(andrej67/iStock/Getty Images)

Satellite wind information on the ocean surface: Scatterometer & Altimeter

Giovanna De Chiara

with contributions from Saleh Abdalla, James Steer, Phil Browne, Tony McNally, Linus Magnusson, Patrick Laloyaux, Sean Healy

ECMWF

Outline

Scatterometer Winds (L2)

- The importance of scatterometer wind observations
- Scatterometer principles
- Data usage at ECMWF and their impact
- How we can improve usage and impact

Altimeter Wind, Waves, Sea Surface Height (L2)

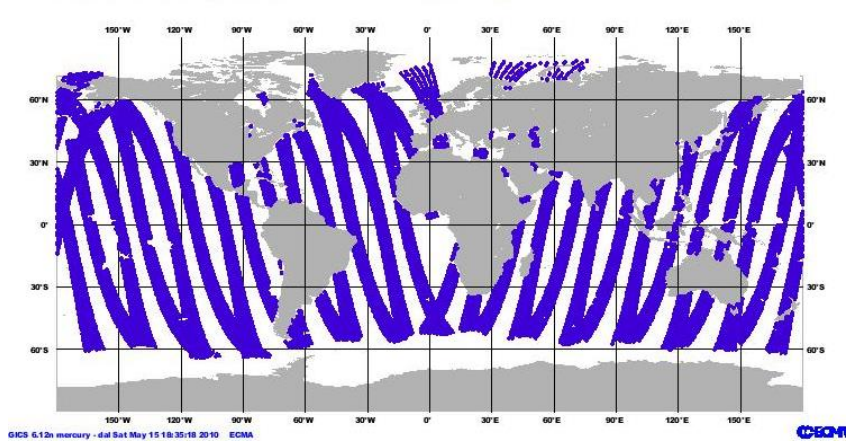
- Altimeter principles
- Use of altimeter data in the wave model
- Altimeter data impacts

Why is Scatterometer important?

The scatterometer measures the ocean surface winds (ocean wind vector).

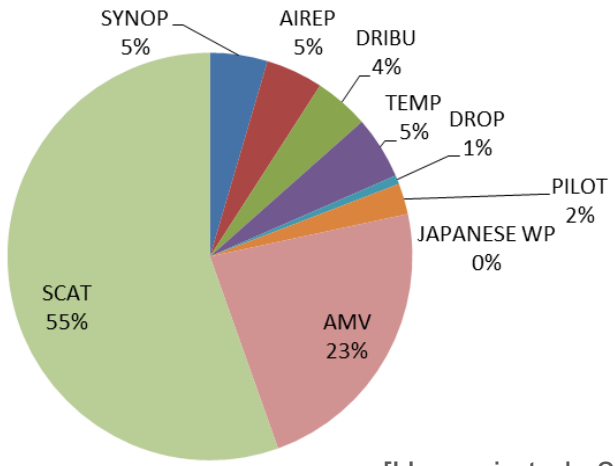
Ocean surface winds:

- affect the full range of ocean movement
- modulate air-sea exchanges of heat, momentum, gases, and particulates
- direct impact on human activities



Wide daily coverage of ocean surface winds
Ex: 1 day of ASCAT-A data

Wind observations below 850 hPa
FSO values relative quantities (in %)



[Horanyi et al., 2013]

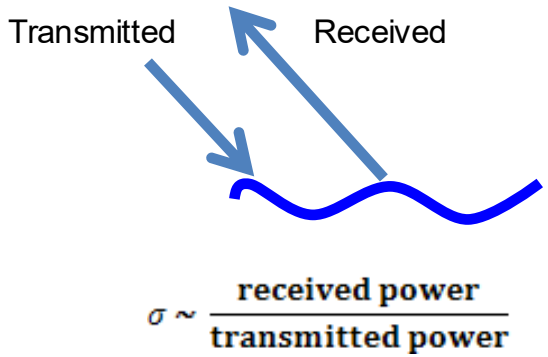
Scatterometer

A Scatterometer is an active microwave instrument (side-looking radar)

- Day and night acquisition
- Not affected by clouds

The return signal, *backscatter* (σ_0 sigma-nought), is sensitive to:

- Surface roughness (ocean)
- Soil moisture (land)
- Ice age (ice)



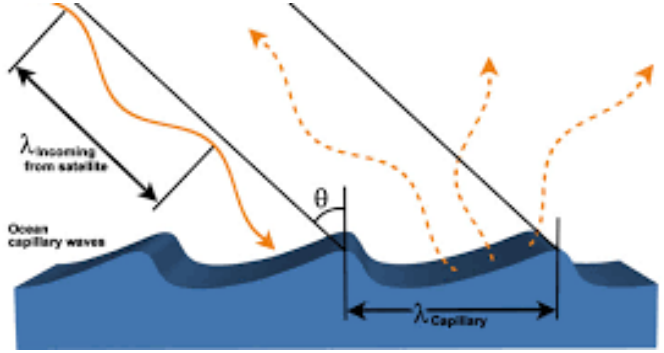
Scatterometer was originally designed to measure ocean wind vectors:

- Measurements sensitive to the ocean-surface roughness due to capillary gravity waves generated by local wind conditions (surface stress)

- Observations from different look angles: wind direction

Scatterometer

Bragg scattering occurs from the ocean capillary-gravity waves (cm-range) that are in resonance with the microwaves



The amount of backscatter depends on:

The frequency and polarization of the emitted wave

- C-band (5.3 GHz): λ ~ 5.7 cm
- Ku-band (13.5 GHz): λ ~ 2.1 cm

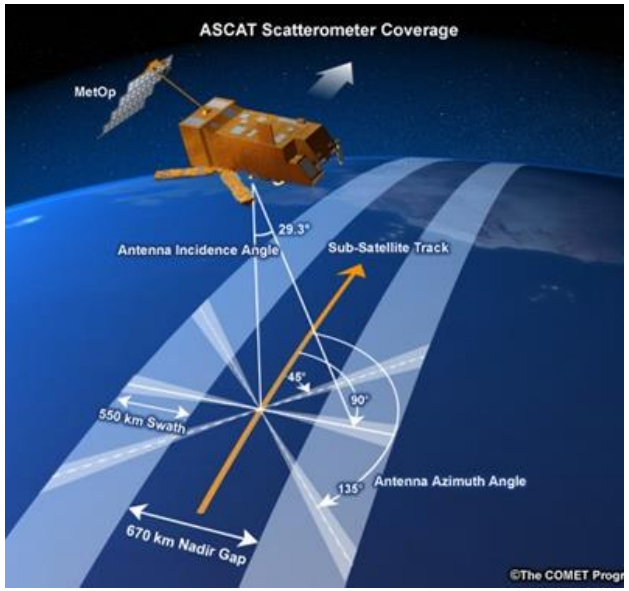
Backscatter *highly* depends on:

- Incidence angle (largest sensitivity to changes in winds between 30 and 60 deg)
- Wind speed
- Relative direction between the surface wind and look angle

C- band scatterometers (Fan beam)

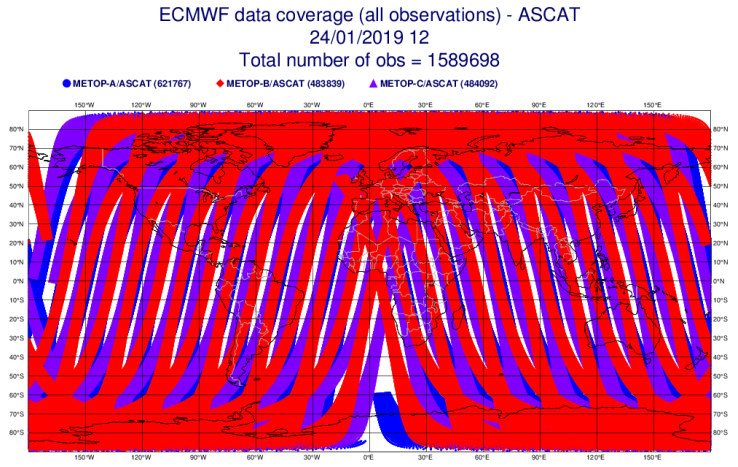
Used on European platforms (1991 onwards):

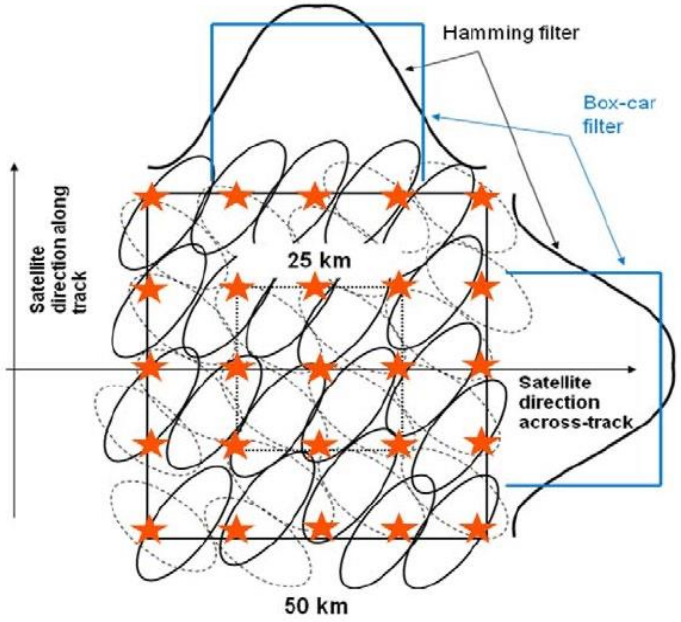
- ✓ SCAT on ERS-1, ERS-2 by ESA
- ✓ ASCAT on Metop-A, **Metop-B, Metop-C** by EUMETSAT
  - f~5.3 GHz (λ~5.7 cm)
  - Two sets of three antennas
  - σ_0 on 6.25 km, 12.5 km or **25 km** grid



Pros and cons:

- ✓ Hardly affected by rain
- ✓ High quality wind direction (especially ASCAT)
- ✓ Two nearly opposite wind solutions
- ✓ Rather narrow swath:
  - ERS-1/2: 500 km
  - ASCAT-A/B/C: 2x550 km





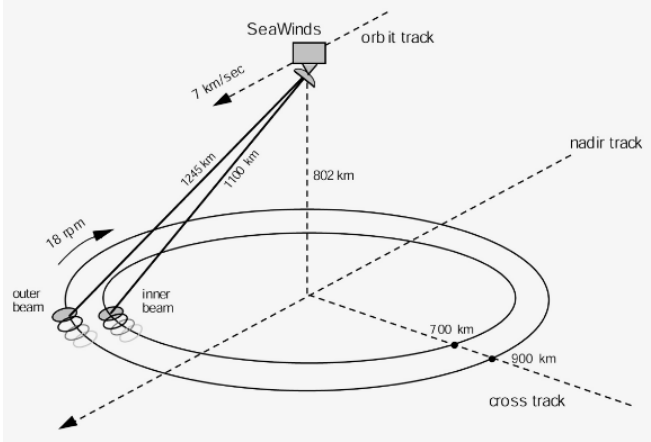
[Eumetsat]

Ku-band scatterometers (Rotating pencil beam)

Used on US, Japanese, Indian and Chinese platforms:

- ✓ NSCAT, QuikSCAT, SeaWinds by NASA (and Japan)
- ✓ Oceansat, ScatSAT by ISRO
- ✓ Haiyang-2A/**B/C**/D by China
- ✓ RapidSCAT on the ISS

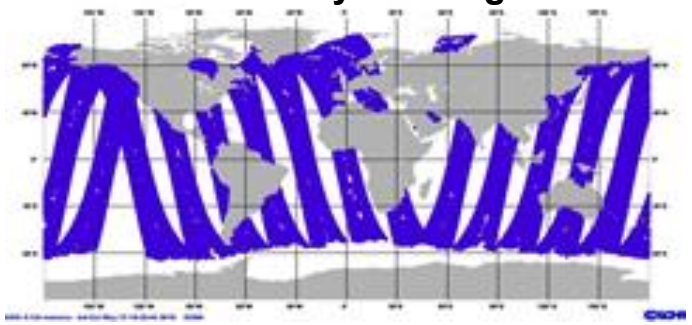
- f~13.5 GHz (λ ~ 2.1 cm)
- Two rotating pencil-beams (4 look angles)



Pros and cons:

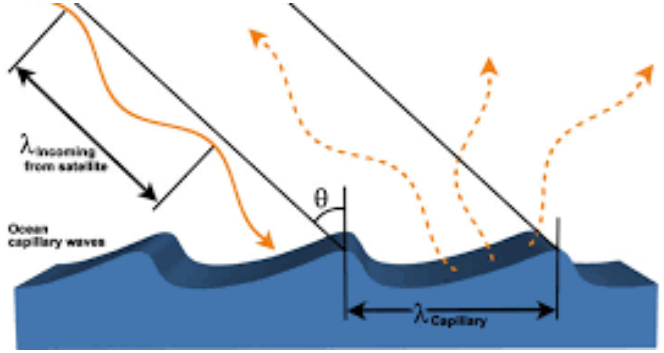
- ✓ Up to four wind solutions (rank-1 most often the correct one)
- ✓ Broad swath (1,800 km)
- ✓ Affected by rain
- ✓ Problems regarding wind direction:
  - azimuth diversity not good in centre of swath
  - outer 200 km only sensed by one beam.

OSCAT daily coverage



Scatterometer

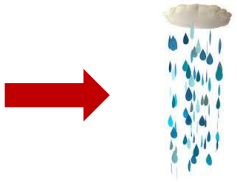
Bragg scattering occurs from the ocean capillary-gravity waves (cm-range) that are in resonance with the microwaves



The amount of backscatter depends on:

The frequency and polarization of the emitted wave

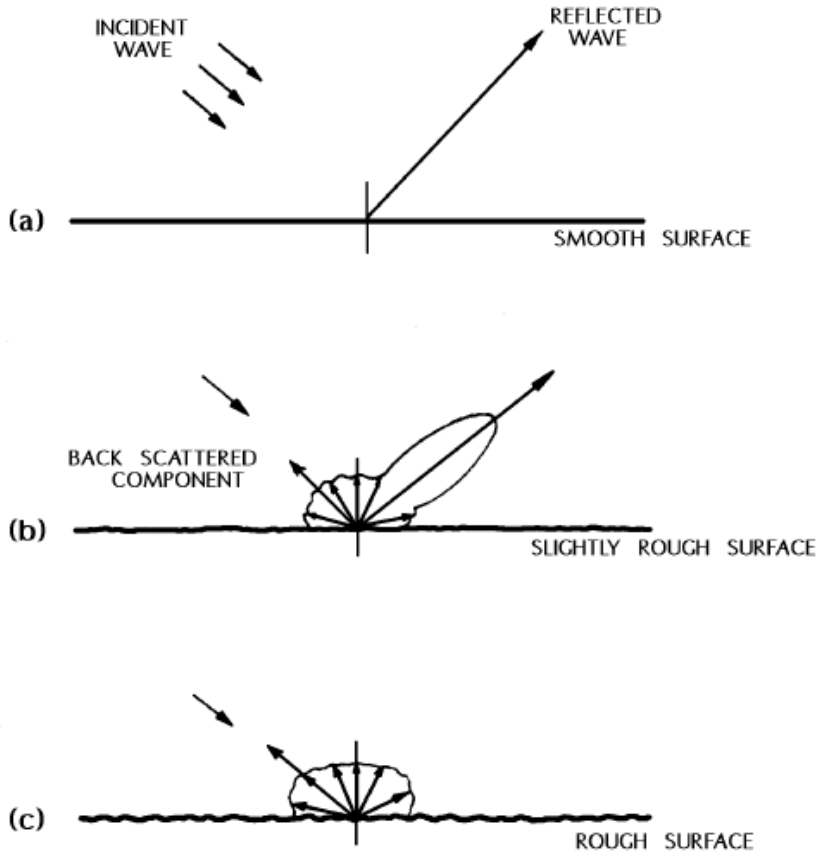
- C-band (5.3 GHz): λ ~ 5.7 cm
- Ku-band (13.5 GHz): λ ~ 2.1 cm



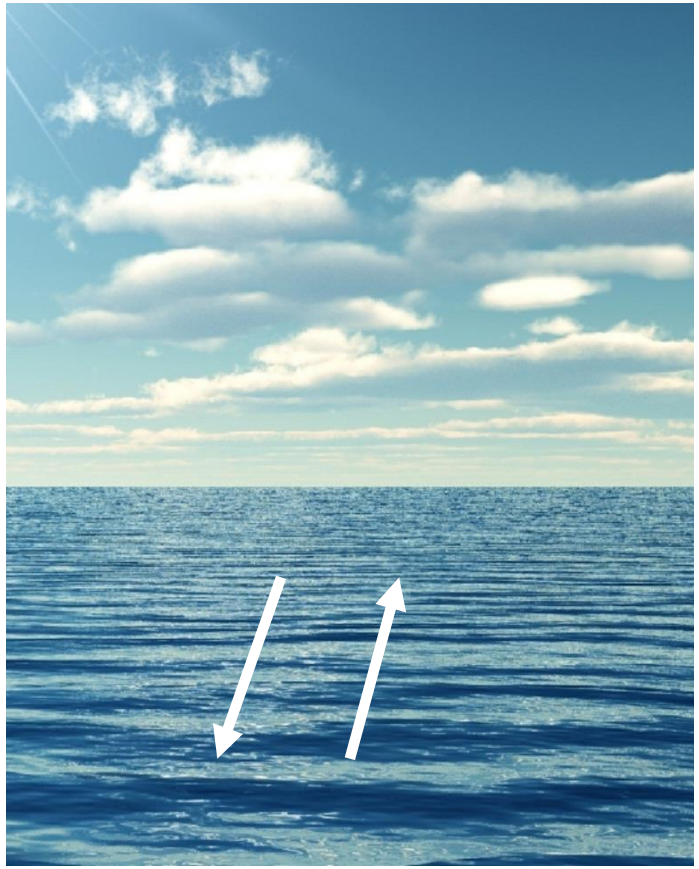
Backscatter *highly* depends on:

- Incidence angle (largest sensitivity to changes in winds between 30 and 60 deg)
- Wind speed
- Relative direction between the surface wind and look angle

Dependency of the backscatter on... Wind speed

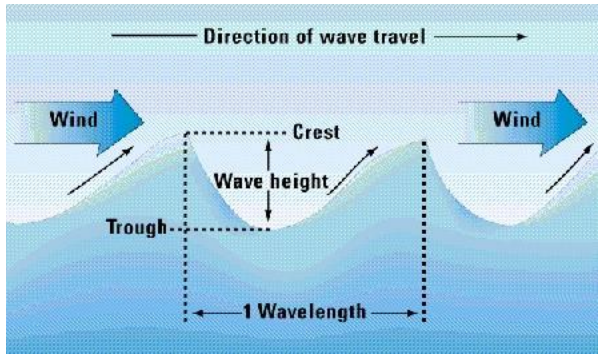


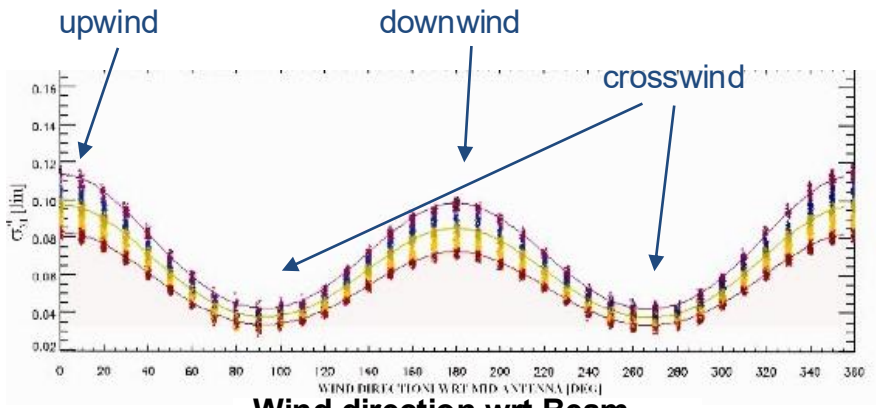
Dependency of the backscatter on... Wind direction



upwind

downwind





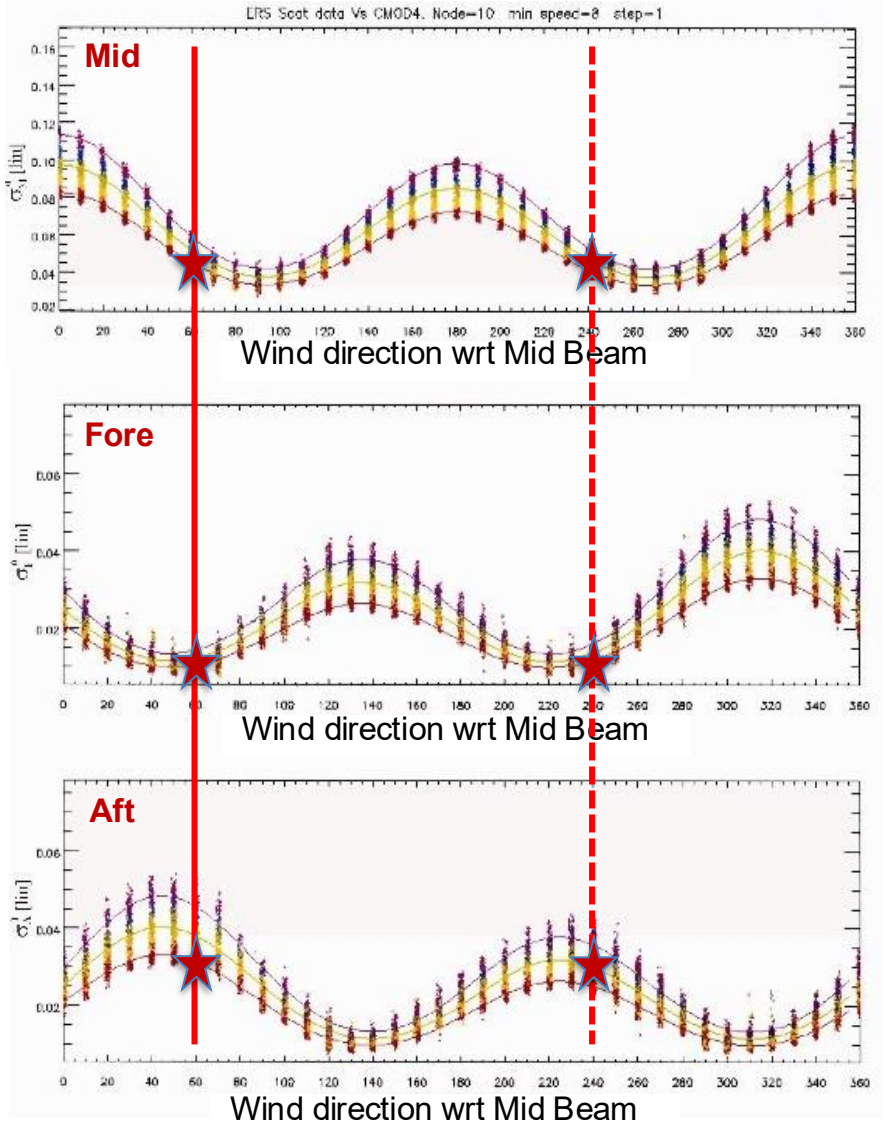
Wind direction wrt Beam

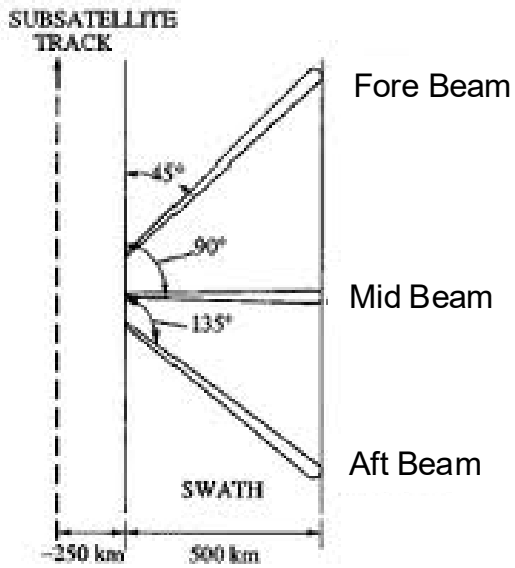
- Asymmetry Upwind – Downwind (particularly small)
- Asymmetry Upwind – Crosswind

Using multiple observations from different azimuth angles improves the accuracy of the derived wind direction

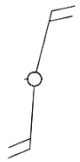
Dependency of the backscatter on... Wind direction

Backscatter response depends on the relative angle between the pulse and capillary wave direction (wind direction)



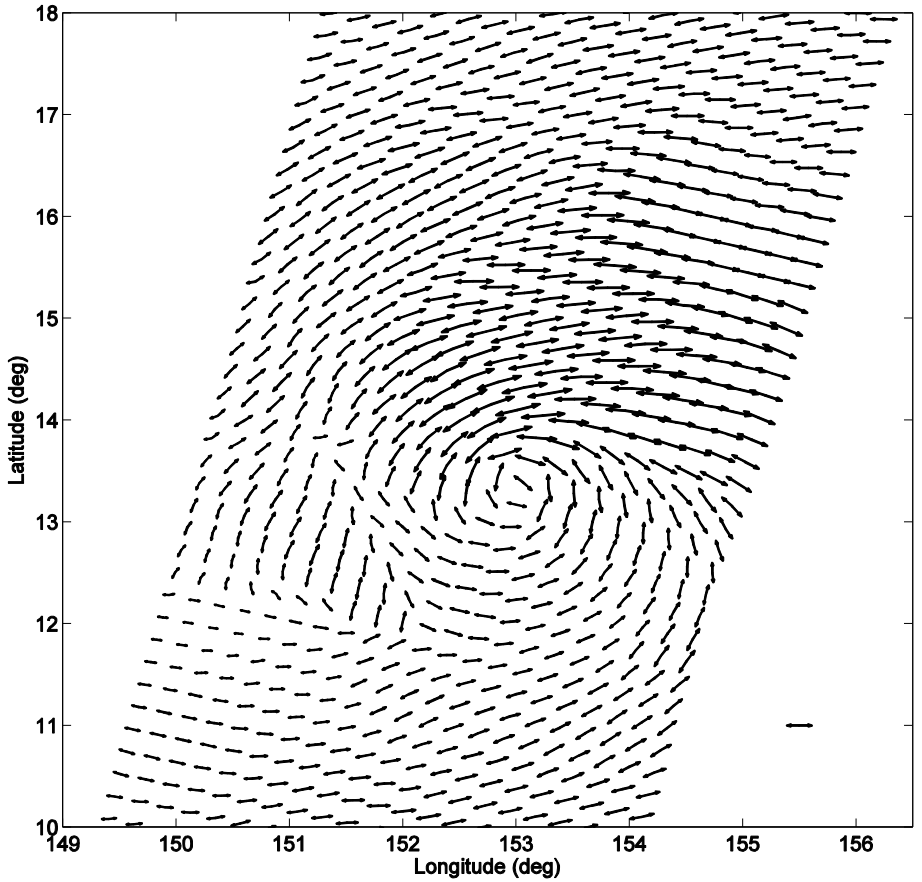


C-band SCAT geometry

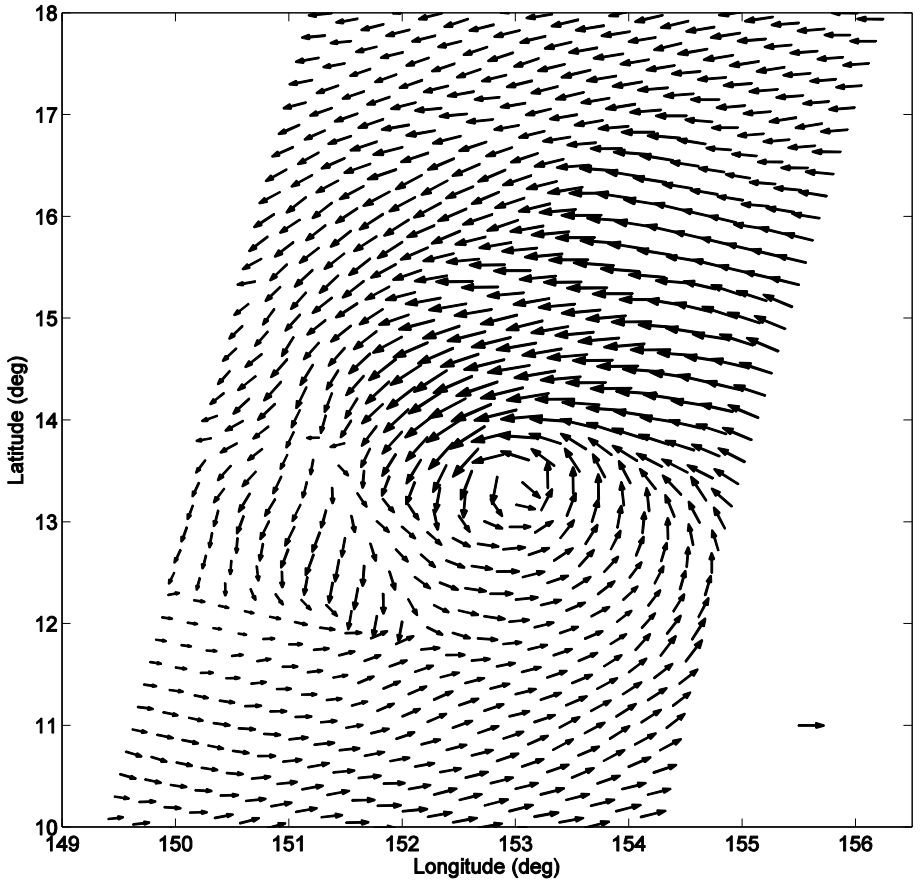


Wind Direction Ambiguity removal

- Measurements affected by noise
- Each wind vector cell has usually two possible solutions for wind direction and speed.
- The correct solution is determined by using NWP forecasts and wind field spatial patterns.



Ambiguities provided



Ambiguities selected

How can we relate backscatter to wind speed and direction?

Measurements sensitive to the **ocean-surface roughness** due to capillary gravity waves generated by local wind conditions (**surface stress**)

The relationship is determined empirically

- Ideally collocate with *surface stress* observations
- In practice with buoy and 10m model winds

$$\sigma_0 = GMF(U_{10N}, \phi, \theta, p, \lambda)$$

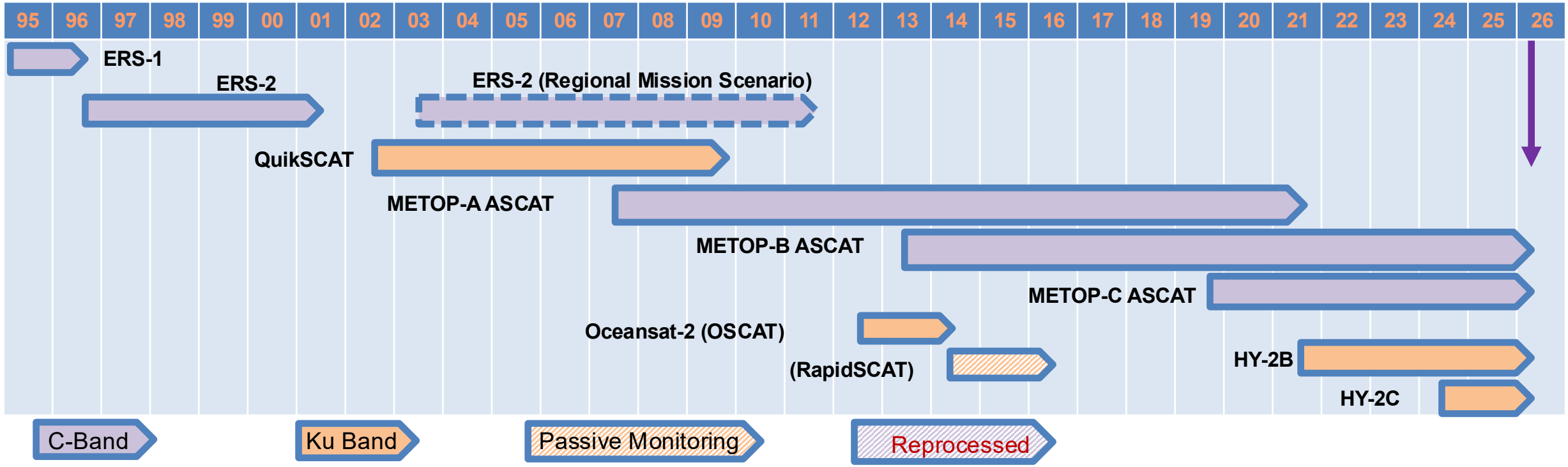
U_{10N}: equivalent neutral wind speed
ϕ: wind direction w.r.t. beam pointing
θ: incidence angle
p: radar beam polarization
λ: microwave wavelength

Geophysical model functions (GMF) families

- C-band: CMOD (currently CMOD5.N in IFS)
- Ku-band: NSCAT, QSCAT

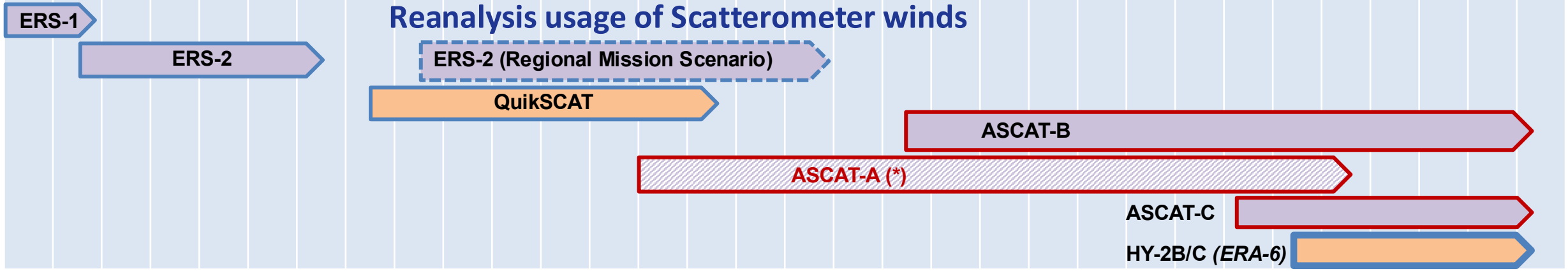
Data usage at ECMWF

Operational usage of scatterometer winds



Under assessment: ~~*HY-2D*~~ *(current data issue), OCEANSAT-3 (Nov '22)*
Launched, waiting for the data to be distributed:
To be launched soon: *Oceansat-3A (Q2 '25), HY-2E (Q1 '26)*

Reanalysis usage of Scatterometer winds

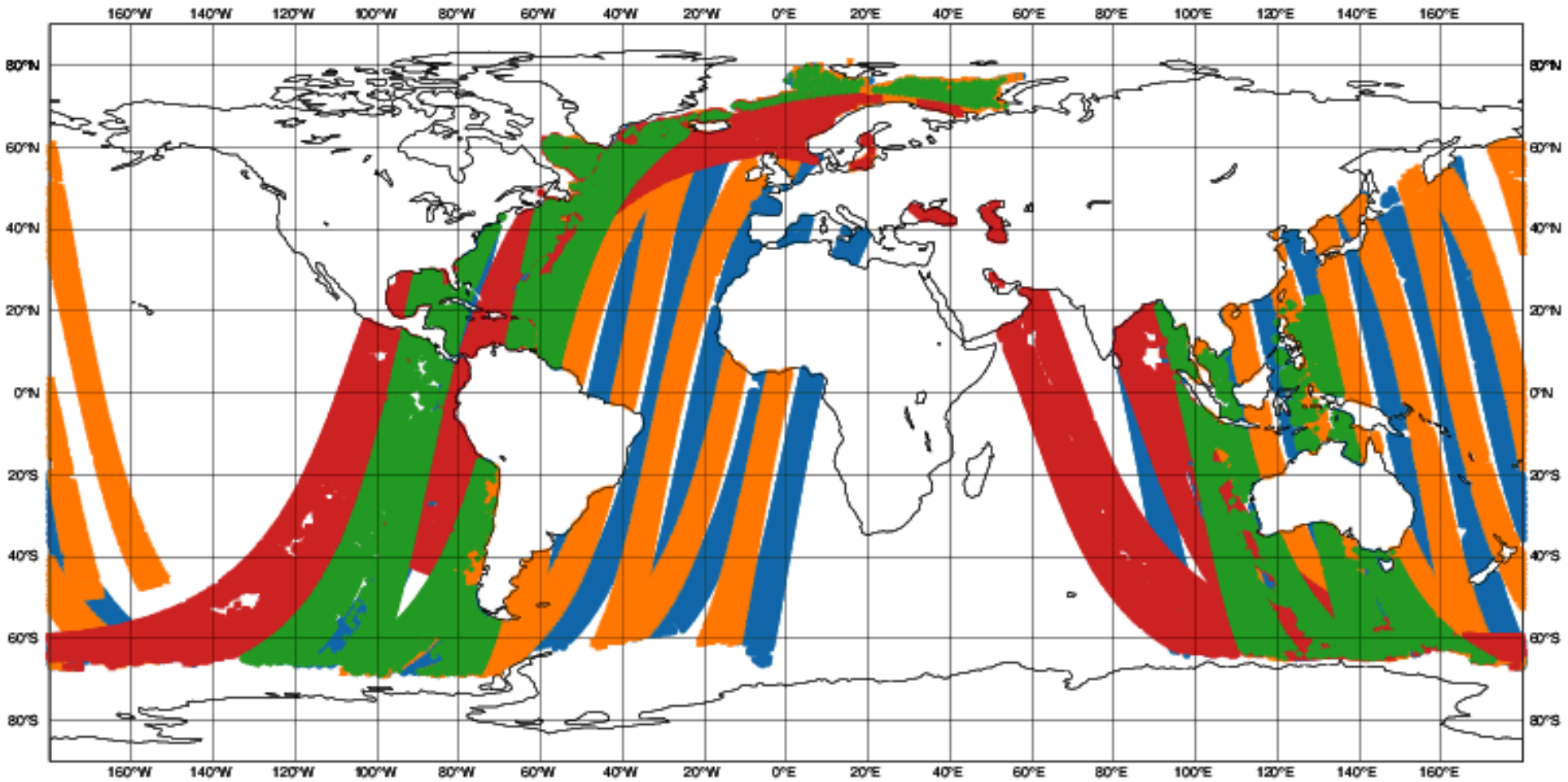


(*)ASCAT-A 1st reprocessed campaign will be used in ERA6

Scatterometer wind data coverage

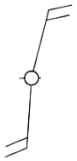
Over a 6-hour window (on 20250327 06 UTC)

METOP-B METOP-C HY-2B HY-2C

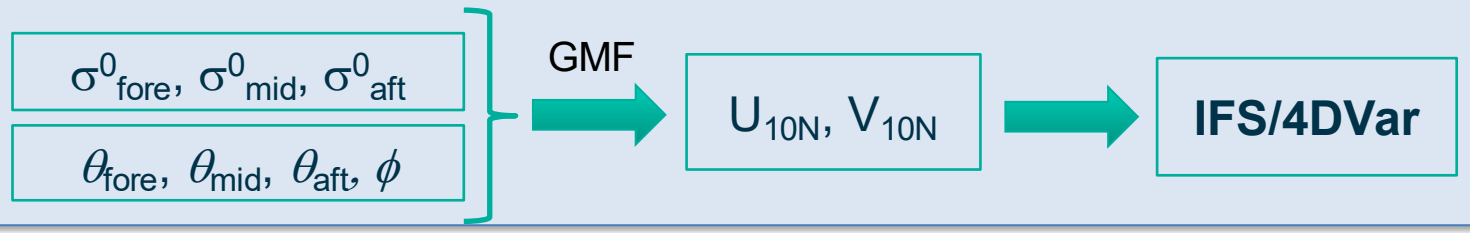


Scatterometer winds assimilation strategy

	C-band	Ku-Band
Resolution	25 km	50 km
σ_0 bias correction	√	-
Wind Inversion	ECMWF (L1 → L2)	L2 from OSI-SAF
Wind Speed bias correction	√	√
QC – (land contamination, sea ice check)	√	√
Rain flag check	-	√
Thinning	50 km	-
Maximum wind speed assimilated	35 m/s	25 m/s
Assigned observation error	2.25 m/s	4 m/s
4D-Var	2 solutions	1 solution
Assimilated as 10m eq. neutral wind (U&V)	√	√



In-house wind inversion for C-Band scatt

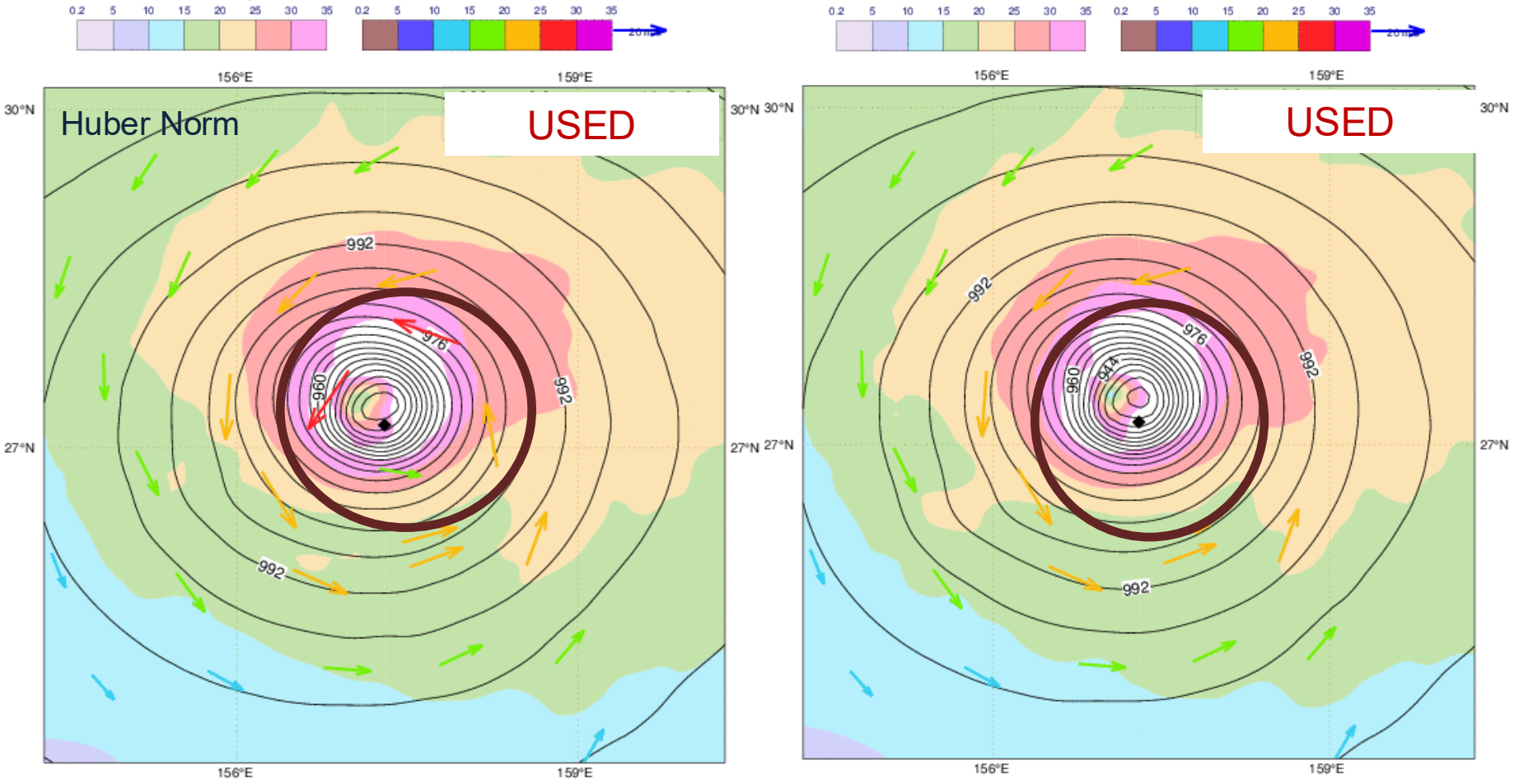


TC QC issues

TC KILO – 2015090812 ASCAT-A Observations

Less observations due to:

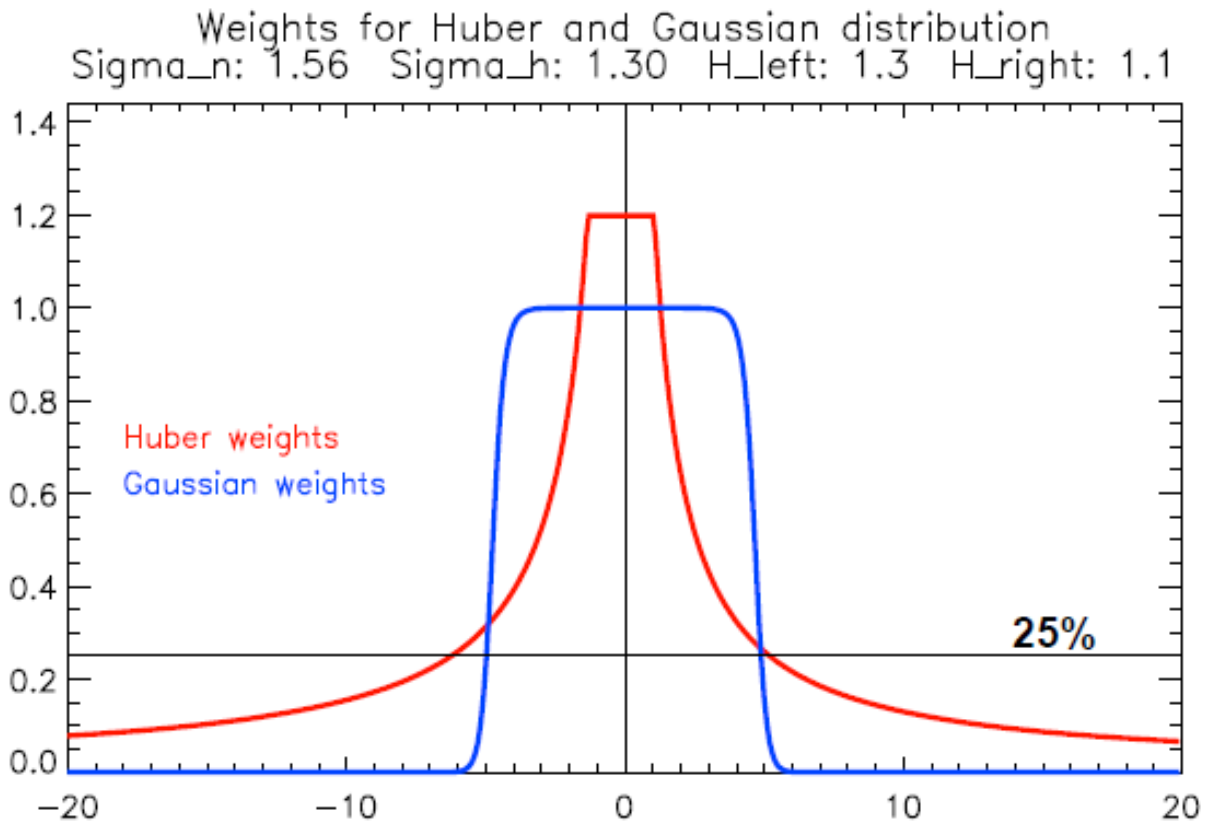
- Thinning
- VarQC



VarQC

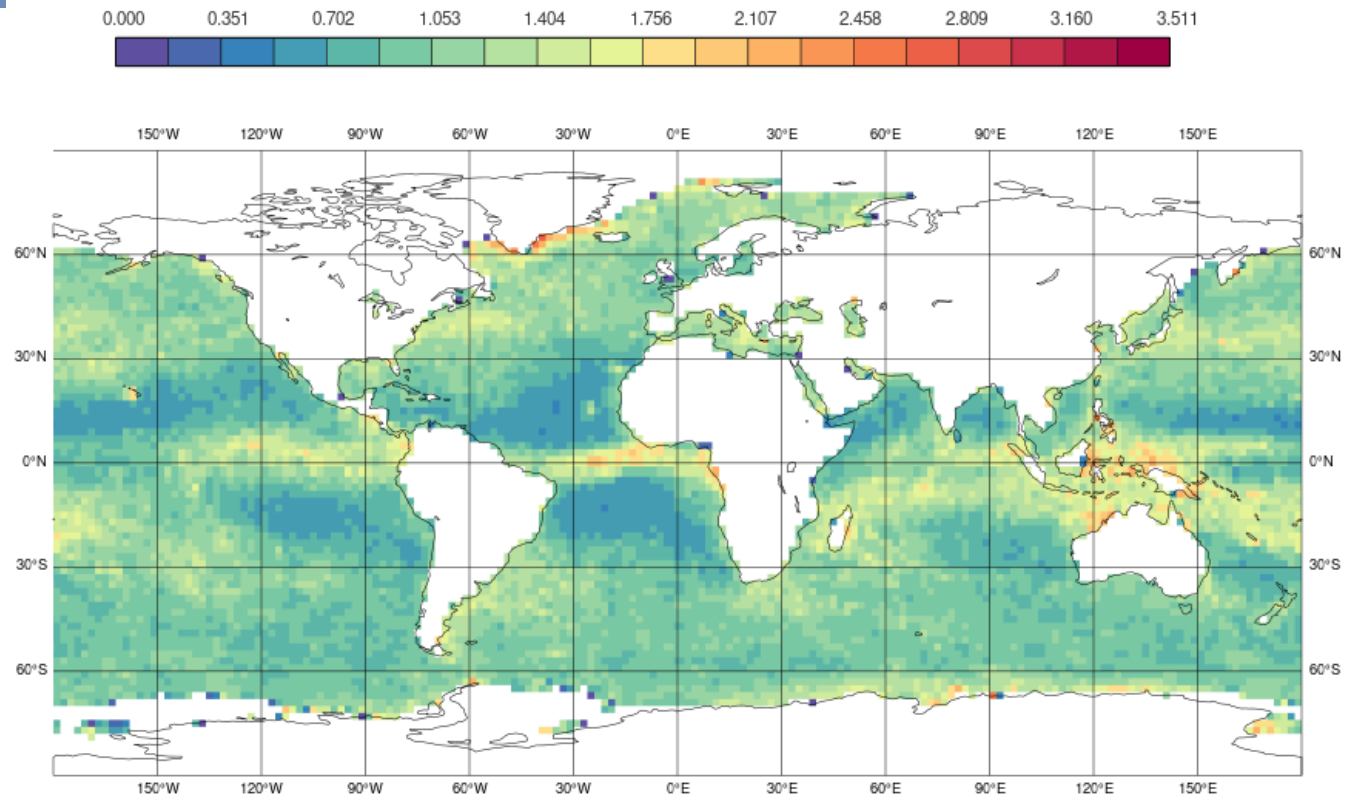
Observation weight: VarQC & Huber Norm

Comparing Observation weights:
Gaussian + flat (VarQC): more weight in the middle of the distribution
Huber Norm: more weight on the edges (to data with large departure)

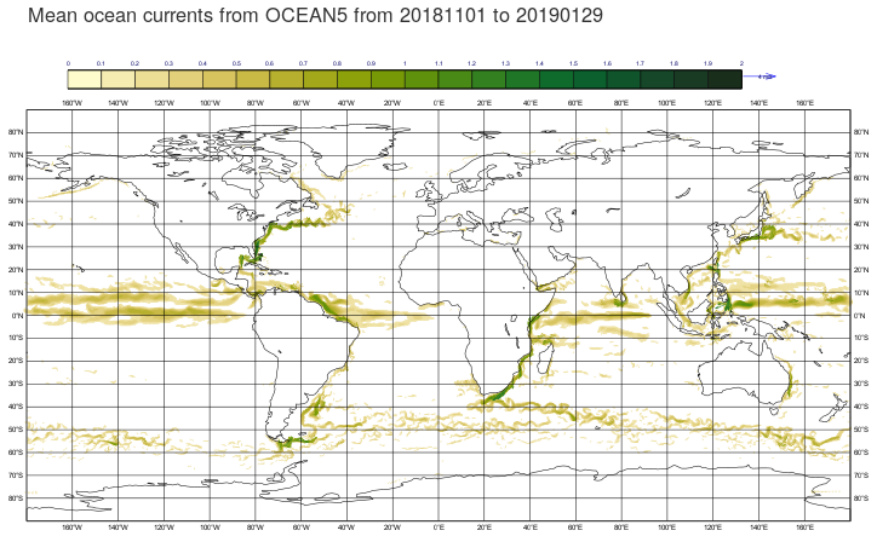


Background Departure

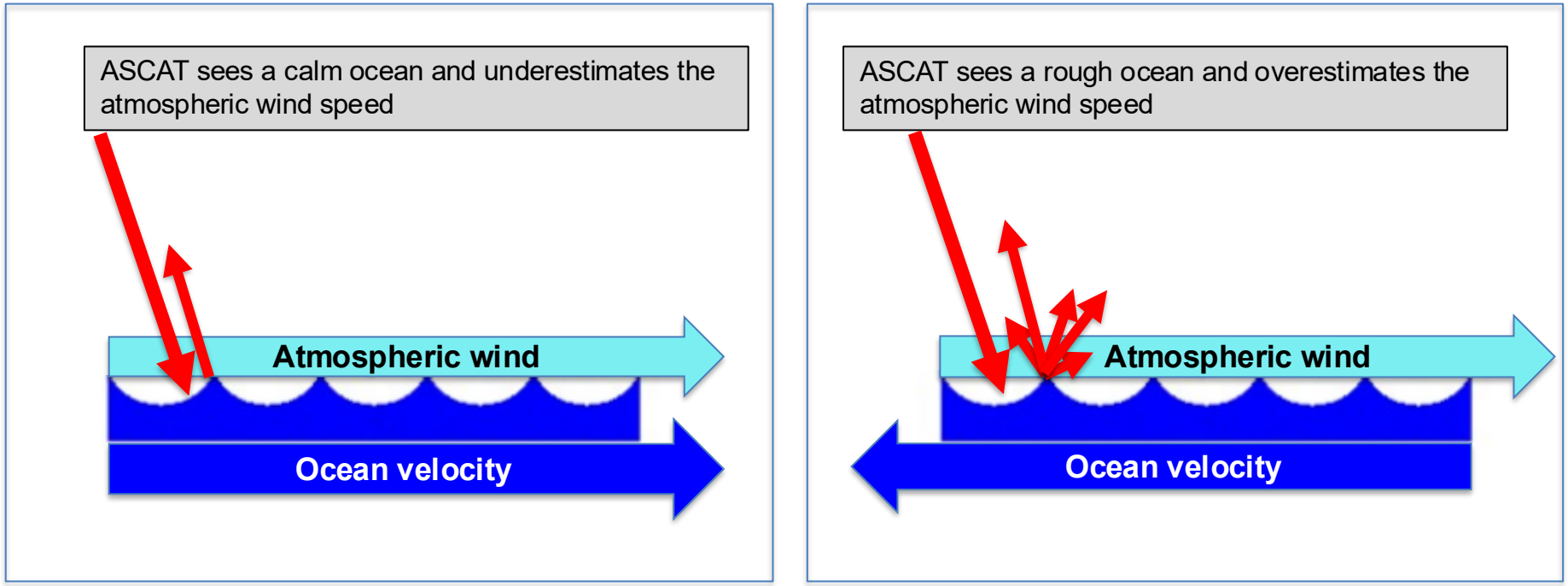
ASCAT-B Wind speed O-B
31 January – 27 March 2025



Wind speed bias in the Tropics:
also due to Ocean Current?



Scatterometer and Ocean Currents



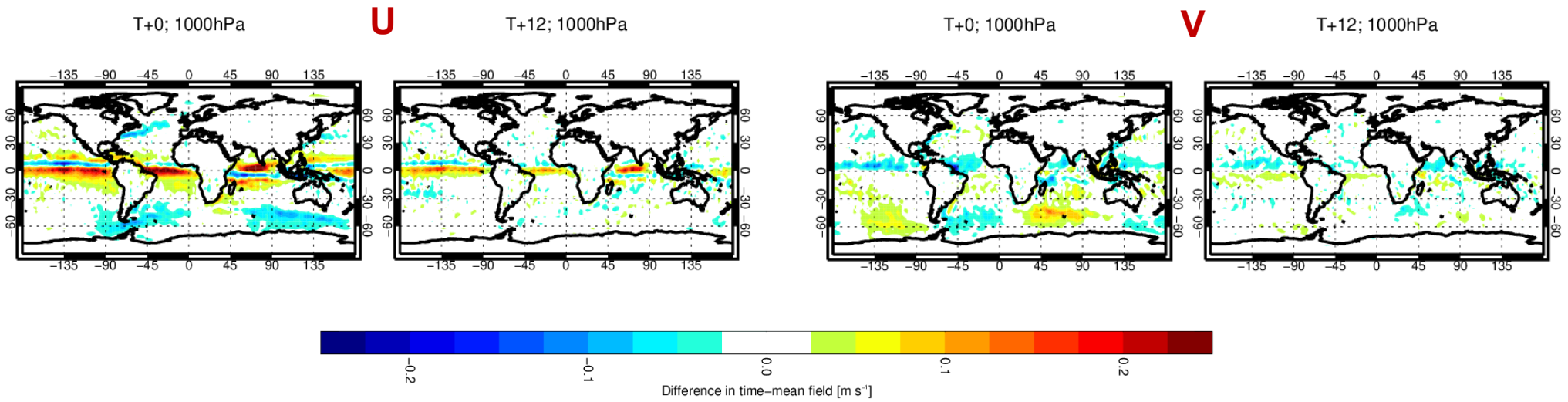
- The scatterometer “sees” the ocean currents
- In operations the scatterometer observation operator does not account for them…
- This will happen in CY49R2 (used for ERA6)

Impact of ocean currents in the scatterometer assimilation

OSEs to separate the impact of the ocean coupling for SCAT only (Dec 21 – Feb 22):

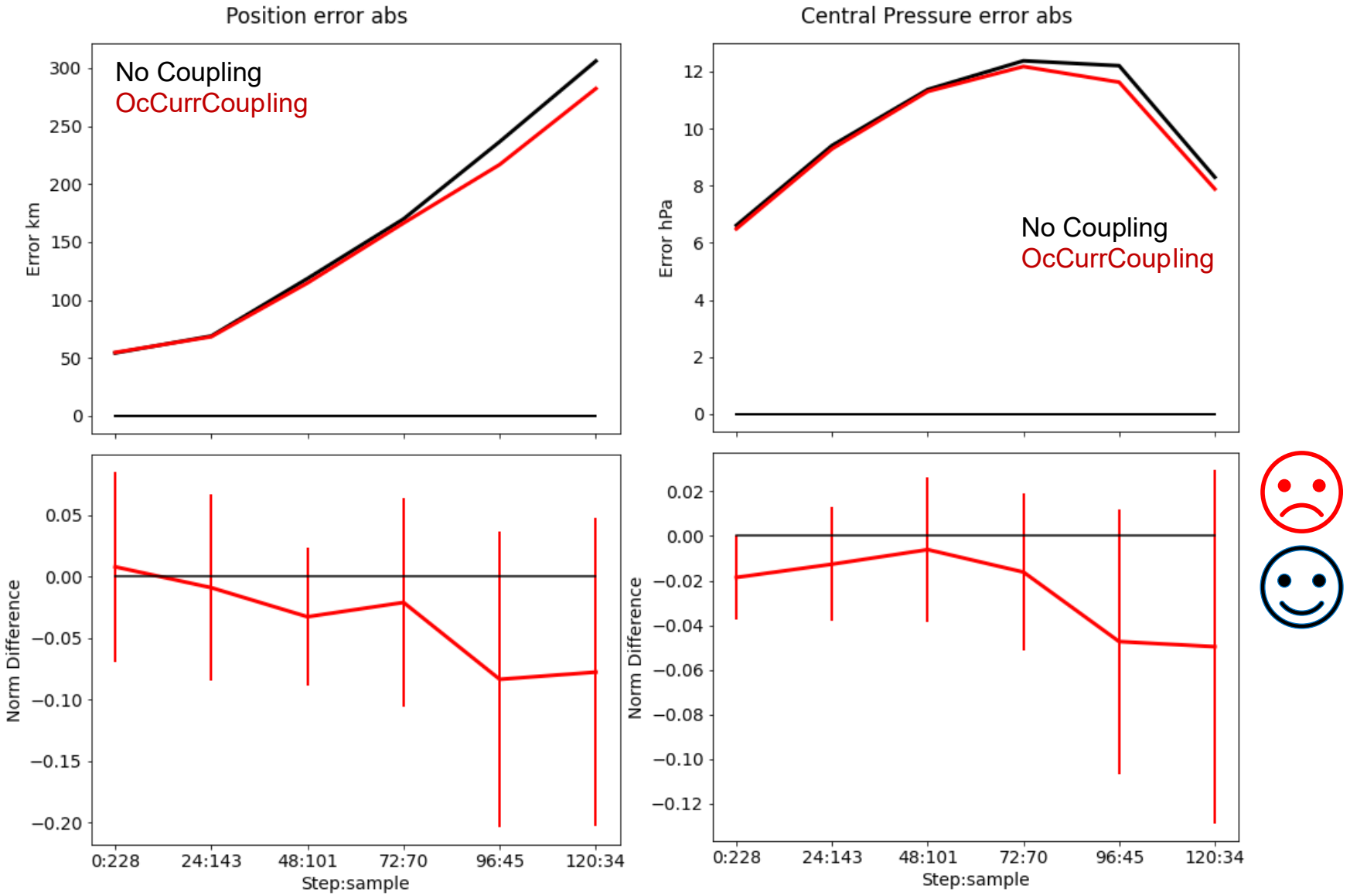
- **OuterLoop_coupling:** ERA6-like configuration where ocean currents are used in the scatt obs oper, BL, wave model, etc
- **Scatt_LECURR_OFF:** ocean currents off for the scatterometer observation operator only

Changes in mean component: Scatt_LECURR_OFF – OuterLoop_coupling



Scatterometer and Ocean Currents

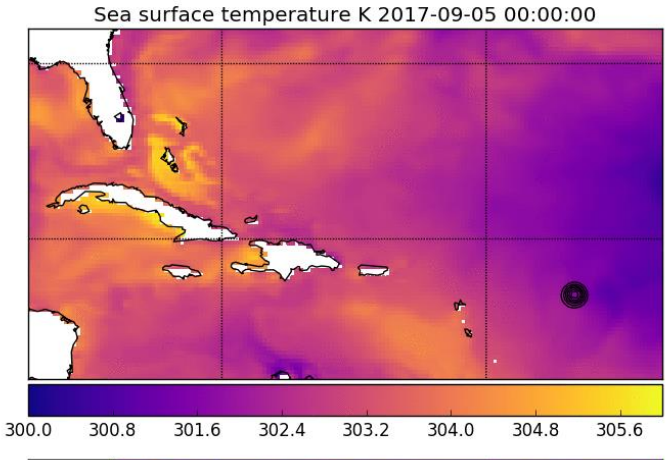
Impact on TC - Results in weakly coupled DA



- ✓ Scatterometer winds are assimilated in the atmospheric model
- ✓ The verification is usually done on atmospheric variables
- ✓ Scatterometers provide measurements at the ocean-atmosphere interface
- ✓ **What about the impact of Scatterometer on the ocean?**

What about the impact of Scatterometer on the ocean?

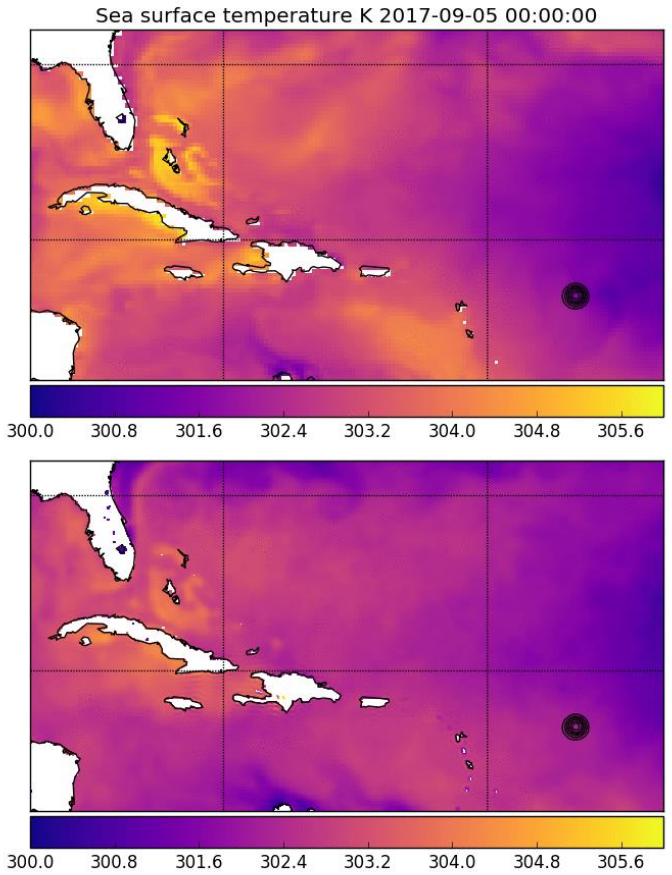
Coupled Data Assimilation (CDA)



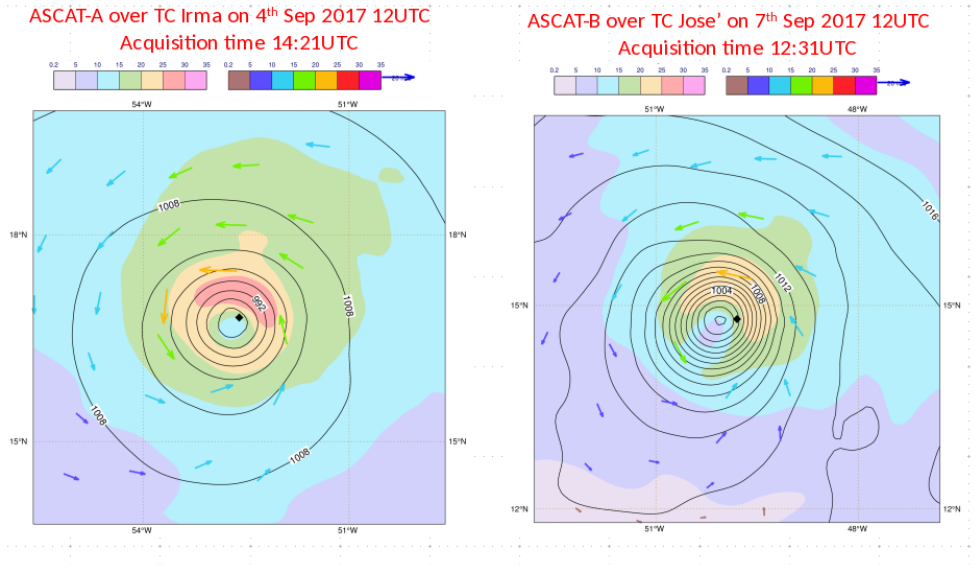
In the **coupled assimilation** the SST shows a clear and immediate impact on SST of the storm winds mixing the ocean (cold wake) and the storm's arrival in the Caribbean damping the usual pronounced diurnal cycle in the SST

Irma/Jose with ocean – atmosphere DA coupling

Coupled Data Assimilation (CDA)



What is the role of ASCAT (and JASON) in the coupled data assimilation during Irma and Jose?



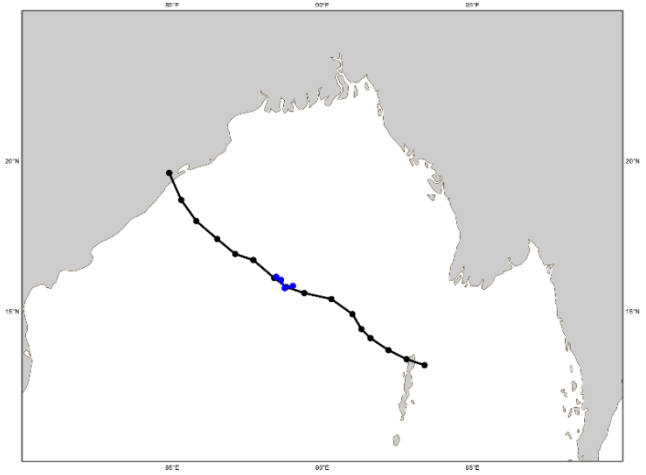
In CDA ASCAT gives SST information below Tropical Cyclones

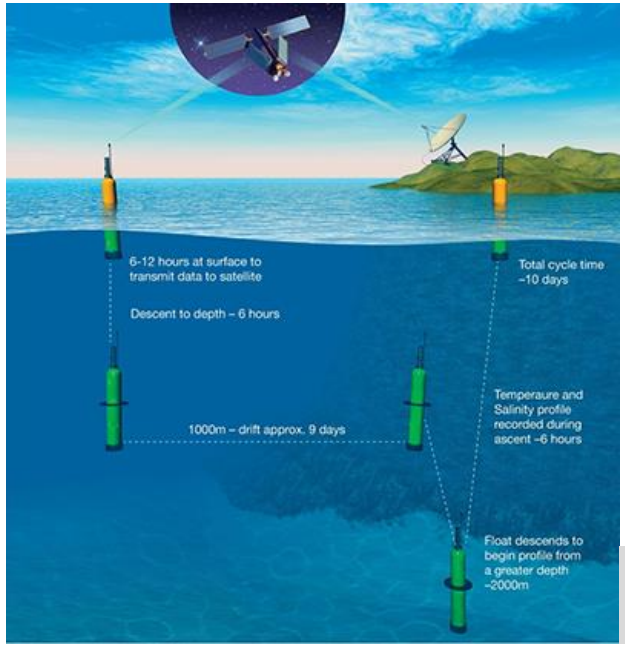
Quantifying heat exchange between the storm and ocean surface is an important factor in predicting the intensification / de-intensification of Tropical Cyclones.

ASCAT sees through the cloud and rain (IR/MW cannot) and informs the coupled analysis of the surface roughening below the storm, in turn influencing the ocean mixing and thus the SST !

Impact of scatterometer winds …on the ocean parameters

Coupled Data Assimilation (CDA)

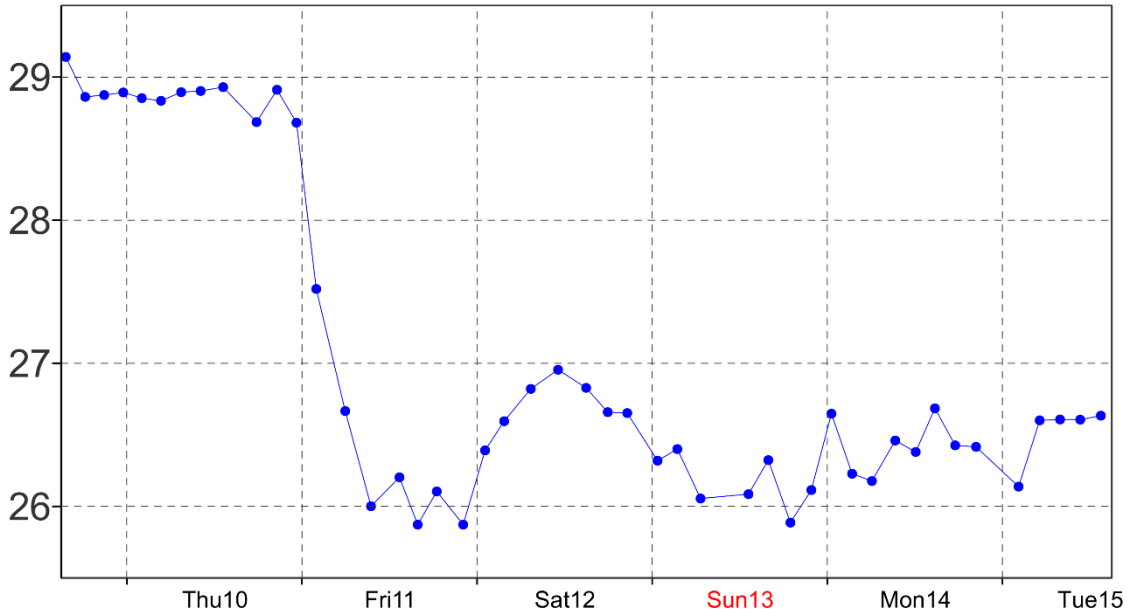




Focus on a specific weather event:

- TC Phailin
- Bay of Bengal
- formed on the 4th October 2013
- Argo probe with high-frequency measurements

Temperature measurements at 40-meter depth

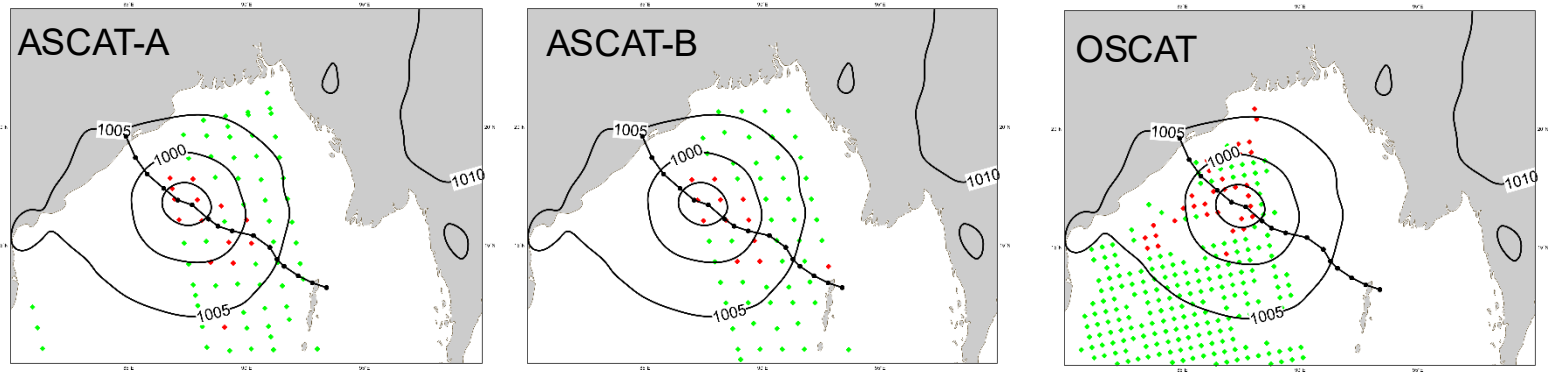


Impact of scatterometer surface wind data in the ECMWF coupled assimilation system
P. Laloyaux, J-N Thépaut and D. Dee. MWR, 2016

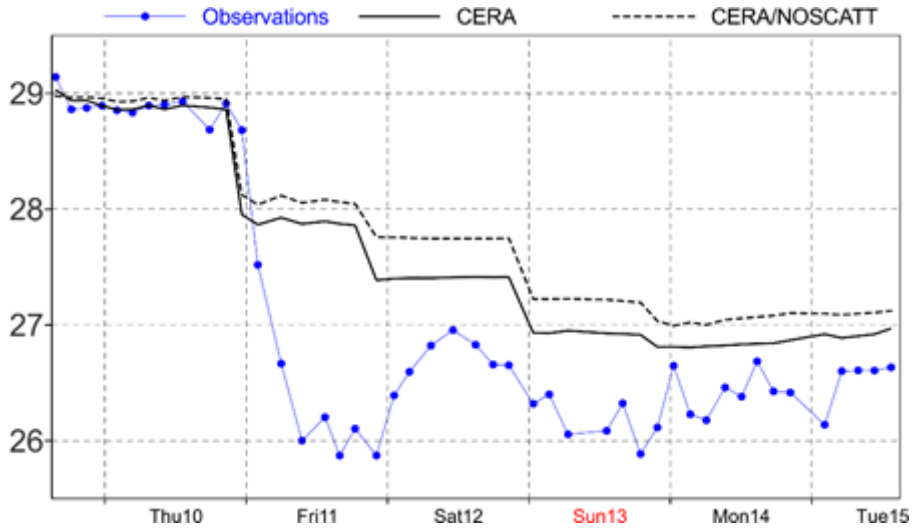
Impact of scatterometer winds …on the ocean parameters

TC Phailin

Wind measurements from scatterometers (ascending pass, 11 October 2013)

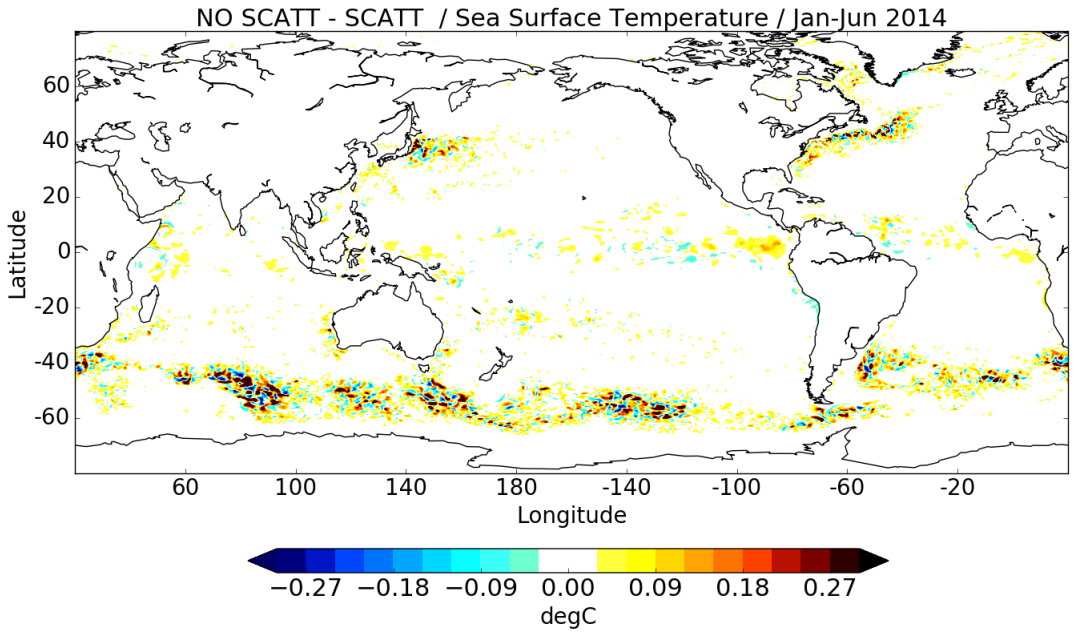


Ocean temperature analysis at 40-meter depth (scatterometer data are assimilated)

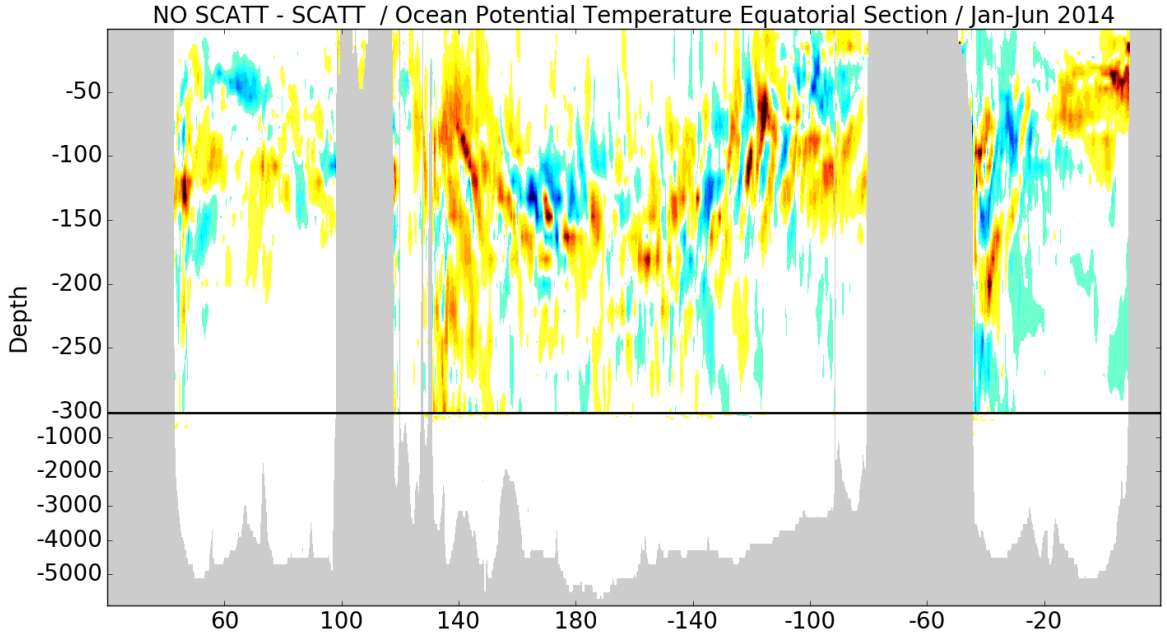


Coupled analysis with Scatterometer winds is closer to the observations with a stronger cold wake

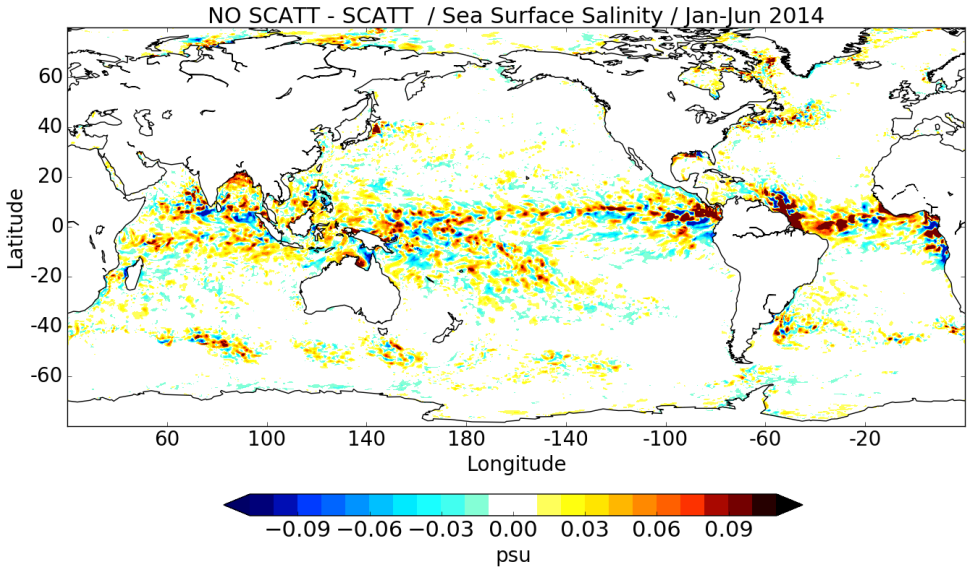
Impact of Scatterometer on Ocean Temperature



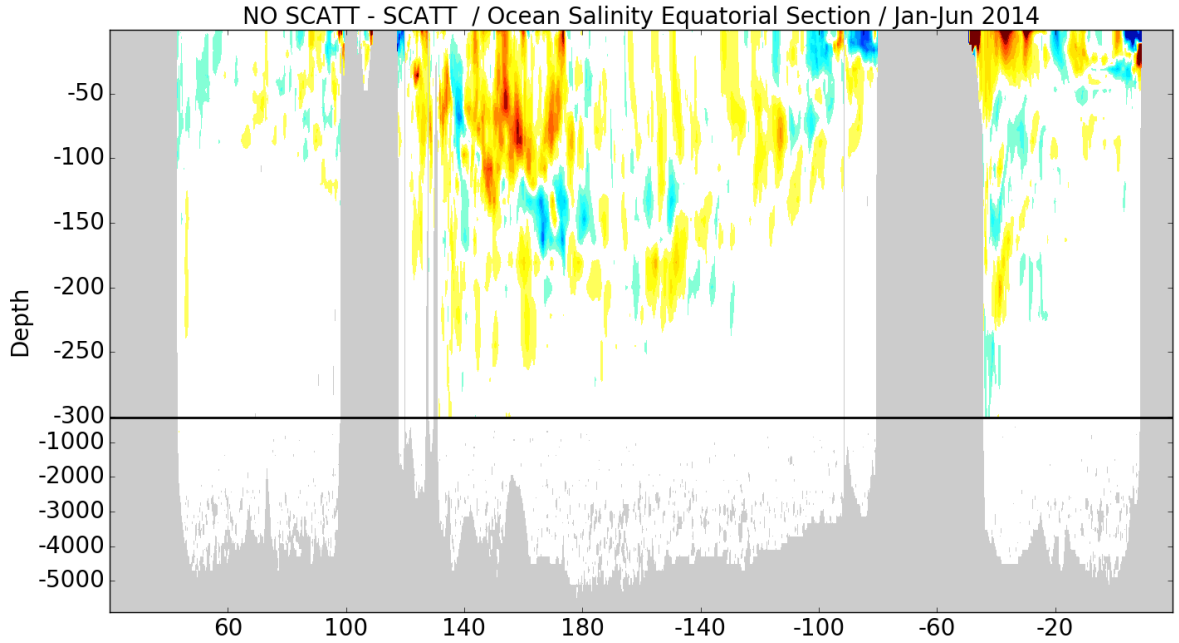
No SCATT – SCATT



Impact of Scatterometer on Ocean Salinity



No SCATT – SCATT



- ✓ Scatterometer over the ocean always assimilated as level 2 observations (wind vectors)
- ✓ Most of the satellite observations are assimilated as Level 1 (radiances, gnss-ro…)
- ✓ Why scatterometer should be an exception?

Assessment of Direct Assimilation of Sigma0 (using ML)

- Why scatterometer observations should be an exception?
  - 4D-Var systems is designed to handle ill-posed (== ambiguous) retrieval problems
  - We are routinely tackling increasingly non-linear forward problems in 4D-Var: ”All-sky, all surface, …”

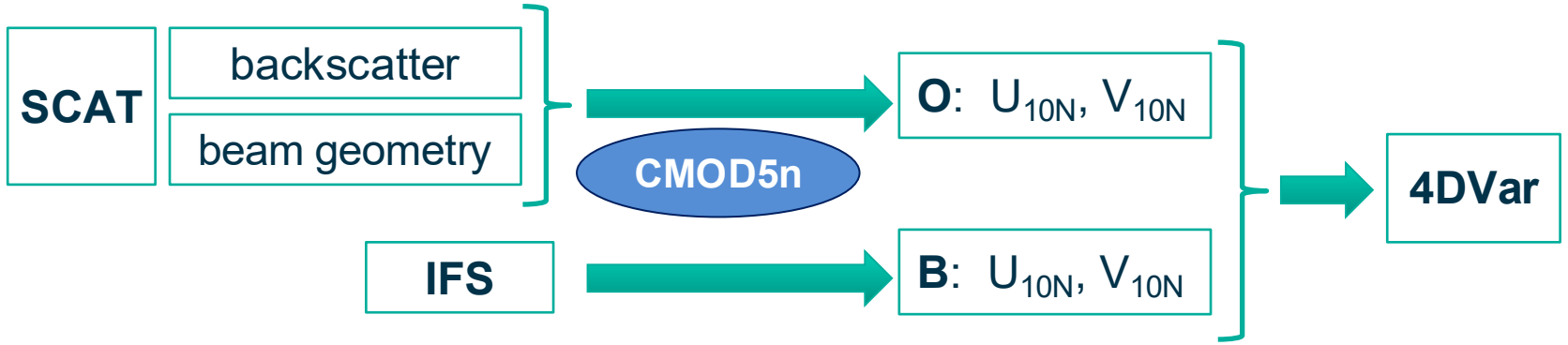
- Some tests were performed in the past but cannot find examples/studies in the literature comparing the impact of assimilating ASCAT sigma0 vs wind retrievals in 3D/4D-Var system

- ***Revisiting the direct assimilation of backscatter (sigma0)***

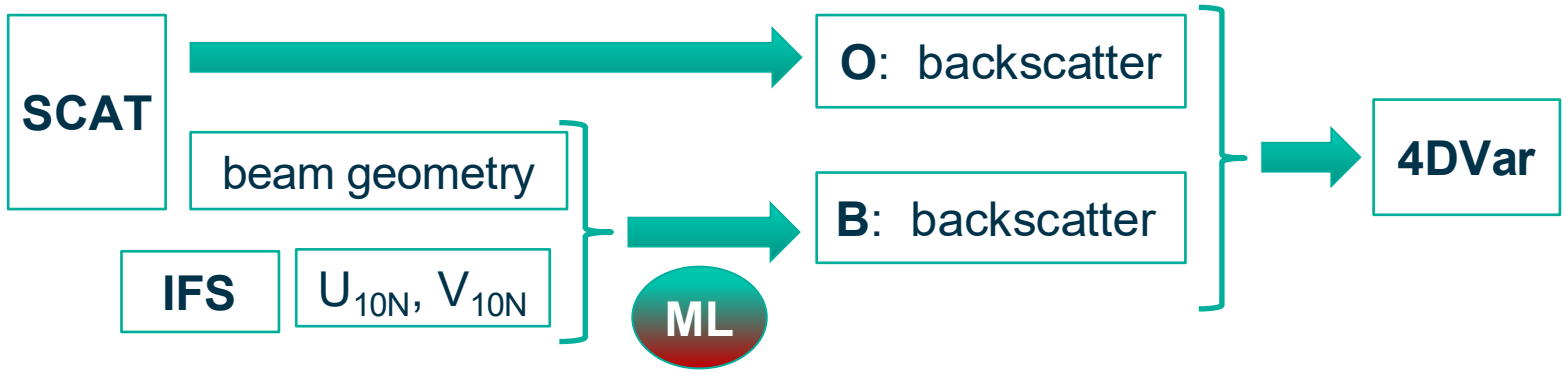
- **Impact experiments**: ASCAT-B/C (other scatts not assimilated)
  - CTL (or U/V): assimilate ambiguous u/v retrievals as done in **operations** (using CMOD5.n)
  - No SCATT: remove all ASCAT data
  - OSI-SAF (KNMI) U/V: OSI-SAF (KNMI) chosen L2 wind retrievals (same as CTL but different wind product)
  - **SIG0: assimilate ASCATs as backscatter (sigma0)**

ASCAT observations Data Assimilation

Current operational approach common to all the NWP centres (based on L2 wind products)



Tests on the assimilation of backscatter



Short-range forecast departure statistics – surface observations

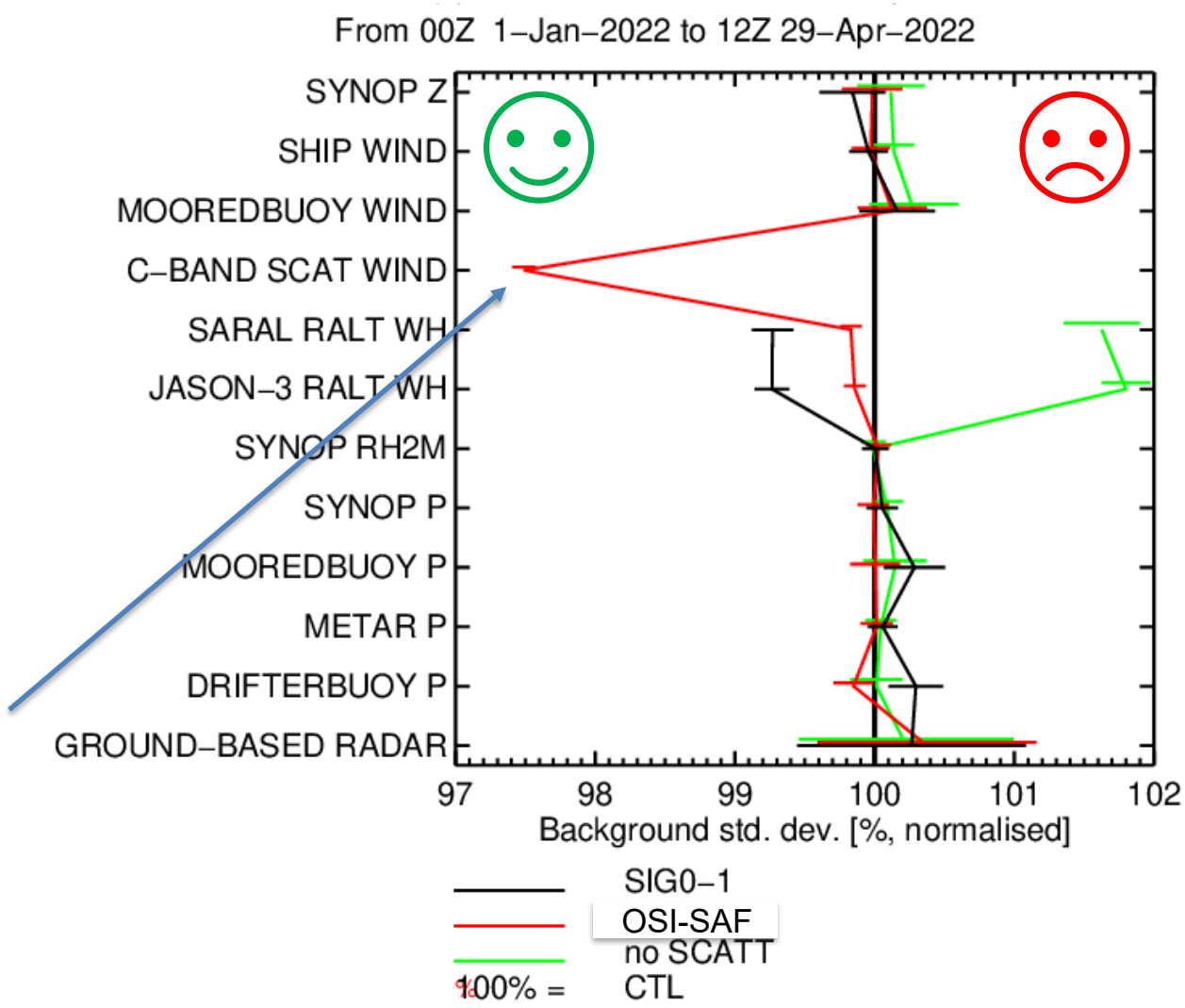
Normalized SD (%) compared to CTL (U/V – what we do now)

- SCATT tends to have good impact on SWH
- *Clear degradation when SCATT removed*

- **SIG0** seems to improve the SWH stats compared to CTL and OSI-SAF

- **SIG0** – may have some surface pressure issues

- OSI-SAF retrieved winds have better scatt departure stats than CTL: (o-b) reduced by more than 2 %

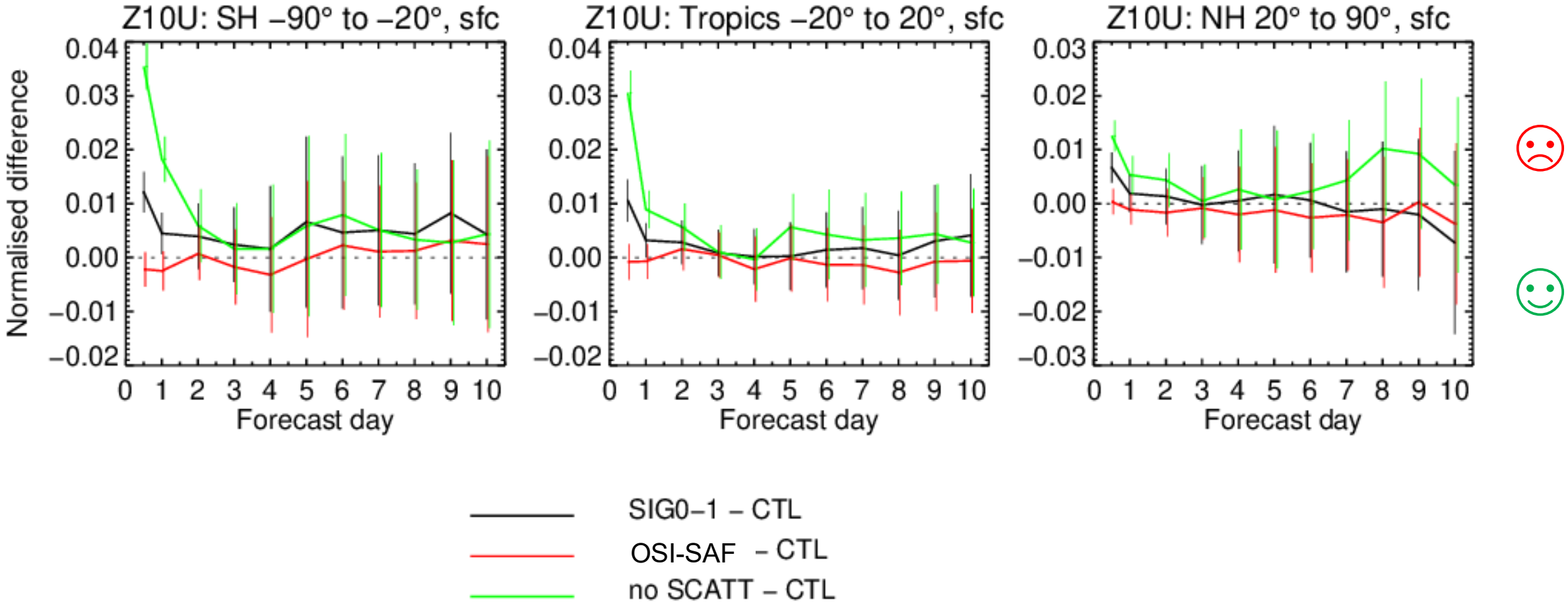


ECMWF

Impact on the medium-range forecast

Root mean square forecast error

U10 m winds vs operational analyses (CTL == what we do now)



ECMWF

Scatterometer measurements over the ocean

Important observations at the ocean interface interface

- Widely used in NWP for over 30 years, assimilated as wind vector
- Positive impact on analysis and the forecast in the atmosphere and ocean waves
- Global scale and extreme events
- In couple systems the impact is seen on the ocean parameters down to the thermocline (-300m)
- Ocean currents have an impact on the scatt assimilation

Can we get closer to what a scatterometer actually measures assimilating backscatter?

- Results suggest that the backscatter assimilation is viable
- Very encouraging results but not “perfect” yet: some forward model issue at high winds, winds not turning as well as using U/V around TC
- In a coupled system, tests on including ocean parameters in the ML forward model could be done

At ECMWF used in operations and in the Reanalysis

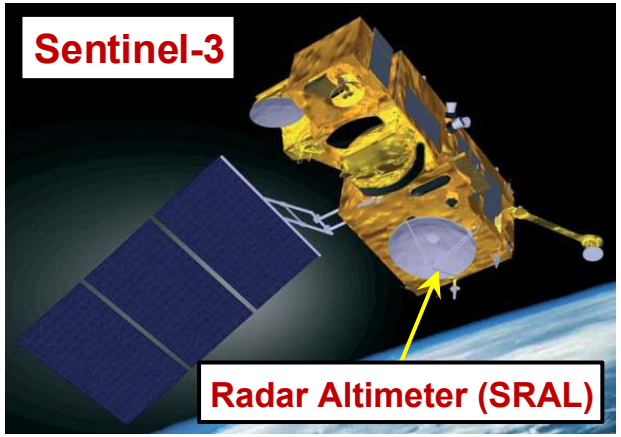
- In **operations** currently using: ASCAT-B/C; HY-2B/C
- Currently testing Oceansat-3
- Soon starting the preparation for SCA-EPS-SG: OSI SAF L2 winds will be considered instead on in-house wind inversion

- In **ERA6:** ERS1/2, QuikSCAT, ASCAT-A/B/C and HY-2B/C will be used
- Any new datasets added to oper will be (possibly) used in ERA6 with a little delay

SCATT question time

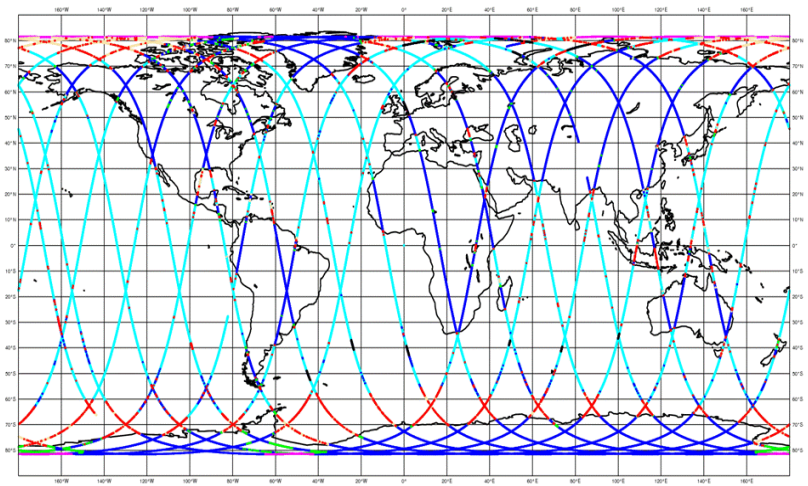
Radar Altimeters

- ✓ Radar altimeter is a nadir looking instrument.
- ✓ Specular reflection.
- ✓ Electromagnetic wave bands used in altimeters:
  - Primary:
    - Ku-band (~ 2.5 cm) – ERS-1/2, Envisat, Jason-1/2/3, Sentinel-3/6
    - Ka-band (~ 0.8 cm) – SARAL/AltiKa (only example)
  - Secondary:
    - C-band (~ 5.5 cm) – Jason-1/2/3, Topex, Sentinel-3/6
    - S-band (~ 9.0 cm) – Envisat

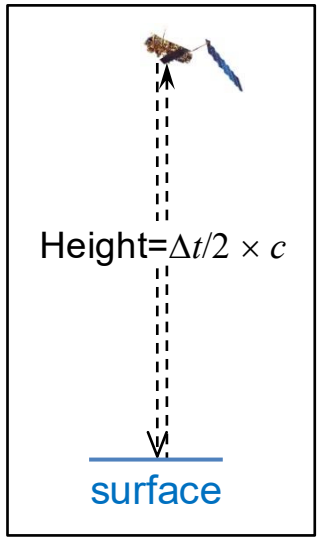


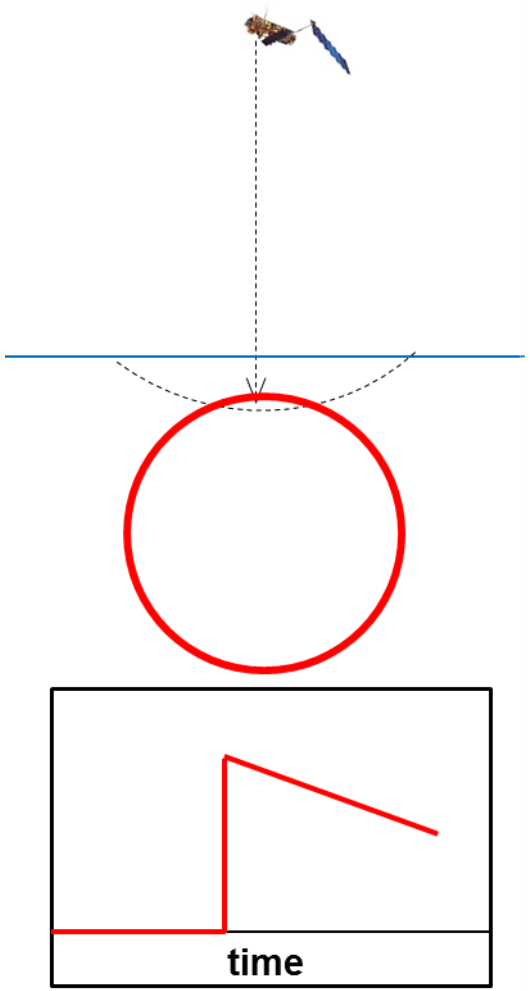
- ✓ Main parameters measured by an altimeter:
  - Significant wave height (*wave model*)
  - Wind speed (*used for verification*)
  - Sea surface height (*ocean model*)

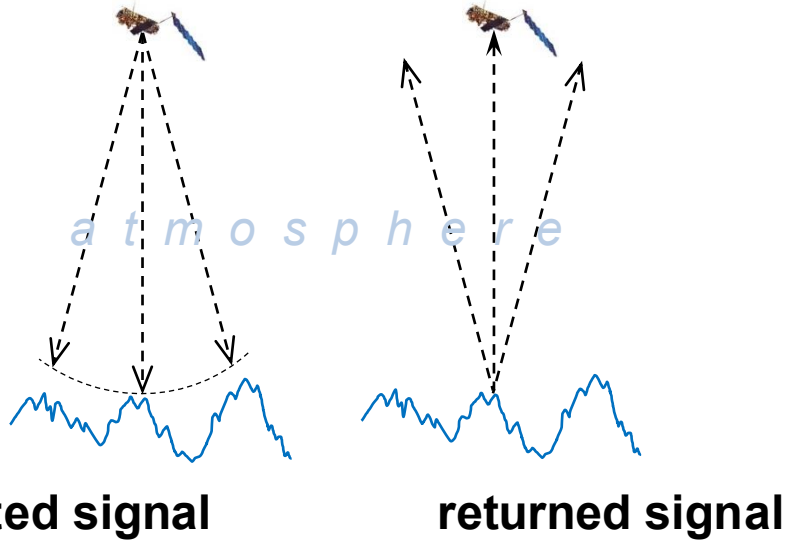
Envisat 1-day coverage

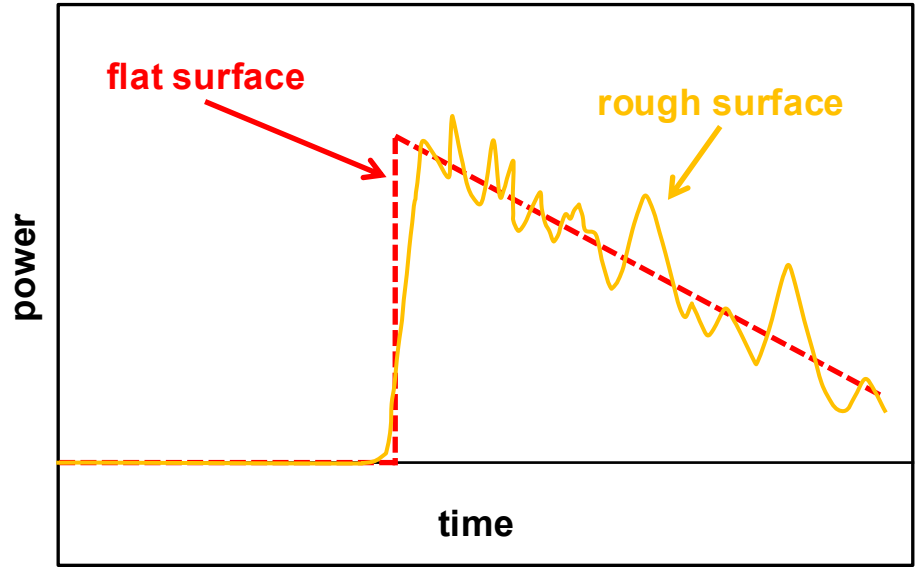


How Altimeter Works

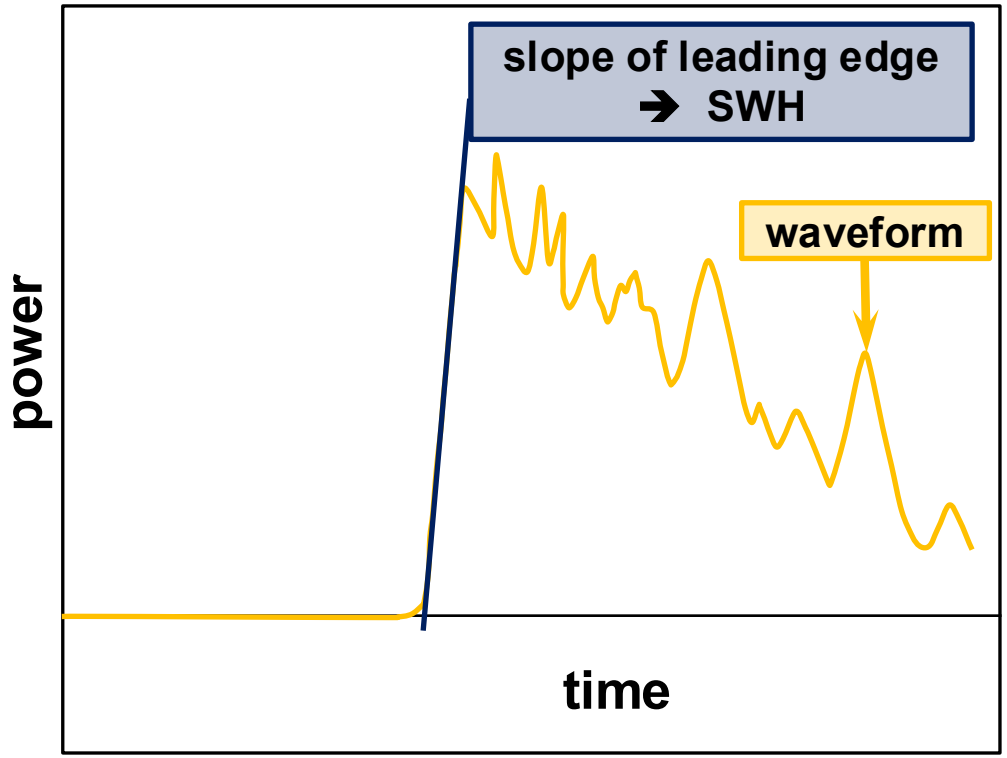






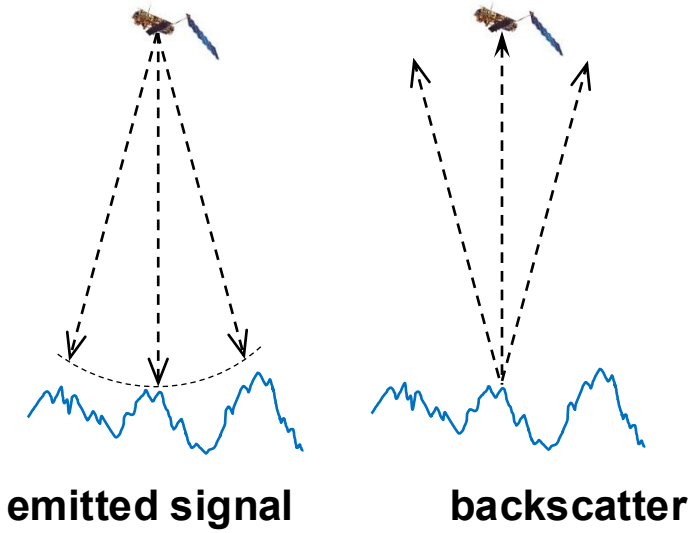


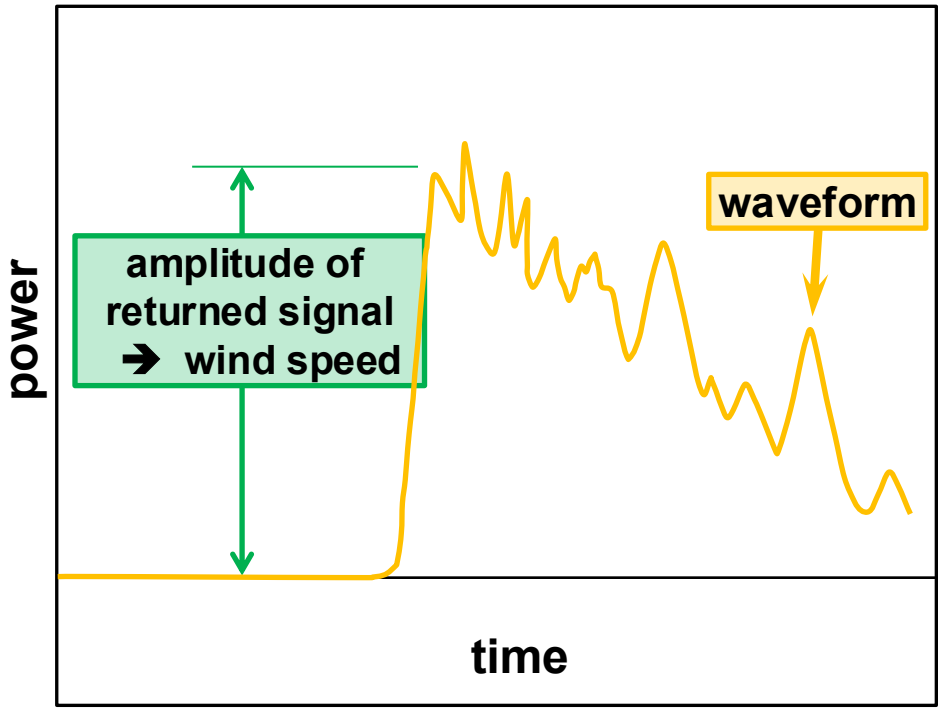
Significant Wave Height (SWH)



- ✓ SWH is the mean height of highest 1/3 of the surface ocean waves
- ✓ Higher SWH → smaller slope of waveform leading edge
- ✓ Errors are mainly due to waveform retracking (algorithm) and instrument characterisation

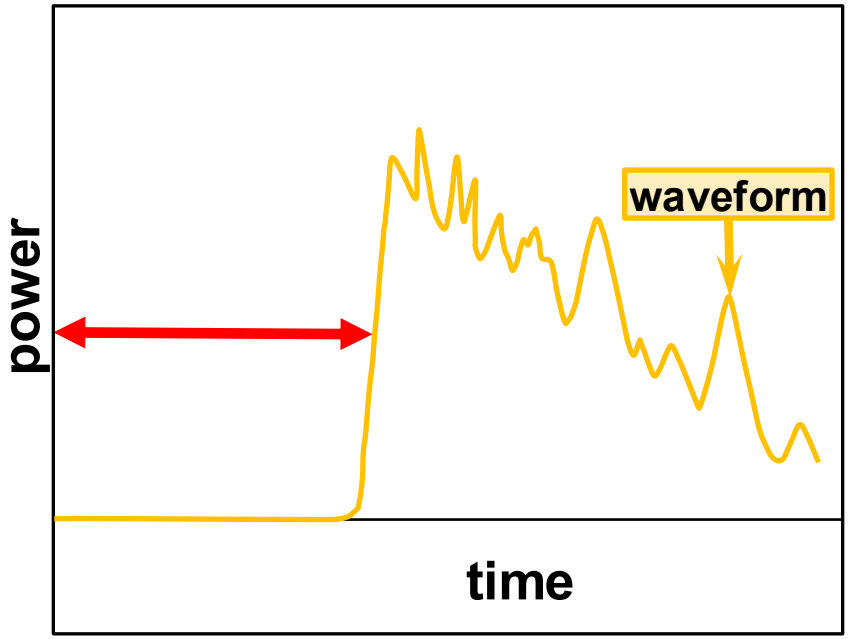
Surface wind speed





- ✓ Backscatter is related to water surface Mean Square Slope (MSS)
- ✓ MSS can be related to wind speed
- ✓ Stronger wind → higher MSS → smaller backscatter
- ✓ Errors are mainly due to algorithm assumptions, waveform retracking (algorithm), unaccounted-for attenuation & backscatter.

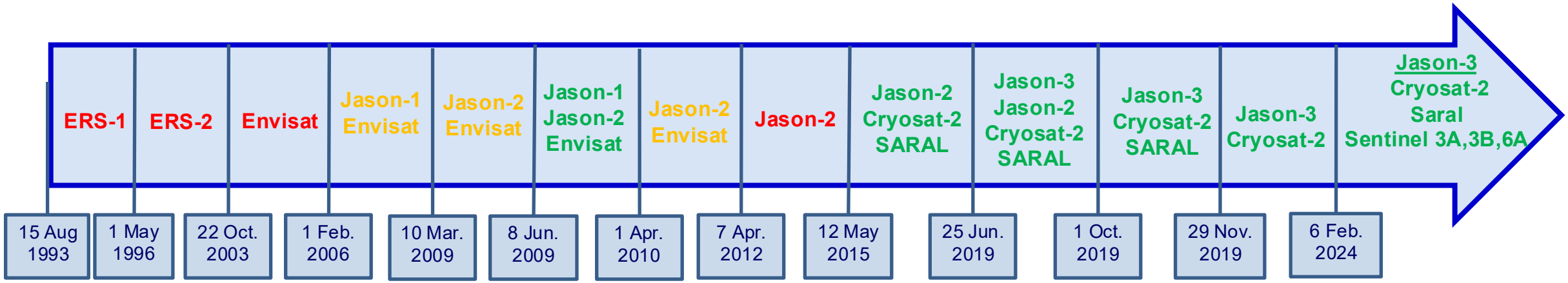
Sea Surface Height



- ✓ Time delay → sea surface height
- ✓ Radar signal attenuation due to the atmosphere is caused by:
  - Water vapour impact: ~ 10's cm.
  - Dry air impact: ~ 2.0 m

  Correction made using radiometer and model data

Operational Assimilation of SWH (wave model)

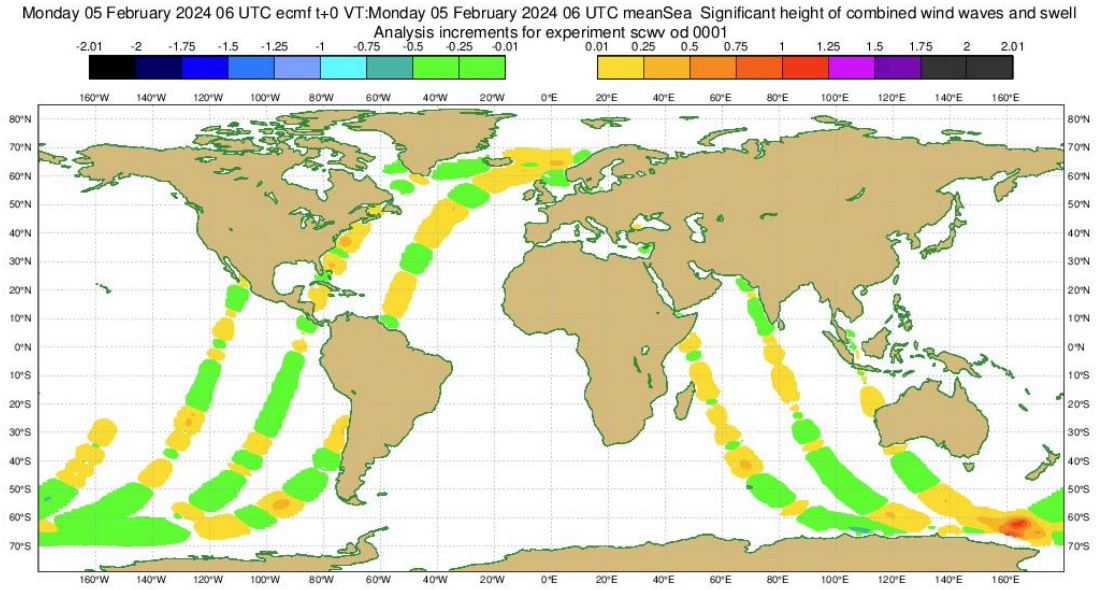


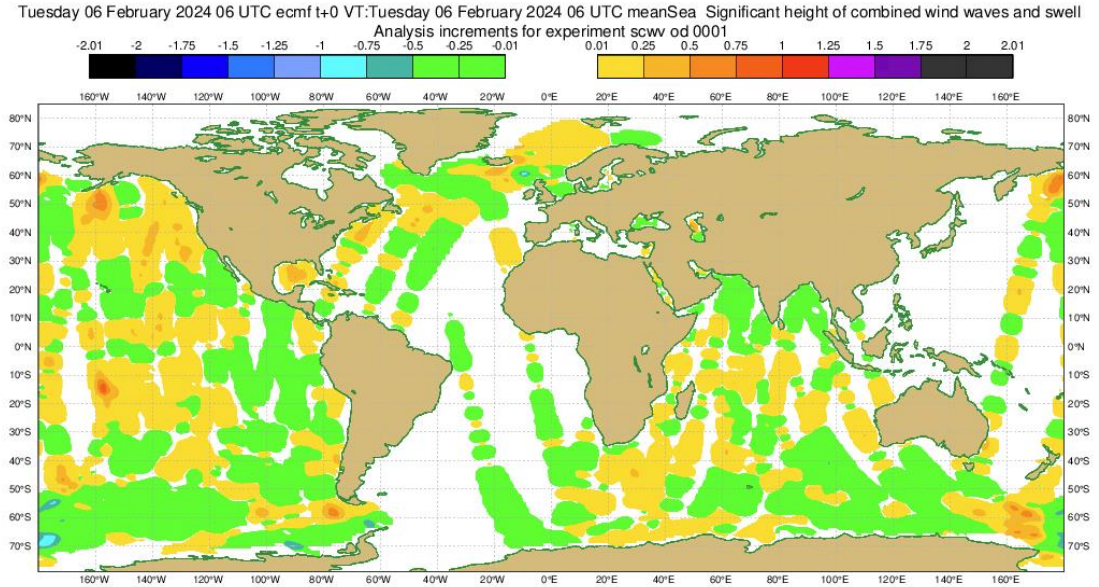
Assimilation method for SWH data:

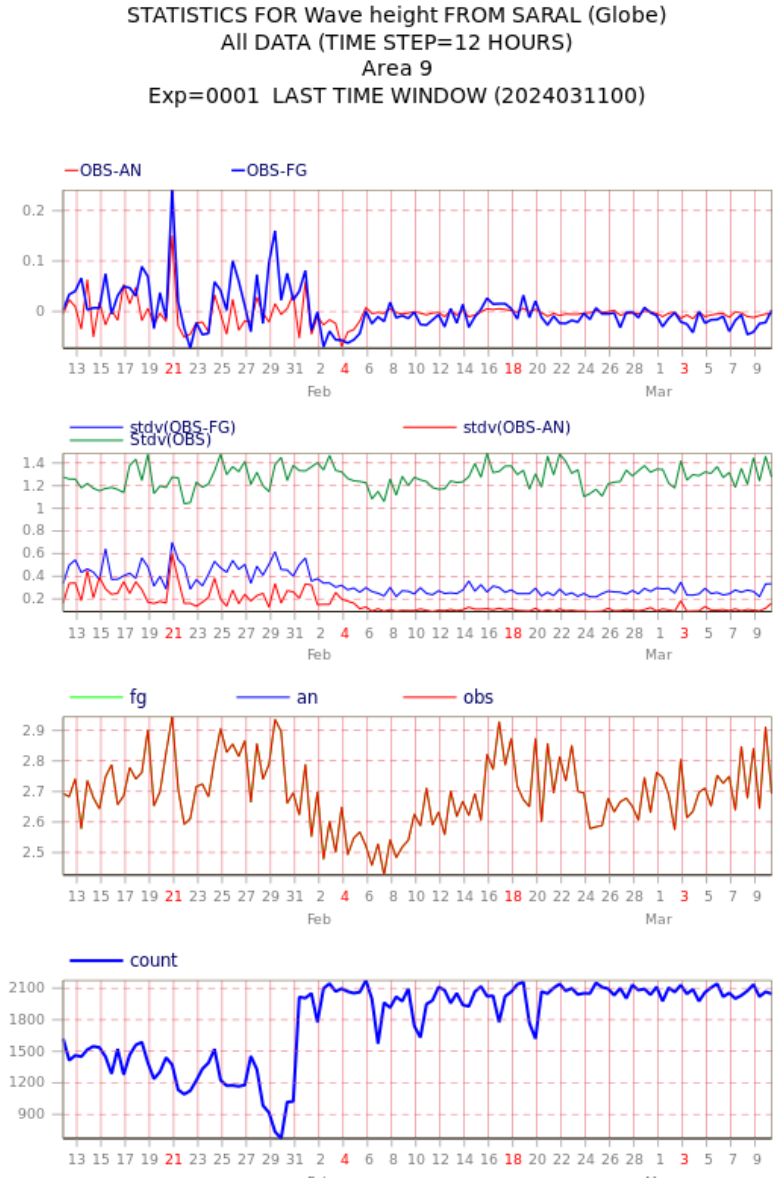
- ✓ Data are subjected to a quality control process (inc. super-obbing).
- ✓ Bias correction is applied.
- ✓ Simple optimum interpolation (OI) scheme on SWH.
- ✓ The SWH analysis increments ➔ wave spectrum adjustments…

Operational Assimilation of SWH (wave model)

Analysis increments from the 6 boundary conditions suite from 5 February 2024 (top) and 6 February 2024 (bottom).







Instrument synergies

Altimeter SWH data available from five satellites – nice synergy!
Plot shows random error reduction of SWH compared to model only.

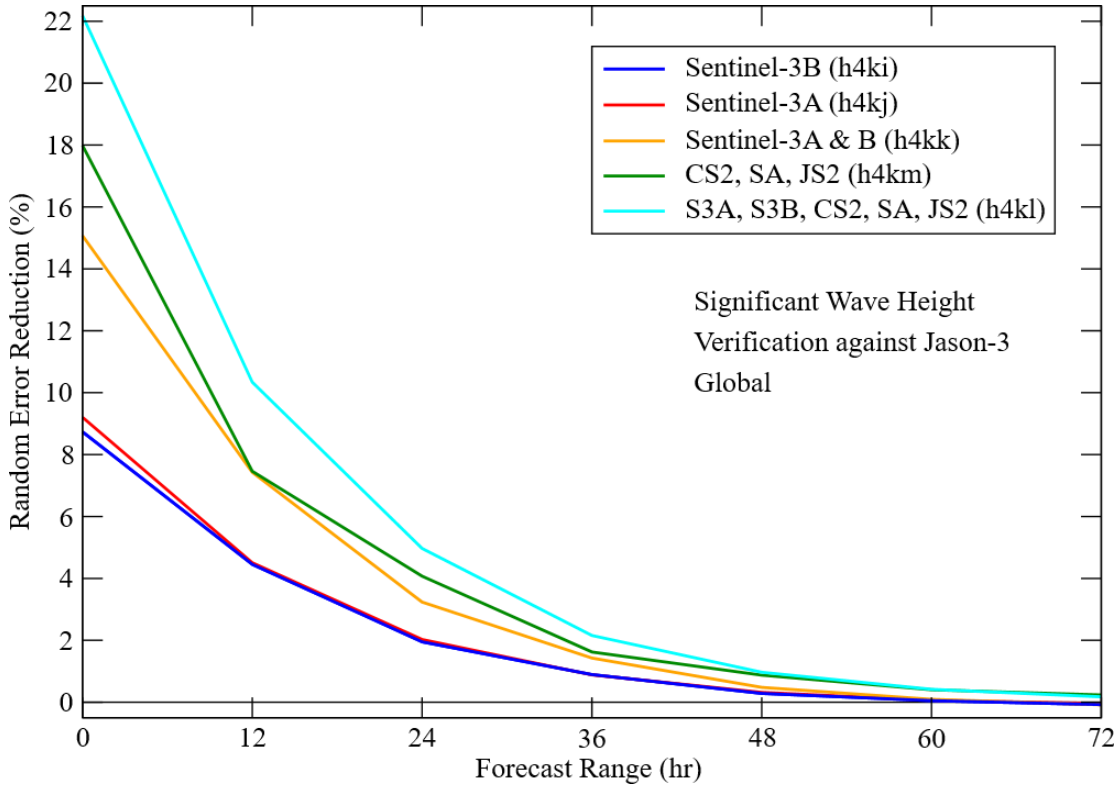
All the five altimeter instruments listed below

Cryosat-2 (CS2)+
SARAL AltiKa (SA)+
Jason-2 (J2)

Sentinel-3A&B

Sentinel-3A

Sentinel-3B



Altimeter Concluding remarks

ECMWF has a long experience with altimetry in the wave model

- Available continuously from 1993 onwards:
  - ERS1/2, Envisat, Jason1/2/3, Cryosat, Saral, Sentinel-3…
  - Now with new missions: CFOSat-SWIM, Sentinel-6,…

Altimeter wind and wave data are used for:

- Data assimilation
- Error estimation
- Use in reanalyses (assimilation and validation)
- Long term assessments & climate studies
- Monitoring of model performance (inc. model resolution) & Assessment of model changes

Thanks!!!