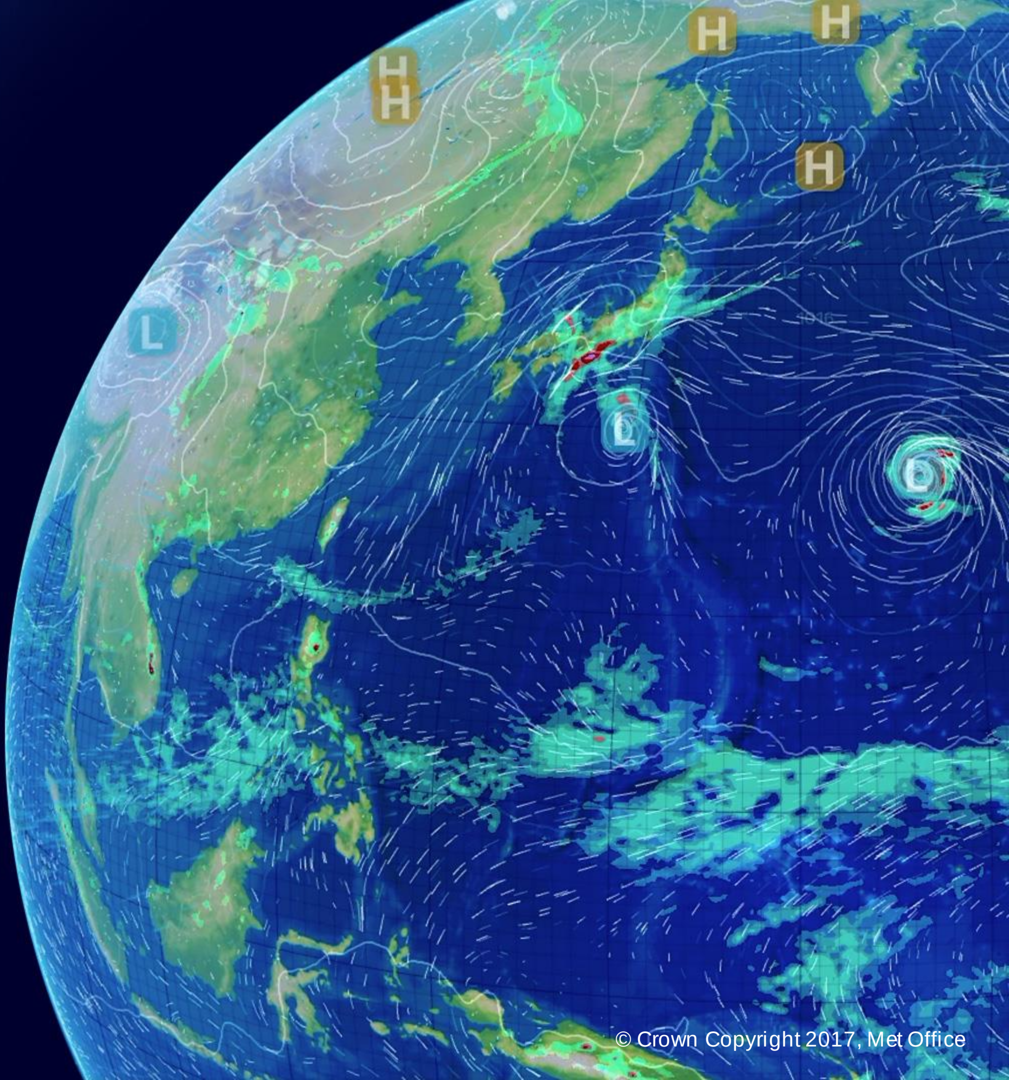
Impact of satellite-derived winds in NWP

Mary Forsythe, James Cotton, Gemma Halloran (Met Office, UK) and Mike Rennie (ECMWF)

EUMeTrain Event week on Winds

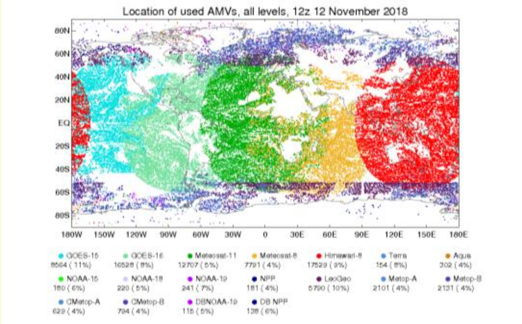
28 Feb – 4 Mar 2022



Contents

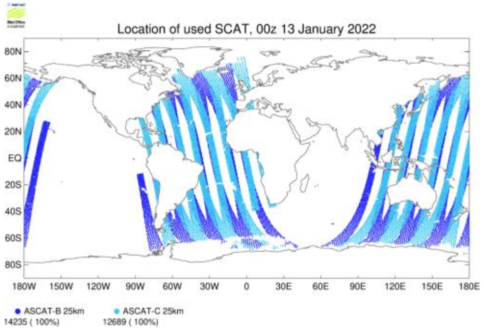
What satellite-derived winds are assimilated?

Atmospheric Motion Vectors (AMVs)



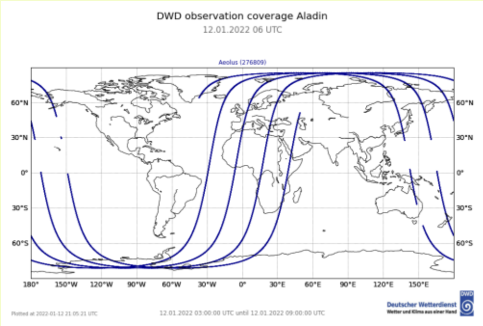
- Global tropospheric winds, but single level
- From tracking clouds and WV in satellite imagery
- Full wind vectors (speed and direction)
- Assimilated in global and regional models

Scatterometer winds



- Near-surface (10m) wind observations over the ocean
- Active sensing
- Full wind vector (wind speed and direction) BUT ambiguous wind solutions
- Assimilated in global and regional models

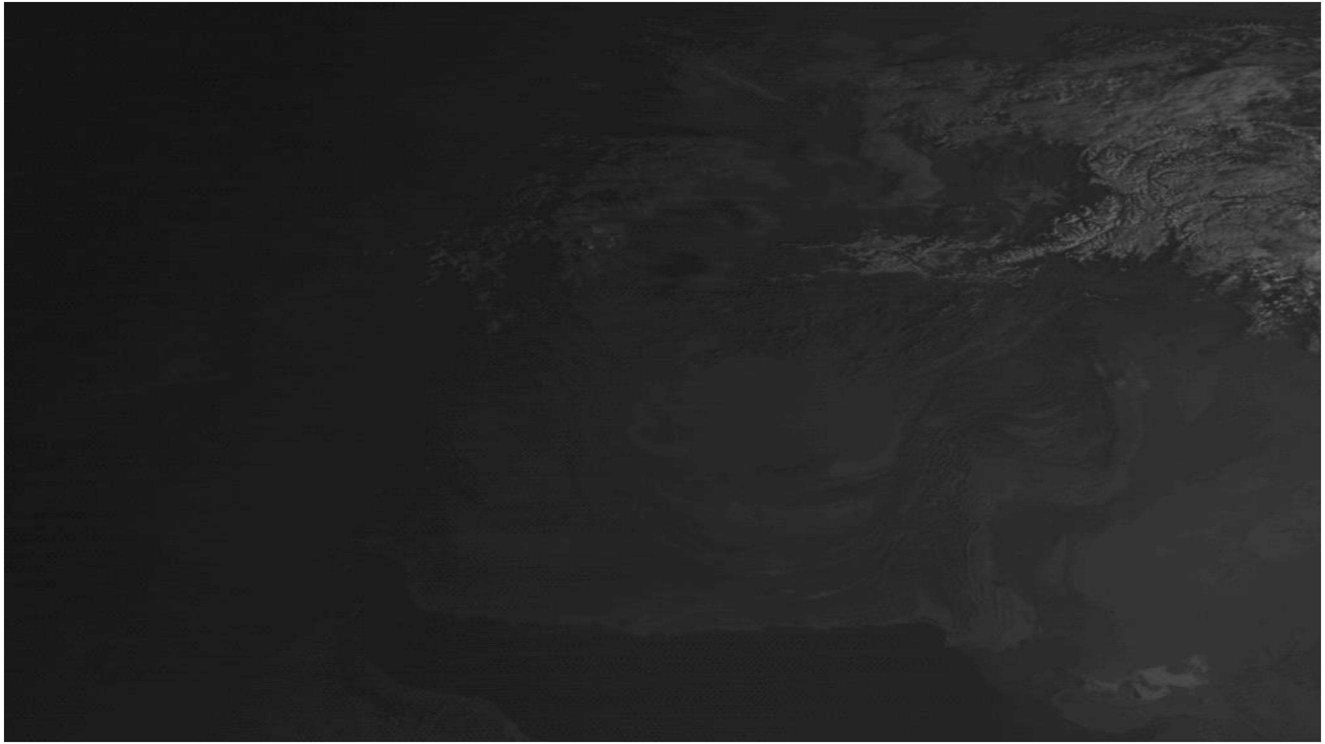
Doppler Wind Lidar (DWL)



- Wind profiles from surface to ~25 km
- Active sensing
- Only one component of the wind, horizontal line of sight (HLOS) ~zonal for much of orbit
- Only from Aeolus, still need to secure operational continuity
- Assimilated in global models

Atmospheric Motion Vectors

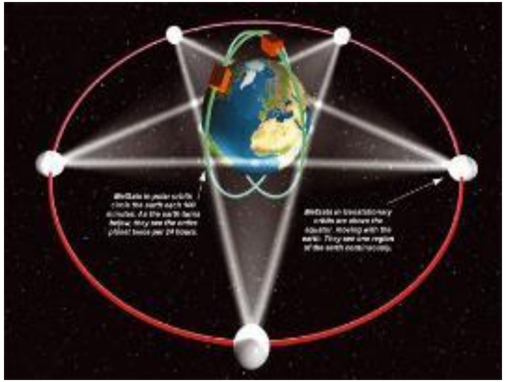
In sequence of images – movement of clouds and moisture



Courtesy of EUMETSAT

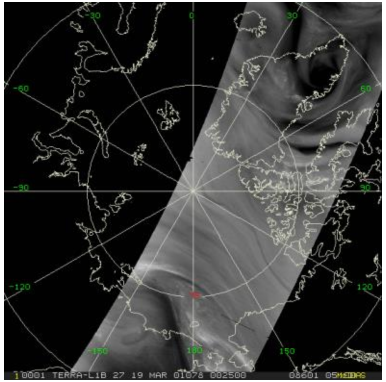
Which satellites?

AMVs are produced from geostationary satellite imagery

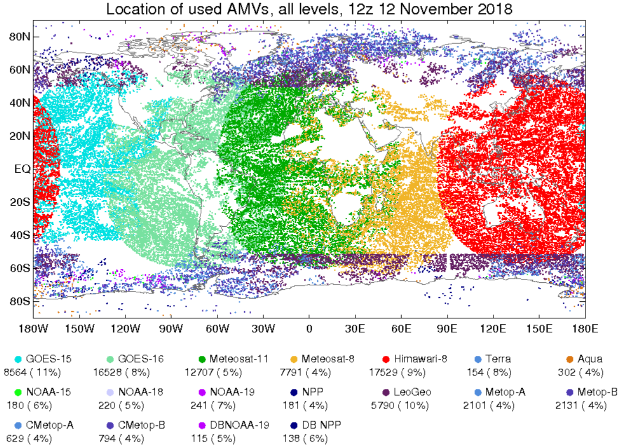


Providing coverage over tropics and mid-latitudes

And from polar satellite imagery



providing coverage in the polar regions, where the overpasses overlap.

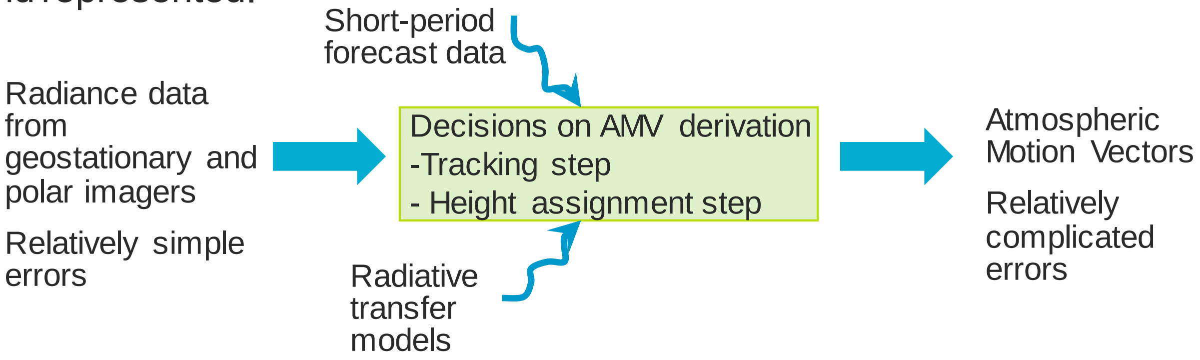


Met Office

AMV challenges

1. Complicated errors

To derive AMVs, we move a long way from the raw radiance data where the errors may be more easily understood and represented.

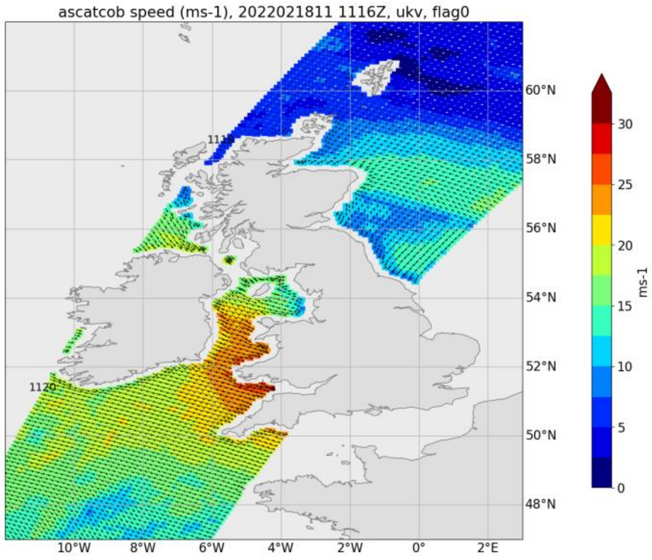


2. Assumptions in derivation and assimilation

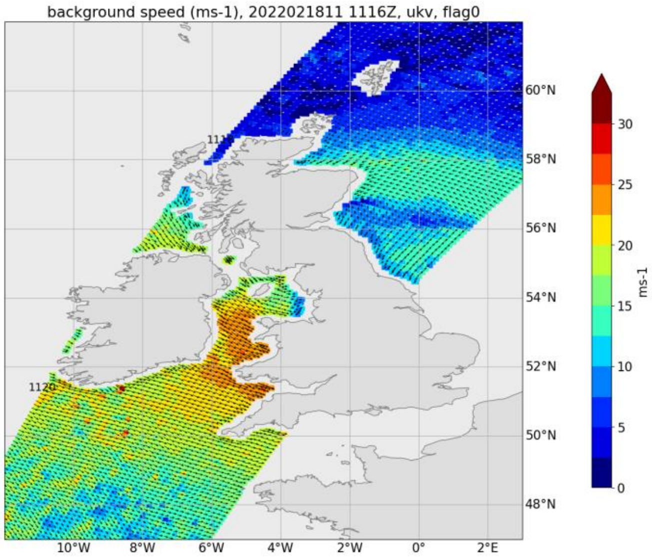
e.g. assume point winds, clouds act as passive tracers, spatially and temporally uncorrelated errors.

Scatterometer winds

Extratropical Storm Eunice impacting the UK on 18 Feb 2022. Red wind warnings issued by the Met Office.



Metop-B ASCAT



UKV model

James Cotton

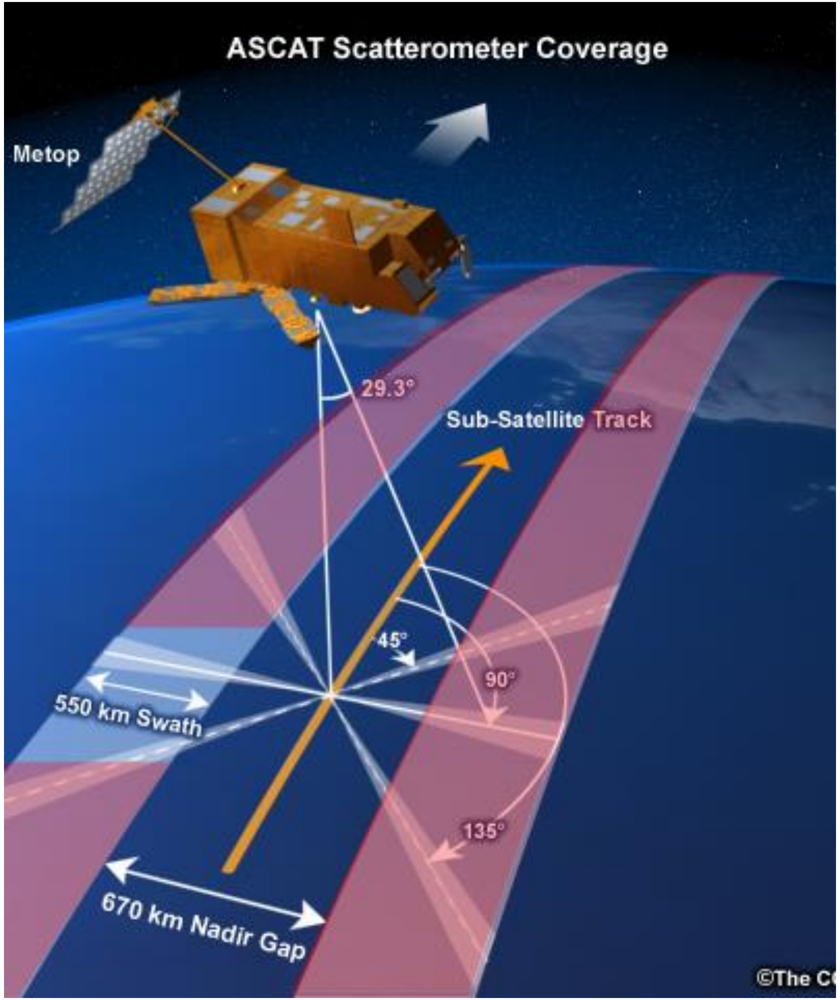
Scatterometers

Scatterometers are ‘active’ radar instruments

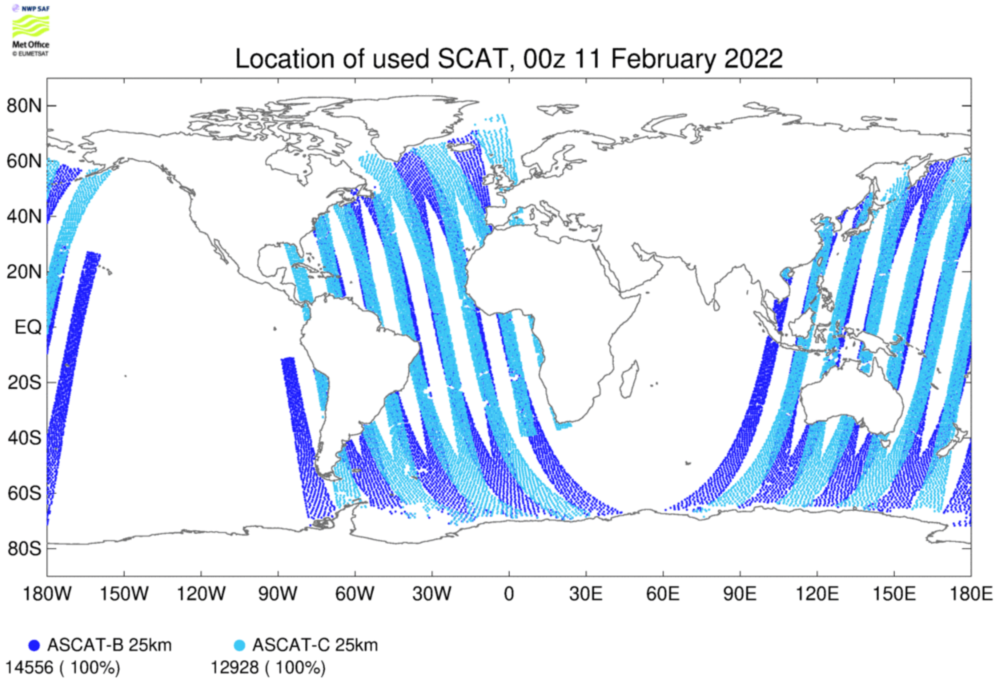
- Emit a pulse and measure returned signal
- Normally flown on-board polar orbiting satellites
- Operate in microwave spectrum: ‘see’ through clouds, rain impacts
- Don’t measure the wind.. measure backscatter

Backscatter response is sensitive to

Ocean	surface wind (via roughness)
Land	soil wetness
Ice	ice age (extent/drift)



Scatterometer coverage



At the Met Office we assimilate data from 2 Metop satellites.

Data is also available from HY-2B/C, CFOSAT

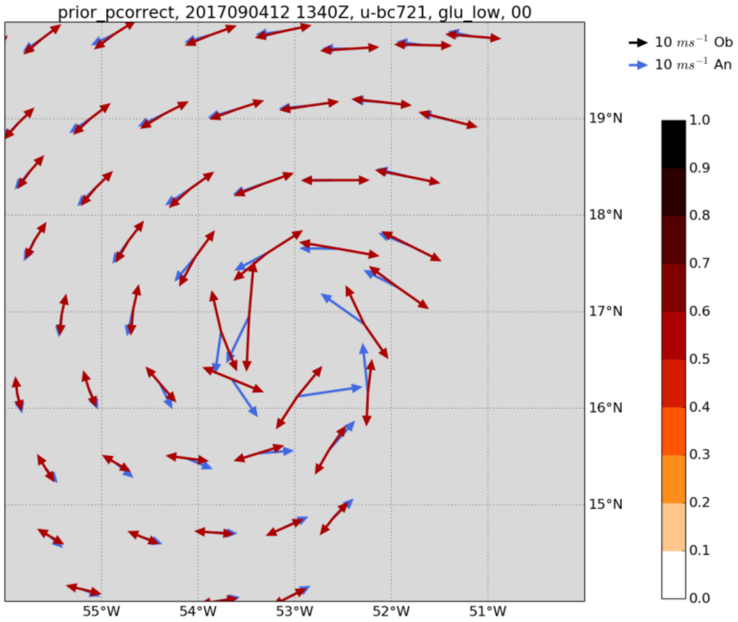
Over the next few years we will see data from Metop-SG, FY-3E, OceanSat-3/3A

Ambiguity Removal

In general scatterometers have 2-4 wind solutions per wind vector cell.

How to handle ambiguity?

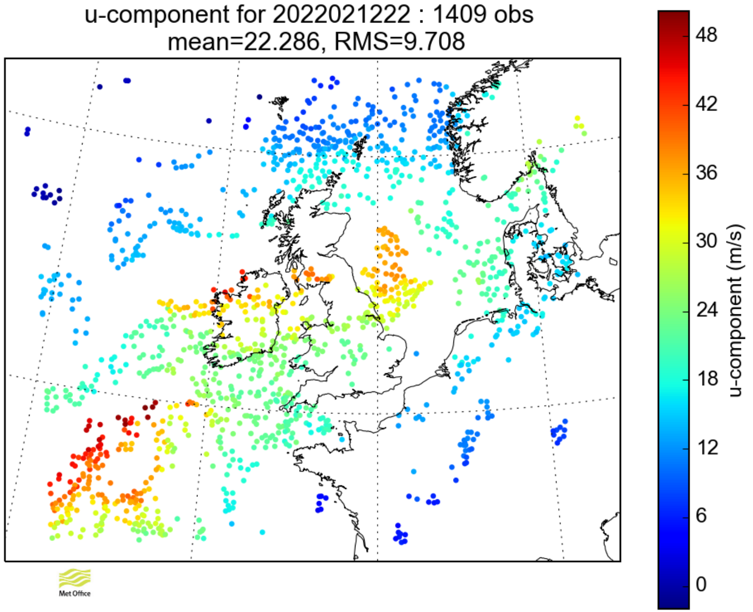
- Smallest inversion residual
- Use producers 'chosen' wind (nowcasting/visualisation)
- Closest to background wind field (O-B monitoring)
- Ambiguity removal based on data assimilation (e.g. 4D VAR)

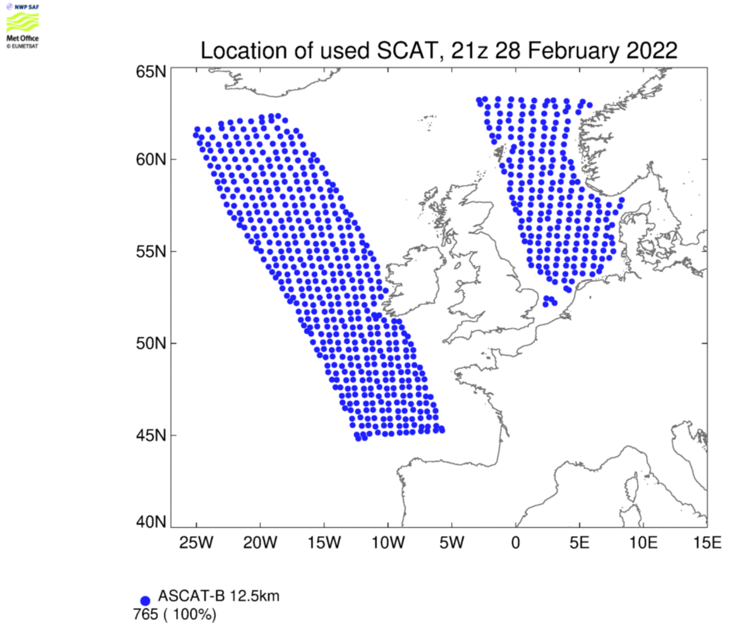


ASCAT = red, model = blue

James Cotton

Wind assimilation in regional models





AMVs: Run the NWC SAF AMV software to generate higher resolution AMVs for our UKV model

Scatterometer winds: assimilate higher resolution products produced by the OSI SAF.

Doppler Wind Lidar (DWL)

DWL measures Doppler frequency shift of backscattered light

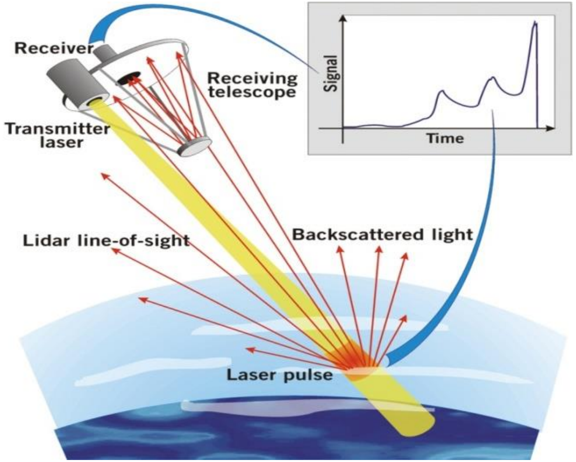
Scattering from

- Air molecules (clear air) – Rayleigh scattering
- Particles (aerosol/cloud) – Mie scattering

Atmospheric backscatter from a laser pulse collected by a telescope, range-gated, and spectrally analyzed to determine the Doppler shift. The range gates, Doppler shift, telescope look-angle and satellite orbit can be used to calculate the wind velocity as a function of altitude.

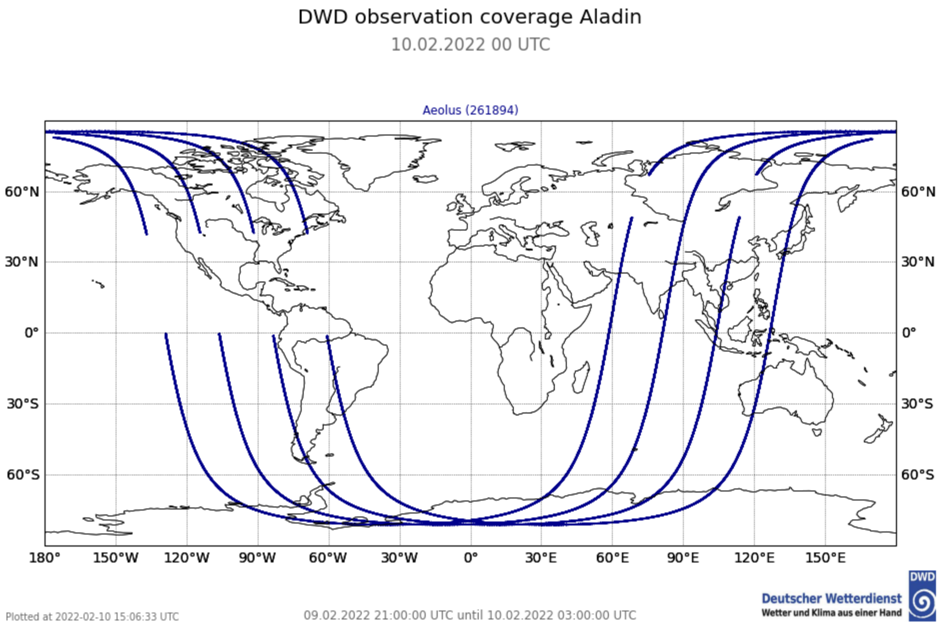
Aeolus mission

- ESA Earth Explorer Core Mission chosen in 1999
- Technology demonstration, ~3 years
- Launched Aug 2018



Gemma Halloran

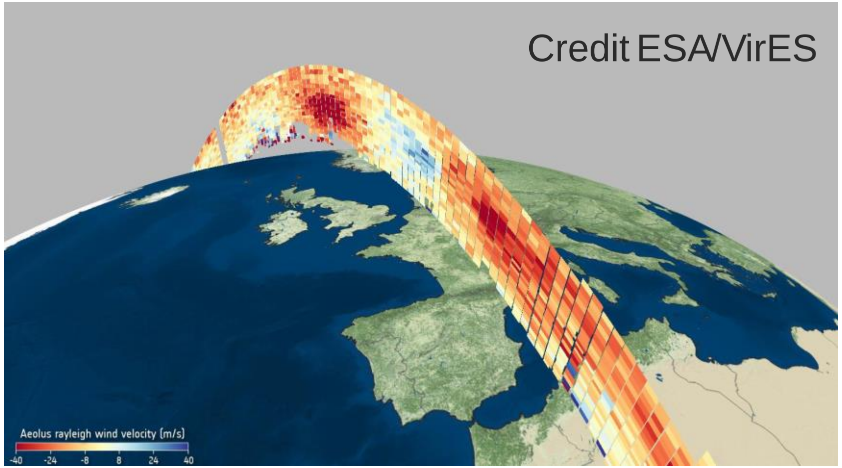
Aeolus winds



Observations available along the satellite ground-track (no swath)

Only one component of the wind along line of sight of the laser - perpendicular to ground track

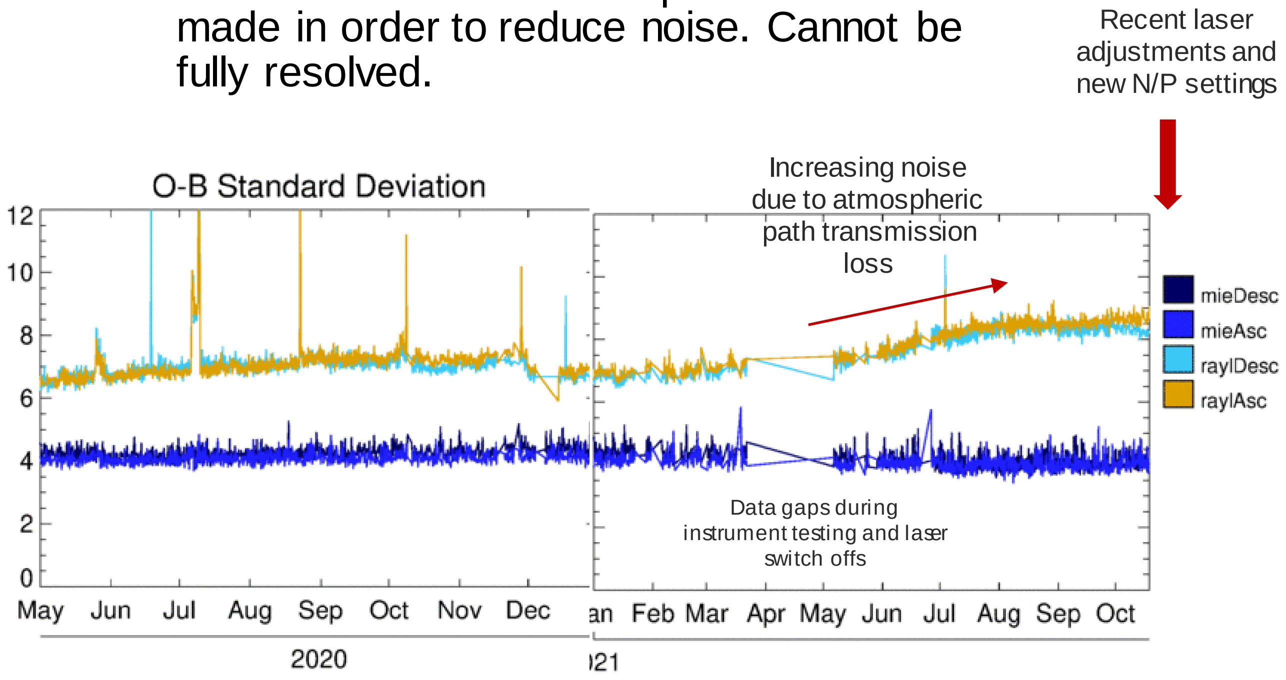
Profile of winds from surface to ~25 km.



Aeolus Challenges

Aeolus is a novel science mission. There have been a number of challenges:

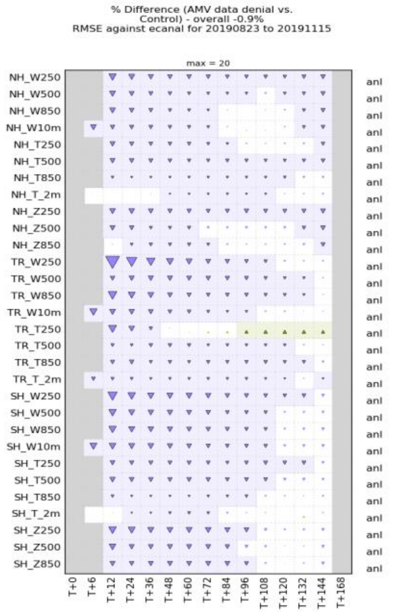
1. Increased dark current "hot pixels" – leading to range bin biases – mitigated by using DUDE cycles
2. M1 mirror temperature bias, more problematic for Rayleigh channel, mitigated using a bias correction scheme
3. Increasing noise due to loss of signal in optical path, thought to be due to laser induced contamination. Optimisations made in order to reduce noise. Cannot be fully resolved.

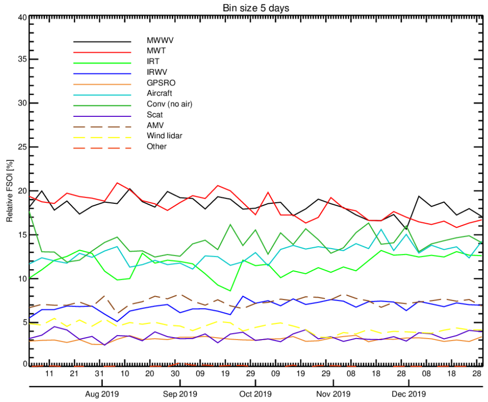


Gemma Halloran

Impact in NWP

- Data denial experiments
- Forecast Sensitivity to Observations Impact (FSOI)





Data Denial Experiments

Periodically run a series of data denial experiments

Most recently for a 3 month period: 15th Aug 2019 - 15th Nov 2019

- Remove a range of observation categories from the data assimilation step (hybrid 4D-Var)
- Forecasts compared to a *control* which uses all observations operational in late 2019 (OS43). Notable absences: Aeolus, Metop-C, some new RO datasets (COSMIC-2, Spire)

Simplification compared to operations

- Reduced horizontal resolution N320
- Effect of withdrawal of observations from ensemble system is ignored (ensemble feeds into deterministic forecasts via forecast error covariance matrix within hybrid 4D-Var)

Work coordinated by Brett Candy

Observation categories withdrawn

Category	Description	Key instruments
Aircraft	temperatures,U,V & RH from aircraft	AMDAR
AMVs	wind vectors from visible and IR imagers onboard geostationary and polar platforms	MSG/SEVIRI, Himarawi/AHI, GOES/ABI. high latitude winds from AVHRR & VIIRS
Geostationary CSR	clear sky radiances from geo IR imagers	MSG/SEVIRI, Himarawi/AHI, GOES/ABI
Ground-based GNSS	total zenith delay, sensitive to total column water vapour and surface pressure from GNSS receivers at a network of stations	Networks in Europe & US
GNSS RO	bending angles sensitive to temperature and humidity	receivers onboard Metop satellites, FY-3C,D
Hyperspectral IR	radiances sensitive to temperature and humidity	AIRS, CrISx2, IASIx2
MW sounders and imagers	radiances sensitive to temperature and humidity	AMSU-Ax5, ATMSx2, AMSR2, SSMIS, GMI, MHSx3, MWHS-2, MWRI
Radiosondes	profiles of temperature, winds and relative humidity	
Scatwind	wind vectors over ocean	ASCATx2, WindSat, ScatSat
Surface - land	temperature, relative humidity, pressure and winds from land stations	
Surface - ocean	temperature, relative humidity, pressure and winds over ocean from buoys, ships and rigs	

From Brett Candy

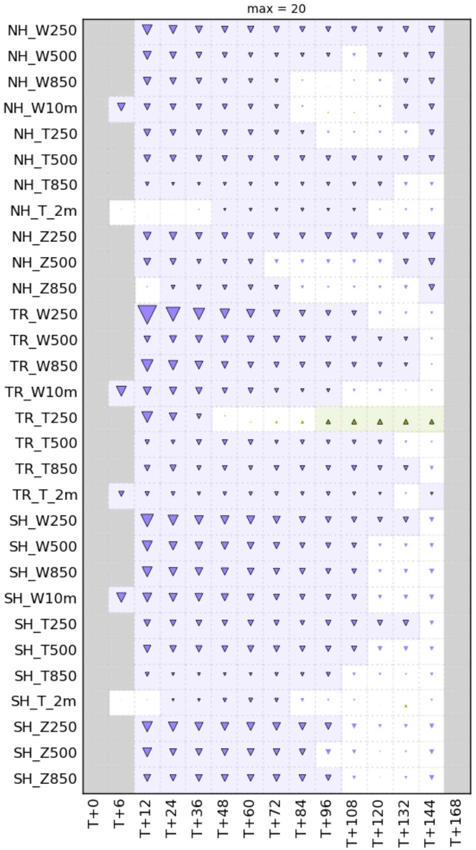
Met Office

Forecast scorecards

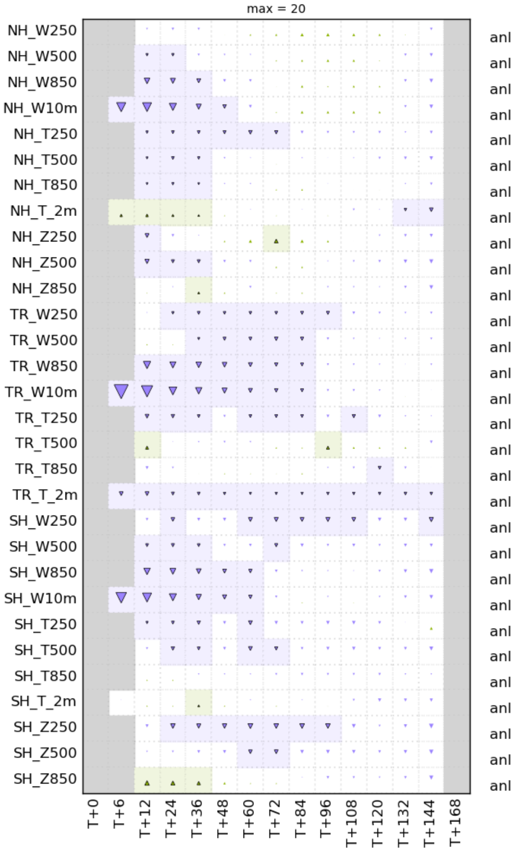
Scorecards verified using independent operational analyses (from ECMWF)

Downward triangles in purple denote detriment in RMS forecast error (against control) – highlighting that the withdrawn data provides benefit

AMVs



Scatterometer winds

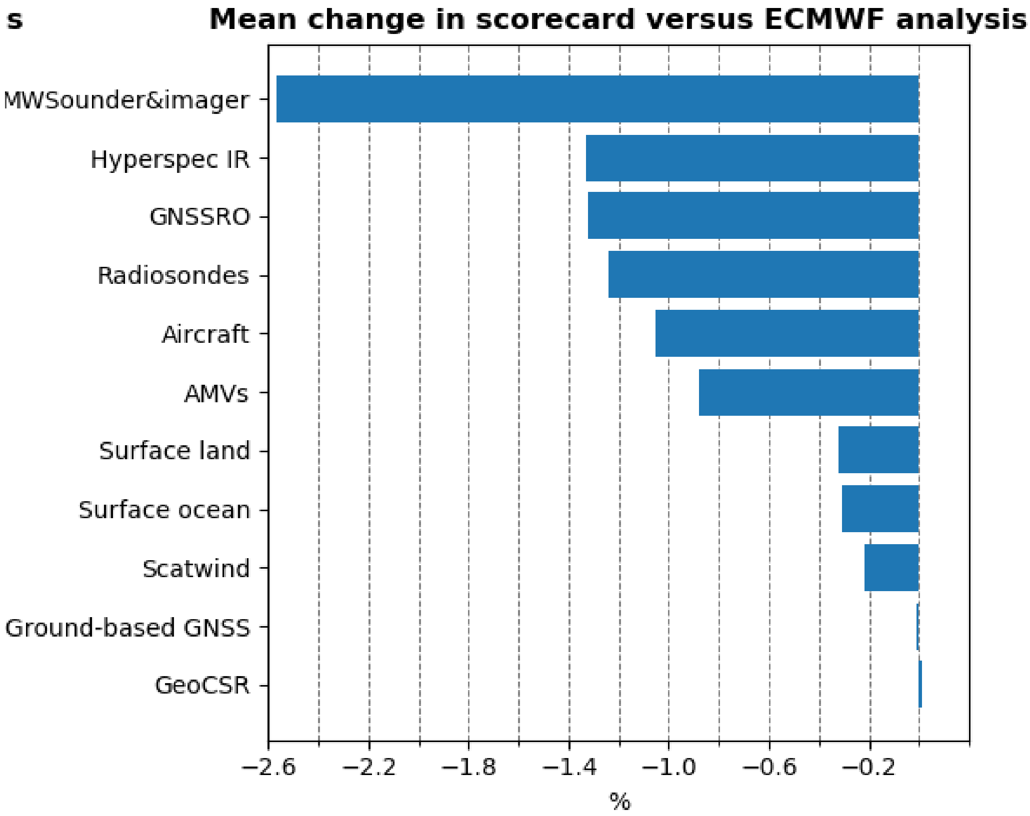


AMVs
largest change – tropical and SH wind fields

Scatterometer winds
largest change – 10 m wind fields globally.

Amy Doherty and James Cotton

Data Denial Impact summary



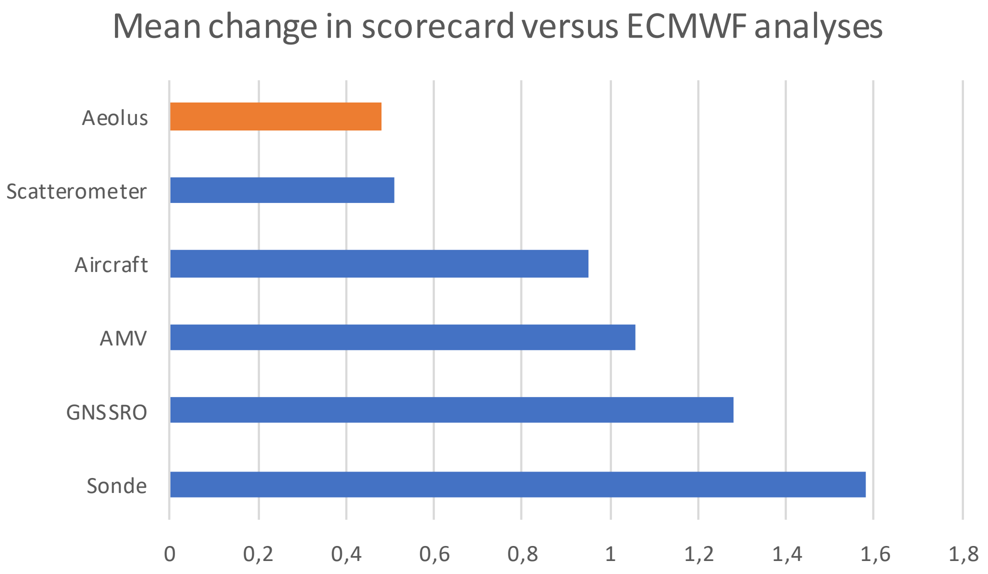
Satellite Sounders, GNSSRO and radiosondes give largest impact.

AMVs & Aircraft also important.

Nearly all observation categories yield benefit.

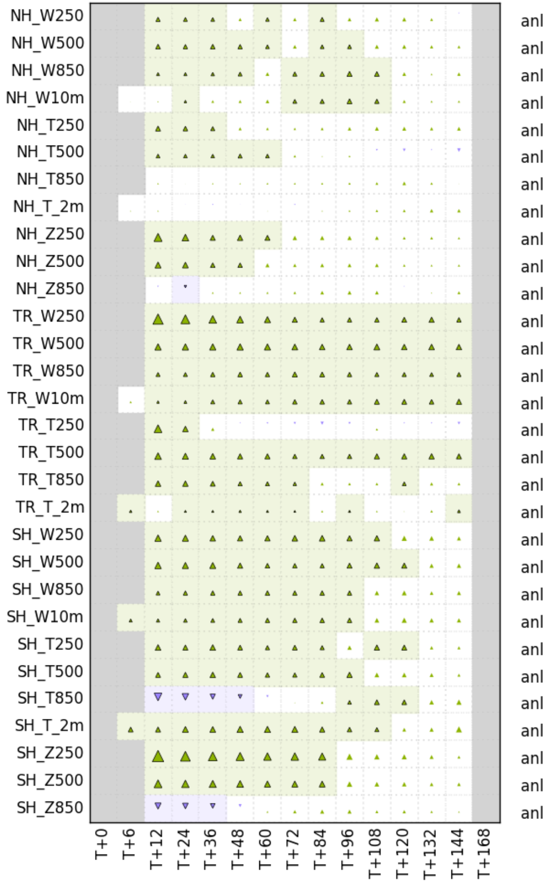
From Brett Candy

How does Aeolus compare?



We ran a shorter data denial period in 12 Sep – 16 Oct 2018 to gauge the impact of Aeolus compared to other observation types.

Aeolus impact similar to impact from scatterometer constellation (4 satellites). Impressive for a single satellite instrument.



Gemma Halloran

Aeolus Impact at ECMWF

Operationally assimilating Aeolus winds for over 2 years

They have run numerous assimilation experiments

The most interesting is a very long, higher resolution (~18 km compared to 29 km in earlier experiments) assimilation trial using reprocessed Aeolus data. Nominal set-up; **29 June 2019 to 6 Feb 2020** (still running – longest OSE for Aeolus!).

Shows the **best impact** we have seen so far from Aeolus

Statistically significant and good magnitude positive impact on **wind, temperature, geopotential and humidity** forecasts in **tropics and polar regions:**

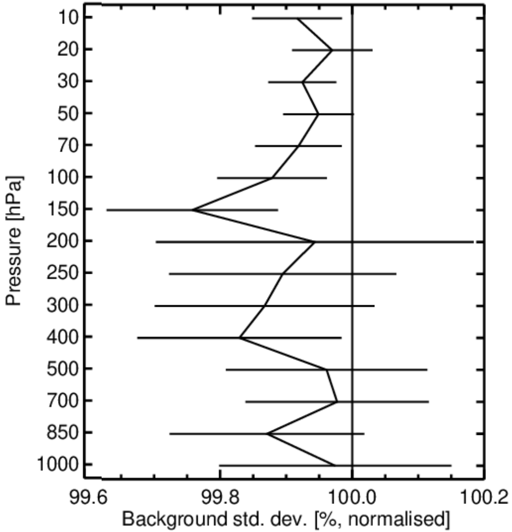
- Up to **10 days** in tropics and S. Hemi. extratropics at 100 and 50 hPa
- **Even N. Hemi. extratropics geopotential at 500 hPa is improved to day 4 by ~1%**

Mike Rennie

Background (short-range forecast) fit to other observations when assimilating Aeolus

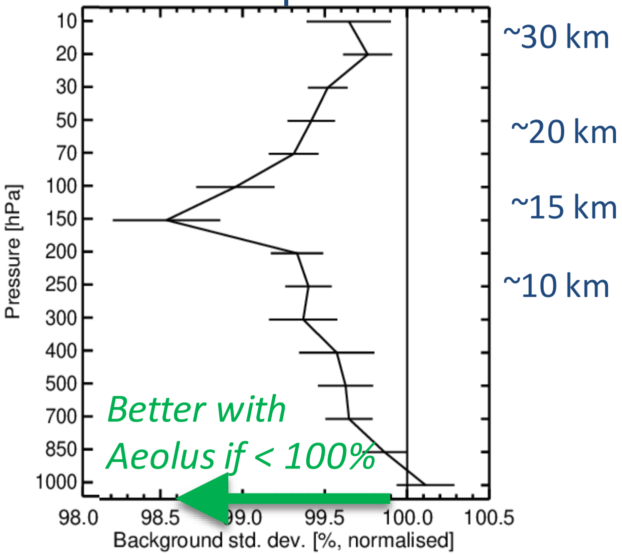
Fit to "conventional" wind observations: from aircraft, radiosondes and radar wind profilers

N. Hemi. extratropics



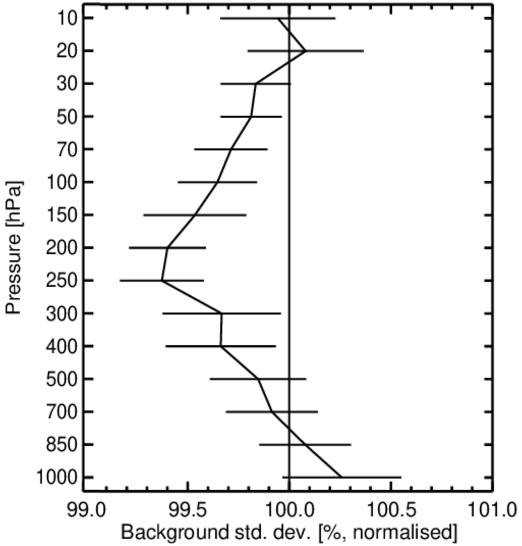
Small positive in NH extratropics

tropics



V. good impact in the tropics

S. Hemi. extratropics



Good impact in SH extratropics; *apart from > 850 hPa*

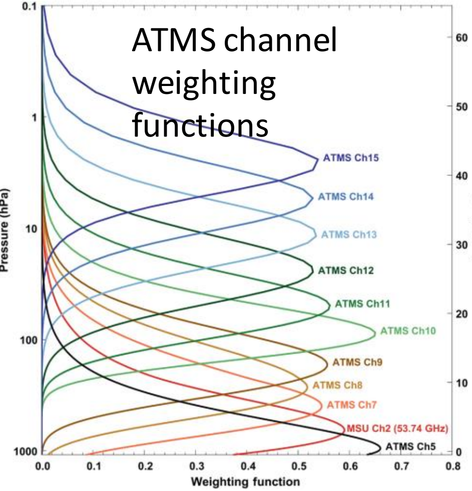
Aeolus' impact largest in tropical upper troposphere – similar previous OSEs

Mike Rennie

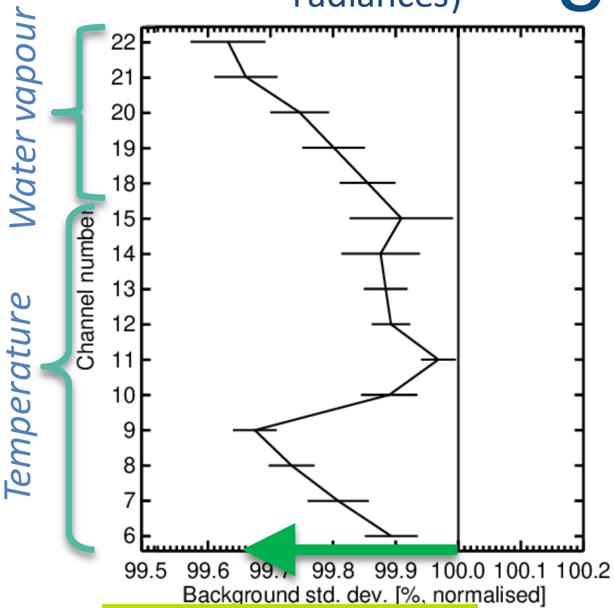
... background fit to other observations when assimilating Aeolus

Fit to important temperature/humidity sensitive data

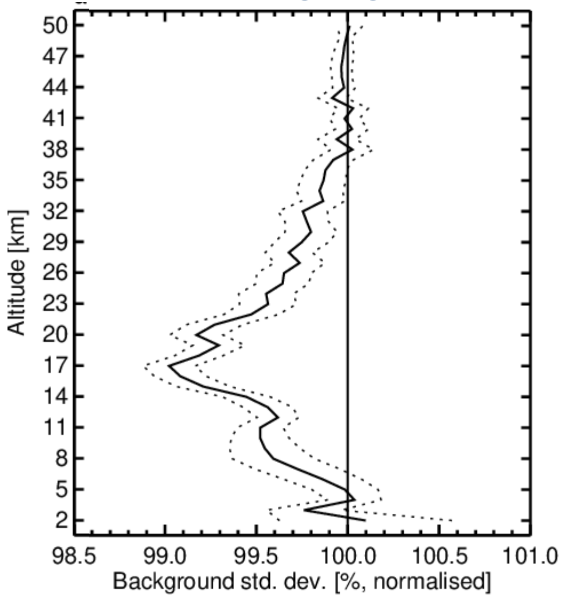
ATMS channel weighting functions



Global, ATMS (microwave radiances)



Global, GNSS radio occultation (bending angles)



Better with Aeolus if < 100%

Strong positive impact: **Aeolus improves wind**, **temperature** and **humidity** background fits, most strongly in **upper troposphere**

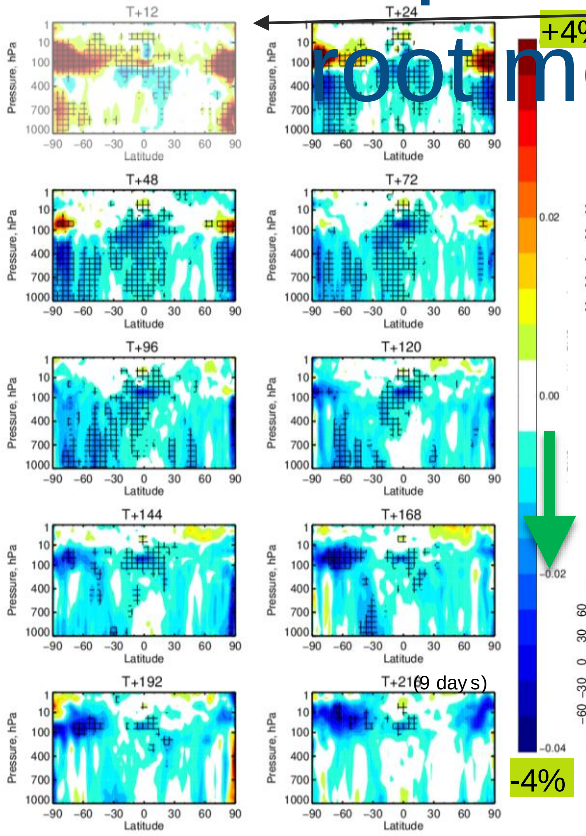
Mike Rennie

Impact of Aeolus: forecast root mean square error

Vector wind RMSE zonal average

Short-range verification by analysis is not trustworthy

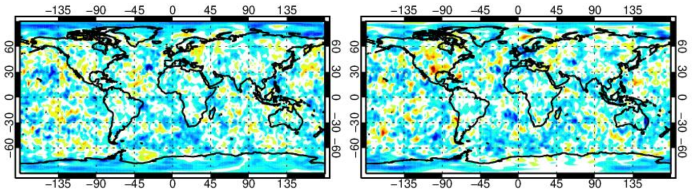
Temperature RMSE zonal average



Vector wind RMSE 500 hPa (±10%)

2 days

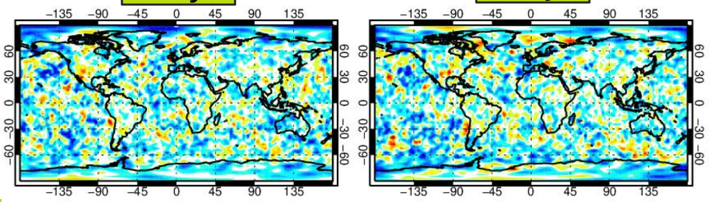
3 days

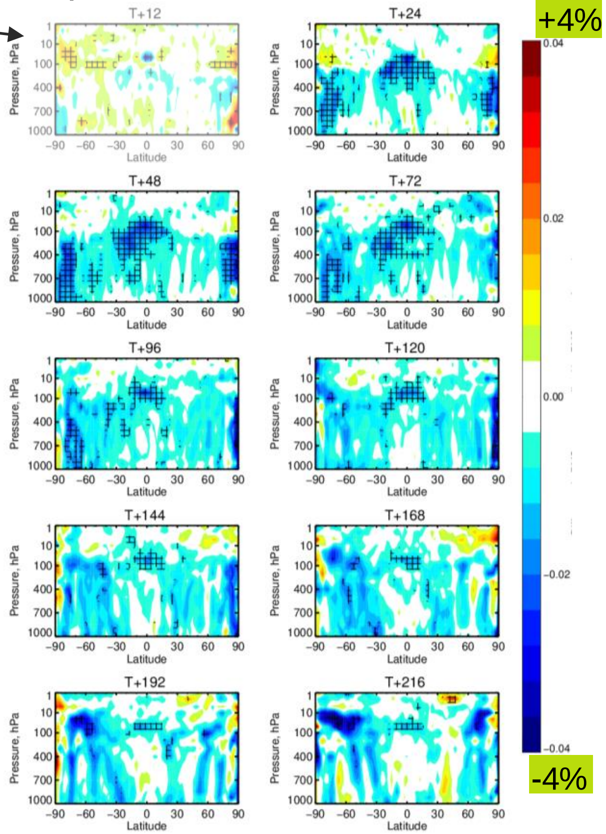


Temperature RMSE 500 hPa (±10%)

2 days

3 days





Better with Aeolus if blue

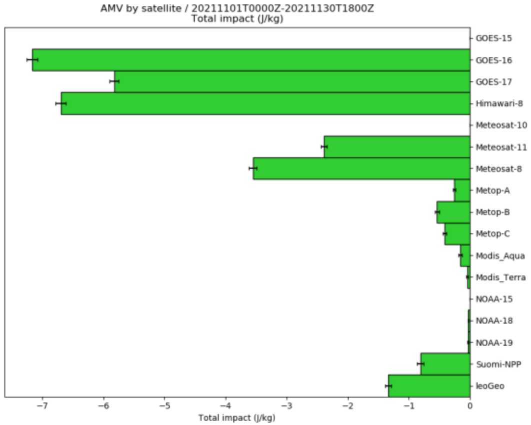
- A lot of positive impact!

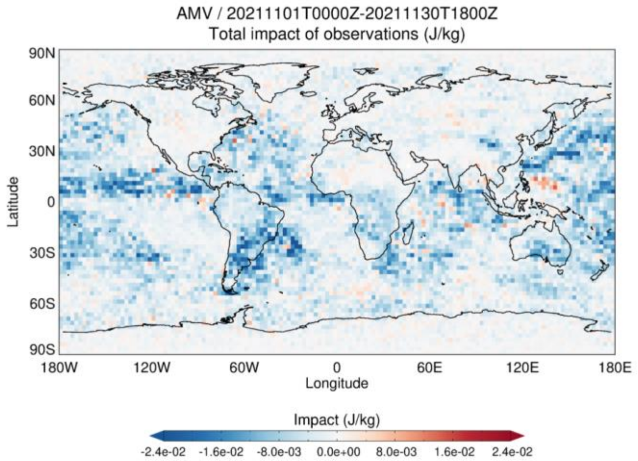
Mike Rennie

Forecast Sensitivity to Observations Impact (FSOI)

- FSOI is a technique to measure the impact on forecast error due to the assimilation of each individual observation. See Lorenc and Marriott (2013)
- Verification: considers the impact at a single forecast lead time, in this case 24 hours.
- Metric: global, total (moist) energy norm, calculated from surface up to 150 hPa.
- Negative FSOI values indicate a beneficial impact i.e., a reduction in forecast error
- Satellite data account for around 70% of the total impact

Lorenc, A. C. and Marriott, R. T. (2013) Forecast sensitivity to observations in the Met Office Global numerical weather prediction system. Q. J. R. Meteorol. Soc., 140, 678, pp 209-224

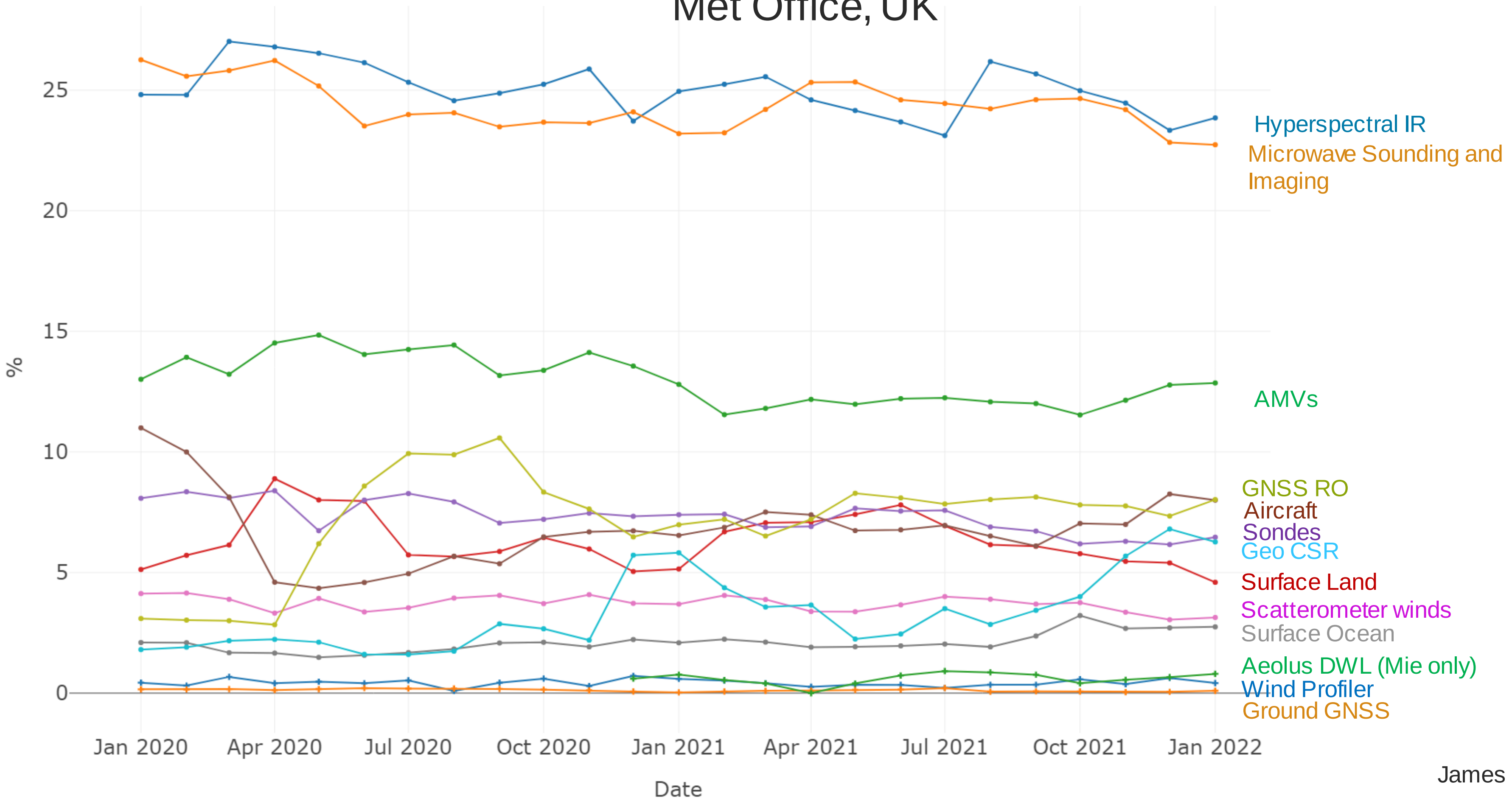




James Cotton

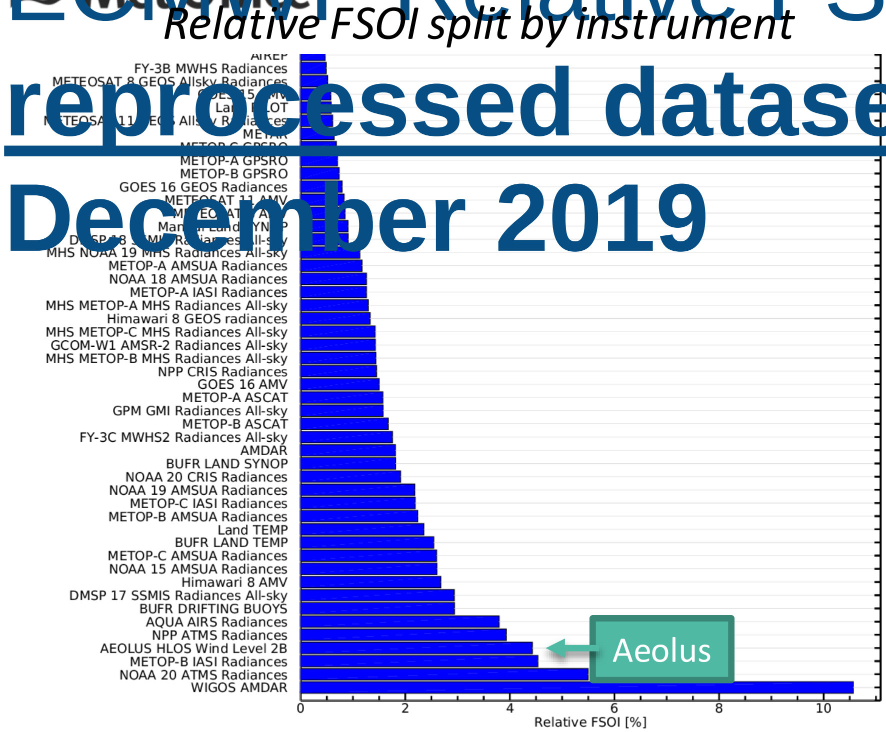
FSOI time series

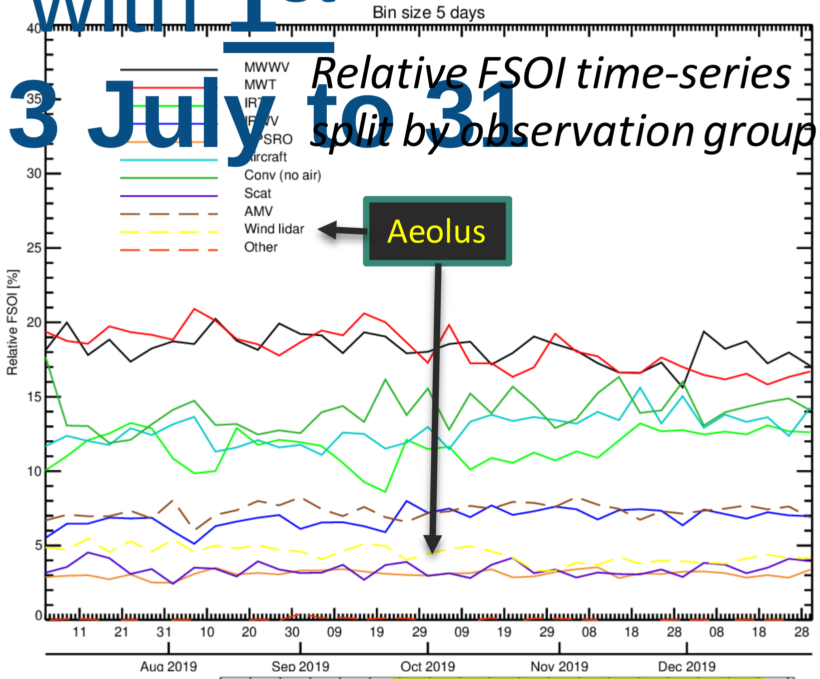
Met Office, UK

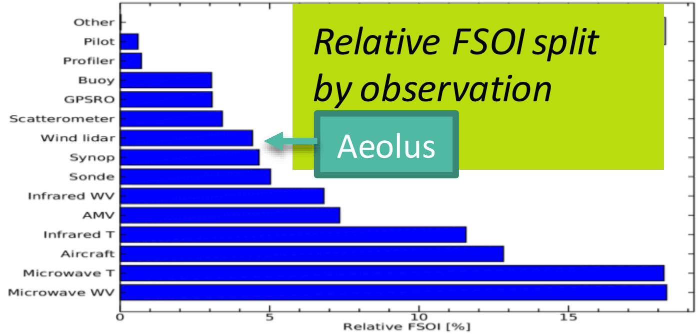


James Cotton

ECMWF Relative FSOI with 1st reprocessed dataset; 3 July to 31 December 2019







- Aeolus does well for **one satellite instrument**
- Aeolus relative FSOI impact decreases with time:
  - ~5% in July 2019; ~4% in Dec. 2019, ~2.5% now

Mike Rennie

Met Office

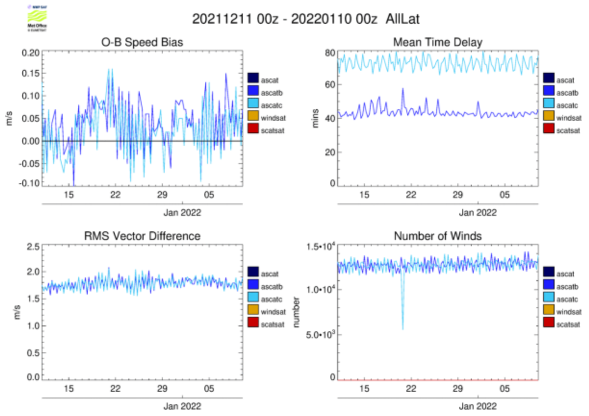
NWP SAF winds monitoring and analysis

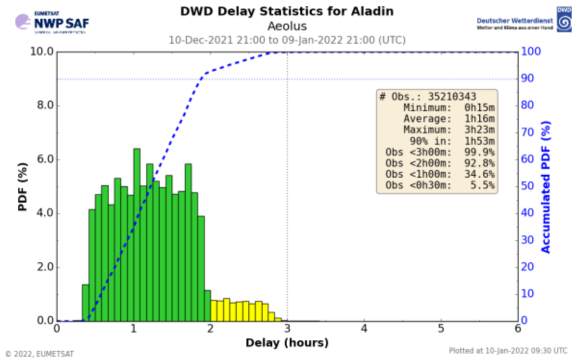
EUMETSAT NWP SAF NUMERICAL WEATHER PREDICTION

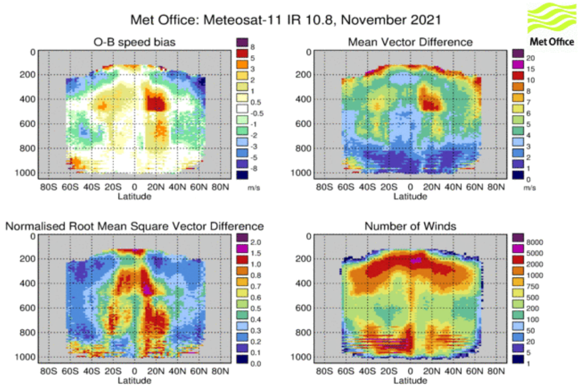
The NWP SAF aims to improve and support the interface between satellite data/products and European activities in NWP.

Met Office

Aims of the NWP SAF monitoring

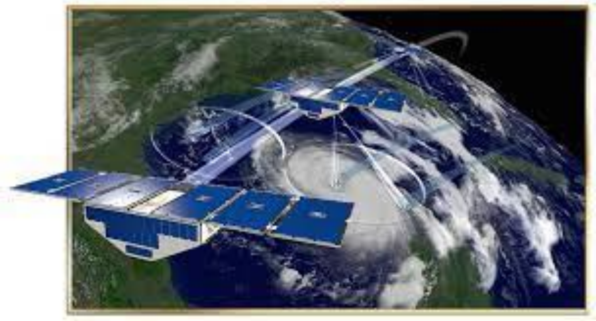


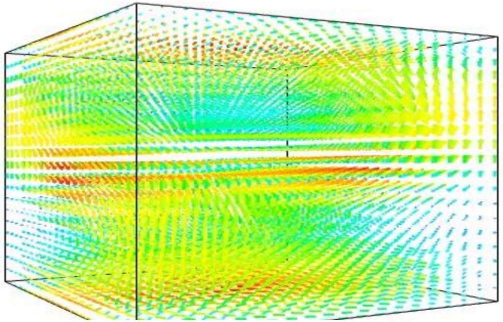


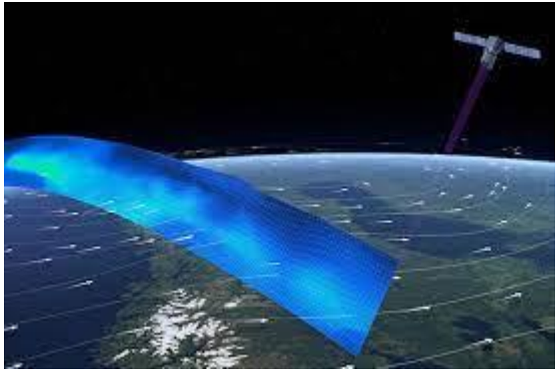


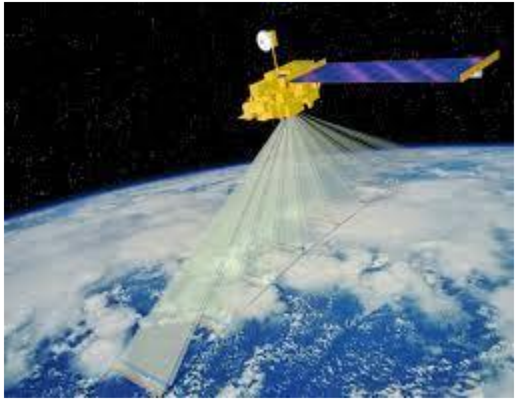
1. Near real-time monitoring to pick up data outages and problems with the data
2. Data coverage and timeliness to help with decision making on which data to assimilate in which models
3. Monthly monitoring to identify more persistent problems in the data
4. Analysis report of AMV monthly monitoring to dig into what is causing the problems – ultimately leading to improvement in AMV derivation and assimilation strategy.

Some thoughts for the future









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Future satellite-derived wind datasets…

- Expect AMVs and scatterometer winds will continue to be a significant part of the Global Observing System for the foreseeable future.

- As we gain increasing benefit from direct cloudy radiance assimilation in 4D-Var we may see the impact of AMVs taper.

- What else?
  - **Future Doppler Wind Lidar missions** - Aeolus follow-on being explored for 2030->
  - **Profile wind information from hyperspectral sounders** MTG-IRS, small satellite constellations (Régis Borde’s talk)
  - Other sources of surface wind data – **GNSS-R winds**
  - **High resolution wind products** – for regional models / nowcasting (Jason Apke’s talk)
  - Other possibles: WIVERN Doppler radar winds, stereo height AMVs…

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Talk Summary

1. Satellite-derived winds are an important source of wind information for the models, showing beneficial impact in data denial experiments and FSOI.
2. Atmospheric Motion Vectors, scatterometer winds and the more recent Doppler Wind Lidar provide complementary information.
3. Wind profile information has been a key unmet need in the global observing system. Aeolus has helped to fill this gap. Follow-on DWL and higher temporal resolution hyperspectral sounders (e.g. MTG-IRS) may help in the future.