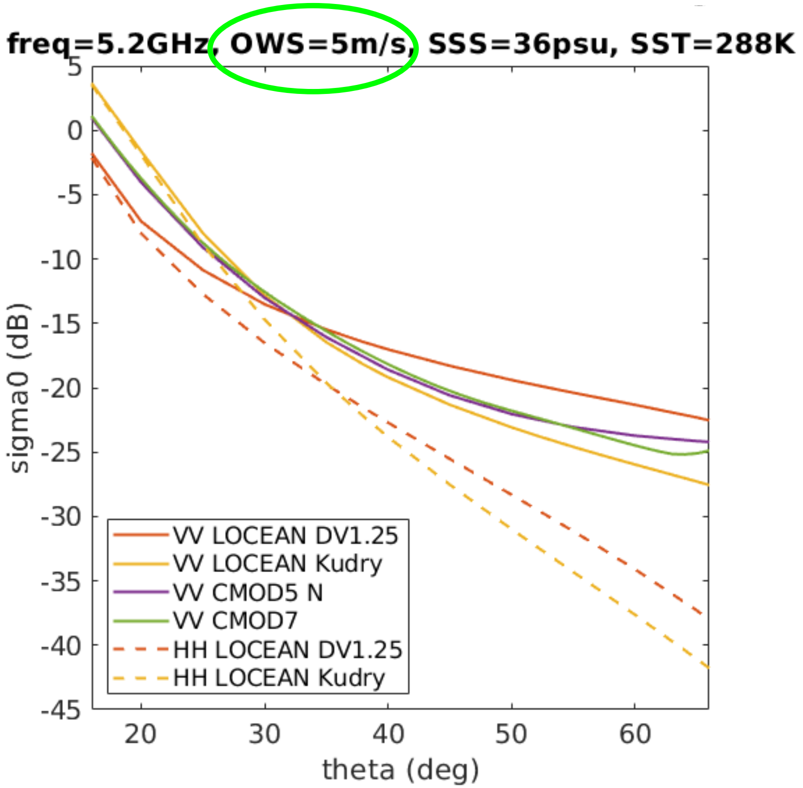


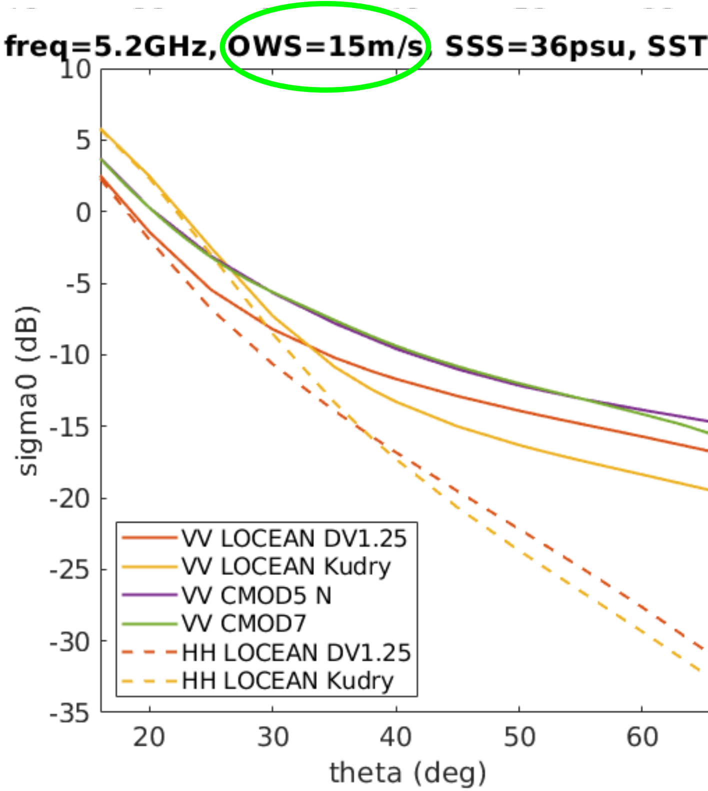


C-band vs θ

- ✓ CMOD VV and DV1.25/SSA2 θ dependency match @ 10 m/s
- × Not for Kudry
- × Particularly not at lower speeds for DV1.25





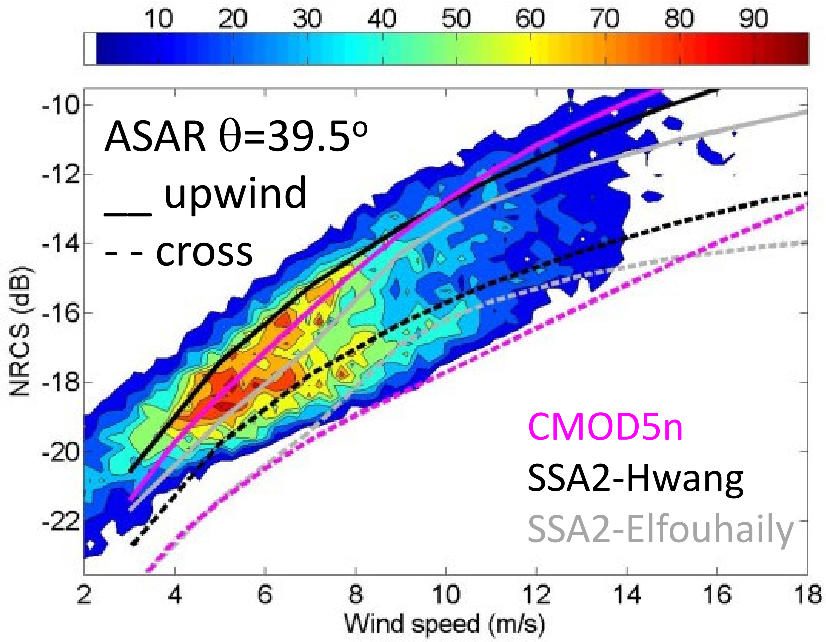


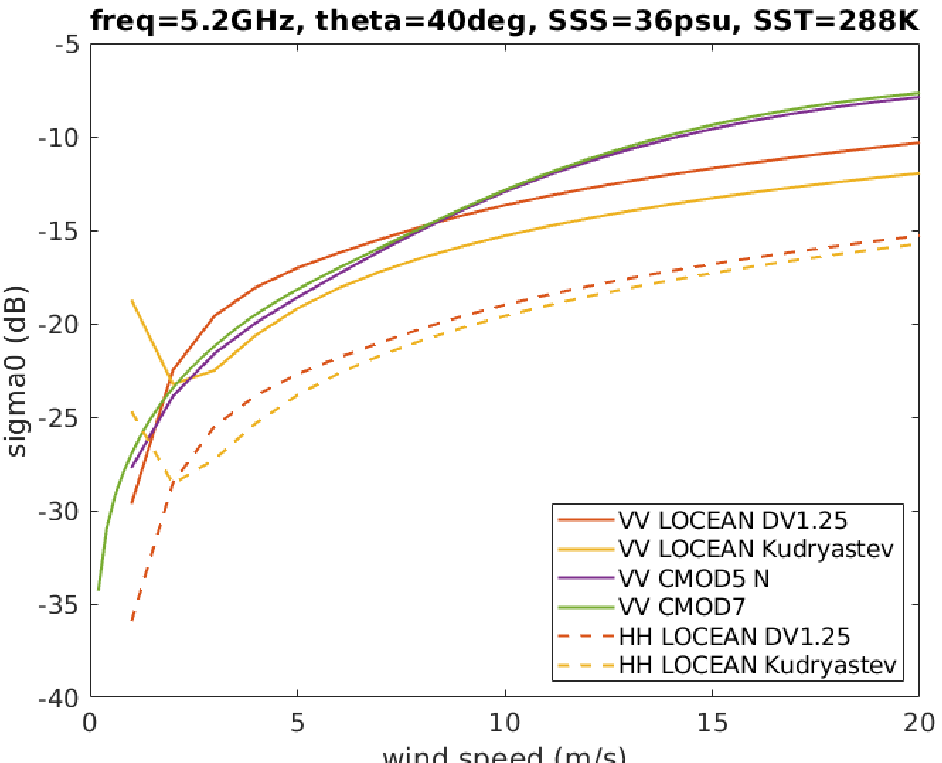
C-band VV

- ASAR not calibrated w.r.t. ASCAT
- Radars need calibrated noise subtraction (noise floor) and linear calibration (dB off-set), e.g., Belmonte et al. (2017) on cone metrics
- ASCAT calibration is checked with transponders; remaining absolute uncertainty ~0.2 dB
- Relative uncertainty CMOD7/CMOD5n typically 0.1 dB
- ASAR noise subtraction?

- C-band VV-HH (θ=45°) = 5.4 dB (Thompson)

- CMOD steeper as function of speed





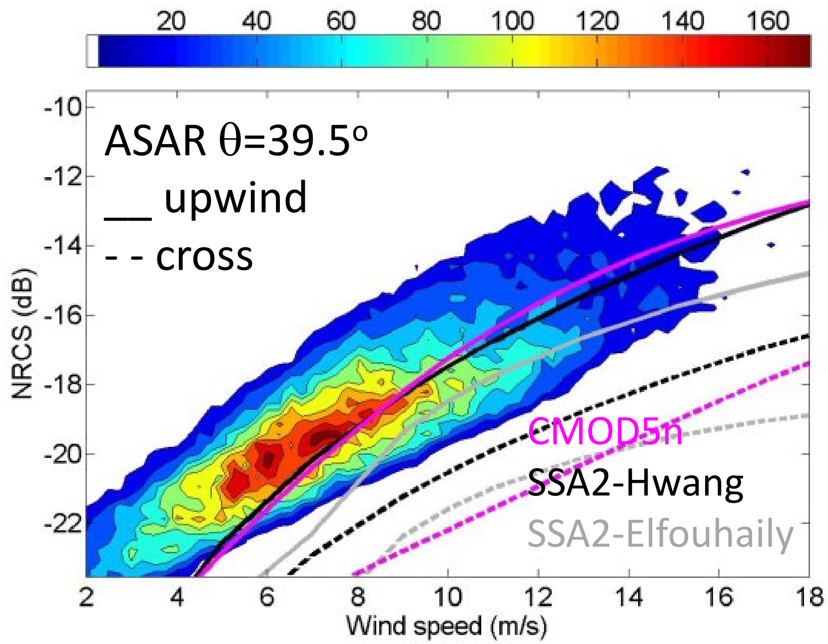
Franco Fois, PhD thesis, 2015

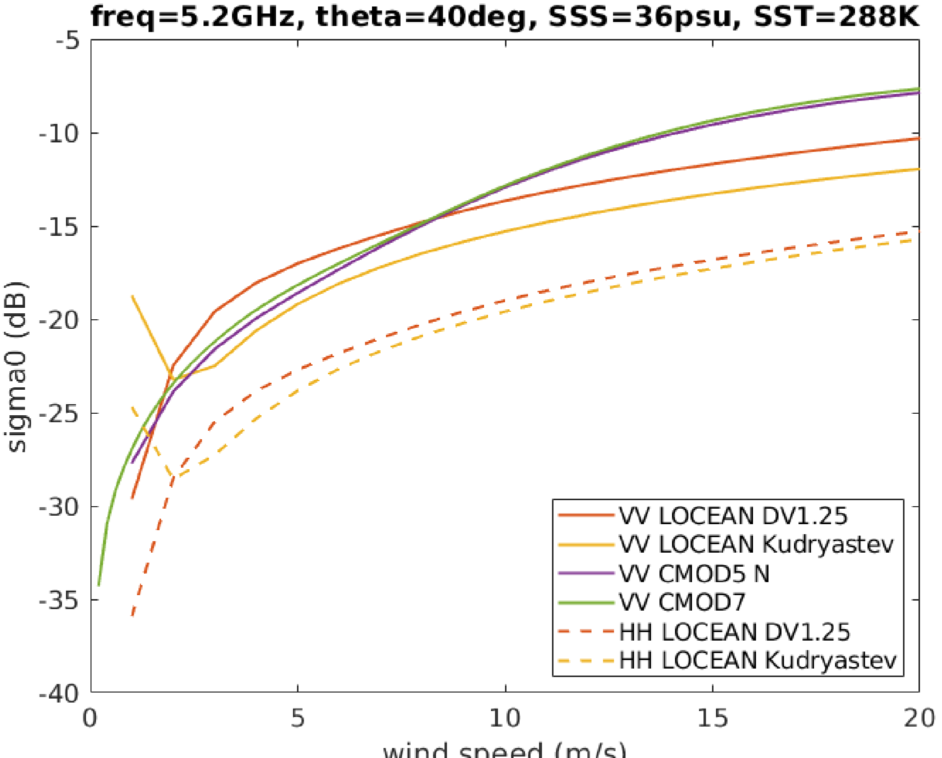
C-band HH

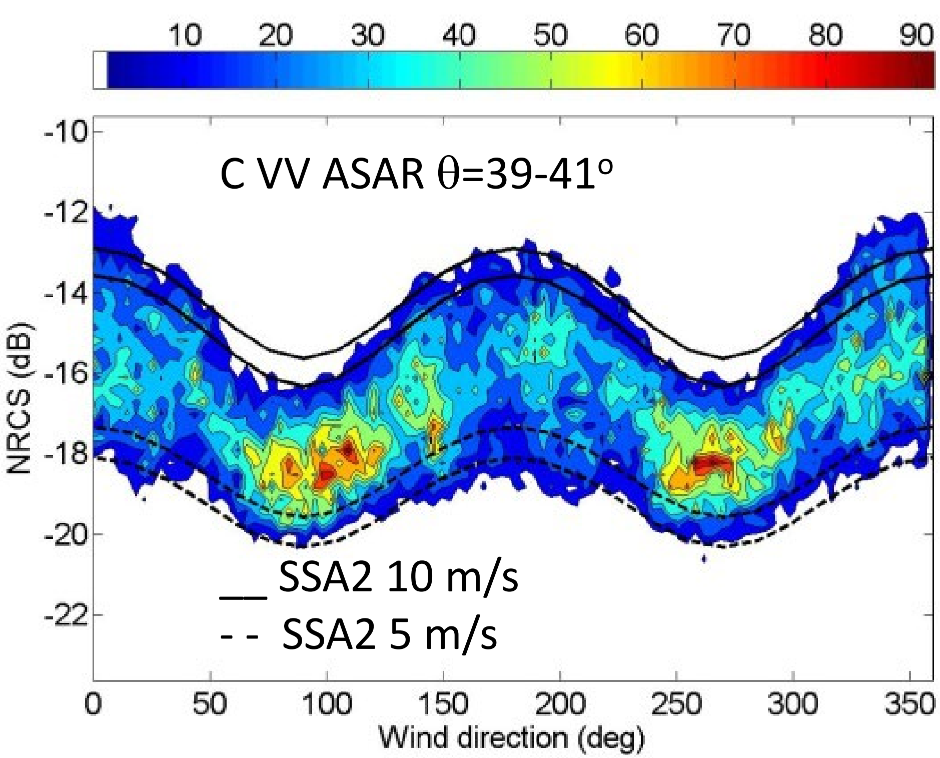
- ASAR not calibrated w.r.t. ASCAT
- Radars need calibrated noise subtraction (noise floor) and linear calibration (dB off-set), e.g., Belmonte et al. (2017) on cone metrics
- ASCAT calibration is checked with transponders; remaining absolute uncertainty ~0.2 dB
- Relative uncertainty CMOD7/CMOD5n typically 0.1 dB
- ASAR noise subtraction?

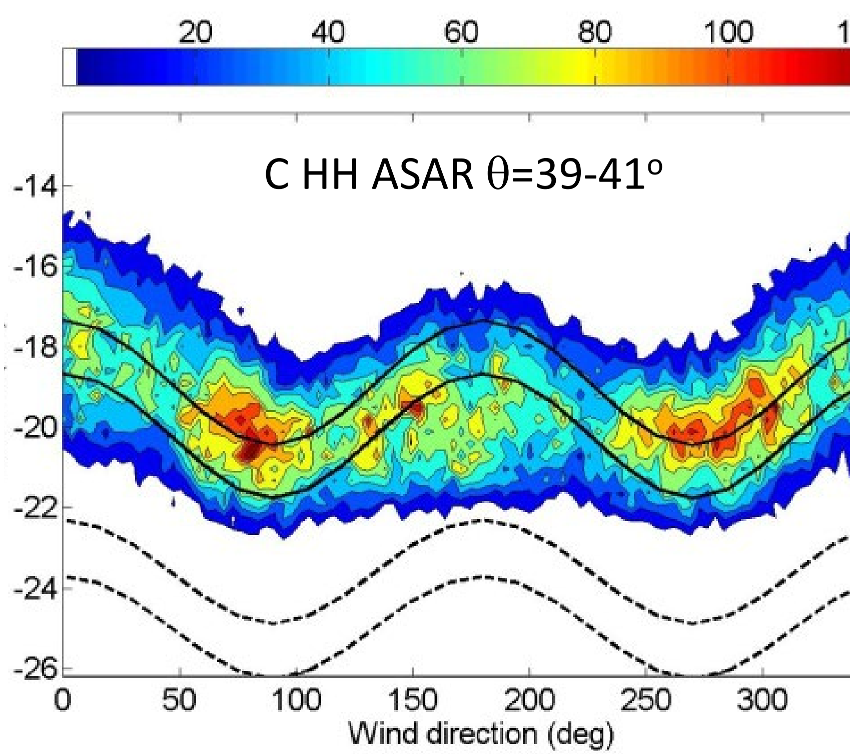
- C-band VV-HH ($\theta=45^{\circ}$) = 5.4 dB (Thompson)

- ➢ CMOD steeper as function of speed



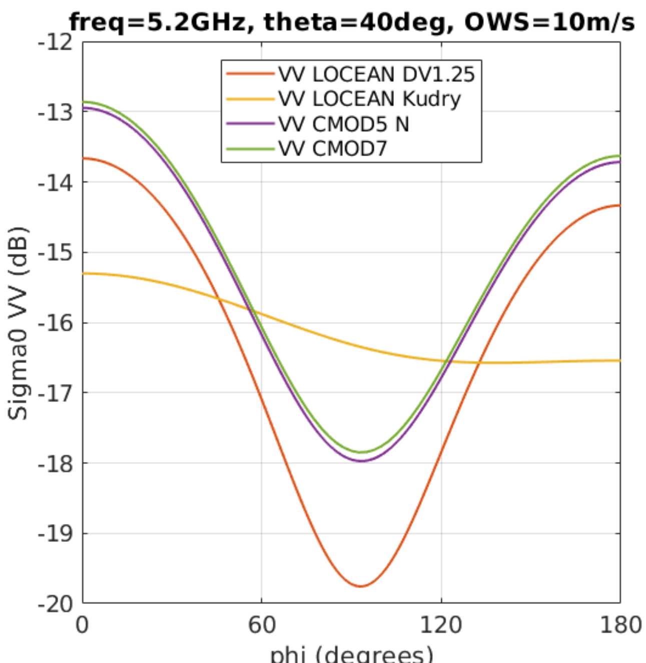






C-band

- ✓ CMOD VV and DV1.25 ϕ modulation match
- ✓ HH DV1.25 matches up/downwind Ku shape
- × Kudry



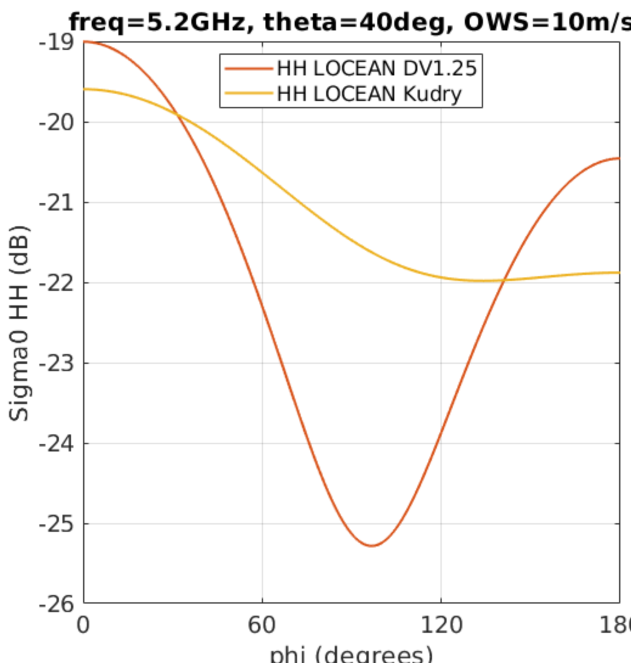
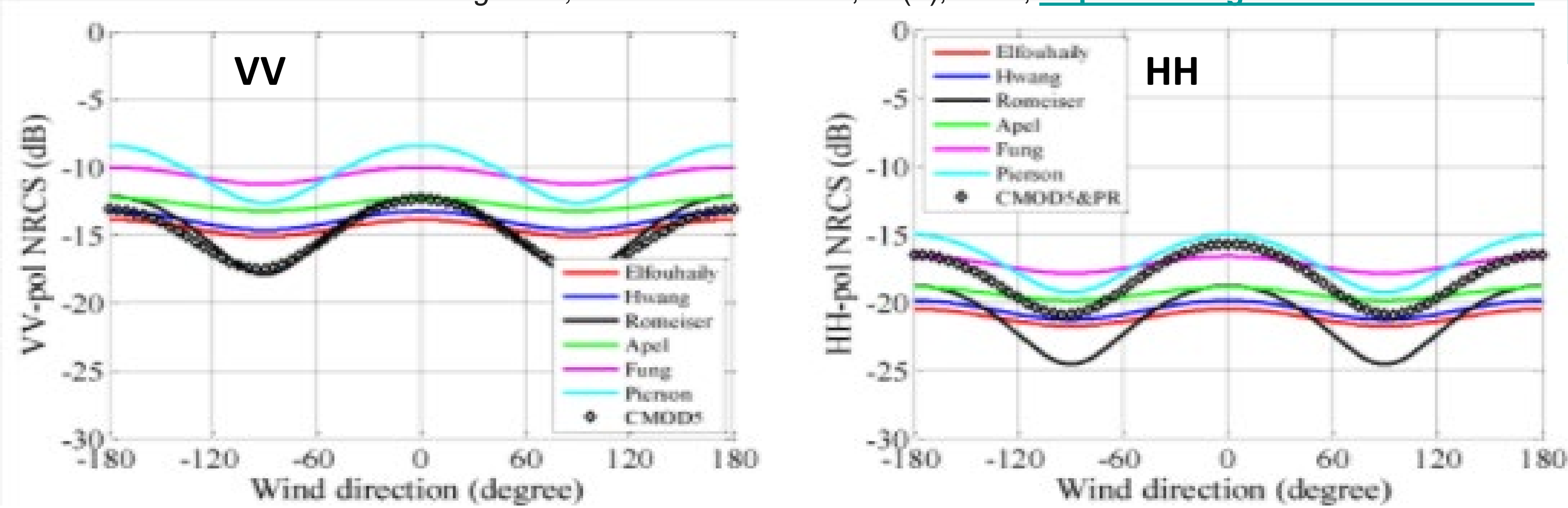


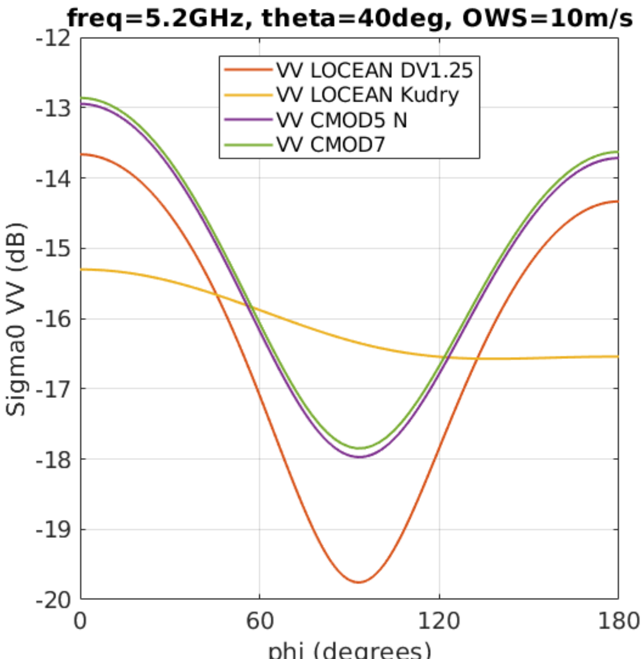
Figure 17. NRCSs estimated in relationship to the wind direction. U_{10} = 10 m/s, $\theta_i = 40°$. (a) VV polarization. (b) HH polarization.

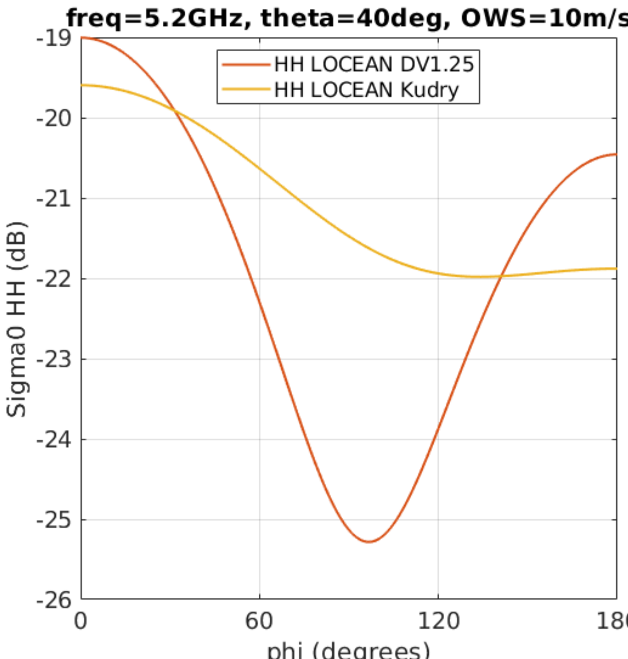
Zheng et al., Remote Sens. **2018**, *10*(7), 1084; https://doi.org/10.3390/rs10071084



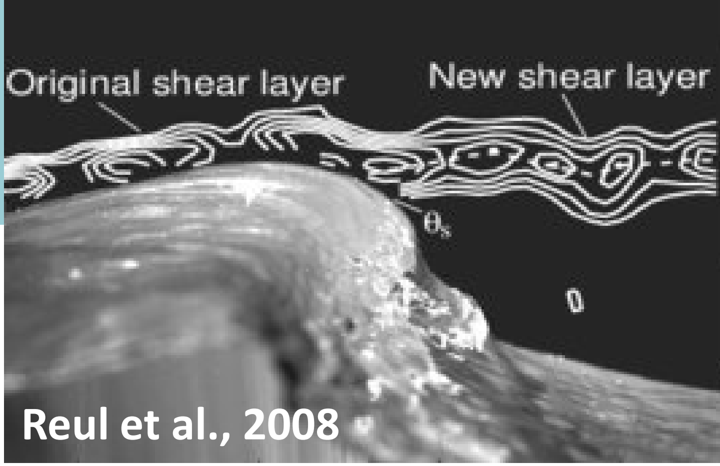
C-band

- ✓ CMOD VV and DV1.25 ϕ modulation match
- ✓ HH DV1.25 matches up/downwind C/Ku shape
- × Kudry





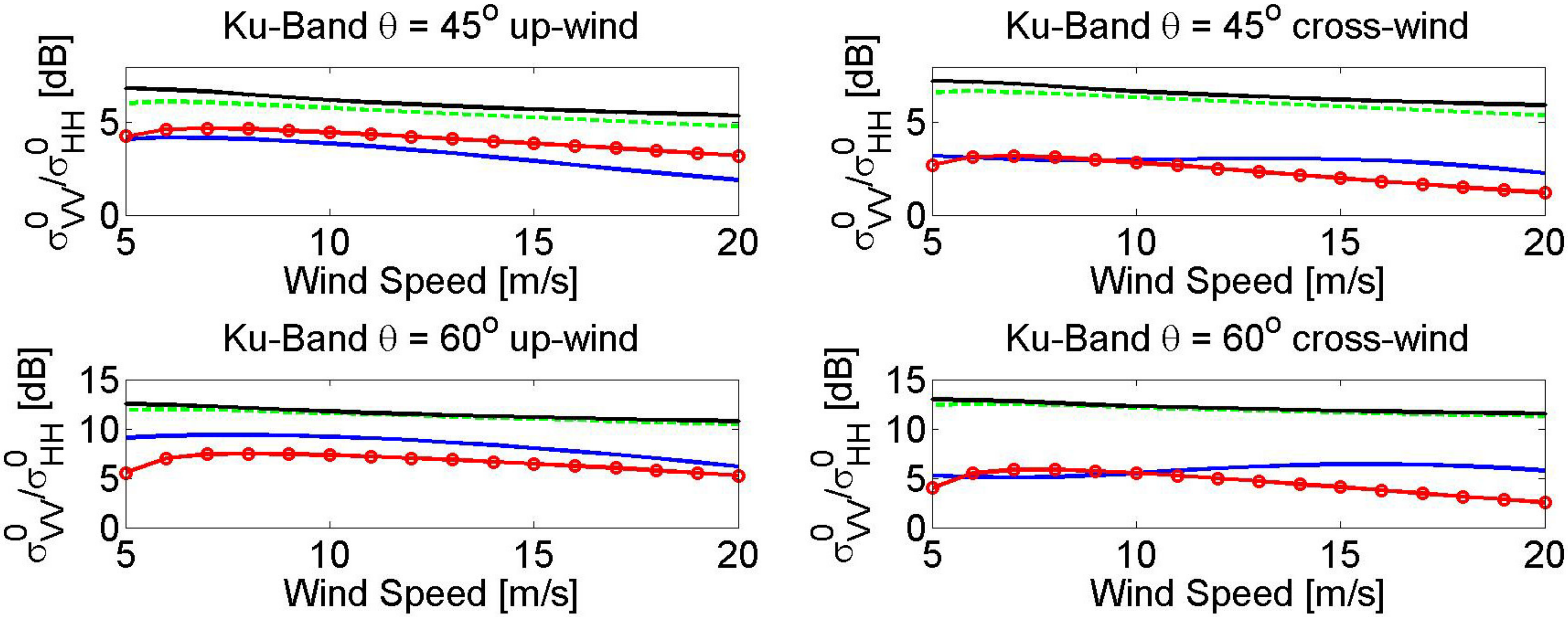
Breaking contribution



Reul et al., 2008

- ❖ Steep breaking waves needed for HH at high θ
- ❖ Non-Bragg scattering spilling breaking waves

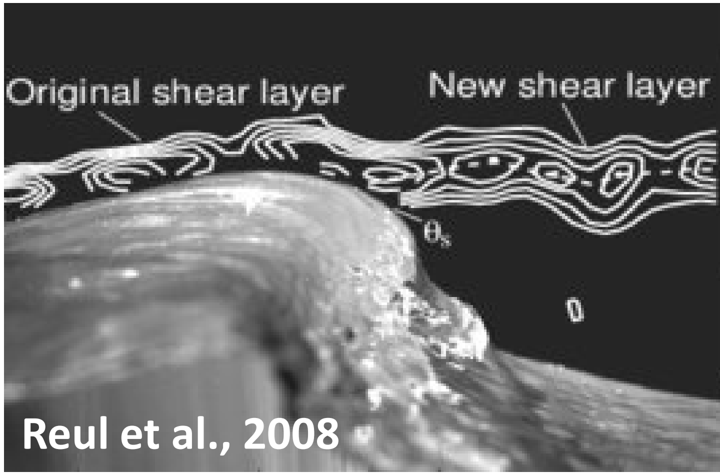
- ➢ Improves polarization ratio



WCA-Elfouhaily WCA-Kudryavtsev WCA-Hw+breaking NSCAT2 GMF

Franco Fois, PhD thesis, 2015

From GMFs to physics



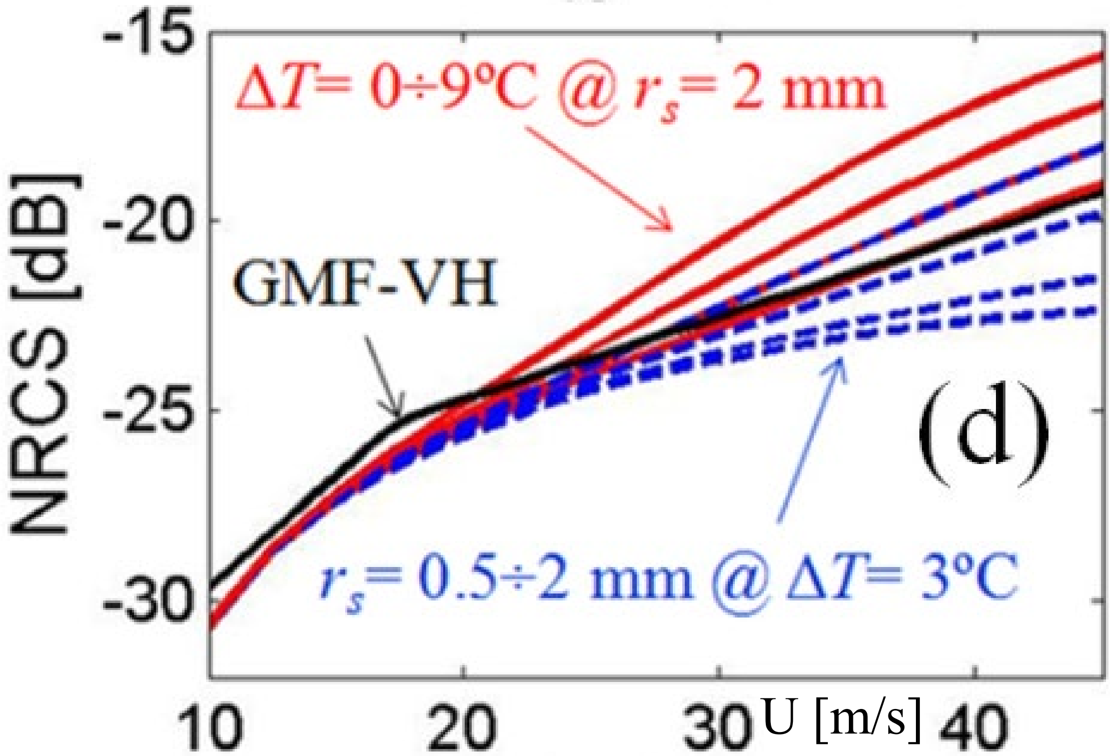
Reul et al., 2008

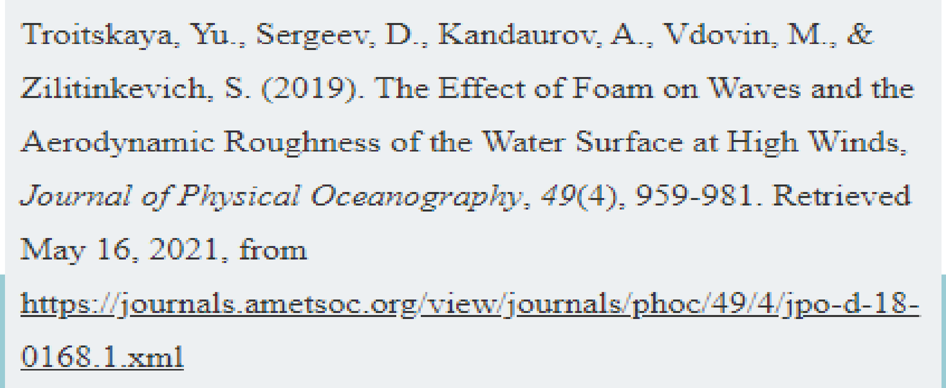
- Hwang & Fois (2015)
- VV GMFs to approximate multifrequency Bragg, i.e., short wave spectrum
- HH and VH GMFs for refining scattering properties, Bragg, specular, non-Bragg scattering spilling breaking waves, foam, . . .

Franco Fois, PhD thesis, 2015

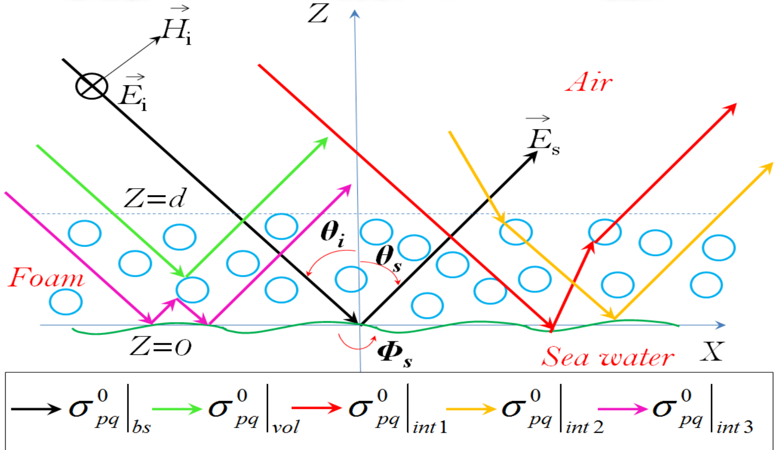
Foam at extremes

- Tb and C-band VH NRCS both linear on dropsonde speed scale (Mouche et al., 2017)
- Foam phenomana is complex and linearity physically not plausible
- Inconsistent with moored buoy in-situ speed (U) scale from 15-25 m/s, which shows non-linear dependency (CHEFS)



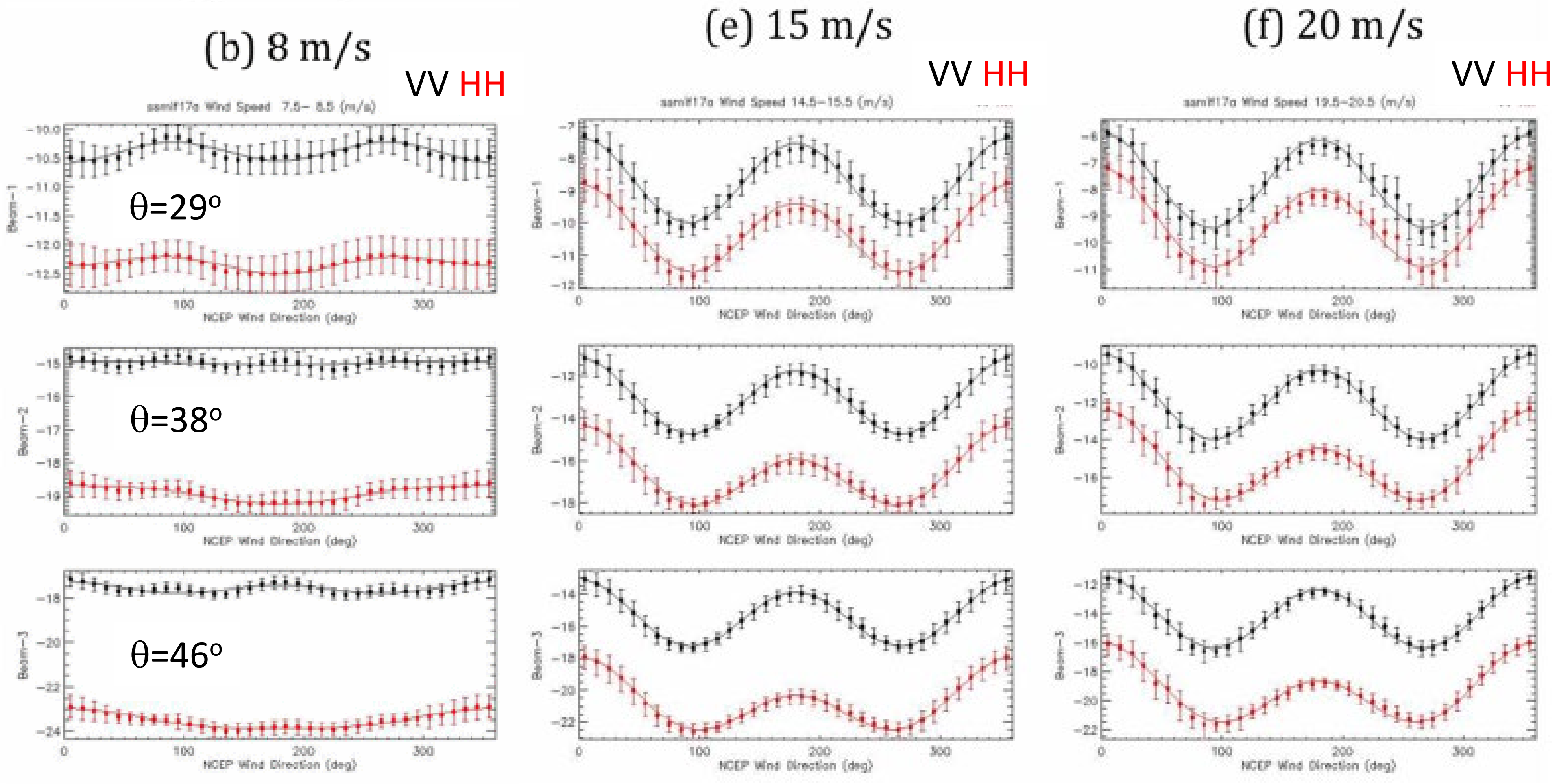


Troitskaya, Yu., Sergeev, D., Kandaurov, A., Vdovin, M., & Zilitinkevich, S. (2019). The Effect of Foam on Waves and the Aerodynamic Roughness of the Water Surface at High Winds, *Journal of Physical Oceanography*, *49*(4), 959-981. Retrieved May 16, 2021, from https://journals.ametsoc.org/view/journals/phoc/49/4/jpo-d-18-0168.1.xml



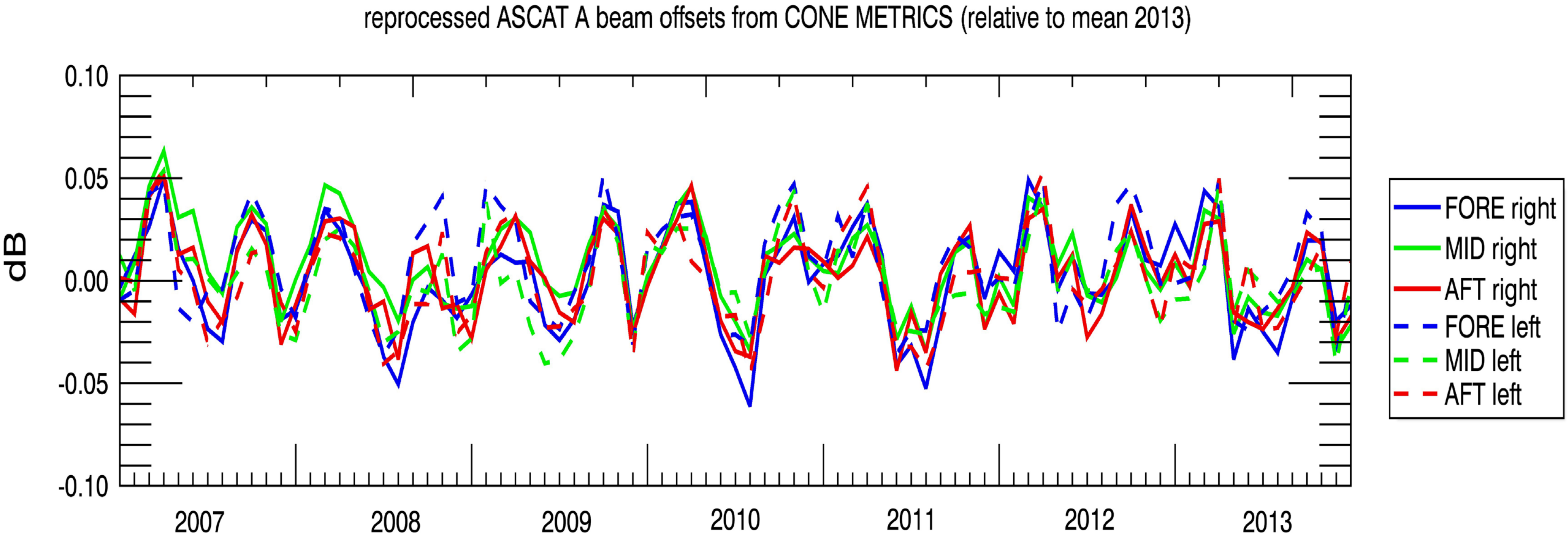
L-band Aquarius

S. H. Yueh *et al.*, "L-Band Passive and Active Microwave Geophysical Model Functions of Ocean Surface Winds and Applications to Aquarius Retrieval," in *IEEE Transactions on Geoscience and Remote Sensing*, vol. 51, no. 9, pp. 4619-4632, Sept. 2013, doi: 10.1109/TGRS.2013.2266915.



ASCAT is very stable

- ASCAT-A beams stay within a few hundreds of a dB (eq. to m/s)
- Cone position variation due to seasonal wind variability (reduced with u10s)
- ➢ Improve ASCAT attitude knowledge? (cf. Long, 1998)
- ➢ Asset for Ku-band scatterometer developments; radiometers
- ➢ Reference for NWP reanalyses
- ➢ Can method be applied for other scatterometers?



Maria Belmonte et al., 2017

Stress-equivalent wind

- Radiometers/scatterometers measure ocean roughness
- Ocean roughness consists in small (cm) waves generated by air impact and subsequent wave breaking processes; depends on gravity, water mass density, surface tension s, and e.m. sea properties (assumed constant)
- Air-sea momentum exchange is described by $\boldsymbol{\tau} = \rho_{air}\, u_* \boldsymbol{u}_*$, the stress vector; depends on air mass density ρ_{air} , friction velocity vector $\boldsymbol{u}_*$
- Surface layer winds (e.g., $\boldsymbol{u}_{10}$) depend on $\boldsymbol{u}_*$, atmospheric stability, surface roughness and the presence of ocean currents
- Equivalent neutral winds, $\boldsymbol{u}_{10N}$, depend only on $\boldsymbol{u}_*$, surface roughness and the presence of ocean currents and is currently used for backscatter geophysical model functions (GMFs)

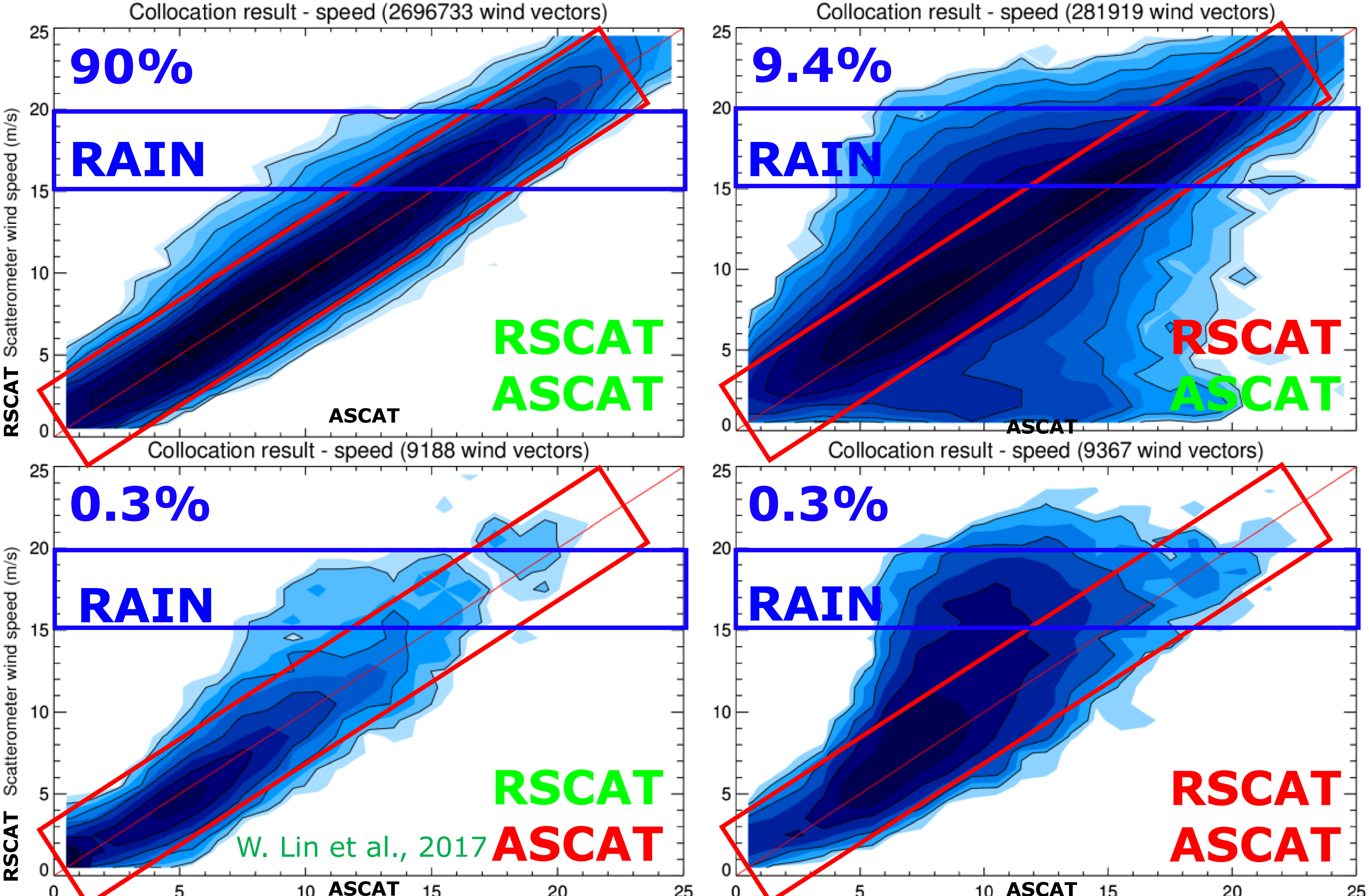
- $\boldsymbol{u}_{10S} = \sqrt{\rho_{air}} \cdot \boldsymbol{u}_{10N} / \sqrt{\rho_0}$ is now used to be a better input for backscatter GMFs (stress-equivalent wind)
- This prevents regional biases against local wind references

Jos de Kloe et al., 2017

Intercalibration and standardization

- Our premise is that for given wavelength, polarization and geometry, σ^0 should be identical in identical geophysical conditions and independent of instrument settings
- We develop generic L2 wind processing for calibrated instrument data
- Noise properties do however affect σ^0 diagnostics, so we develop noise models too to better understand our retrievals and diagnostics
- KNMI is particularly interested to remove (σ^0–dependent) instrument biases as they interfere with Ku-band wind and SST dependencies (Stoffelen et al., 2017; Wang et al., 2017; Belmonte et al., 2017)
- Comparison of ScatSat with QSCAT, RSCAT and OSCAT behavior for given Geophysical Model Function GMF and NWP input to obtain consistency
- CFOSAT, HY-2 and WindRad scatterometers will follow

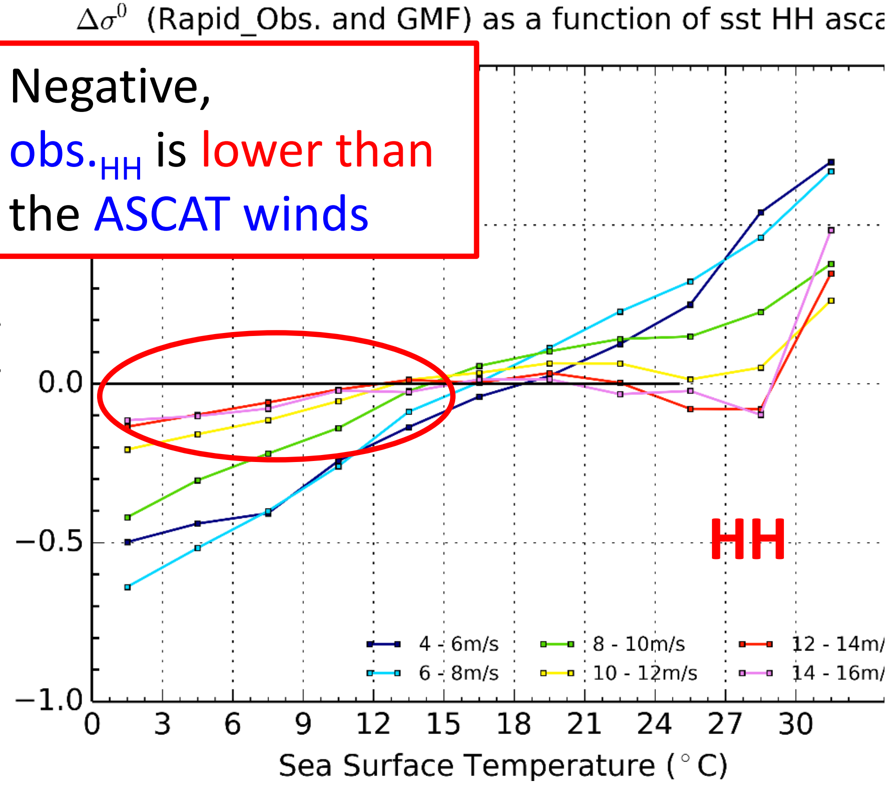
Rain & QC affect ocean calibration



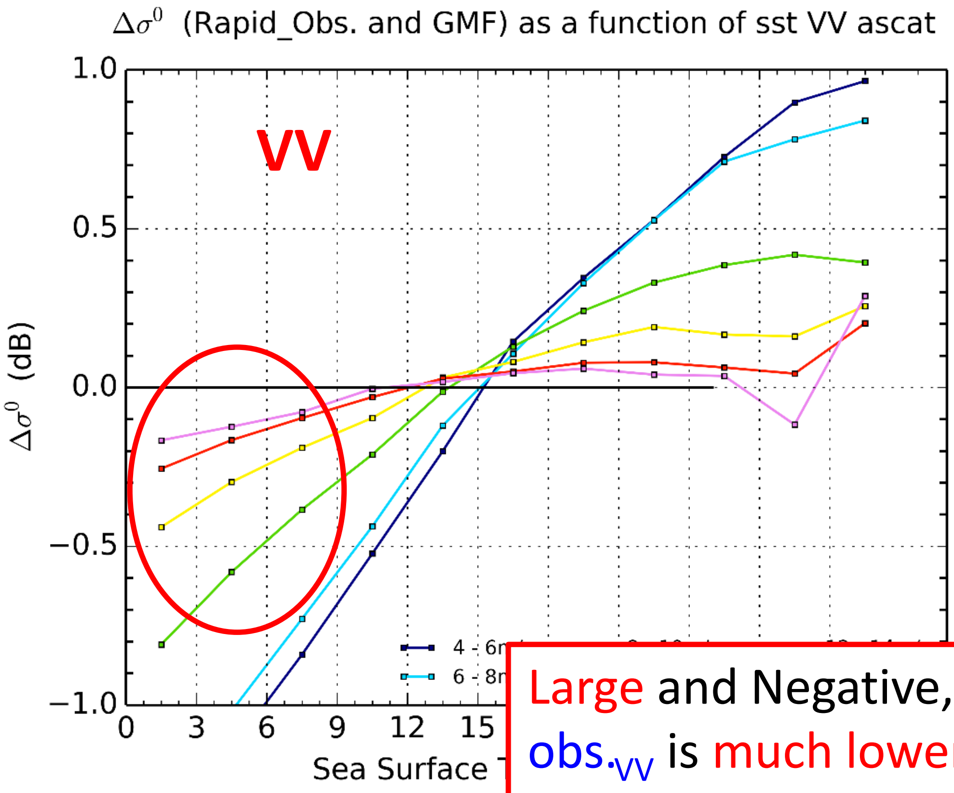
W. Lin et al., 2017

$\Delta\sigma^0$ RSCAT minus ASCAT

$\Delta\sigma^0$ RSCAT minus simulated by NSCAT4 GMF with *ASCAT* winds



Negative,
obs.$_{HH}$ is lower than
the ASCAT winds



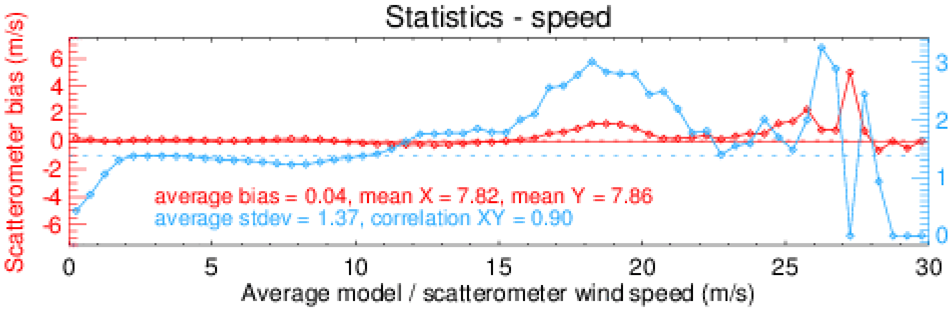
Large and Negative,
obs.$_{VV}$ is much lower
than the ASCAT winds

Inner-Swath Cases, i.e., collocated HH&VV

Basic dependencies similar to those in physically-based models

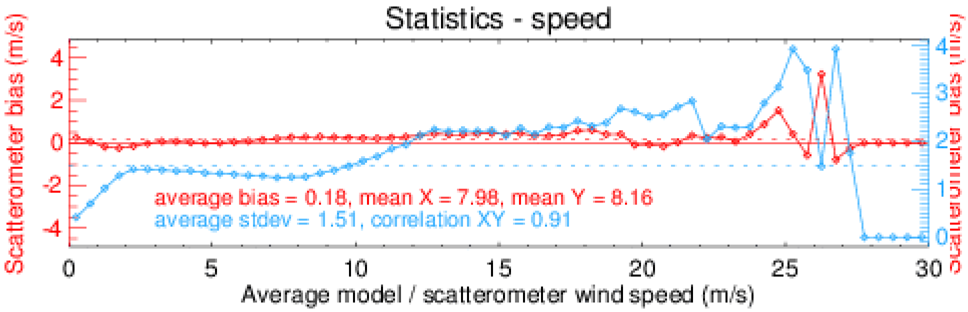
Zhixiong Wang et al., 2017

ScatSat retrievals

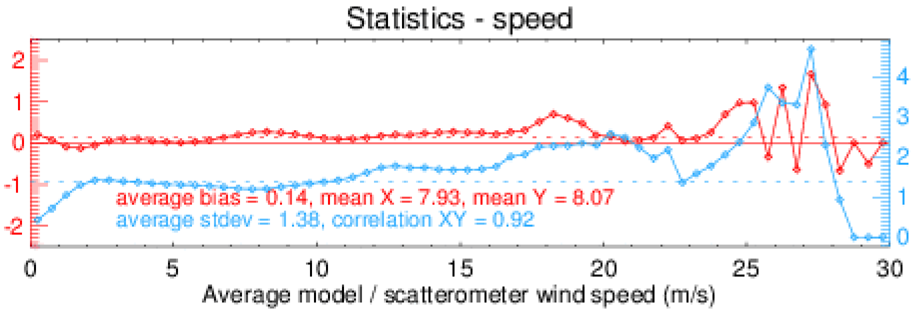


VV only

- ✓ After correction for $\sigma^0 >= -19$dB:
  $\sigma^0\,(\text{new}) = \sigma^0\,(\text{old}) + [\sigma^0(\text{old})+19]*0.11$
- ✓ QC not normalized
- ✓ Non-linear σ^0 calibration !



HH only



HH + VV

- ➢ After Cal/Val some unexplained non-linear behaviour in Ku-band systems

Anton Verhoef et al., 2017

Intercalibration

Can we make further improvements? Yes, we can:

- Pencil-beam scatterometers provide fixed combinations of polarization, incidence angle and azimuth angle at each WVC; these could be used for 4D “cone metrics” and provide a measure for long-term σ^0 stability and consistency
- Ocean calibration needs development for new class of CFOSAT and WindRad rotating fan-beam scatterometers; NSCAT-ERS collocations may be used
- NWP ocean calibration procedures will provide first guidance for CFOSAT and WindRad
- Effects of rain, SST need to be further controlled in any Ku approach, be it “cone metrics” or NWP based
- A stable non-synchronous satellite instrument remains extremely useful for intercalibration and geophysical development, which latter is needed for improved error budgets for some calibration methods
- Error propagation in calibration methods and wind retrieval need to be better understood; “cone metrics” (MLE) provides measure of noise
- “cone metrics” will be used to improve GMFs to better describe measured σ^0 PDF
- Improve understanding of in situ wind references to allow absolute wind calibration at high and extreme winds (CHEFS)

Inconsistencies in wind references

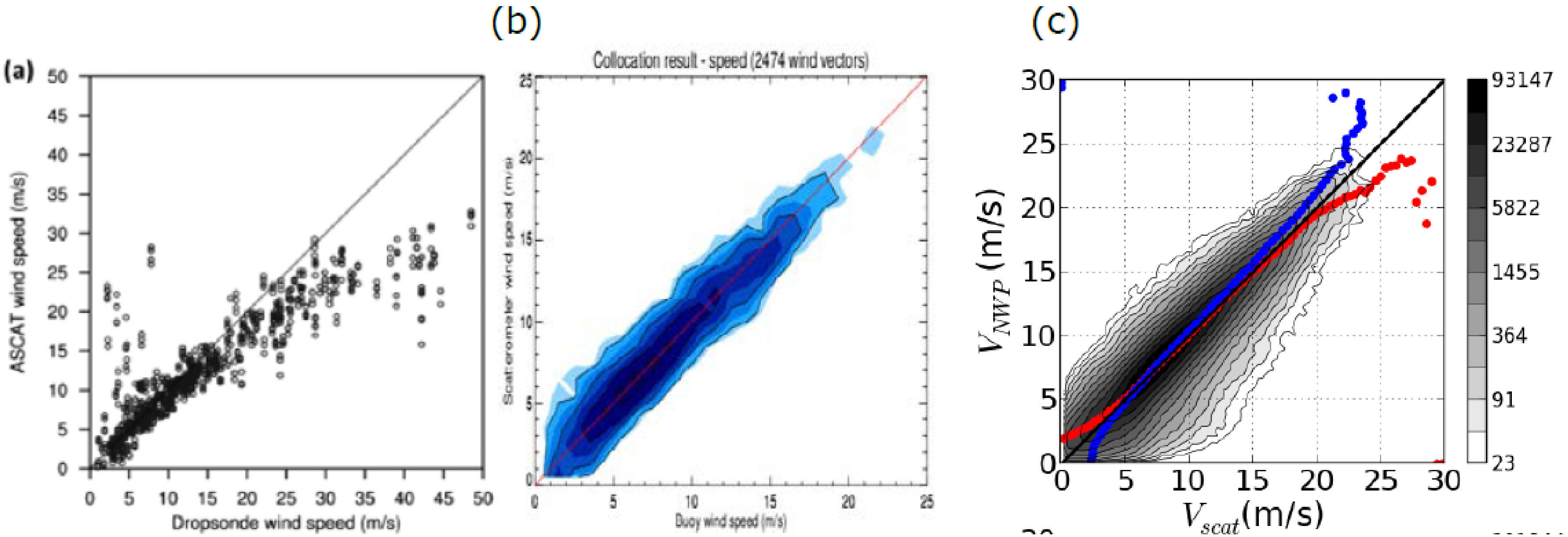
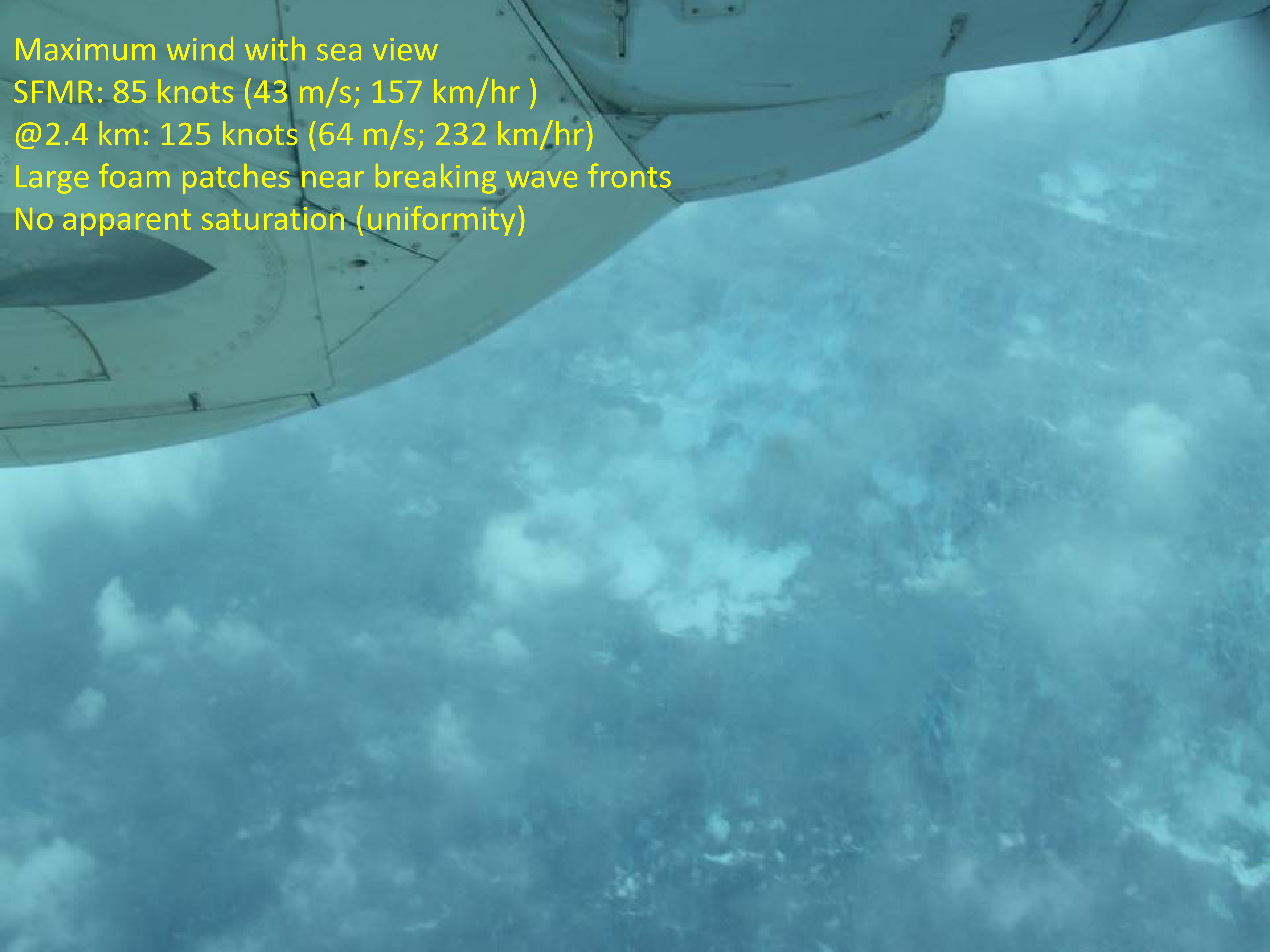


Figure 3.3: ASCAT wind speed scatter plots of a) ASCAT versus drop sondes (from [37]), b) ASCAT versus moored buoy winds and c) ECMWF NWP winds versus ASCAT. Using drop sondes, moored buoy winds and NWP references above 15 m/s may result in discrepancies due to height and position reprepresentation differences.

- Are dropsondes too high, or moored buoys and ECMWF too low at 15-25 m/s ?
- EUMETSAT CHEFS project addresses this; WL150 not suitable for calibration

K.-H. Chou et al., 2013



Maximum wind with sea view

SFMR: 85 knots (43 m/s; 157 km/hr)

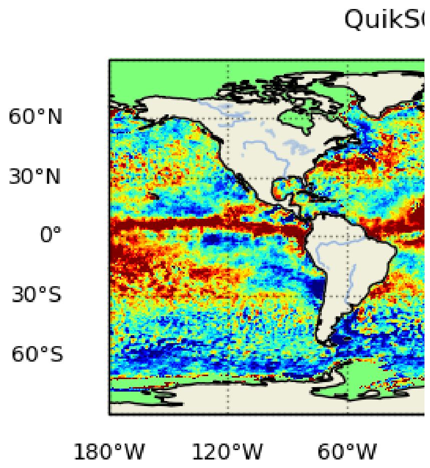
@2.4 km: 125 knots (64 m/s; 232 km/hr)

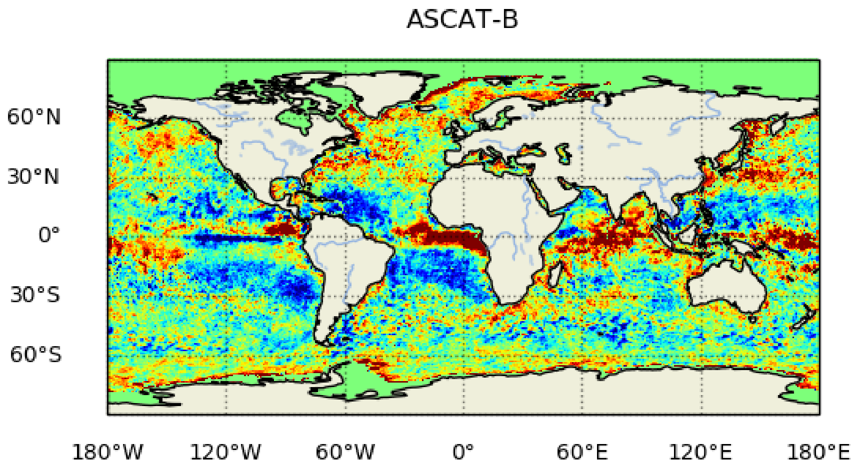
Large foam patches near breaking wave fronts

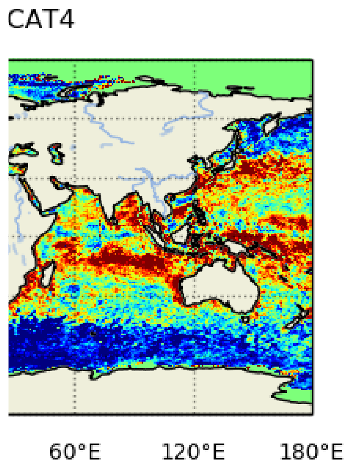
No apparent saturation (uniformity)

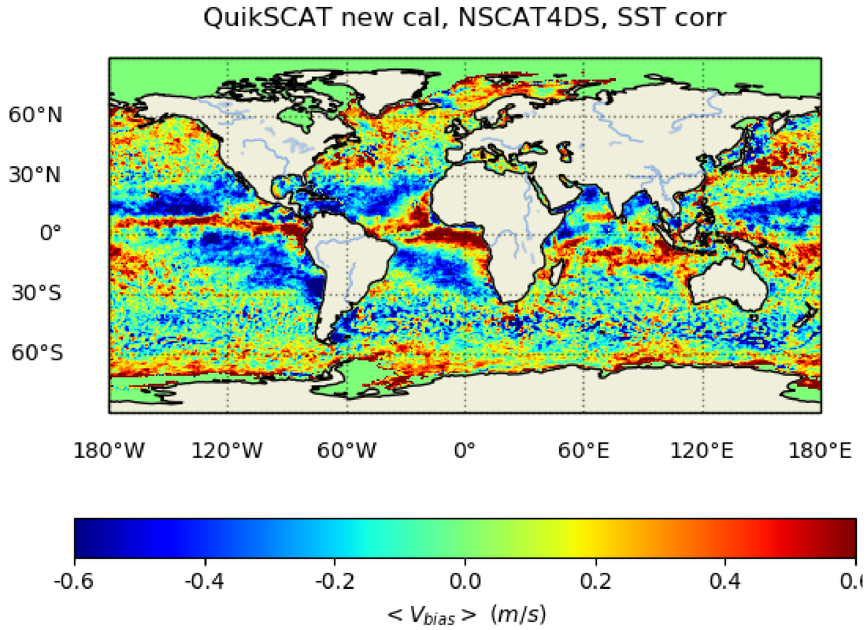
Turbulent sea in the eye (with no wind!)

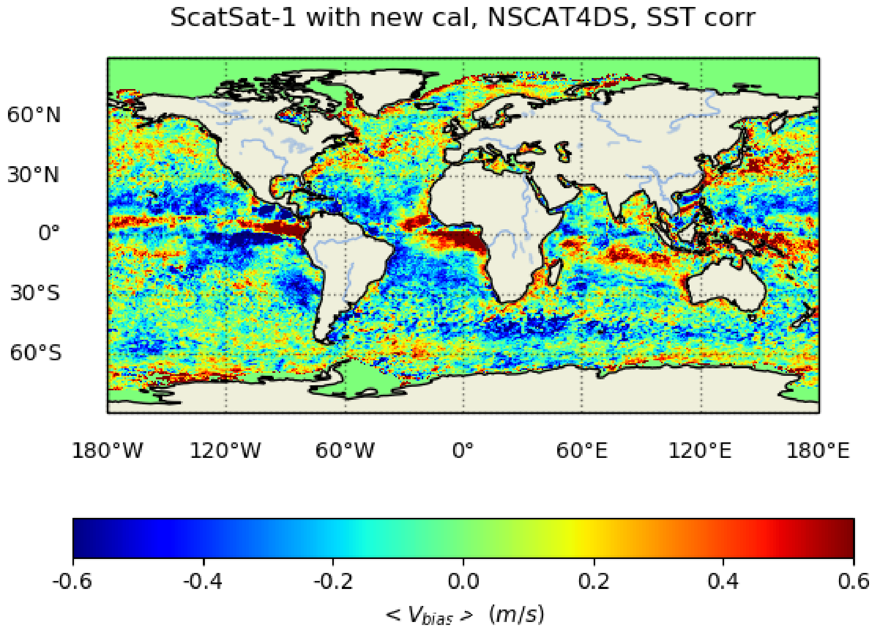
Global wind speed biases


QuikS


ASCAT-B


CAT4


QuikSCAT new cal, NSCAT4DS, SST corr


ScatSat-1 with new cal, NSCAT4DS, SST corr

Model Wind Errors

- Typically 0.5 to 1 m/s in component bias and SD (10-20%) on model scales
- Underestimation of wind turning in NWP model: surface winds more aligned to geostrophic balance above than to pressure gradient below → stable model winds are more zonal with reduced meridional flows
- Sandu (ECMWF) reports that turbulent diffusion is too large (enlarged to reduce sub-grid mesoscale variability) which helps improve the representation of synoptic cyclone development at the expense of reducing the ageostrophic wind turning angle ...

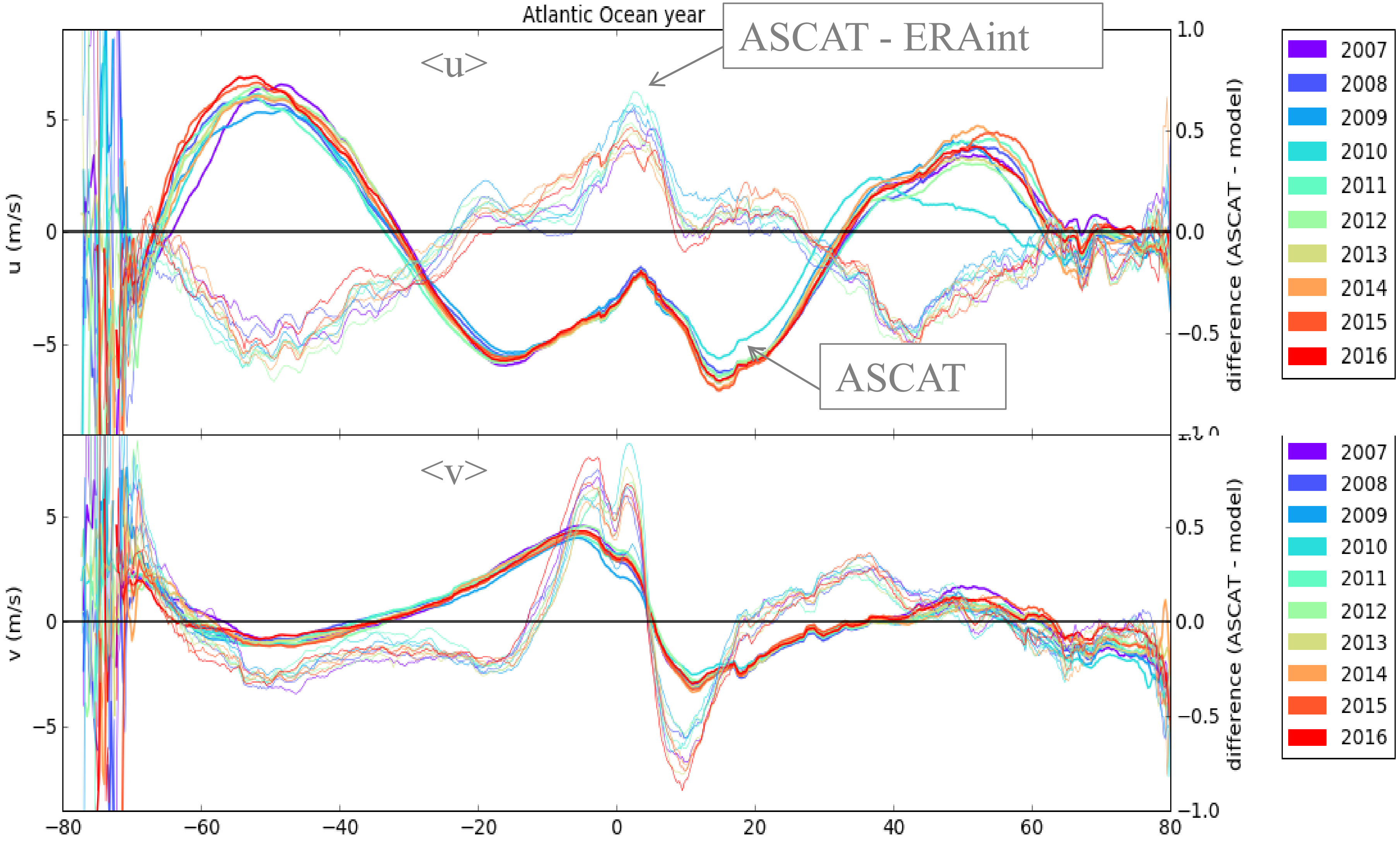
→ It is a problem that the ocean is forced in the wrong direction though

- Other processes poorly represented include 3D turbulence on scales below 500 km and wide-spread wind downbursts in (tropical) moist convection (King et al., 2017)

→ Atmospheric mesoscale variability stirs the ocean and enhances fluxes

→ Adaptive bias correction needed for data assimilation and ocean forcing

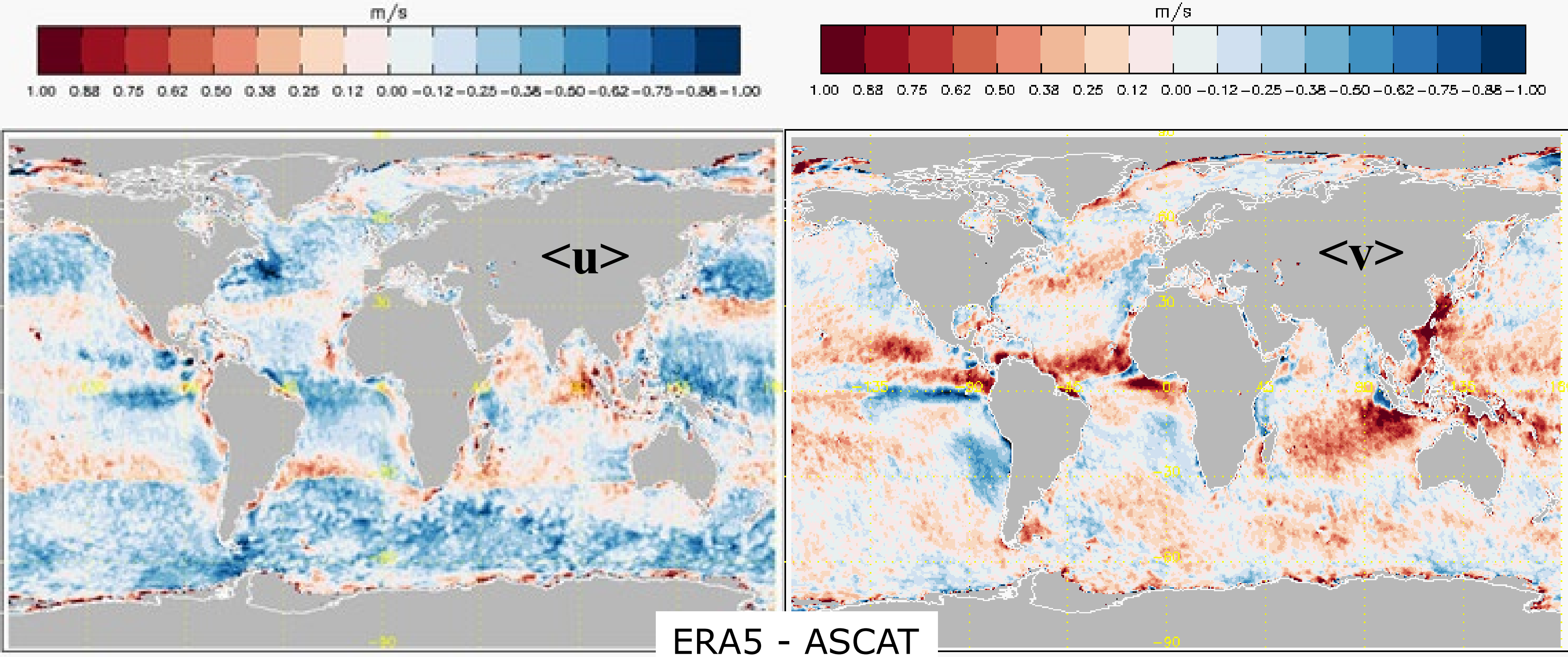
Zonal, Meridional Errors



→ Systematic errors are larger than interannual variability

Zonal, Meridional Errors

ERA5 has spatial error patterns similar to ERAint (only reduced in amplitude by ~20%)

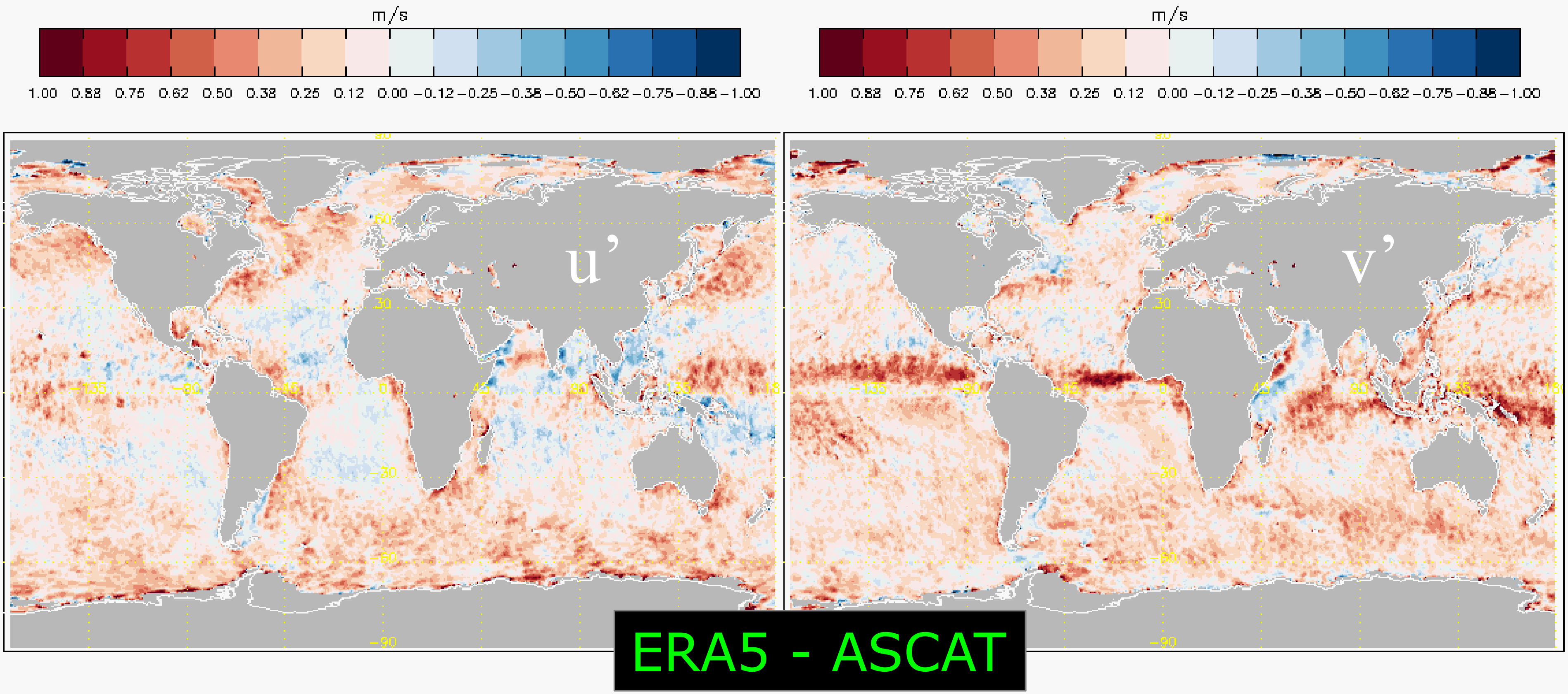


ERA5 - ASCAT

→ Excess mean <u>model</u> zonal winds (blues at mid-latitudes and subtropics)
→ Defective mean <u>model</u> meridional winds (reds at mid-lats and tropics)

Belmonte and Stoffelen, 2019

Transient Wind Errors



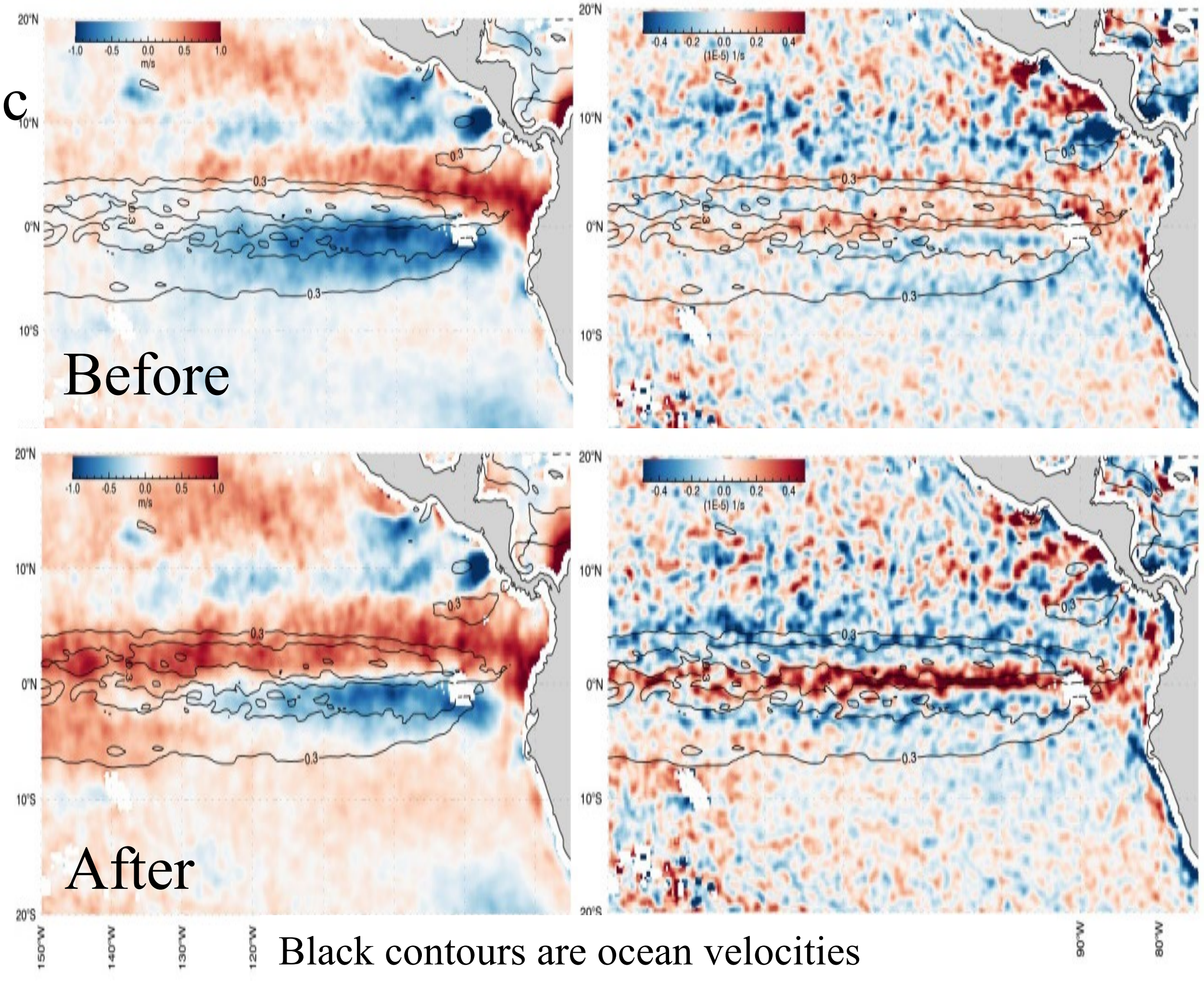
→ Defective model wind variability overall:
  - Zonal (left) and meridional (right) at mid-to-high latitudes
  - Particularly meridional deficit along ITCZ
  - Locally enhanced along WBCs (ARC, ACC, GS, KE currents)

Belmonte and Stoffelen, 2019

Effect of Globcurrent

Eastern Tropical Pacific

- → Globcurrent accentuates SST effects in ASCAT winds that are missing in ECMWF winds
- → Provides much better alignment of ECMWF discrepancies with branched SEC (N and S) to show positive curl error in between



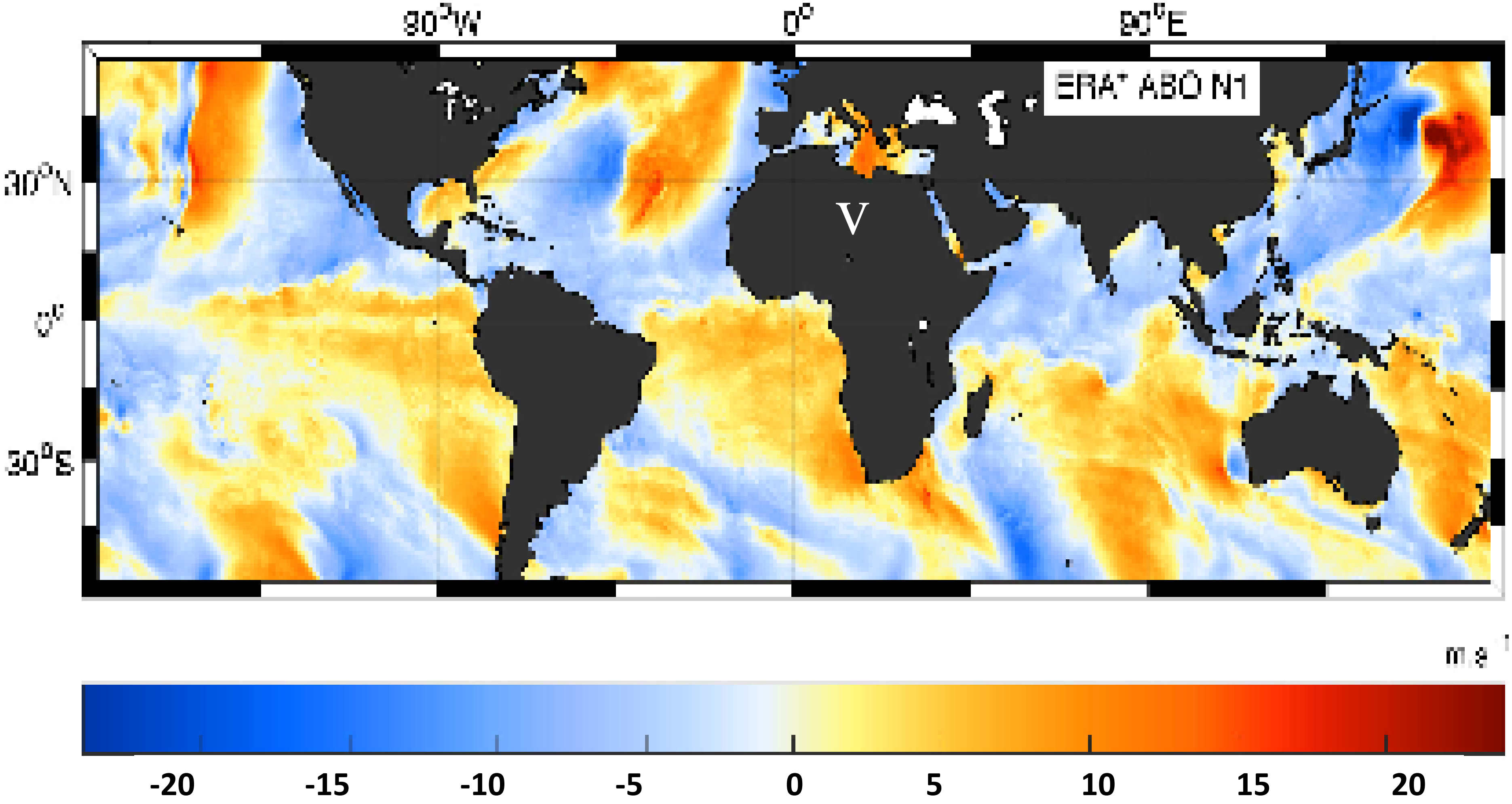
Black contours are ocean velocities

Mean wind speed differences to ERA5

Mean wind stress curl differences to ERA5

Belmonte and Stoffelen, 2019

Corrected ERA with ASCAT, OSCAT

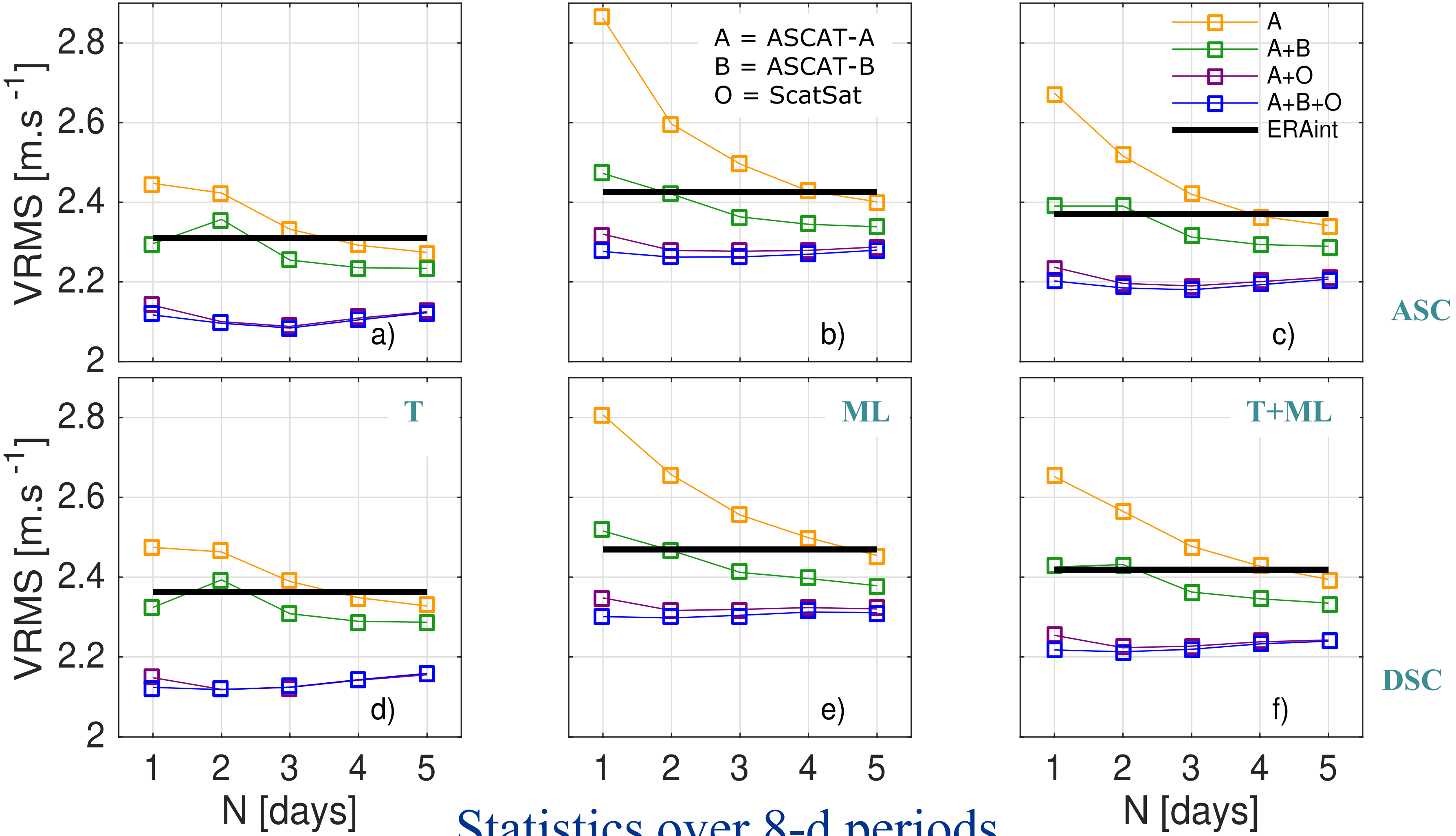


Corrected wind component (v) 20130115 at 06 UTC with 1-day average of ASCAT-A, -B and ScatSat

Trindade et al., 2019

Verification of ERA* with HSCAT

ASCAT and ScatSat at 9:00-9:30 LTAN and HY2A SCAT at 6 am/6 pm LTAN



Statistics over 8-d periods

Trindade et al., 2019

Model Corrections

① Due to the persistence of the bias between model and scatterometer data it is possible to add small scale information, i.e., include some of the physical processes that are missing or misrepresented in ERAi, and reduce the ERAi errors

② ERA* shows a significant increase in small-scale true wind variability, persistent small scales are kept in SC, due to oceanic features such as wind changes over SST gradients and ocean currents

③ Although the method is dependent on sampling, it shows potential, notably in the tropics, due to the scatterometer constellation

④ Temporal windows could be several days for ocean forcing fields in case of fewer scatterometers as the corrections appear rather stable

⑤ From the statistical and spectral analyses, the optimal configuration to introduce the oceanic mesoscale is the use of complementary scatterometers and a temporal window of two or three days.

⑥ ERA* effectively resolves spatial scales of about 50 km, substantially smaller than those resolved by global NWP ocean wind output (about 150 km)

⑦ Adaptive SC will be very useful as variational bias correction in NWP data assimilation as it reduces o-b variances by about 20%.

Trindade et al., 2019

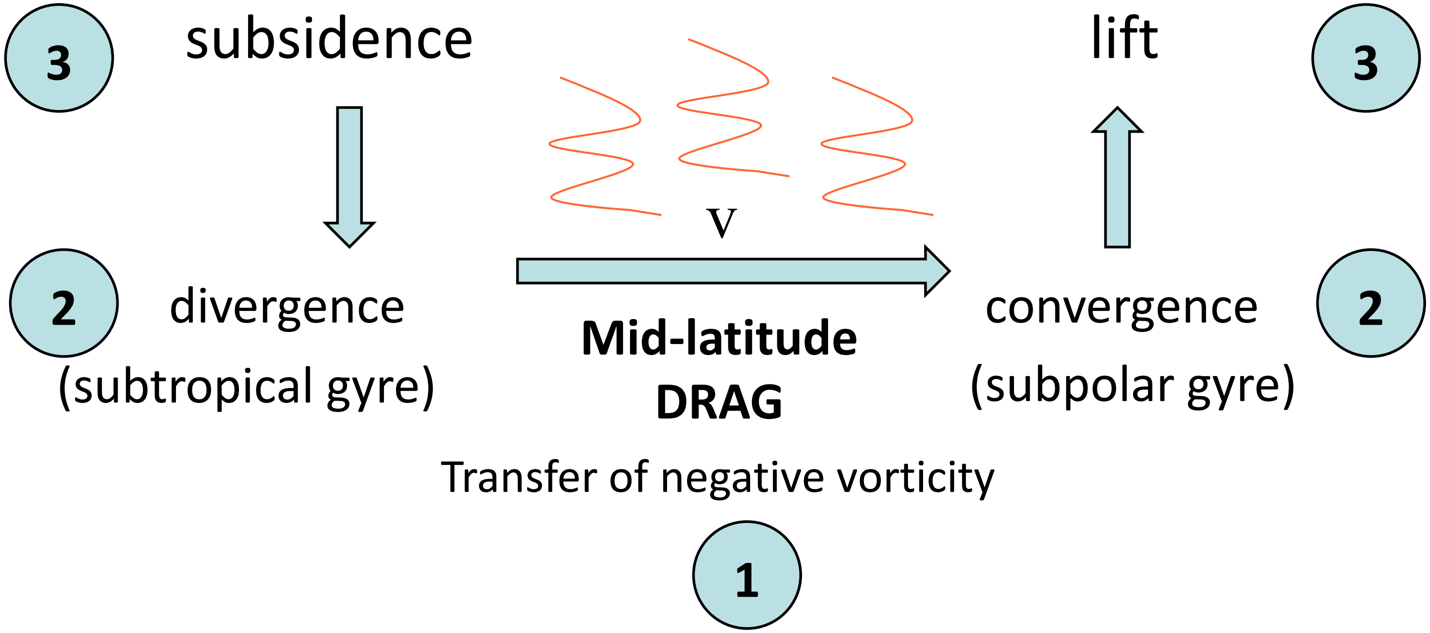
Further references

- scat@knmi.nl
  - Registration for data, software, service messages
  - Help desk
- www.knmi.nl/scatterometer
  - Multiplatform viewer, tiles!
  - Status, monitoring, validation
  - Validation reports, ATBD and User Manuals
- NWP SAF monitoring www.metoffice.gov.uk/research/interproj/nwpsaf/monitoring.html
- Copernicus Marine Environment Monitoring Service marine.copernicus.eu/
- 2016 scatterometer conference, www.eumetsat.int/Home/Main/Satellites/Metop/index.htm?l=en
- May 2017 TGRS special issue on scatterometry
- IOVWST, coaps.fsu.edu/scatterometry/meeting/
- Google Scholar Ad Stoffelen

Error Mechanism ?

At **mid-latitudes**, missing wind variability in ERA can be associated to:

- Excess zonal mean model winds and defective poleward flows
- Excess cyclonic stress curl
- Defective subtropical divergence and defective subpolar convergence



③ subsidence

lift ③

V

② divergence

(subtropical gyre)

Mid-latitude DRAG

convergence ②

(subpolar gyre)

Transfer of negative vorticity

①

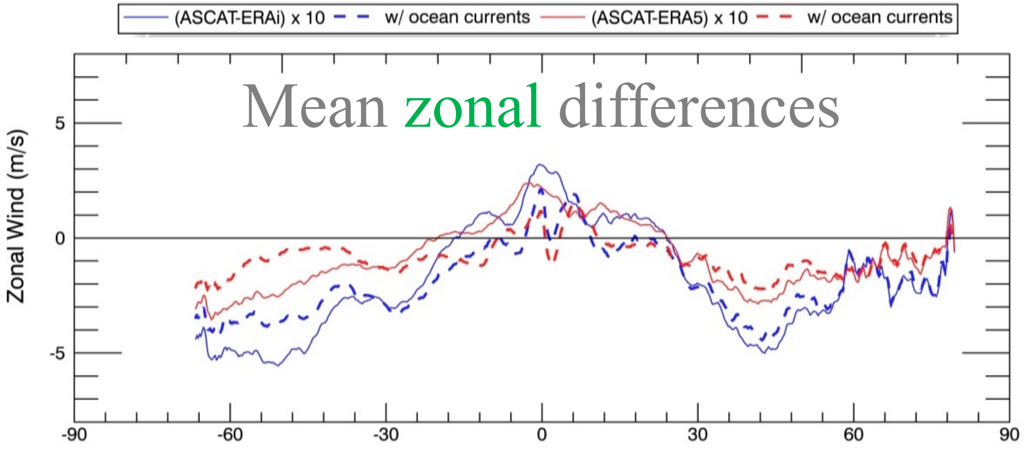
→Missing 3D turbulence weakens (poleward) flow in Ferrel Cell

→Ocean forcing implications?

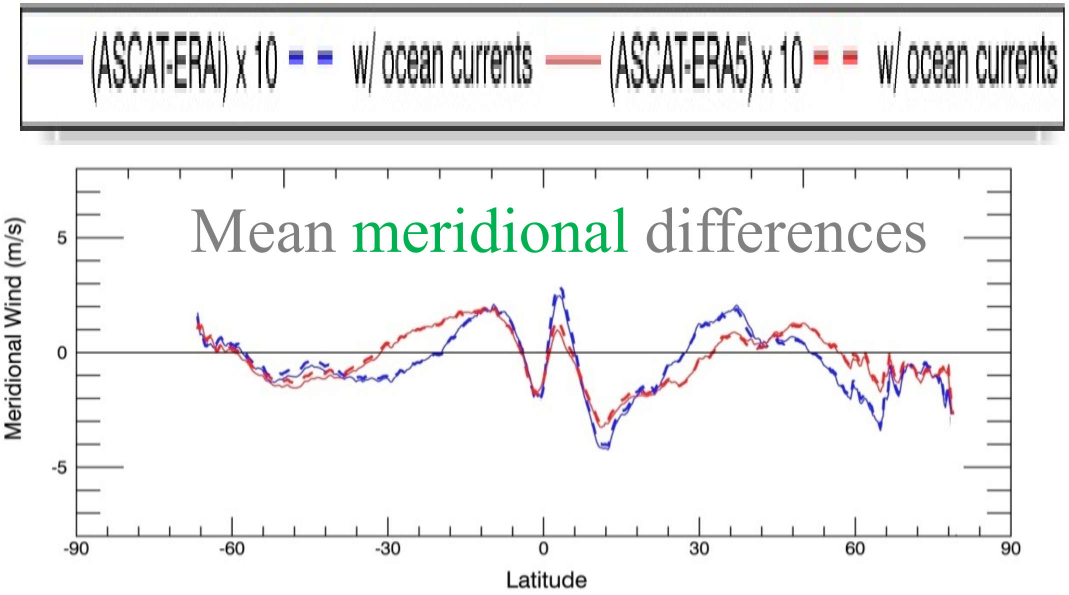
Belmonte Rivas & Stoffelen, 2019

Effect of Globcurrent

- → Globcurrent notably relieves the zonal wind biases



- → Globcurrent has no effect on the smaller meridional wind biases

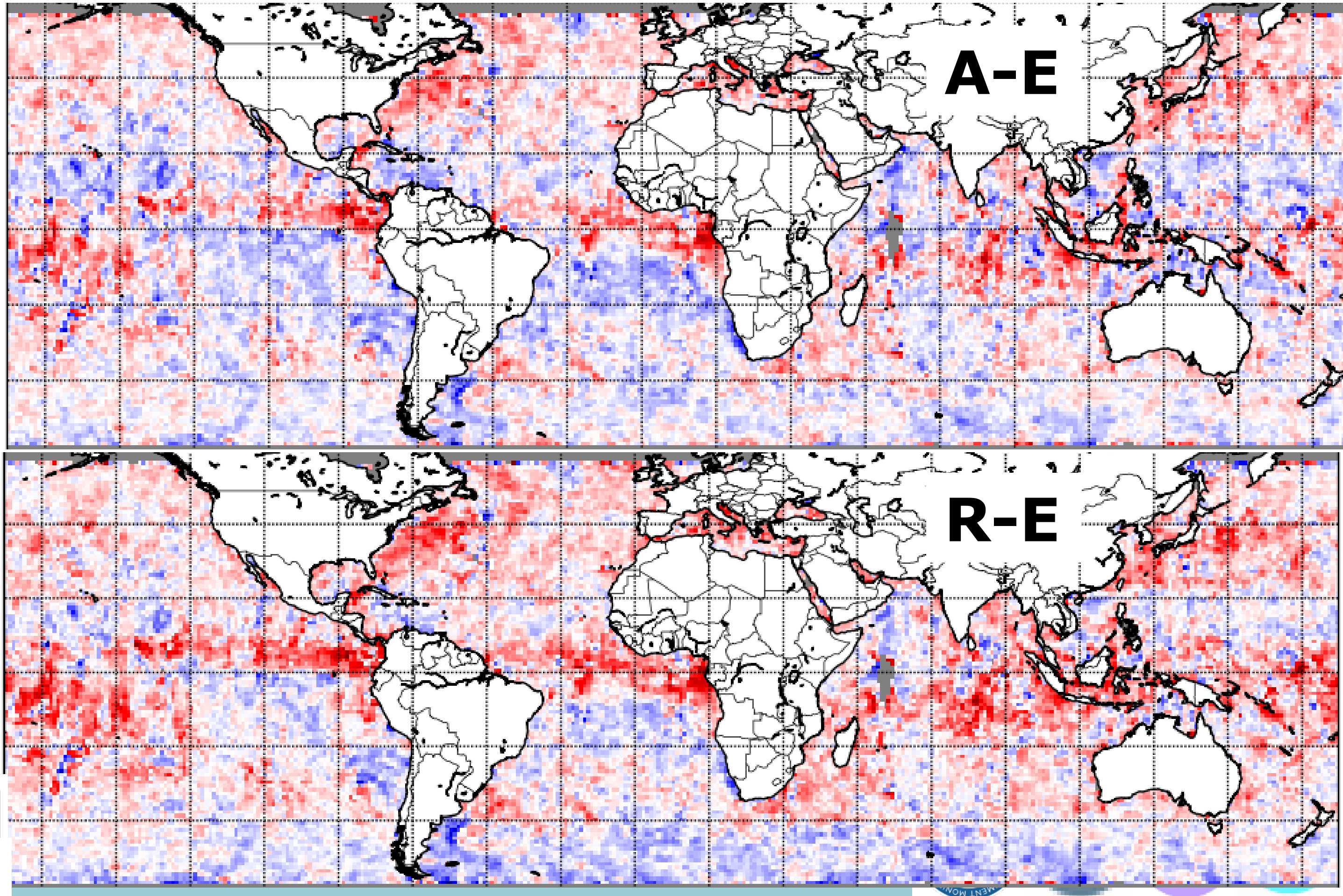


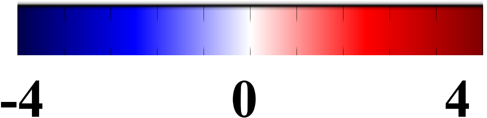
Belmonte and Stoffelen, 20

Bias patterns with NWP

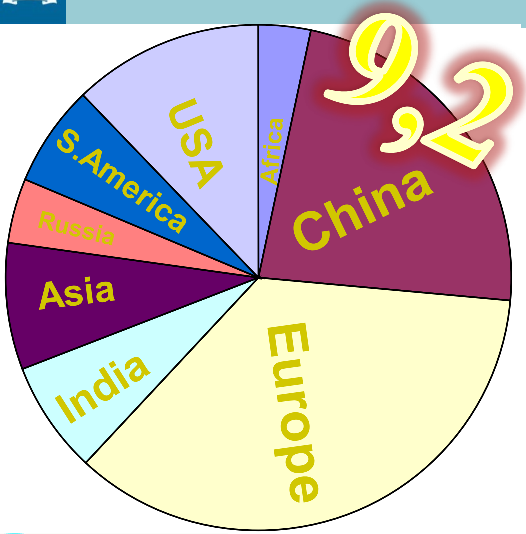
- Systematic wrong ocean forcing in the tropics over extended periods
- Violates BLUE in data assimilation systems (DAS)
- Similar patterns every day, due to convection, parameterisation, current

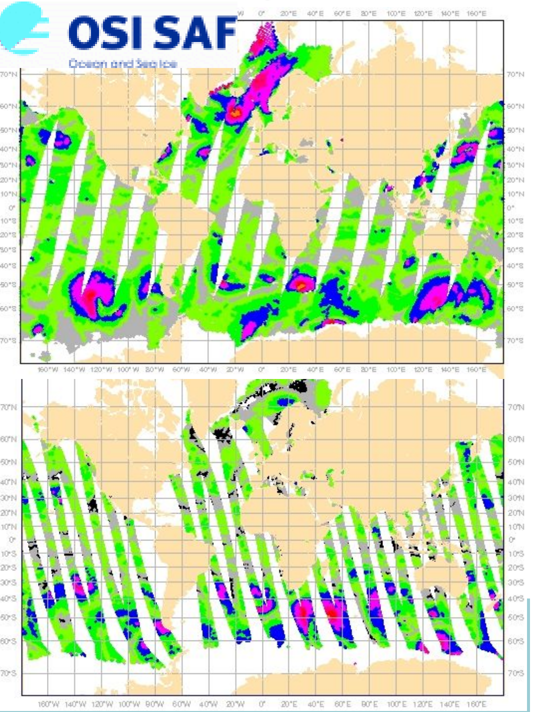
- Correct biases before DAS
- Correct ocean forcing in climate runs
- Investigate moist convective processes
- Correct NWP for currents to obtain stress





Satellite Wind Services





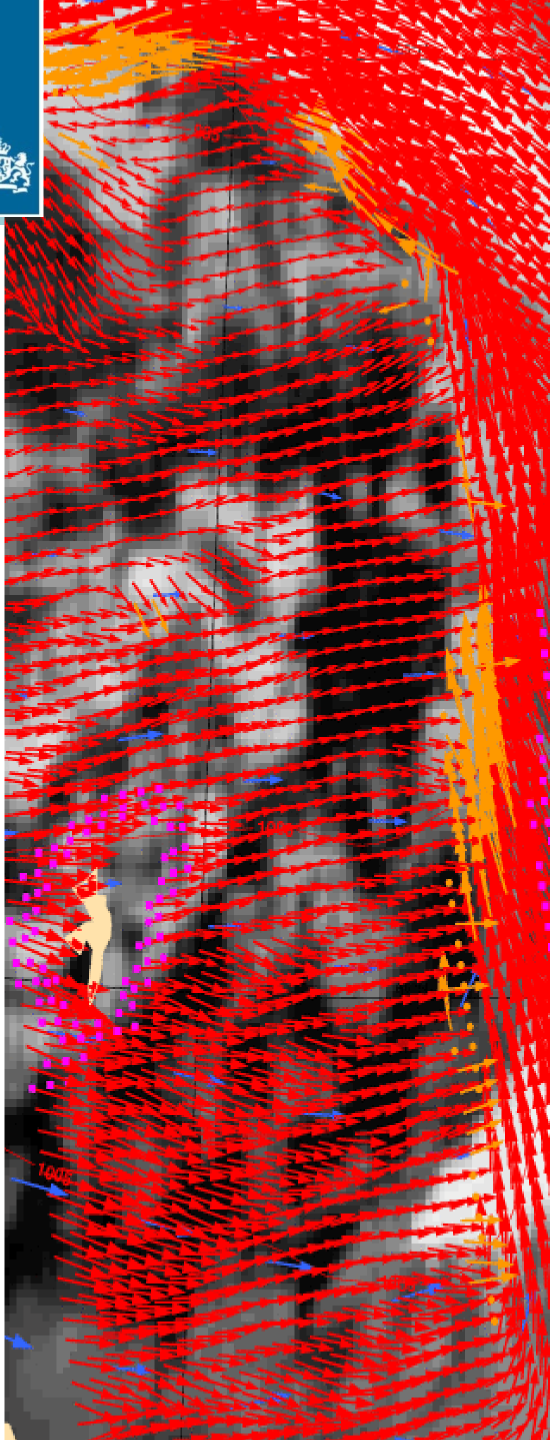
- ➢ 24/7 Wind services (EUMETSAT SAF)
  - – Constellation of satellites
  - – High quality winds, QC
  - – Timeliness 30 min. – 2 hours
  - – Service messages
  - – QA, monitoring
- ➢ Software services (NWP SAF)
  - – Portable Wind Processors
  - – ECMWF model comparison
- ➢ Organisations involved: KNMI, EUMETSAT, EU, ESA, NASA, NOAA, ISRO, CMA, WMO, CEOS, ..
- ➢ Users: NHC, JTWC, ECMWF, NOAA, NASA, NRL, BoM, UK MetO, M.France, DWD, CMA, JMA, CPTEC, NCAR, NL, . . .

More information:

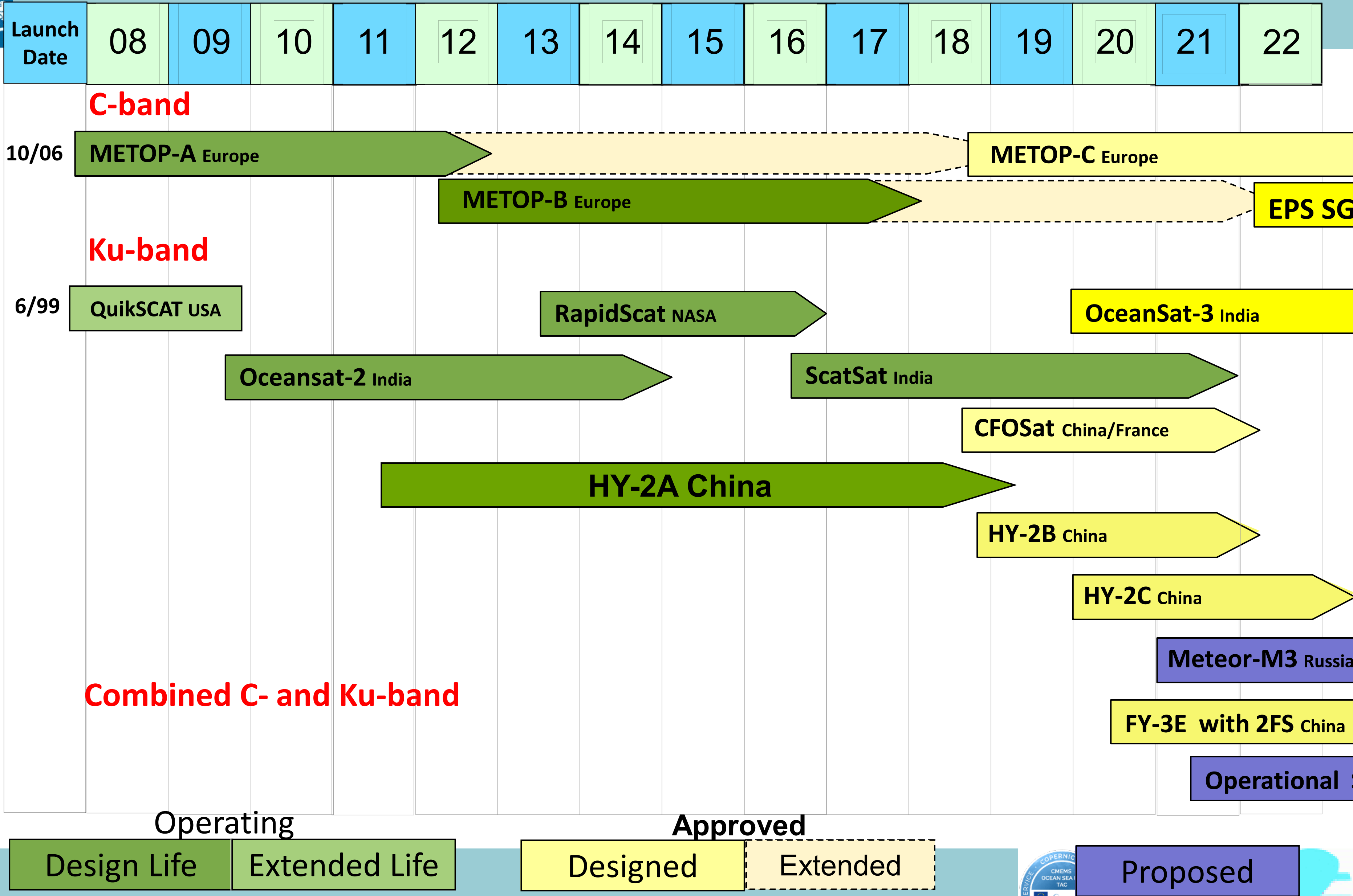
www.knmi.nl/scatterometer

Wind Scatterometer Help Desk

Email: scat@knmi.nl



GLOBAL SCATTEROMETER MISSIONS (CEOS VC)



Launch Date | 08 | 09 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22

C-band

10/06 METOP-A Europe

METOP-C Europe

METOP-B Europe

EPS SG

Ku-band

6/99 QuikSCAT USA

RapidScat NASA

OceanSat-3 India

Oceansat-2 India

ScatSat India

CFOSat China/France

HY-2A China

HY-2B China

HY-2C China

Meteor-M3 Russia

Combined C- and Ku-band

FY-3E with 2FS China

Operational

Operating

Design Life

Extended Life

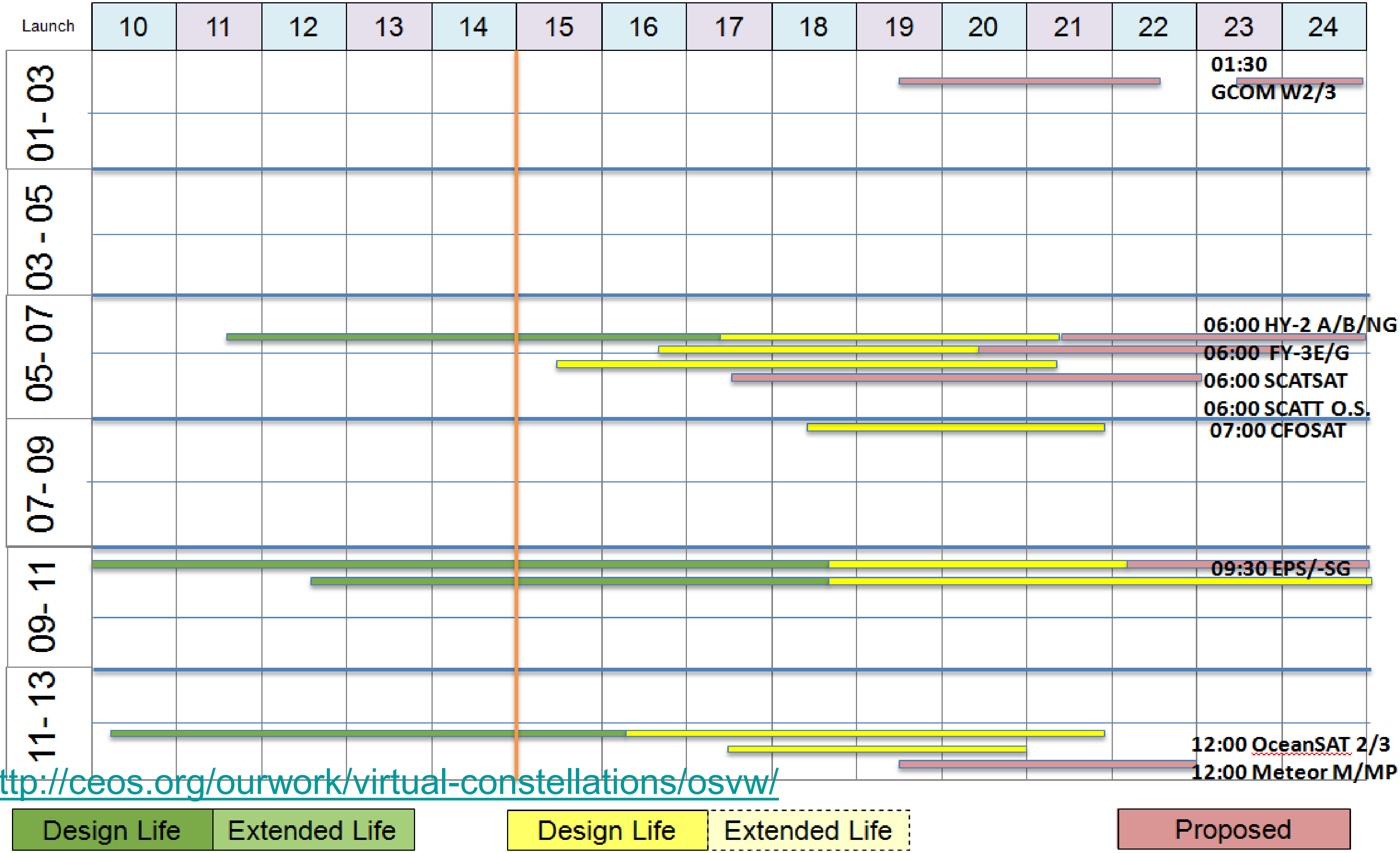
Approved

Designed

Extended

Proposed

CEOS Virtual Constellation

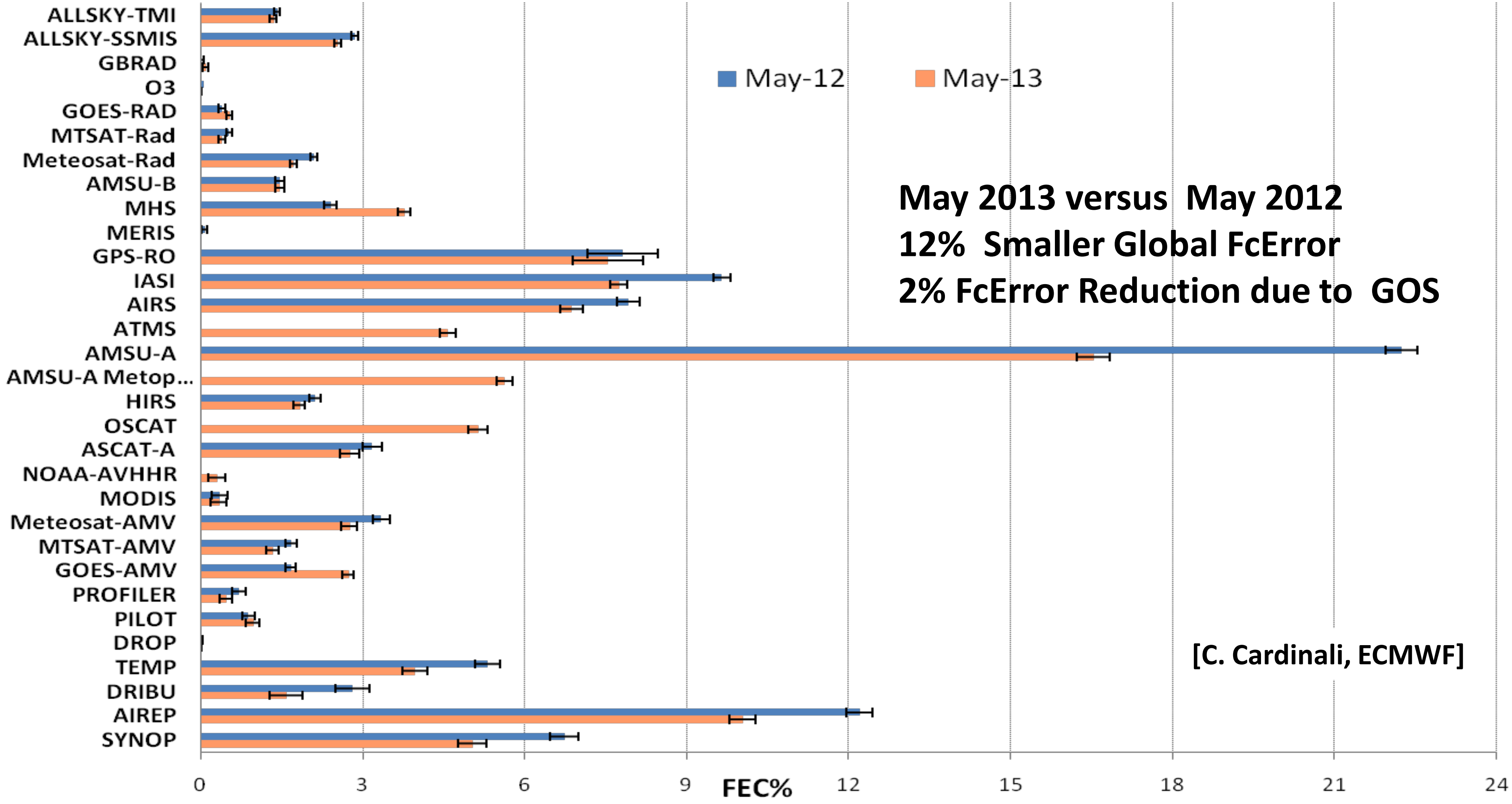


http://ceos.org/ourwork/virtual-constellations/osvw/

Dec 2014

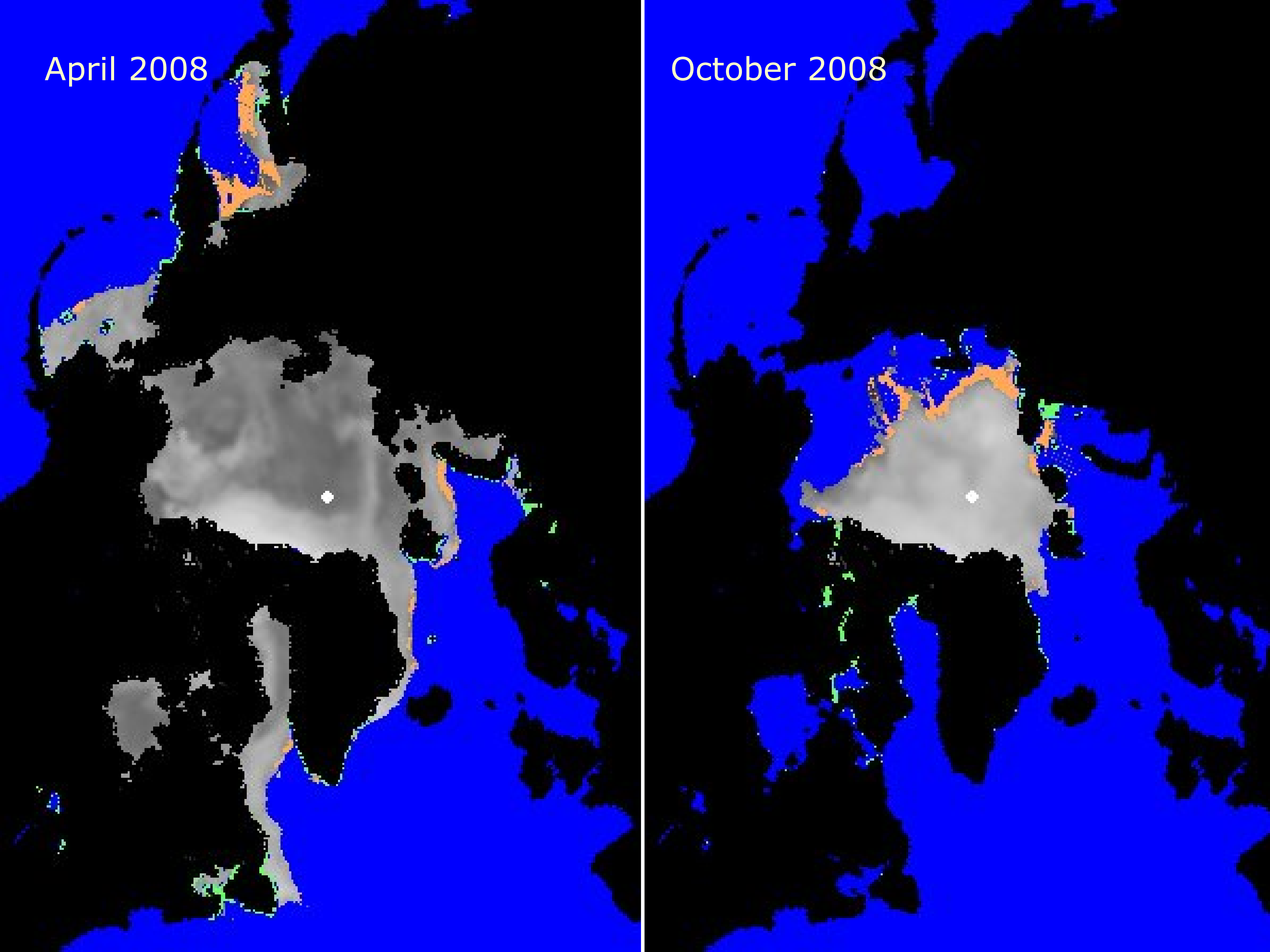
Impact of assimilated observations on Forecast Error Reduction

The ***forecast sensitivity to observations*** measures the impact of the observations on the short-range forecast (**24** hours). The forecast sensitivity tool developed at ECMWF computes the Forecast Error Contribution (FEC) that is a measure (%) of the variation of the forecast error (as defined through the dry energy norm) due to the assimilated observations.

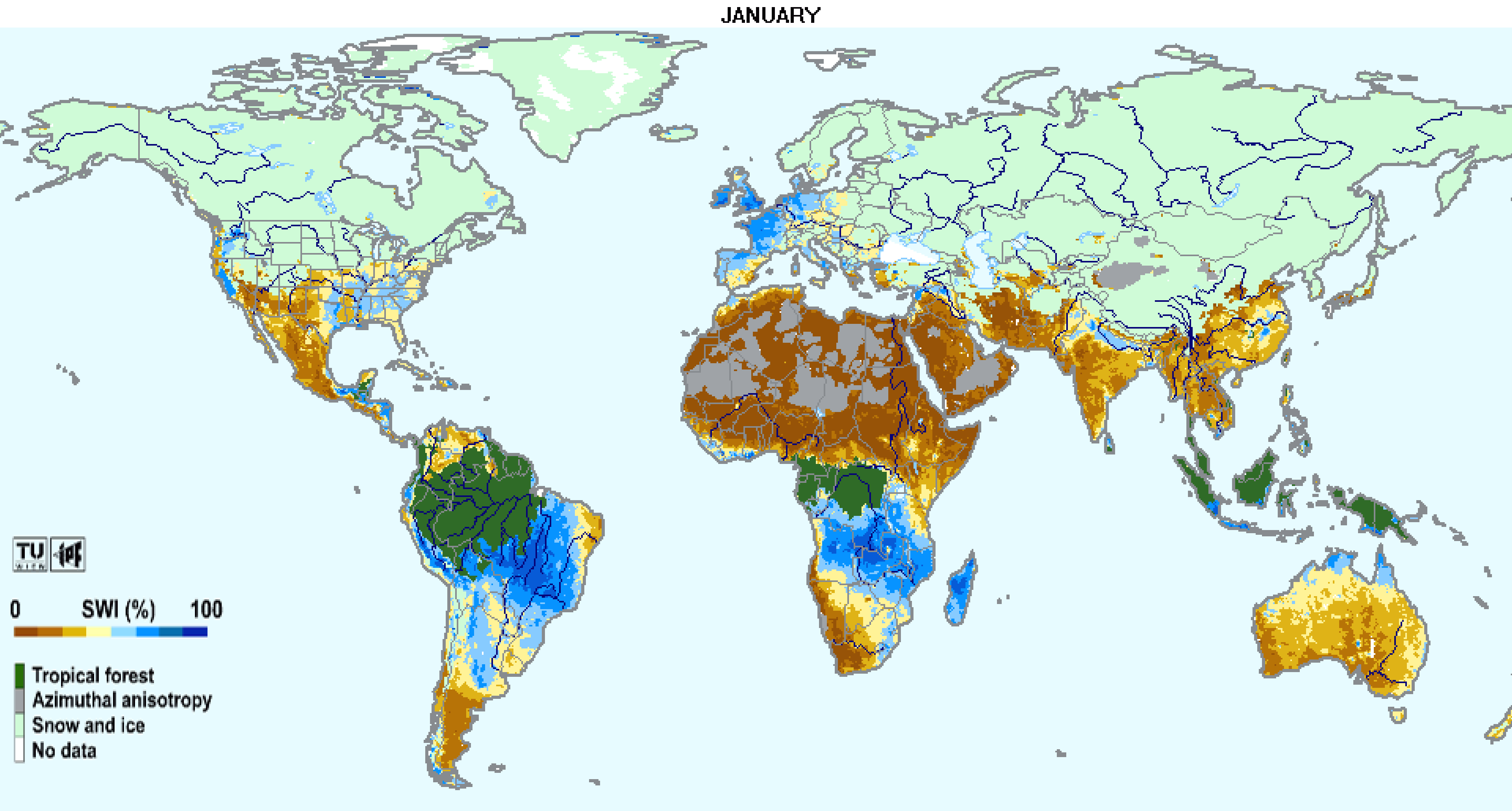


May 2013 versus May 2012
12% Smaller Global FcError
2% FcError Reduction due to GOS

[C. Cardinali, ECMWF]


April 2008
October 2008

Soil Water Index



Vegetation and rain too

Training/interaction

- Training Course Applications of Satellite Wind and Wave Products for Marine Forecasting
  vimeo.com/album/1783188 (video)
- Forecasters forum
  training.eumetsat.int/mod/forum/view.php?f=264
- Xynthia storm case
  www.eumetrain.org/data/2/xynthia/index.htm
- EUMETrain ocean and sea week
  eumetrain.org/events/oceansea_week_2011.html (video)
- NWP SAF scatterometer training workshop
  nwpsaf.eu/site/software/scatterometer/
- Use of Satellite Wind & Wave Products for Marine Forecasting
  training.eumetsat.int/course/category.php?id=46 and others
- Satellite and ECMWF data vizualisation
  eumetrain.org/eport/smhi_12.php?
- MeteD/COMET training module
  www.meted.ucar.edu/EUMETSAT/marine_forecasting/