Satellite retrievals of total column water vapor and clouds

P2: Observation-based weather analysis and Nowcasting (QPN)

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Freie Universität Berlin

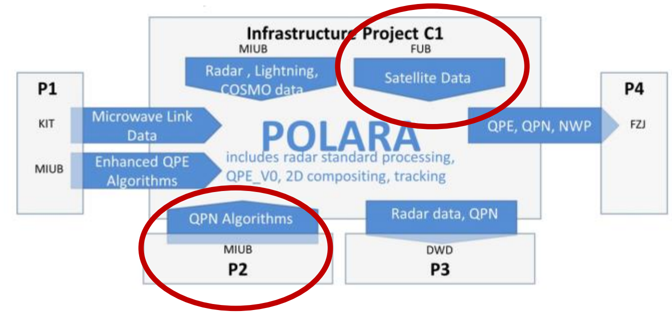
RealPEP 2 Meeting
28/29 April 2022, Bonn, Germany

Review

RealPEP

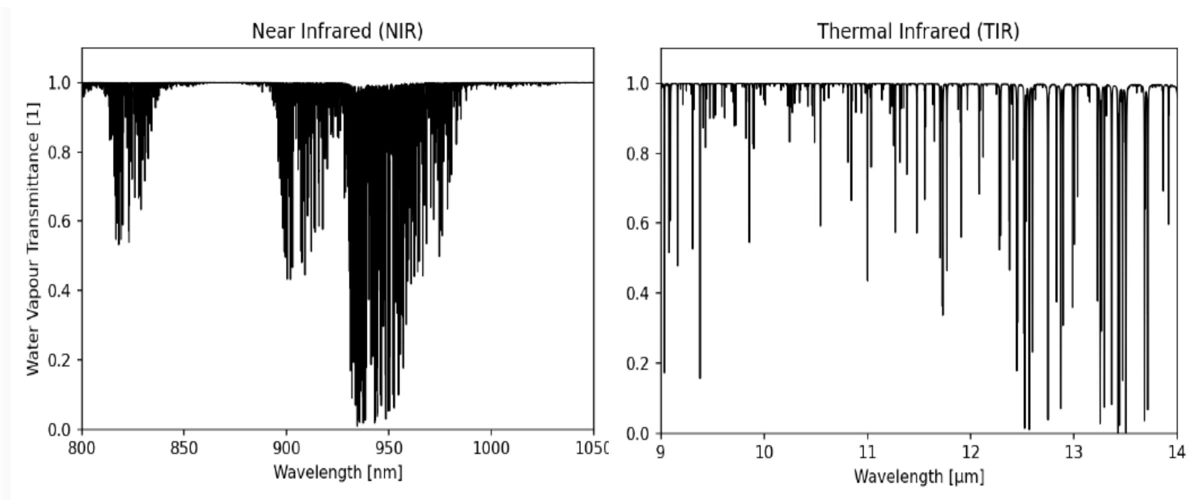
- FUB was in C1 infrastructure project in phase 1

Now in P2!



- Collecting, developing and processing satellite-based observations of total column water vapor (TCWV) and clouds for assessment of **statistical relationship between observed TCWV variabilities and (convective) cloud development at later time steps**:

→ Using passive VIS/NIR/TIR measurements!



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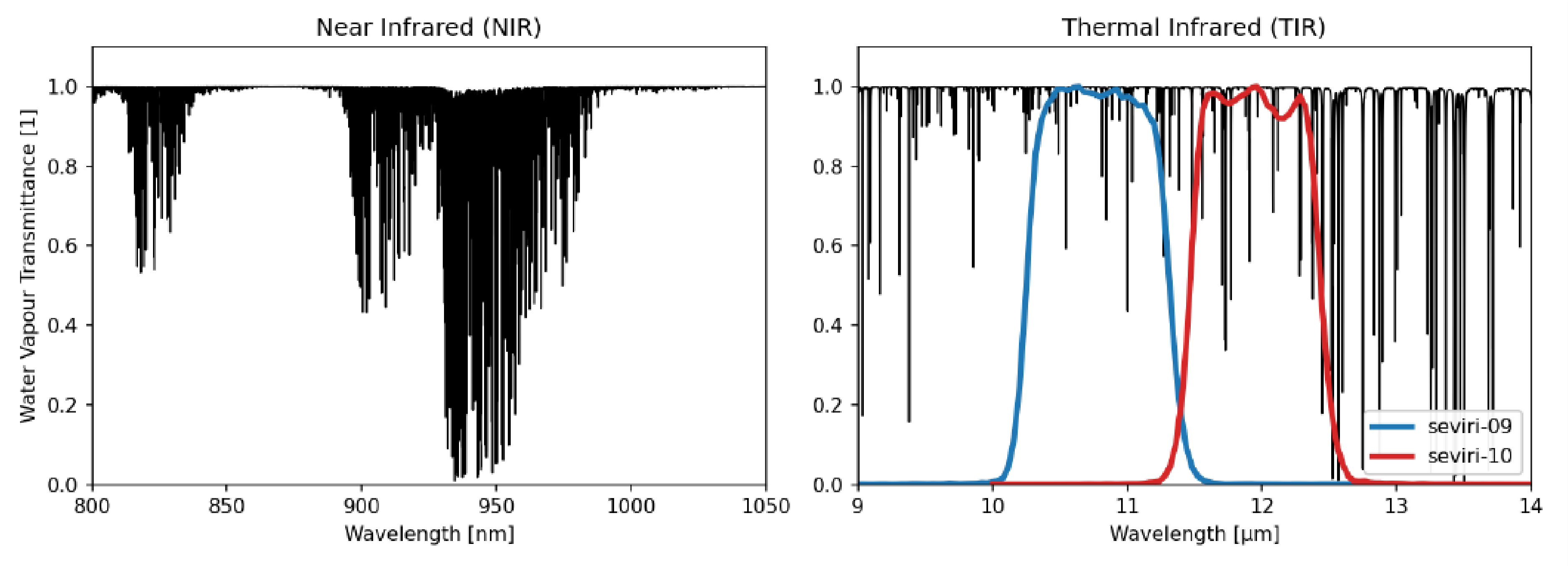
MSG-SEVIRI TCWV retrieval

- Split-window in Thermal Infrared (TIR) 11 µm and 12 µm
- Both window channels with little absorption by gases
- 12 µm is „dirtier“ wrt water vapour, lower temperatures

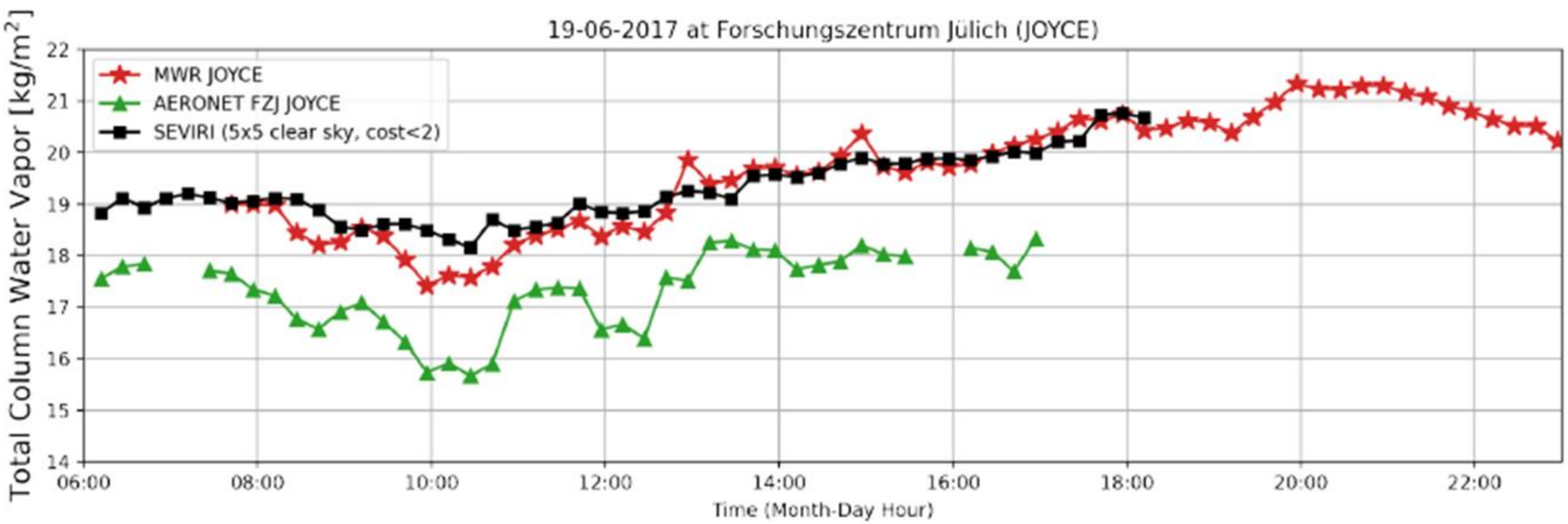
→ TCWV/T_s + uncertainties at 15 min. temporal resolution, $4x7km^2$ spatial resolution



MSG-SEVIRI TCWV retrievals

Advantages:
- Applicable to any sensor with similar TIR bands
- Day- and nighttime retrievals
- Time series of TCWV
- Sensitive over dark and water surfaces

Challenges/disadvantages:
- Prior knowledge needed on surface emissivity & T/WV atmospheric profiles
- Sensitive to thin clouds
- Relatively slow processing



From El Kassar, Carbajal Henken & Preusker, 2021

MSG-SEVIRI TCWV retrievals

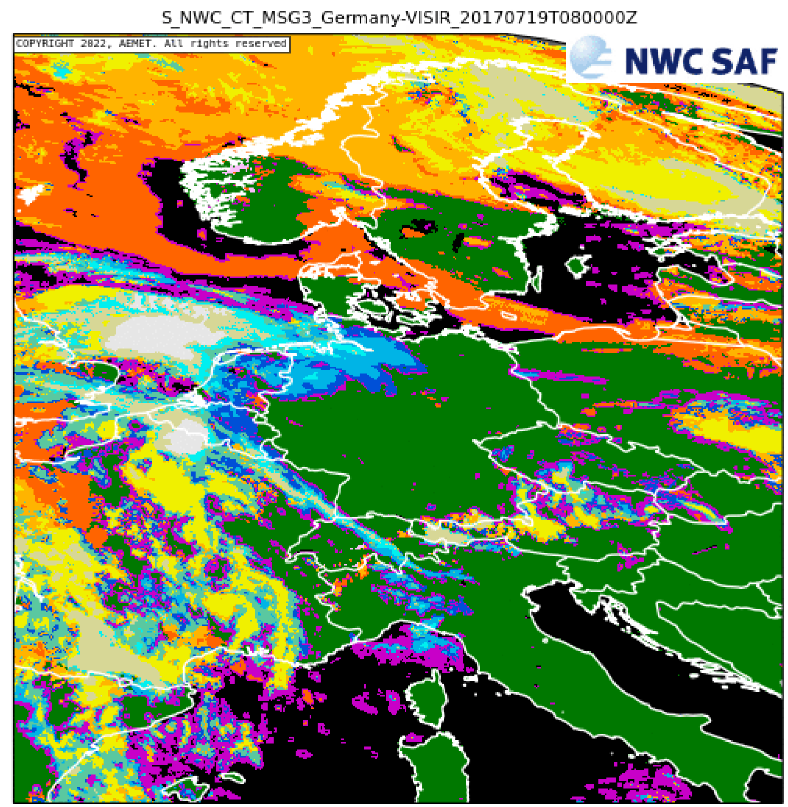
DFG RealPEP

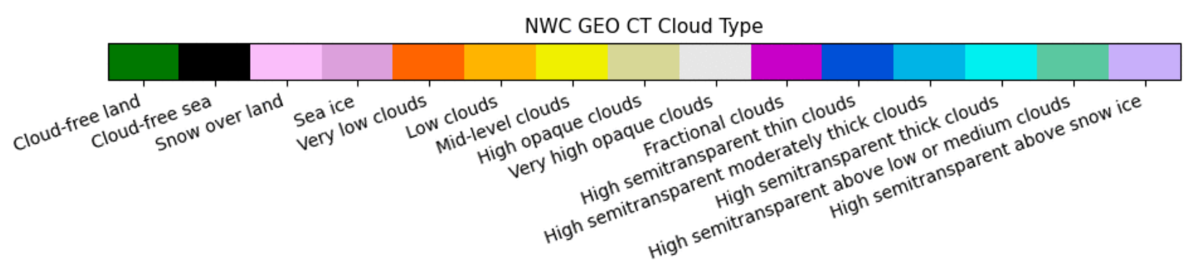
Done and work in progress

- Small adjustments in retrieval framework
- Collected L1 data
- Processed NWCSAF cloud mask
- Processing of 6 years of TCWV fields for Germany

Outlook

- Add to match-up dataset with TCWV from OLCI and GPS and NWCSAF cloud products

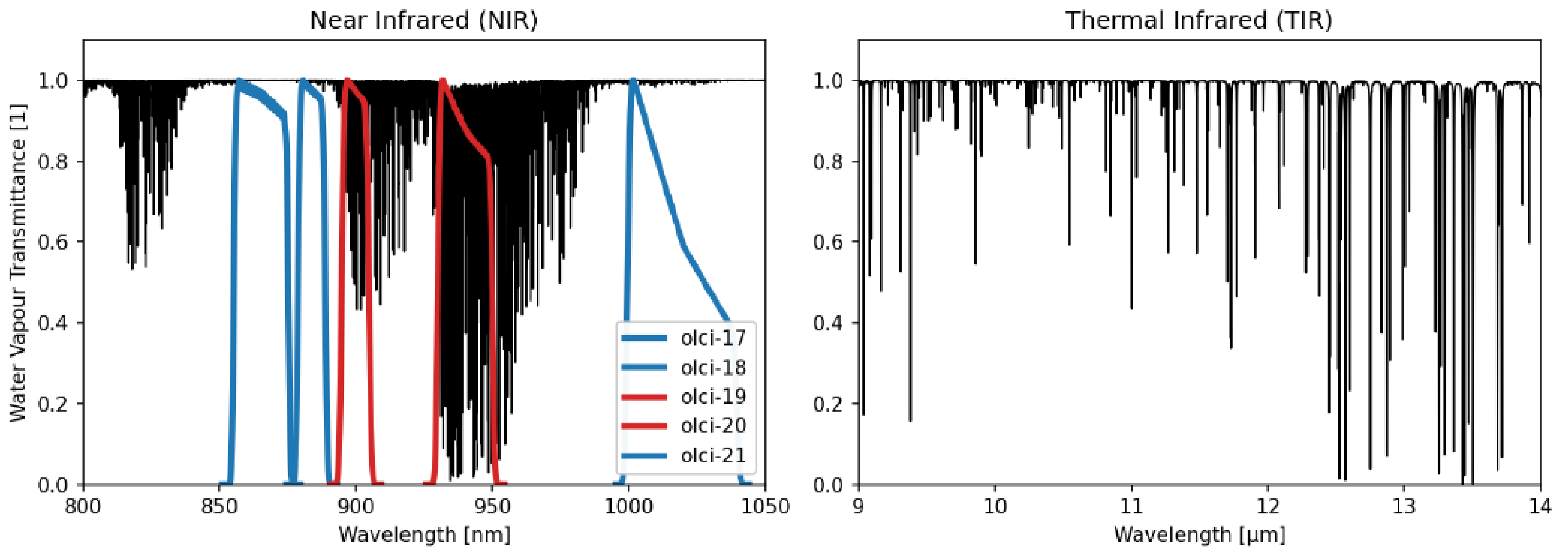




OLCI TCWV retrievals

- ρστ absorption band (850 nm to 1000 nm) in the Near-Infrared (NIR), OLCI has 5 bands
- Strong absorption feature of WV, very sensitive
- Aiming for MTG-FCI-like configuration (OLCI 885 nm and 900 nm)

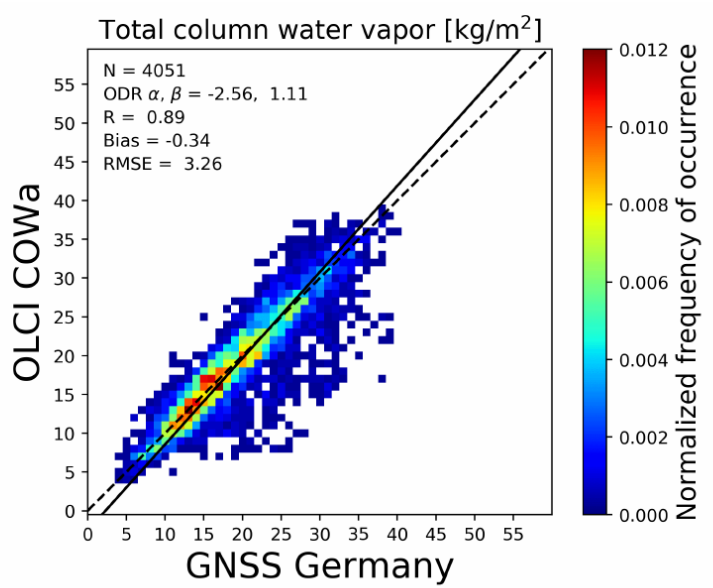
→ TCWV + uncertainty, ~2 times daily in the morning, 300x300m^2 spatial resolution

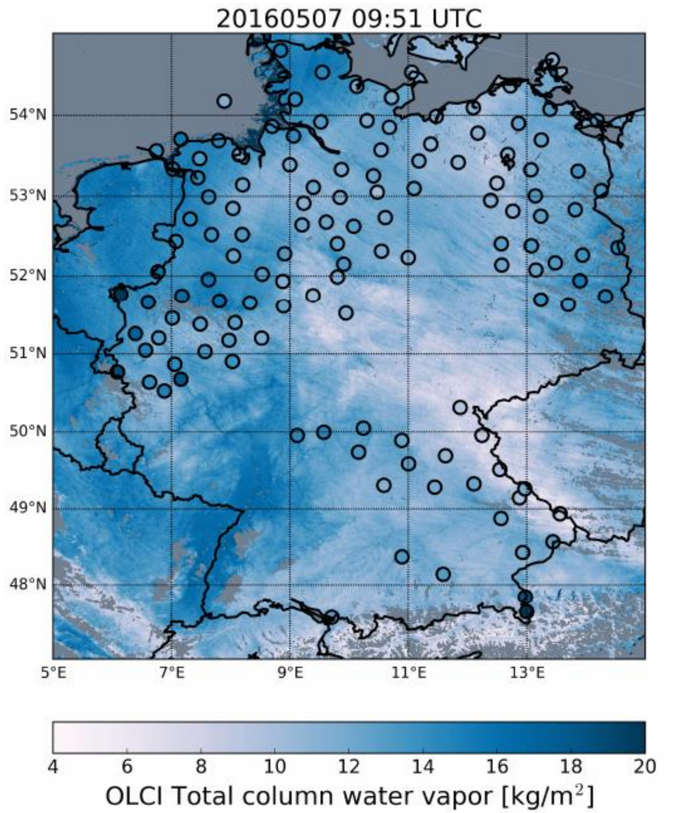


OLCI TCWV retrievals

Advantages:
- Applicable to any sensor with similar ρστ bands
- Very sensitive over land and bright surfaces
- Very high spatial resolution allowing obs of small-scale features in WV field
- Very fast processing

Challenges/disadvantages:
- Low accuracy over water and dark surfaces
- Sensitive to thin clouds over dark surfaces
- Only daytime TCWV retrievals





From Preusker, Carbajal Henken & Fischer, 2021

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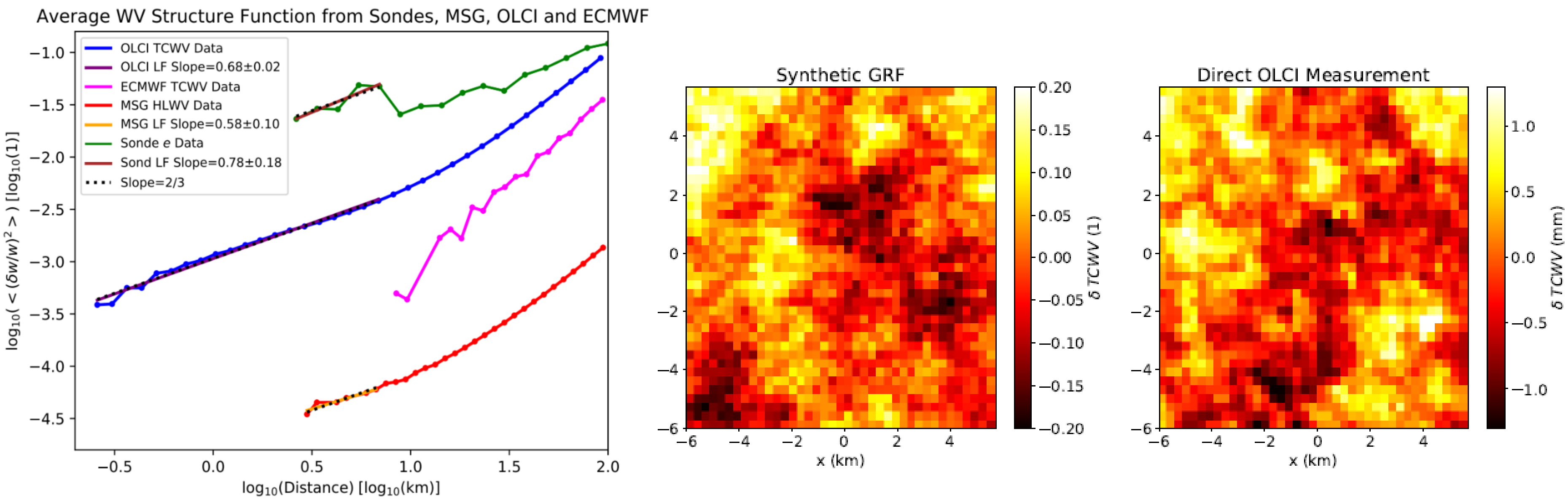
OLCI TCWV

Done and work in progress

- Collected L1 data
- Introduced new, improved cloud mask
- Processed years 2019-2021

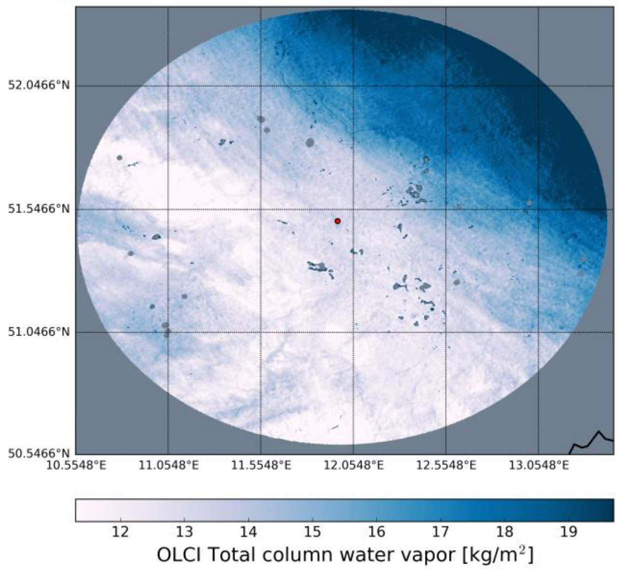
Outlook

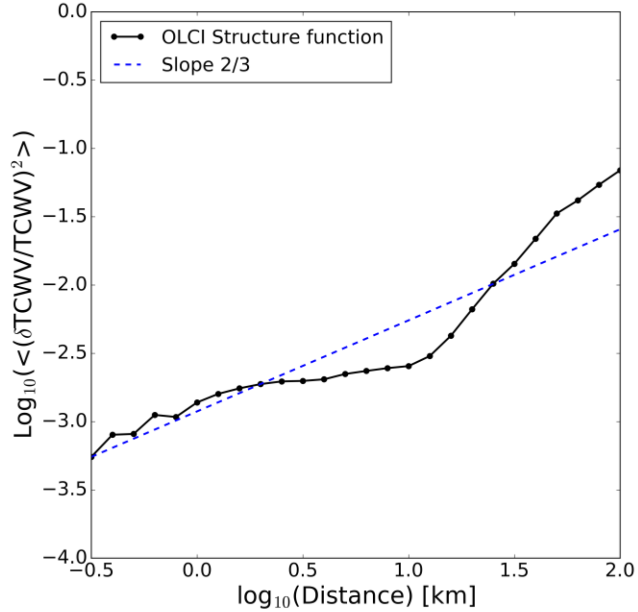
- Looking into the **structure function** → how the TCWV variance scales with the distance (Calbet et al. 2022, submitted)

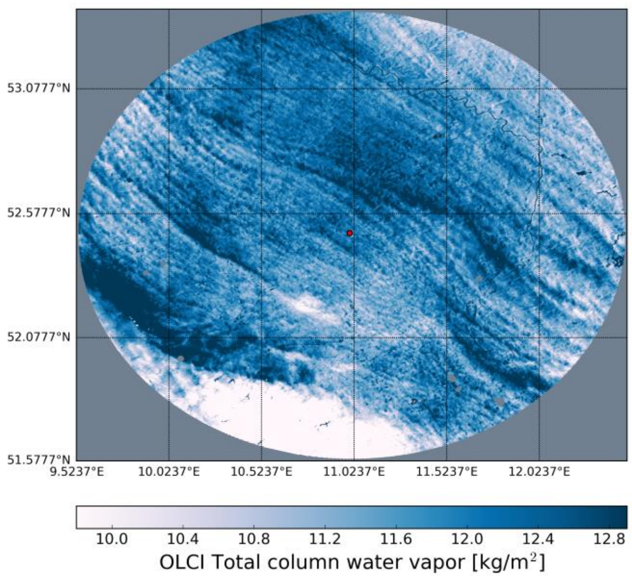


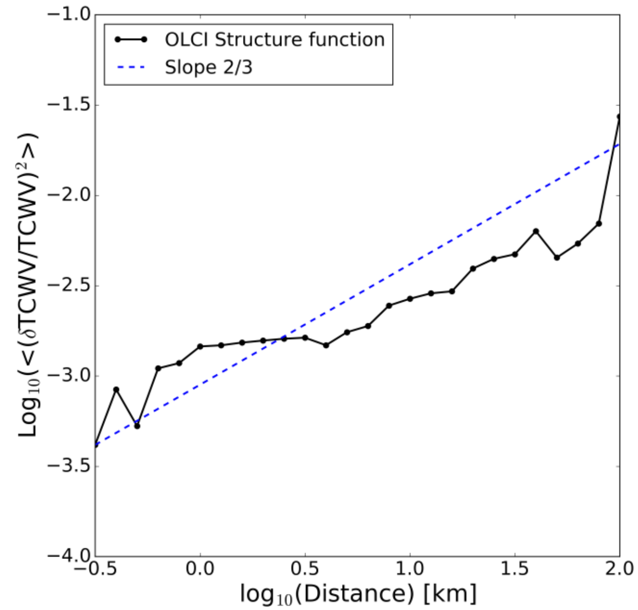
From Calbet et al., 2022

OLCI TCWV









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OLCI TCWV

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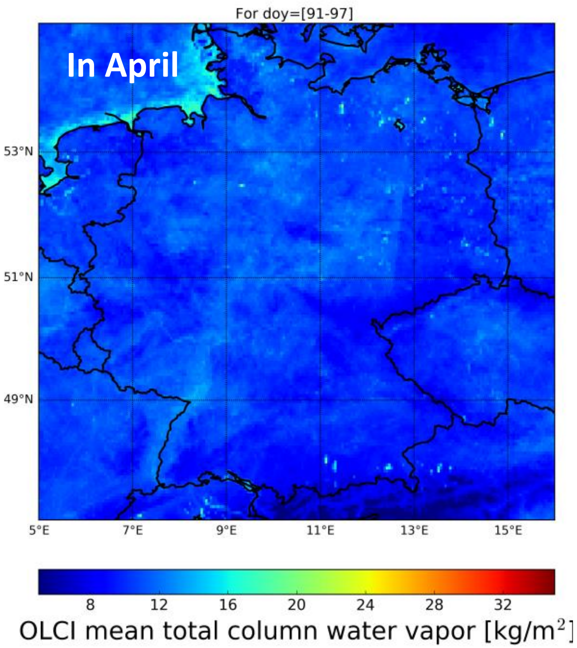
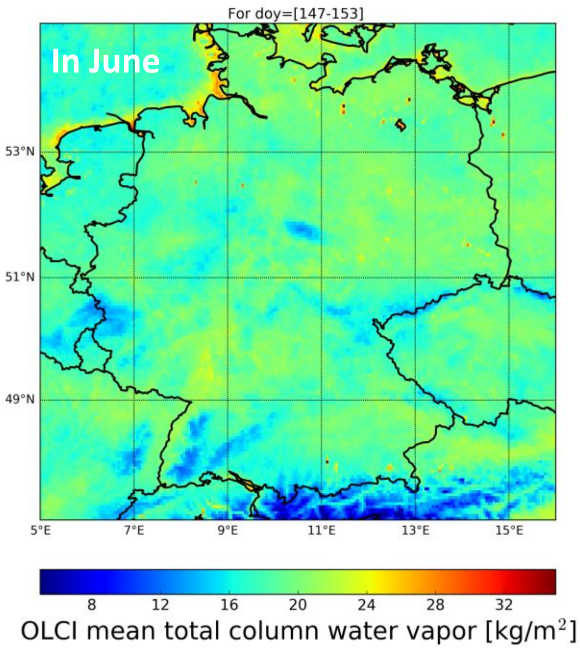
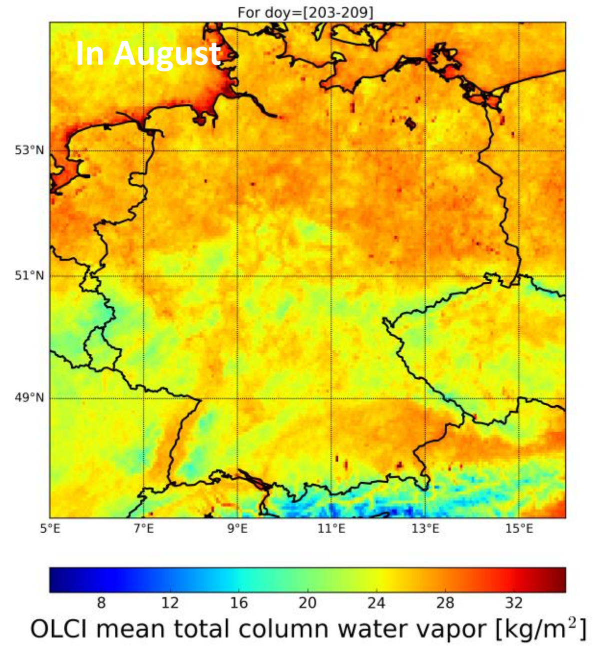
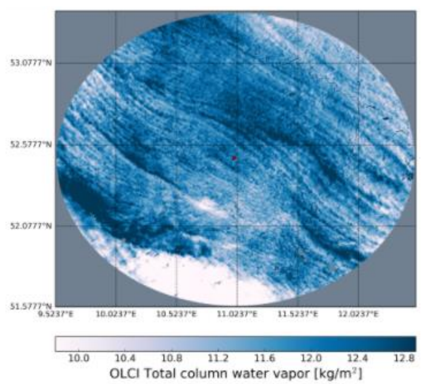
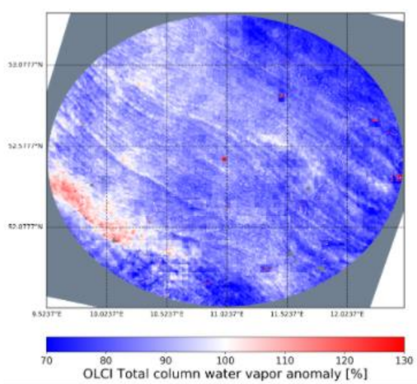
OLCI 2-weeks climatology based on 6 years of observations

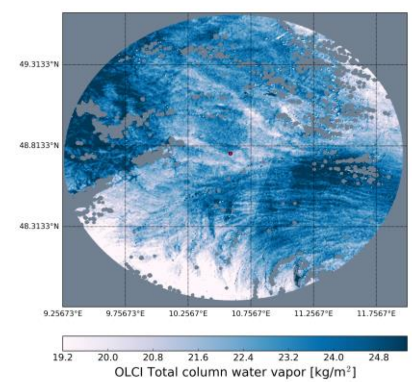


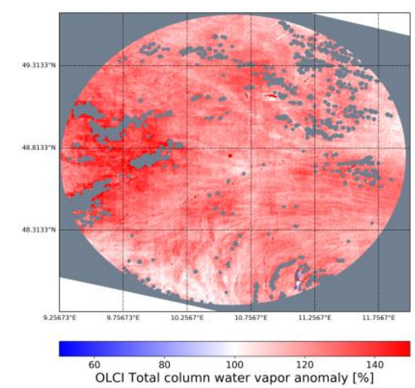












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NWC-SAF Software

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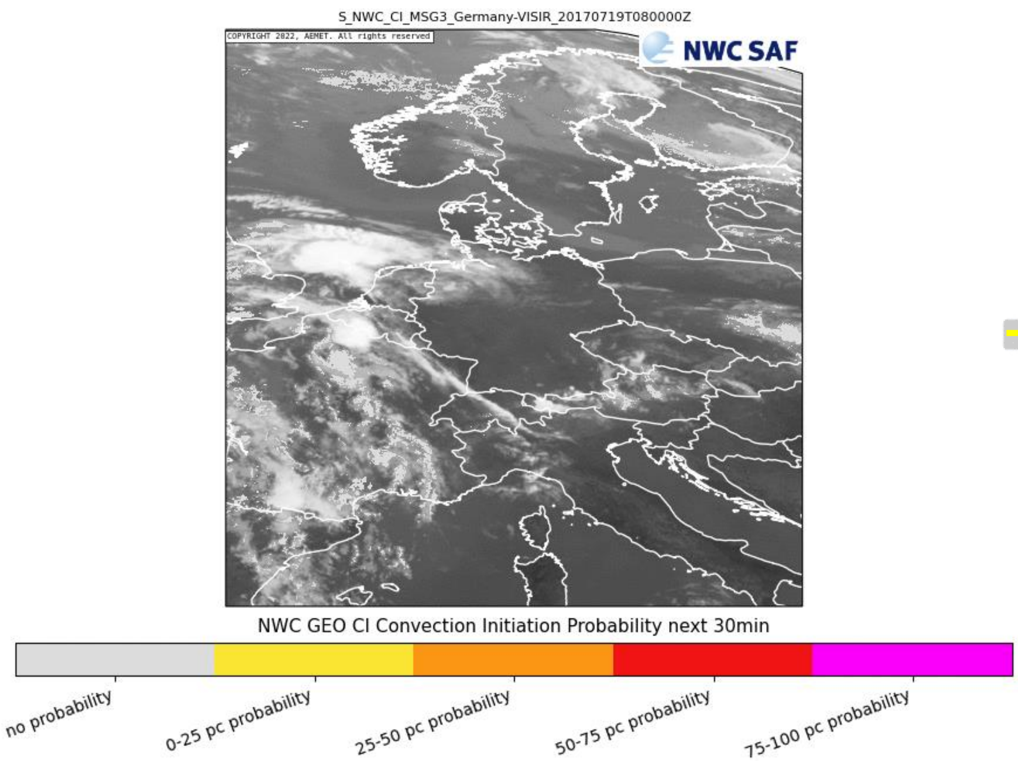
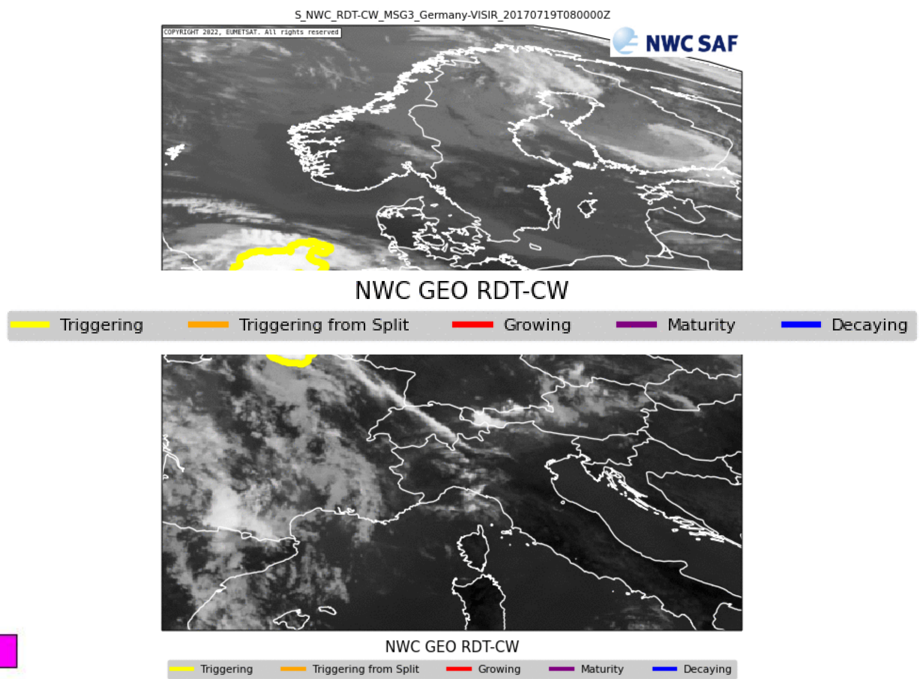
- Cloud types
- In-cloud convective initiation
- Rapid thunderstorm developement





NWC-SAF Software

Done and Work in progress

- Completed our set-up for processing
  - L1 SEVIRI with conversion from native to HRIT format
  - Reanalysis ERA5 as aux input

- Processing
  - Finished 2016-2018
  - Running 2019-2021

Outlook

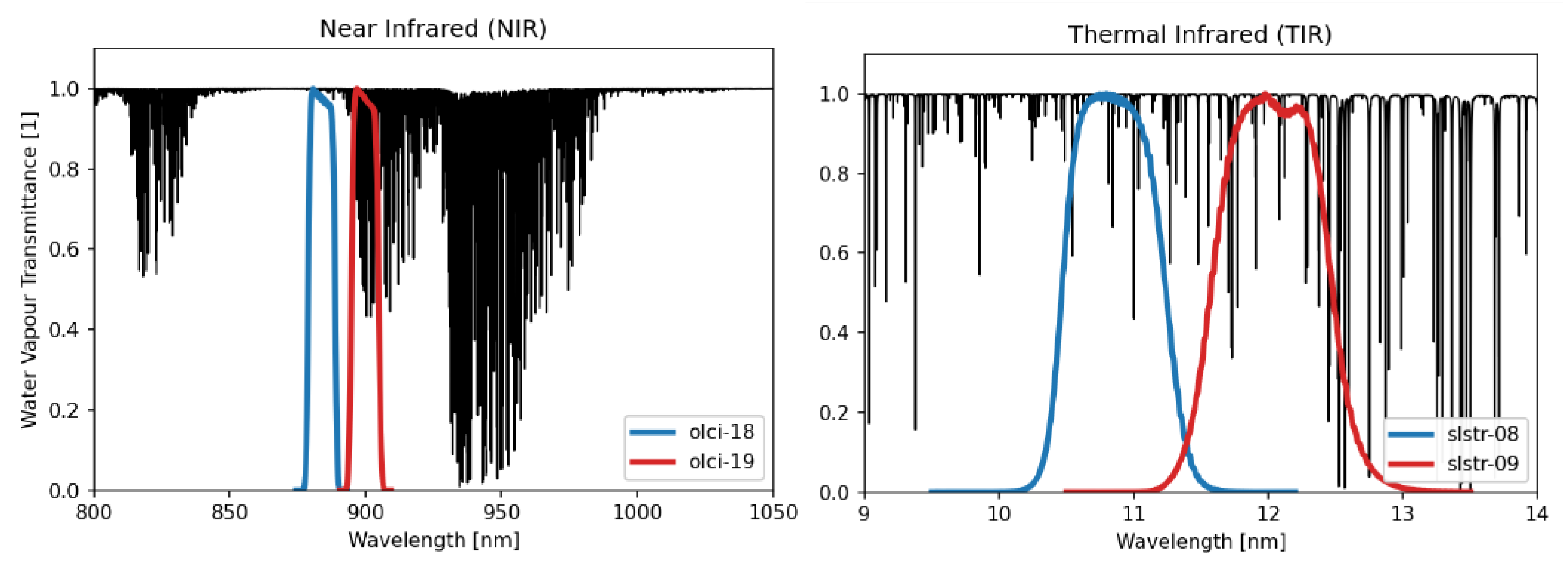
- Decide on CT/CI and RDT products

NIR+TIR combination

NIR + TIR strengths and weaknesses complement each other

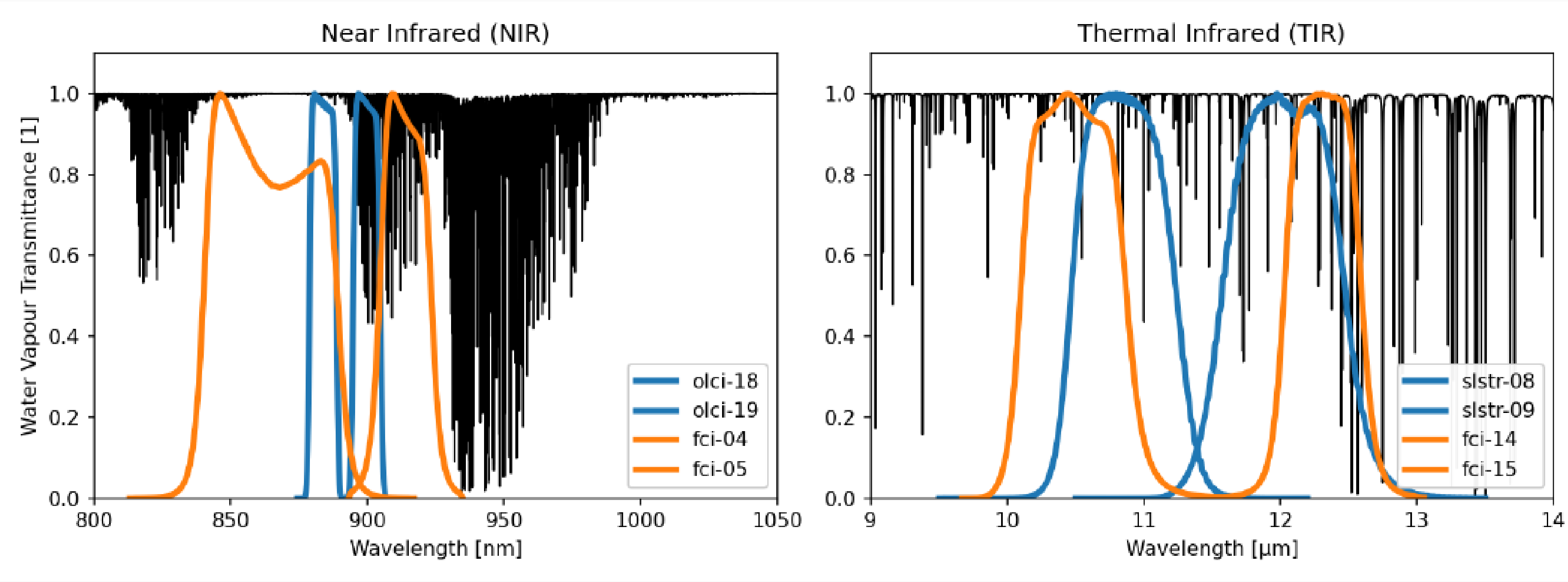
- Use forward models of both presented algorithms
- Profit from good WV retrievals over bright and dark surfaces

→ Combine OLCI with SLSTR (both passive imagers on Sentinel-3 satellites)



Towards TCWV from MTG-FCI

OLCI+SLSTR syngergy TCWV retrieval framework serves as MTG-FCI precursor

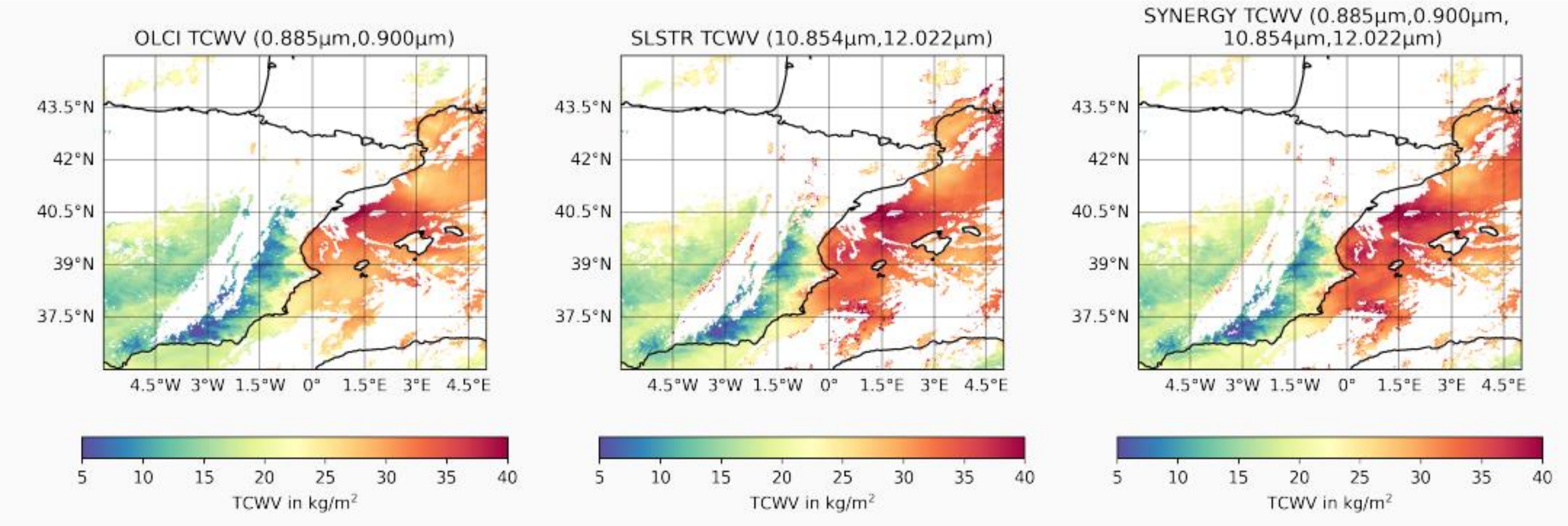


Towards TCWV from MTG-FCI

RealPEP

OLCI+SLSTR syngergy TCWV retrieval framework serves as MTG-FCI precursor

- „Dynamic range“ of TCWV values higher for syngergy product
- Gravity wave-like features observable over water and land surfaces



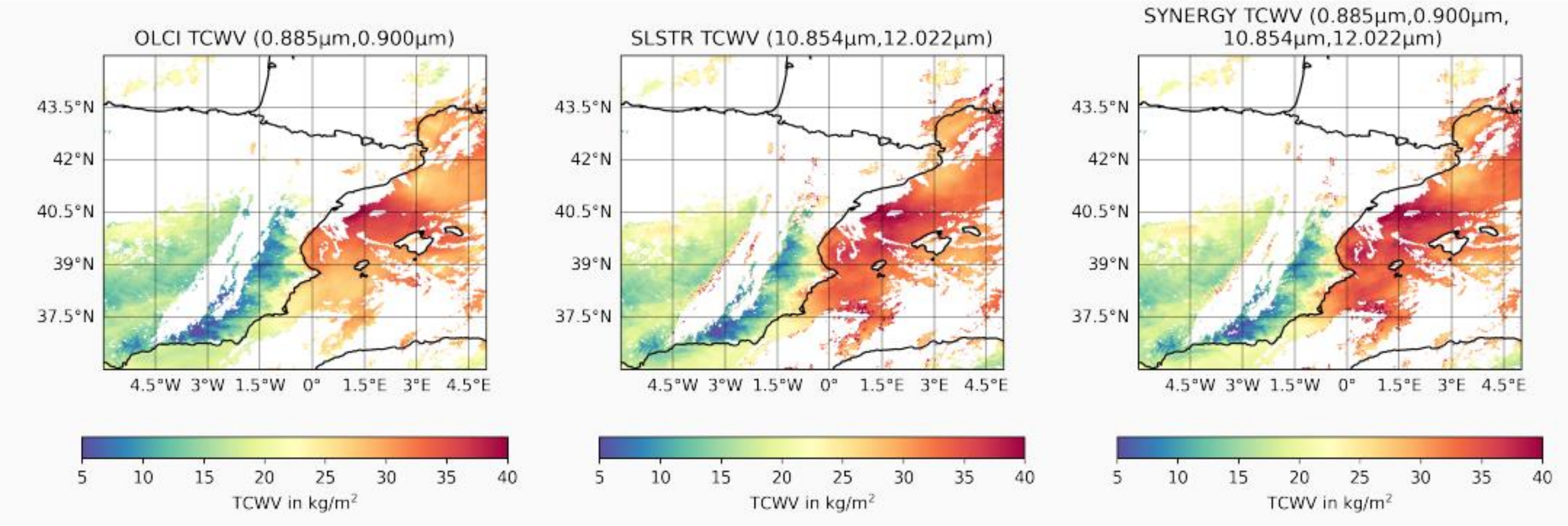
Towards TCWV from MTG-FCI

Done and work in progress

- Fine-tuning of prototype algorithm

Outlook

- Processing and validation with ground-based observations
- Investigate possible speed-up techniques, e.g., use of LUTs for TIR forward model



Summary on updates

Towards MTG-FCI TCWV retrievals

- benefitting from TCWV MSG-SEVIRI TIR and OLCI-SLSTR NIR-TIR retrievals
- Cooperation with EUMETSAT/NWCSAF

WP-P2-3: Development of TCWV retrieval algorithm for MTG-FCI (FUB, 1-24m)

Extended datasets/match-up

- OLCI TCWV 3 years
- GPS TCWV 1 year
- MSG-SEVIRI TCWV
- MSG-SEVIRI NWCSAF Cloud products

OLCI TCWV small-scale structures

- Structure function

WP-P2-4: Coherence of small-scale spatio-temporal TCWV variability (FUB, 1-30m)

Thanks!

Additional slides

Objective:
develop an observation-based ensemble nowcasting scheme, which makes use of microphysical process detection and tendencies derived from polarimetric weather radar and **satellite observations to significantly enhance lead time and skill.**

H4: Exploitation of the OLCI-Sentinel-3 and MTG-FCI observational capabilities with their higher spatio-temporal resolution will further advance CI detection in both clear-sky and cloudy regions.

H5: Information on potential convective initiation estimated from satellite cloud and total water vapor column retrievals, can be succesfully exploited as a proxy for future new cells, which increases the lead time of radar-based nowcasting.

WP-P2-3: Development of TCWV retrieval algorithm for MTG-FCI (FUB, 1-24m)

- Newest imager observational capabilities for clouds and water vapor in Europe (2022)
- NIR channels allow for improved TCWV retrievals → indicated by first RTTOV-based sensitivity studies (work in progress). Also improved cloud masking expected.
- Set-up of TCWV processor for connection to POLARA
- Publication

WP-P2-4: Coherence of small-scale spatio-temporal TCWV variability (FUB, 1-30m)

- Investigation of relationships between small-scale spatial TCWV variability from OLCI and temporal variabilities from GPS and MTG-FCI for different weather conditions to further advance (WP-P2-5)
- Assess whether similar relationships are observed in the ICON simulations
- Assess impact of including satellite-based TCWV fields in NWP assimilation process (WP-P3-3).

WP-P2-5: Advanced convective initiation detection (FUB, 12-36m)

- Increased spatio-temporal resolution of MTG-FCI will allow for more accurate identification of regions with increased CI probabilities at relevant time scales of minutes
- Identify and establish new TCWV-based CI proxies to increase lead time of new developing convective cells in radar-based nowcasting (as described in WP-P2-6).
- Preparation and provision of MTG-FCI cloud observations and derived cloud CI proxies for nowcasting of ´new convective cell development to increase lead times in precipitation nowcasting (WP-P2-6).
- Preparation and provision of MTG-FCI cloud products and CI proxies for a machine-learning-based precipitation nowcasting method (WP-C1-2).
- Set-up of CI processor for connection to POLARA
- Publication

Cooperations

Internal cooperations

- FUB with UniBonn within P2 on merging radar and satellite observations to improve precipitation nowcasting
- FUB with P3 on ICON relationship and TCWV assimilation assessment.
- FUB with C1 on machine-learning- and satellite-based precipitation nowcasting method
- FUB and UniBonn with P1 and P4 within evaluation/feedback rounds.

External cooperations:

- EUMETSAT
  - Andi Walther, RTTOV
  - (Rene Preusker, OLCI)
- Xavier Calbet from AEMET: use of high resolution OLCI TCWV to assess impact of TCWV variability within larger IASI footprint on retrievals → publication

Challenges

RealPEP

MTG-FCI

- Getting L1 and L2 data as quickly as possible once available
- quick processing for producing CI statistics

Merging SPROGS QPN fields with RNN QPN fields obtained from satellite-based input data.

Obtaining sophisticated **metrics on TCWV** variability from OLCI

- data gaps due to clouds, water surfaces (no retrievals)

Joint Evaluation

- how will feedback from P3 and P4 for P2 look like?
- What kind of evaluation/validation metrics are used, which ones are considered crucial?
- How can the impact of single changes on the overall outcome be assessed (e.g. new QPN product with added value from satellite observations on new flood prediction simulations)
- etc.

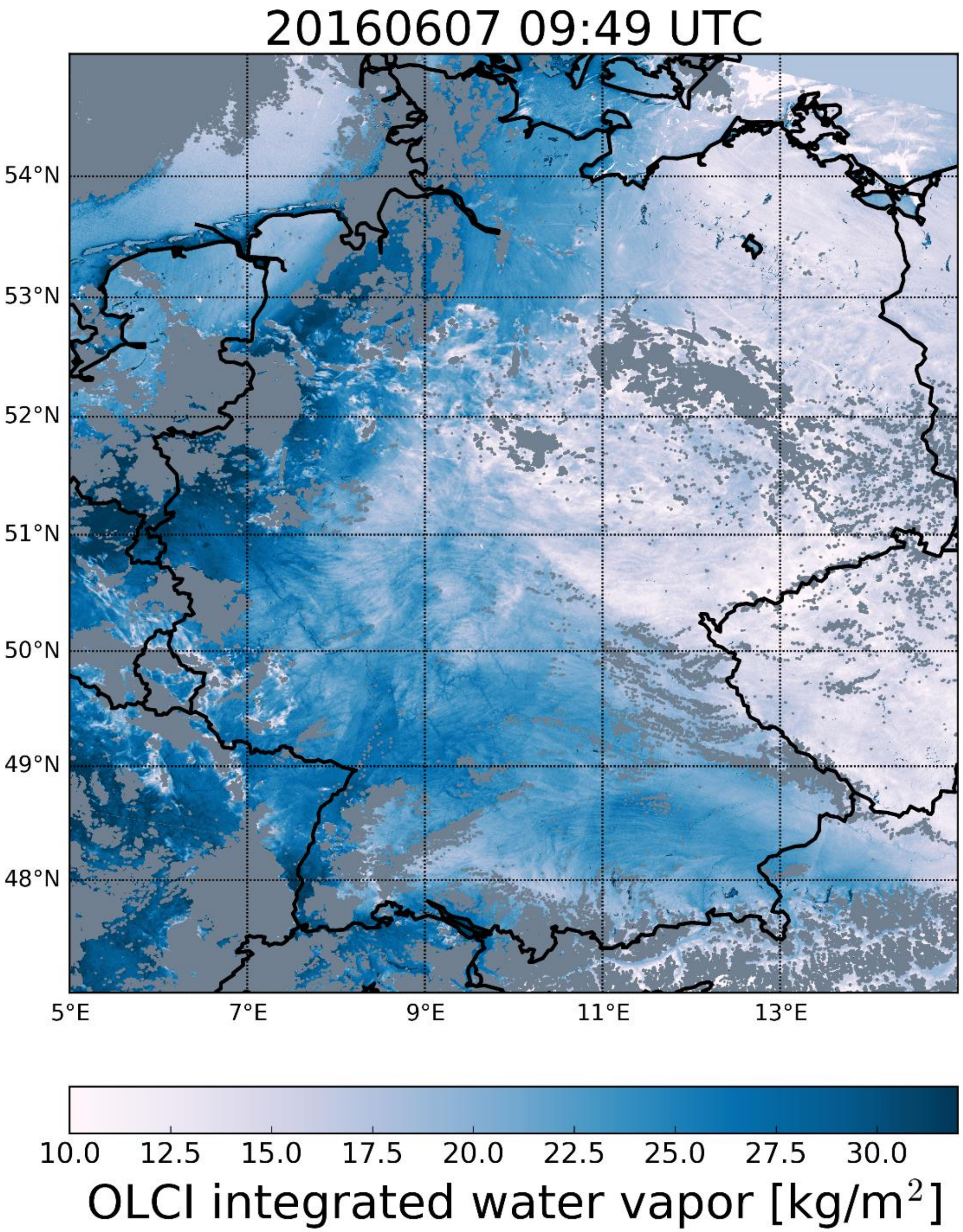
RNN P2 vs. C1

P2 alone is providing a combined nowcasting, which is SPROG with satellite-based CI information included. For that, C1 is only providing the technical set up of an RNN.

P2 uses the RNN to link satellite-based information on cell initiation with their subsequent development into QPE fields; this link is then used to enrich the SPROG nowcast with the new cells.

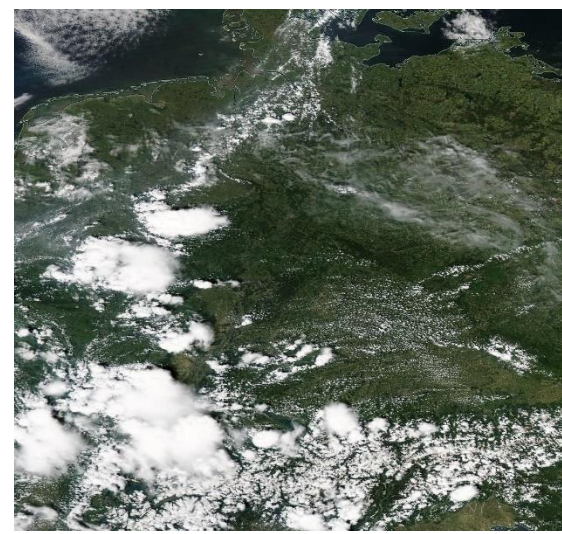
In parallel, C1 will provide a radar-only (QPE) and in a second step a radar-satellite-based nowcasting exclusively based on the training of a PredRNN.

OLCI TCWV example



MODIS-Terra at 10.20 UTC

MODIS-Aqua at 12.05 UTC



OLCI TCWV validation

RealPEP

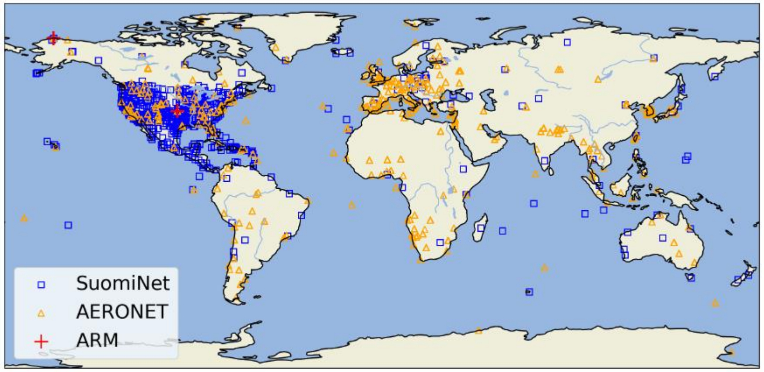


Figure 3. Geographic distribution of ground-based observational sites for the three global validation data sets.

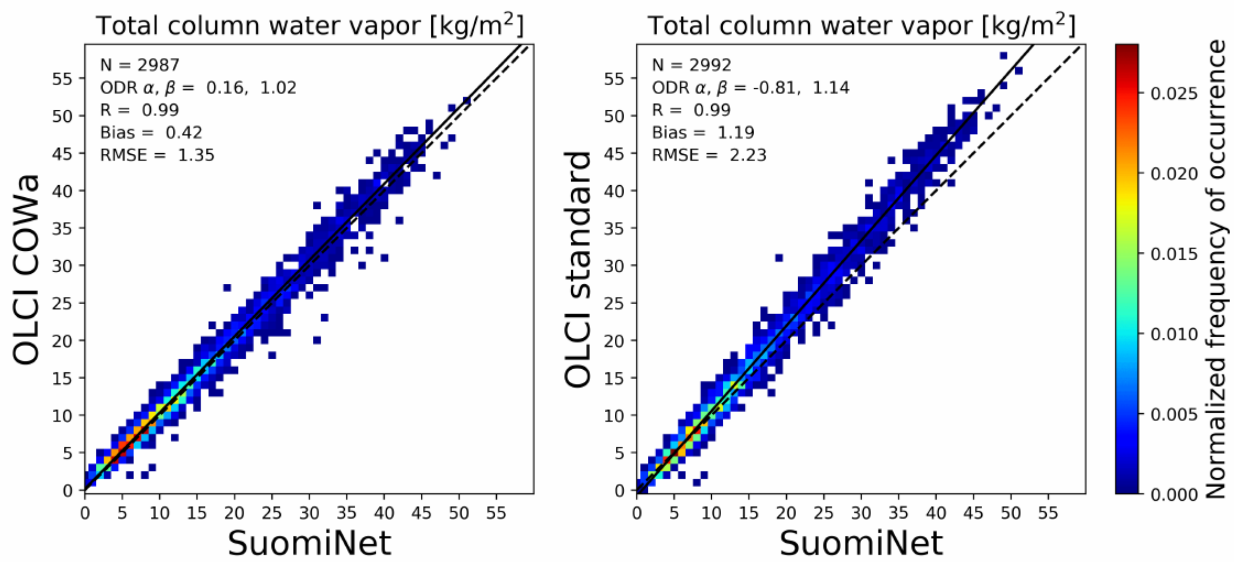


Figure 6. Normalised frequency of occurrence of the TCWV products for the comparison of the OLCI COWa TCWV retrieval algorithm (left) and the OLCI standard TCWV processor (right) against SuomiNet. Symbols and abbreviations same as in Figure 4.

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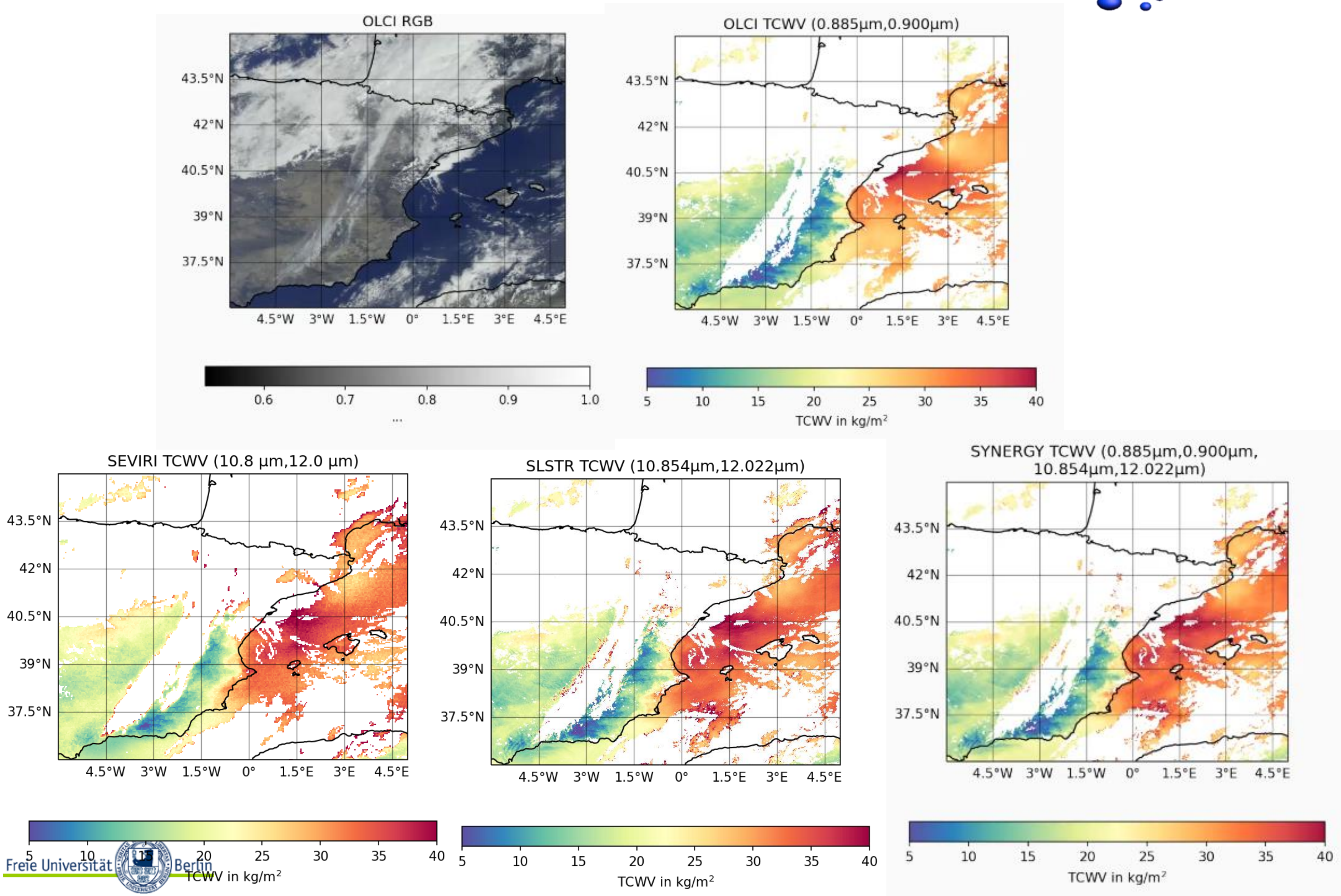
Current work & Outlook



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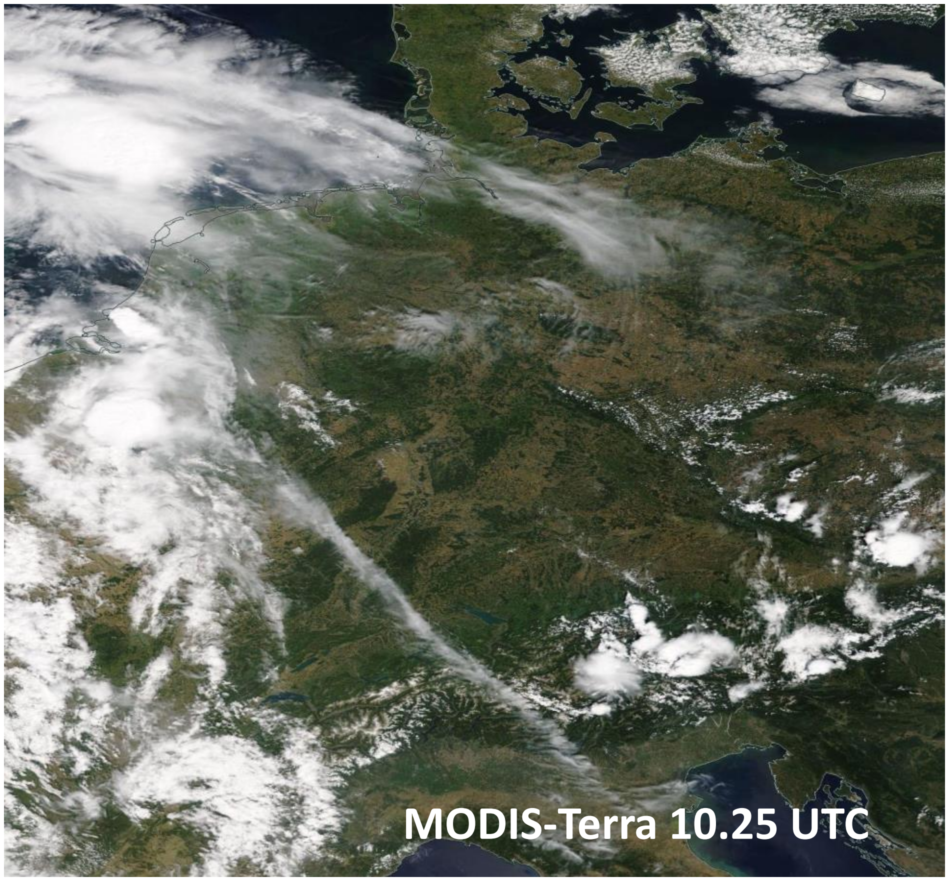
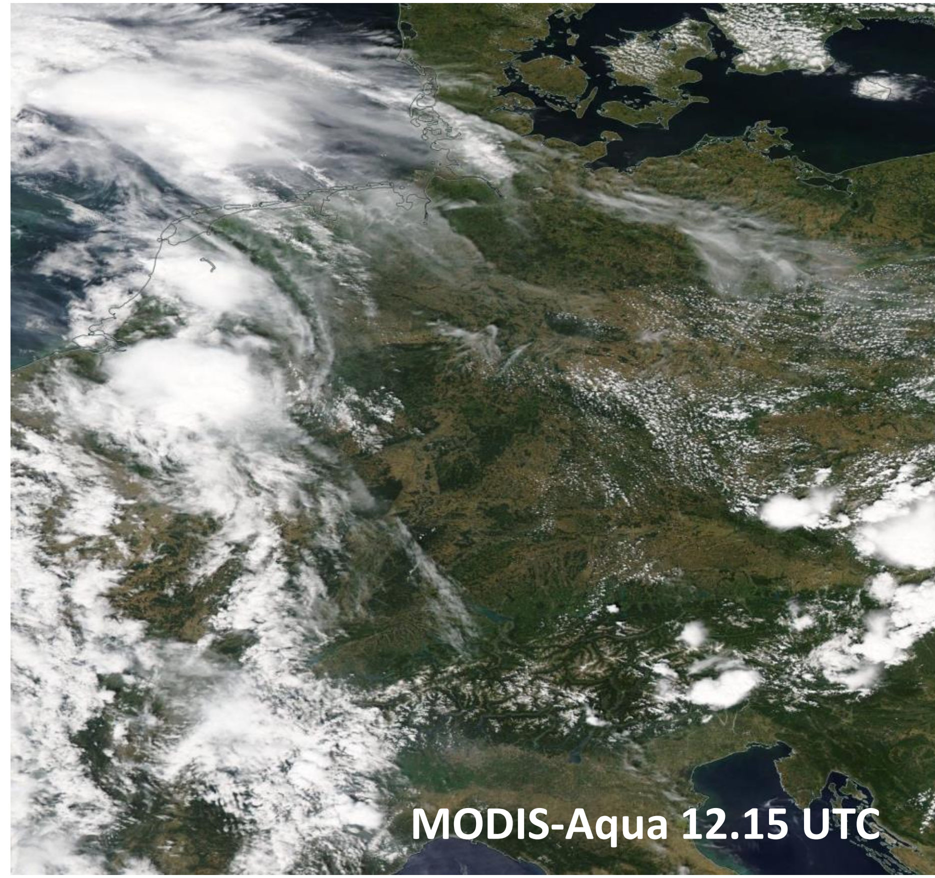
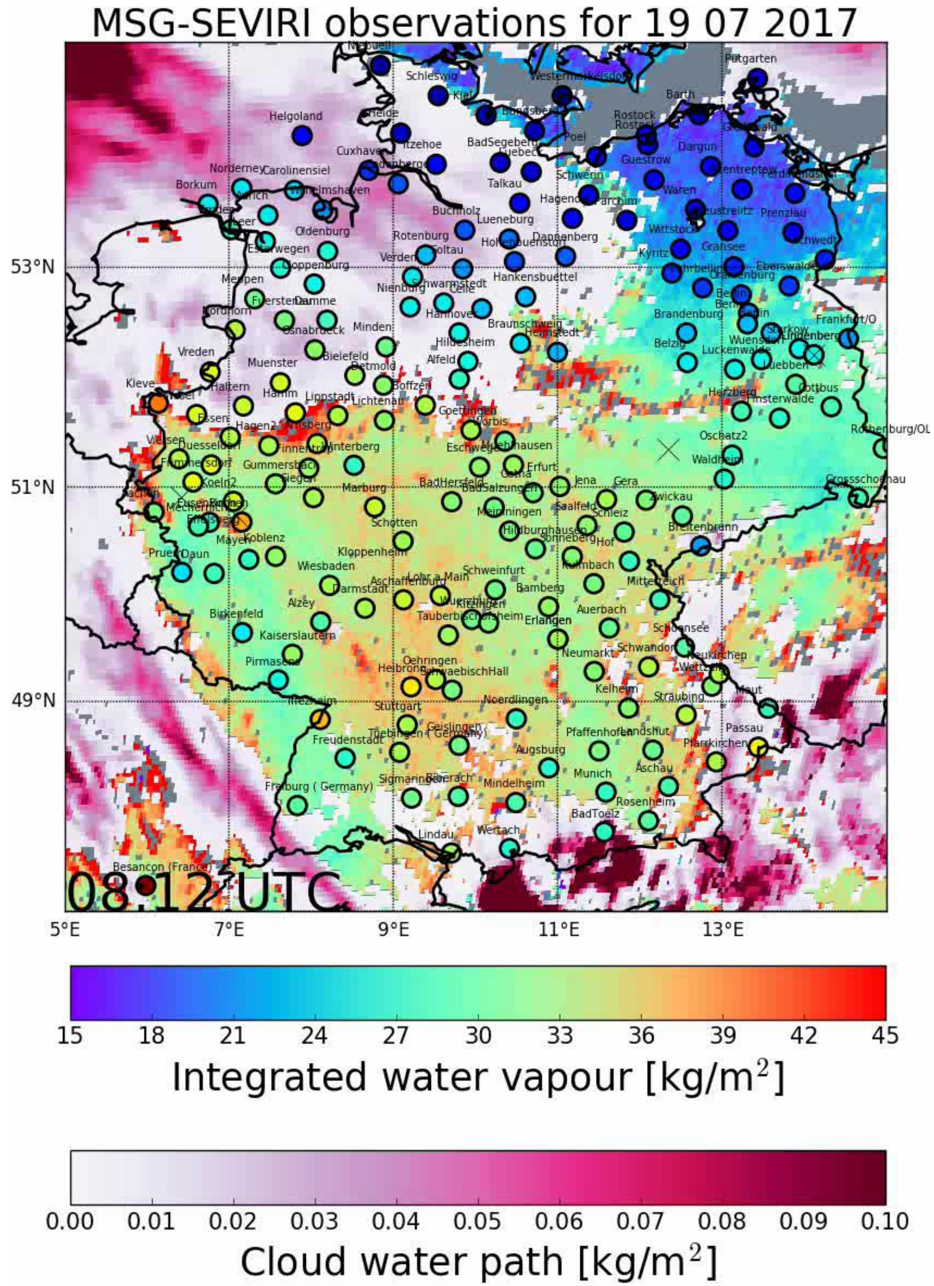
Case study day 19 July 2017



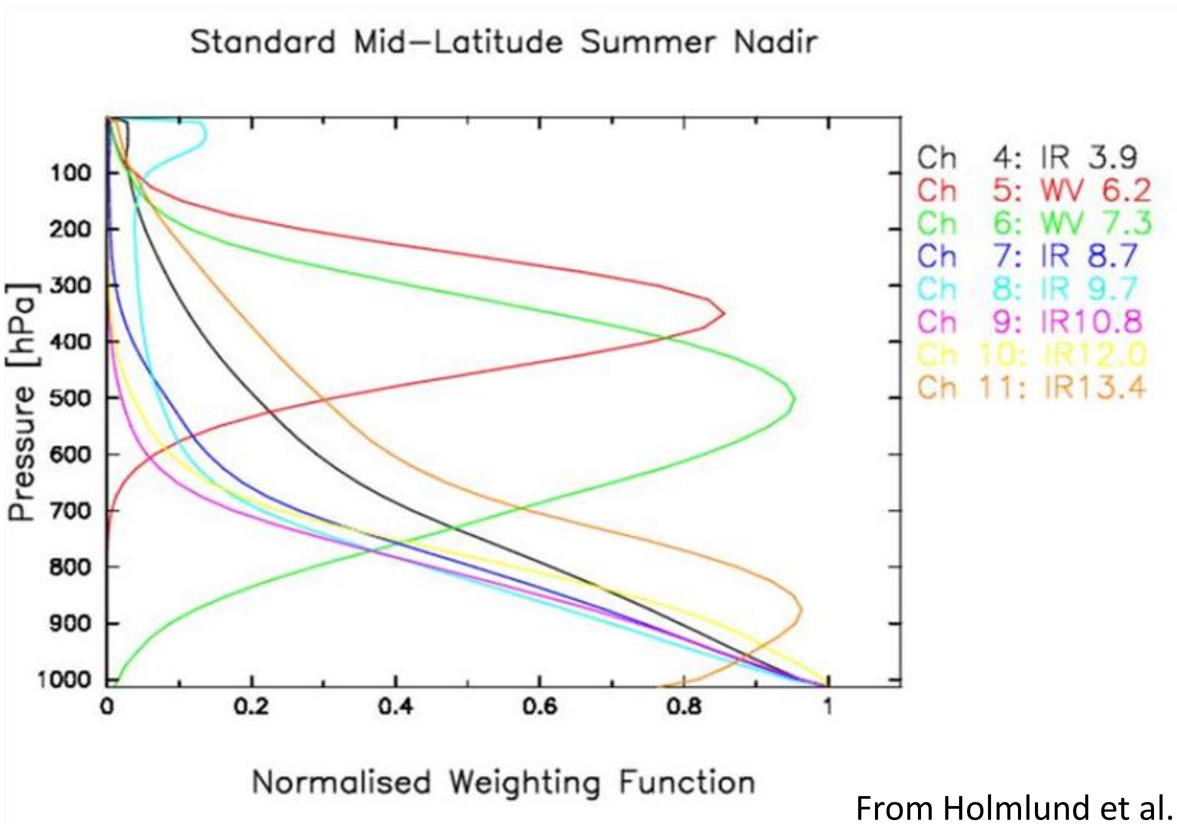


Case study day 19 July 2017



MSG-SEVIRI

- MSG geostationary satellite, MTG follow-up mission (2022)
- SEVIRI: passive imager with channels in VIS/NIR/TIR
- Temporal resolution 15 min., spatial resolution ~4km x 7 km (in Germany)
- Measurements used: **Brightness temperatures (BTs) at 10.8 and 12 micron**
  - Both window channels
  - Differential water vapor absorption



From Holmlund et al. 2004

Flow-chart MSG IWV-Ts retrieval

DFG

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Pre-processing: prepare GPS data, MSG L1 native data, ERA5 data, emissivity maps

Read in global settings, paths to data, RTTOV etc.

Read in MSG L1 data
Get date, time step

Collect auxiliary data:
- MSG L2 cloud data at time step
- ERA5 hourly data
- GPS at time step
- Emissivity at date

All?
No
Yes

Per pixel (lat, lon)
MSG cloud mask

Clear-sky

Read in auxiliary data per pixel: ERA5, Emissivity, GPS (apriori)

Inverse technique
With RTTOV as forward model

Convergence?
Yes/no
Get retrieval info

Save retrieval results + aux:
IWV, Ts, uncertainties, lat/lon, viewing geometry, retrieval information

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MSG-SEVIRI vs. MTG-FCI

MSG-SEVIRI

- 3 km spatial resolution at sub-satellite point
- 15 min temporal resolution
- Spectral channels:

Table I. Spectral channel characteristics of SEVIRI providing central, minimum, and maximum wavelength of the channels and whether the channel is an absorption or a window channel. A concise summary of the use of the spectral channels is given in the section titled "SEVERI spectral channels."

Channel no.		Characteristics of spectral band (μm)			Main gaseous absorber or window
		λ_{cen}	λ_{min}	λ_{max}	
1	VIS0.6	0.635	0.56	0.71	Window
2	VIS0.8	0.81	0.74	0.88	Window
3	NIR1.6	1.64	1.50	1.78	Window
4	IR3.9	3.90	3.48	4.36	Window
5	WV6.2	6.25	5.35	7.15	Water vapor
6	WV7.3	7.35	6.85	7.85	Water vapor
7	IR8.7	8.70	8.30	9.10	Window
8	IR9.7	9.66	9.38	9.94	Ozone
9	IR10.8	10.80	9.80	11.80	Window
10	IR12.0	12.00	11.00	13.00	Window
11	IR13.4	13.40	12.40	14.40	Carbon dioxide
12	HRV	Broadband (about 0.4 – 1.1)			Window/water vapor

From Schmetz et al. 2002

MTG-FCI

- 1 km spatial resolution at sub-satellite point for VIS/NIR channels
- 10 min temporal resolution, 2.5 min for local scale (Europe)
- Spectral channels:

Instrument information

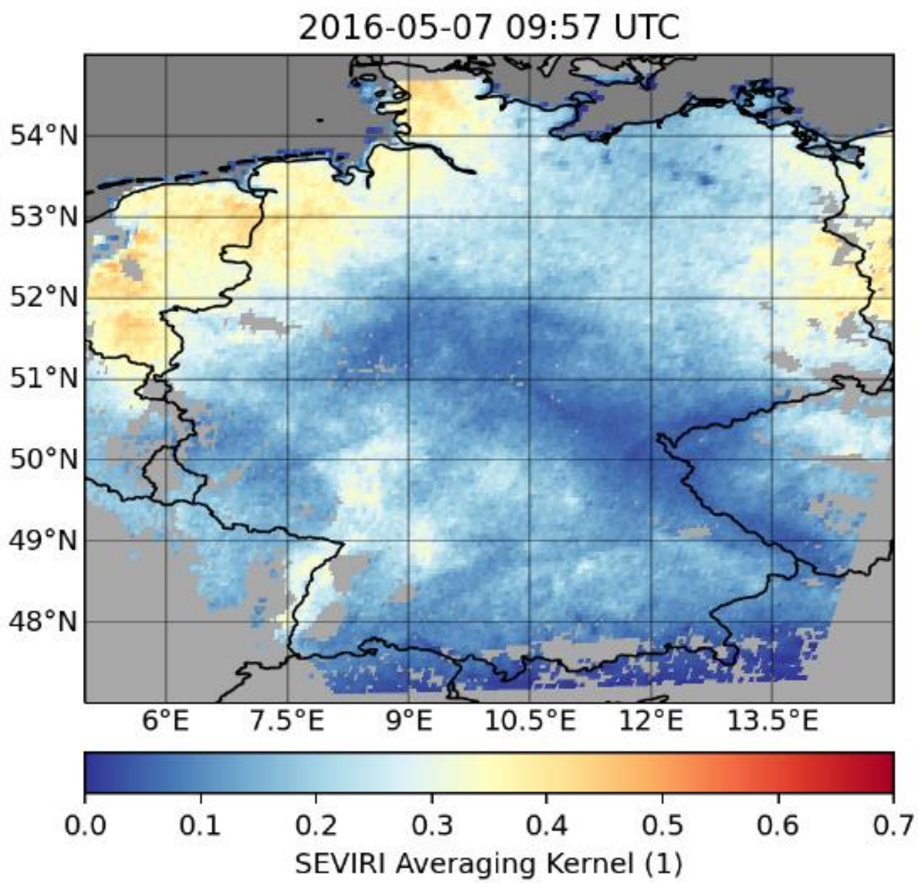
CHANNEL	CENTRE WAVELENGTH	SPECTRAL WIDTH	SPATIAL SAMPLING DISTANCE (SSD)
VIS 0.4	0.444 µm	0.060 µm	1.0 km
VIS 0.5	0.510 µm	0.040 µm	1.0 km
VIS 0.6	0.640 µm	0.050 µm	1.0 km; 0.5 km*
VIS 0.8	0.865 µm	0.050 µm	1.0 km
VIS 0.9	0.914 µm	0.020 µm	1.0 km
NIR 1.3	1.380 µm	0.030 µm	1.0 km
NIR 1.6	1.610 µm	0.050 µm	1.0 km
NIR 2.2	2.250 µm	0.050 µm	1.0 km; 0.5 km*
IR 3.8 (TIR)	3.800 µm	0.400 µm	2.0 km; 1.0 km*
WV 6.3	6.300 µm	1.000 µm	2.0 km
WV 7.3	7.350 µm	0.500 µm	2.0 km
IR 8.7 (TIR)	8.700 µm	0.400 µm	2.0 km
IR 9.7 (O_3)	9.660 µm	0.300 µm	2.0 km
IR 10.5 (TIR)	10.500 µm	0.700 µm	2.0 km; 1.0 km*
IR 12.3 (TIR)	12.300 µm	0.500 µm	2.0 km
IR 13.3 (CO_2)	13.300 µm	0.600 µm	2.0 km

From: https://www.eumetsat.int/website/home/Satellites/FutureSatellites/MeteosatThirdGeneration/MTGDesign/index.html

MSG-SEVIRI TCWV retrievals

- Averaging Kernel
- Values between 0 and 1:
- Indication of how much improvement of prior information could be made using the measurements

$$A = G \cdot K = \frac{\partial \hat{x}}{\partial x}$$



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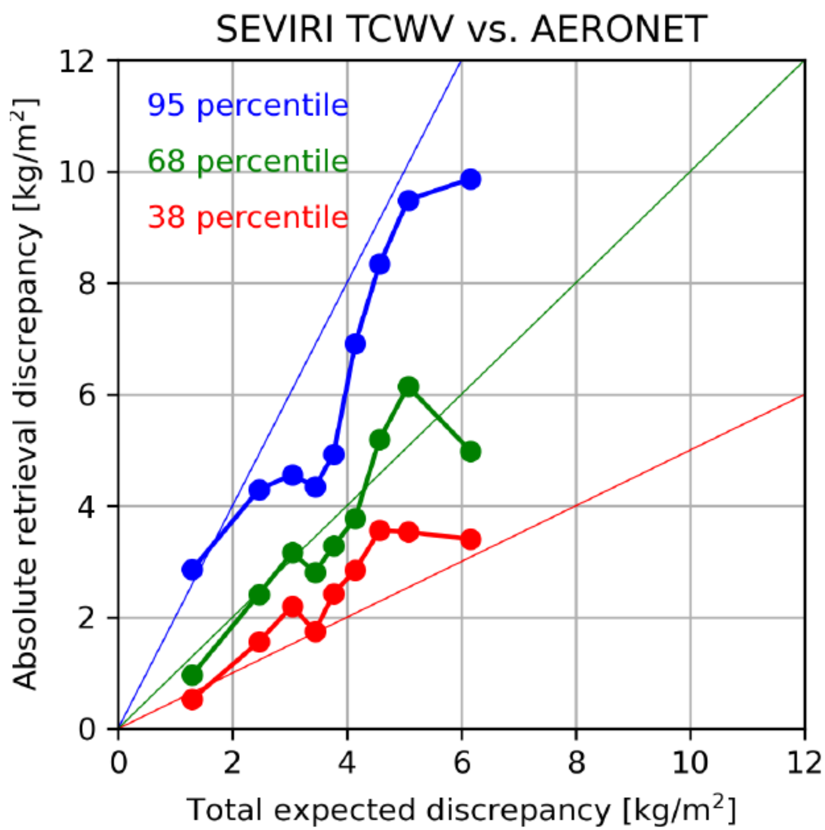
MSG-SEVIRI TCWV retrievals

RealPEP

- Comparing absolute retrieval error $|TCWV_{SEVIRI} - TCWV_{AERONET}|$ with total expected discrepancy

$$\epsilon_{tot} = \sqrt{\epsilon_{SEVIRI}{}^2 + \epsilon_{AERONET}{}^2 + \sigma_{SEVIRI}{}^2 + \sigma_{AERONET}{}^2}$$

- Compute per bin:
  38, 68 and 95 percentile values
  (0.5, 1 and 2 std)
  relation to expected retrieval error
- Distribution of retrieval errors roughly Gaussian



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CI probability from TCWV obs

RealPEP

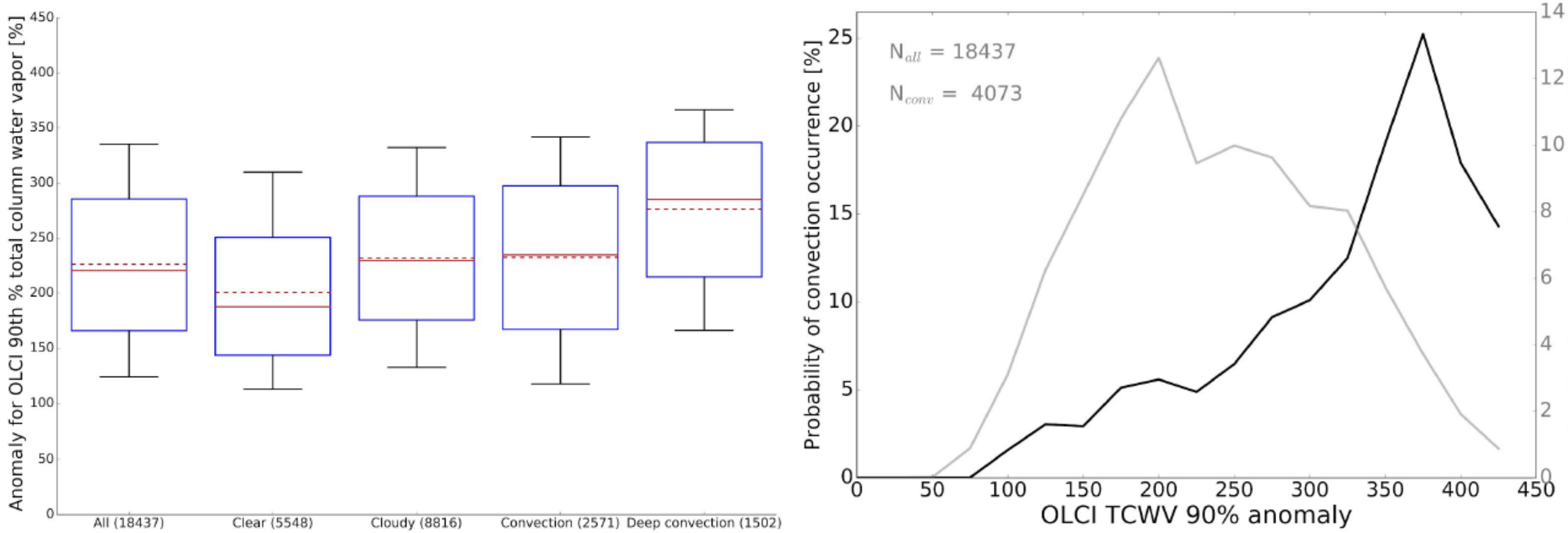


Figure 4: Distributions of the 90 percentile OLCI TCWV anomaly for all match-ups and stratified according to the cloud type as observed by MSG-SEVIRI in the 3 hour time period after the OLCI overpass. Distributions are shown via a) box-plots (red solid line = median, red dotted line = mean, blue lines = 25 and 75 percentile, black lines = 10 and 90 percentile) and b) probability of convection occurrence (solid black line). N_{all} includes all clear-sky/cloudy cases and N_{conv} includes only convection and deep convection cases.

Data (Future data)

- Geostationary satellite **MSG/SEVIRI** **(2022: MTG/FCI(,LI,IRS))**
  - Time resolution: 15 min.
  - Spatial resolution: ~ 4x7 km^2
  - Variables from SEVIRI: CF, COT, REF, CPH, CWP, CTP, CTH, CTT, (IWV)
  - **IWV,** (Lightning, clear sky profiles of humidity and temperature)

- Polar orbiting satellites:
  - Passive imagers **MODIS** + **MERIS/AATSR** **(2017 Sentinel 3 a/b/c/d, 2020 POST-EPS)**:
    - Time resolution: ~ 2 times daily (n times!)
    - Spatial resolution: ~ 1x1 km^2 (0.5kmx0.5km)
    - Variables: CF, COT, REF, CPH, CWP, CTP, CTH, CTT, IWV
  - Active instruments **CPR** and **CALIOP** **(202? Earthcare , but difficult orbit for Polar):**
    - Time resolution: ~ 2 times daily
    - Spatial resolution: 1-d track
    - Variables: vertical profiles of clouds, cloud typing

- Ground-based observations **GNSS:**
  - Time resolution: 15 min.
  - Spatial resolution: ~400 stations in German network
  - Variable: IWV

WP-C1-1 Acquisition and evaluation of satellite observations and related products (m1-m6)

What done so far:

- Adjustment of MERIS and MODIS IWV retrieval algorithms for OLCI
  - Some technical updates
  - Extended collection of OLCI L1 and L2 data (EUMETSAT CODA) retrieval of IWV (2016-2019)
- Extended collection of MSG cloud products (2016-2019)
  - preparing switch to MSG-SEVIRI CPP CLAAS Ed. 2 → improved cloud products, mainly cloud (cirrus) detection (avail. Until 2017)
- Collection of MSG L1 native data (CM-SAF) (2018-2019)
  - Python satpy tool for reading in this data format
- Request for COSMO data (DWD) → rather do comparison with ICON data from Klaus
- Extended collection of GPS IWV data in Germany (2013-2019)
- Preparation of various datasets for ingestion into MSG-SEVIRI IWV retrieval (RTTOV)
  - Climatological atmospheric profiles and surface variables based on 30y ERA5

WP-C1-5 Convective Initiation (m7-m36)

Method

- Identify **convective cloud structures** using MSG-SEVIRI cloud products (years 2016-2019) → determine time of convective initiation → Each time step evaluate spatial structures and **temporal change** in specific cloud properties
- Combine with spatial high resolution **IWV fields** from OLCI, MODIS (later MSG) → cases with not too many clouds in morning
- Compute **measures** of heterogeneity and variability to describe IWV fields quantitatively, deviations from climatological IWV fields.
- Study **statistical relationship** between IWV field measures and convective cloud structures → estimate **probability of convective initiation** from IWV fields → used in P2 to initiate potential new sells in nowcasting procedures

- Later (Phase 2), include newly developed **Meteosat Third Generation (MTG) IWV fields**!
  - Has water vapor channel
  - Higher temporal and spatial resolution

WP-C1-6: Development of IWV algorithm for MSG V1 (m1 – m36)

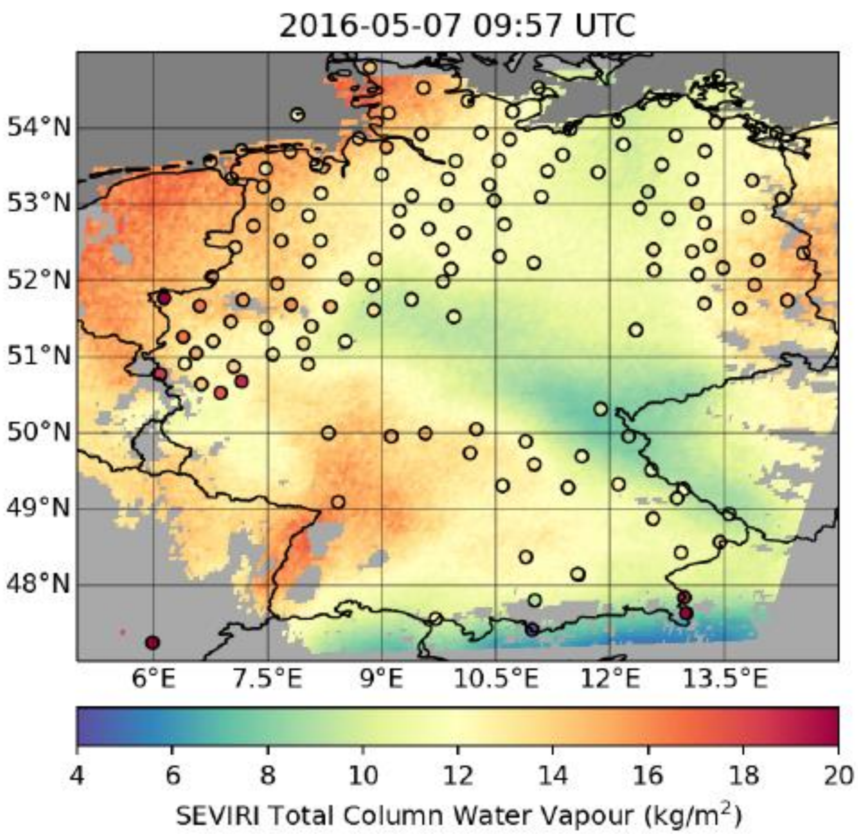
- Development of **new IWV retrieval algorithm** using MSG-SEVIRI TIR measurements
- Resulting IWV fields: cloud-free scenes above land with spatial resolution of 4 km x 7km over Germany at **15 min. temporal resolution**
- 1D-var inversion scheme, **RTTOV** as forward model, a-priori knowledge from NWP + GPS
- IWV retrieval uncertainty on pixel-basis (instrument, atmospheric profiles, surface emissivity)
- **Low precision** due to surface emissivity variability → **constrain** MSG-SEVIRI IWV products using the IWV products from dense **GNSS** network in Germany with 15 min. temporal resolution (as well as OLCI and MODIS IWV products)
- Also use GNSS IWV for **validating** the new IWV product, also during development

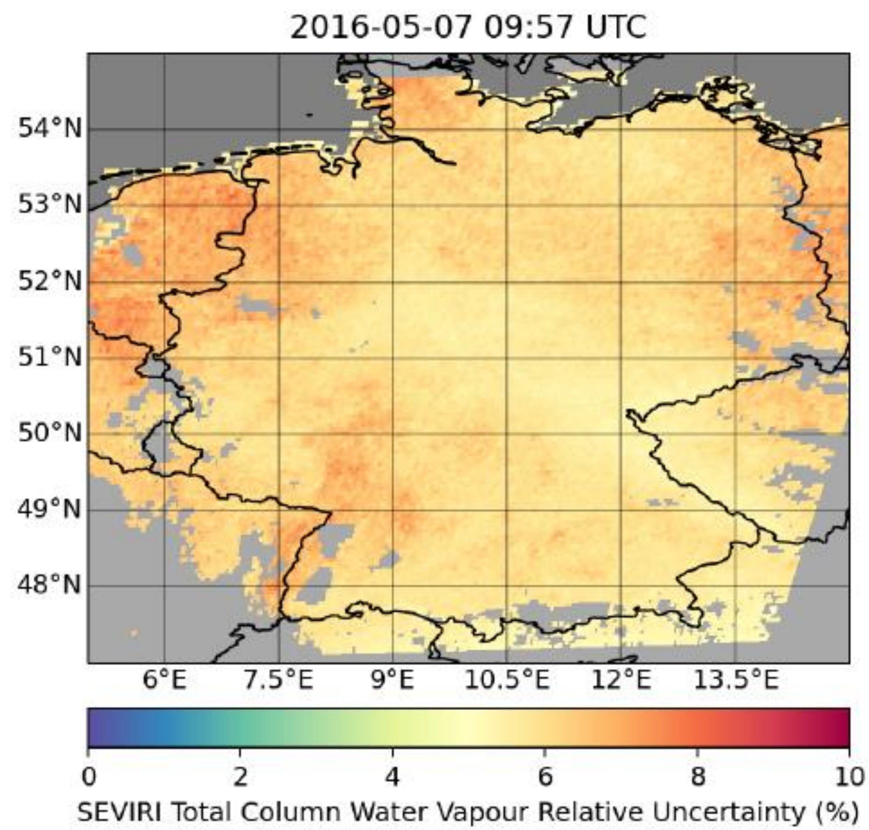
M-C1-4: Provision of MSG-based IWV and CI algorithms (m36)

MSG-SEVIRI TCWV retrievals

- TCWV+T_s from TIR measurements at 11 and 12 μm, 15 min. res, 4x7km^2
- Forward model (RTTOV) embedded in OE method

→ TCWV uncertainties





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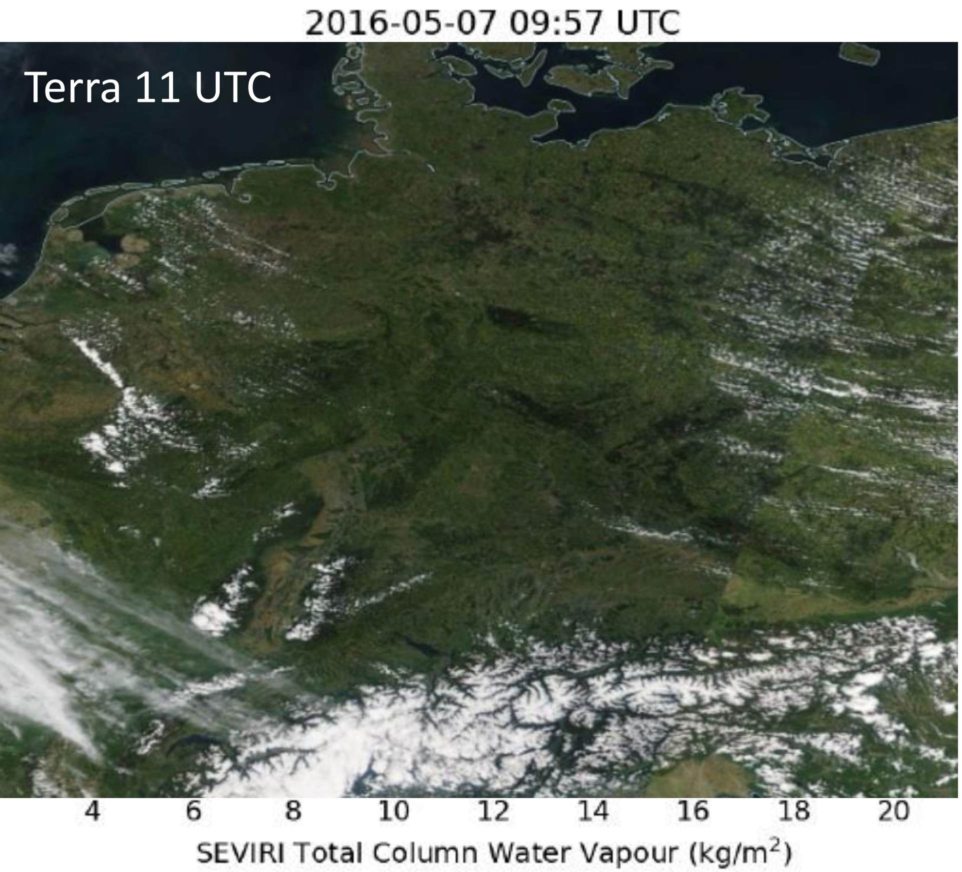
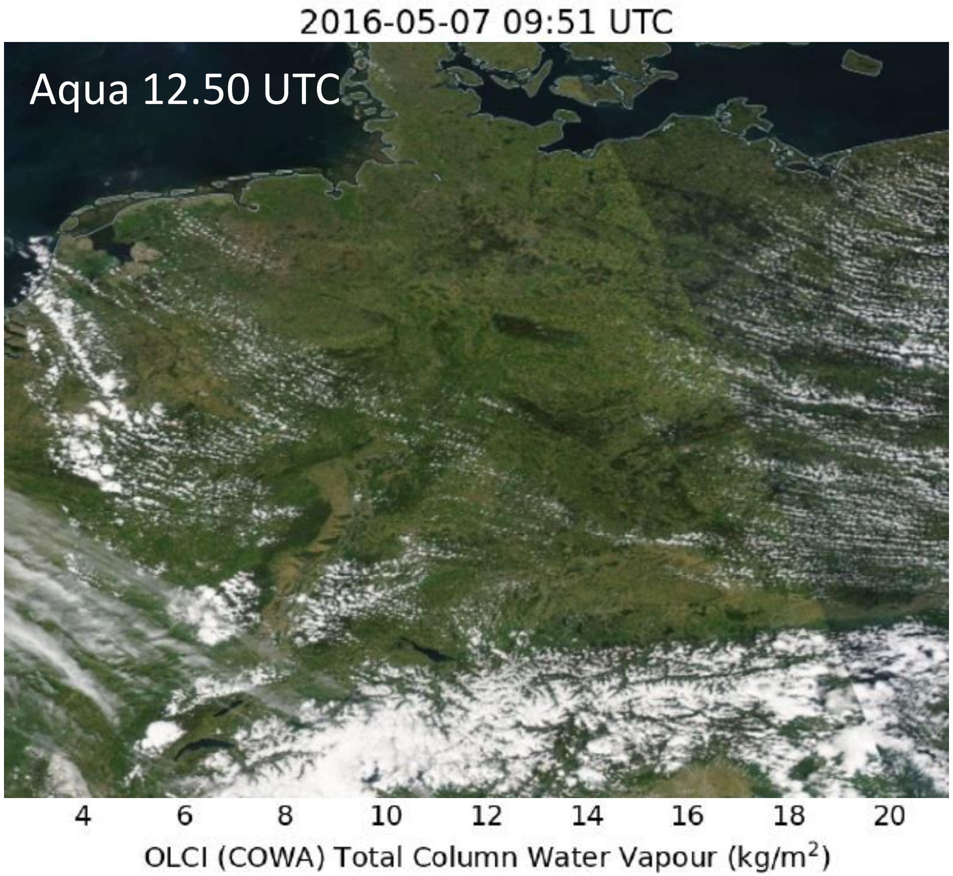
From El Kassar, Carbajal Henken & Preusker, 2021

MSG-SEVIRI TCWV retrievals

Comparison of SEVIRI ~4x7km^2 TCWV to the OLCI COWa 300x300m^2 TCWV

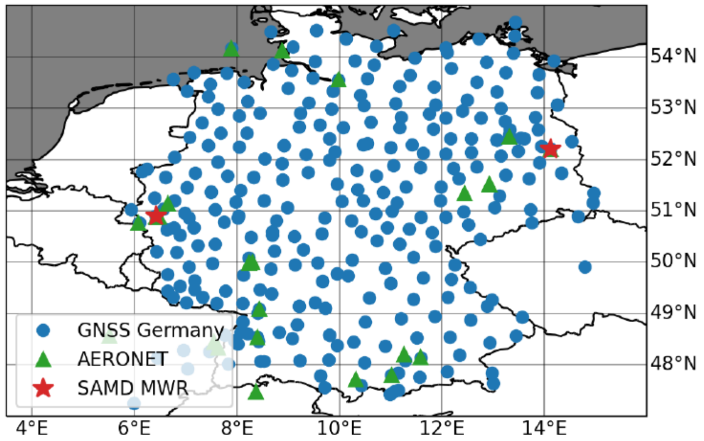


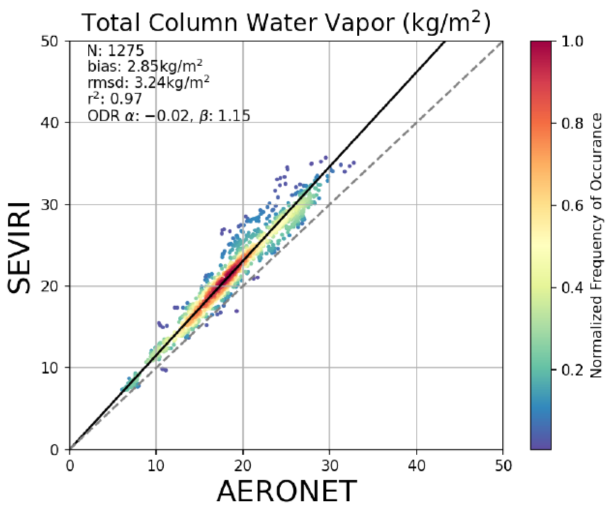


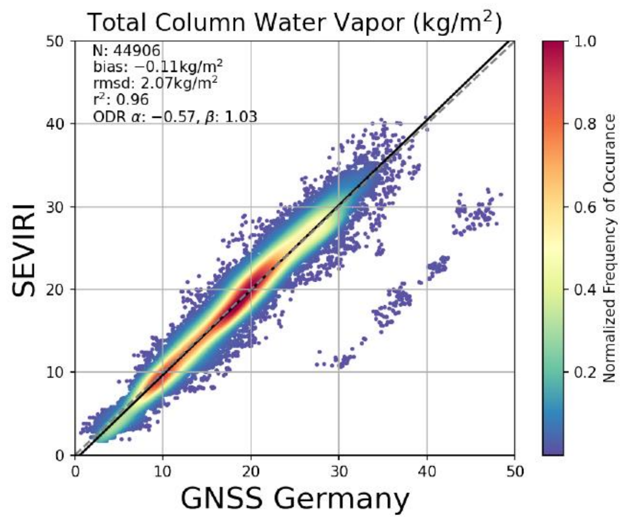
From El Kassar, Carbajal Henken & Preusker, 2021

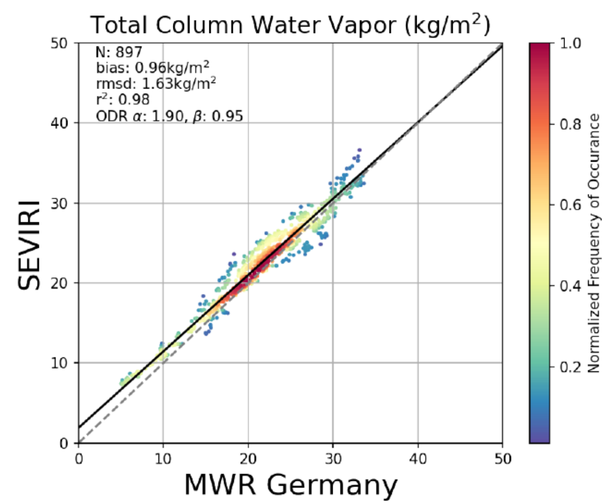
MSG-SEVIRI TCWV retrievals

- Validation study with ground-based observations in Germany
- Absolute biases between 0.11 and 2.85 kg/m²
- RMSD between 1.63 and 3.24 kg/m²
- PC between 0.96 and 0.98









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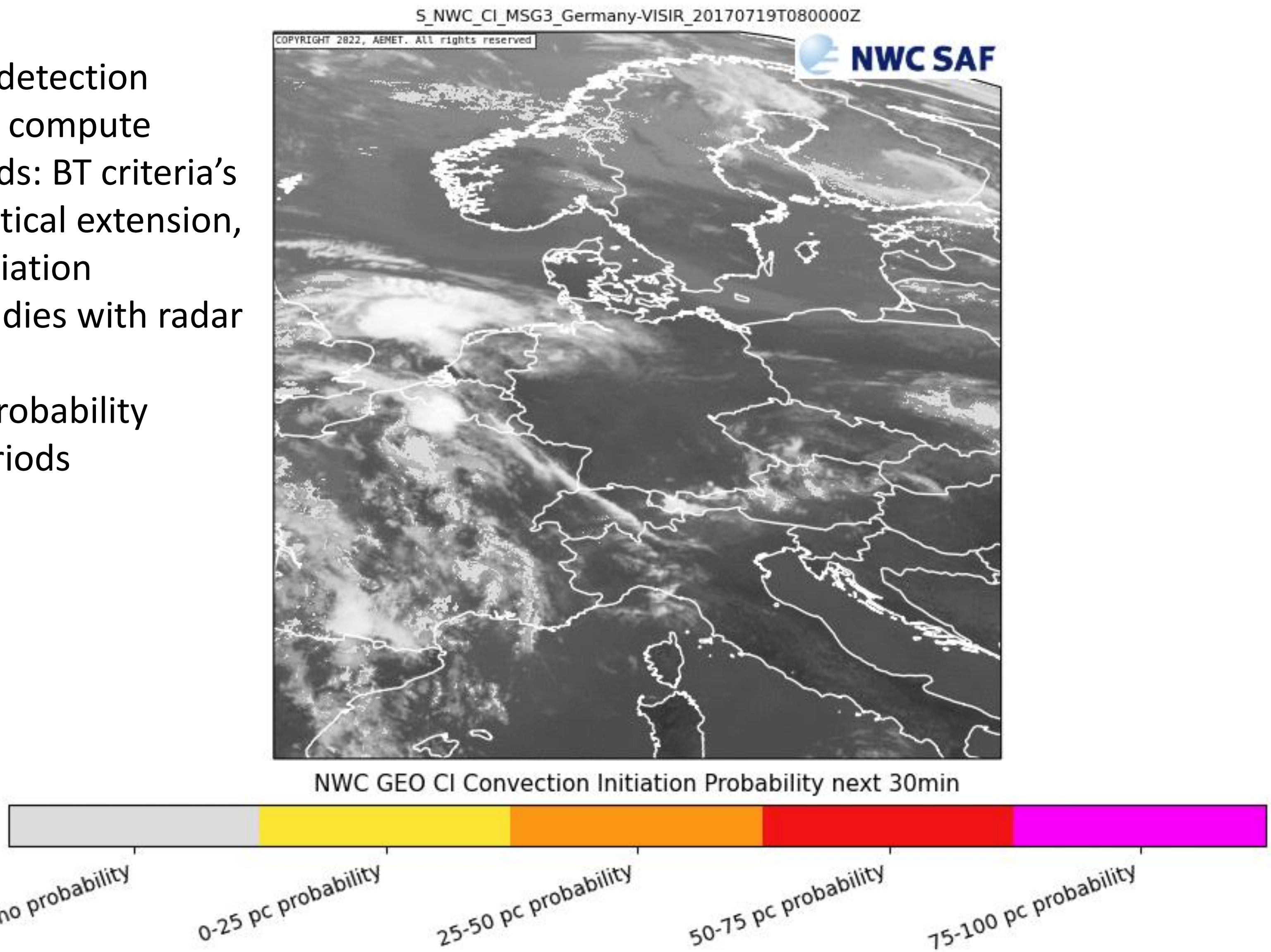
NWC-SAF Software

- NWC SAF (EUMETSAT) provides SW Package for generating satellite products with **direct application in nowcasting** (GEO v2018)
- Input: MSG-SEVIRI measurements, NWP data (reanalysis ERA5)
- GEO products regarding convection: storm monitoring at different development stages:
  - Any cloudy time: several cloud products like **CT** and **CTTH**
  - Pre-convective: **iSHAI** (imaging Satellite Humidity and Instability)
  - Convective Initiation: **CI**
  - Developing convective storm: **RDT** (Rapid Developing Thunderstorm)

NWC-SAF Software

CI

- 1) Warm cell detection
- 2) Tracking to compute dynamic trends: BT criteria's related to vertical extension, updrafts, glaciation
- Validation studies with radar objects
- 4 classes of probability
- 3 forecast periods



NWC-SAF Software

RDT

- Object-oriented analysis of satellite images: detection, tracking, discrimination, forecasting
- Includes: overshooting tops, lightning jumps
- From few pixels to large-scale
- Multi-description of convection: yes/no convection, phase, position, overshooting tops, Rainfall activity, severity
- Validation studies with radar obs and experts