Performances and benefits of a 1D-VAR approach applied to TCWV retrieval and WTC for the Sentinel 3A/B topography missions

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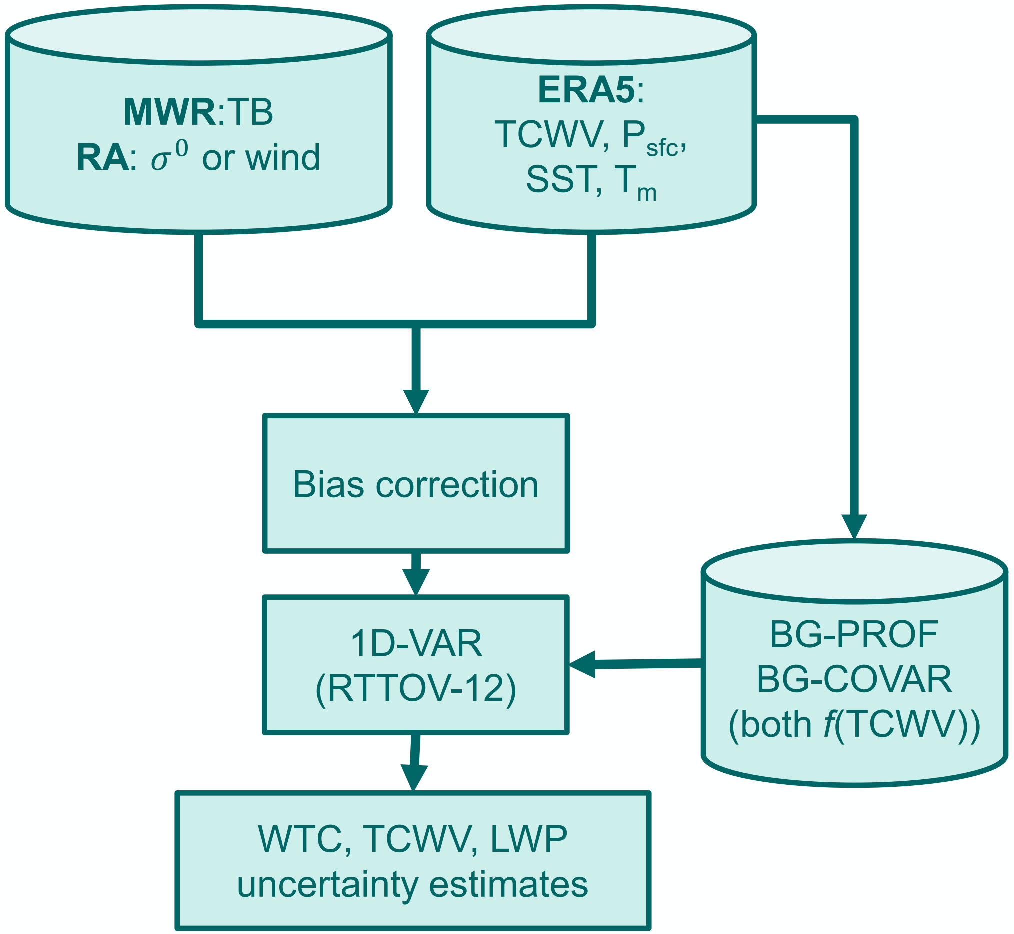
AMTROC (Altimeter 1D-VAR Tropospheric Correction) spoilers …

- **First demonstration …**
  - … of the potential of a 1D-VAR retrieval in an operational environment dedicated to altimetry
  - … of an approach where each retrieval comes with an **uncertainty** and a **self-consistent validity flag**
  - … that the 1D-VAR WTC retrieval shows performances at the level of the operational product at global scale
- **Looking into the details, the situation is contrasted in that …**
  - … **1D-VAR performs better** than the S3 operational (ANN-based) approach **at high latitudes and over the tropical warm pool**
  - … **the operational approach** shows better performance over **mid-latitudes**

Study background

- **AMTROC / EUMETSAT (03/2019 - 12/2019)**
  - Implement 1D-VAR retrieval of TCWV and WTC above the ice-free open ocean from MWR observations onboard the S3 series
    - *Reduce biases in TCWV and WTC*
    - *Establish per-observation uncertainty*
    - *Provide per-observation quality flag*
    - *Apply to one year of S3-A data*
- **AMTROC CCN / EUMETSAT (03/2021 – 03/2022)**
  - Update and improve 1D-VAR retrieval scheme
    - *Process S3-A and S3-B full data records (from launch to 04/2021)*
    - *Evaluate against other operational/experimental products*

AMTROC 1D-VAR retrieval scheme



Input from S3:

MWR TBs, σ^0

Input from NWP:

TCWV, PSFC, SST, TM

Input from NWP (static):

Background T, q profiles and background error covariance from NWP, both function of TCWV

Output:

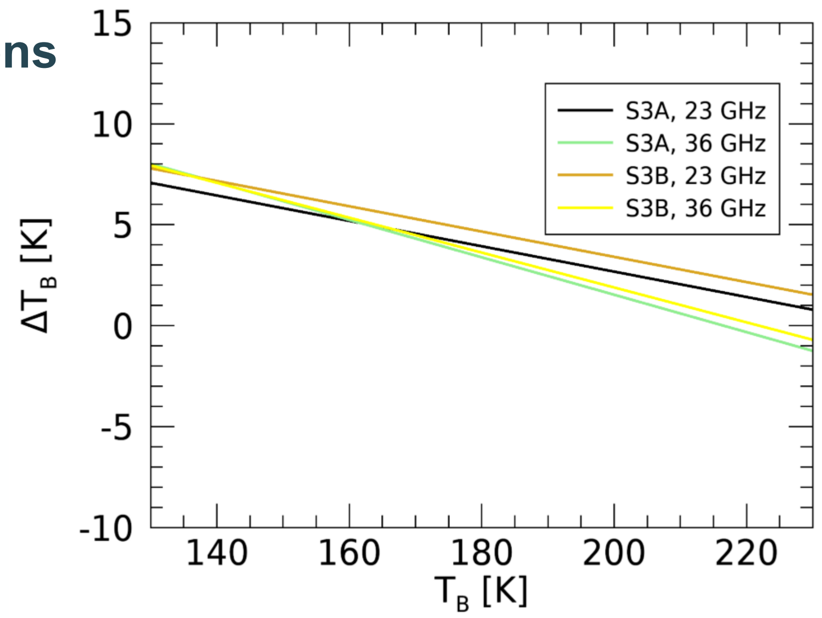
TCWV + uncertainty
WTC + uncertainty
LWP + uncertainty

Applying 1D-VAR / Optimal Estimation to TCWV / WTC retrieval

- **TCWV, WTC, and LWP are strongly constrained by MWR observations, making the retrieval relatively independent from the background state**
- **Because the above is true in nature, one can obtain accurate retrievals using any method (1D-VAR, ANN, other)**
- **However, 1D-VAR additionally allows:**
  - to conceptually and practically distinguish between the different forms of input
  - to calculate a posteriori errors considering contributions from the background
  - to individually quantify the amount of information the observations have contributed (versus the background)
- **Good, well collocated external information used for the retrieval is crucial for performance.**
- **Applied tools: NWP SAF 1D-VAR v2.0 with RTTOV v12**

Bias correction

- **Optimal estimation / 1D-VAR procedures require the observations to be on average unbiased compared to the forward model**
- **Use ocean observations over range of actual TBs to derive O-B biases:**
  - Collocate individual observations with NWP *T/q* profiles
  - Calculate cloud-free simulated TB
  - Evaluate histograms of all-sky, observed minus cloud-free simulated TBs
- **Practical implementation:**
  - Derive O-B biases for different TB ranges in 5 K intervals
  - Fit derived bias against TB
  - Correction: Δ TB = $a_0 + a_1 \times$ TB

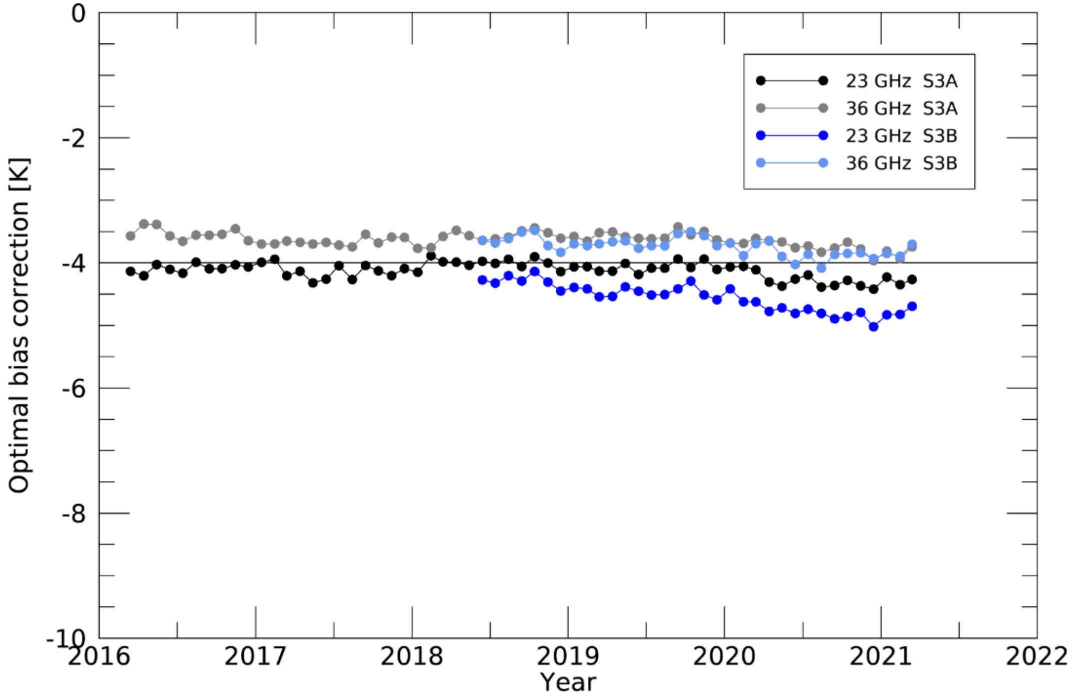


$$\Delta T_B = a_0 + a_1 \cdot T_B$$

Satellite	Frequency	a0	a1
S3A	23 GHz	15.2358	-0.062787
S3A	36 GHz	20.0633	-0.092646
S3B	23 GHz	15.9284	-0.062587
S3B	36 GHz	19.1671	-0.086366

Bias correction

- Bias very smooth over time
- 36 GHz S3A/B very well intercalibrated
- 23 GHz S3A/B differ by ~0.3 K
- Overall bias -4 K (satellite warmer than reanalysis)
- Slight apparent 'drift' observed, especially in S3B 23 GHz



Validation: Scope

- **In-depth comparison of the performances of the 1D-VAR products with**
  - the operational S3 topo. products: CLS ANN, ECMWF
  - alternative solutions for S3 topo. : GPD+
  - solutions from other instrument on-board S3: AIRWAVE from SLSTR

	TCWV+UNC		WTC+UNC		LWP+UNC		ATT_Ku+UNC	
	S3A	S3B	S3A	S3B	S3A	S3B	S3A	S3B
1D-VAR	X+X	X+X	X+X	X+X	X+X	X+X	X	X
OPERATIONAL (ANN)	X	X	X	X	X	X	X	X
ERA5	X	X						
GPD+			X	X				
AIRWAVE	X+X	(X+X)						

Validation: Scope

- **S3 operational: CLS Neural Network solution:**
  - Frery, M.-L., et al. (2020). Sentinel-3 Microwave Radiometers: Instrument Description, Calibration and Geophysical Products Performances. Remote Sensing, 12(16), 2590. https://doi.org/10.3390/rs12162590
  - Global semi-physical empirical approach
  - NN learning based on TB simulated from ECMWF analysis

- **GPD+ for S3 (Eumetsat):**
  - https://www.eumetsat.int/S3-altimetry-GPD-WTC
  - GNSS (Global Navigation Satellite Systems) derived Path Delay Plus (GPD+) algorithm
  - space-time objective analysis, of all available valid WTC measurements (from the on-board MWR, scanning imaging MWR (SI-MWR) and GNSS) in the vicinity of the estimation point.

Validation: Scope

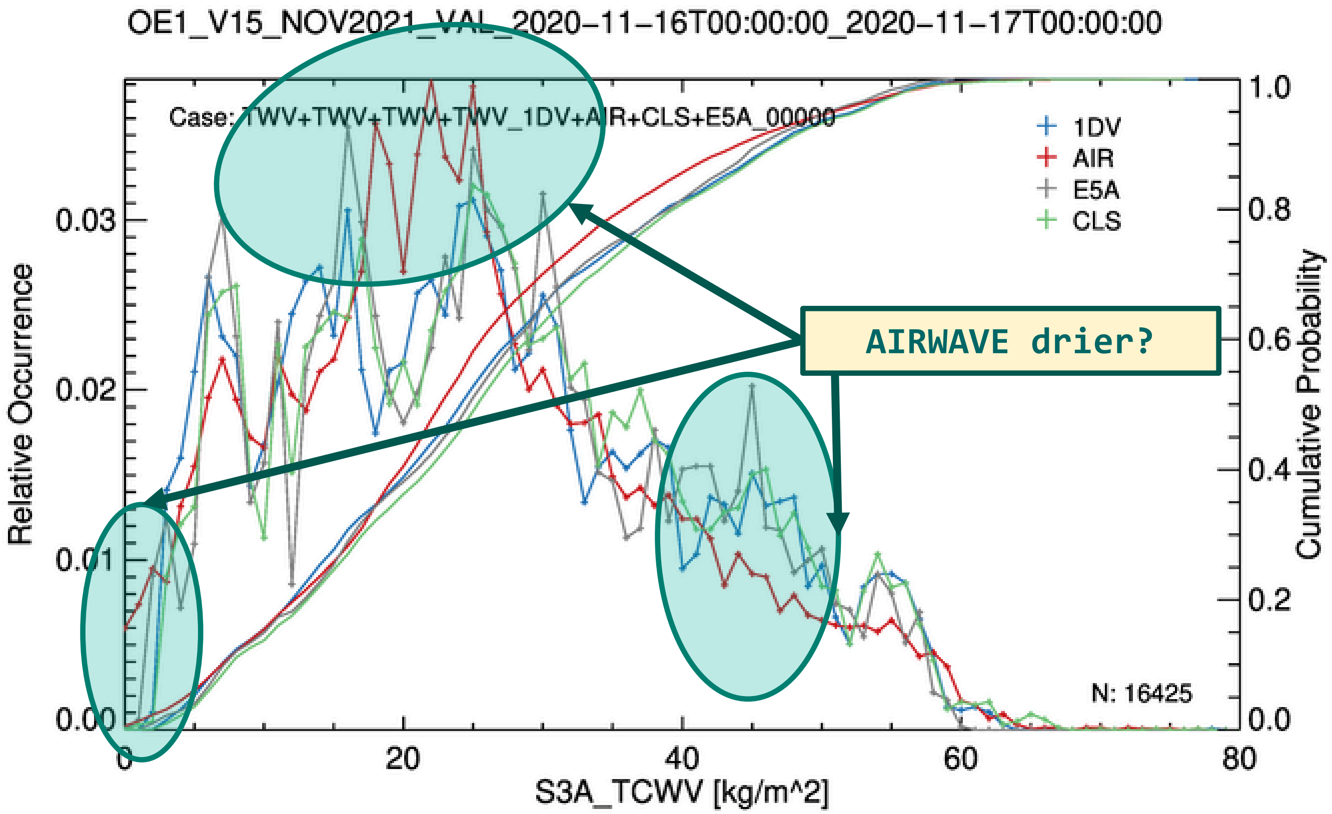
- **AIRWAVE for SLSTR (Eumetsat):**
  - https://www.eumetsat.int/AIRWAVE-SLSTR
  - Advance Infra-Red WAter Vapour Estimator
  - The algorithm exploits the TIR channels (11 and 12 µm) of ATSR-like instruments and the dual viewing geometries to infer the TCWV in clear sky over water surfaces
  - Specific and demanding pre-processing of AIRWAVE retrievals
    - Identify all AIR 3-min granules with a temporal overlap with the investigated 1DV orbit
    - Median of all cloud-free observations within 10 km radius around center of MWR footprint

Validation: Approach

- **Validation on individual retrievals**
  - Consider full days (~14 full orbits, comprising ~45.000 1D-VAR retrievals)
  - Visual and statistical analysis
  - Investigate specific scenarios: low cloud cover, S3A *vs.* S3B, …
- **Global analysis**
  - Gridding of retrievals (monthly, 4°×4°)
  - Visual analysis of retrieval differences
  - Crossover analysis for WTC
- **The „truth“ is not known**
  - Very limited availability of independent measurements (radiosondes, GNSS) offshore
  - Resort to plausibility considerations
  - Crossover analysis for WTC

Validation: TCWV Individual Retrievals: **1DVAR close to NN**

Distribution of TCWV from 1DVAR, CLS NN, AIRWAVE & ERA5



Validation: TCWV Individual Retrievals: **1DVAR close to NN**

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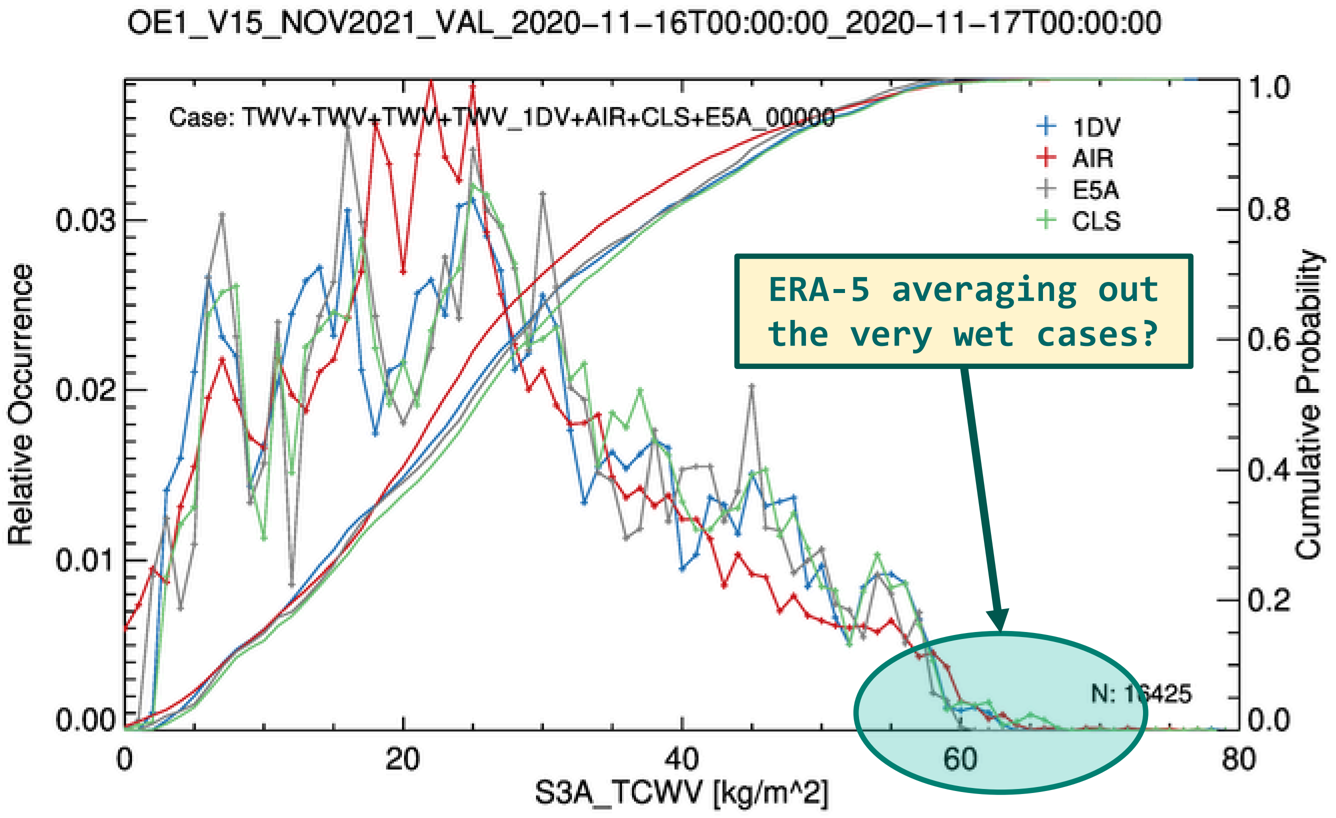
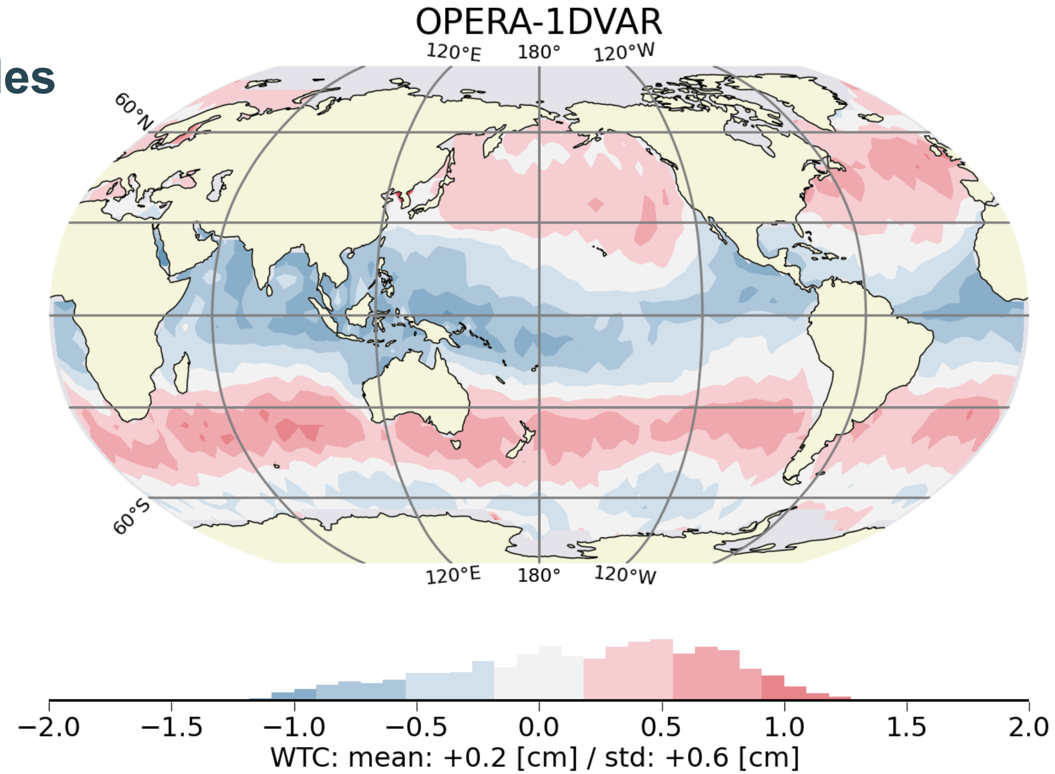


Validation: Geographical distribution CLS_NN – 1D-VAR

- 1D-VAR **wetter** than WTC_Opera over the **tropics**, especially over the indo-pacific warm pool
- 1D-VAR **drier** than WTC_Opera at **mid-latitudes**
- 1D-VAR **wetter** than WTC_Opera at (southern**) high latitudes**

(confirmed by independent GPD+ Fernandez et al. validation,

also true for GPD+ solution and ERA5)



Validation: variance of SSH (sea surface height) differences at crossovers

- **Absolute performance metric specific to altimetry**
- Definition: SSH = Altitude – (altimeter range - (sum of corrections))
- Main assumption: the ocean is stable over a period of 10 days
- Translated as: a new correction has better performance if it reduces the variance of SSH at cross-overs

VAR_ΔSSH: variance of the differences between SSH ascending pass – SSH descending pass at Xovers

The best WTC used to compute SSH minimizes VAR_ΔSSH for Xovers <= 10 days

- SSH reference computed with correction_reference
- SSH target computed with correction_target

ΔVAR_ΔSSH = VAR_ΔSSH_target - VAR_ΔSSH_ref

ΔVAR_ΔSSH < 0 ➔ target > reference

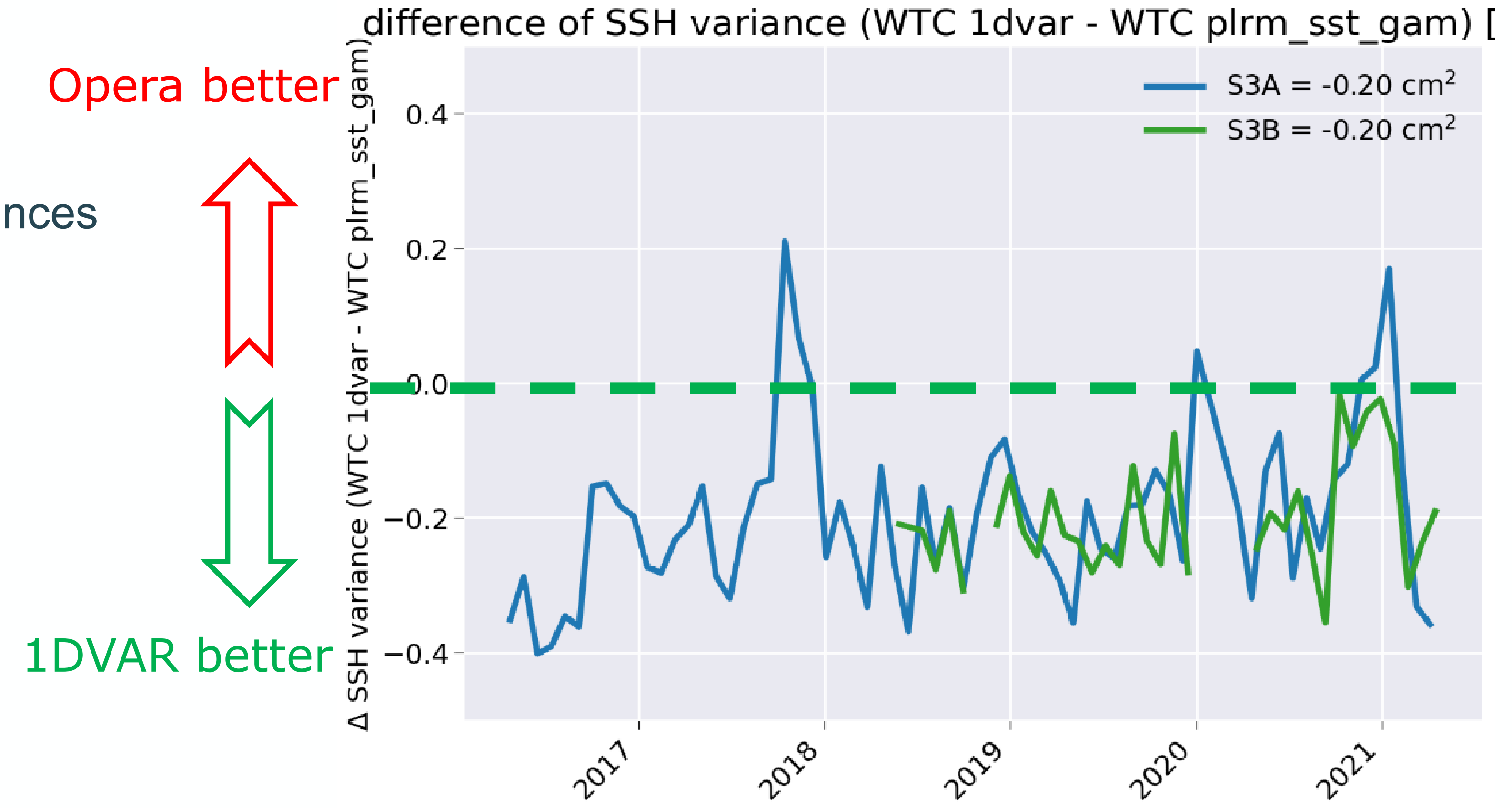
ΔVAR_ΔSSH > 0 ➔ reference > target

Validation: WTC Retrievals, Crossover Analysis

- Comparison of WTC 1DVAR against WTC CLS NN opera 5-p « PLRM SST GAM » (best solution)

- 1D-VAR provides slightly better performances than operational NN 5-p

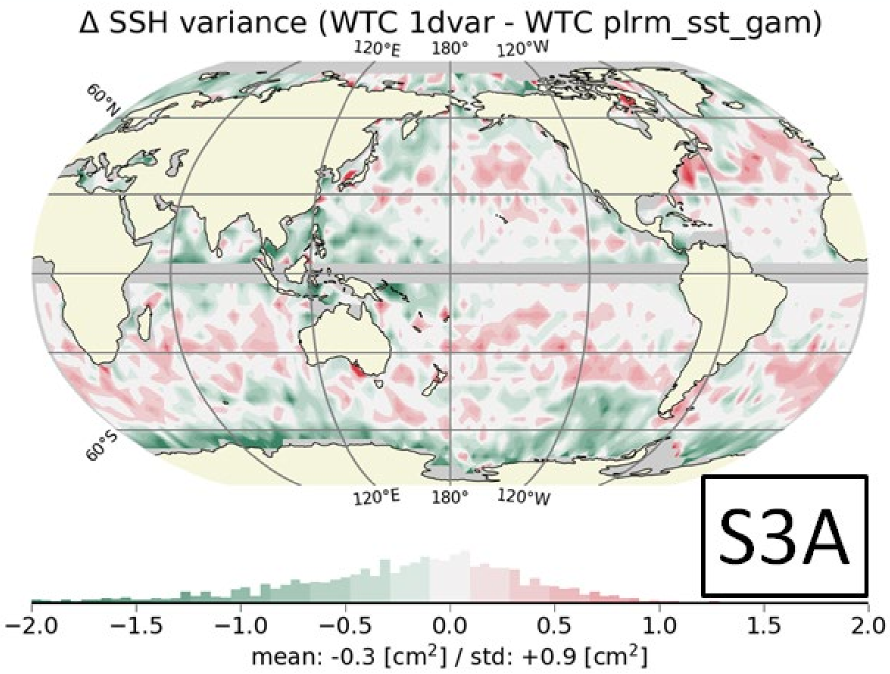
- (as a matter of comparison, MWR improves ECMWF by about 2 cm²)



Validation: WTC Retrievals, Crossover Analysis

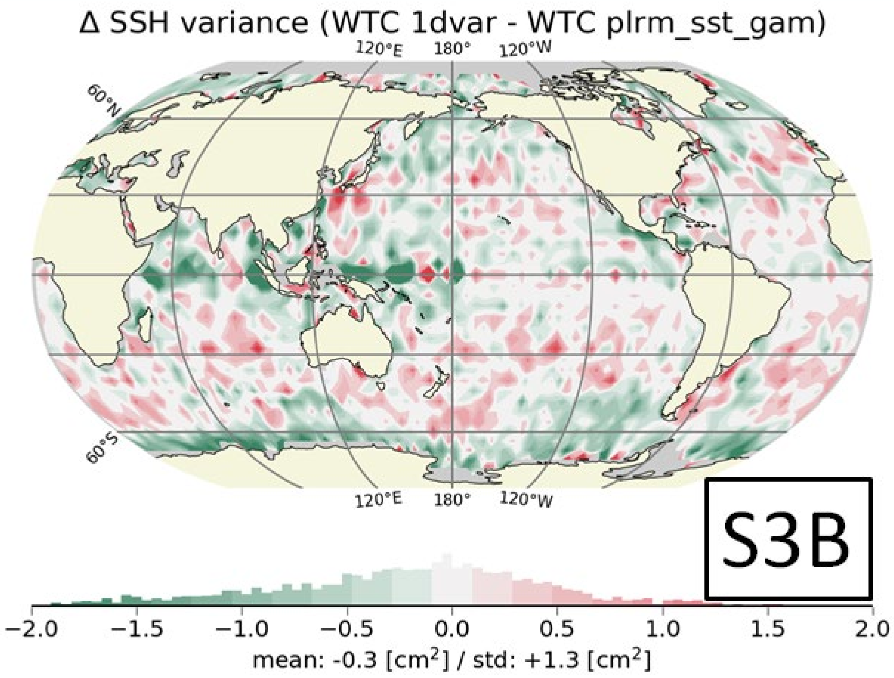
- Comparison of WTC 1DVAR against WTC CLS NN opera 5-p « PLRM SST GAM » (best solution)

- Global statistics hide contrasted distribution



Opera better

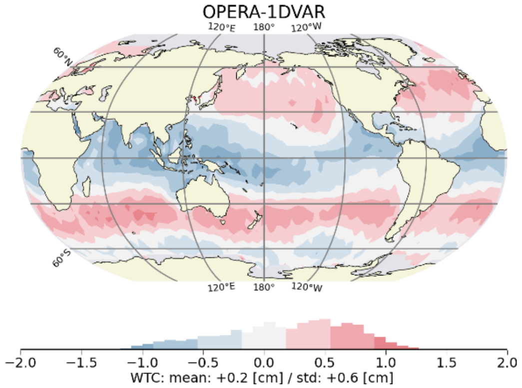
1D-VAR better



Validation: WTC Retrievals, Crossover Analysis

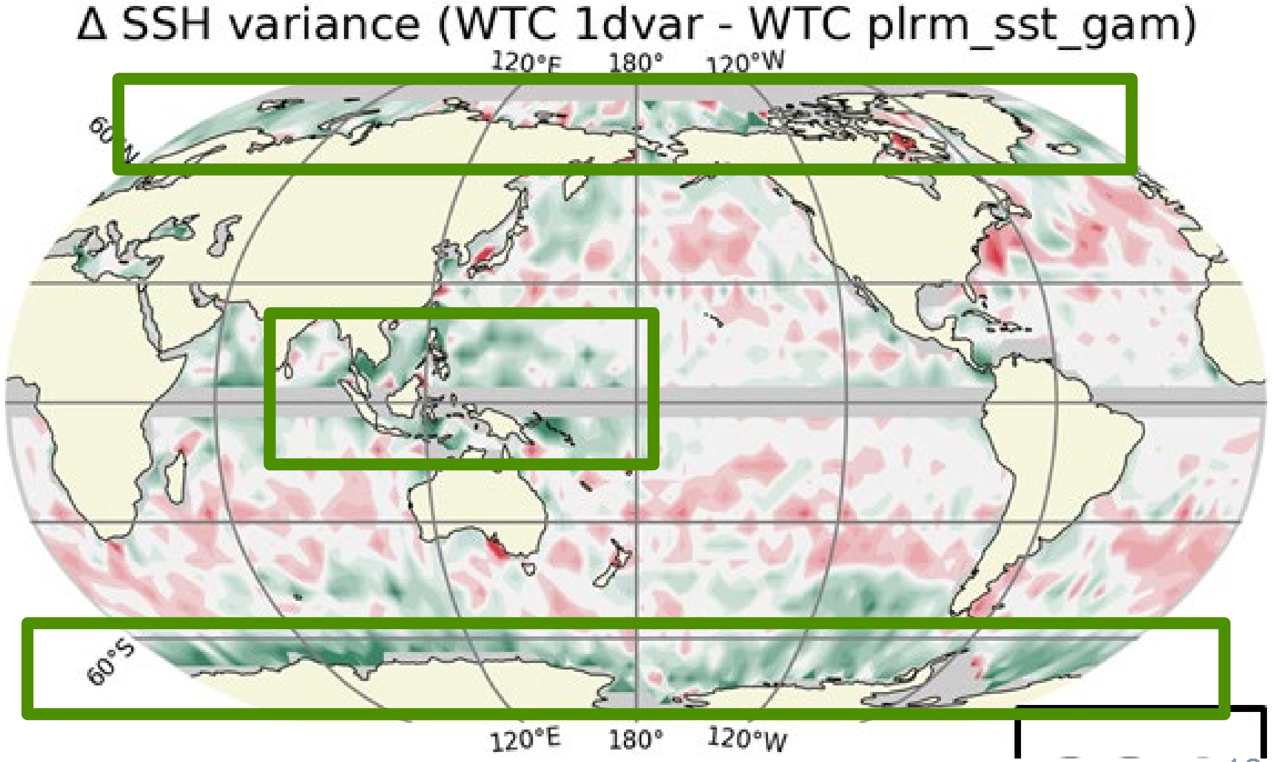
- Comparison of WTC 1DVAR against WTC CLS NN opera 5-p « PLRM SST GAM » (best solution)

- **1DVAR performs better** at high latitudes where 1DVAR is **wetter** than Opera over the indo-pacific warm pool



Opera better

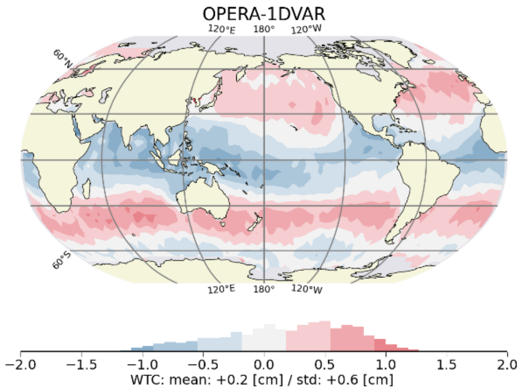
1D-VAR better

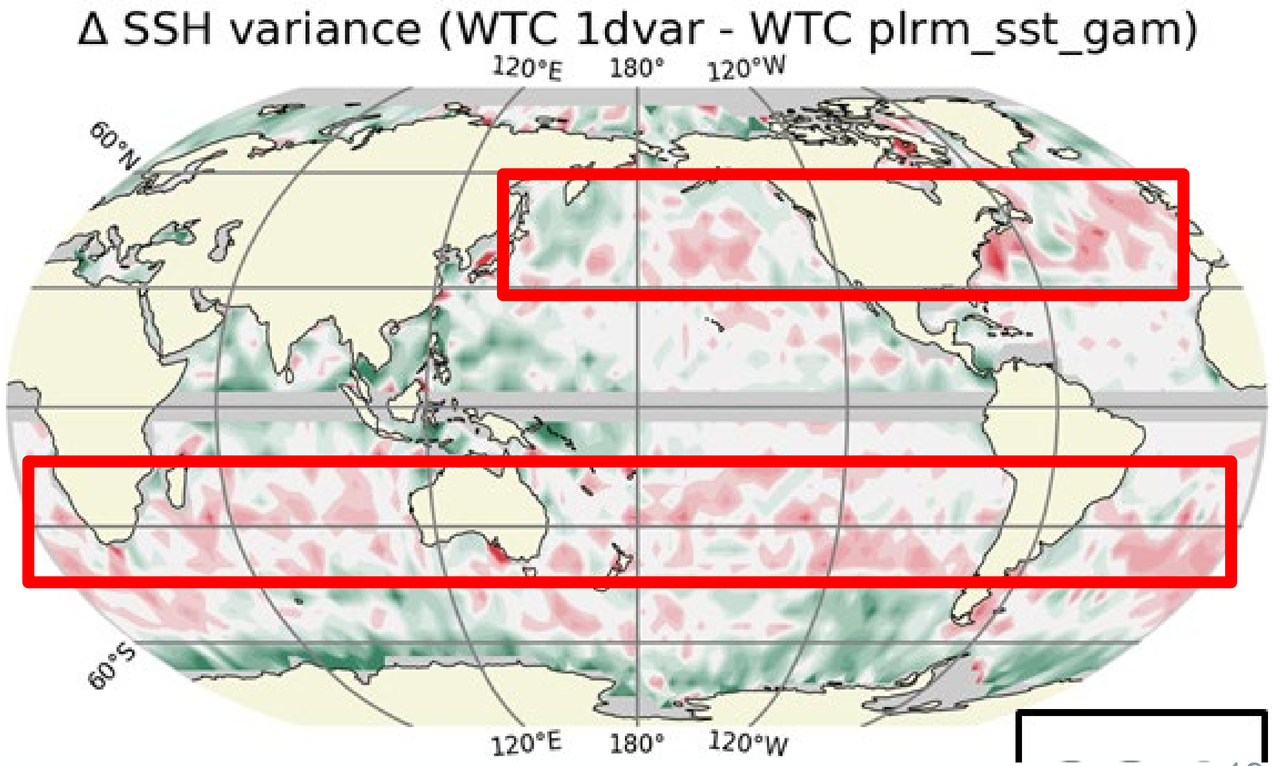


Validation: WTC Retrievals, Crossover Analysis

- Comparison of WTC 1DVAR against WTC CLS NN opera 5-p « PLRM SST GAM » (best solution)

- **CLS NN opera. performs better** at high latitudes where OPERA is **wetter** than 1DVAR





Opera better

1D-VAR better

Validation: Conclusions

- **TCWV**
  - 1D-VAR retrieval success: ca. 95-96 %
  - Excellent agreement between S3A and S3B
  - Good agreement between 1D-VAR, OPR, ERA-5. AIRWAVE drier, esp. near 15-25 kg/m³
- **WTC**
  - 1D-VAR and operational WTC retrievals show similar performances
    - *1D-VAR overall slightly better than 5p PLRM slightly better than 3p SAR*
    - *Opera WTC better at mid-latitudes*
    - *1D-VAR better at high latitudes and over the warm pool*
  - Reason for the observed differences not yet completely understood
- **1D-VAR is a mature algorithm, at the level of operational products**
- **+ uncertainty + bias monitoring + …. room for improvements :-D**

Looking …

- **… aside**
  - **ESA LTDP FDR4ALT** (PI CLS): Apply 1D-VAR MWR retrieval to ERS-1/2 and Envisat
  - Join the dots (AMTROC+FDR4ALT): Generate a methodologically consistent time series …
    - *… for TCWV, WTC, and LWP (plus uncertainties)*
    - *… covering the 30+ years time period starting in 07/91 (gap: 04/12 – 03/16)*
- **… beyond**
  - Investigate the synergetic use of concomitant MWR and SLSTR observations
    - *➔ Identify retrieval adverse meteorological situations?*
    - *➔ Improve TCWV / WTC accuracy closer to the coast?*
  - Apply 1D-VAR to Sentinel-6 observations (AMR-C + HRMR)
    - *➔ Improved retrieval accuracy?*
  - Apply 1D-VAR to Jason-3 AMR
    - *➔ Fill the gap in the ERS-1/2, ENV, S3-A/B time series?*

Meteosat-8, 15 January 2006, 15:30 UTC
Channel 05 (WV6.2)
Source: EUMETSAT

Thank you for your attention