Present and future observational landscape in Numerical Weather Prediction

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European Centre for Medium-Range Weather Forecasts

Data Assimilation Workshop, Bonn, 9-10 April 2025

HIMAWARI-8 (© JMA)
RGB 1km resolution

Thanks to many colleagues (also acknowledged in the relevant slides): Bruce Ingleby, Sean Healy, Michael Rennie, David *Duncan, Katie Lean, Niels Bormann, Mohamed Dahoui, Francis Warrick, Chris Burrows, Naoto Kusano, Ethel Villeneuve, Josef Schröttle, Mark Fielding, Marta Janiisková, Cristina Lupu, Samuel Quesada Ruiz, Tobias Necker, Volkan Firat, Alan Geer, Philipp Lopez, Liam Steele, Peter Lean, Robin Hogan, Marco Matricardi, Bill Bell, Mohamed Dahoui…*

Observations are at the heart of everything we do…

AI-based direct obs prediction

Forecast verification

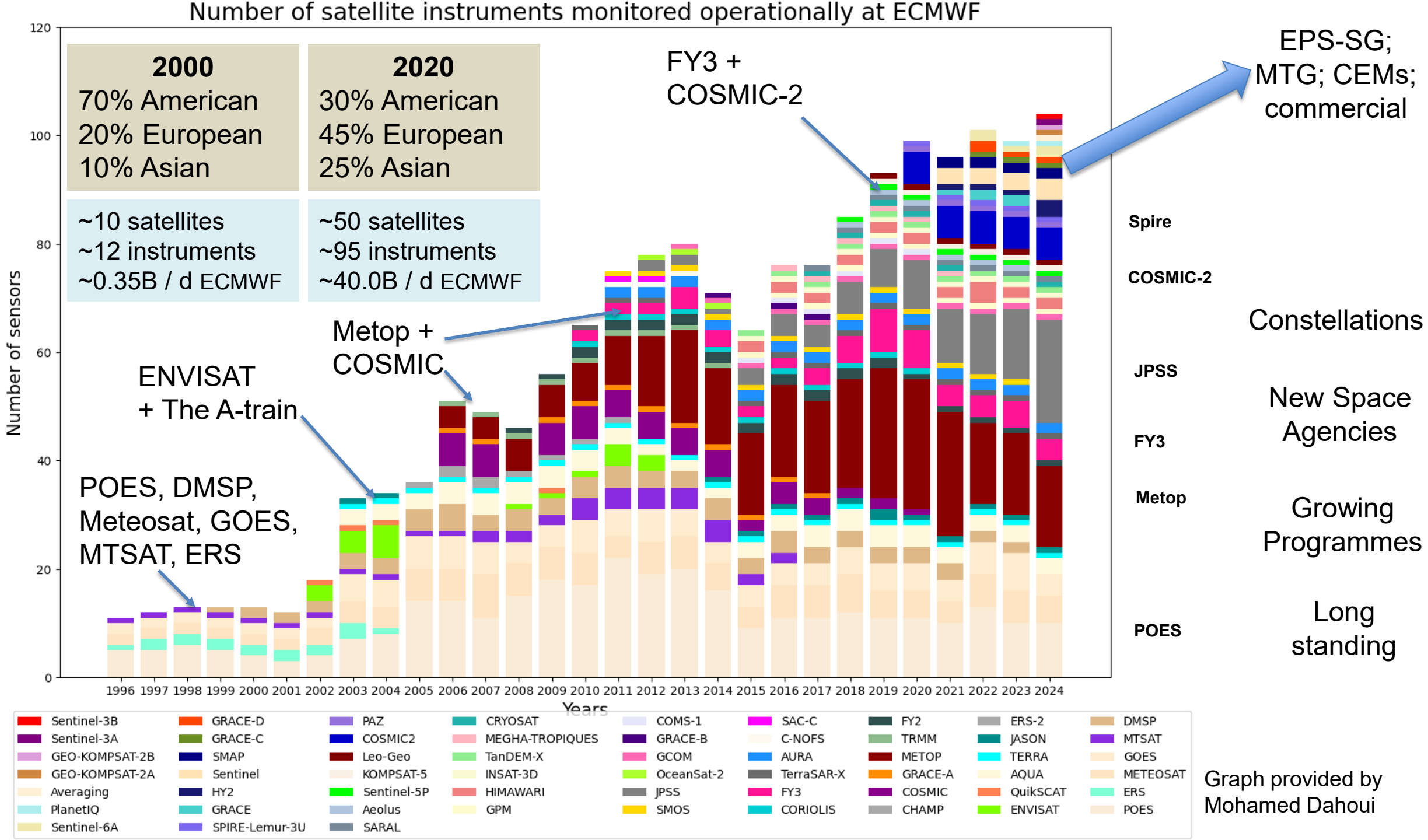
Model evaluation/ development

Parameter estimation

Model initialization using data assimilation (this talk, for the atmosphere)

Reanalysis / climate applications and ML model training

…and this is not likely to change in the future



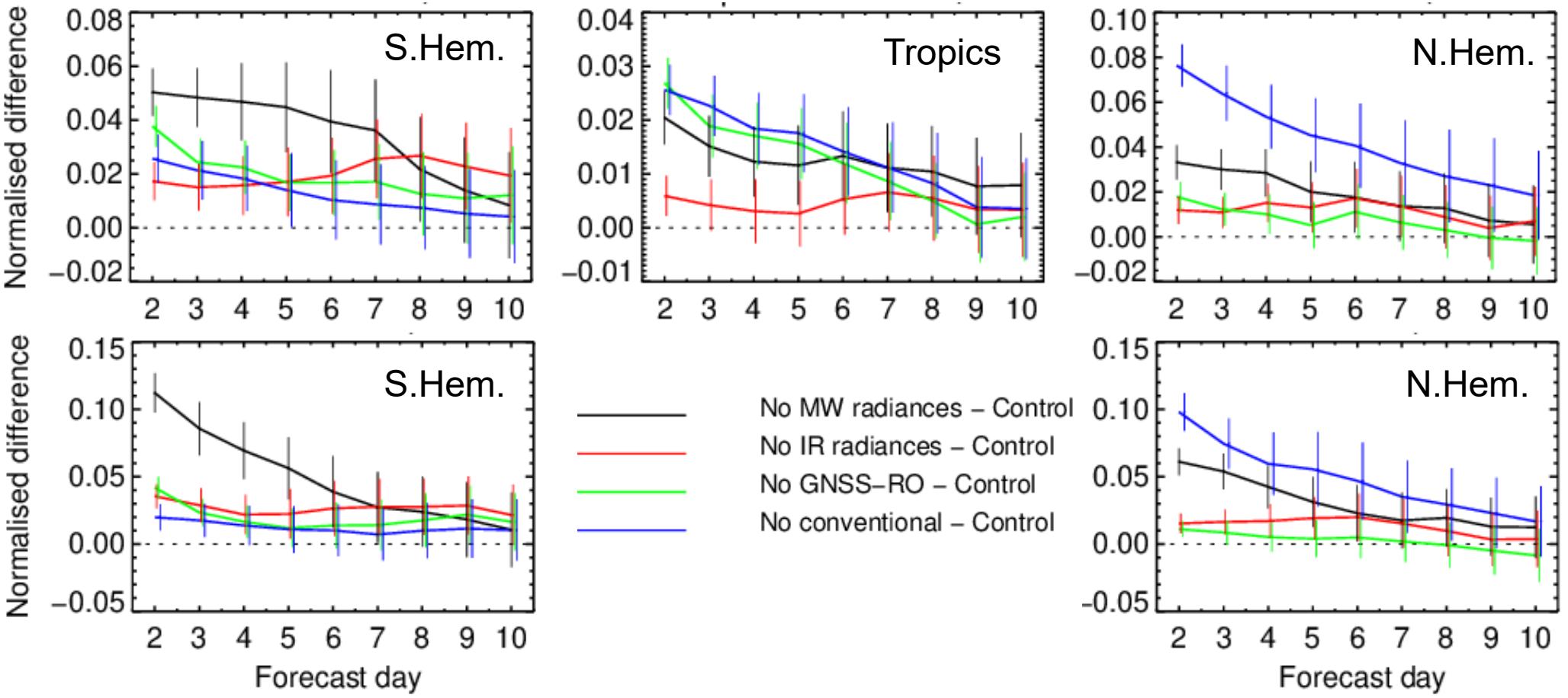
Graph provided by Mohamed Dahoui

Understanding the observations value via observing system experiments

June – August 2022 & December 2022 – February 2022/23

4D-Var combines different strengths of different observing systems
Large impact from satellite data, particularly in the Southern Hemisphere

Curves above the zero line implies a degradation in the forecast when a certain dataset is taken out



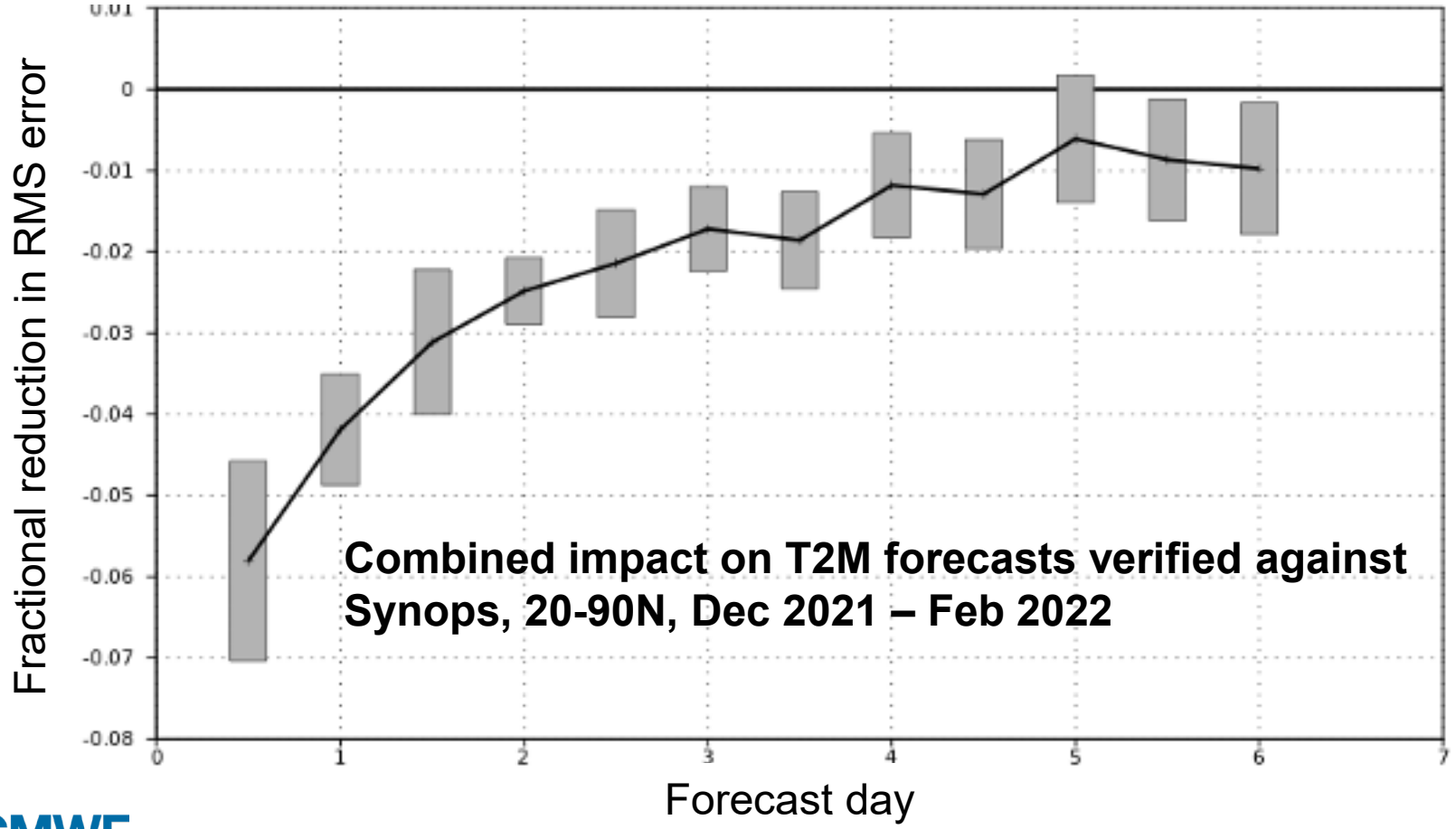
200 hPa wind

500 hPa geopotential

Credits: Niels Bormann

Two metre temperature analysis (T2M) in 49R1

- Assimilation synop/metar temperature and humidity assimilation introduced in 49R1 (November 2024). Combined with changes in land and snow data assimilation led to big improvements in T2M forecasts extending into the medium-range

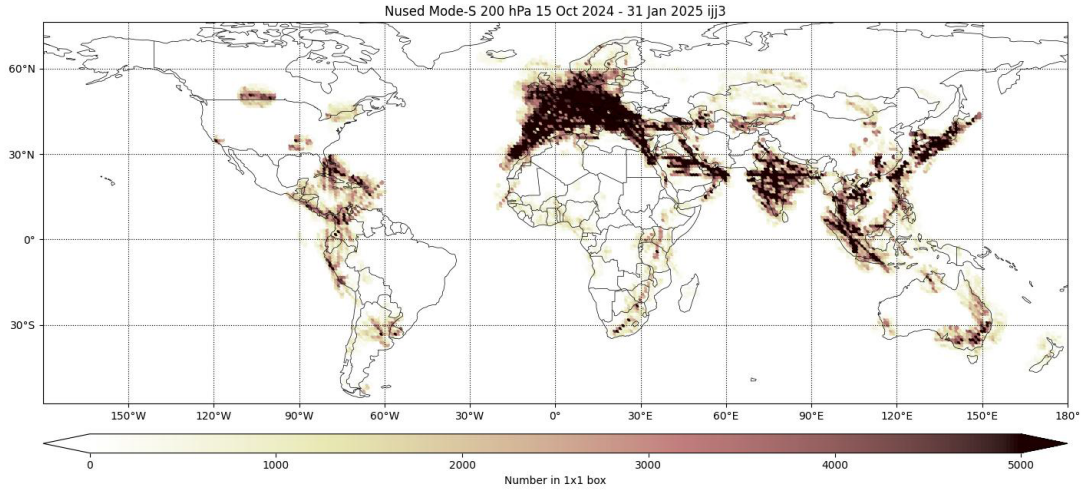


ECMWF

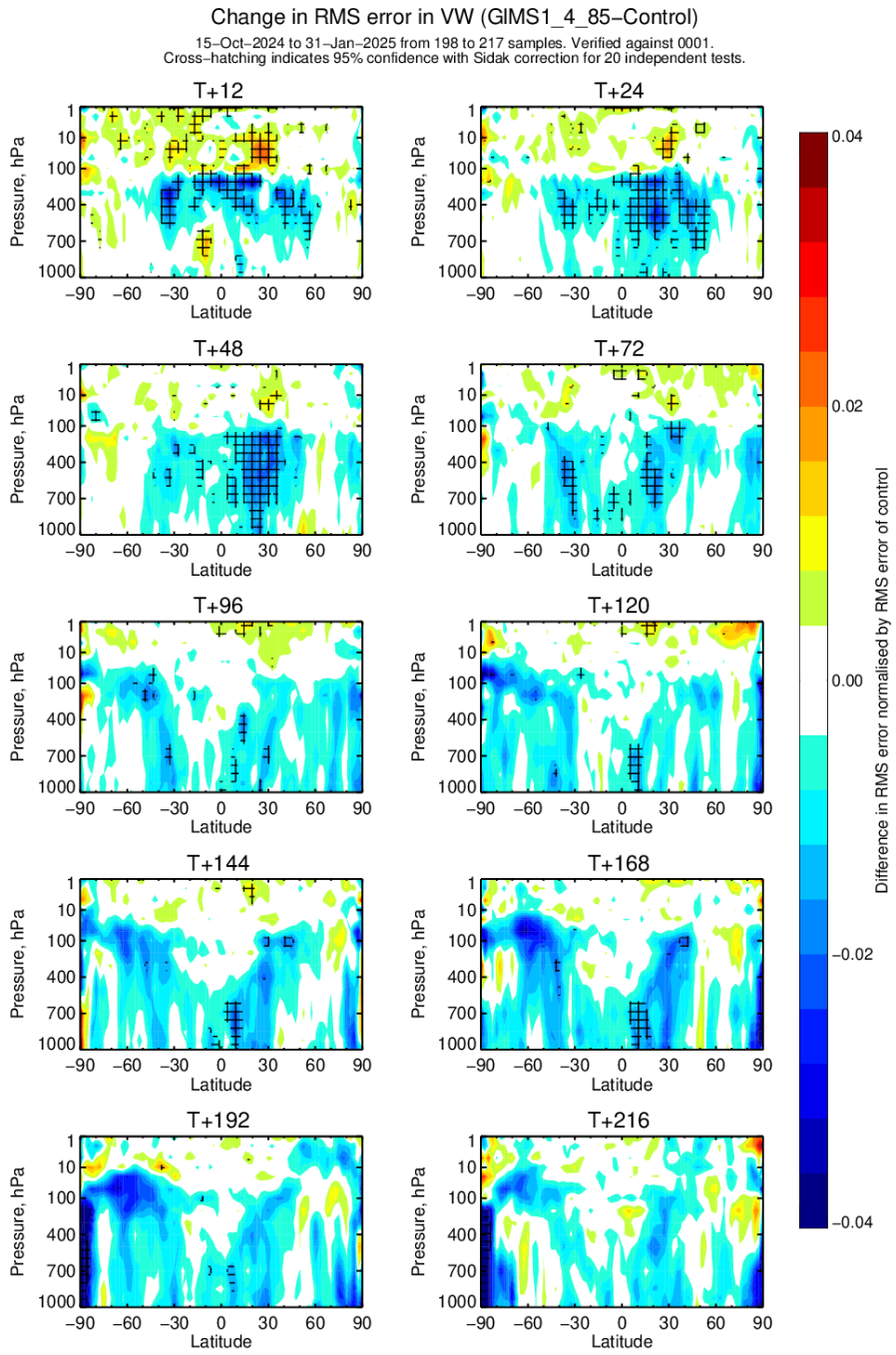
Credits: Bruce Ingleby, Kenta Ochi, Ewan Pinnington, Patricia de Rosnay

Global Mode-S aircraft data: soon to be operational!

- Large numbers in parts of middle east, India, Japan, SE Asia, at 200 hPa
- Moderate numbers in Caribbean, SE Australia
- Low numbers elsewhere



- Benefit from 60S to 60N up to 150 hPa for winds, up to day 8
- Especially in the Tropics
- Hatching shows 95% confidence



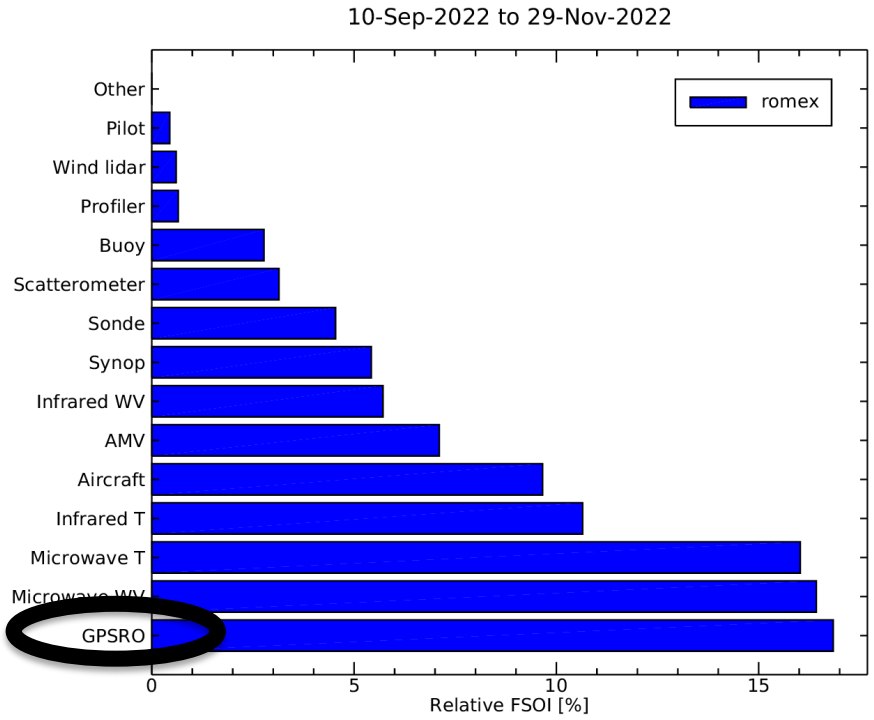
Blue is better

Credits: Bruce Ingleby

ROMEX Experiments – international collaboration with multiple NWP and processing centres on GPSRO data exchange

id	daily number	description
ctrl	7000	Baseline (all GNSS-RO data excl. commercial and Chinese data)
ROMEX	33,000	**Ctrl** + Commercial and Chinese data = All ROMEX data

Blue is better



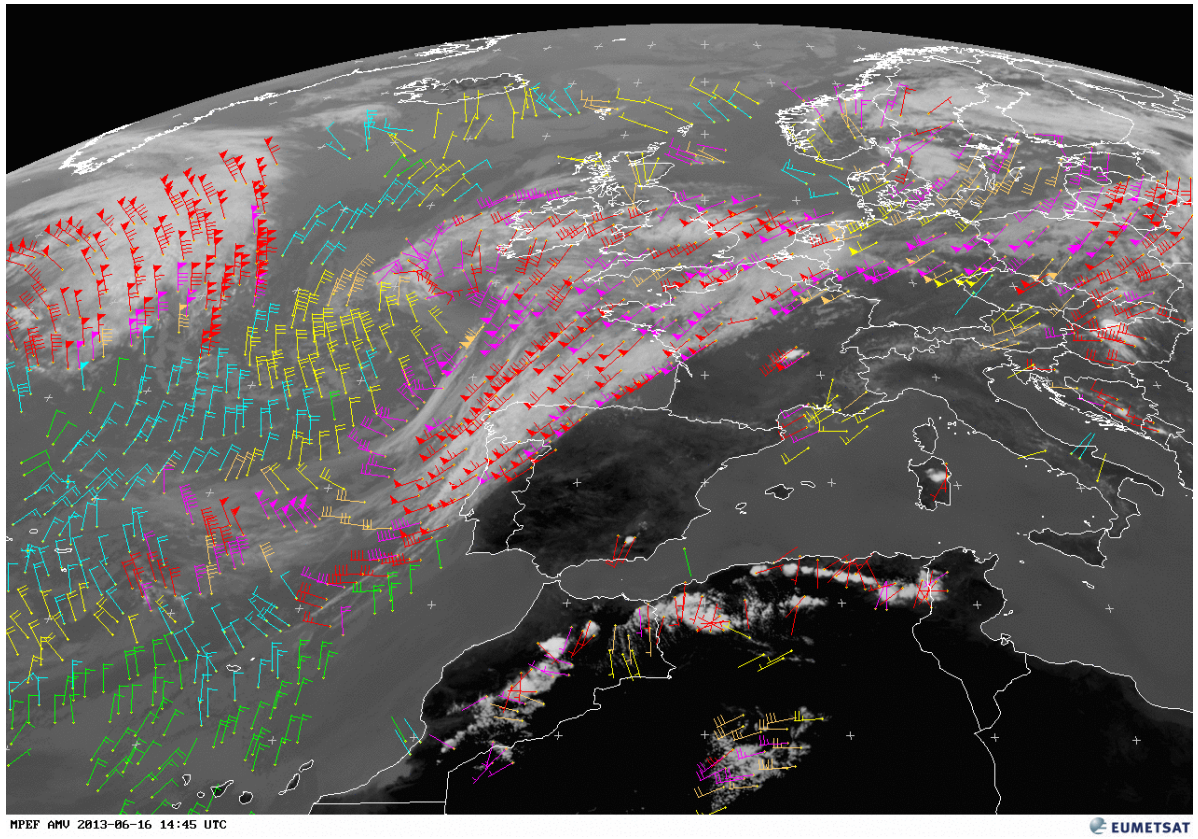
Credits: Katrin Lonitz, Sean Healy

RMS Z degradations caused by cold bias in troposphere – also seen at other NWP centres

But random errors improved by ROMEX compared to control!

Good forecast impact as shown by the Forecast Sensitivity to Observations Impact (FSOI) - no signs of saturation!

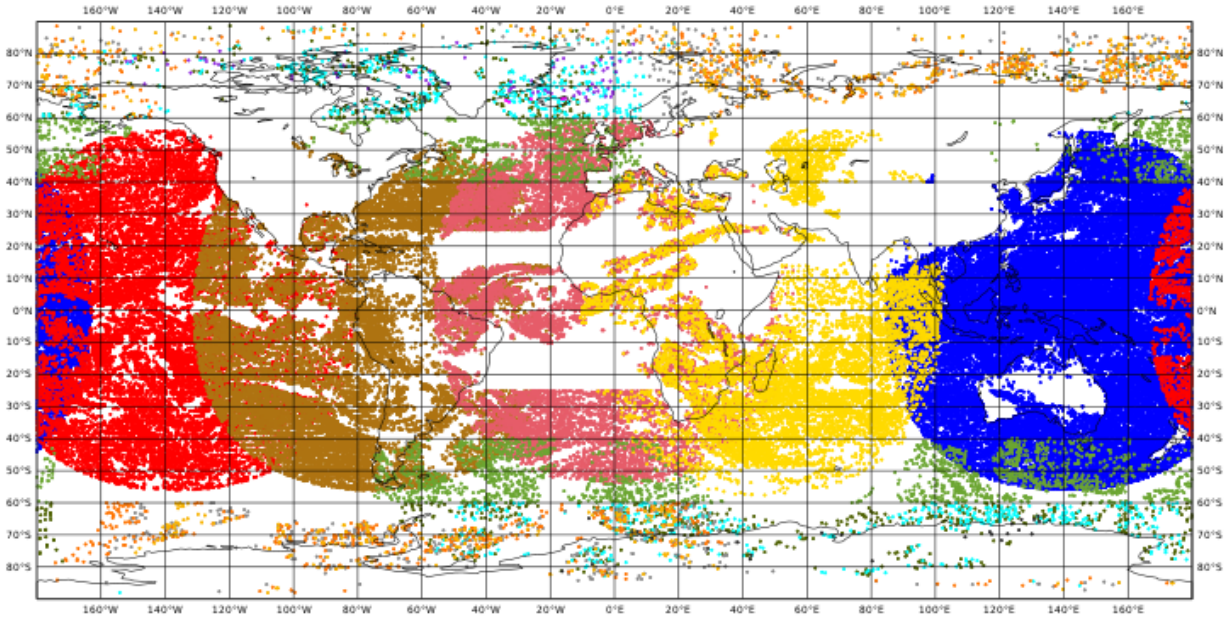
Current AMV Usage in the ECMWF Model



Animation from: oiswww.eumetsat.org/IPPS/html/MSG/PRODUCTS/AMV/WESTERNEUROPE/index.htm

Assimilating in region of 230,000 winds per 12 hour cycle cycle

Metop-B Metop-C Meteosat-9 Meteosat-10 Himawari-9 NOAA-15 NOAA-18 NOAA-19 NPP NOAA-20 GOES-16 GOES-18 Terra Dual-Metop



Credits: Francis Warrick

Assimilation Experiments with MTG AMVs

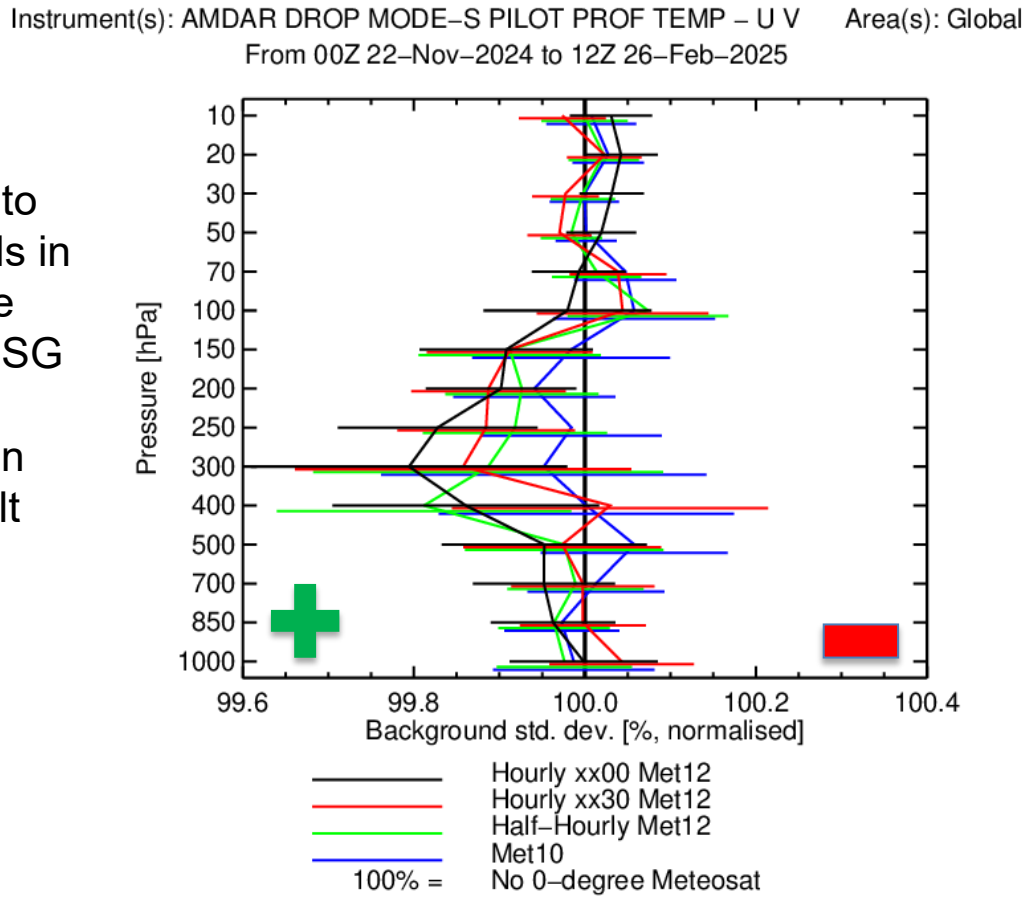
Forecast fit to:

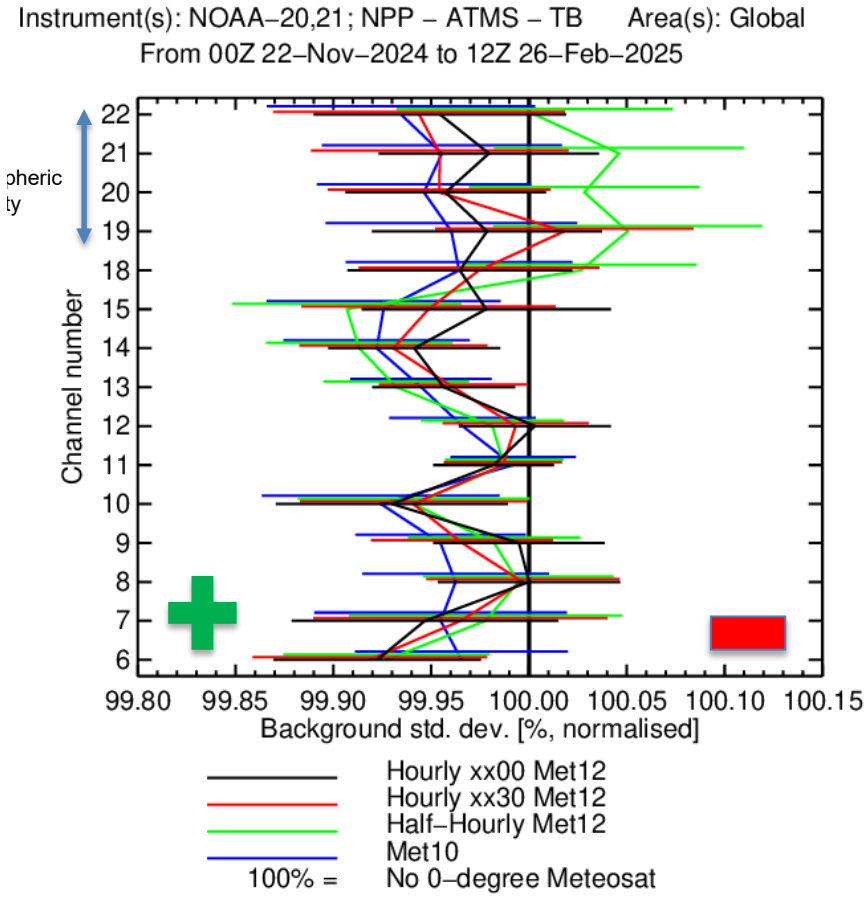
AIRCRAFT winds

ATMS

Better forecast fit to conventional winds in upper troposphere from MTG than MSG

Hourly assimilation gets a better result than half-hourly



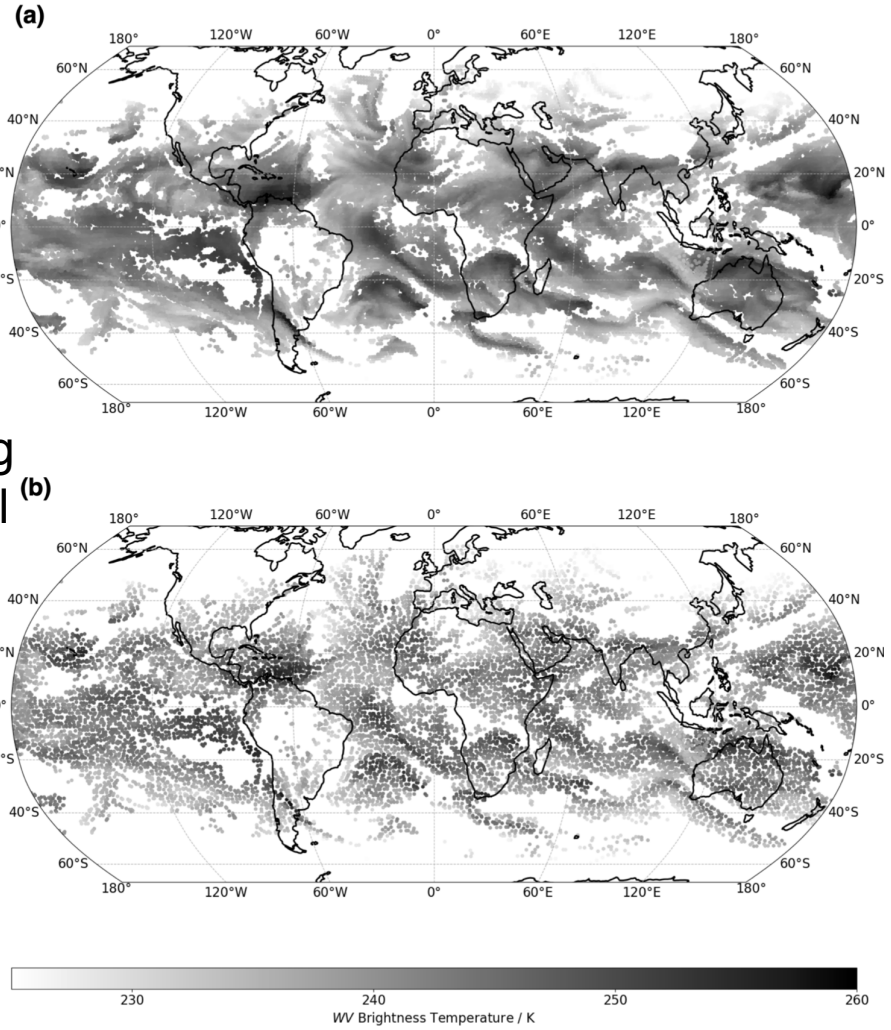


Credits: Francis Warrick

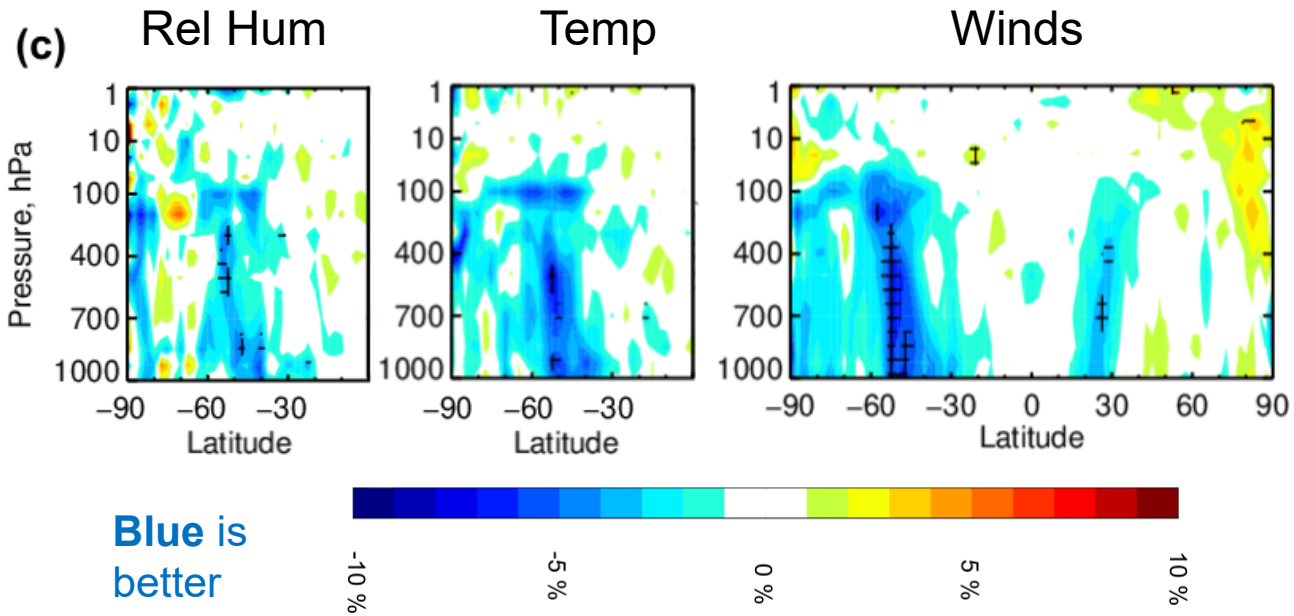
Humidity analysis successfully extracts information from spatially denser observations

75 km thinning
in Cy50R1/DestinE

125 km thinning
operational until
Cycle 48r1



Reduction in RMS at day 5 in high-res experiments
(for the period 1-25 December 2022)



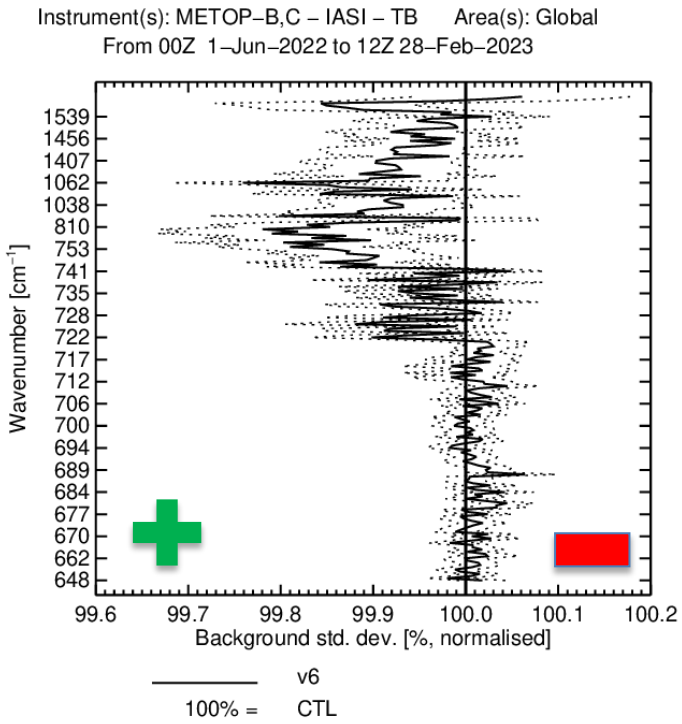
Blue is
better

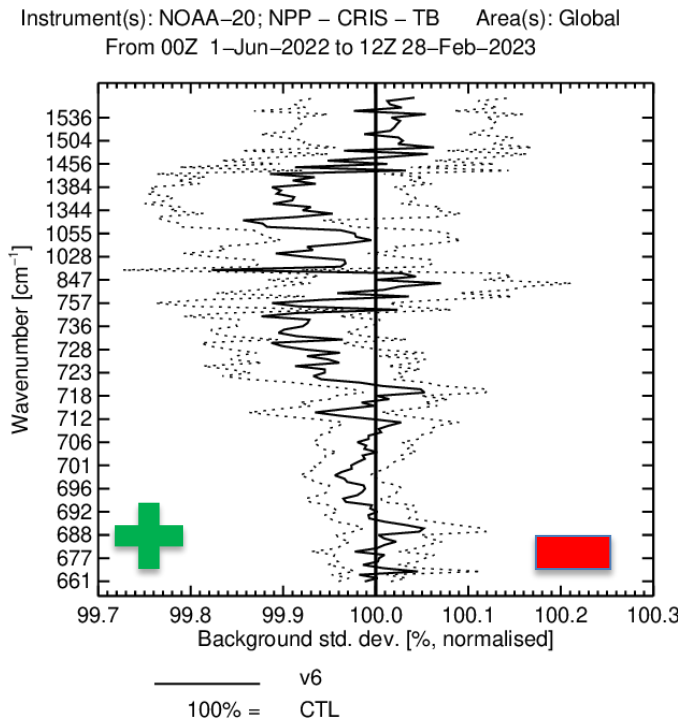
See poster by Josef Schroettle

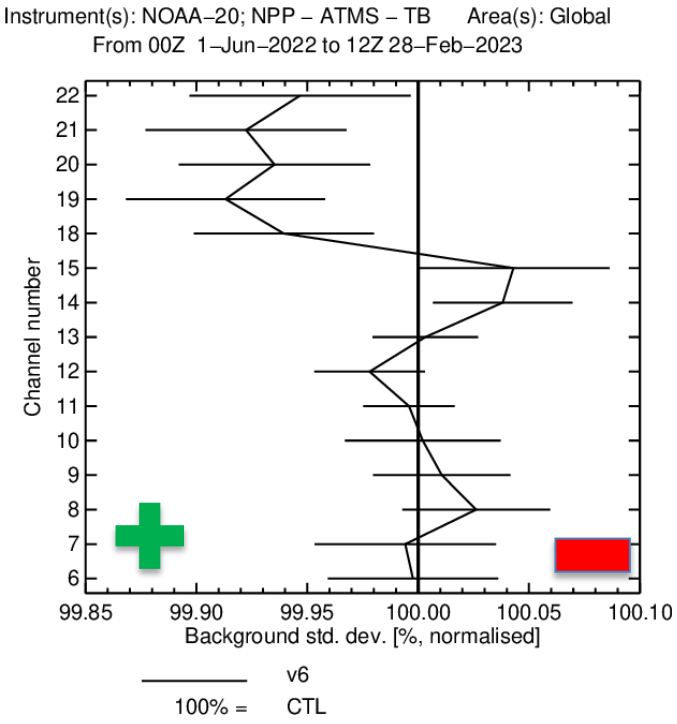
Assimilation of the IR GEOS window channel

Additional channel : improved fit to observations
Nearly 11 % more observations assimilated

Fit to observations – improved against operational configuration (i.e. no IR GEOS window channel assimilated)





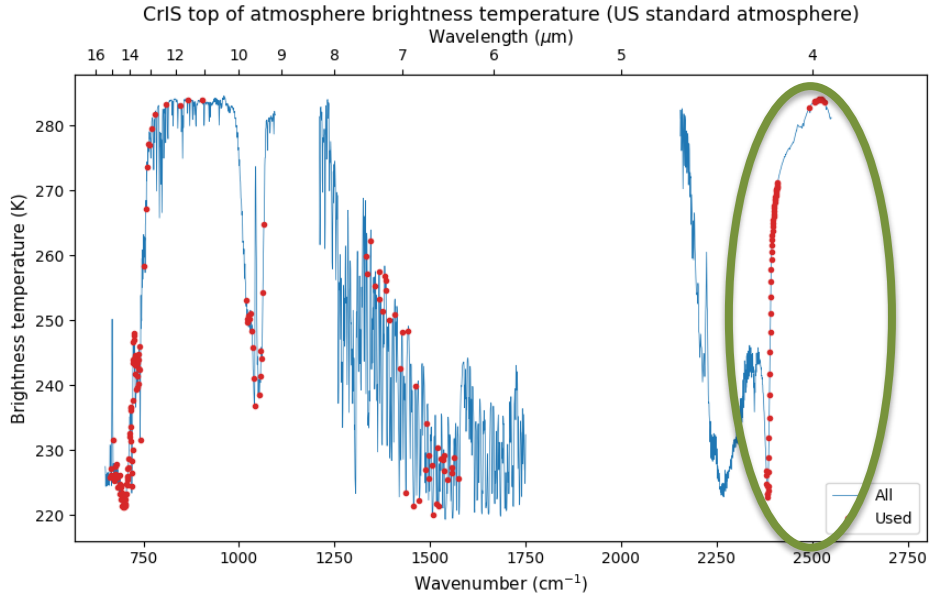


ECMWF

Credits: Ethel Villeneuve, Samuel Quesada Ruiz

CrIS short-wave observations (active at 49R1)

- The short-wave part of the IR spectrum has been largely neglected so far in NWP:
  - Non-local thermodynamic equilibrium (NLTE) effects must be included in the RT
  - The solar contribution must also be included
  - Observation errors are highly sensitive to the scene.

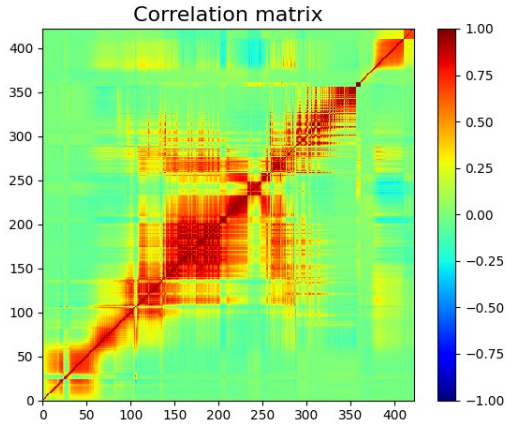


- To address the 3rd point, observation errors are computed in radiance units and converted to brightness temperature units with a scene-dependent scaling based on the derivative of the Planck function.

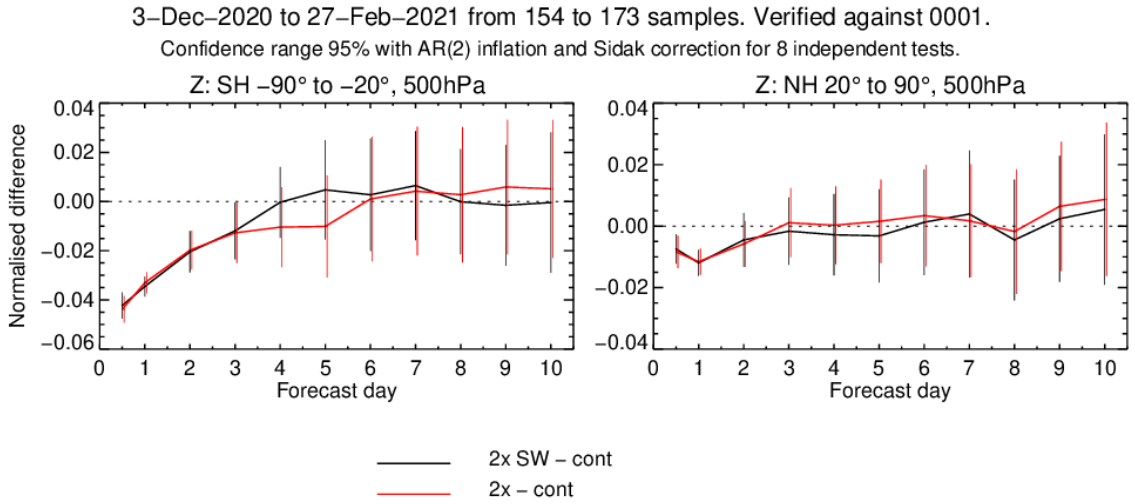
$$\mathbf{R}_{BT} = \mathbf{K}\mathbf{R}_{rad}\mathbf{K}^{T}$$

where the diagonals of **K** are the reciprocal of

$$\frac{dB}{dT} = \frac{c_1 c_2 \nu^4 e^{c_2\nu/T}}{(e^{c_2\nu/T} - 1)^2}$$



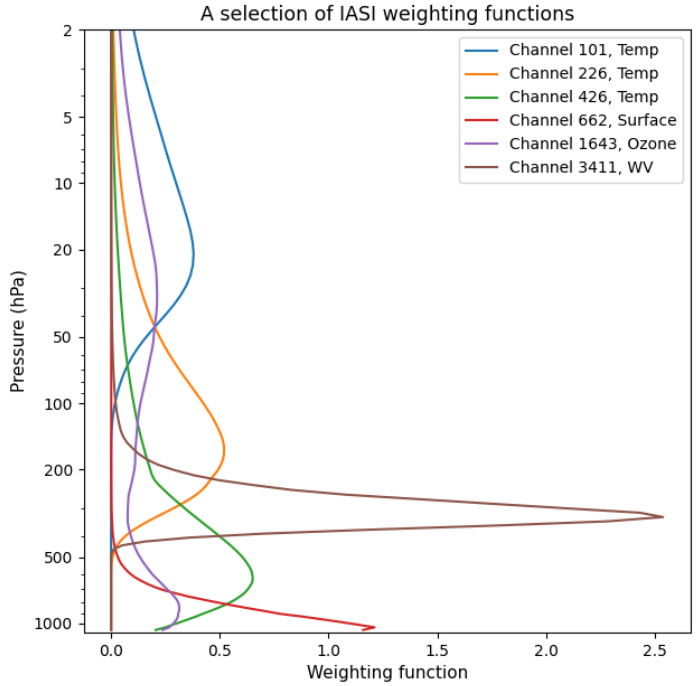
- The impact of the addition of the SW channels along with the RT improvements and scene-dependent errors are generally positive



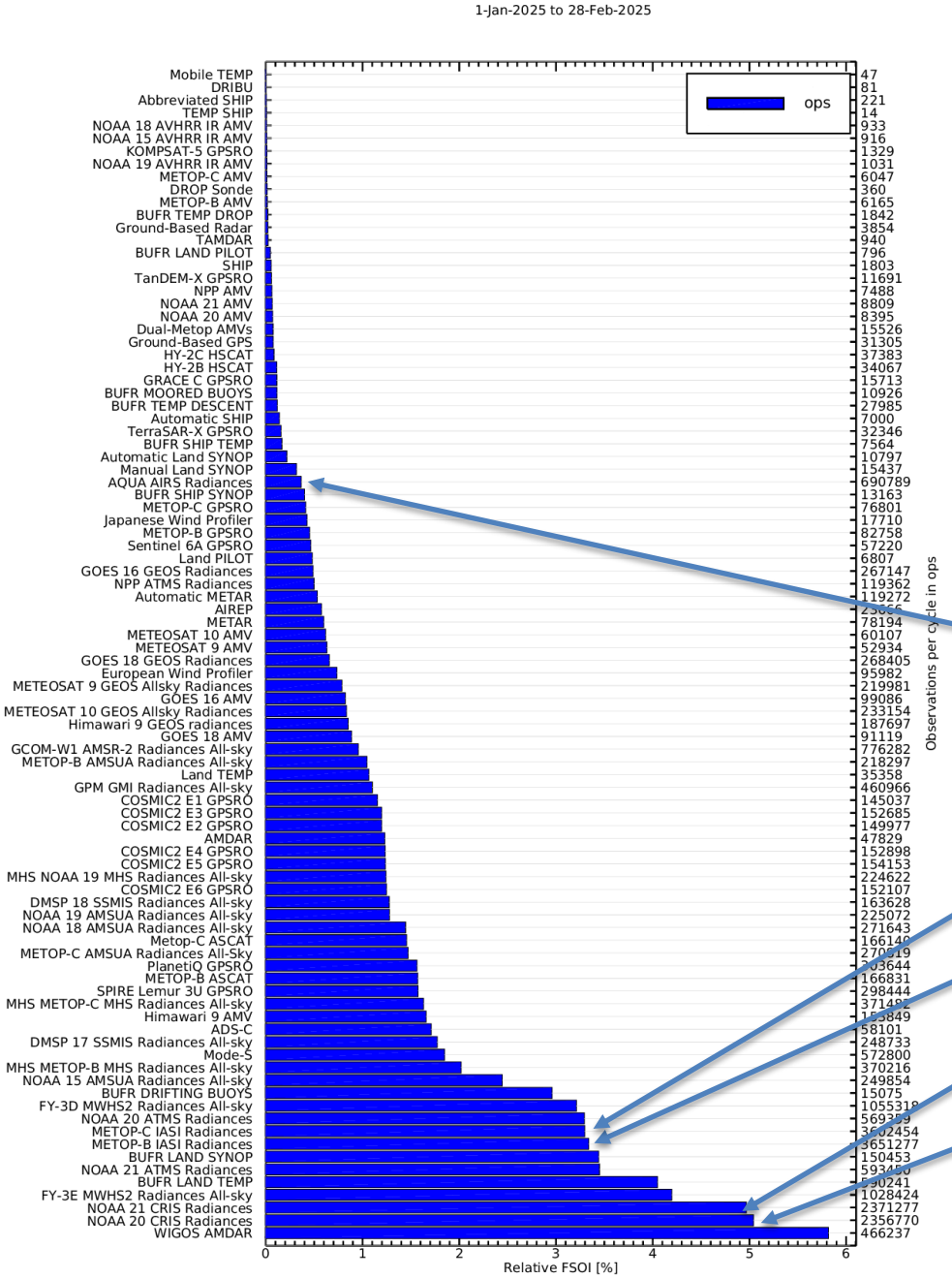
Credits: Chris Burrows

Hyperspectral infrared observations (AIRS 2xIASI, 2xCrIS)

- Hyperspectral IR accounts for 50% of all observations assimilated at ECMWF.
- Observations give information on stratospheric/tropospheric temperature, humidity, ozone and surface emission.



- Cloud is radiatively nonlinear, so we do clear-sky assimilation currently.



- FSOI gives a broad indication of the importance of different observation types in an assimilation system.
- Hyperspectral IR is among those with the largest impact.

AQUA AIRS

Metop-C IASI

Metop-B IASI

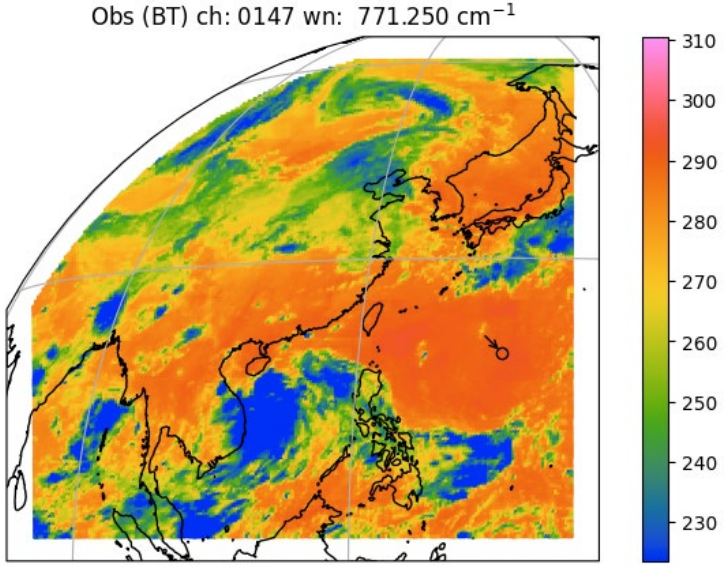
NOAA-21 CrIS

NOAA-20 CrIS

Impact assessment of FY-4B GIIRS in preparation for MTG-S IRS

- The first operational hyperspectral infrared sounder onboard Chinese geostationary satellite FY-4B
- Assimilation of the GIIRS is expected to improve numerical weather prediction in East Asia.
- The investigation is also an opportunity to prepare for MTG-S IRS, which will be launched July 2025.

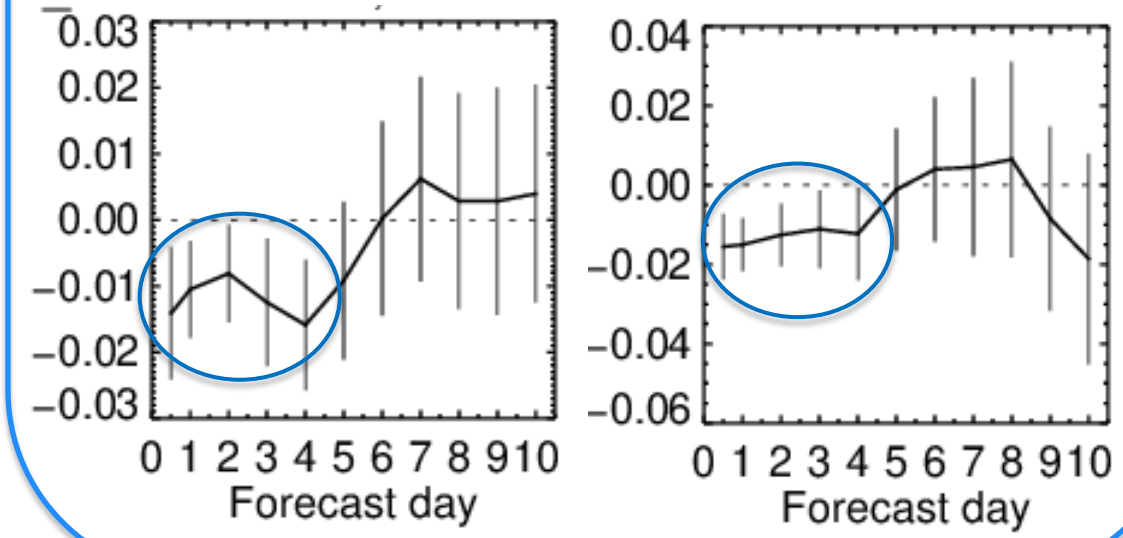
FY-4B GIIRS Observation at 01UTC 24th Sep 2023



Initial assessment of FY-4B GIIRS with the IFS

The results of GIIRS assimilation show improvement of temperature and relative humidity forecast in the lower troposphere over the GIIRS domain.

Change in RMS of forecast error; T1000(left) and RH1000(right)
Period: 8th June – 31st August 2023



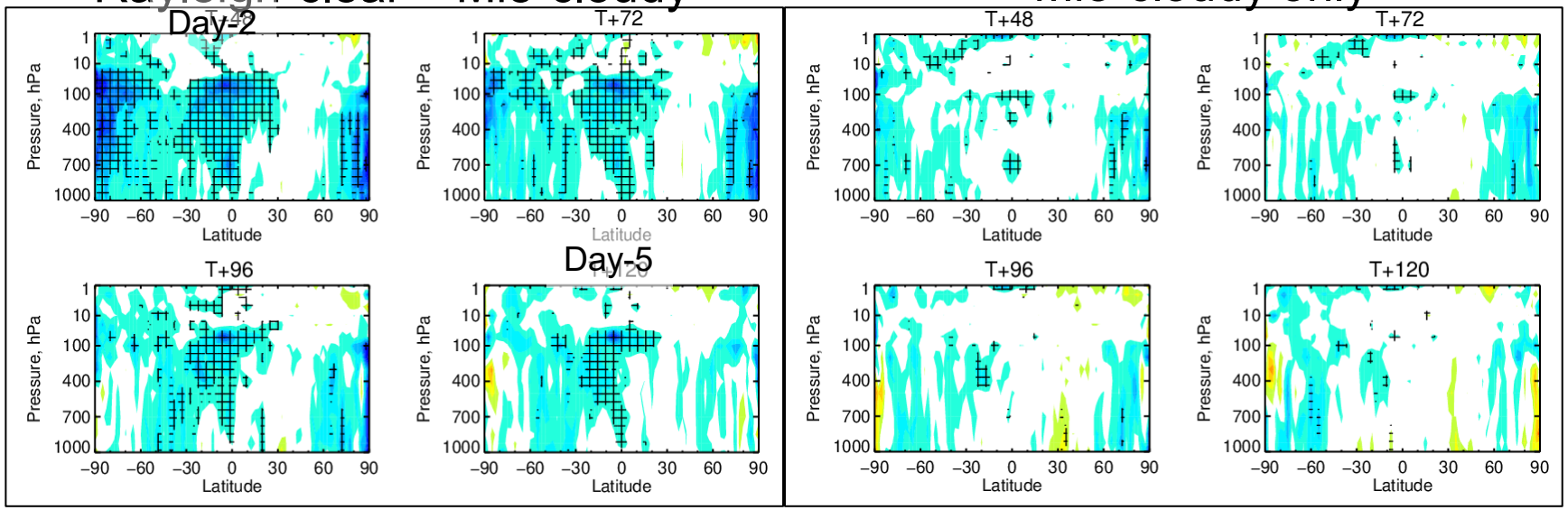
Credits: Naoto Kusano (JMA)

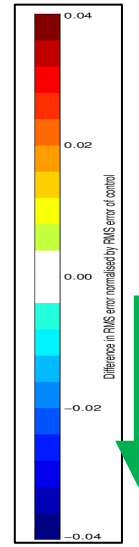
Typical impact of Aeolus L2B HLOS winds from FM-B laser B16 reprocessing

Verification against operational analysis

29 June 2019 to 6 Oct 2020

Rayleigh-clear + Mie-cloudy | Mie-cloudy only



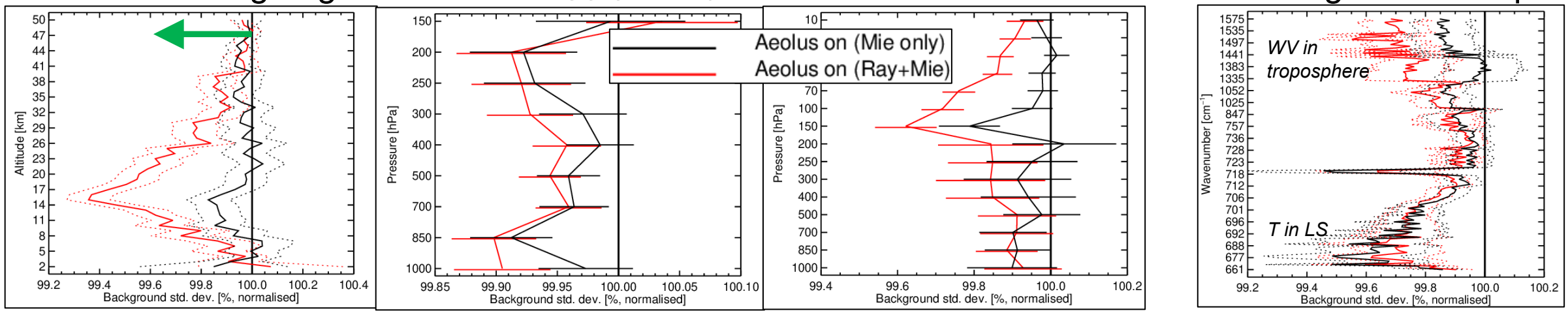


***u-wind**, normalised change in RMS error (±4% scale)*

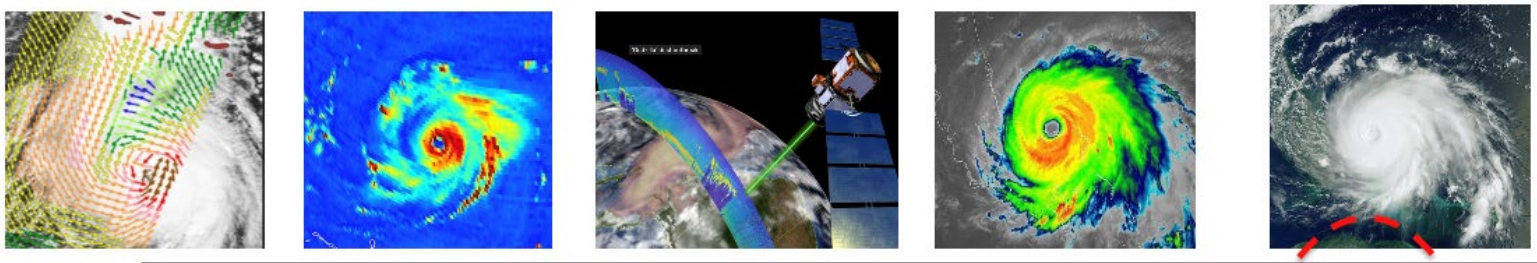
Credits: Mike Rennie

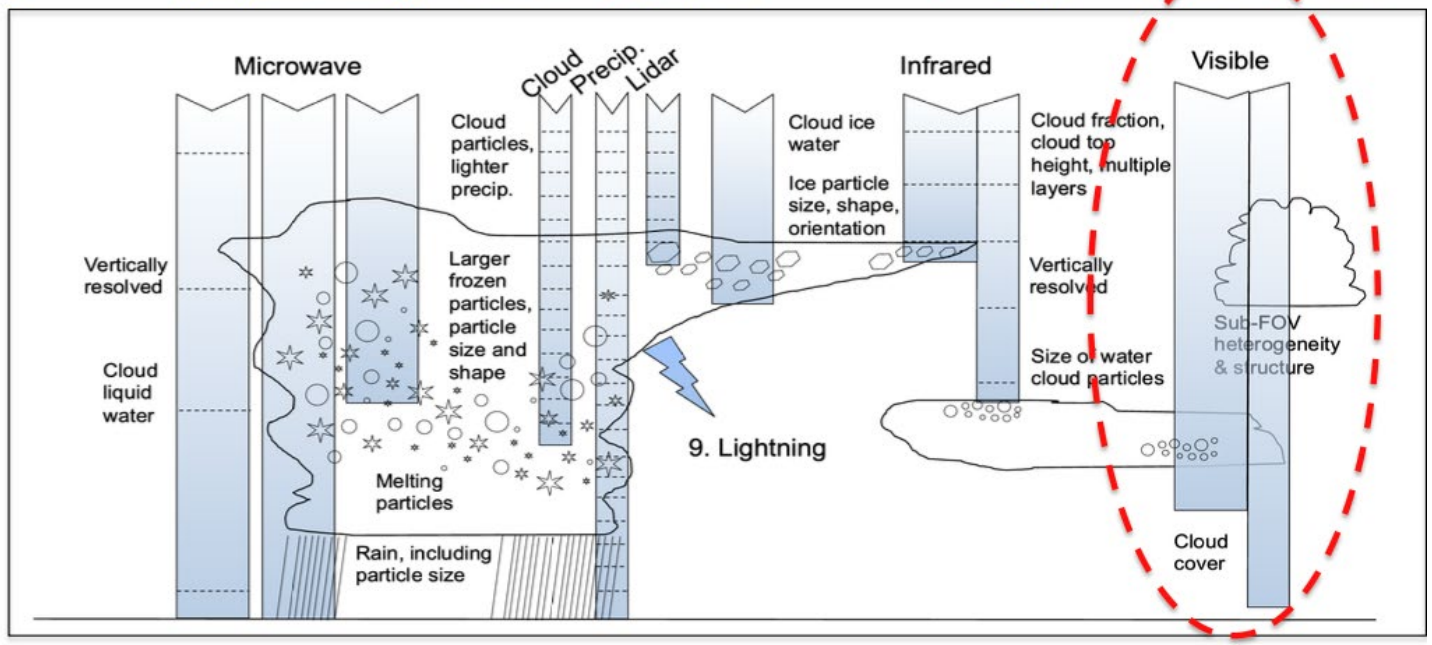
Background (up to 12 hours) departure statistics

GNSS RO bending angle | AMV vector wind | Conventional vector wind | CrIS brightness temps



Continue to push boundaries of satellite observation exploitation





Assimilation of cloud lidar and radar observations and cloud-affected radiances at all frequencies is the next exciting frontier for satellite exploitation.

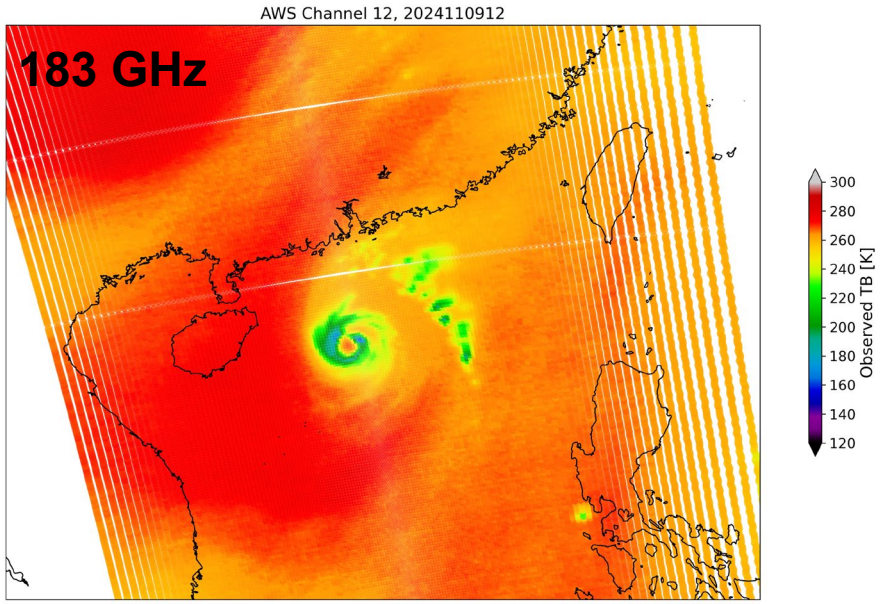
- Satellite observations make a major contribution to the Earth system data which are routinely assimilated into models to determine the initial conditions for weather forecasts.
- Cloud-affected observations are becoming more relevant thanks to advances in modelling and assimilation
- Short-wave (solar spectrum) frequencies are largely underused in NWP applications
- All-sky IR radiances are not yet exploited
- Actively sensed observations of clouds and aerosols from radars and lidars are not yet exploited
- These observations can provide valuable additional information about clouds and aerosols, complementing what is available from IR and MW data (also considering new sensors).

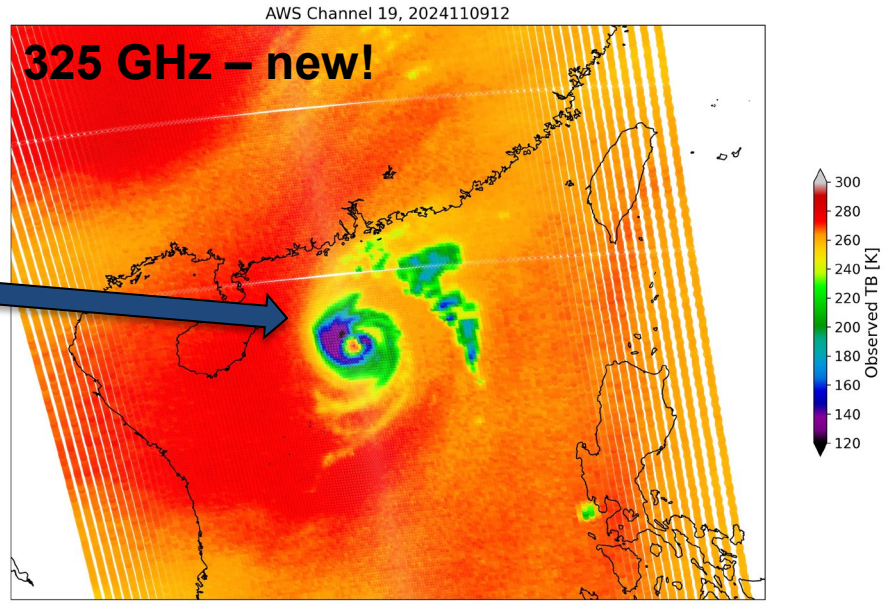
Arctic Weather Satellite (AWS)

ESA mission with EUMETSAT support

Launched on SpaceX rideshare in August 2024

- First meteorological satellite launched by an agency following '**new space**' approach – **36 months from contract to space**!
- Also holds traditional sounder bands at 50-60 GHz for temperature and 183 GHz for humidity (like AMSU-A & MHS)
- First MW sounder with '**sub-mm**' wavelengths (>300 GHz) – much more sensitivity to ice clouds than we've had before





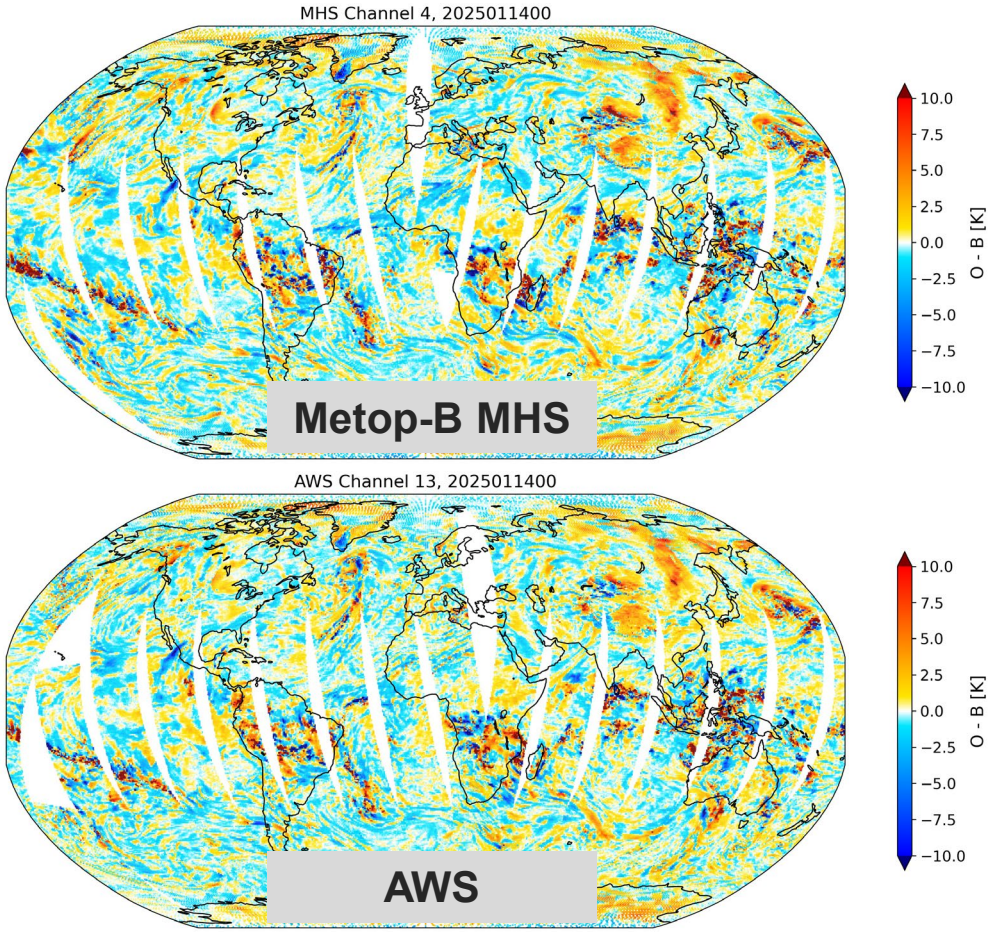
AWS is ~1 m^3 and 125 kg:
roughly a washing machine

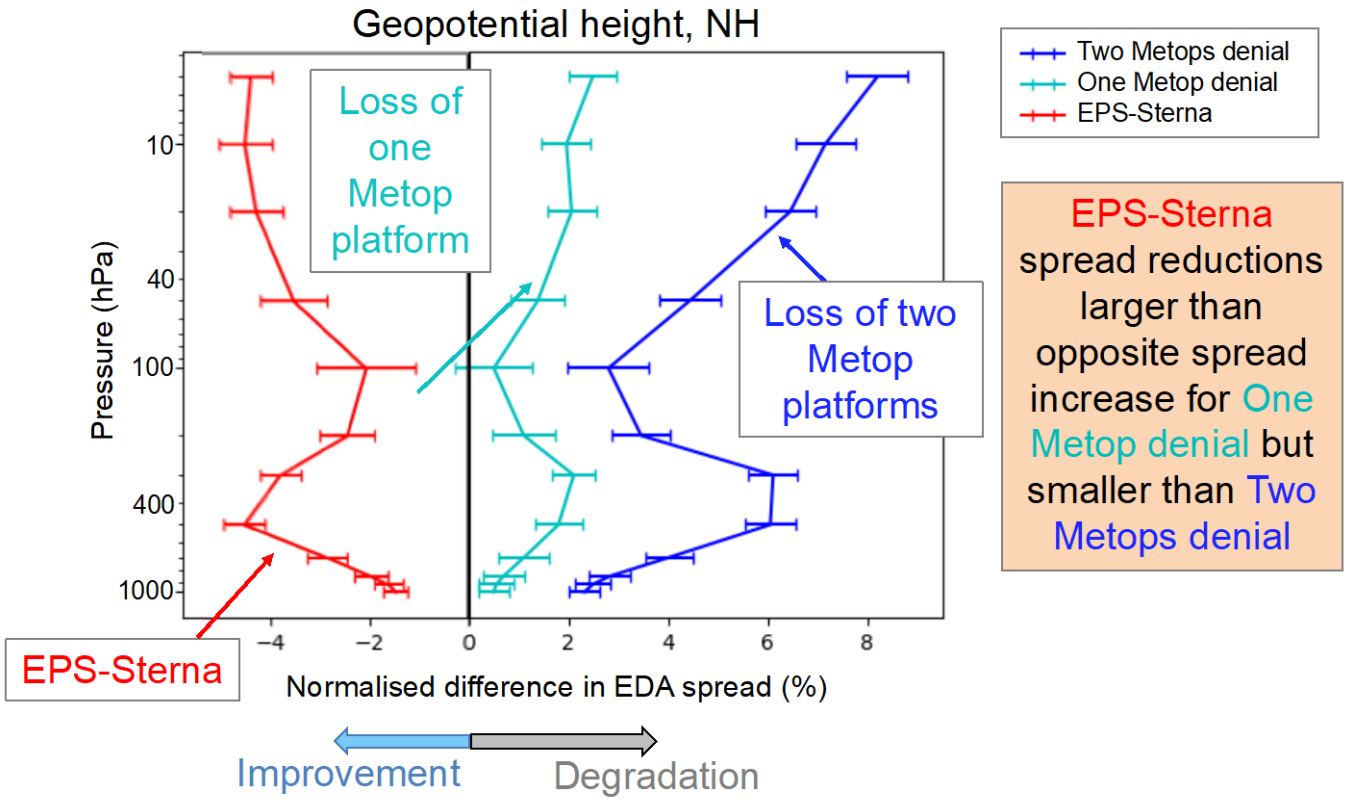
Arctic Weather Satellite (AWS)

Prototype for proposed constellation EPS-Sterna

→ 6 satellites in 3 orbits covering 2029-2042 **– 20 in total**
→ **EDA-based study used to predict NWP impact**

Instrument performance is comparable to AMSU-A & MHS in early trials





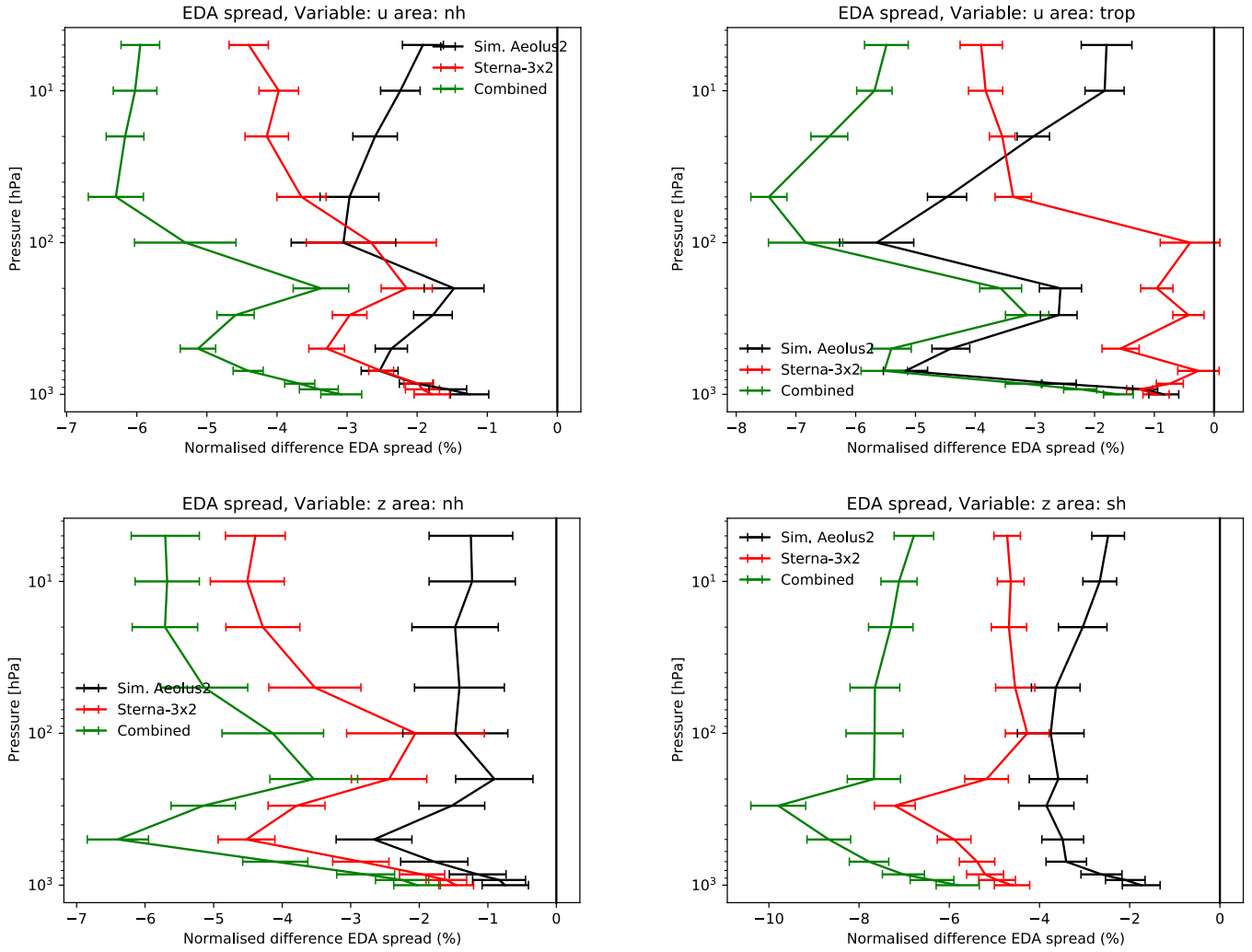
EPS-Sterna spread reductions larger than opposite spread increase for One Metop denial but smaller than Two Metops denial

From *Lean et al. (2023)*: https://doi.org/10.21957/0a695fcc39

ECMWF

Credits: David Duncan, Katie Lean

Combined impact of Aeolus-2 and EPS-Sterna (6 satellites)



Ensemble Data Assimilation spread reduction due to new observations

Combined impact of the two systems clearly superior to either individually

Complementary impact

EPS-Sterna has bigger impact on extra-tropical geopotential heights, but Aeolus-2 still makes useful contribution

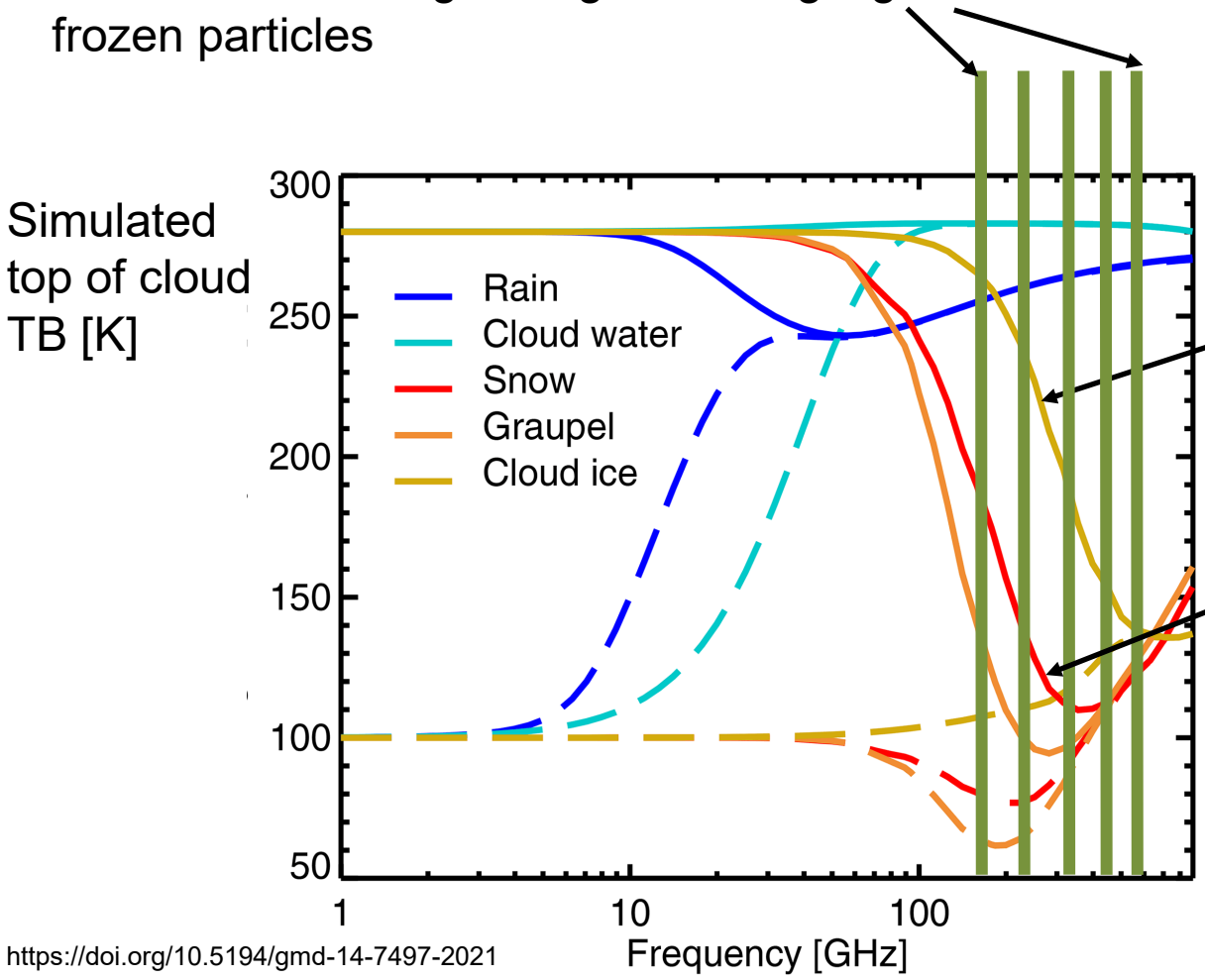
Aeolus-2 has bigger impact on zonal winds in tropics, but EPS-Sterna impact significant at 50 hPa and above

ECMWF

Credits: Mike Rennie, Katie Lean, Sean Healy, Niels Bormann

Scientific preparations for the Ice Cloud Imager (ICI) on METOP_SG

- Cooperation between EUMETSAT, NWP-SAF, Chalmers University and ECMWF among others
- ICI has 13 channels at 183, 243, 325, 448 and 664 GHz observing strong scattering signals from frozen particles



https://doi.org/10.5194/gmd-14-7497-2021

Ice cloud modelled by large column aggregate

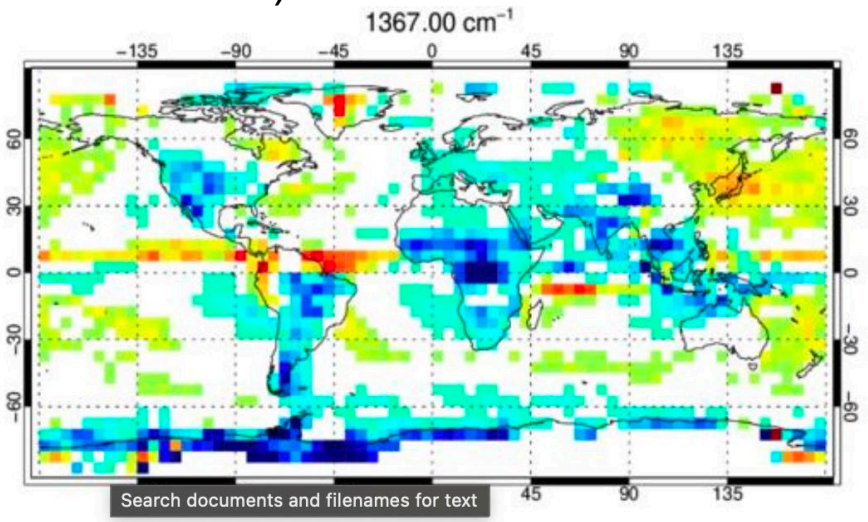
Snow precipitation in atmosphere modelled by large plate aggregate

Particle shapes and optical properties from the ARTS database (https://doi.org/10.5194/essd-10-1301-2018) combined with RTTOV assumptions of particle size distribution

Credits: Alan Geer

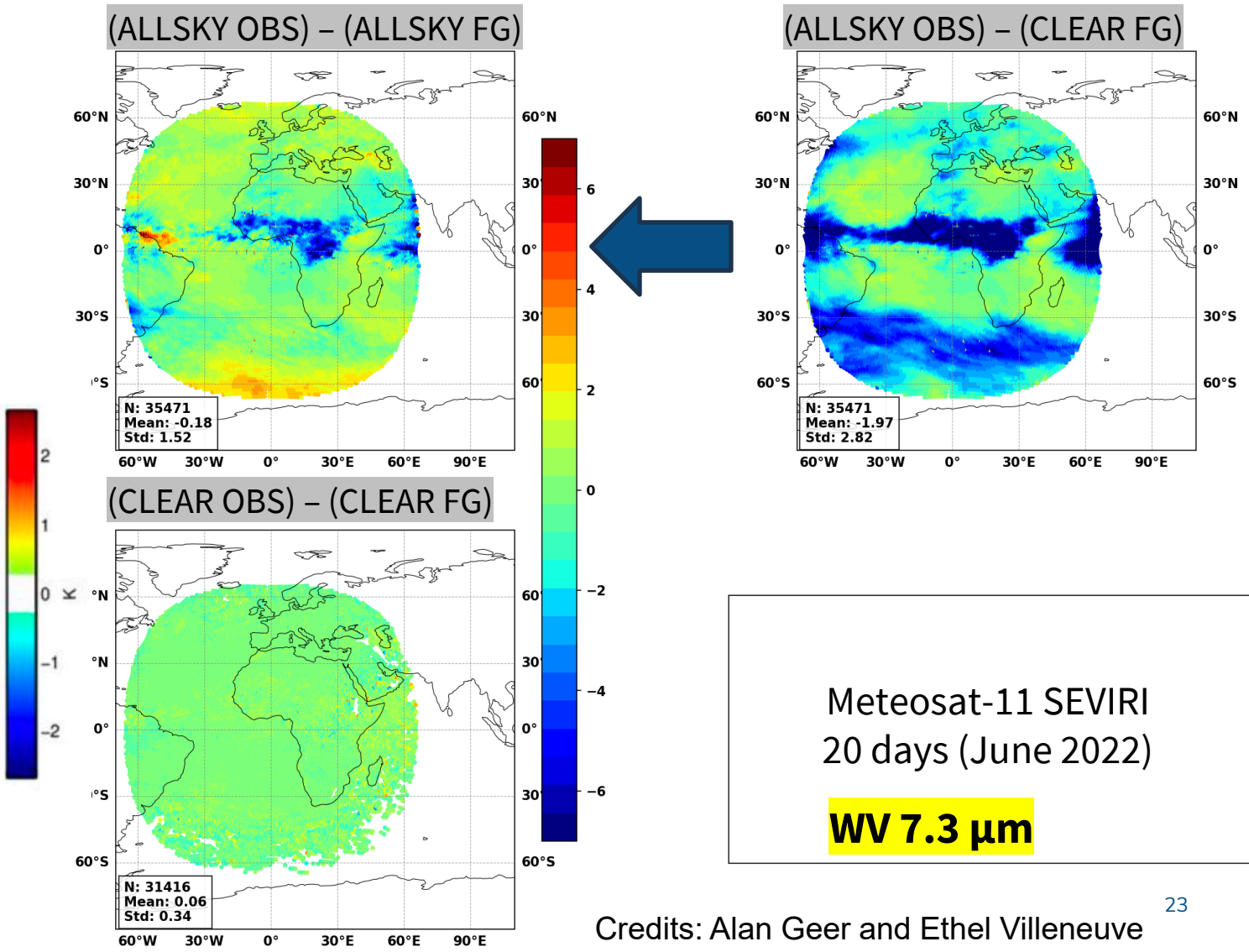
Preparing the all-sky IR

- Based on previous work using IASI water vapour channels by A. Geer (2019, https://doi.org/10.5194/amt-12-3629-2019) revisited in current model cycle.
- Application to GEOS water vapor channels (6.2 and 7.3 microns)



IASI low-peaking water vapour channels O-B

Similar biases between different sensors, indicating a (known) model deficiency in ice clouds.

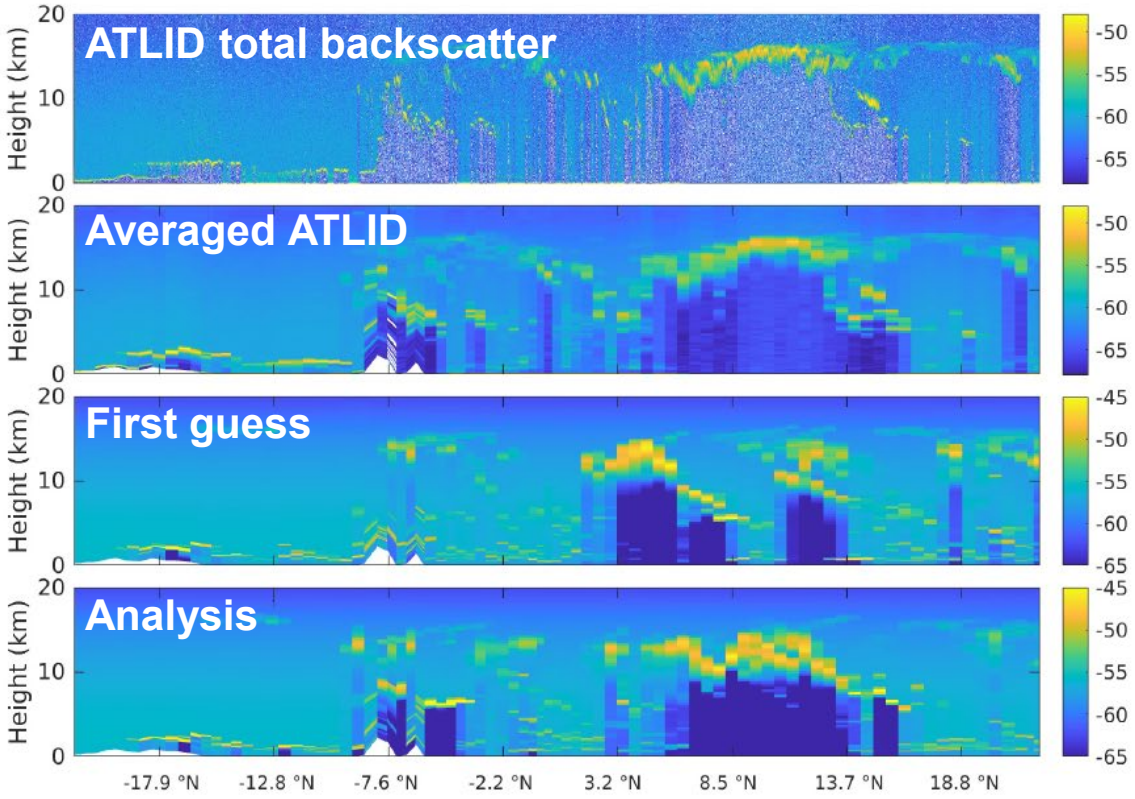


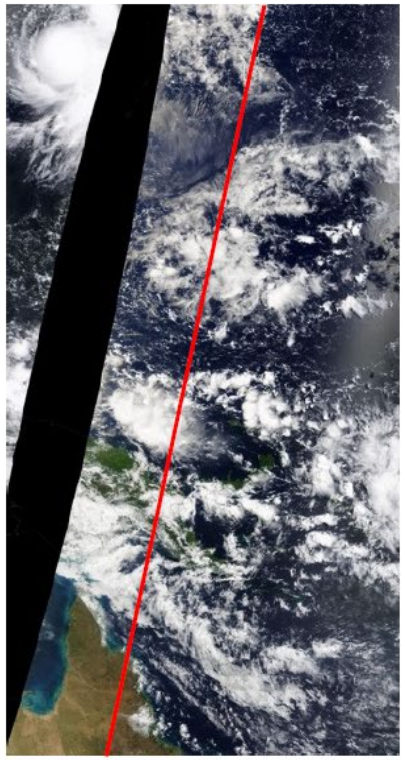
Meteosat-11 SEVIRI
20 days (June 2022)

WV 7.3 µm

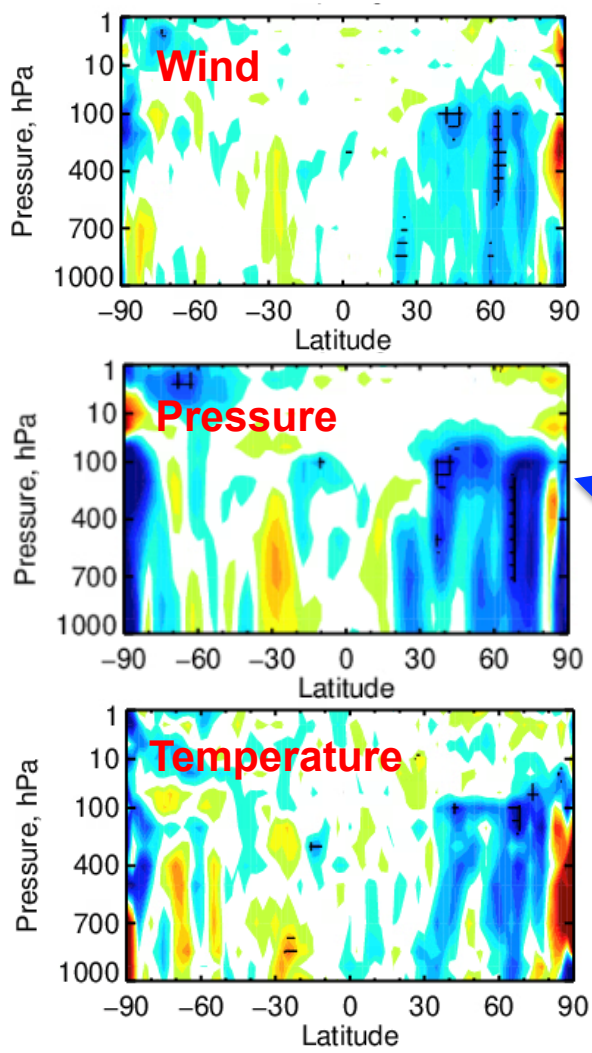
Credits: Alan Geer and Ethel Villeneuve

Assimilation of EarthCARE radar and lidar





Impact on 5-day forecast skill, Aug-Oct 2024



Up to 4% reduction in RMSE

Blue is better

- Assimilation of CPR reflectivity and ATLID total backscatter into the ECMWF model improves forecast skill
- Working on assimilation of ATLID into aerosol forecasts from IFS-COMPO used by CAMS

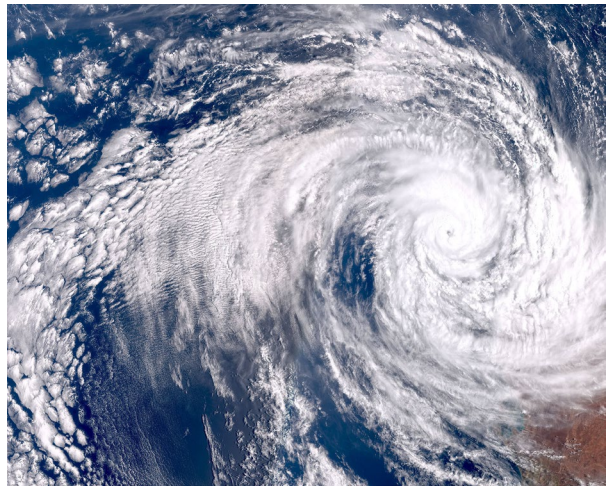
ECMWF

Credits: Mark Fielding, Marta Janisková

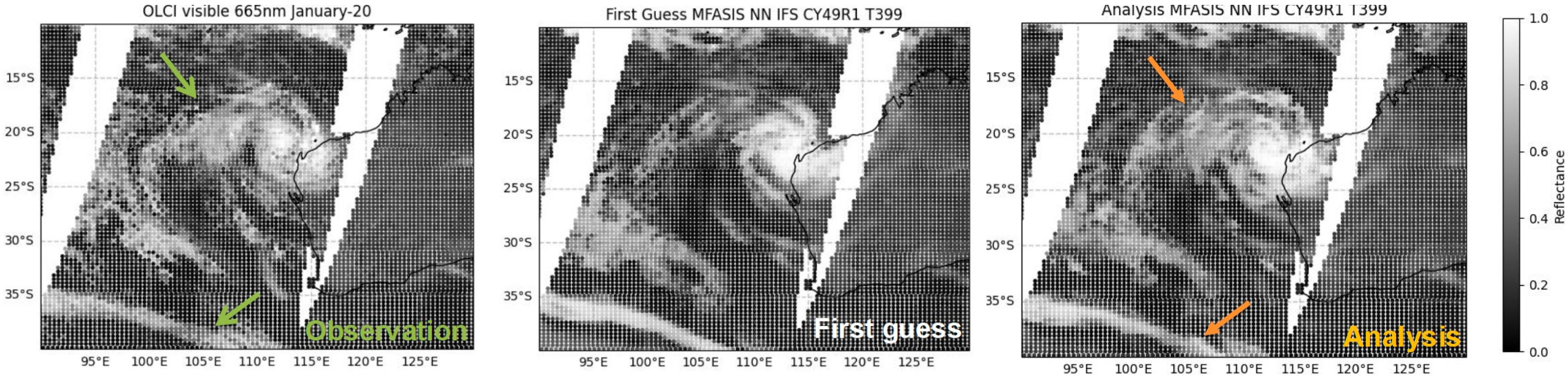
Seeing the unseen: First visible reflectance assimilation IFS

- **DA / Model:** IFS CY49R1.0 TCo399
- **Observations**: LEO Sentinel 3/ OLCI 655nm visible reflectance in BUFR (Volkan Firat)
- **RT model:** RTTOV 13.2 / MFASIS NN (Scheck et al. 2023)
- **Period:** Dec 2024 – Feb 2025
- **Observation error:** 0.25 (reflectance units)
- **Superobbing:** N256 (□40km)
- **Coverage:** Ocean + Land
- **Two configurations:** Full vs depleted observing system (Depleted = Conventional obs. Only)

Cyclone Sean as seen by the Ocean and Land Colour Instrument on Sentinel 3, 20 January 2025



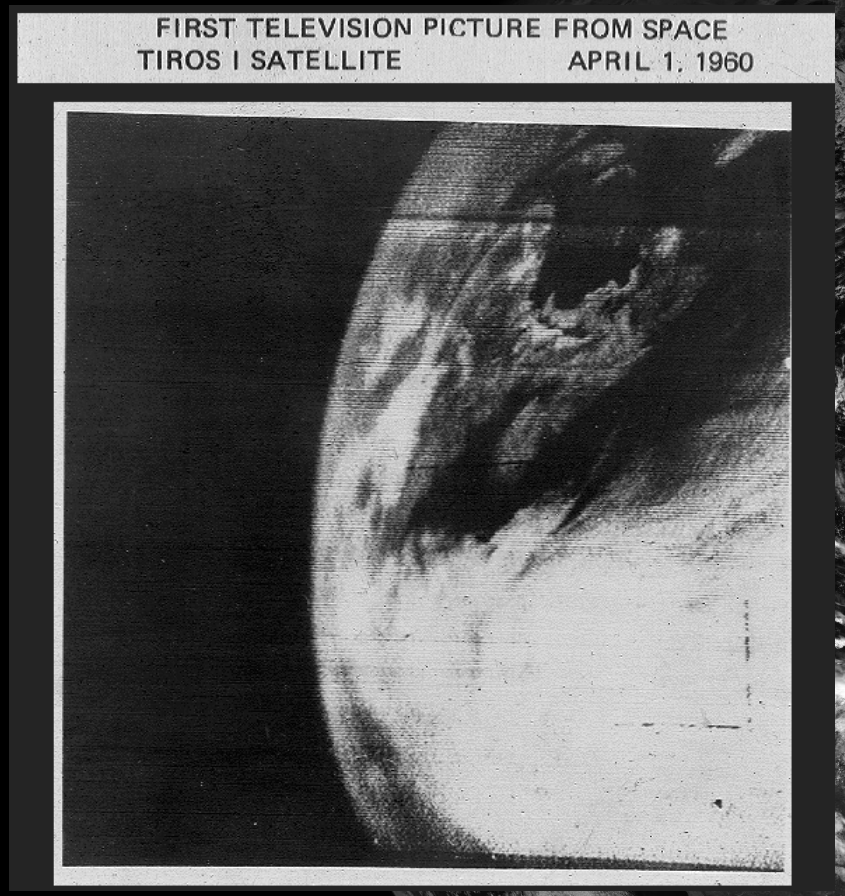
https://www.eumetsat.int/image-week-cyclone-sean



Credits: Tobias Necker, Cristina Lupu, Samuel Quesada Ruiz

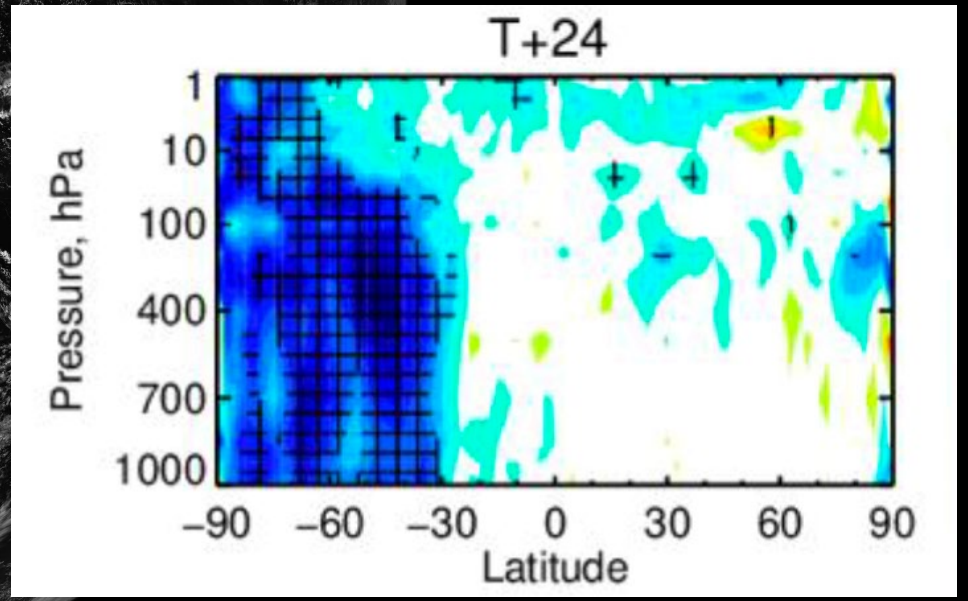
See poster by Tobias Necker

A new look at old observations….



HIMAWARI-9 AHI
Band 3 (red, 0.6 μm, 500m)
First visible image in 2017
© JMA

RMSE reduction due to assimilation of OLCI visible reflectances at 665nm in a depleted observing system-> huge implications for reanalysis!



1 Dec 2024 – 24 Feb 2025

Summary and take-home messages

- A wide range of observations are currently assimilated in the IFS 4D-Var – all providing a positive impact on the forecast
- Large impact of in-situ T2m observations in Northern Hemisphere, aircraft data also very important
- Investigation of observation impact is performed using observing system experiments (data denial) for current observations
- Preparations for new sensors are constantly happening
- Future sensors are tested using the Ensemble of Data Assimilation (EDA) framework
- New observations sensitive to clouds are now being tested for assimilation (cloud radar/ lidar, MW at higher frequencies, etc..)
- Successful near-real-time monitoring and first-ever successful all-sky cloud visible assimilation in IFS
- Depleted observing system experiments suggest huge potential of VIS data for re-analysis