Satellite wind information on the ocean surface: Scatterometer & Altimeter

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with contributions from Saleh Abdalla, Hao Zuo, Magdalena Balmaseda, Tony McNally, Linus Magnusson, Patrick Laloyaux, Sean Healy

(andrej67/iStock/Getty Images)

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)

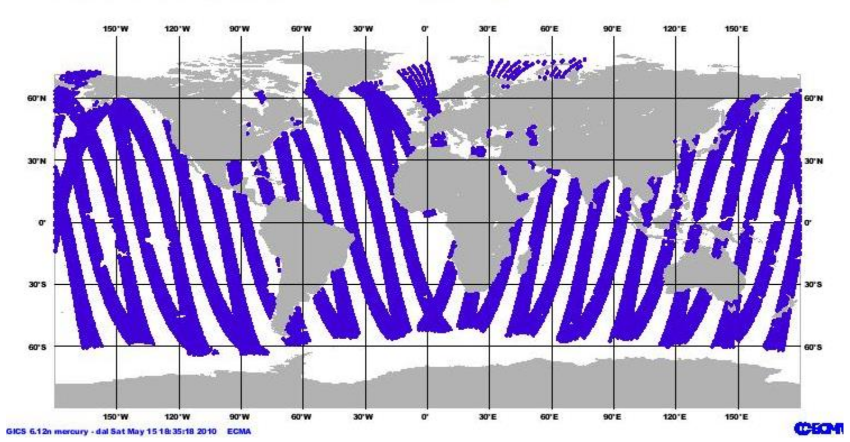
- Altimeter principles
- Use of altimeter data in the wave and ocean models
- Altimeter data impacts

Why is Scatterometer important?

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

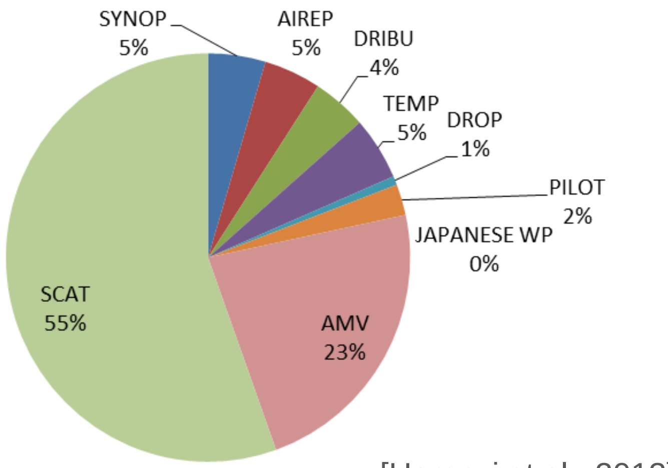
Ocean surface winds:

- 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 %)

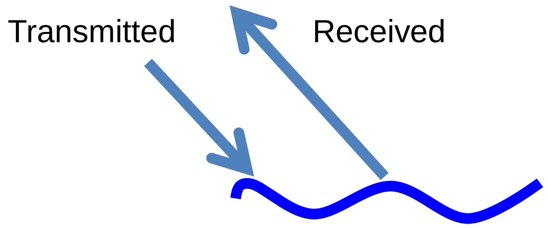


[Horanyi et al., 2013]

Scatterometer

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

- Day and night acquisition
- Not affected by clouds



$$\sigma \sim \frac{\text{received power}}{\text{transmitted power}}$$

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

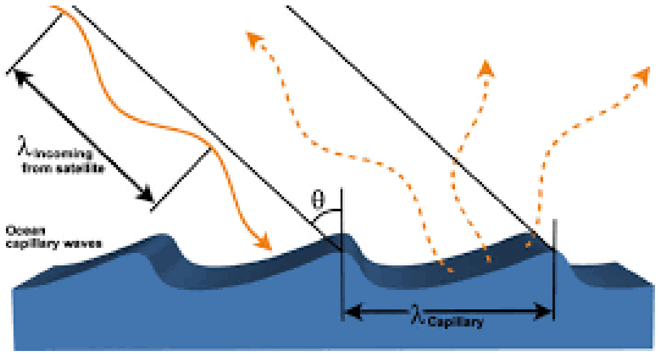
- Surface wind (ocean)
- Soil moisture (land)
- Ice age (ice)

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



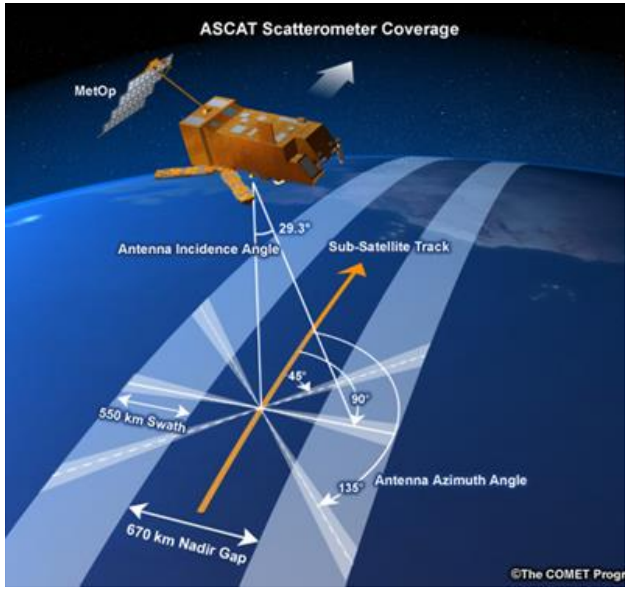
The amount of backscatter depends on:

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

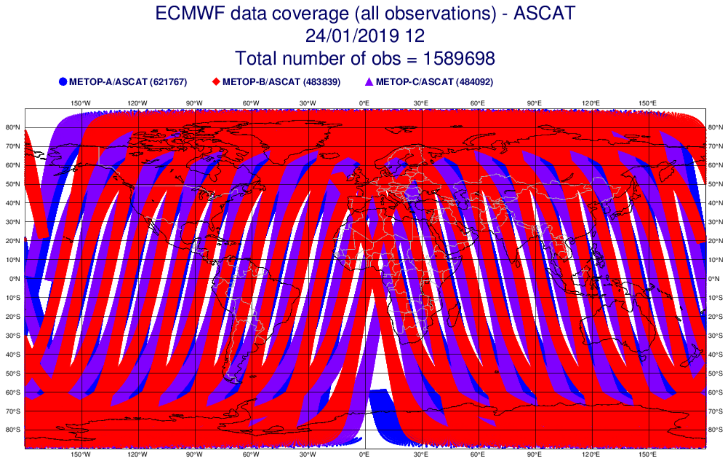
Backscatter *highly* depends on:
- Incidence angle (largest sensitivity to changes in winds between 30 and 60 deg)
- Wind speed
- Relative direction between the surface wind and look angle

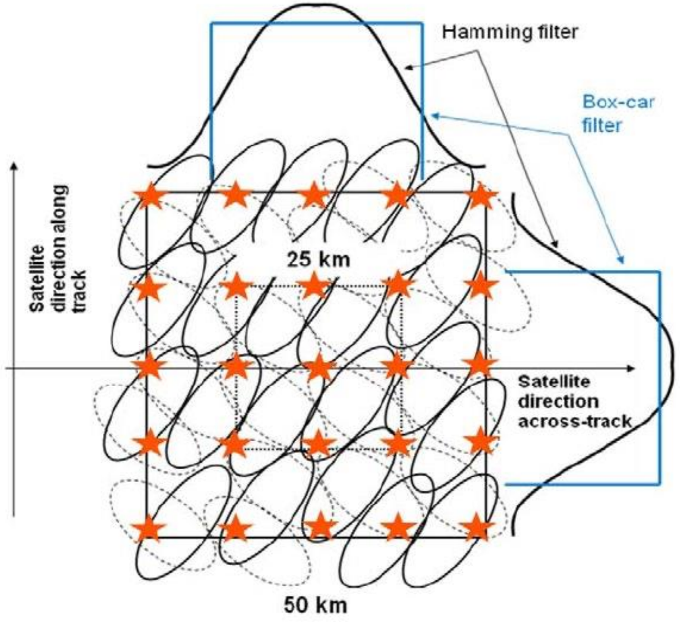
C- band scatterometers (Fan beam)

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 a 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





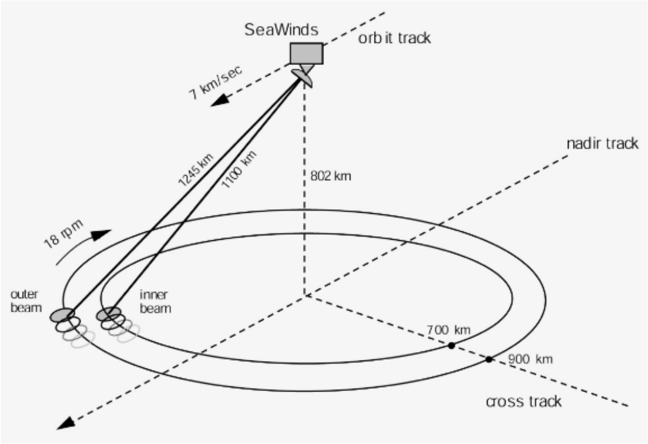
[Eumetsat]

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

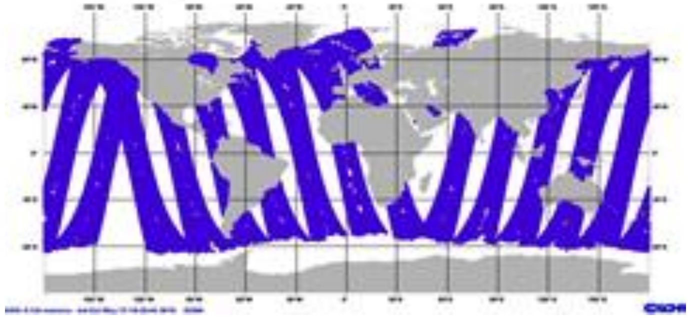
  - f~13.5 GHz (λ ~ 2.1 cm)
  - Two rotating pencil-beams (4 look angles)



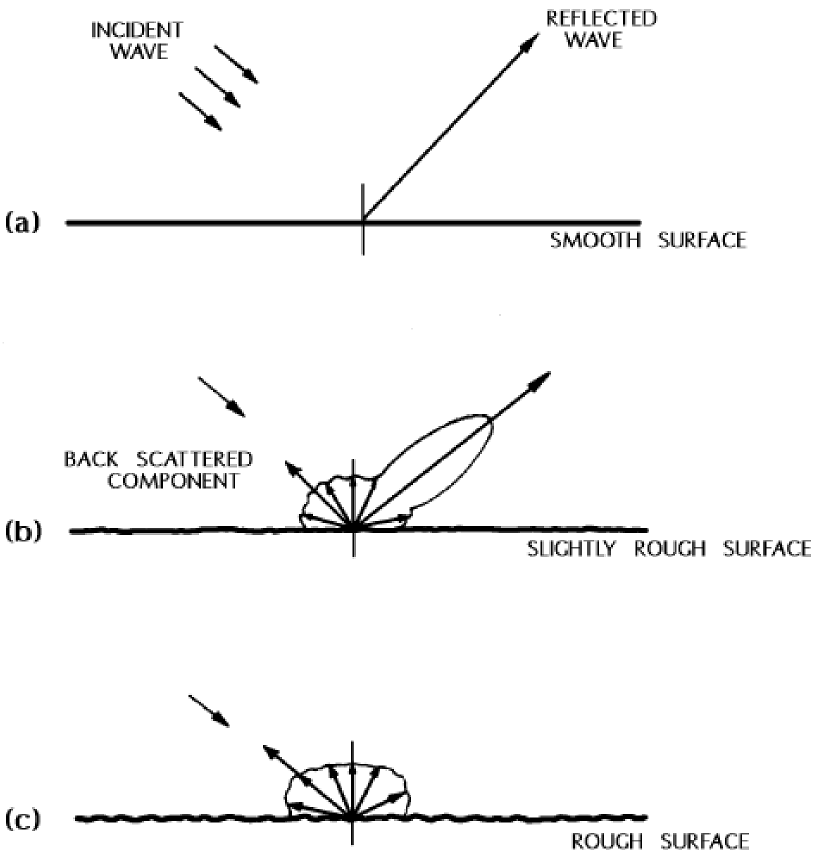
Pros and cons:

- ✓ 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.

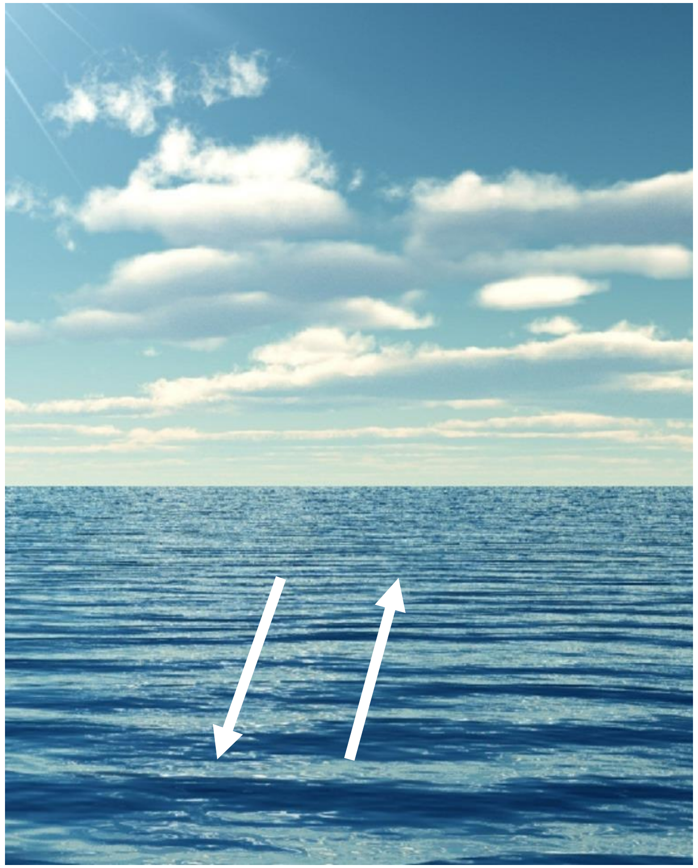
OSCAT daily coverage



Dependency of the backscatter on... Wind speed

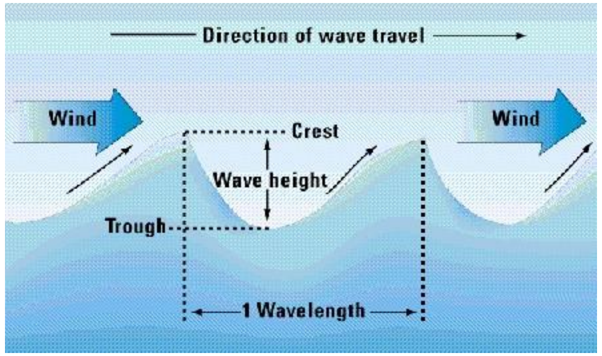


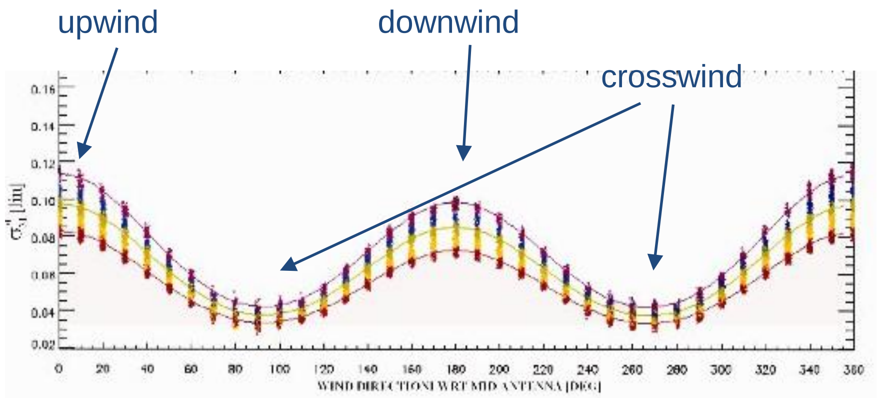
Dependency of the backscatter on... Wind direction



upwind

downwind





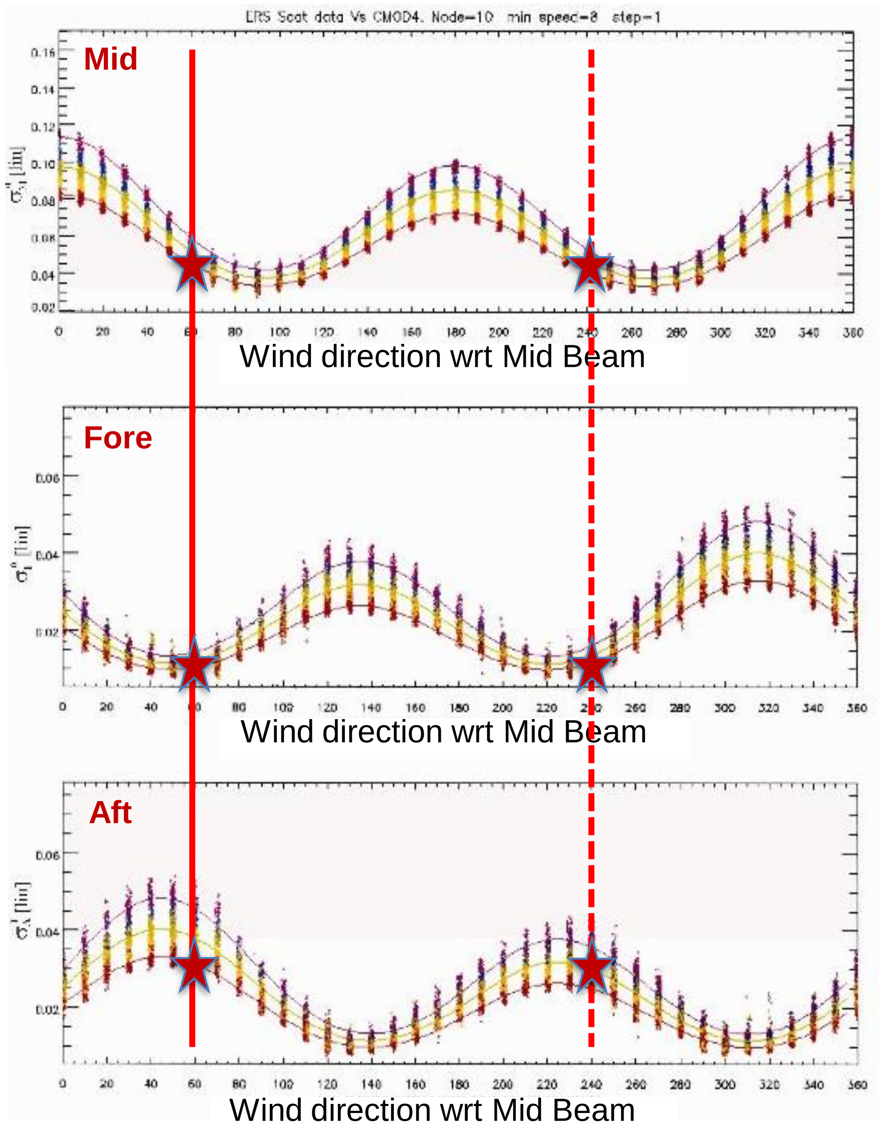
Wind direction wrt Beam

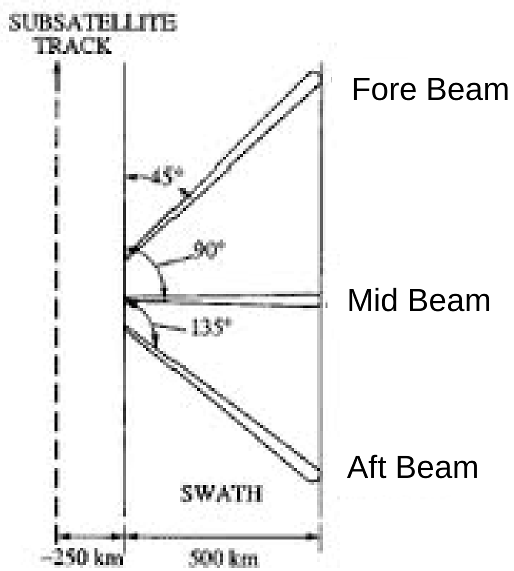
- Asymmetry Upwind – Downwind (particularly small)
- Asymmetry Upwind – Crosswind

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

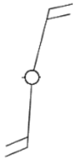
Dependency of the backscatter on... Wind direction

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

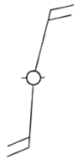




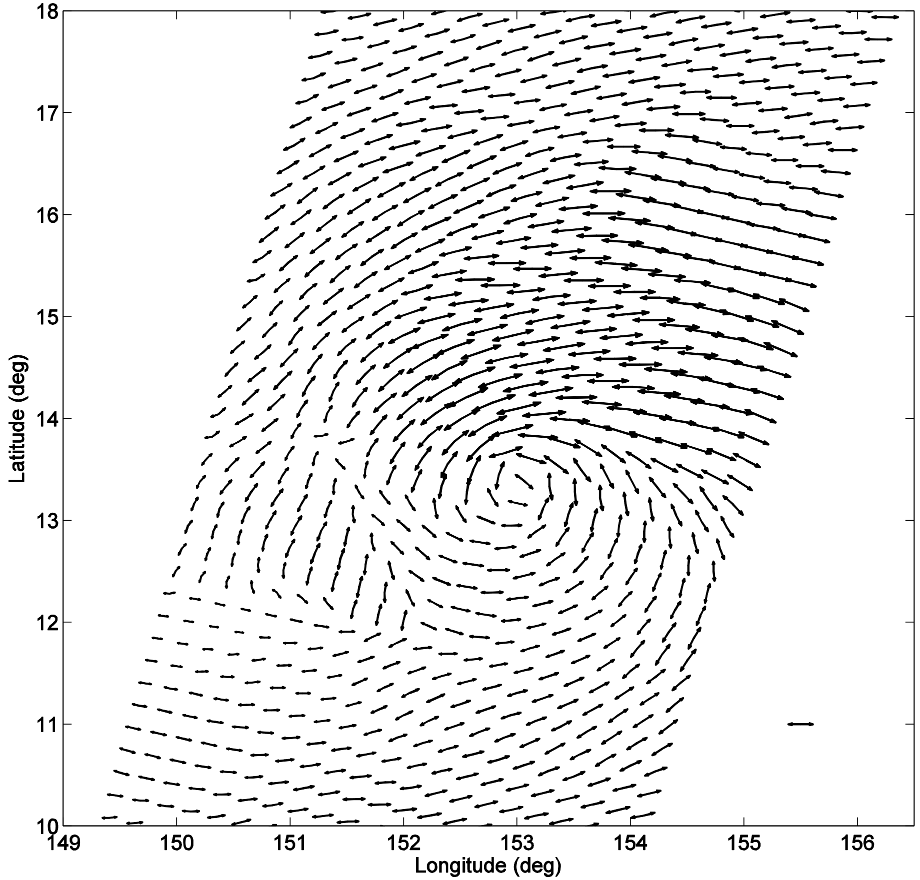
C-band SCAT geometry



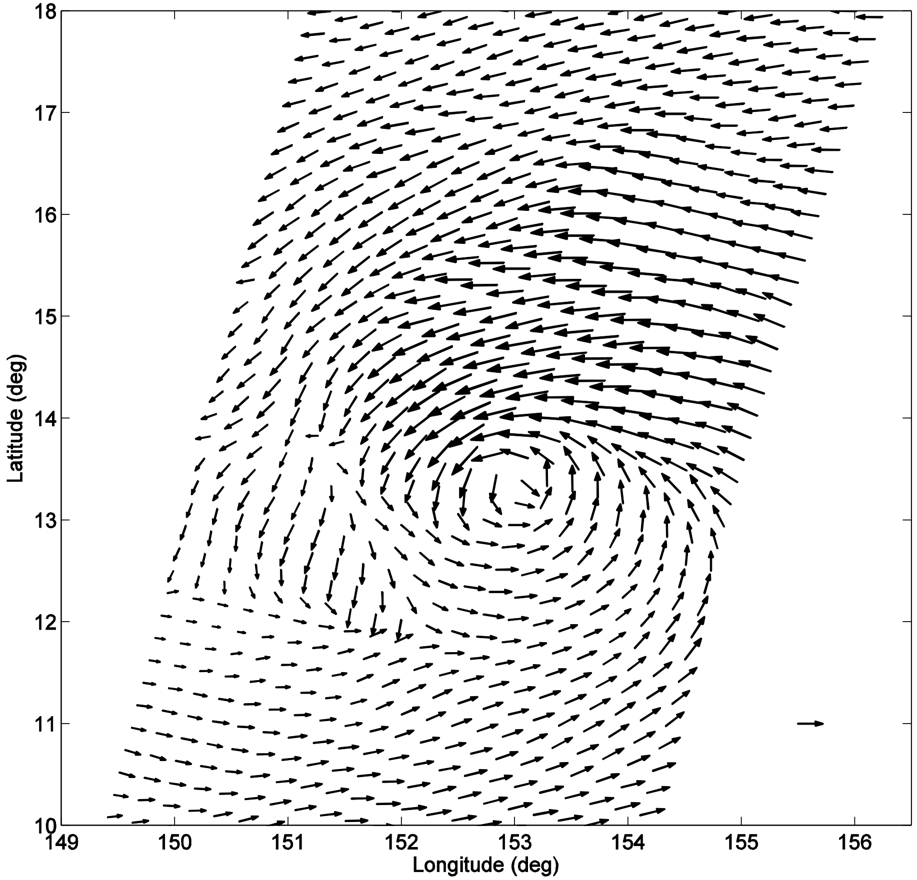
Wind Direction Ambiguity removal



- 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

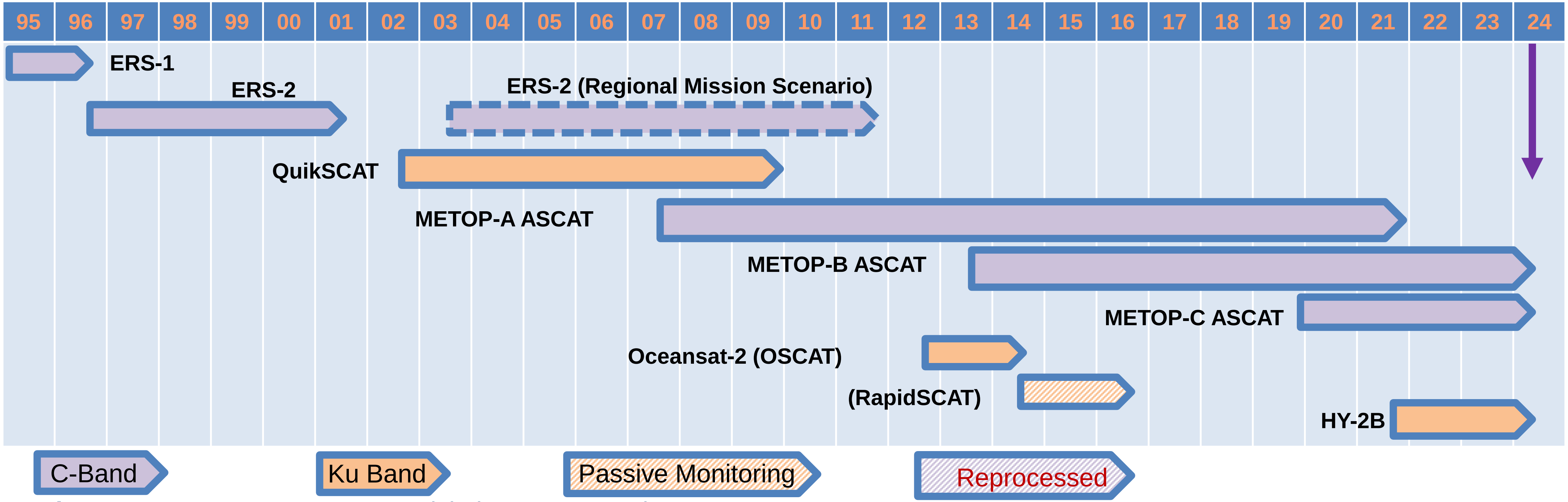
$$\sigma_0 = GMF(U_{10N}, \phi, \theta, p, \lambda)$$

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

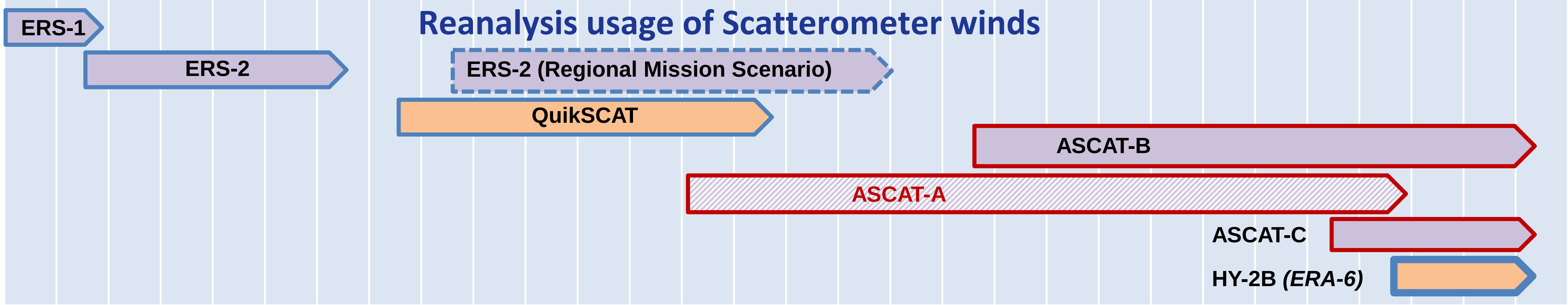
Operational usage of scatterometer winds at ECMWF



Under assessment: *HY-2C, HY-2D (aiming at Q2 2024)*

Waiting for data to evaluate: *Oceansat-3 (Nov '22), WindRad (July '21)*

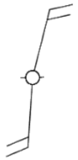
Reanalysis usage of Scatterometer winds



ASCAT-A 2nd reprocessed campaign will be assessed in the next months to be used in ERA6

Scatterometer winds assimilation strategy

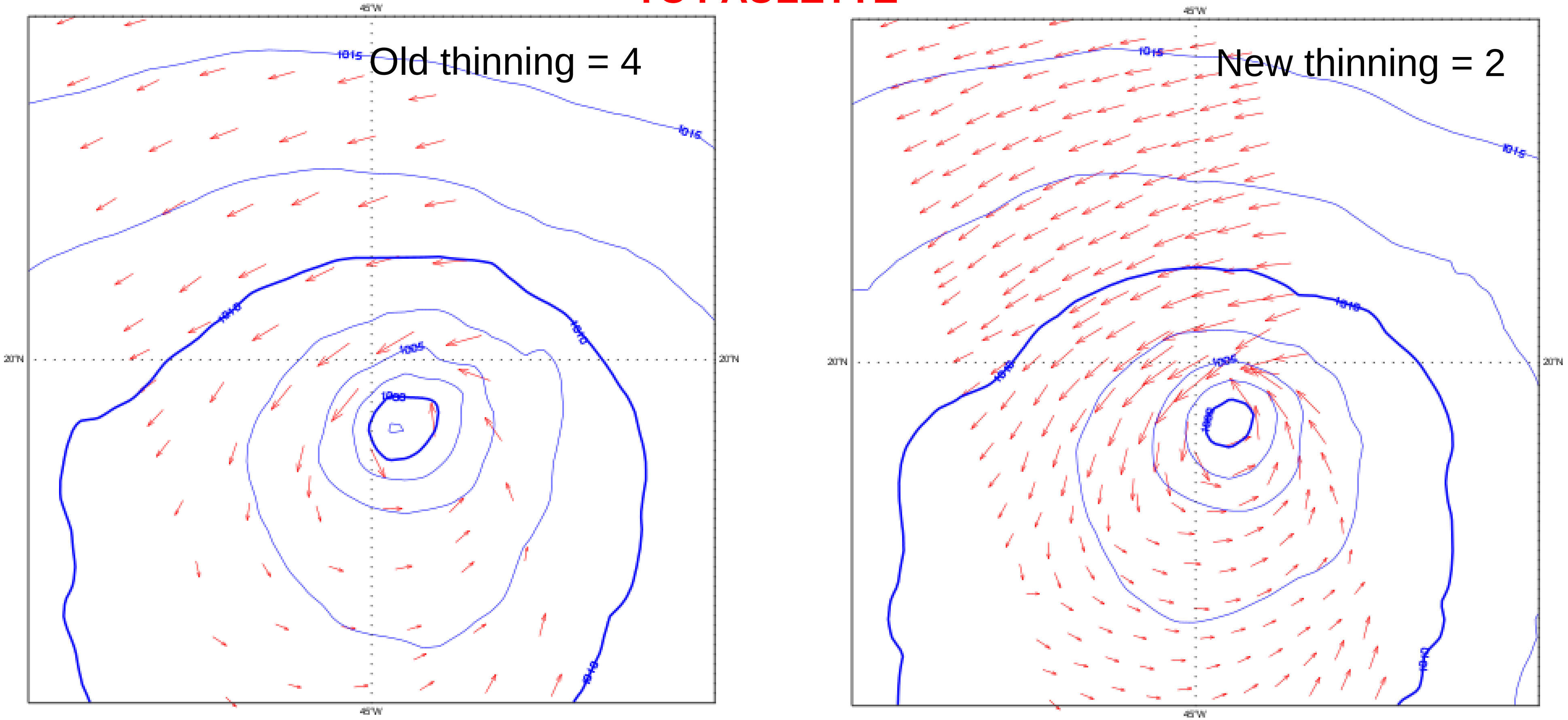
	C-band	Ku-Band
Resolution	25 km	50 km
σ_0 bias correction	√	-
Wind Inversion	ECMWF	KNMI
Wind Speed bias correction	√	√
QC – (land contamination, sea ice check)	√	√
Rain flag check	-	√
Thinning	50 km	-
Maximum wind speed assimilated	35 m/s	25 m/s
Assigned observation error	2.25 m/s	2 m/s
4D-Var	2 solutions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



ASCAT reduced thinning

A reduced thinning provides more information in more dynamic cases like tropical cyclones (TCs).
Thinning 2 is in operations since Q2 2023.
When increasing the observations we need to inflate the Observation Error (old OE=1.5 m/s, new OE=2.25 m/s).

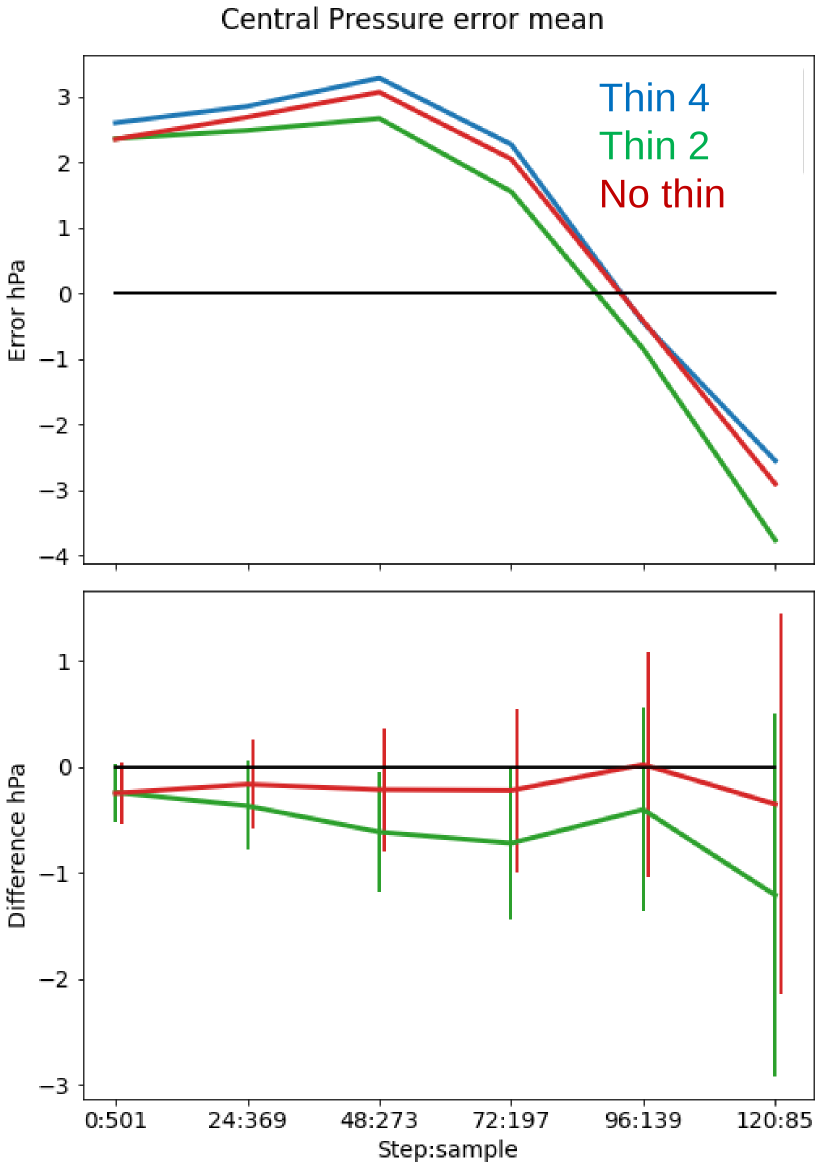
TC PAULETTE

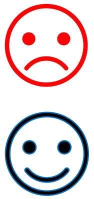


Contour line = AN mslp

IMPACT ON Tropical Cyclones

3 months experiments (20190815 – 20191118) at Tco1279





Global statistics over 3 months of:

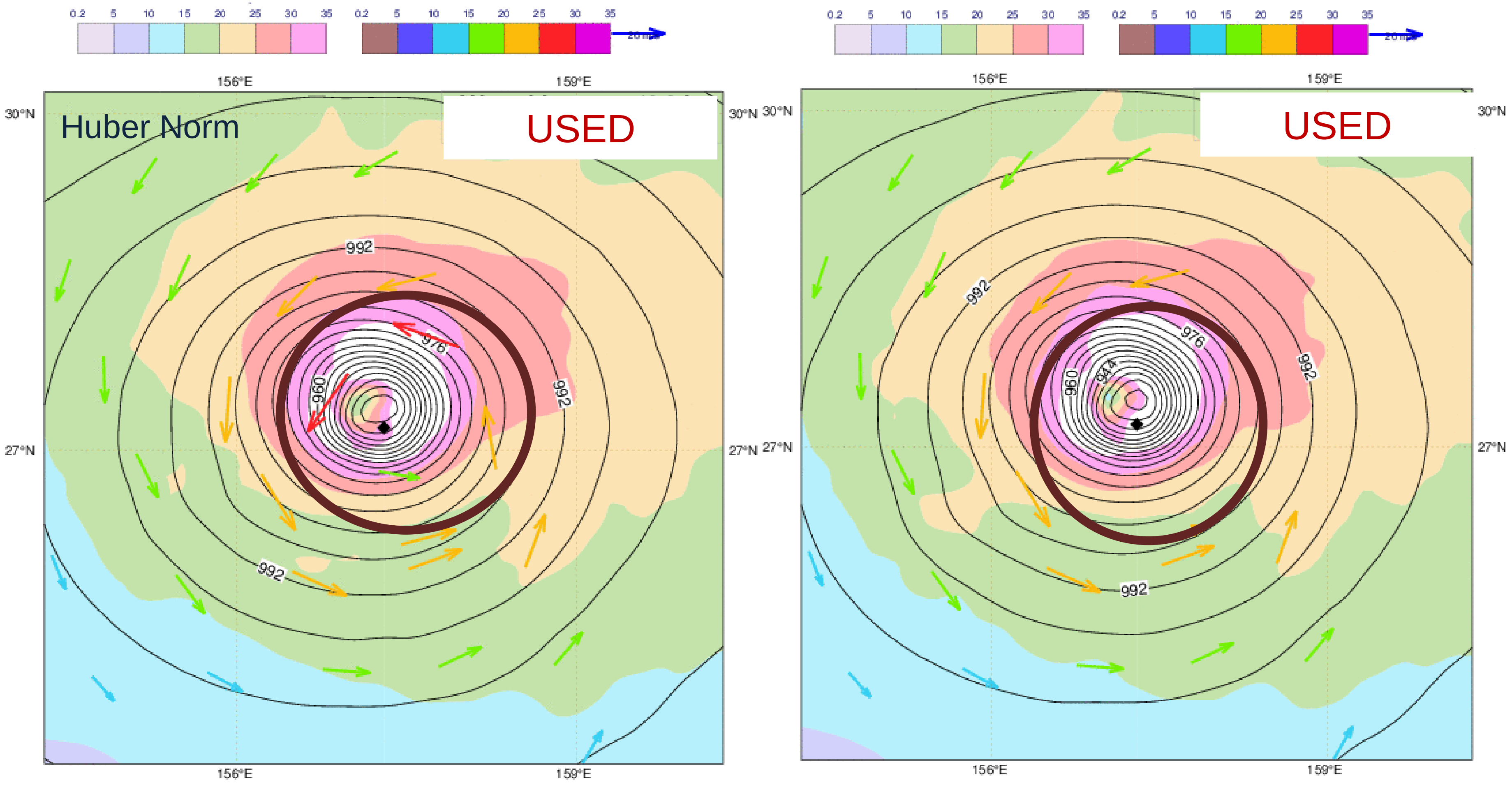
- Slightly improved mean absolute error for position and intensity
- Reduced bias in intensity

TC QC issues

TC KILO – 2015090812 ASCAT-A Observations

Less observations due to:

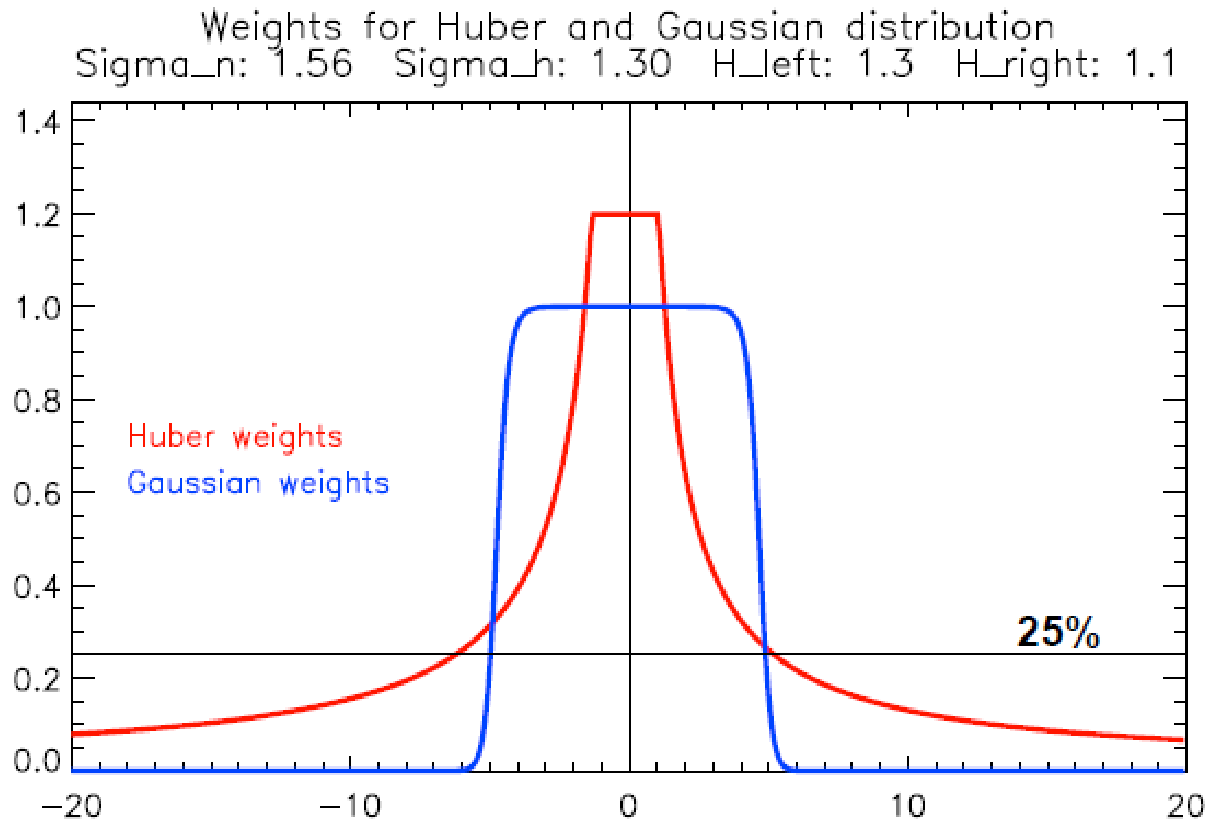
- Thinning
- VarQC



VarQC

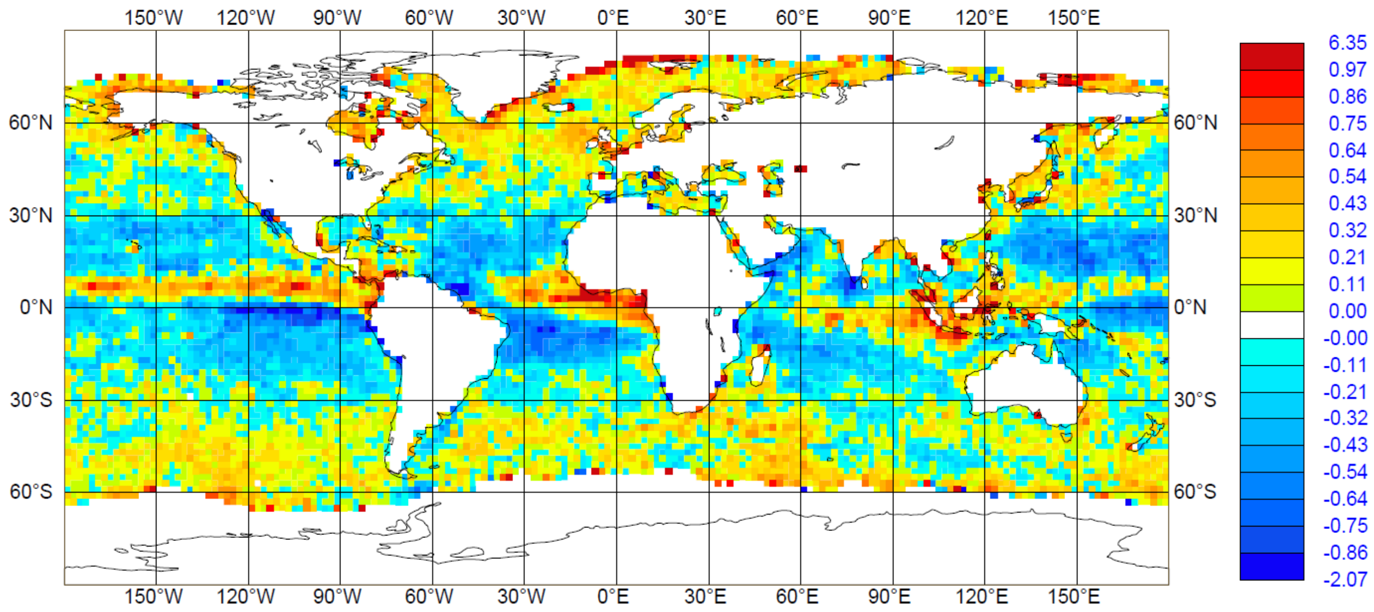
Observation weight: VarQC & Huber Norm

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)



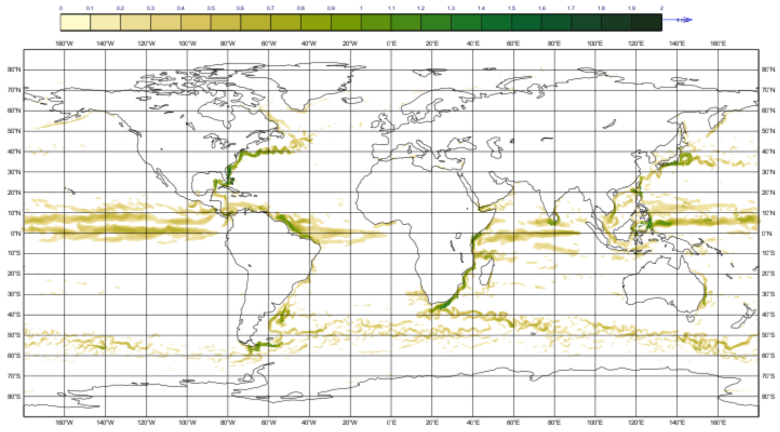
Background Departure

ASCAT-A Wind speed O-B

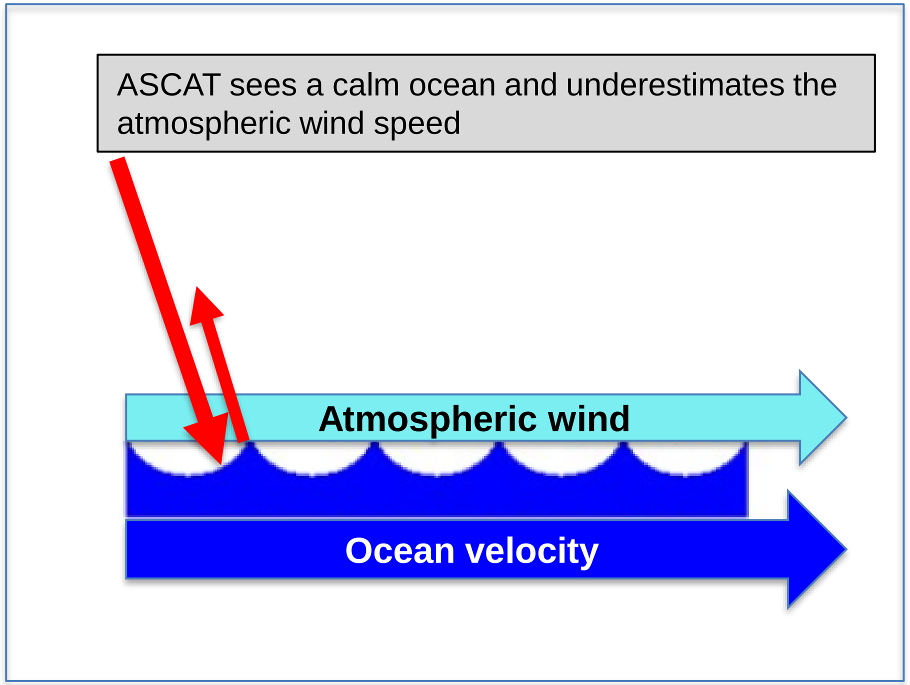


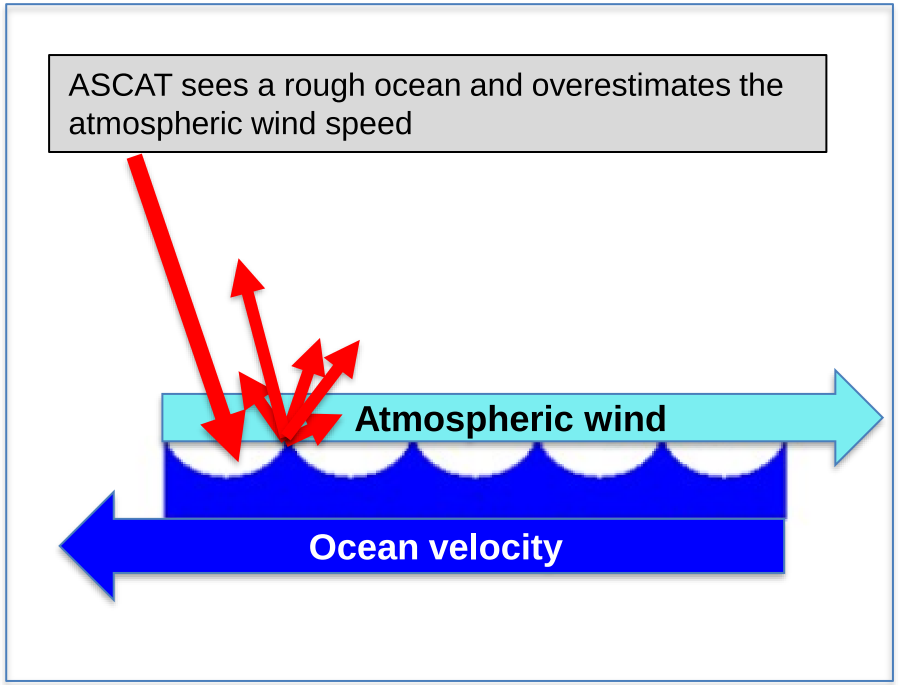
Wind speed bias in the Tropics: also due to Ocean Current?

Mean ocean currents from OCEAN5 from 20181101 to 20190129



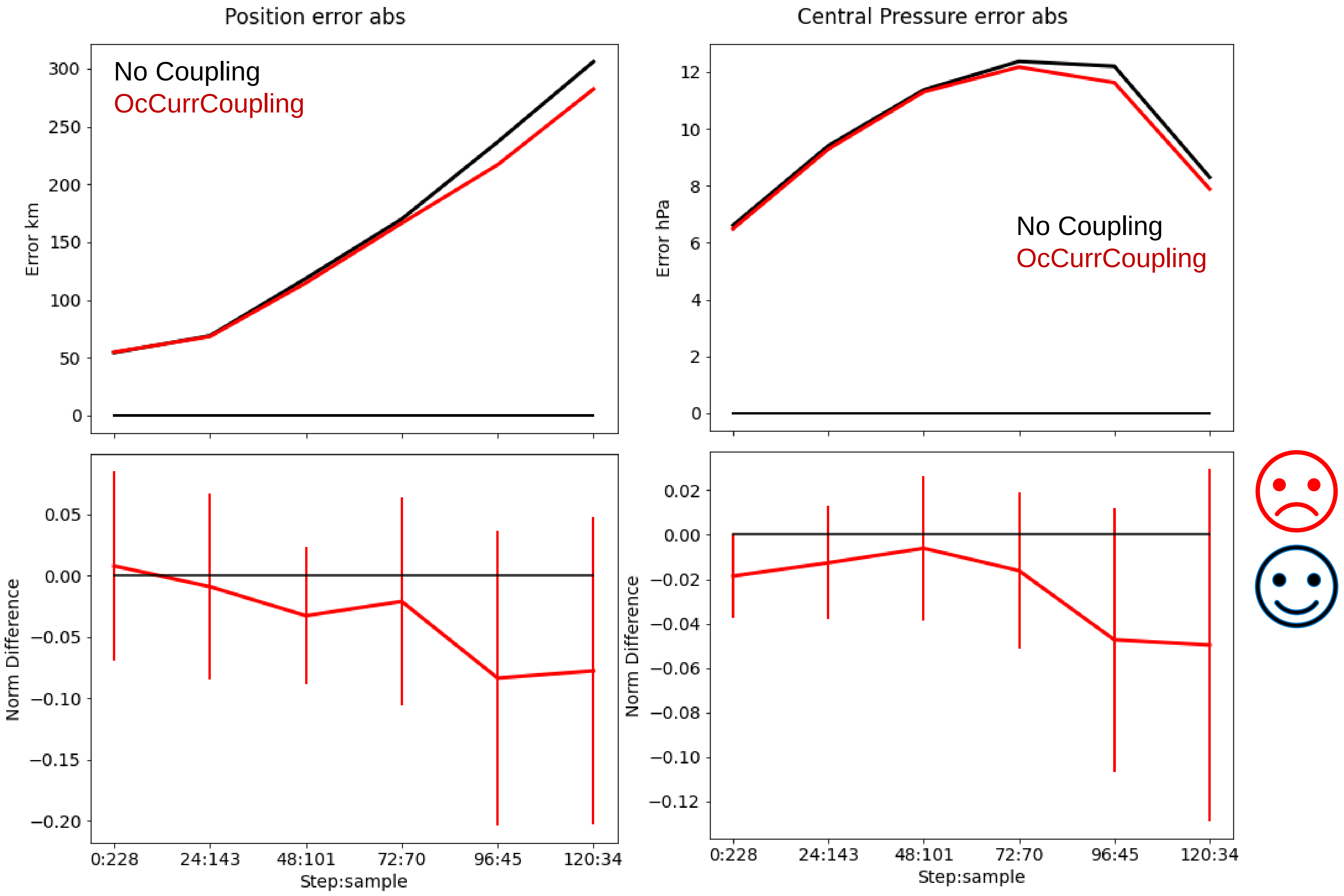
Scatterometer and Ocean Currents





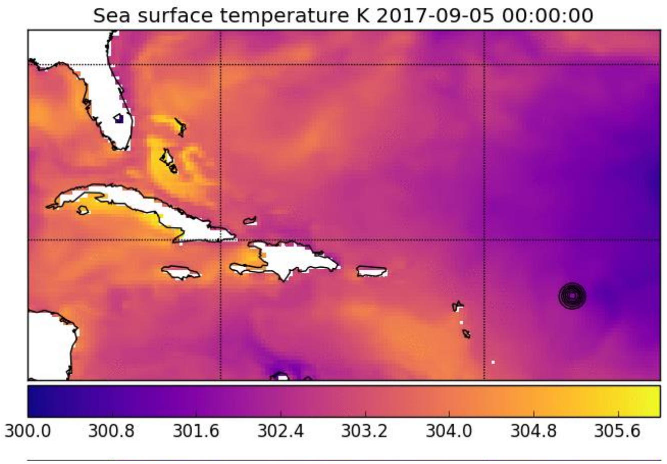
Scatterometer and Ocean Currents

Impact on TC - Preliminary results in weakly coupled DA



What about the impact of Scatterometer on the ocean?

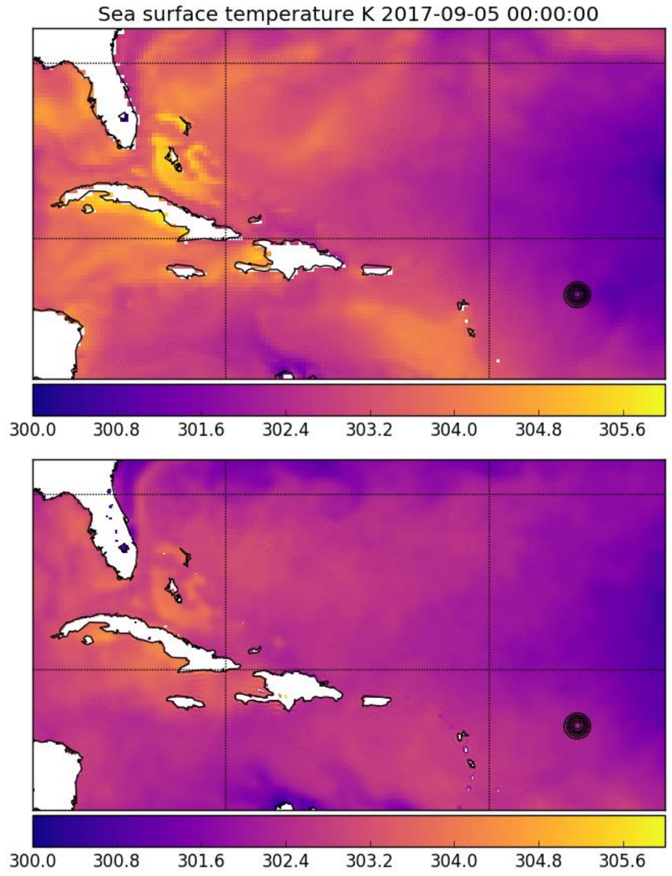
Coupled Data Assimilation (CDA)



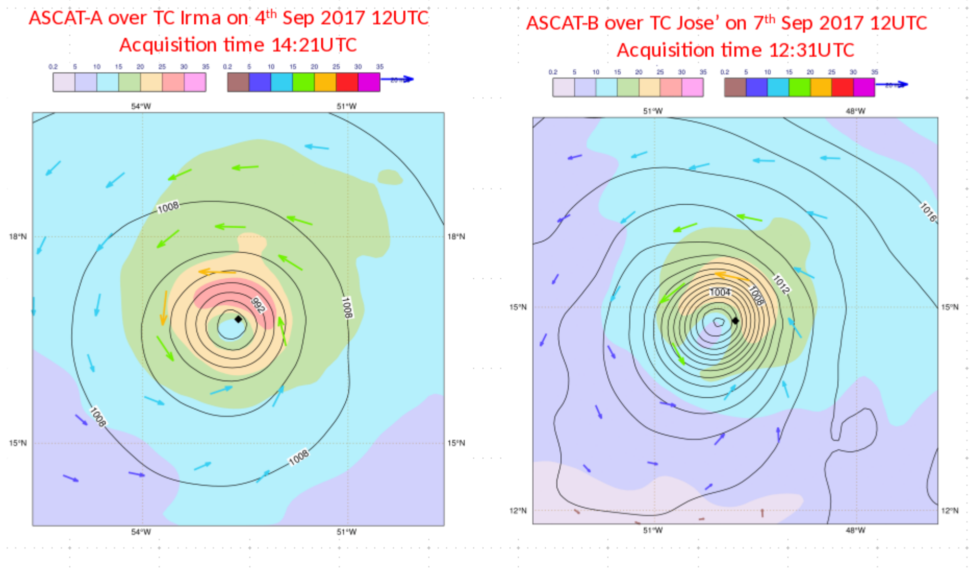
In the **coupled assimilation** the SST shows a clear and immediate impact on SST of the storm winds mixing the ocean (cold wake) and the storm's arrival in the Caribbean damping the usual pronounced diurnal cycle in the SST

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?



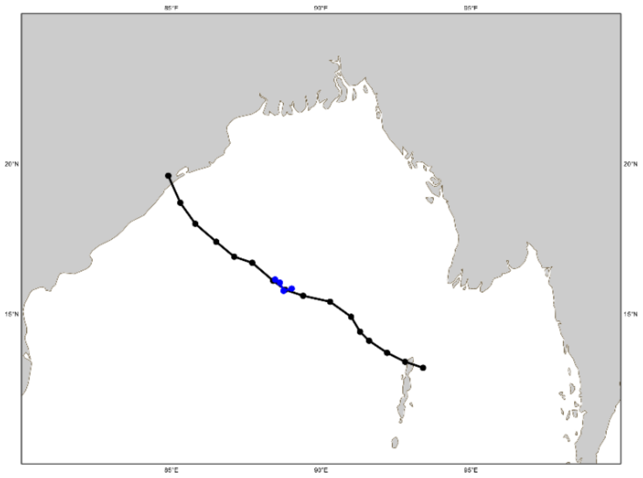
In CDA ASCAT gives SST information below Tropical Cyclones

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

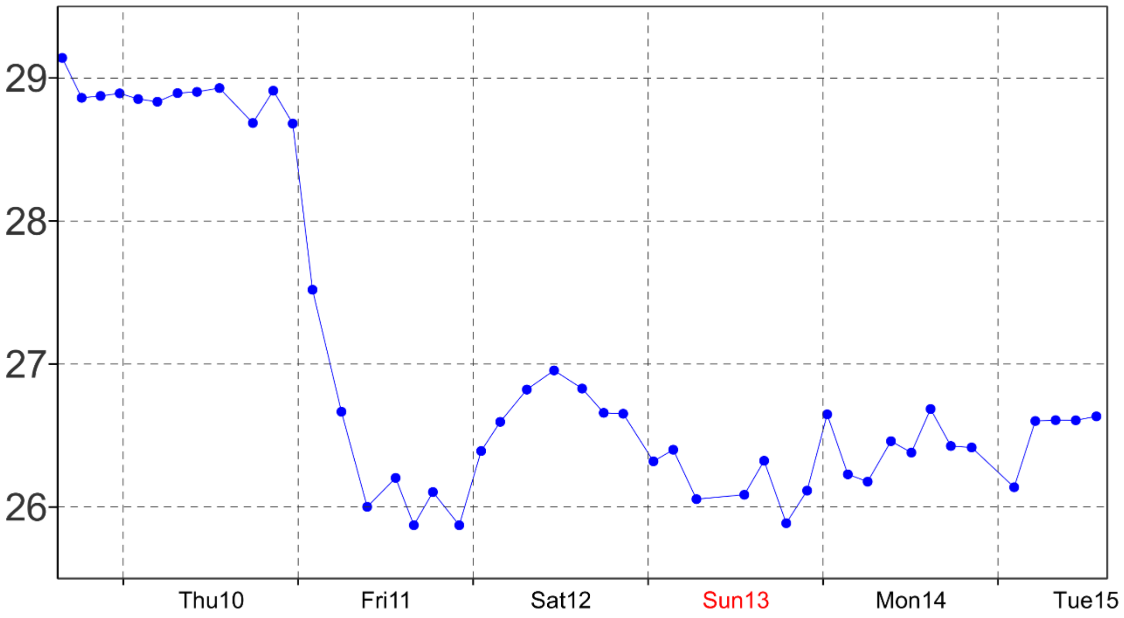
Coupled Data Assimilation (CDA)

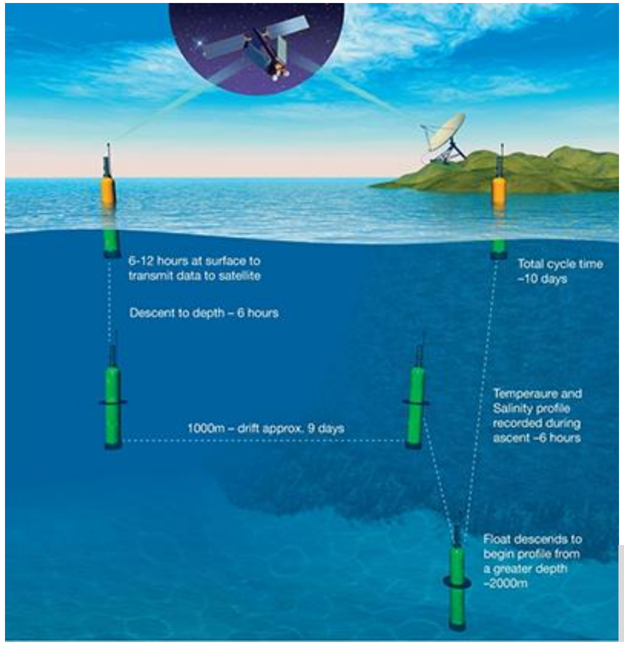


Focus on a specific weather event:

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

Temperature measurements at 40-meter depth



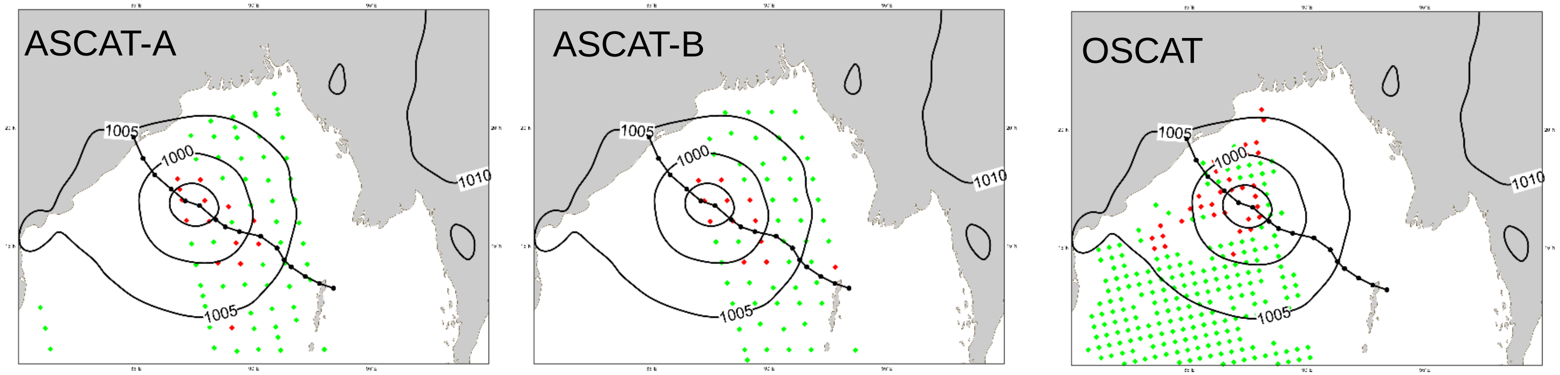


Impact of scatterometer surface wind data in the ECMWF coupled assimilation system
P. Laloyaux, J-N Thépaut and D. Dee. MWR, 2016

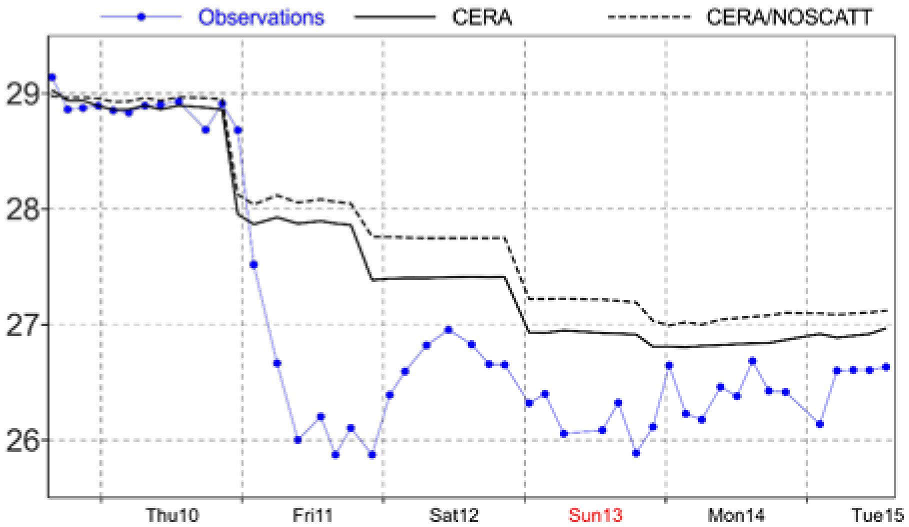
Impact of scatterometer winds …on the ocean parameters

TC Phailin

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

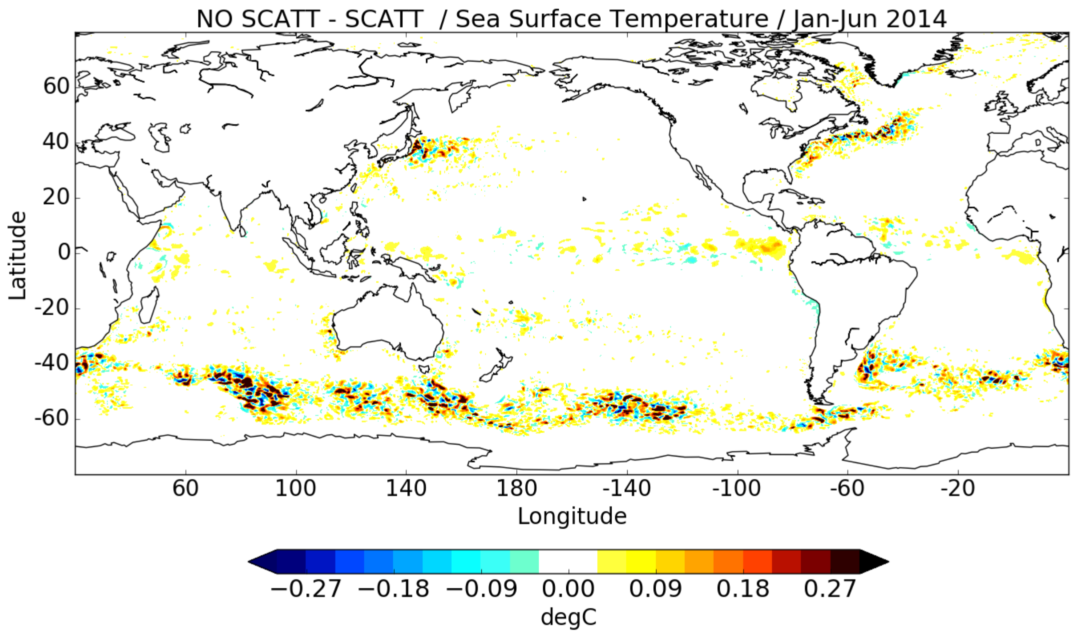


Ocean temperature analysis at 40-meter depth (scatterometer data are assimilated)

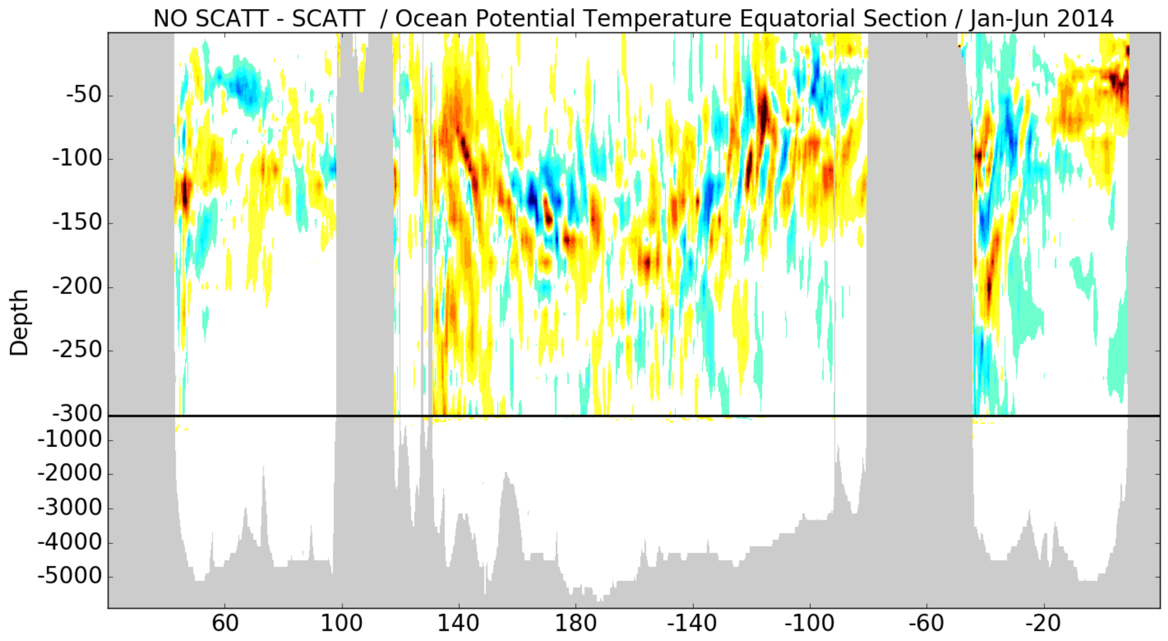


Coupled analysis with Scatterometer winds is closer to the observations with a stronger cold wake

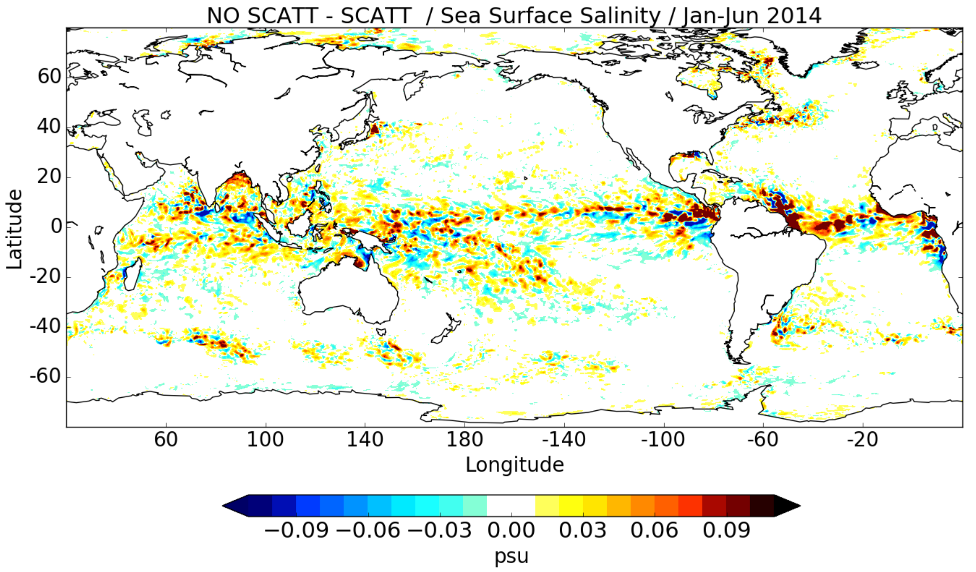
Impact of Scatterometer on Ocean Temperature



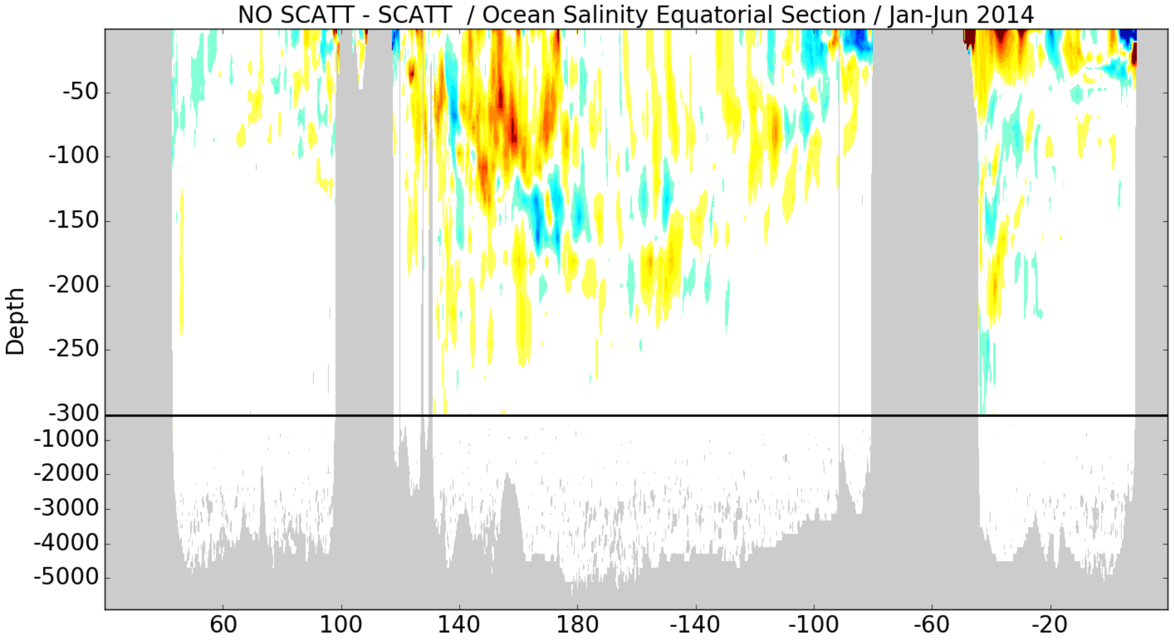
No SCATT – SCATT



Impact of Scatterometer on Ocean Salinity



No SCATT – SCATT



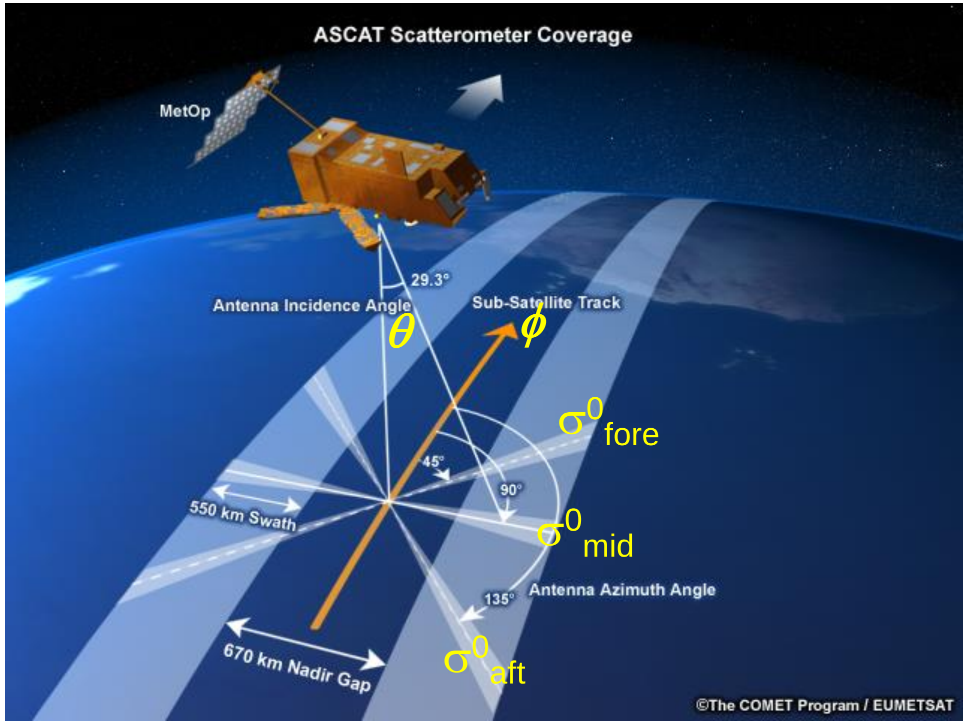
Area of research: *L2 wind products vs backscatter*

(in the framework of a EUMETSAT project)

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

σ^0_{fore}, σ^0_{mid}, σ^0_{aft}
θ_{fore}, θ_{mid}, θ_{aft}, ϕ

$\xrightarrow{\text{GMF}}$ U_{10N}, V_{10N} $\rightarrow$ **IFS/4DVar**



ECMWF research project testing the assimilation of backscatter

σ^0_{fore}, σ^0_{mid}, σ^0_{aft}
θ_{fore}, θ_{mid}, θ_{aft}, ϕ

- **air density,**
- **ocean currents,**
- **precipitation,**
- **… etc.**

ML $\rightarrow$ **IFS/4DVar**

Direct assimilation of Scatterometer Backscatter over the ocean

Objective:

- Revisit the direct assimilation of scatterometer backscatter triplets in the ECMWF 4D-Var
- The idea was explored in the early 2000’s but never taken further

Activities:

- ASCAT backscatter (sigma0) observation operator (+ tangent linear and Adjoint) to simulate backscatter using IFS model fields
- Use of Artificial Neural Network (ANN): advantage of flexibility in adding new parameters in the ObsOP
- Run impact experiments to compare the L2 winds versus the L1 backscatter impact

Procedure for ANN training and deployment

Training

Data covering a given time period (we used 1 year)

(+ Scat geometry: incidence angle and azimuth angle)*

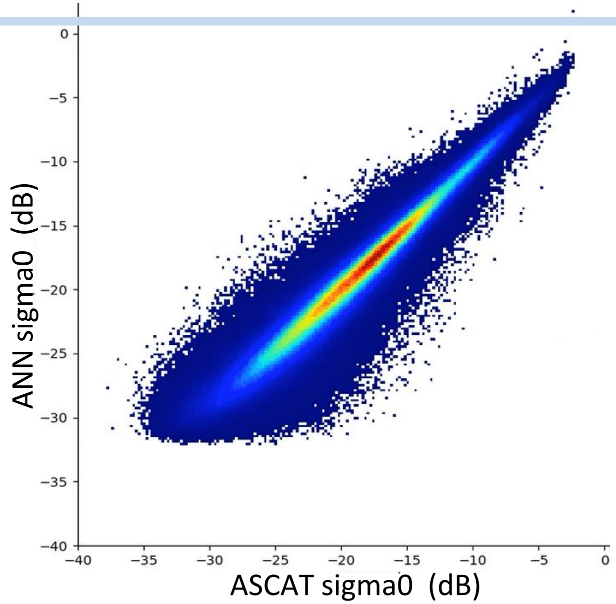
Model wind*
ASCAT Sigma0
ANN
ANN GMF

Deployment = Independent validation

Data covering another time period (1 year) or for another instrument.

Model wind*
ANN GMF
ANN Sigma0
ASCAT Sigma0

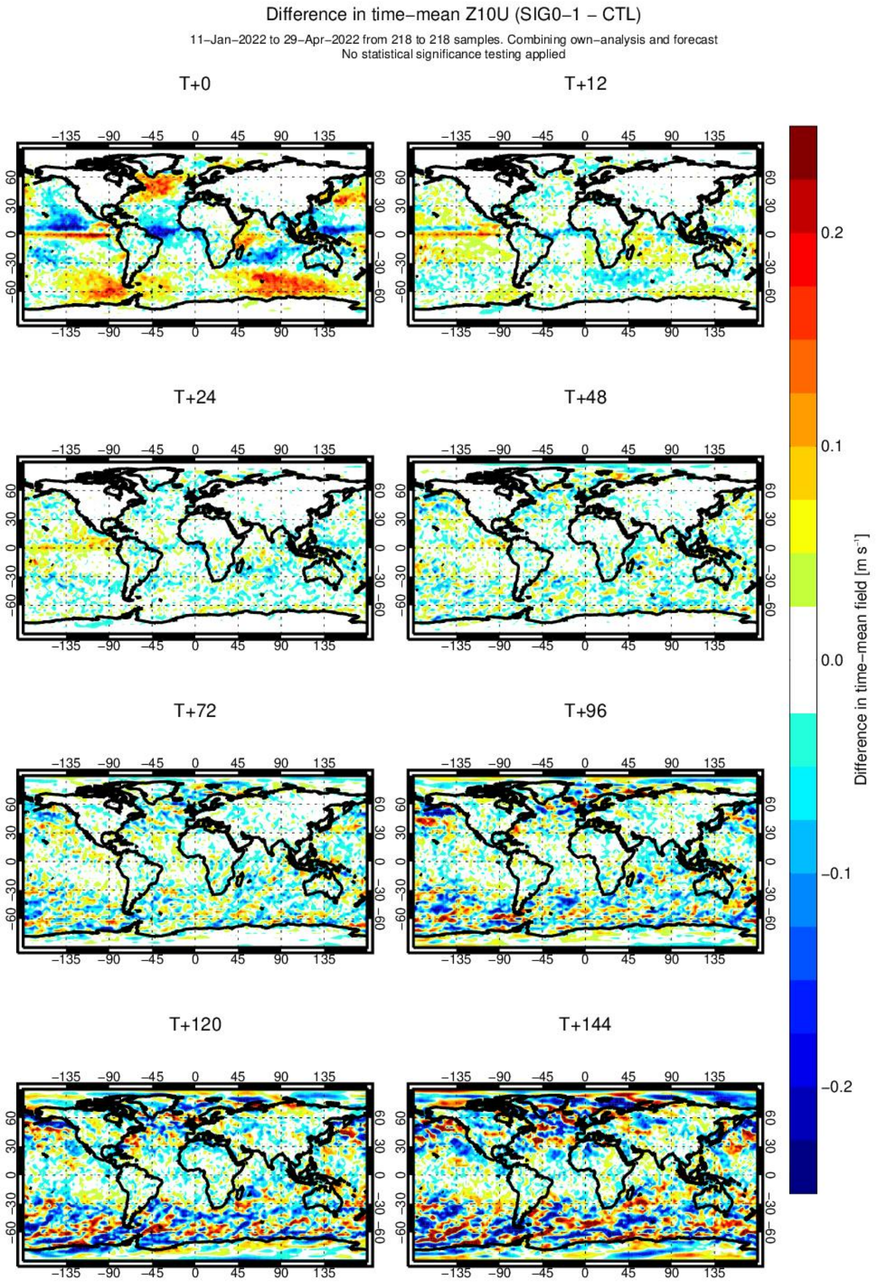
(+ Scat geometry incidence angle and azimuth angle)*



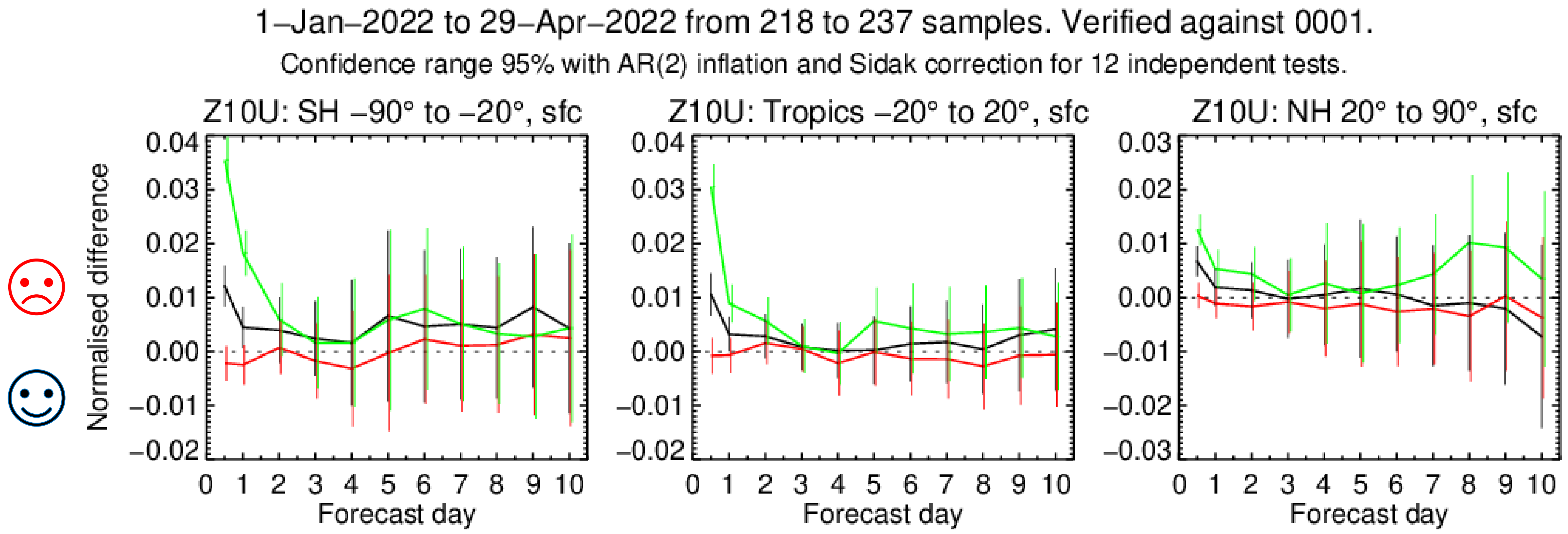
ECMWF

U10m
Mean state changes

SCAT SIGMA0 vs SCAT U/V



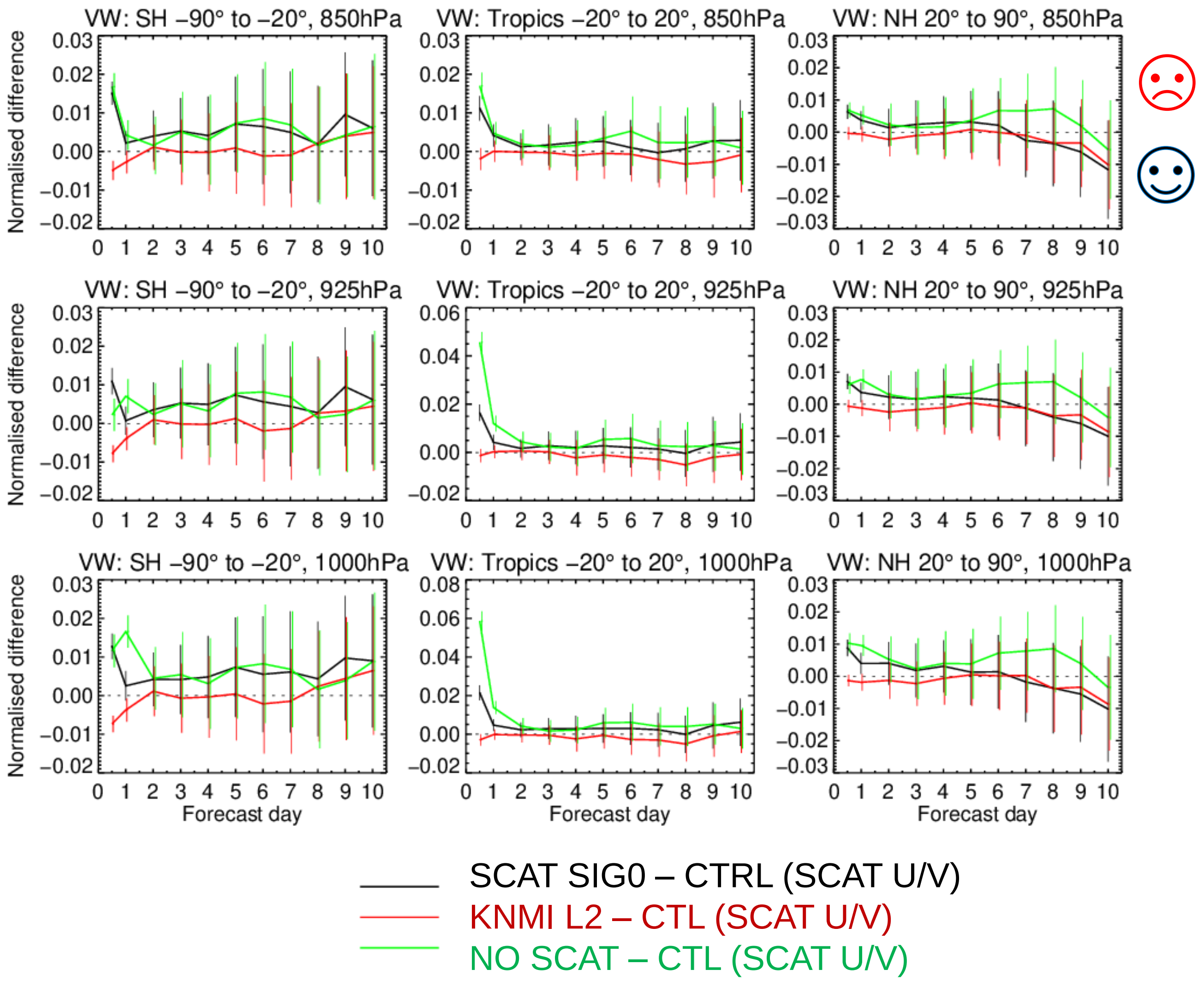
Impact on geopotential height forecast error
verified vs operational analyses (CTL == what we do now – ASCAT U/V)



SCAT SIG0 – CTRL (SCAT U/V)
KNMI L2 – CTL (SCAT U/V)
NO SCAT – CTL (SCAT U/V)

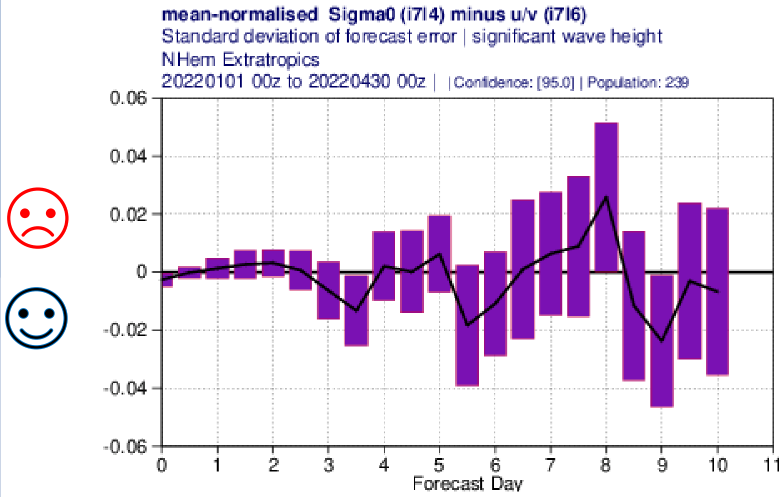
Impact on vector winds forecast error
verified vs operational analyses (CTL == what we do now – ASCAT U/V)

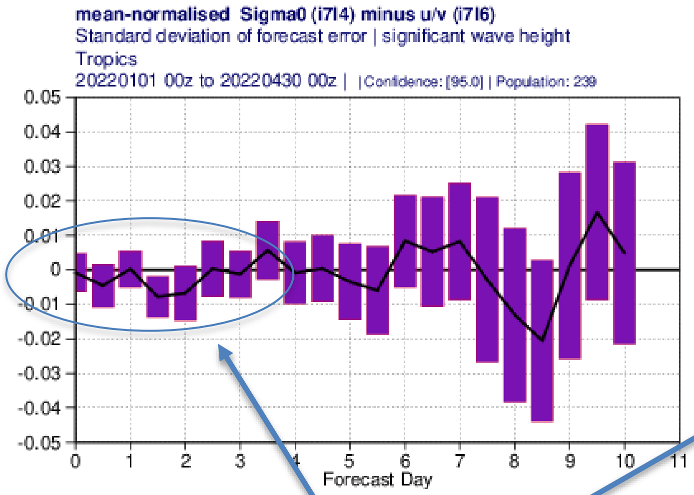
- Sigma0 assimilation slightly increases the vector wind forecast error compared to the assimilation of U/V
- KNMI winds scores slightly better than CTL (but they have seen an ECMWF forecast in the 2D-Var)
- No SCAT is clearly degrading the forecast

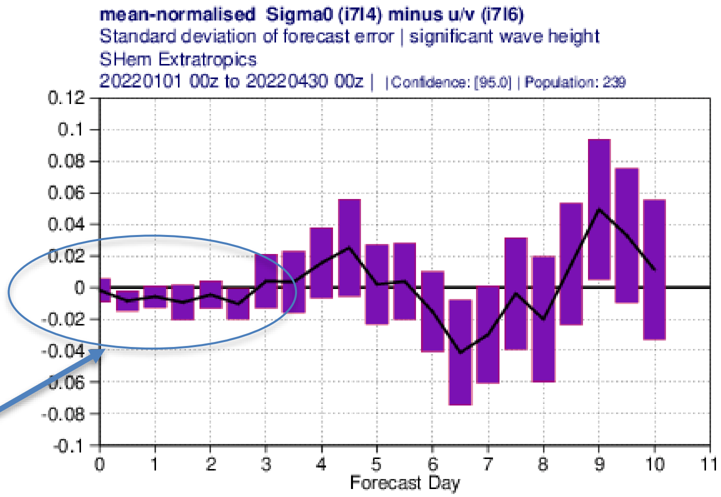


Verification against buoys: **significant wave height**

- Sigma0 vs CTL (SCAT U/V). Below 0 good!

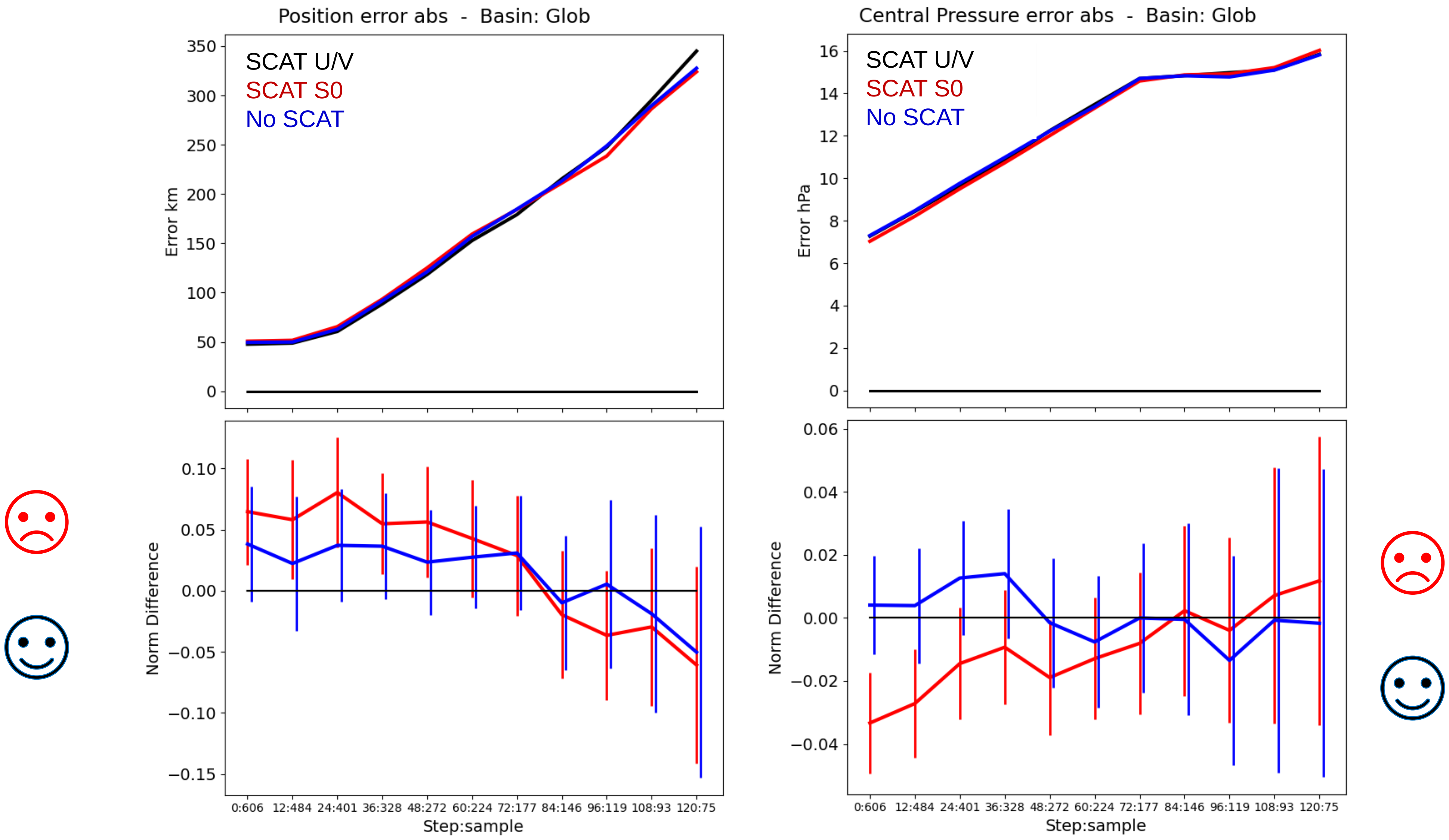






Some indication that SWH better in sigma0 experiment

Impact of assimilating Sigma0 on TC statistics: Apr-Oct 2022



Scatterometer Concluding remarks

Scatterometer observations widely used in NWP

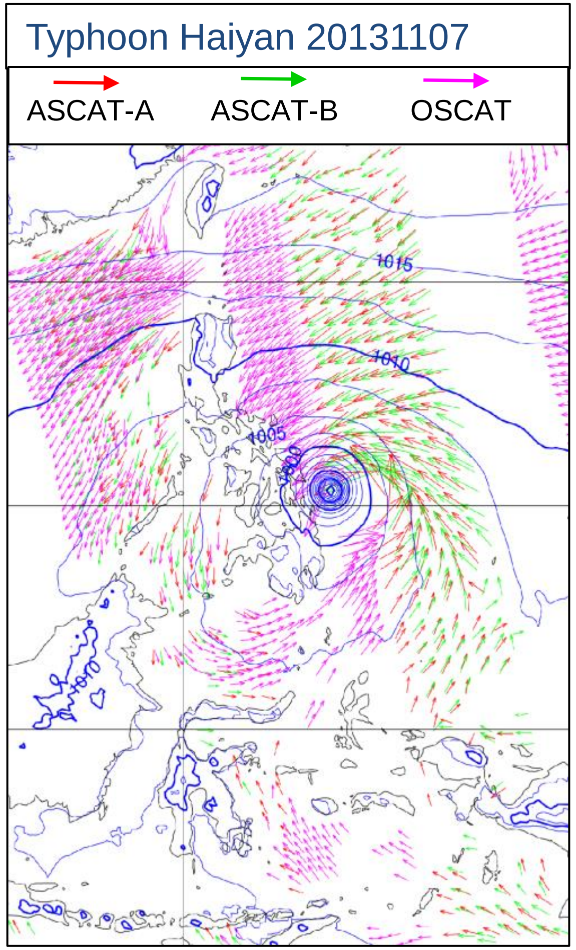
- Ocean wind vectors
- Positive impact on analysis and the forecast
- Global scale and extreme events
- Impact on Atmospheric, Ocean and Wave model

ECMWF has a long experience with scatterometry

- Available continuously from 1991 onwards:
- GMF development
- Monitoring, validation, assimilation, re-calibration

On-going efforts to improve usage and impact

- Improve QC
- Adapt observation errors
- Include dependency from other geophysical quantities (i.e. Ocean Currents)
- Currently testing the assimilation of the backscatter rather than the wind



Use in the Reanalysis

- ERS1/2 and QuikSCAT in ERA-Interim
- + ASCAT-A, ASCAT-B, ASCAT-C and HY-2B products used in ERA5 and soon in *ERA6*

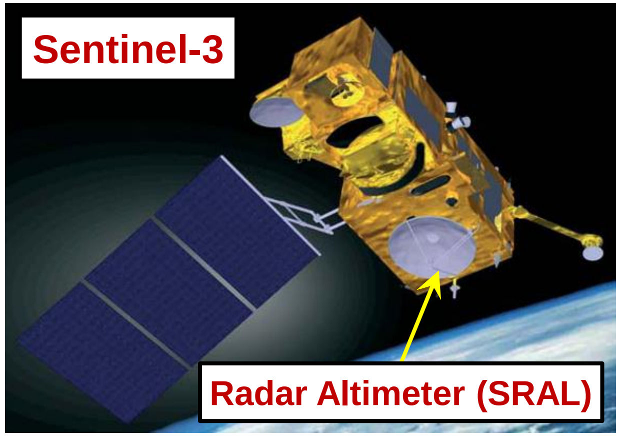
Question time

Radar Altimeters

✓ Radar altimeter is a nadir looking instrument.

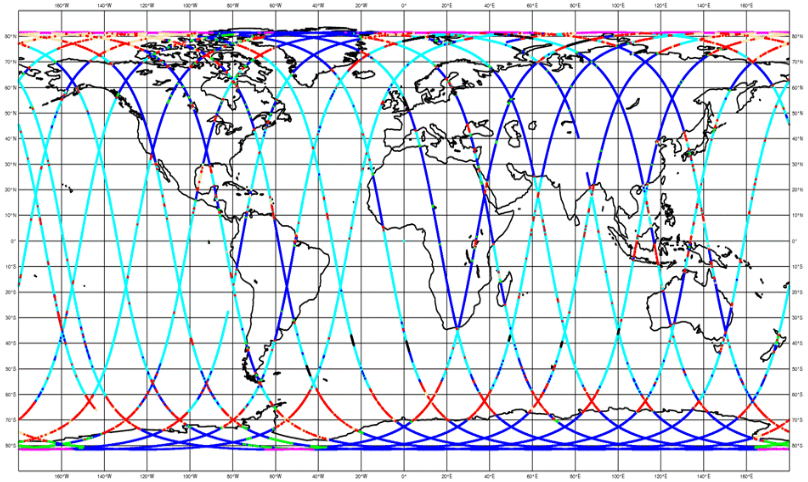
✓ Specular reflection.

✓ 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

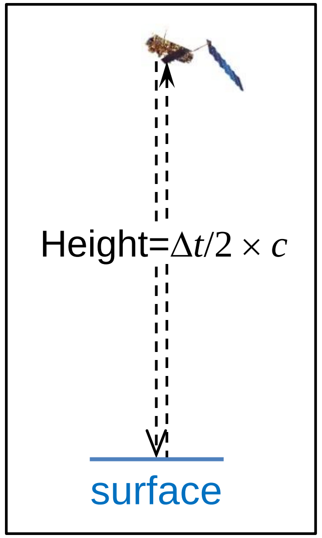


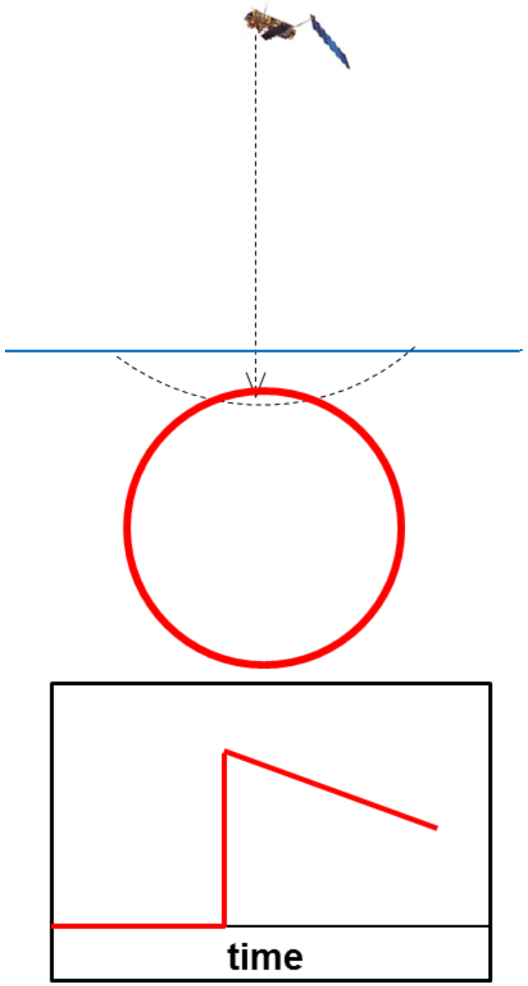
✓ Main parameters measured by an altimeter:
- Significant wave height (*wave model*)
- Wind speed (*used for verification*)
- Sea surface height (*ocean model*)

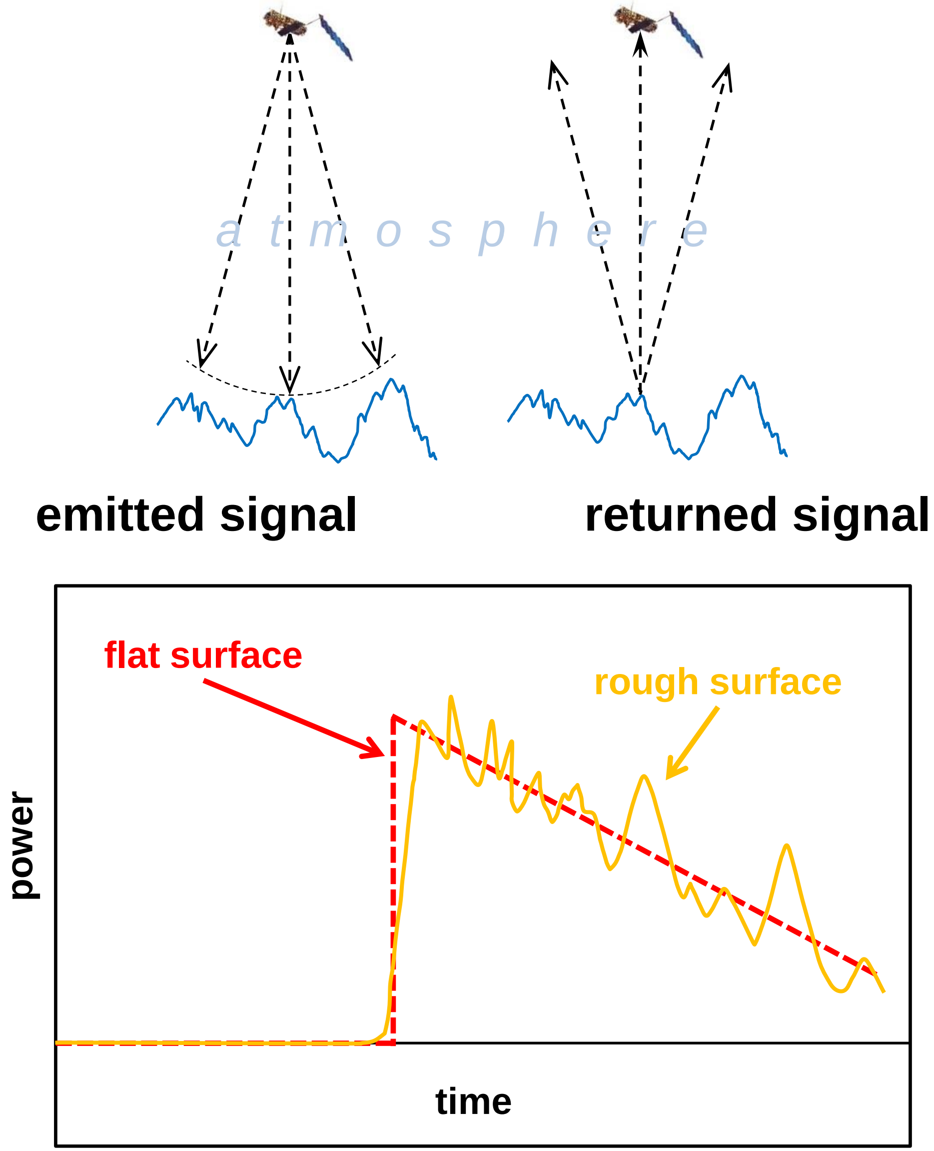
Envisat 1-day coverage



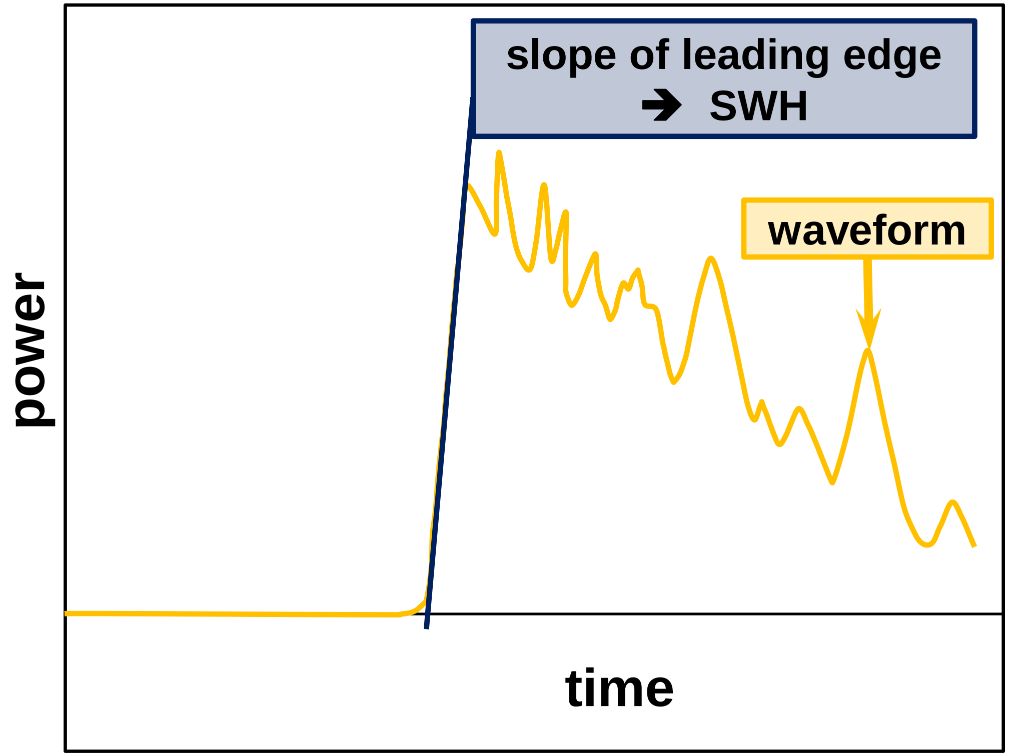
How Altimeter Works





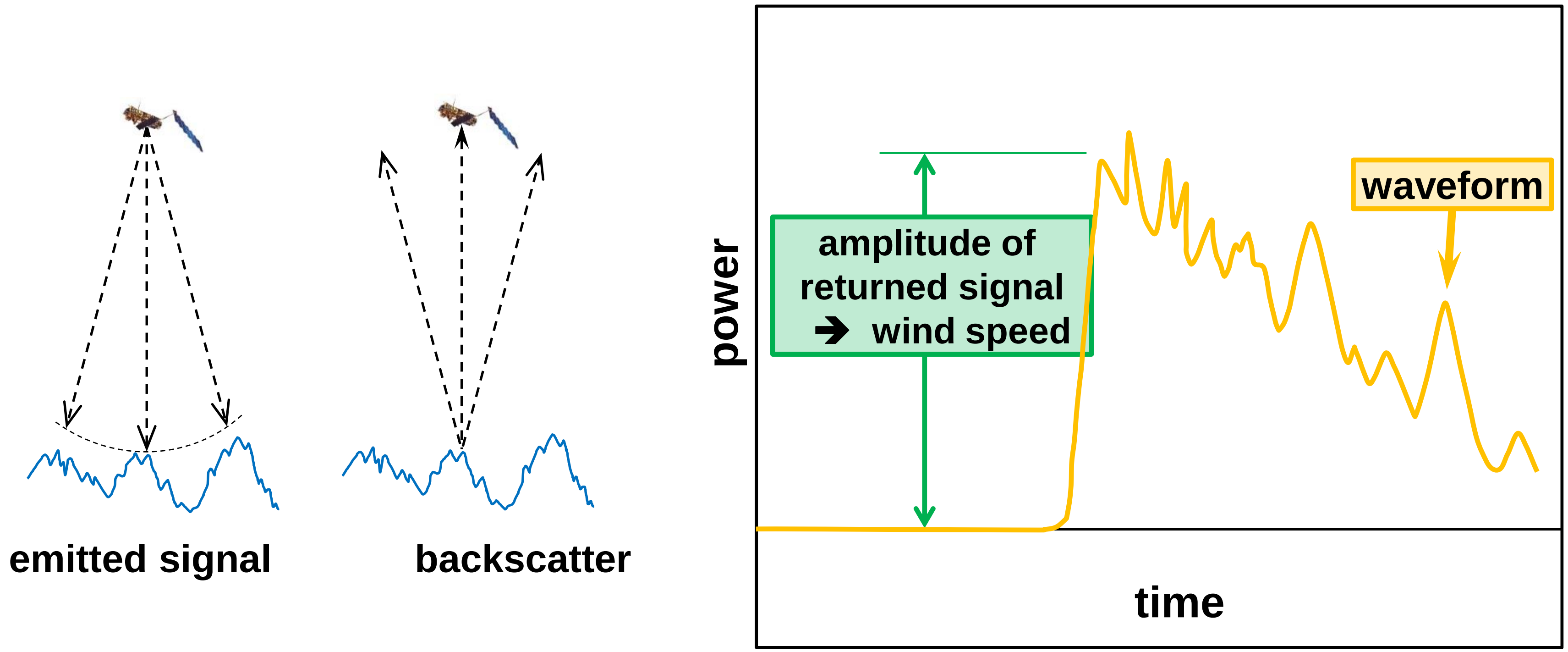


Significant Wave Height (SWH)



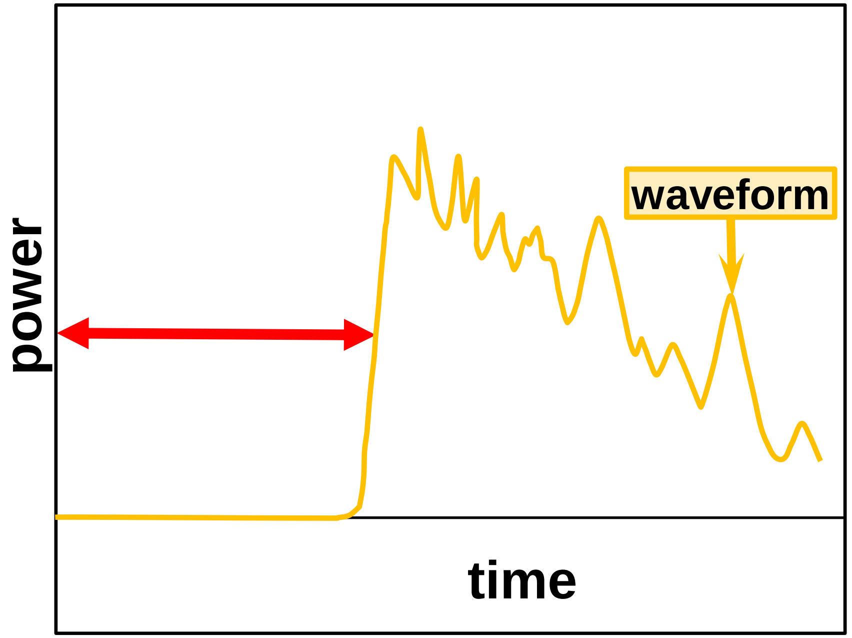
- ✓ SWH is the mean height of highest 1/3 of the surface ocean waves
- ✓ Higher SWH → smaller slope of waveform leading edge
- ✓ Errors are mainly due to waveform retracking (algorithm) and instrument characterisation

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

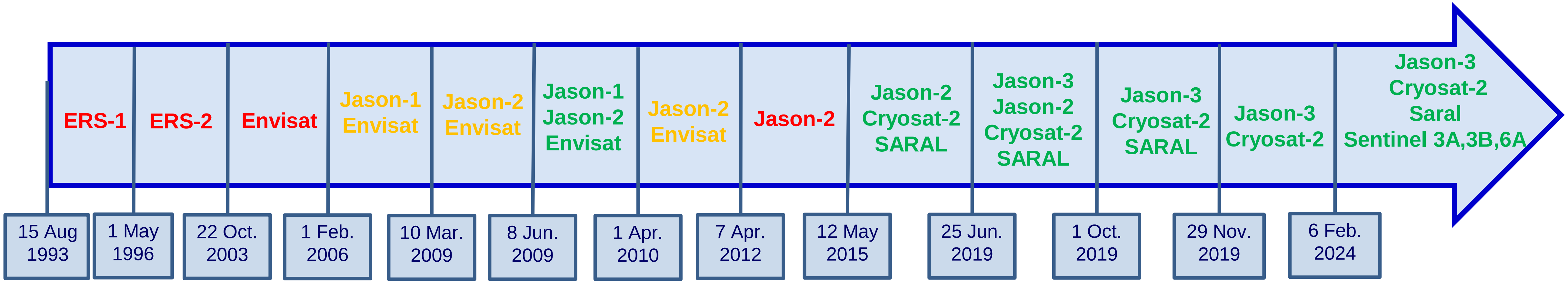


- ✓ Time delay → sea surface height

- ✓ 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)

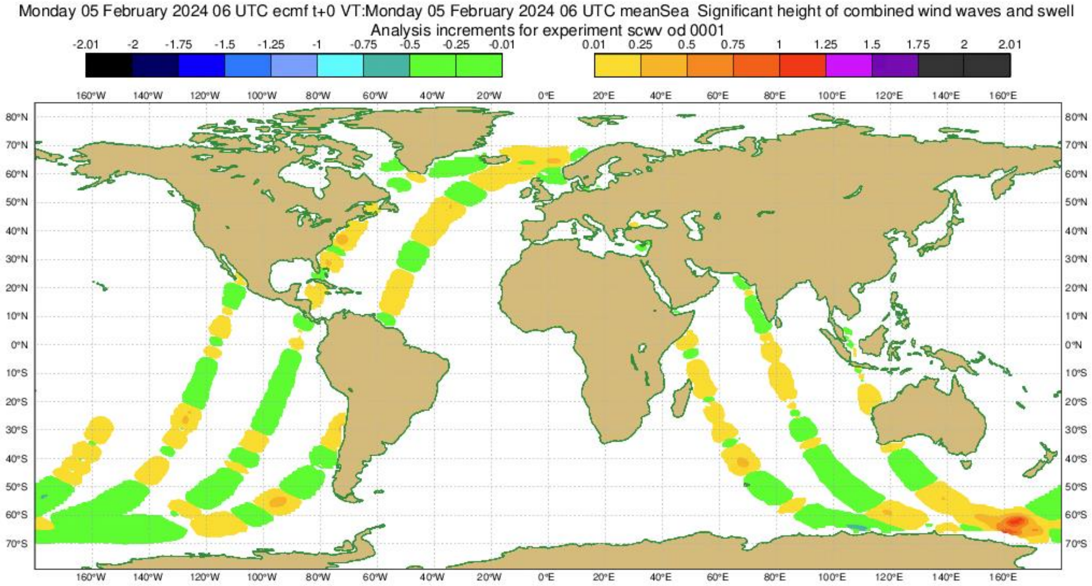


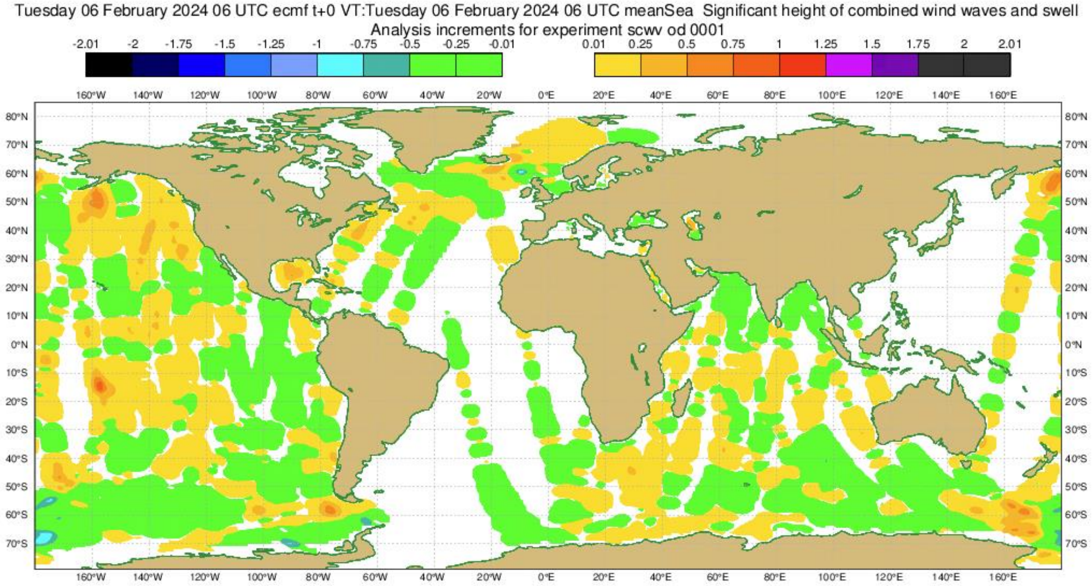
Assimilation method for SWH data:

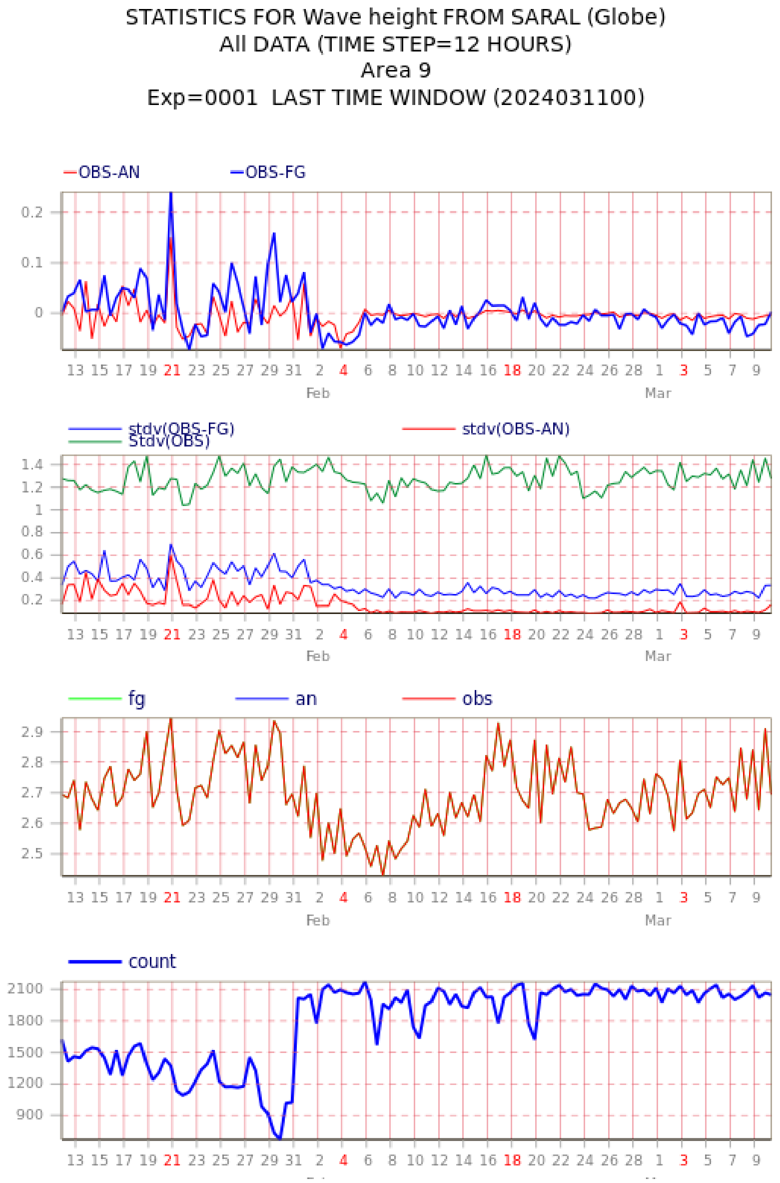
- ✓ Data are subjected to a quality control process (inc. super-obbing).
- ✓ Bias correction is applied.
- ✓ Simple optimum interpolation (OI) scheme on SWH.
- ✓ The SWH analysis increments ➔ wave spectrum adjustments…

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 sinergies

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

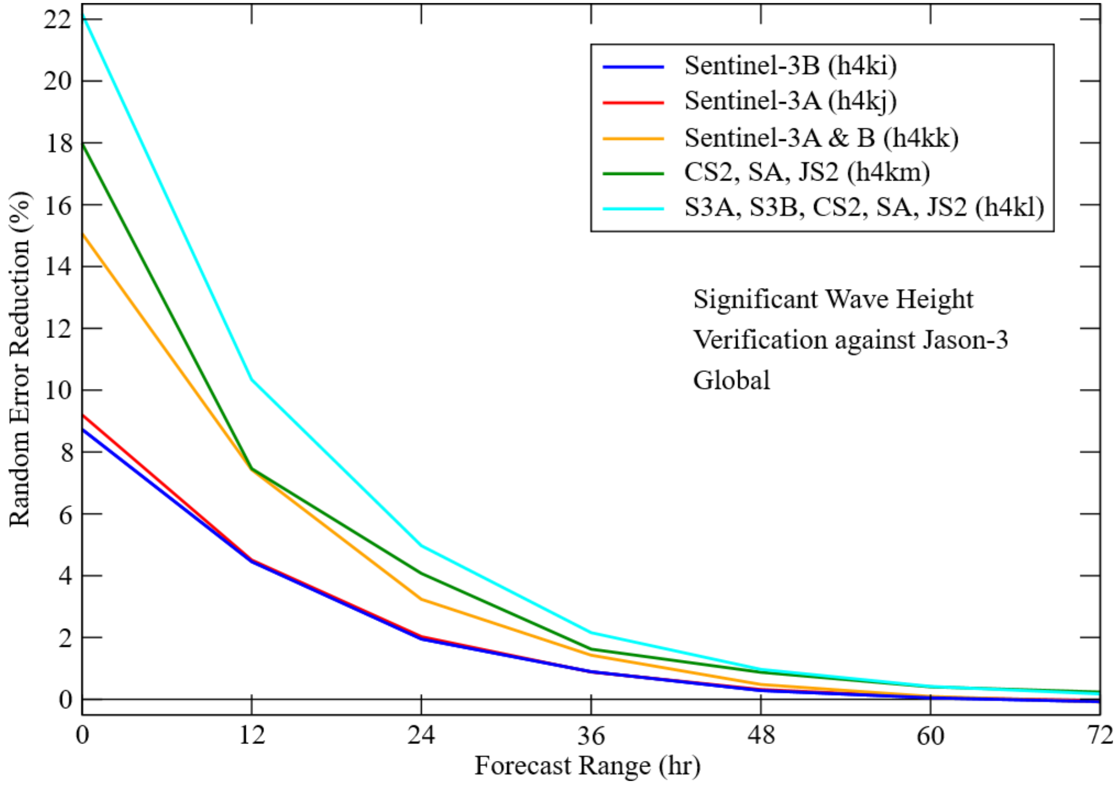
All the five altimeter instruments listed below

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

Sentinel-3A&B

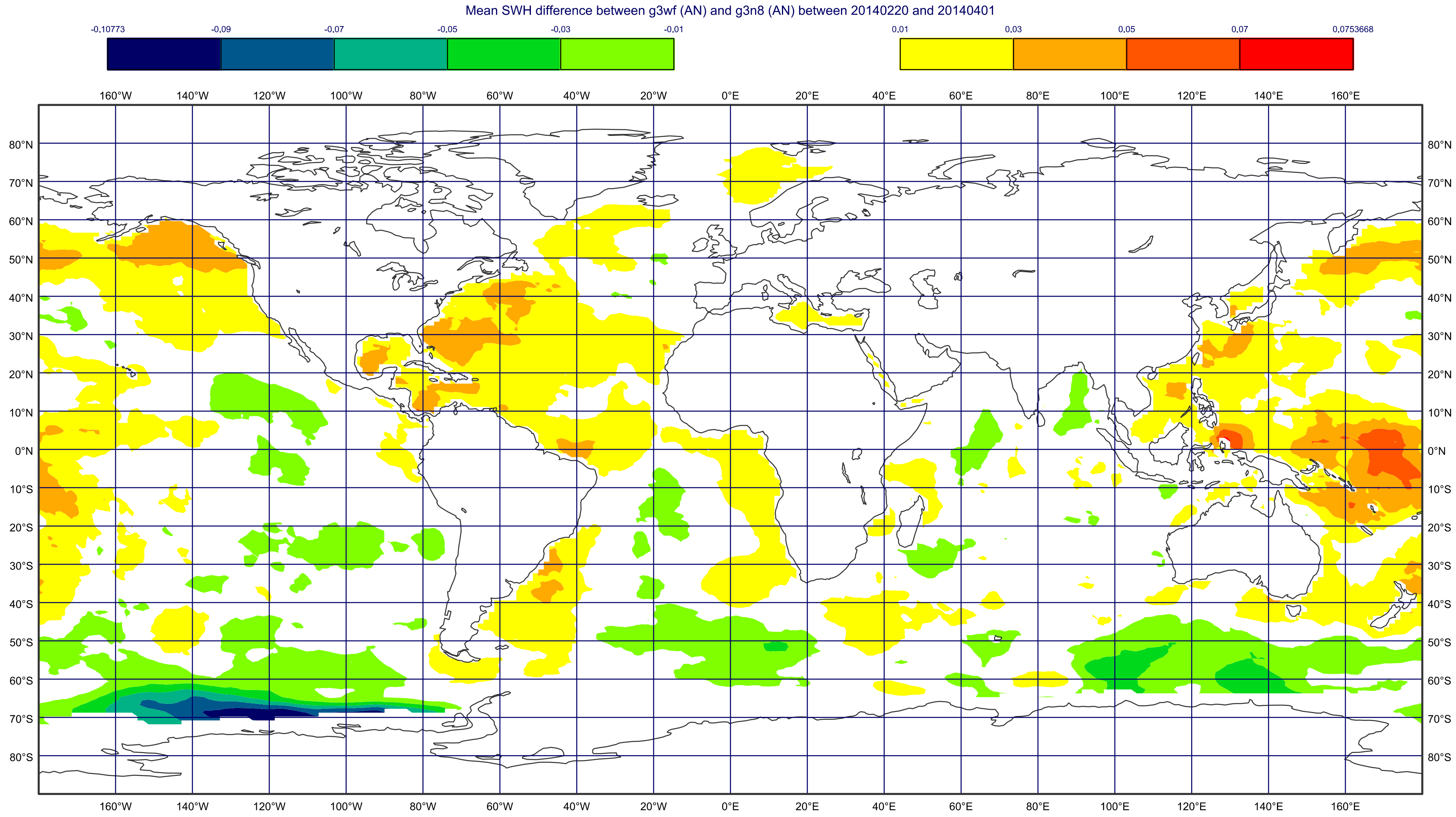
Sentinel-3A

Sentinel-3B

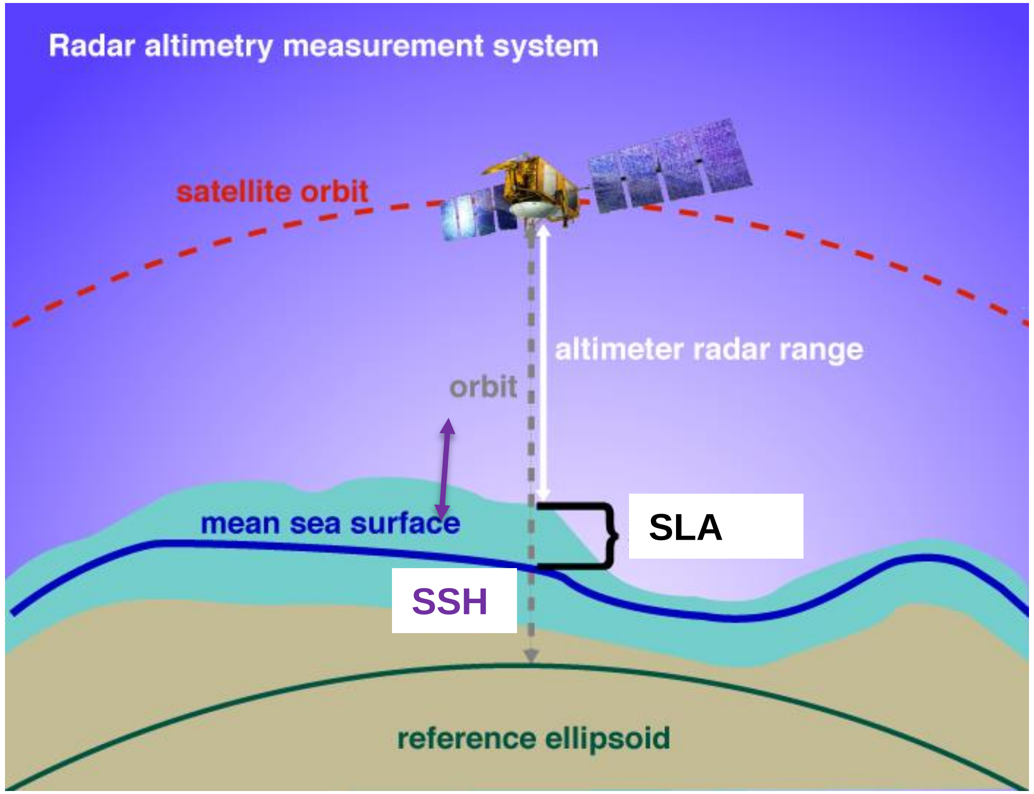


Impact of SWH assimilation

Impact of one additional altimeter on the SWH analysis [CS & J2] - [J2 only]



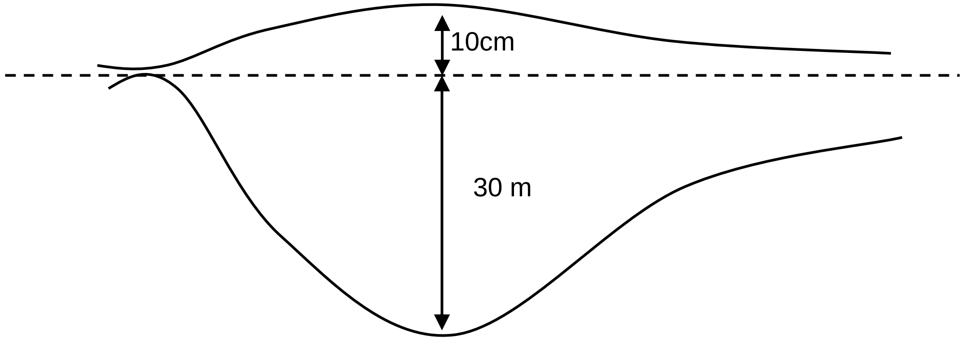
Altimeter data in the Ocean Analysis System



The altimeter measures the range which can be used to determine Sea Surface Height (SSH)

SLA = Sea Level Anomaly

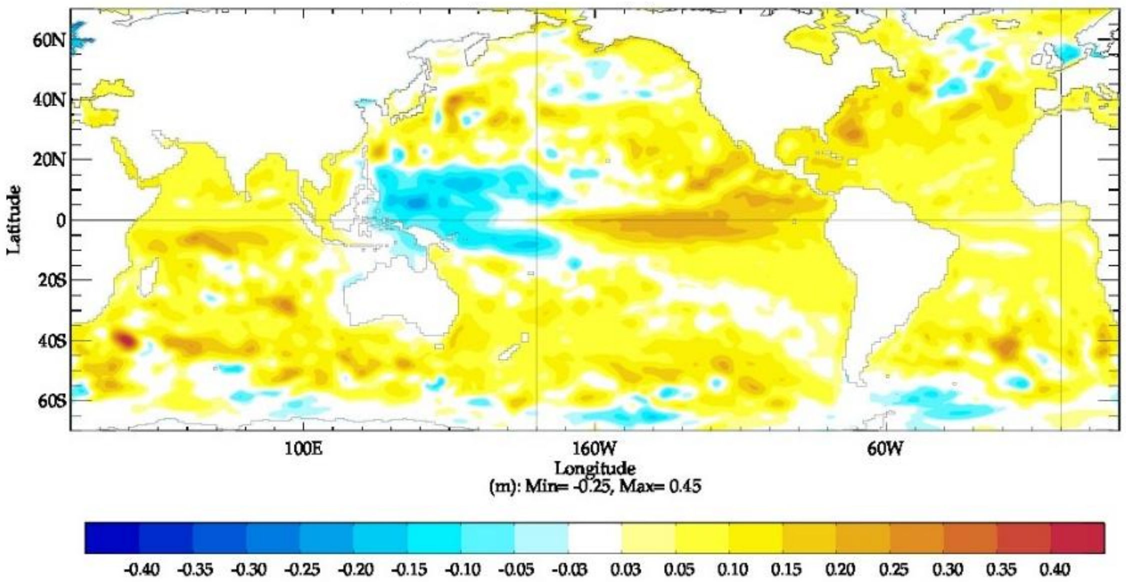
Assimilated in the ocean model



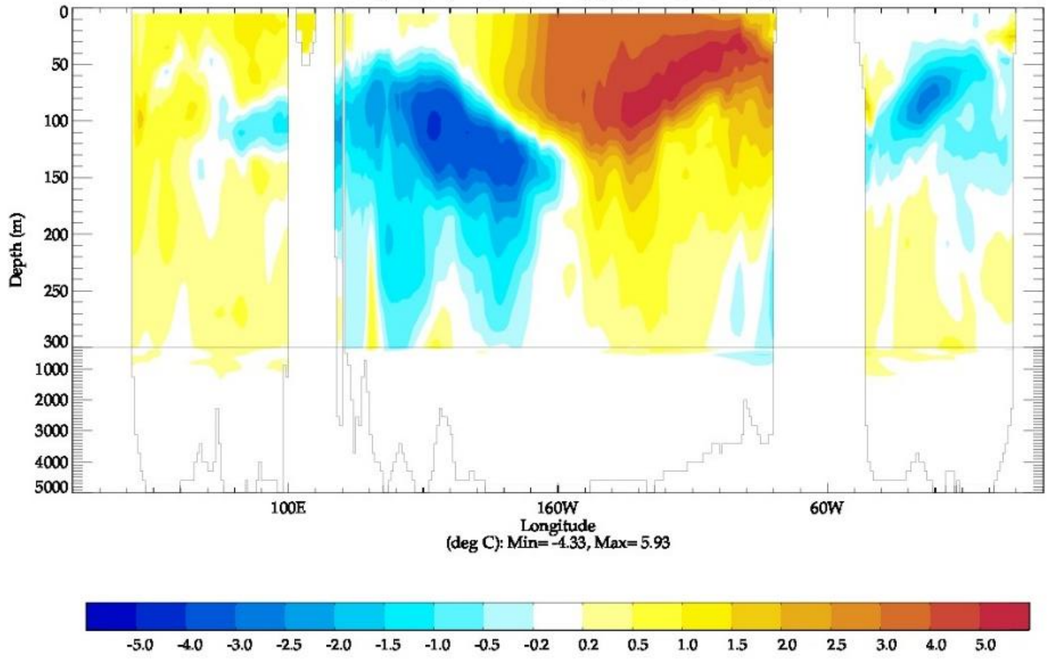
From sea level observation it is possible to infer information on the vertical density structure

Why do we need SLA?

SL Anomalies Feb 2016

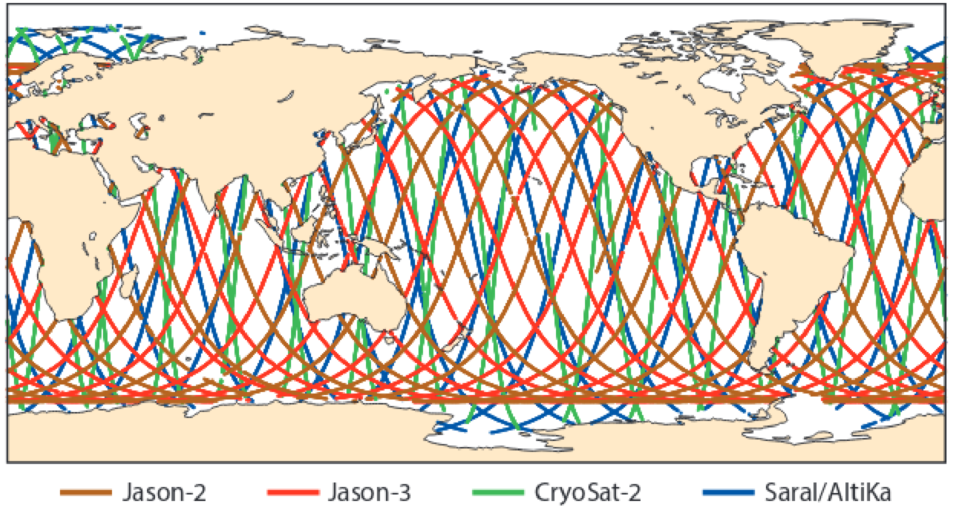


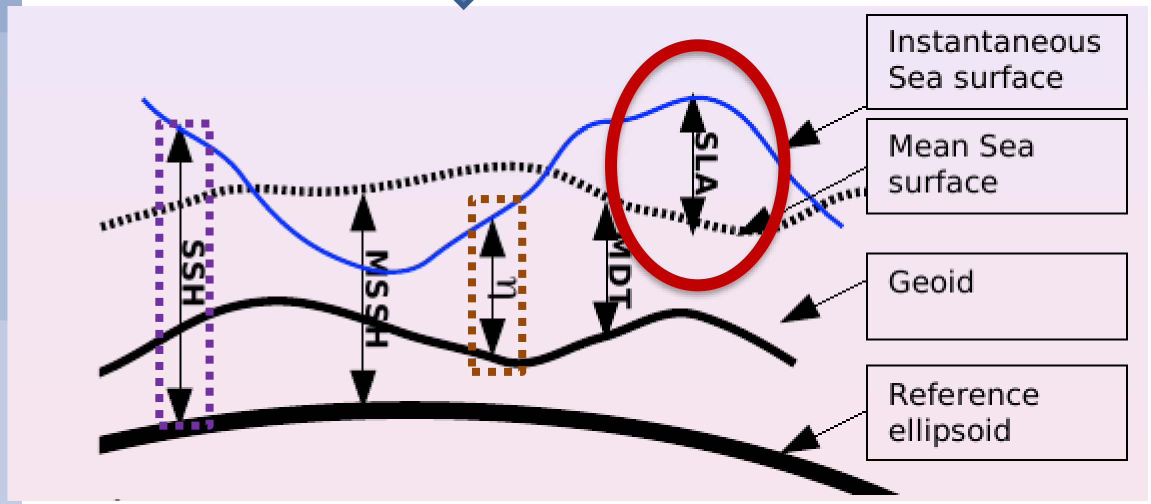
Lon/Depth Temp anom Feb 2016



El Nino 2015/2016

From Sea Surface Height to Sea Level Anomaly





Altimeter measures SSH (respect reference ellipsoide)
Model represents η (SSH referred to the Geoid)

SSH-Geoid= η

Geoid was poorly known (until recent years) and changes in time

Alternative: Assimilate Sea Level Anomalies (SLA) with respect to a time period

Obs: SSH anomalies = SSH-MSSH = Obs SLA
Mod: η anomalies = η – MDT = Mod SLA

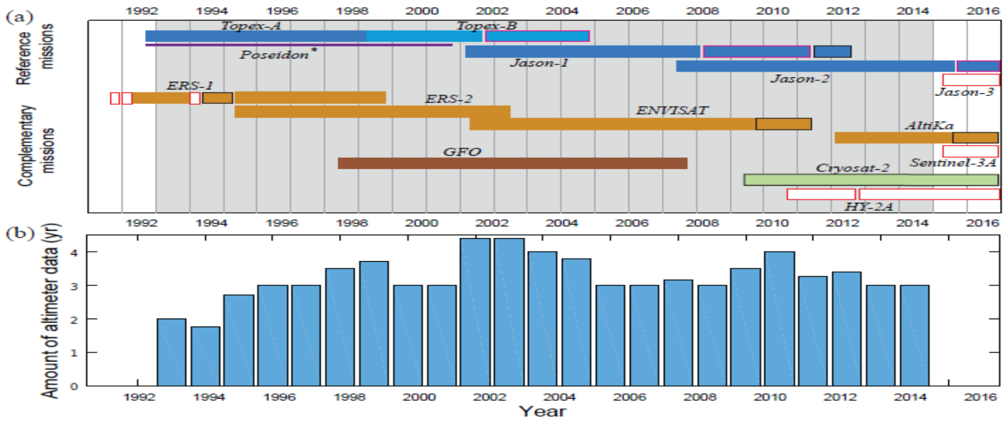
Where: MSSH= Temporal Mean SSH ;
MDT = Temporal Mean of model SL (Mean Dynamic Topography)
MSSH – Geoid = MDT

Assimilation of SLA as implemented in OCEAN5

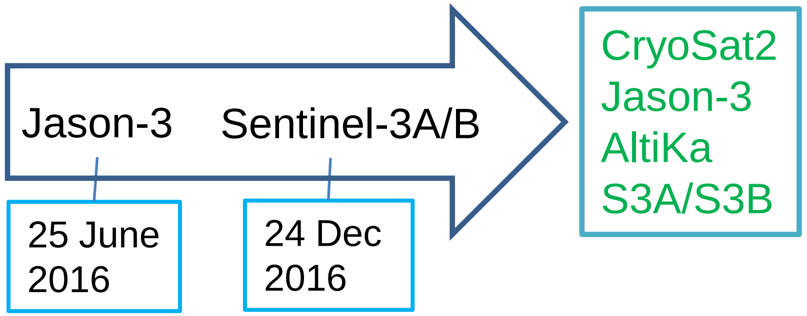
- Assimilate L3 along-track SLA data to constrain regional sea-level changes
- Assimilate L4 gridded MSLA maps to constrain global mean sea-level changes (via freshwater balance)
- Assimilate SLA with a model MDT (Mean Dynamic Topography) approach (require pre-computation)
- Apply cut-off to remove all high-latitude SLA data, as well all near coast observations.

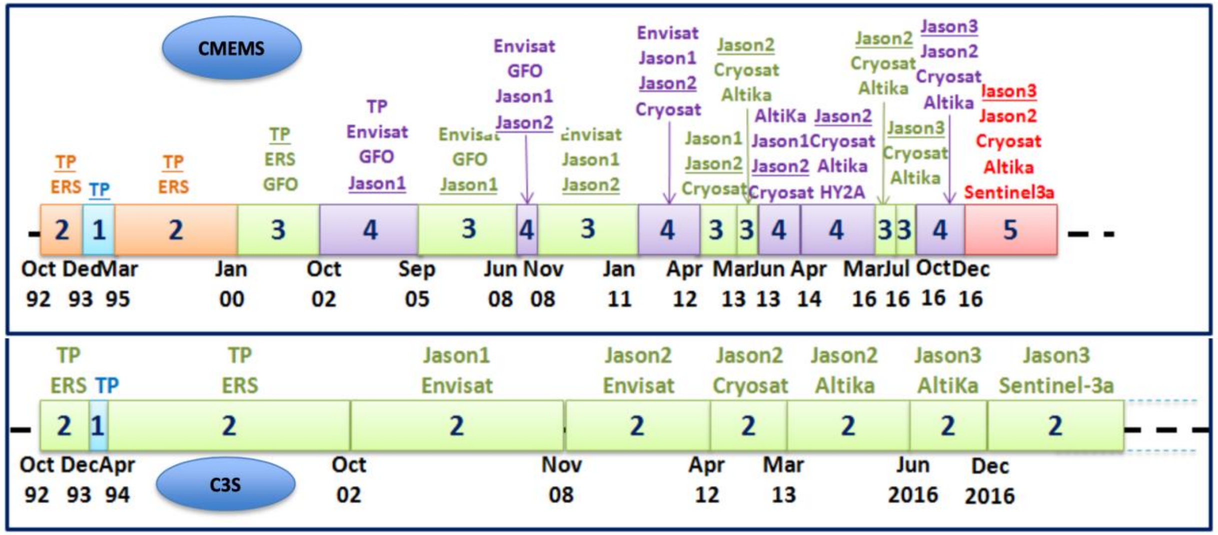
The effectiveness of SLA DA is mostly determined by elements listed above, but is also affected by bias correction settings; balance operator, BKG errors settings for other variables; consistency of the available SLA data; land freshwater input at the river mouths; treatment of freshwater constrain; etc

Available L3 along-track SLA data



Number of available SLA missions



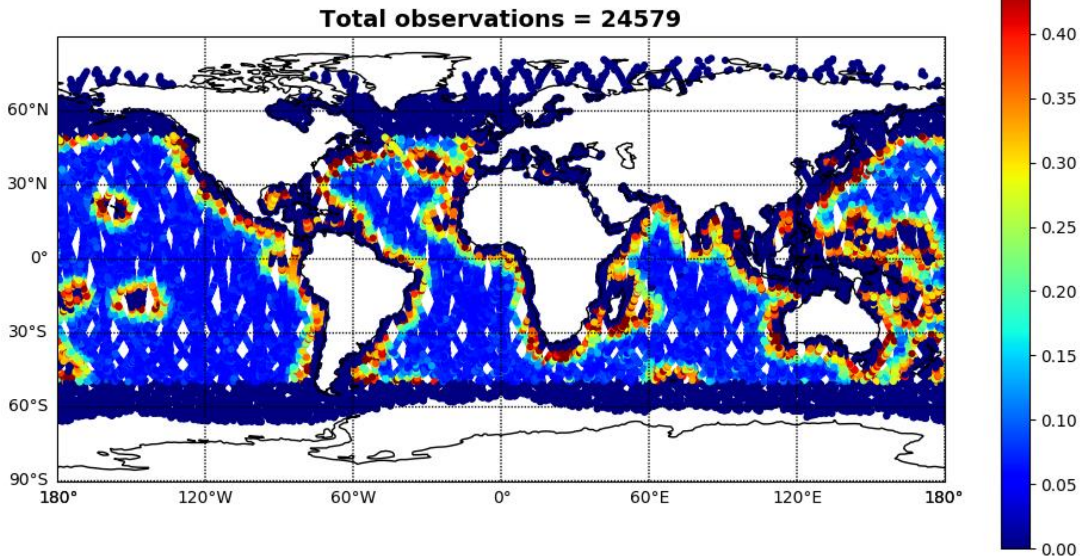


JF Legeais, et al., DUACS DT2018, poster

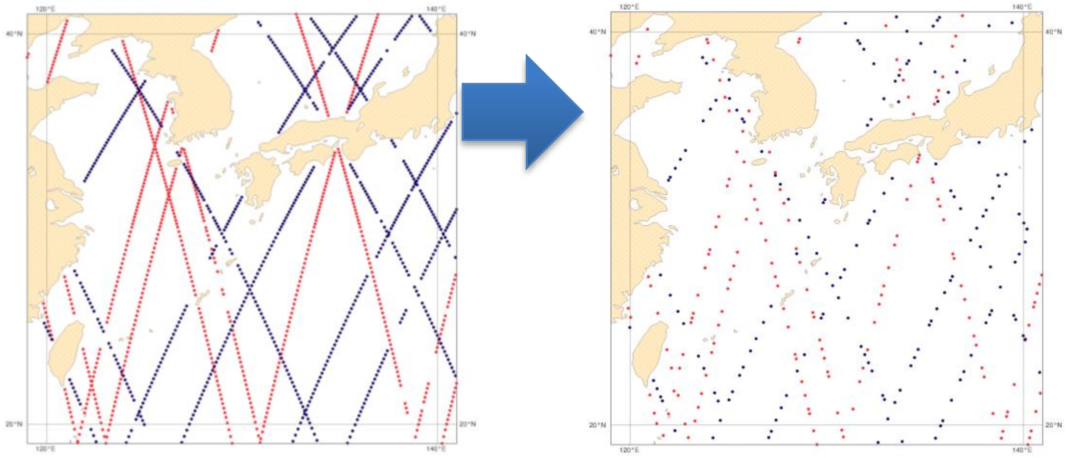
Assimilation of SLA: pre-process obs

- **The SLA along track data has very high spatial (9-14km) resolution for the operational ocean assimilation systems.**
  - Features in the data which the model can not represent
  - “Overfitting” to SLA obs
- **This can be dealt with in different ways:**
  - Inflate the observation error
  - Construction of “superobs” or thinning

Inflate OBE std dev of SSH



Thinning of SLA obs



ERS-2: 13005 Envisat: 0 Envisat N: 0

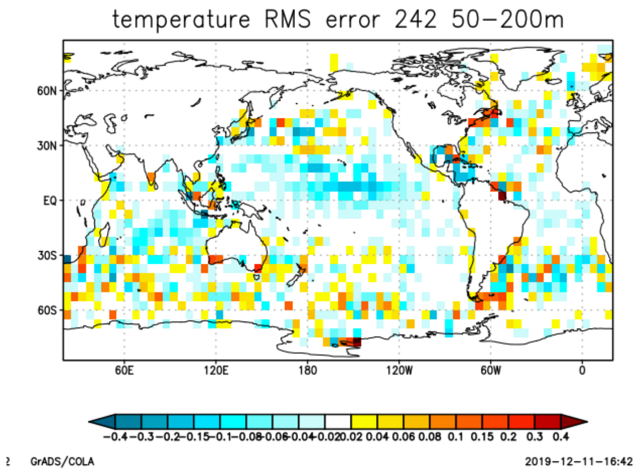
Jason-1 N: 0 Jason-2: 0 T/P: 13219

Assimilation of SLA: impact on the ocean state

Assimilation of SLA improves simulated ocean states

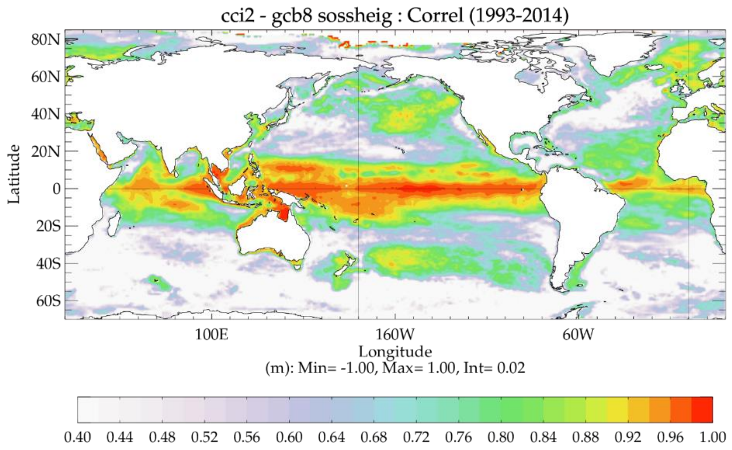
- Global mean sea-level changes
- Regional sea-level changes
- Subsurface temperature and salinity
- Large-scale ocean circulations

T ∆RMSE (O-B):
assim. SLA – not assim. SLA



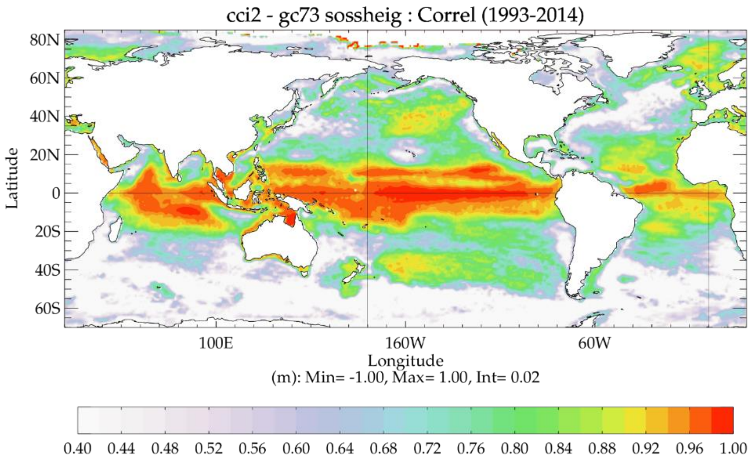
Temporal correlation (monthly) to AVISO data

ORAS5-NoAlti



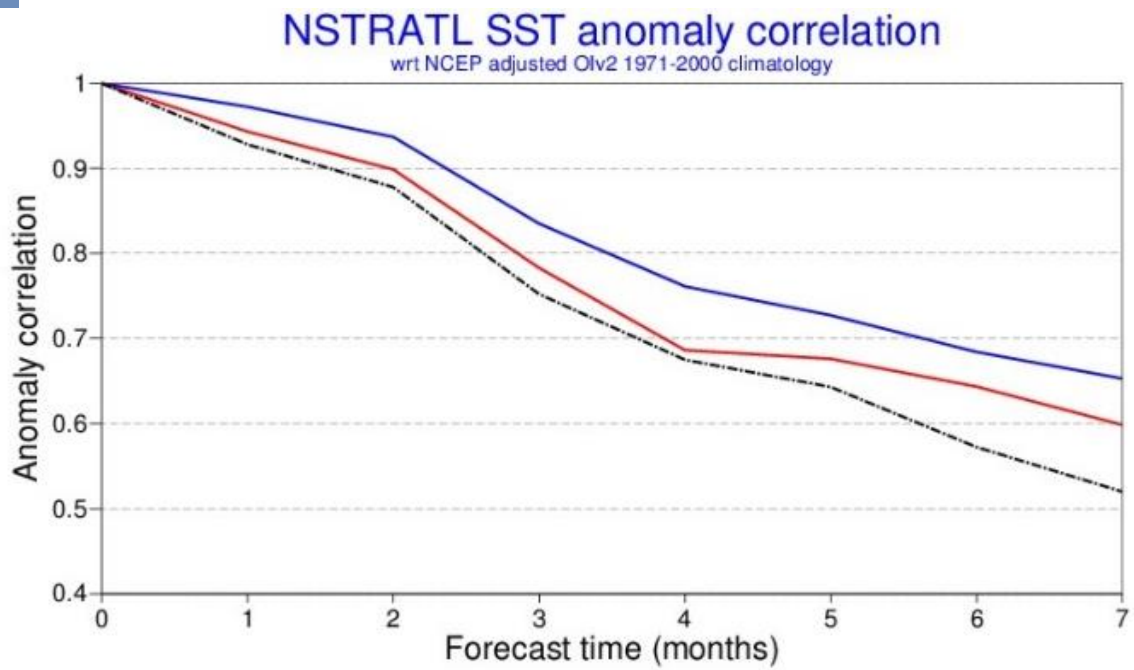
Zuo et al., 2018

ORAS5



Impact of Altimeter SLA on Seasonal forecast

No Alt ocean ini
Seasonal Fc with Alt



Consistent Improvement of Skill over the Atlantic Ocean

Shown are Northern Subtropical Atlantic.
Potential for prediction of tropical cyclones.

In other regions the impact is not so obvious and varies with season.

In the Pacific, skill is improved mainly in forecasts initialized during spring (important for ENSO onset).

Courtesy of Magdalena

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

Altimeter sea level anomaly:

- Use for assimilation and validation
- Significant impact for surface and sub-surface ocean
- Importance for reanalysis and climate studies
- Uncertainty from the ensemble members potentially used for model error

Thanks!!!