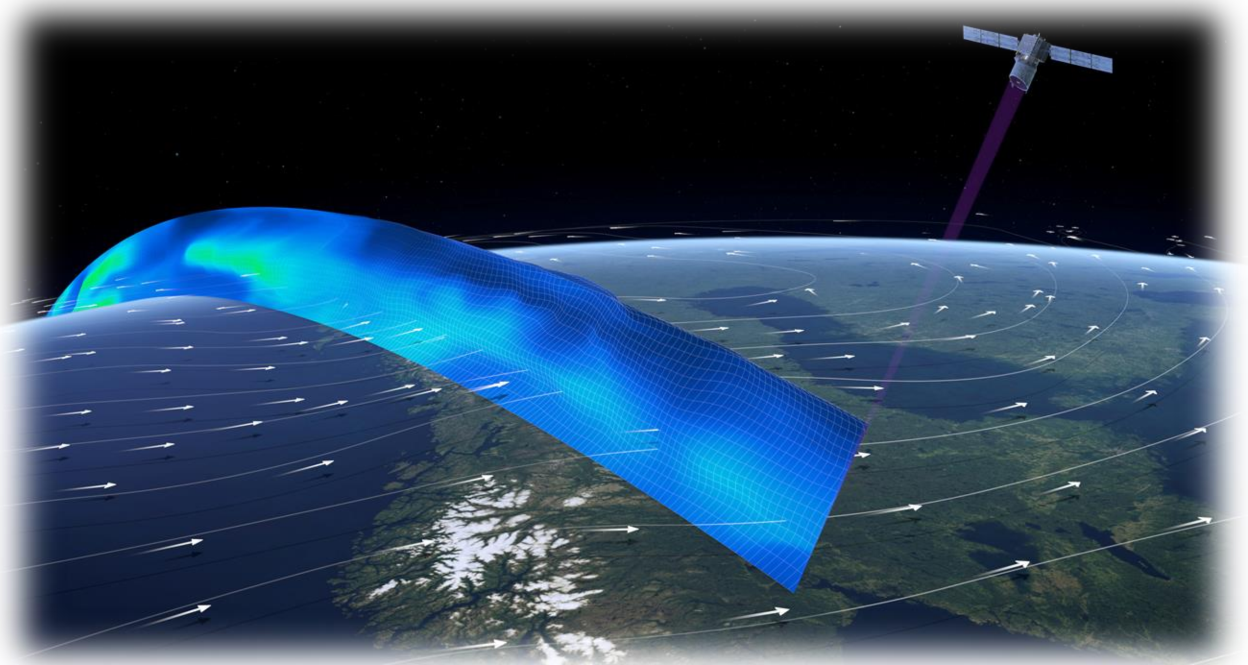
Assessment of the Impact of Aeolus Doppler Wind Lidar Observations for Use in Numerical Weather Prediction at ECMWF

EGU2020: Sharing Geoscience Online, 28/4/2020

by Michael Rennie and Lars Isaksen



European Space Agency

Aeolus products

esa

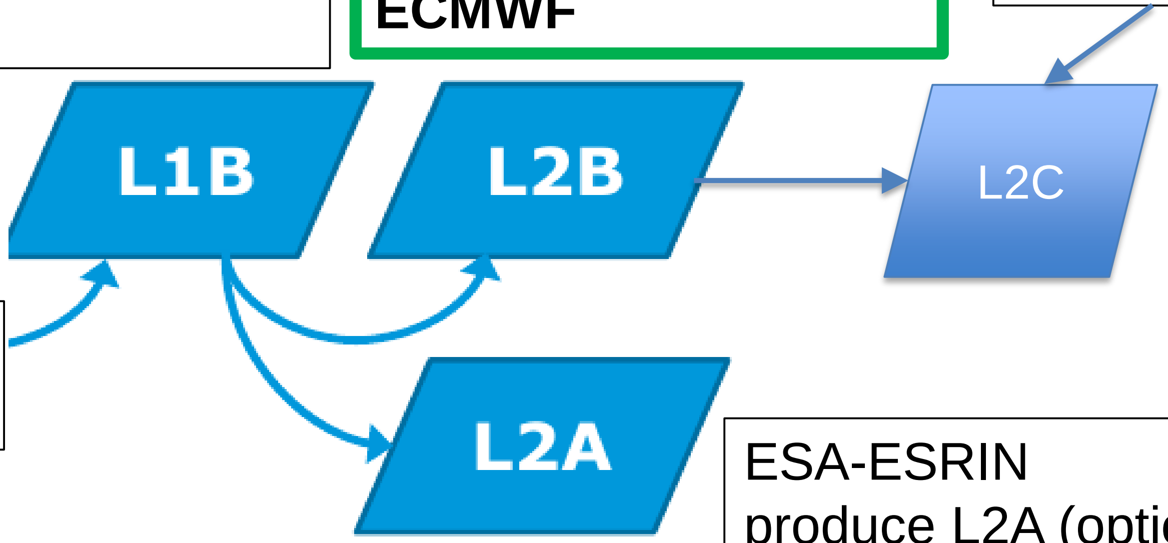
ESA-ESRIN produce **Level-1B** data (calibrated signal levels)

Level-2B wind product (suited for Numerical Weather Prediction (NWP)); produced by **ECMWF**

ECWMF data assimilation analysis

- ***From 12 May 2020 (TBC):*** L2B BUFR from ECMWF to EUMETSAT for distribution on GTS/EUMETCast (public data release)

L0 and L1A data



ESA-ESRIN produce L2A (optical properties) product

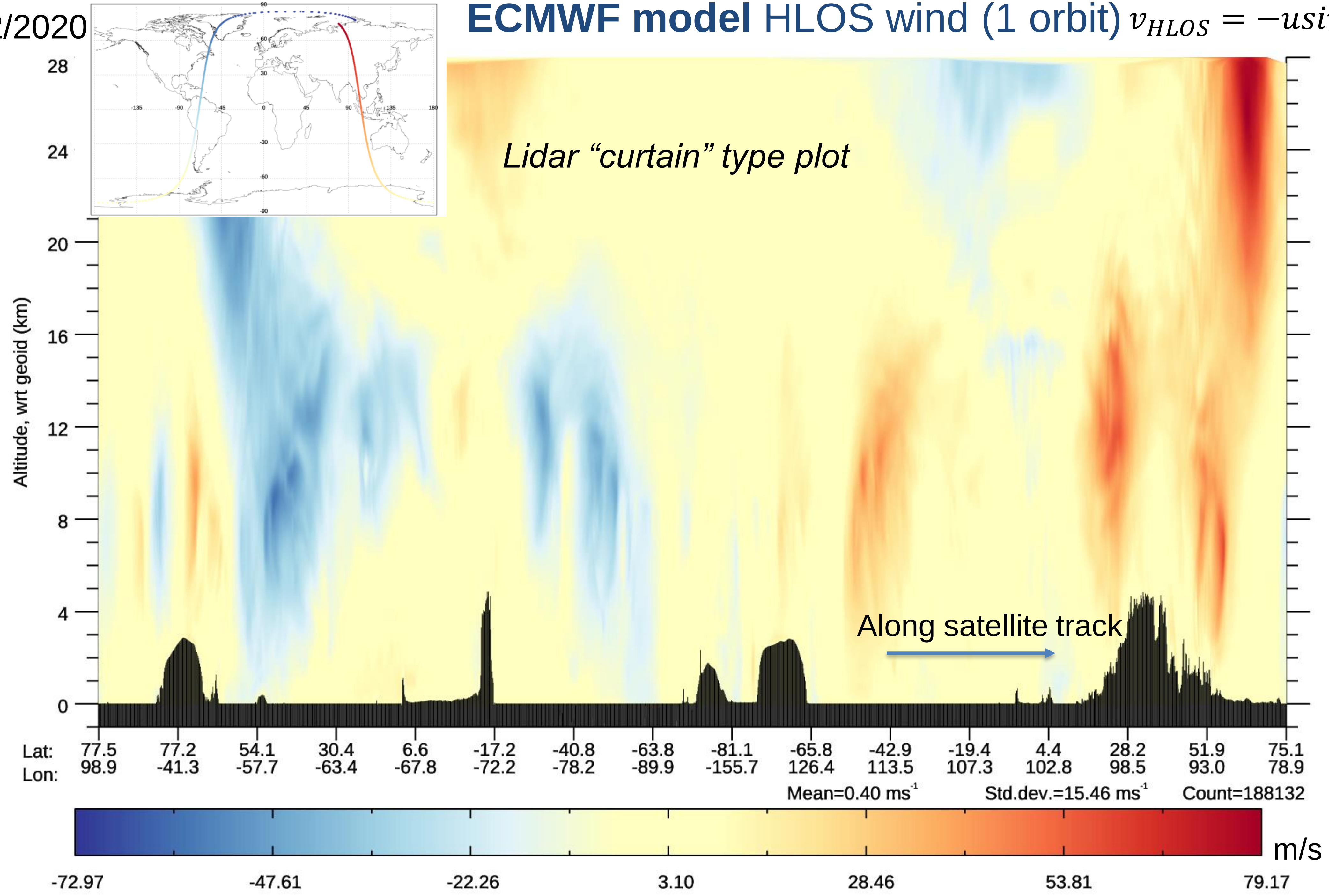
ECMWF

Wind products available in NRT for benefit of NWP

Examples of Aeolus Level-2B horizontal line-of-sight (HLOS) winds

10/2/2020

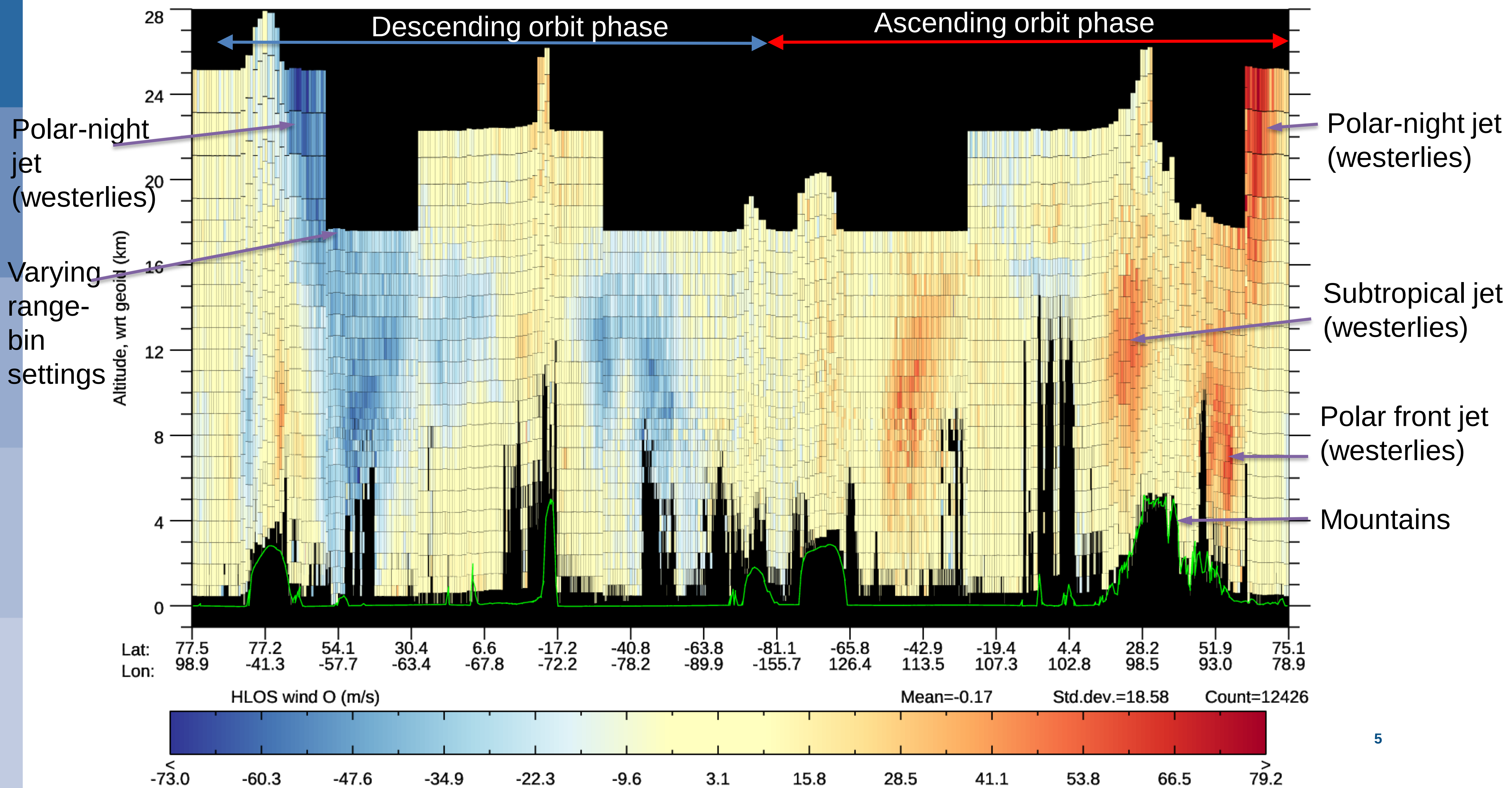
ECMWF model HLOS wind (1 orbit) $v_{HLOS} = -u sin\emptyset - v cos\emptyset$



Aeolus HLOS winds are positive if wind blowing away from satellite

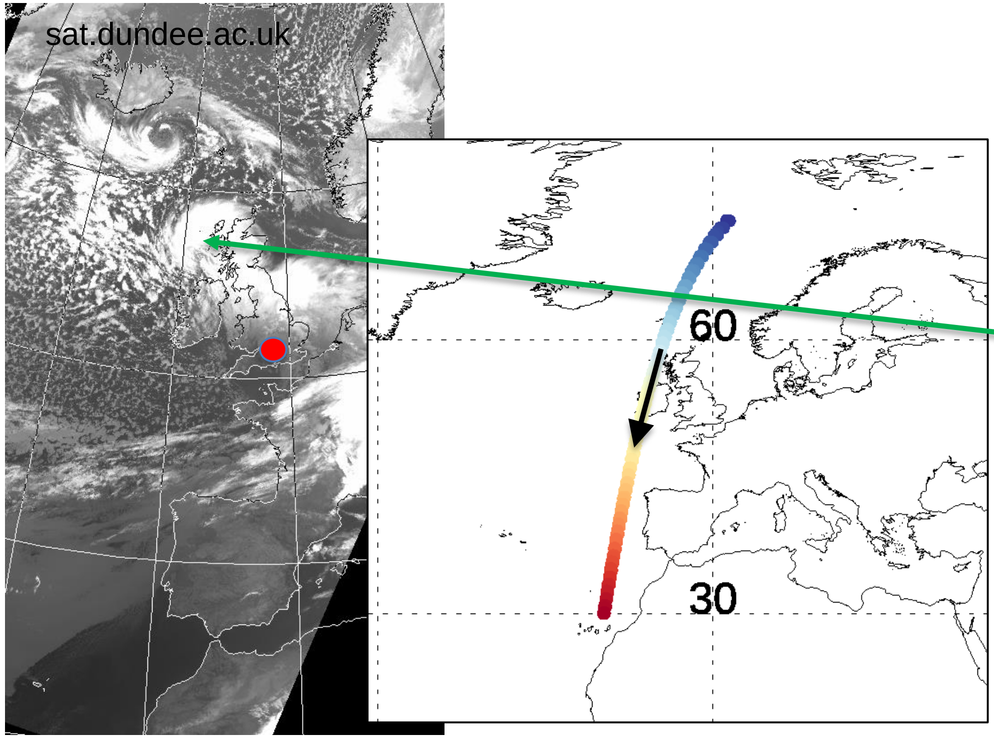
10/2/2020

Aeolus L2B Rayleigh-clear **and** Mie-cloudy HLOS winds (**1 orbit**)

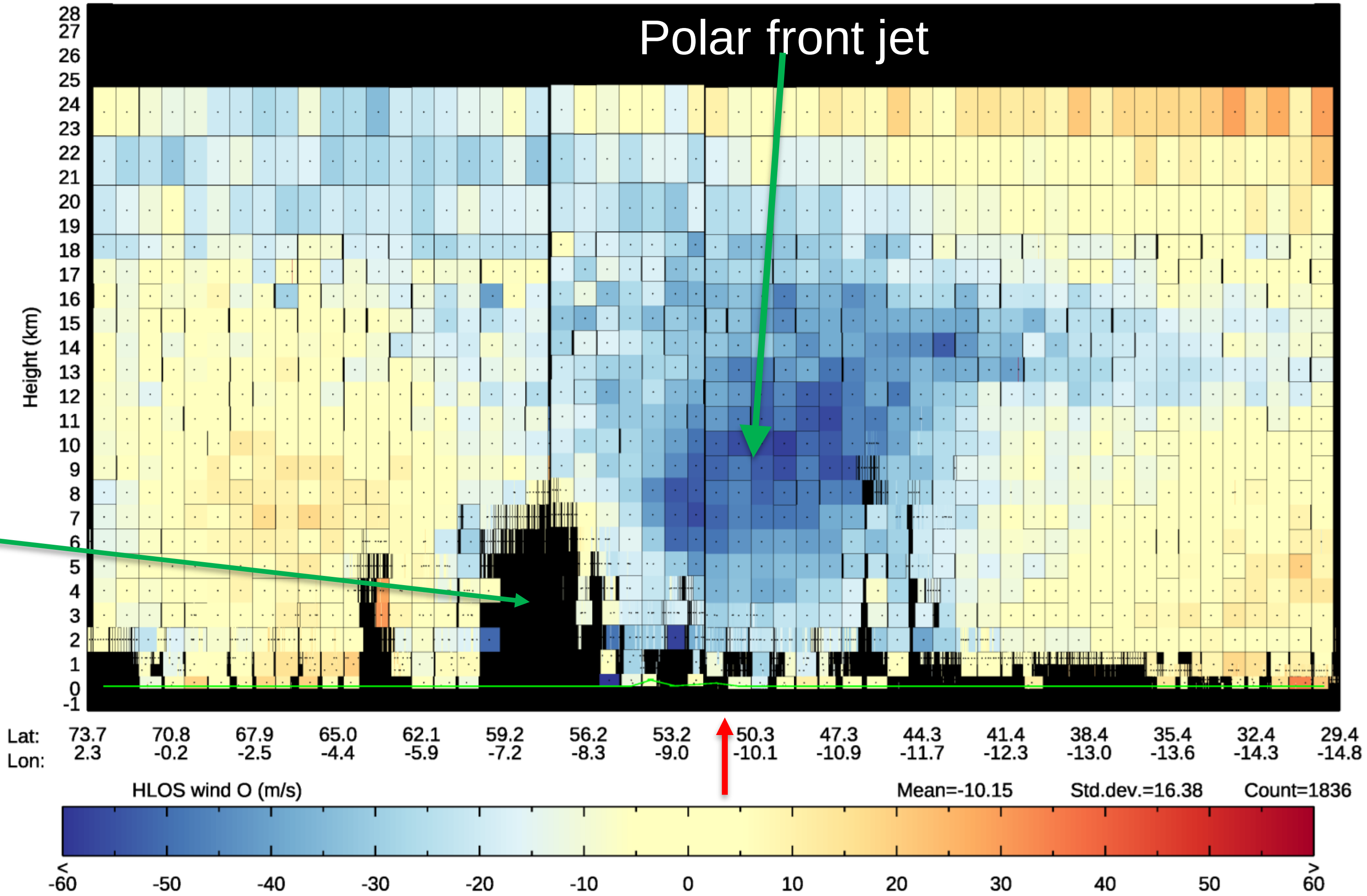


A very windy day in north-west Europe (10/3/2019)

Photo from my garden near Reading:
apart from low level clouds, sky was clear

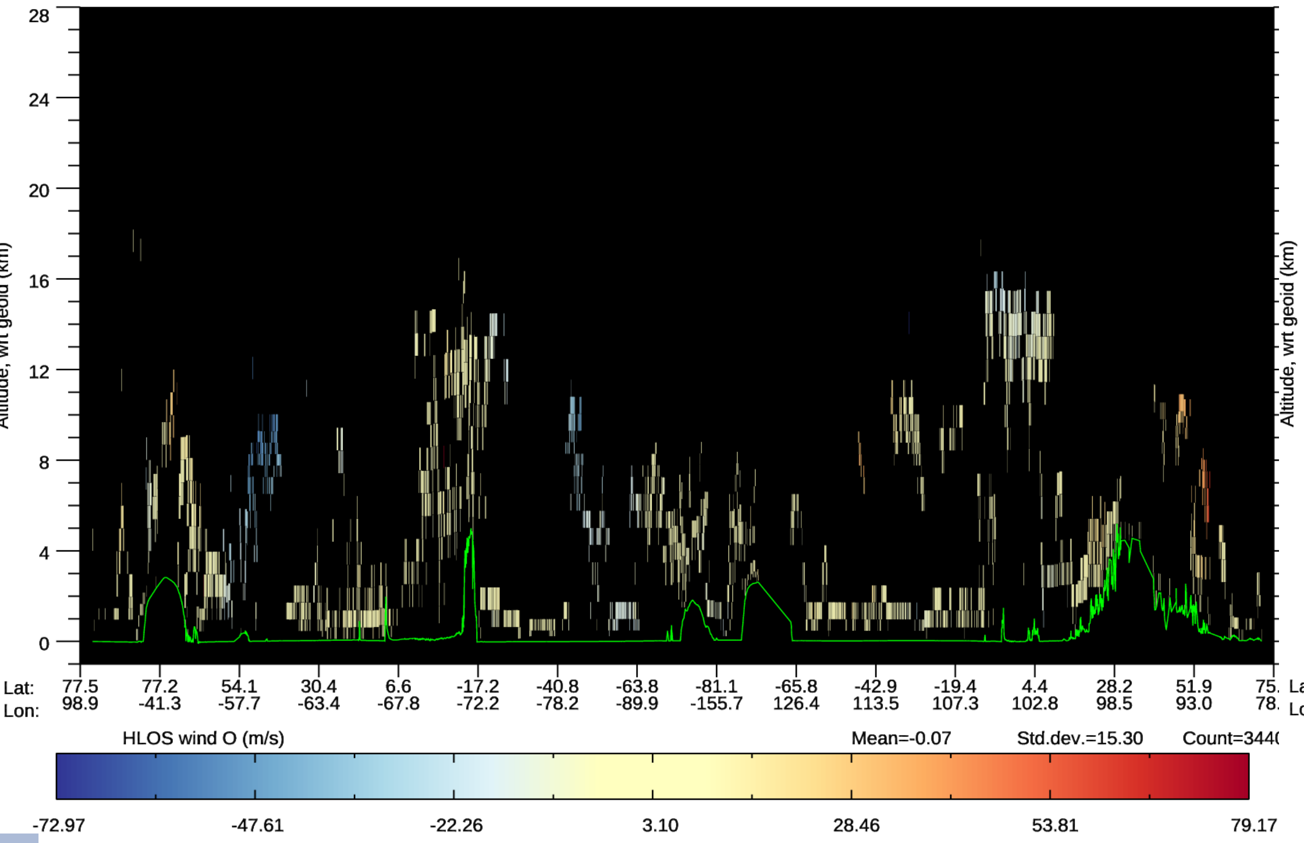


What Aeolus observed (Rayleigh + Mie winds) near the low



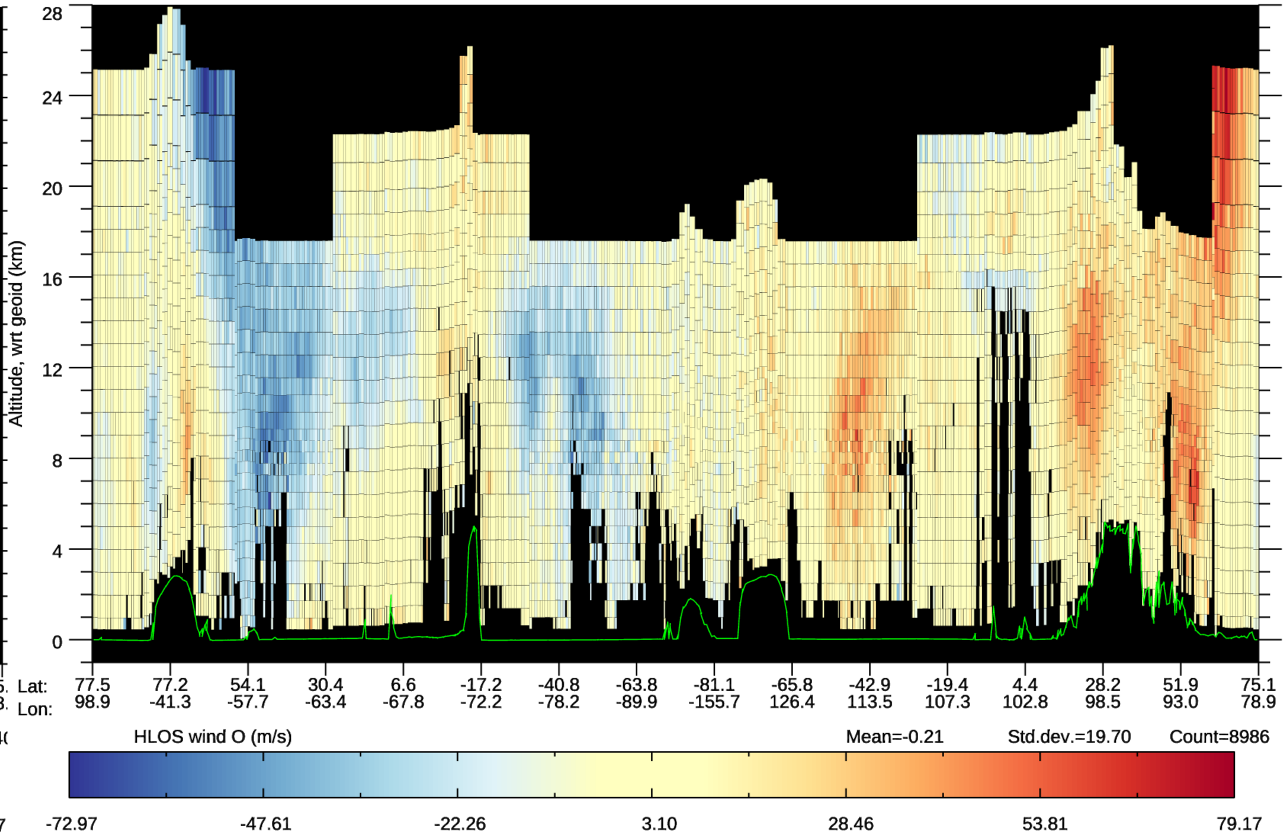
Rayleigh and Mie winds are complimentary

Mie-cloudy L2B HLOS winds



~12 km horizontal averages

Rayleigh-clear L2B HLOS winds



~80 km horizontal averages

ECMWF

Aeolus use in NWP at ECMWF

Aeolus use in global Numerical Weather Prediction at ECMWF

- We have demonstrated positive impact in Observing System Experiments (OSEs) for three different periods
  - However, magnitude of the impact is smaller than hoped for pre-launch, due to:
    - **Data quality is not as good as expected** pre-launch i.e. noisier winds, larger biases than expected
    - Larger noise is an instrumental issue that *on ground processing* cannot resolve (lower laser energy than expected and unexpected signal loss in receive path)
    - **Have developed a bias correction scheme for Aeolus as part of the ECMWF data assimilation system to allow use in operations – since 20th April 2020 this no longer needed**
- But **NWP impact is still good** for one instrument on one satellite, compared to other satellite instruments
- Hence Aeolus Level-2B HLOS wind was operationally assimilated **since 9th January 2020**
- Other NWP centres, such as DWD, Met Office, Météo-France, US agencies are also showing positive impact from Aeolus

L2B HLOS (horizontal line-of-sight) wind data assimilation

- ECMWF Observation operator*:* HLOS wind operator (*point-wind version)*
  - Interpolation of model wind (*u*,*v*) to obs geolocation **point**
  - Calculate HLOS wind from model (*u*,*v*)
  - Dot product of wind vector with laser pointing unit vector

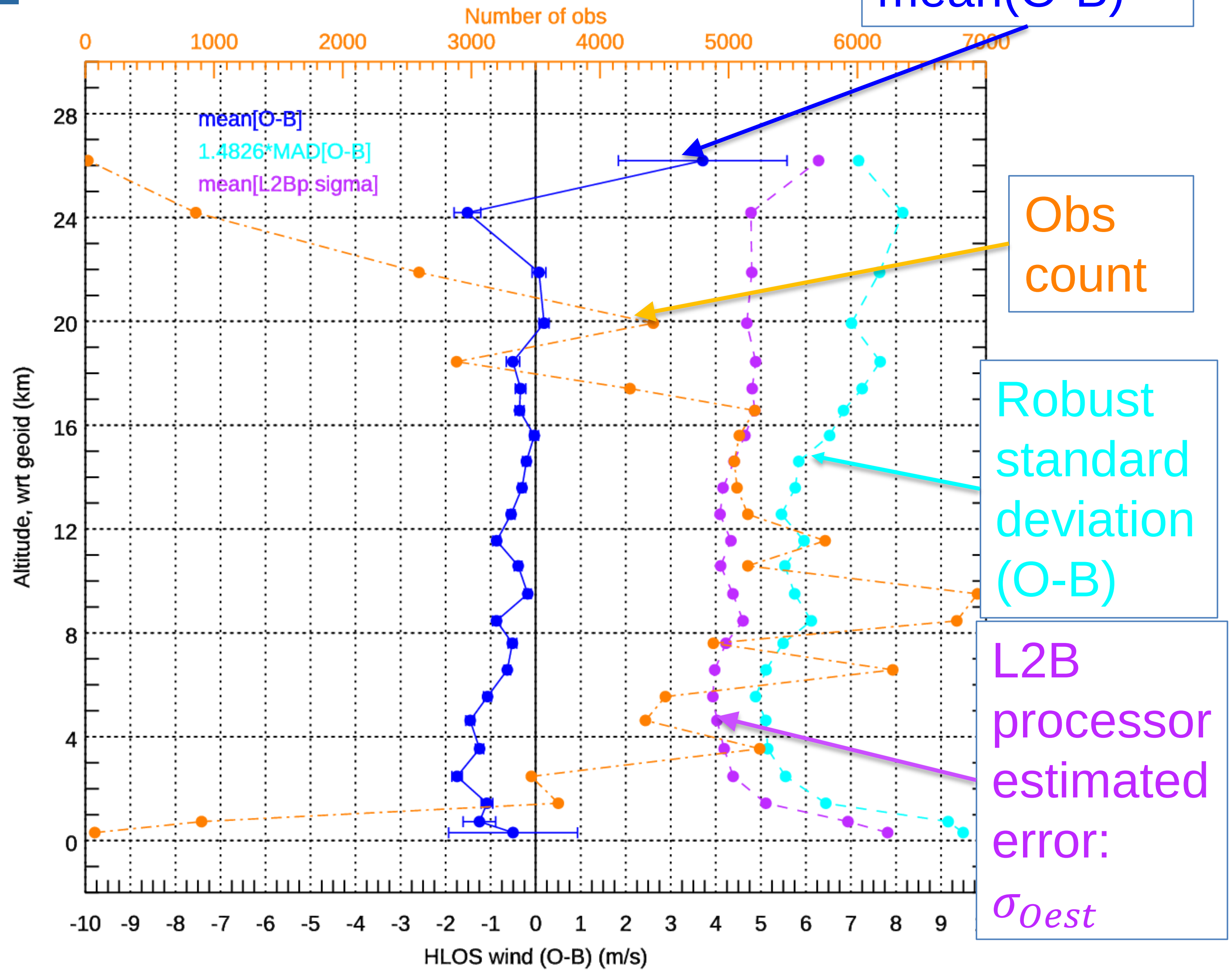
$$v_{HLOS} = -u sin\emptyset - v cos\emptyset$$

∅=azimuth angle of line-of-sight

- Weaknesses:
  - HLOS wind assumed to be a “point” observation rather than actual spatial average
    - However ECMWF model effective resolution is 4-8 times the grid spacing (~36-72 km horizontally), so may not matter
    - Probably more important to consider the Aeolus’ vertical averaging
  - Ignores vertical wind component *w (should be close to zero over e.g. 80 km averaging, but may be important in certain conditions e.g. convection, gravity waves)*
  - L2B **Rayleigh** wind retrieval uses *a priori* knowledge of *T, p* (a small dependence on ECMWF model) due to Doppler broadening, but is not important compared to other errors sources
- **Assigned observation error** is a function of the L2B processor estimated instrument error – now being refined to include representativeness error for Mie

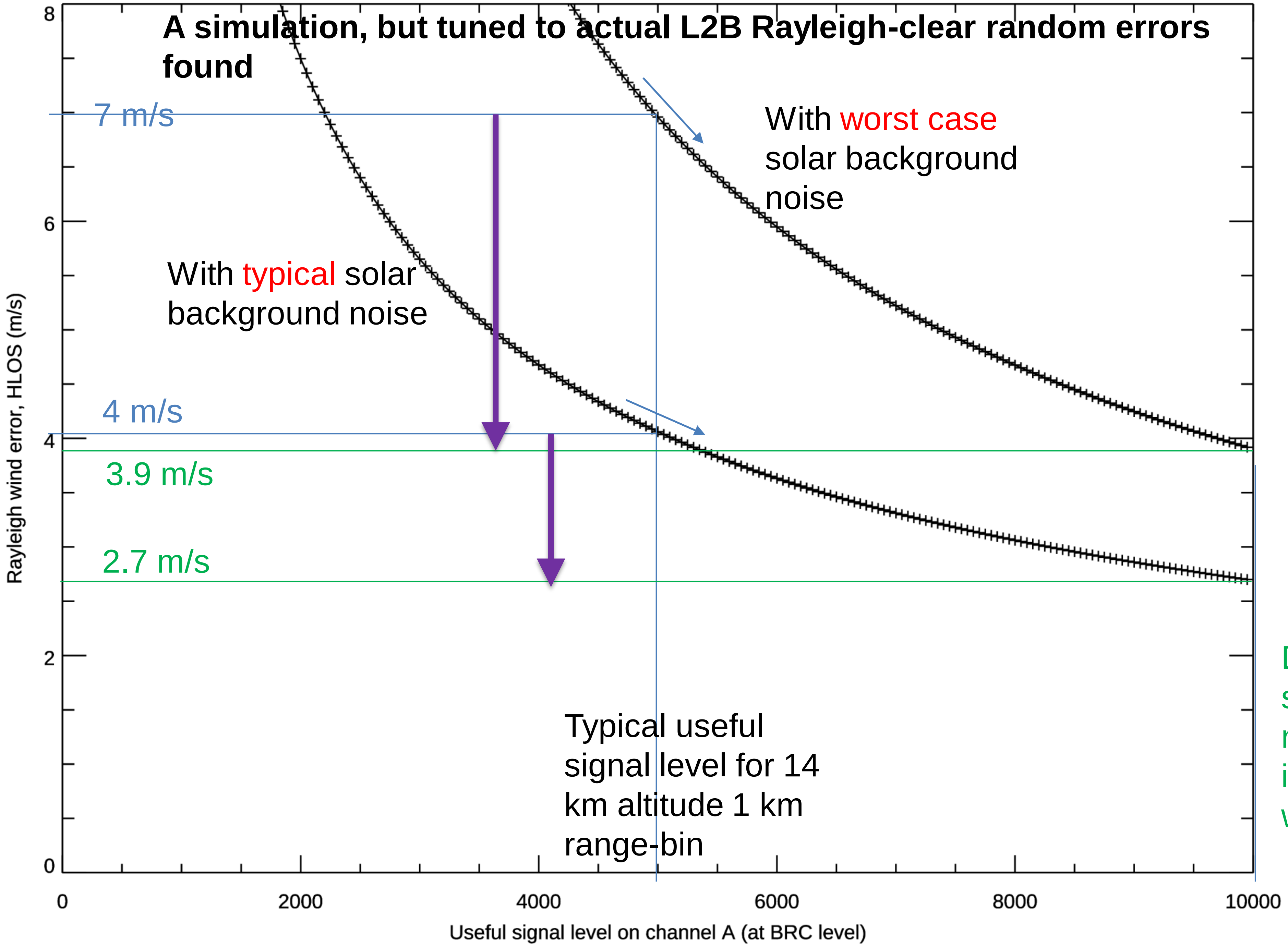
ECMWF

Global HLOS wind O-B departure statistics for L2B **Rayleigh-clear**, **10 orbits on 21/1/20**



- Global average bias is reasonable
- Robust st. dev. (O-B):
  - Profile average = **5.95 m/s**
  - At 5 km = **5 m/s**

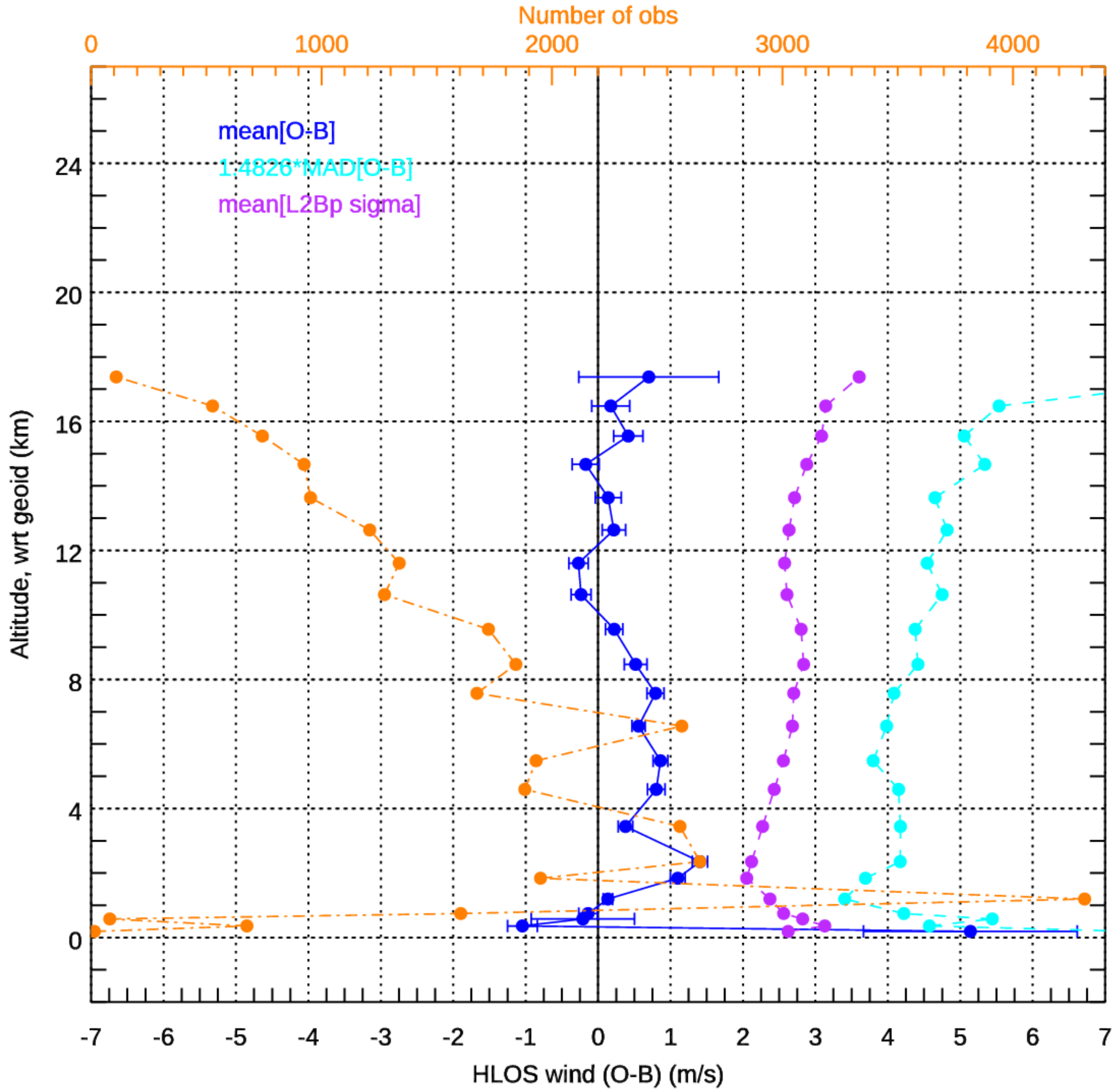
- *Estimated* observation error from O-B departures $\sqrt{st.dev.(O-B)^2 - \sigma_B{}^2}$
  - Profile average **= 5.6 m/s**
  - At 5 km **= 4.6 m/s**
  - **Larger than we hoped for before launch**
- **Radiosonde has stdev(O-B) around 2 m/s**



Given our current useful signal versus solar background noise **we have a lot to gain** from more useful signal, particularly in polar summer conditions

Doubling useful signal would massively improve Rayleigh winds!

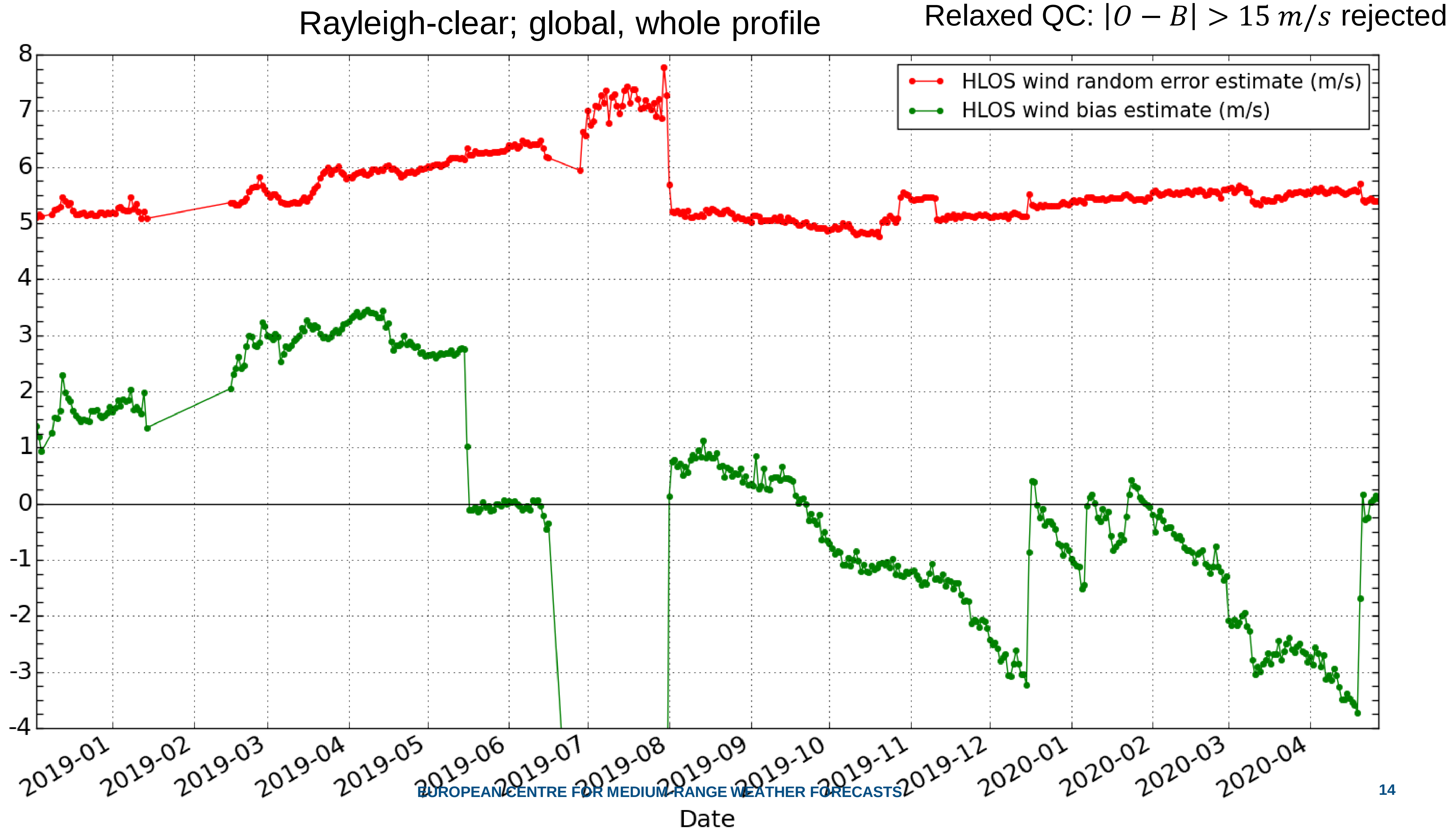
Global HLOS O-B statistics for **L2B Mie-cloudy**, **10 orbits on 21/1/20**



- Global average bias is reasonable and stable with time
- Global average robust std. dev. (O-B):
  - Profile average = **4.2 m/s**
  - At 1-2 km ~ **3.5 m/s**

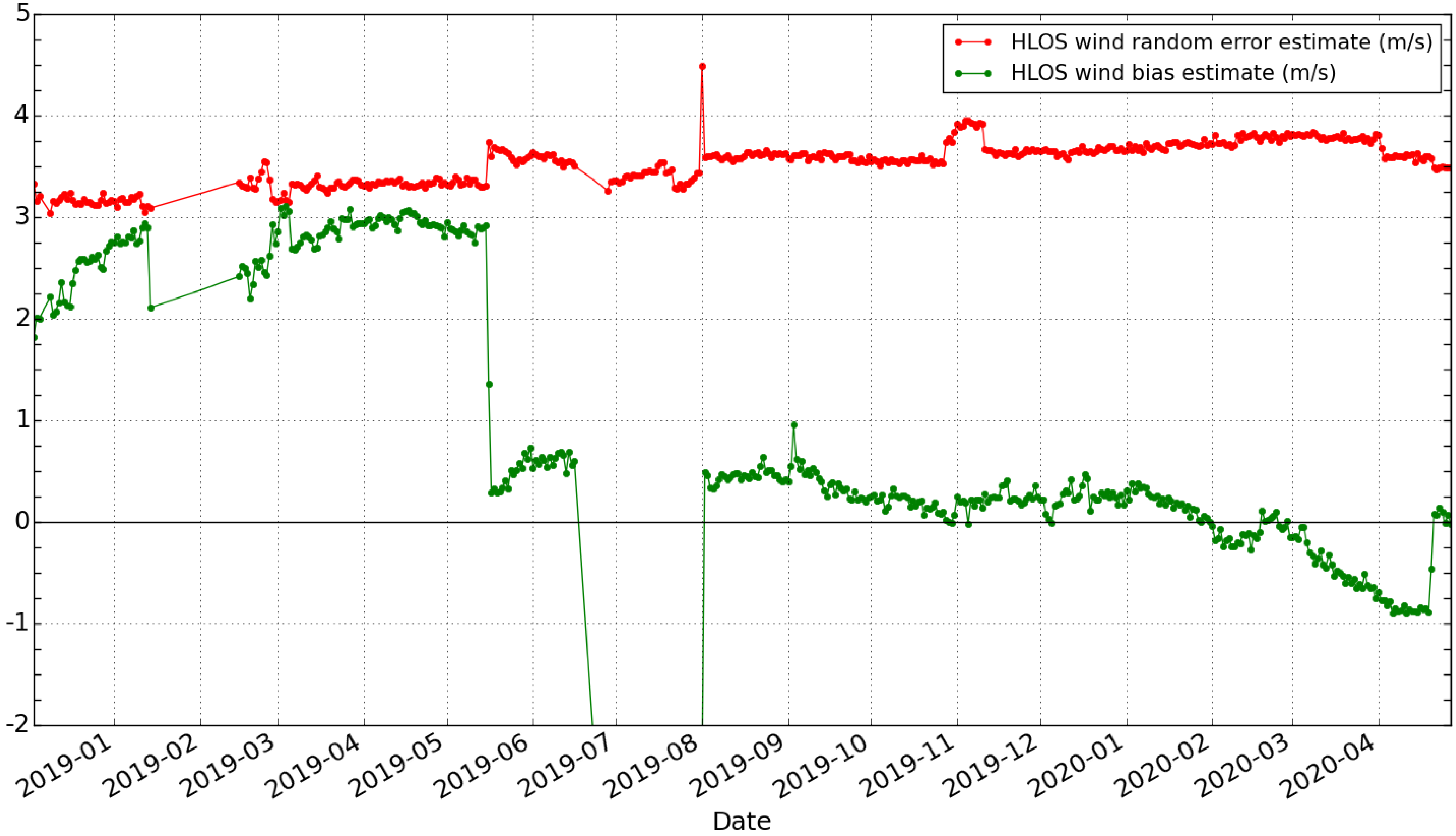
- *Estimated* observation random error from O-B departures $\sqrt{st.dev(O-B))^2 - {\sigma_B}^2}$ is
  - Profile average = **3.7 m/s**
  - At 1-2 km = **2.9 m/s**
- Mie averaging length scale is ≤ 14 km (Rayleigh is ≤ ~84 km)
- Mie noise better despite much better horizontal resolution than Rayleigh

Long term trends in quality of operationally produced Level 2B winds



Mie-cloudy; global, whole profile

QC: $|O - B| > 10\ m/s$ rejected

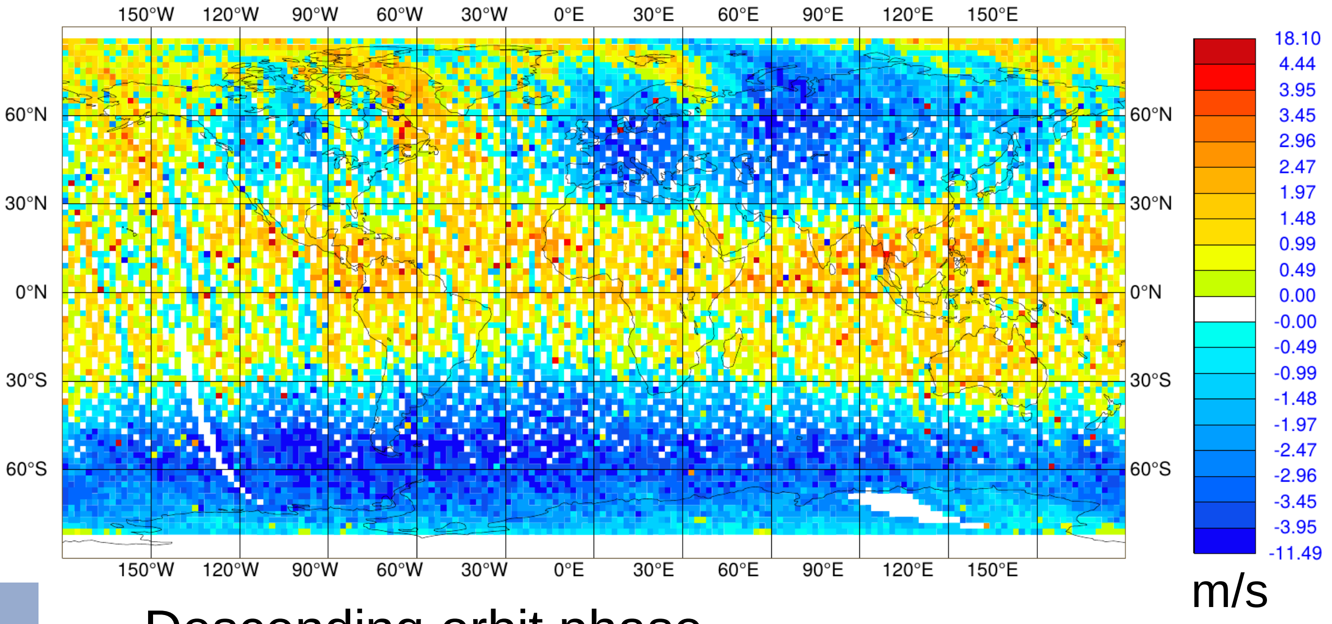


A major breakthrough in Autumn 2019: explanation was found for dominant source of Rayleigh wind bias which varies on less than one orbit time-scales

- Investigations showed Rayleigh wind bias, which varies along the orbit, is strongly correlated with the ALADIN telescope primary mirror temperature variations
- Temperatures vary due to varying Earthshine and the mirror's thermal control
  - Temperature variations correlate with outgoing SW and LW radiation
- *Mechanism:* thermal variations alter primary mirror shape, causing angular changes of light onto spectrometer, causing apparent frequency changes
- **Bias correction** using measured telescope primary mirror temperatures was demonstrated to work in offline testing and was implemented in operations on 20 April 2020

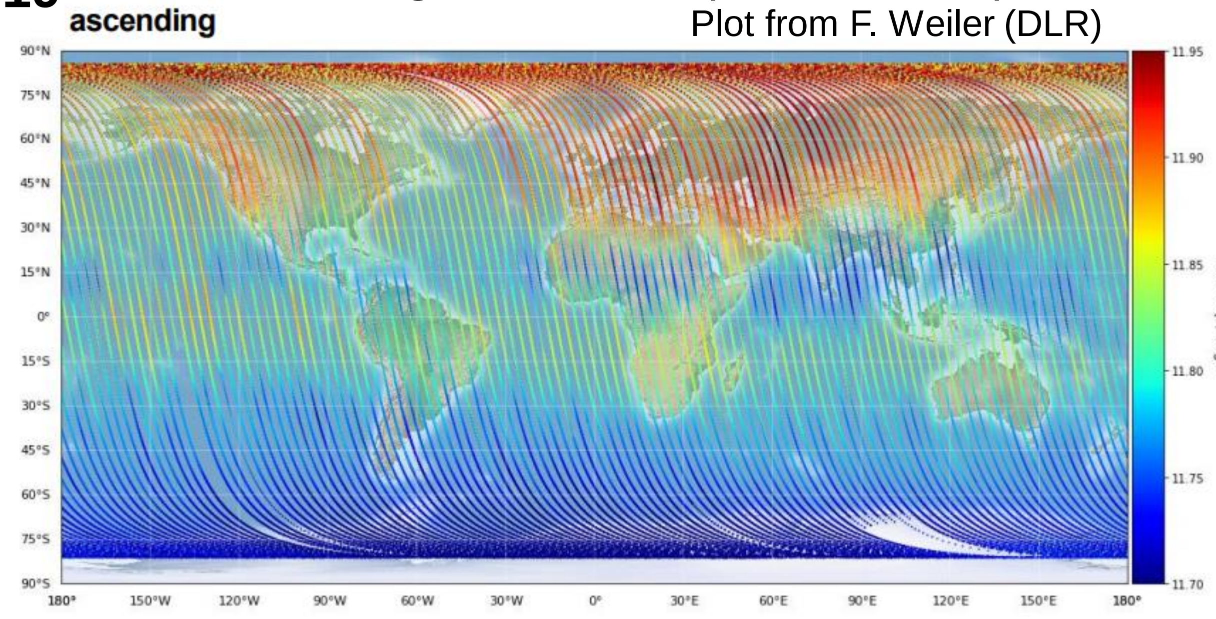
Rayleigh has large biases which vary with geolocation

Ascending orbit phase **e.g. 6/8/2019 to 7/9/2019**

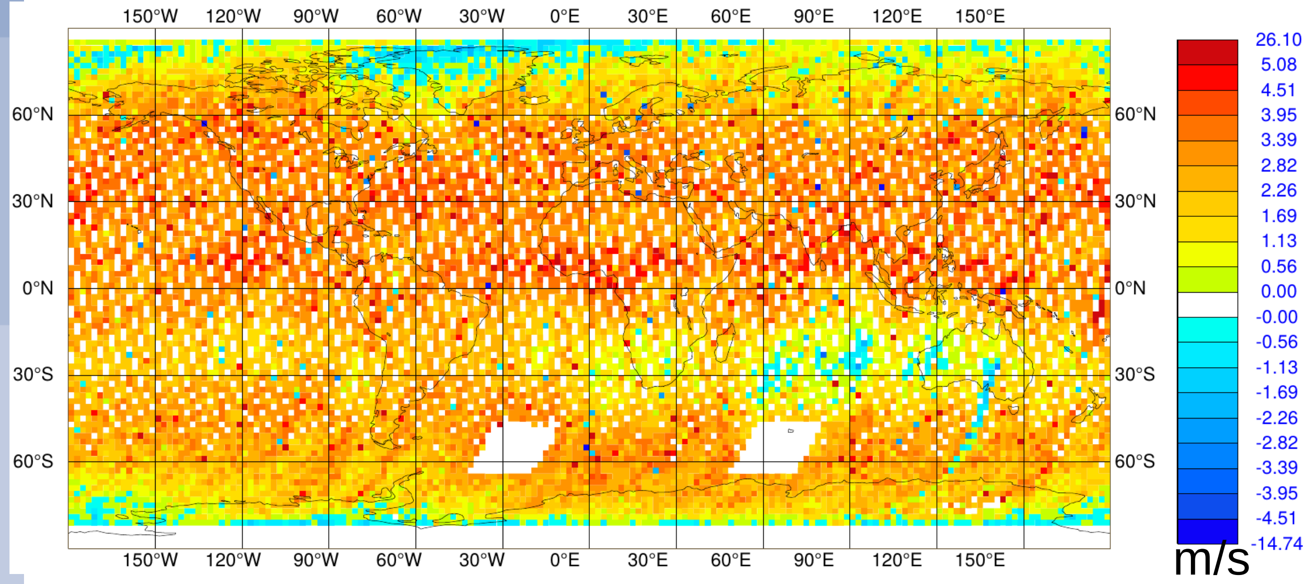


Average M1 telescope mirror temperature

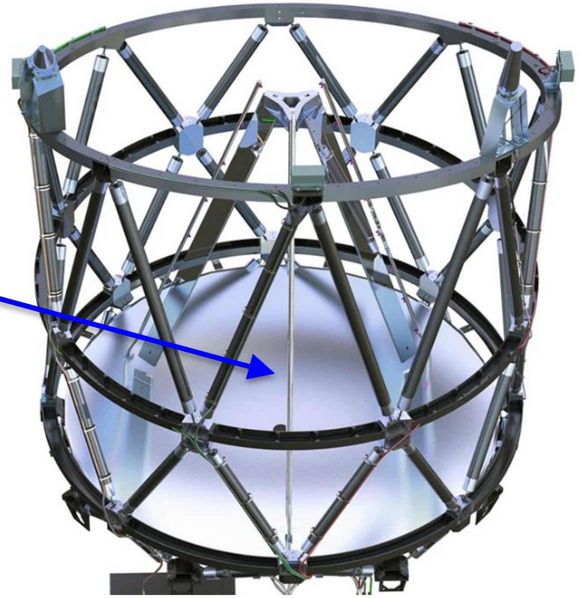
Plot from F. Weiler (DLR)



Descending orbit phase



M1 mirror
Ø 1.5 m

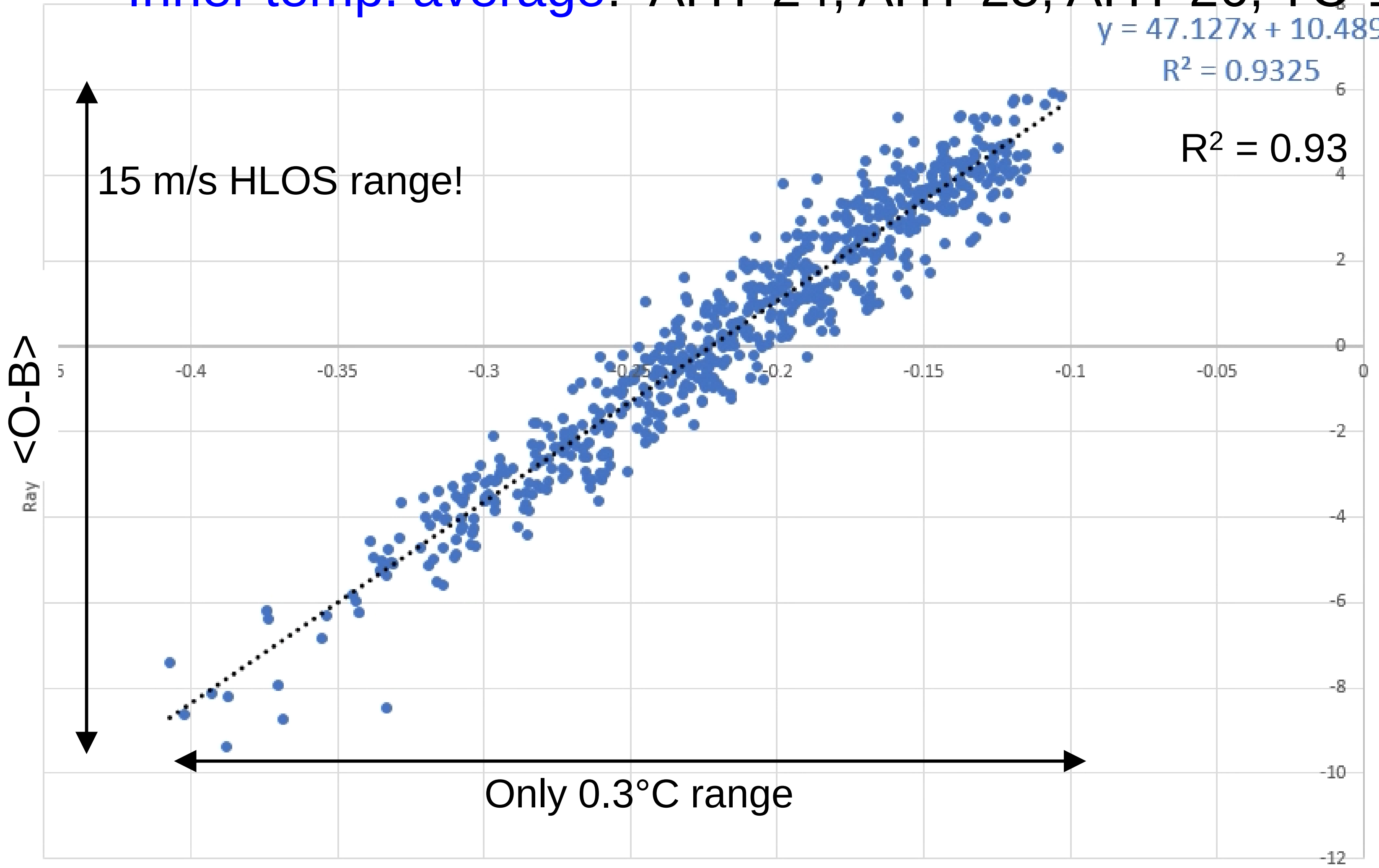


Regression of <O-B> versus M1 temperature function

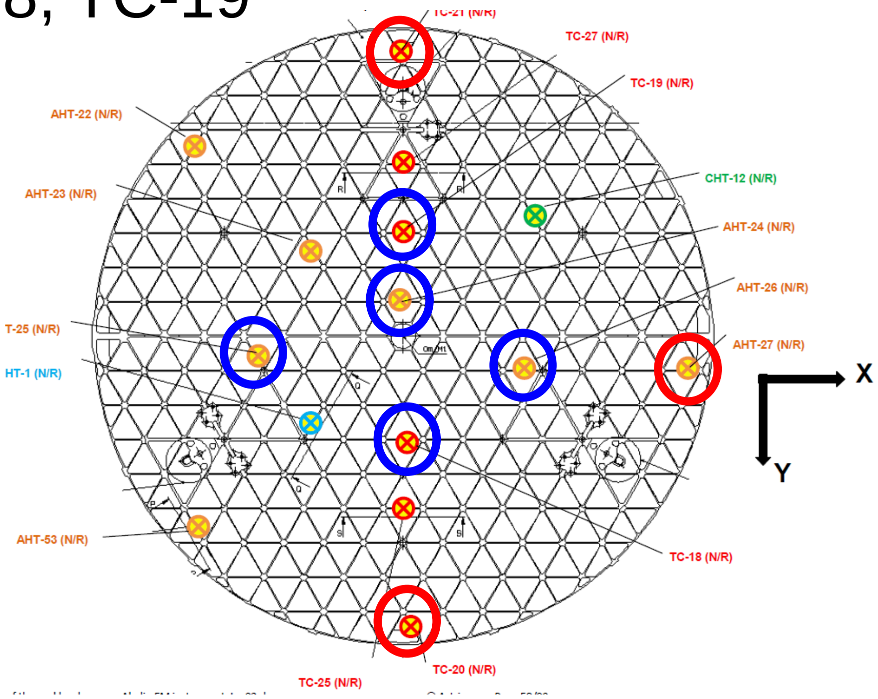
Best results on 8/8/19 obtained with:

Outer temp. average: AHT-27, TC-20, TC-21

Inner temp. average: AHT-24, AHT-25, AHT-26, TC-18, TC-19

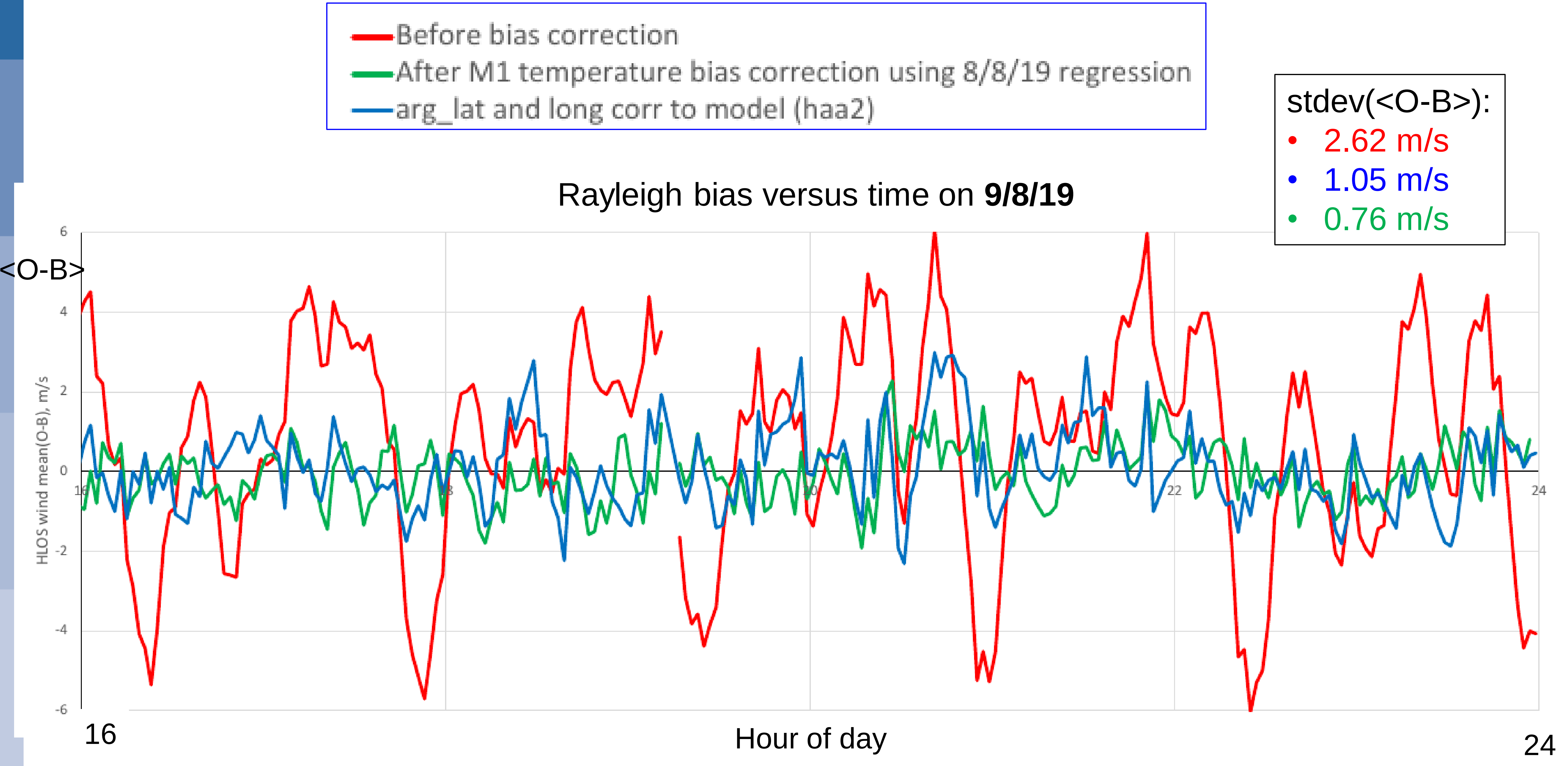


__Outer__ minus __inner__ M1 temperature function (°C)



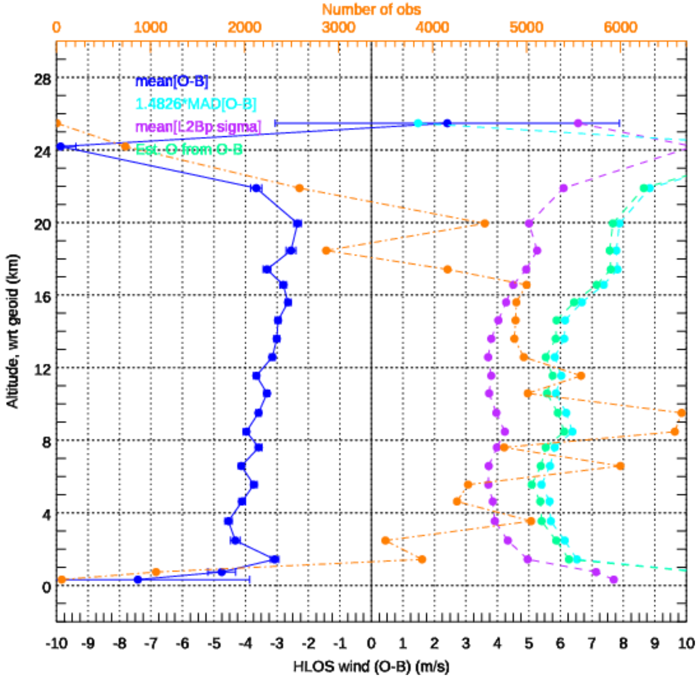
Demonstrates the power of NWP models for helping to determine the source of errors in observations

Example of bias correction

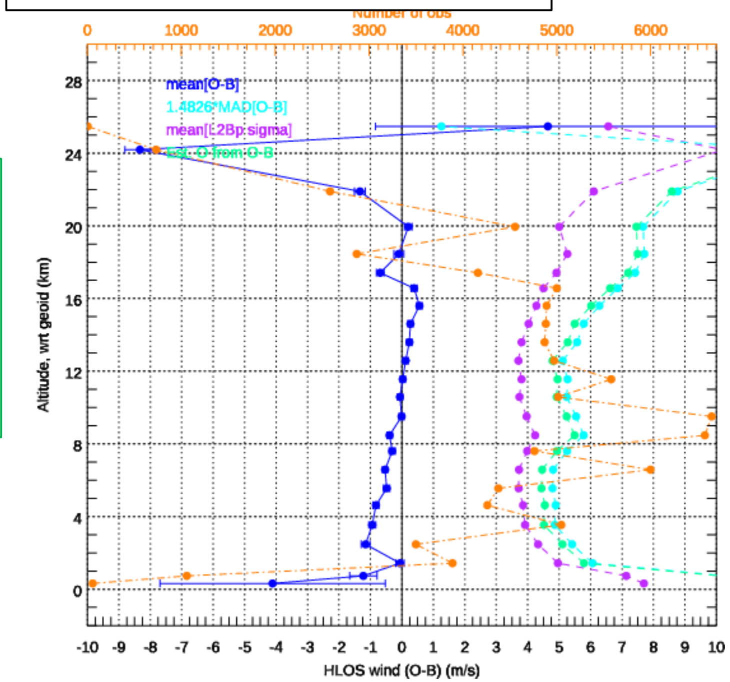


Effect of M1 temp. bias correction (new L2B processor) on Rayleigh data for 5/4/20

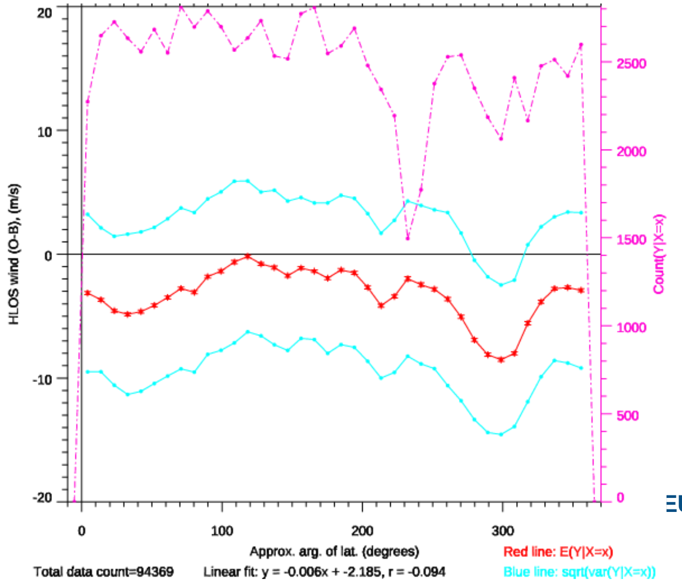
Without M1 bias correction



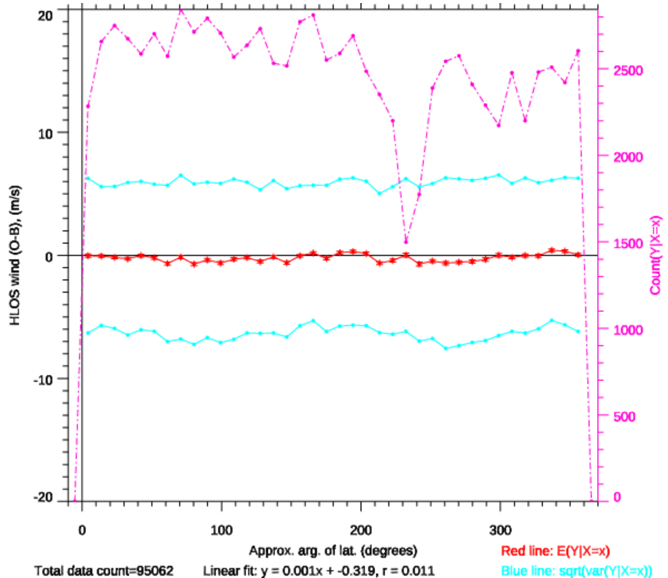
With M1 bias correction



- Global robust stdev(O-B) improved by ~0.6 m/s
- Global bias of -3.5 m/s removed



Bias versus argument of latitude (orbit phase angle) removed



Assessment of Aeolus NWP impact at ECMWF

- **O**bserving **S**ystem **E**xperiments
- Three periods have been investigated so far
  1. September 12th to October 16th 2018 (**early FM-A (first laser)**)
  2. April to June 2019 (**end of FM-A period**)
  3. **Focus today on:** August to December 2019 (**FM-B (second laser))**

NWP impact of Aeolus with FM-B laser – August 2nd until 31st December 2019

- Experiments with operational Level-2B data, and full observing system for other data
- T_{CO}399 (~29 km model grid)
- Test data used **does not have M1 bias correction**, therefore **apply bias correction to ECMWF model wind as function of "orbit phase angle" and longitude**
- Assigned observation errors use L2Bp instrument noise error estimates
  - Simple model: multiplicative factor to get more agreement with Desroziers diagnostics

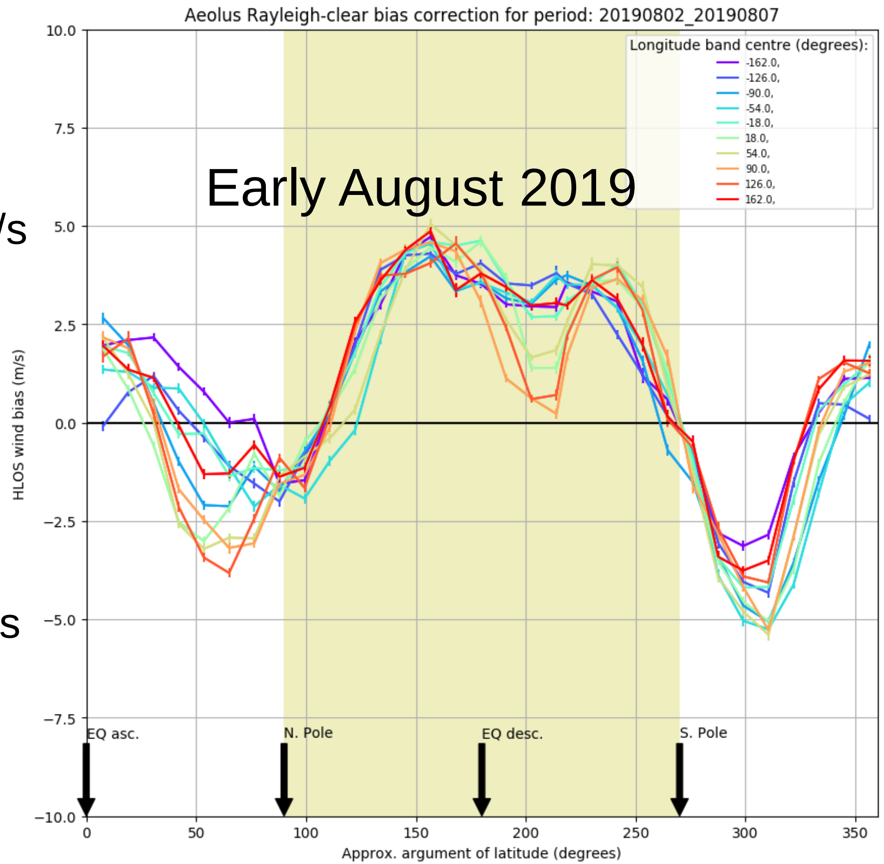
Bias correction using the ECMWF model as a reference

- Implemented bias correction scheme: *<O-B>* vs. *“orbit’s argument of latitude” and longitude; look-up table*
- Updates to bias correction look-up table done every few days in experiments
- Mie biases stable with time and do not require the longitude dimension

Example of how **Rayleigh** biases varied during the FM-B period

+5 m/s

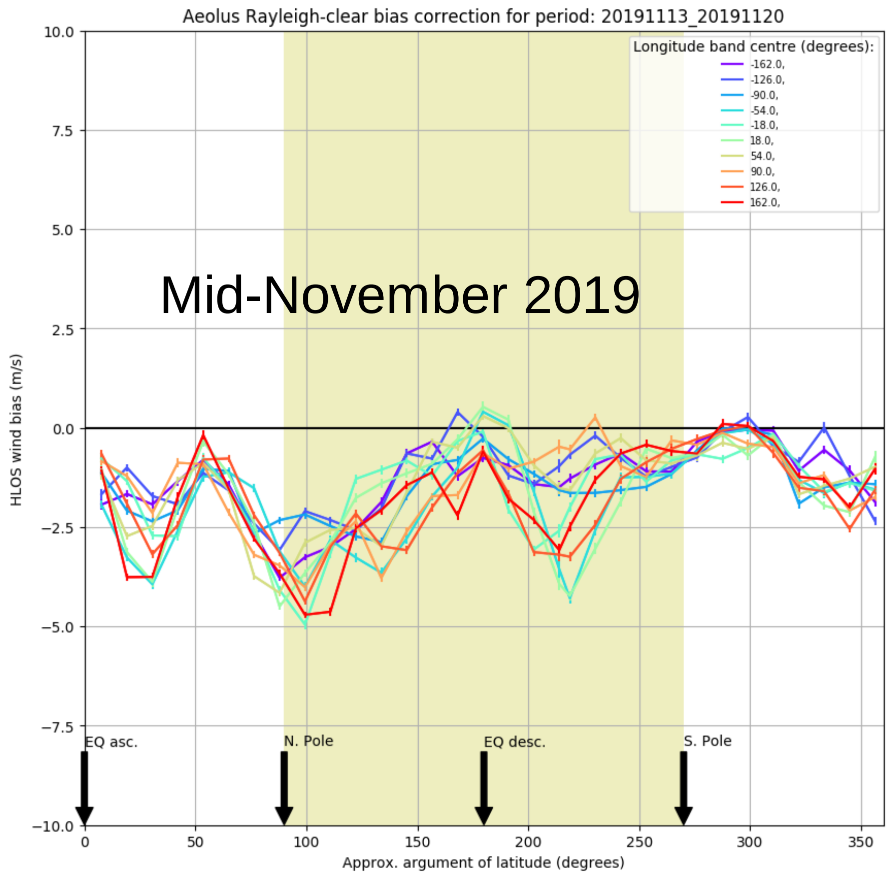
-5 m/s



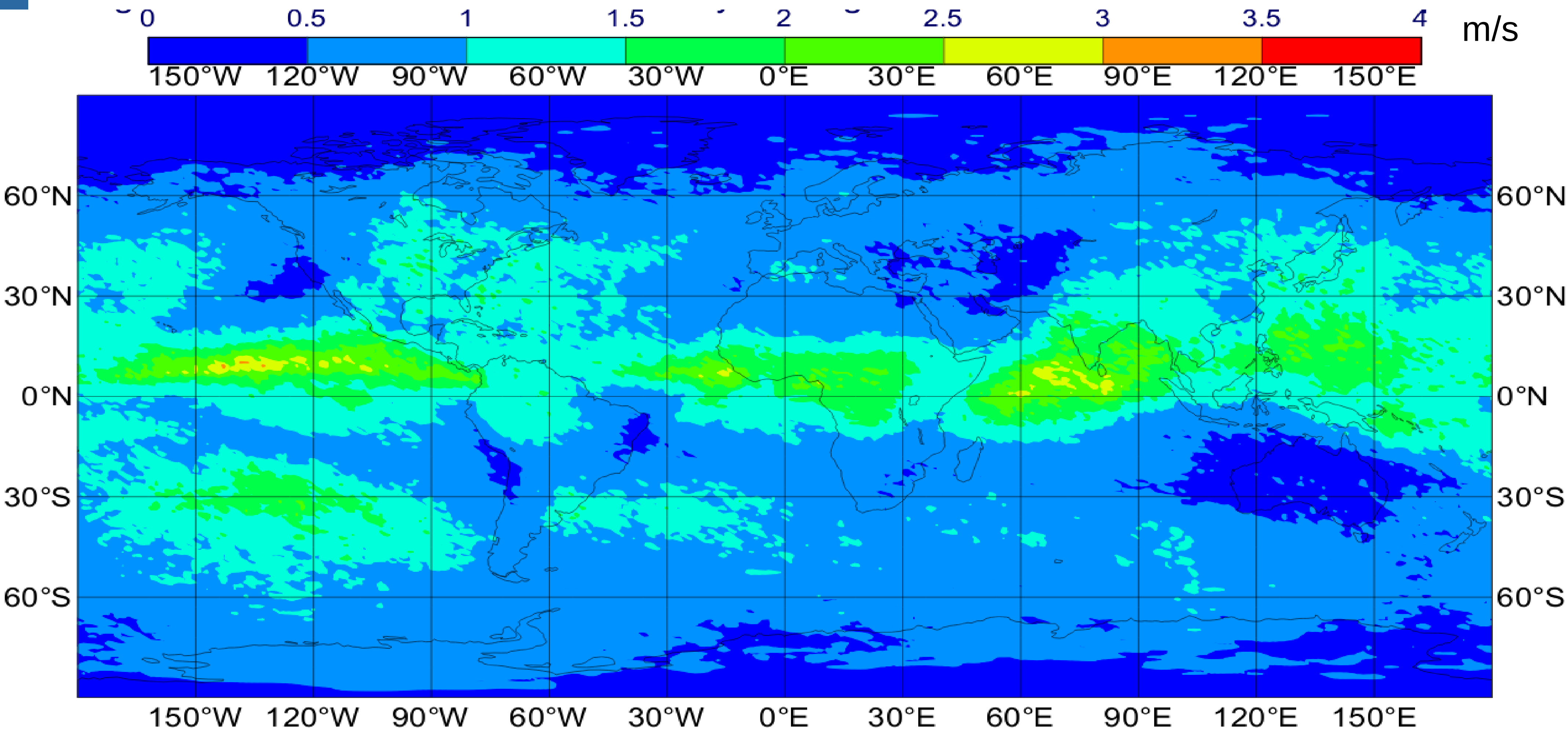
M1 temperature induced biases were larger in N. hemi. summer

+5 m/s

-5 m/s



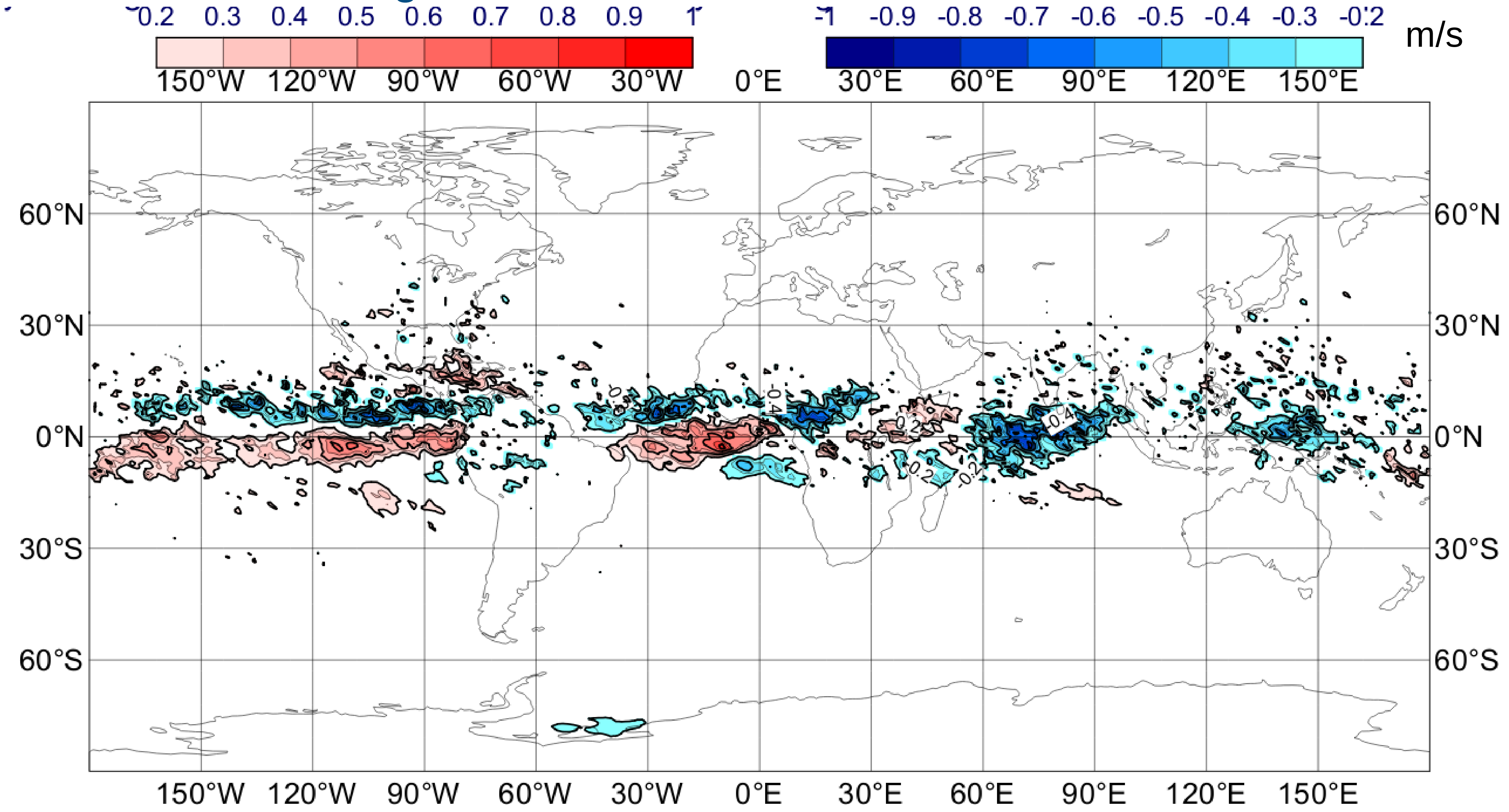
Changes in the u-wind analysis at 250 hPa (~10 km) due to assimilating Aeolus Rayleigh-clear+Mie-cloudy winds (for August to October 2019)



Stdev of analysis differences (exp – control)

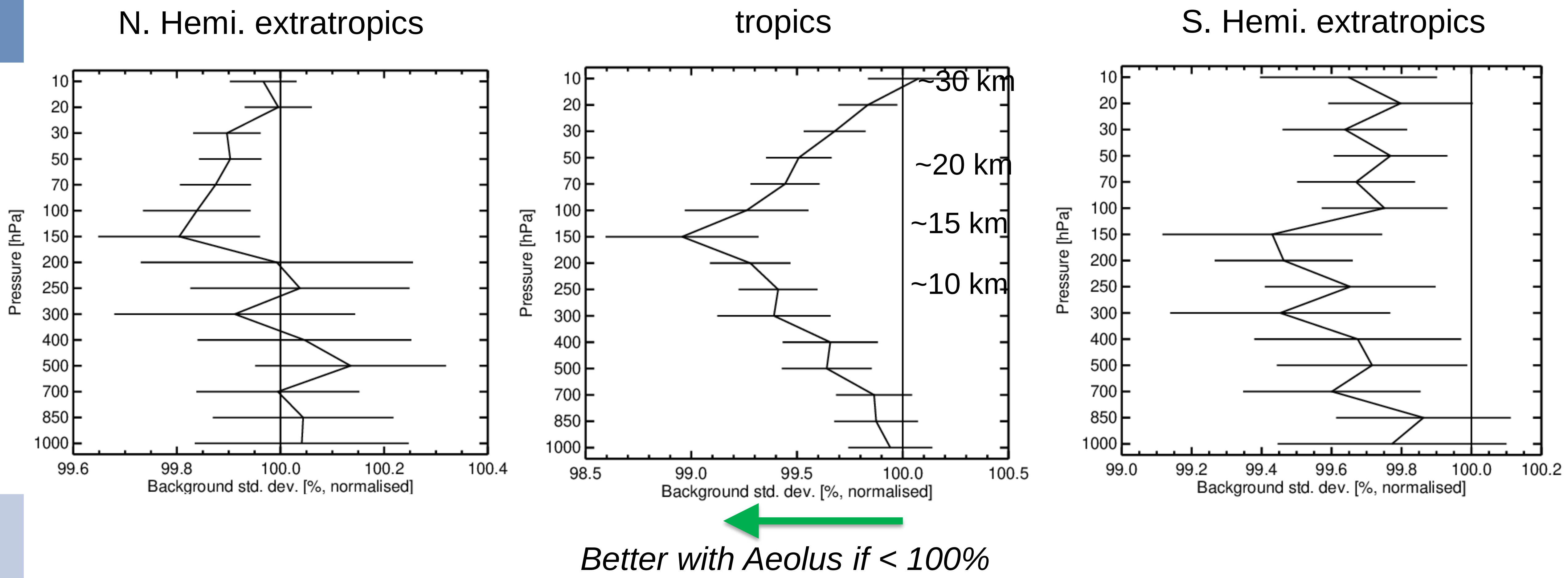
Largest changes made in the tropical upper troposphere and SH extratropical cyclone development areas over the ocean

Mean change in analysis u-wind at 150 hPa (~15 km) due to Aeolus – suggests Aeolus is correcting model biases here



Background fit to other observations when assimilating Aeolus (Rayleigh-clear + Mie-cloudy) – results of OSE (for period 2/8/19 to 31/12/19)

Conventional vector wind observations i.e. aircraft, radiosondes, wind profilers

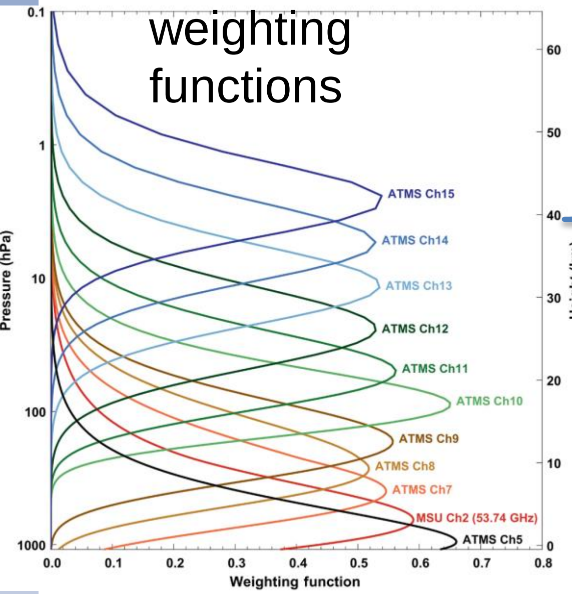


Aeolus impact best in the tropical upper troposphere

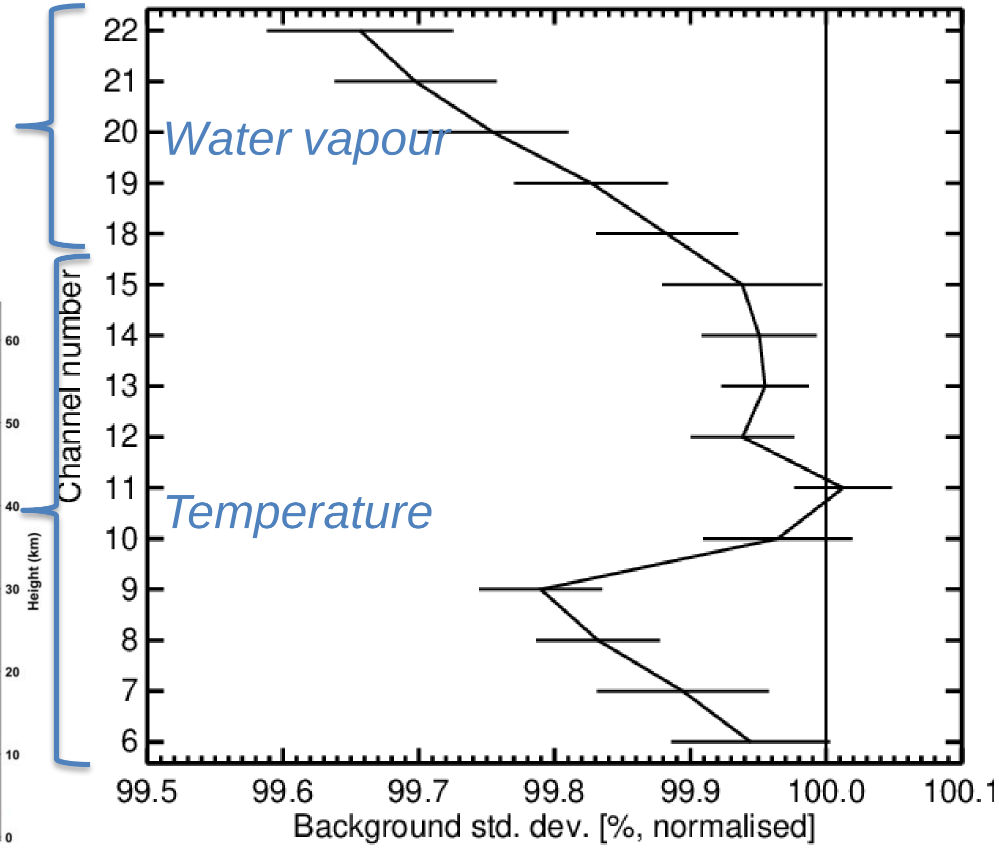
Background fit to other observations when assimilating Aeolus

Important MW and temperature/humidty sensitive data

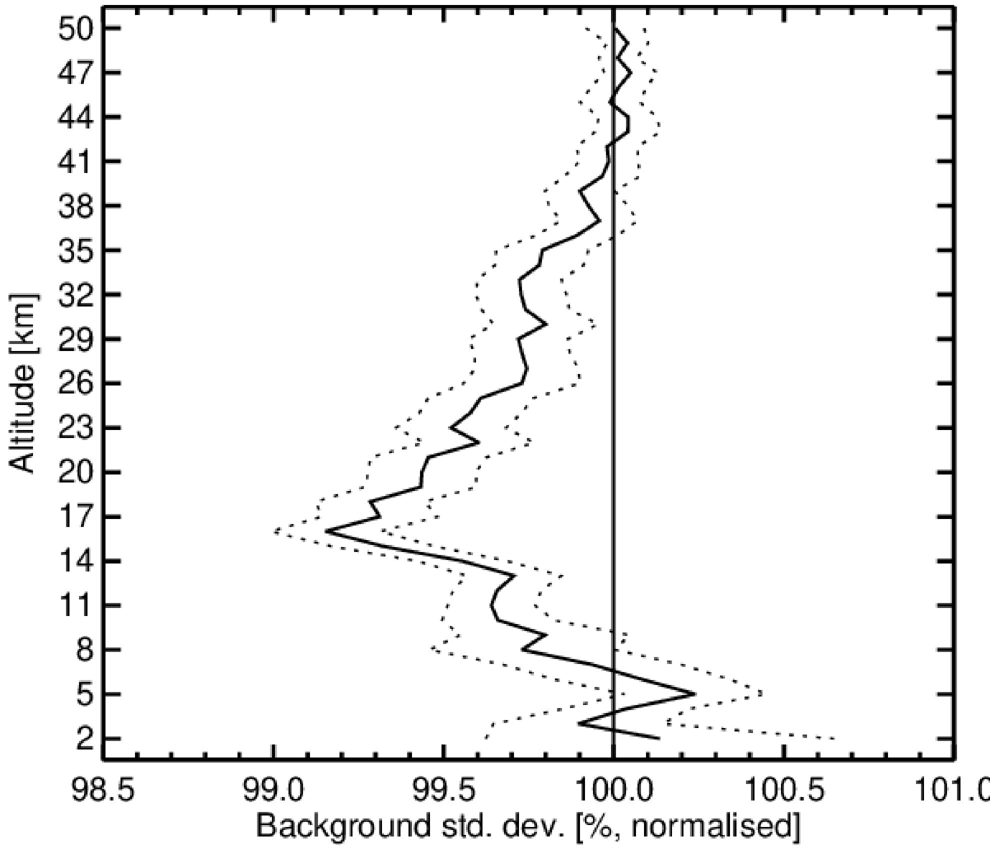
ATMS temp. weighting functions



Global, ATMS (microwave radiances)



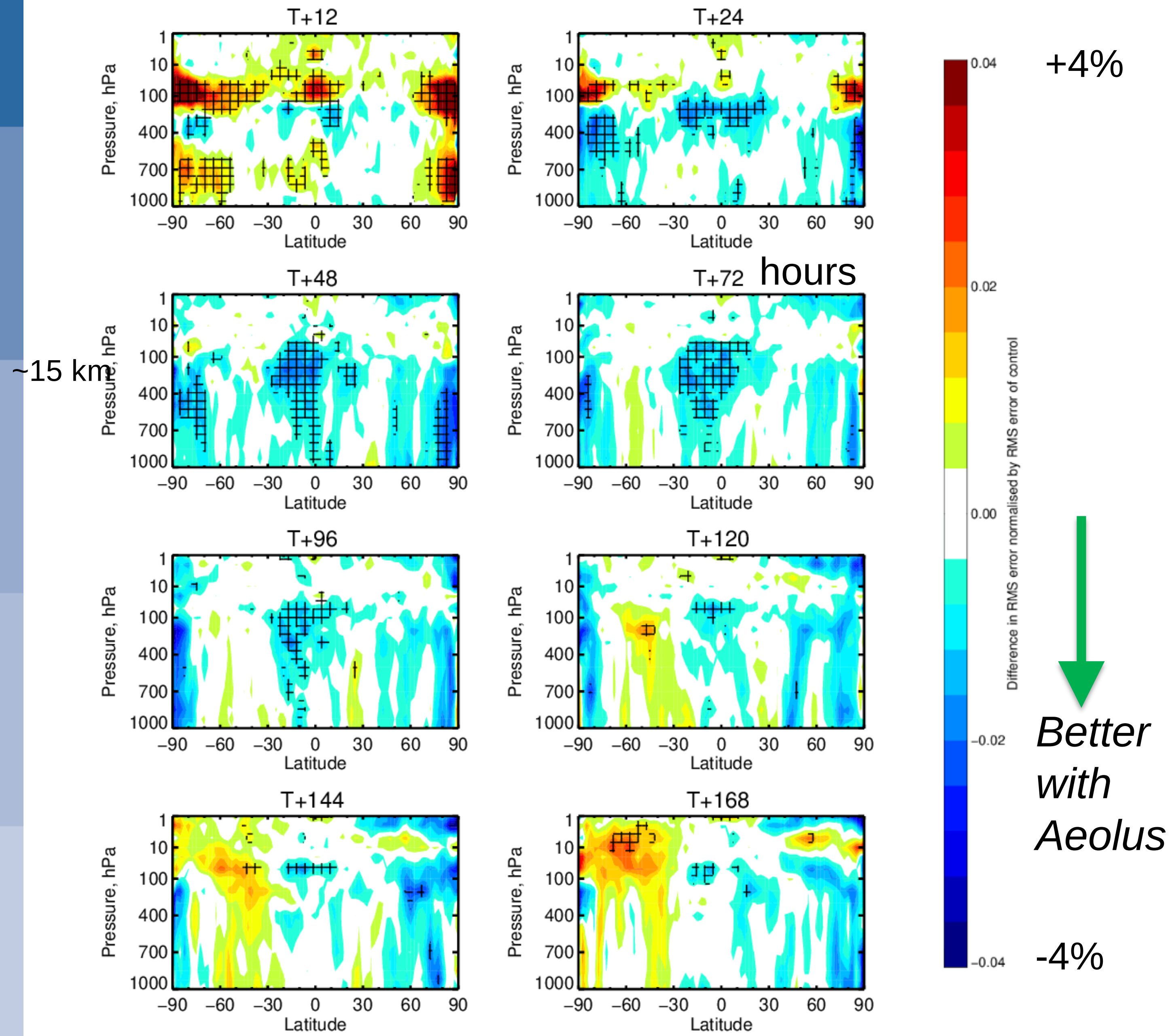
Global, GPS radio occultation (bending angles)



ECMWF

Aeolus is improving wind, temperature and humidity

Vector wind root mean square error impact of Aeolus (Rayleigh-clear + Mie-cloudy)

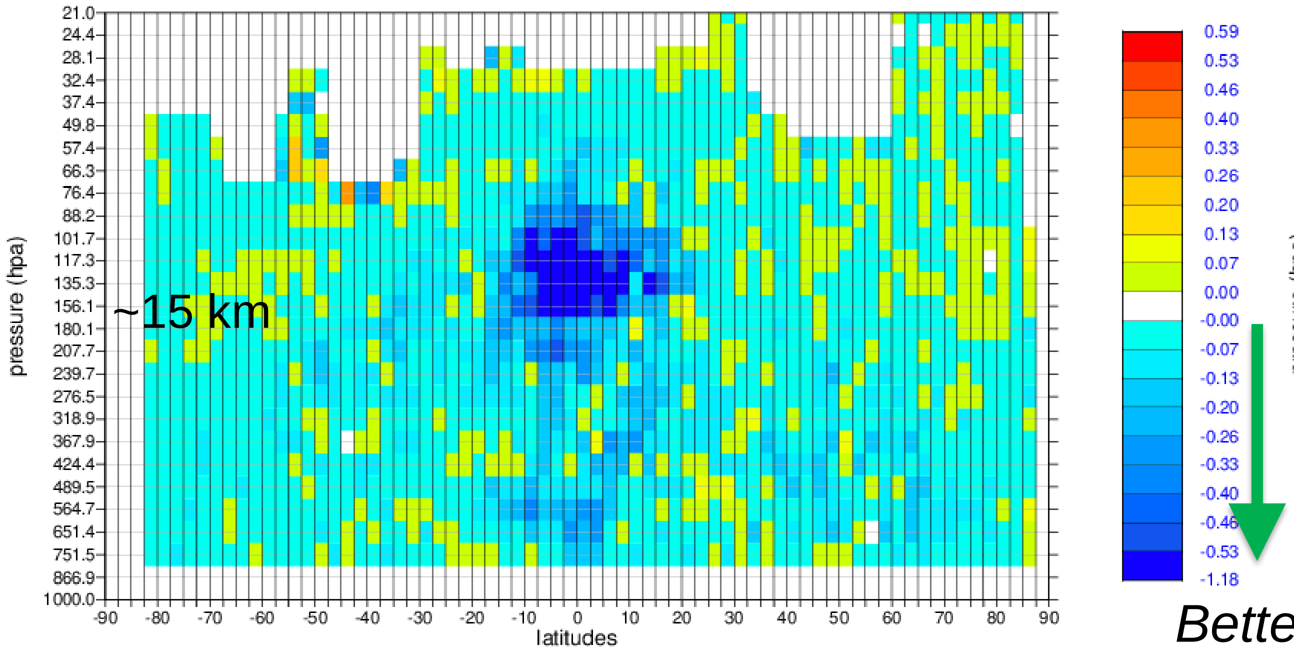


- Positive impact is strongest in the tropical upper troposphere and polar troposphere; at day two forecast range
- Longer range negative impact at upper levels in the SH is negative seems to be sensitive to weight given to Mie winds
- Similar impact patterns are seen for temperature and humidity forecasts

Another metric: Zonal average view of Aeolus Forecast Sensitivity Observation Impact (FSOI) – short range forecast impact on global dry energy norm

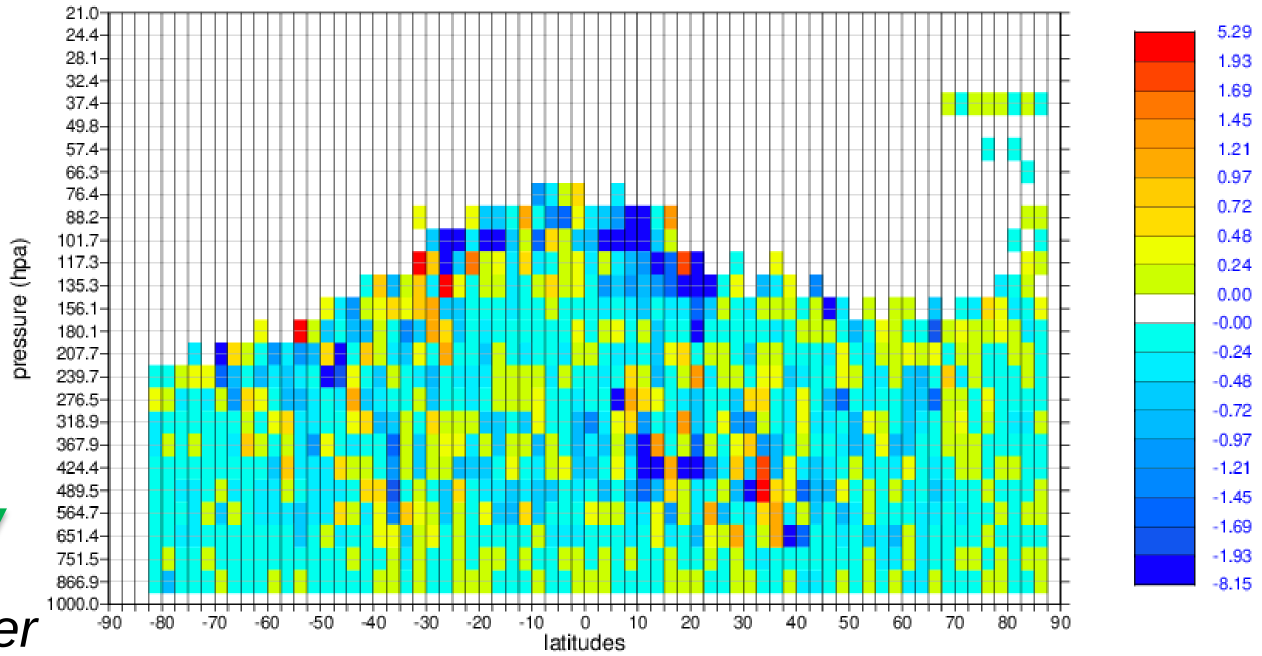
Results from operational assimilation

Zonal average Rayleigh-clear FSOI



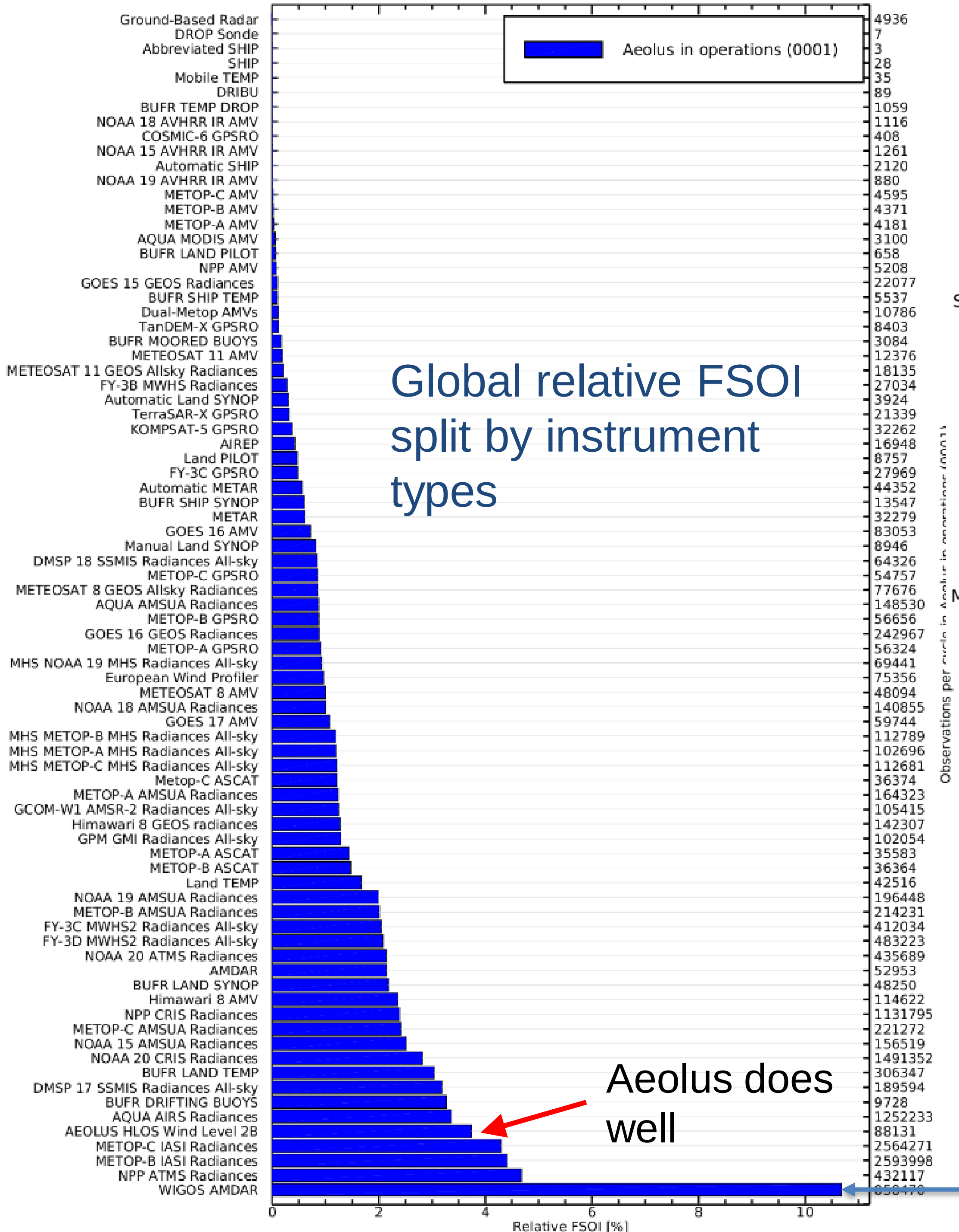
Better with Aeolus

Zonal average Mie-cloudy FSOI



Rayleigh has smaller magnitude impacts than Mie, but more consistently positive, with a larger impact in the tropical upper troposphere – agrees with OSEs

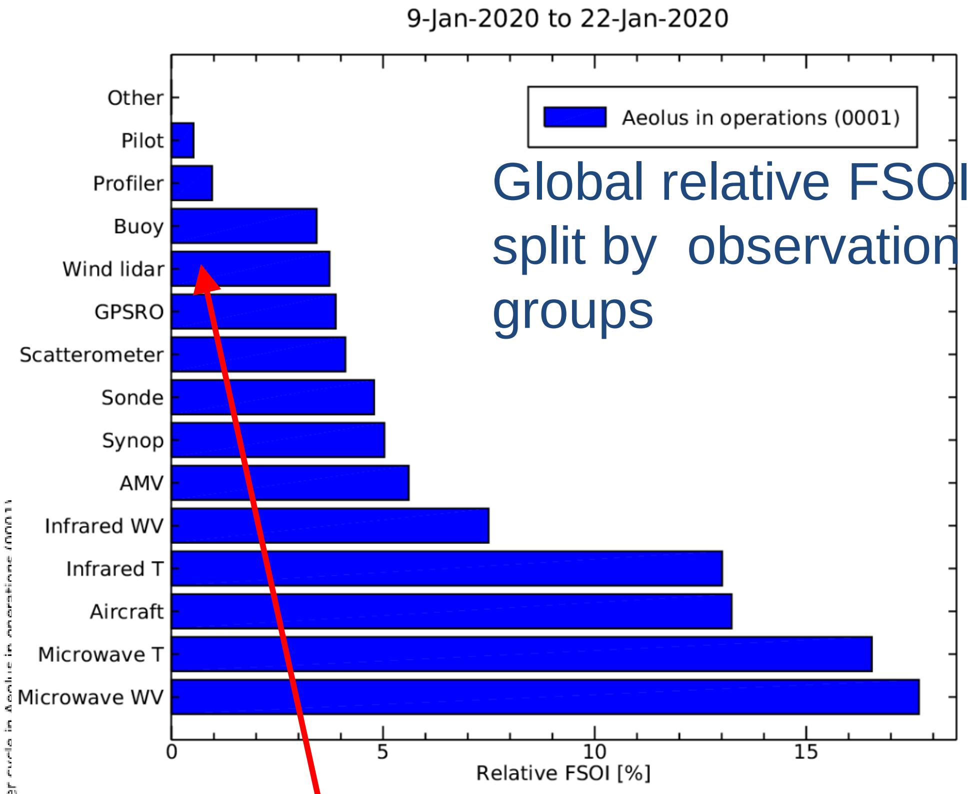
Mie has bigger magnitudes but more mixed positive/negative – it is thought that better modelling of observation errors will improve this



Global relative FSOI split by instrument types

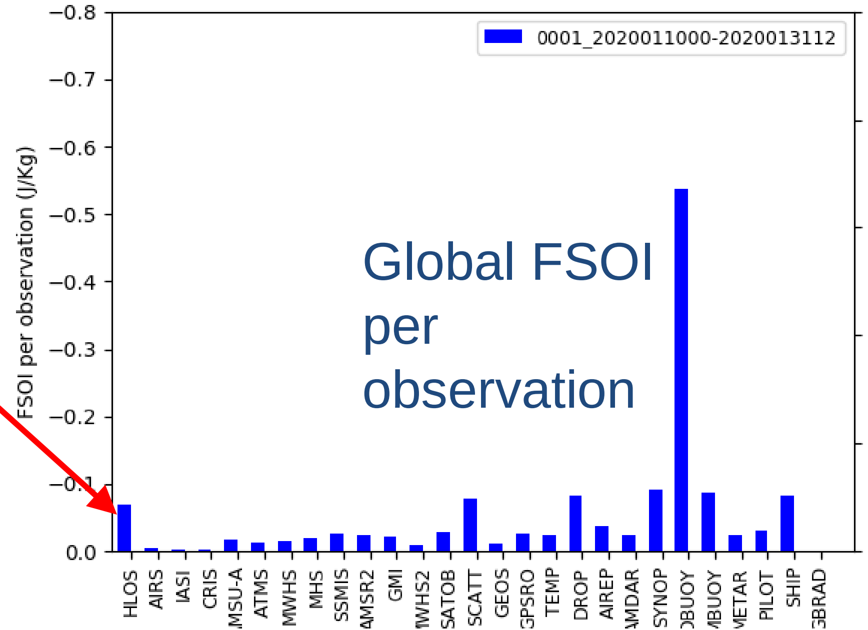
Aeolus does well

Aircraft obs



Global relative FSOI split by observation groups

Good for one satellite

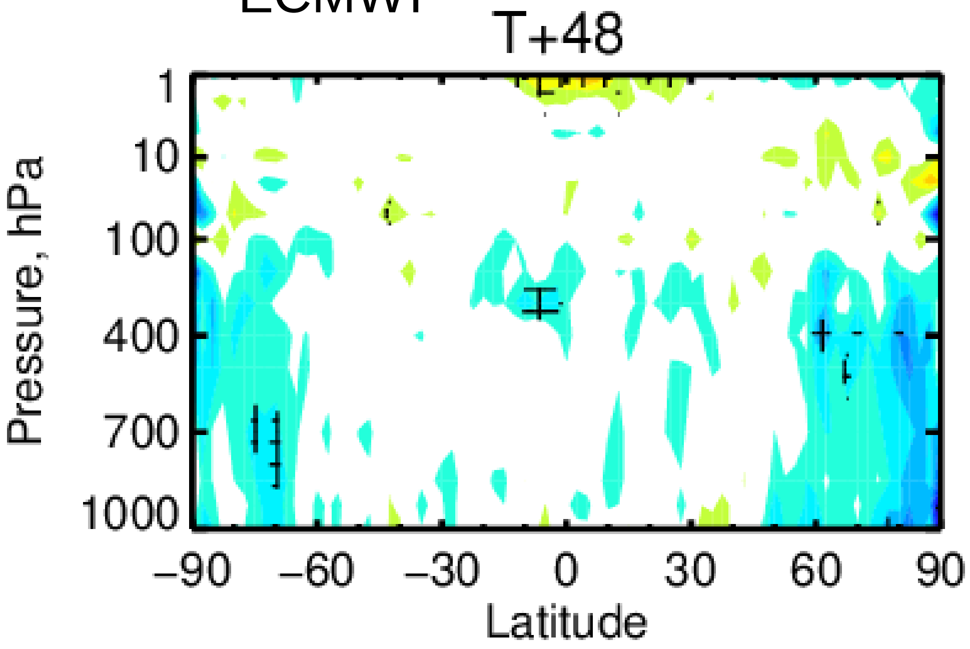


Global FSOI per observation

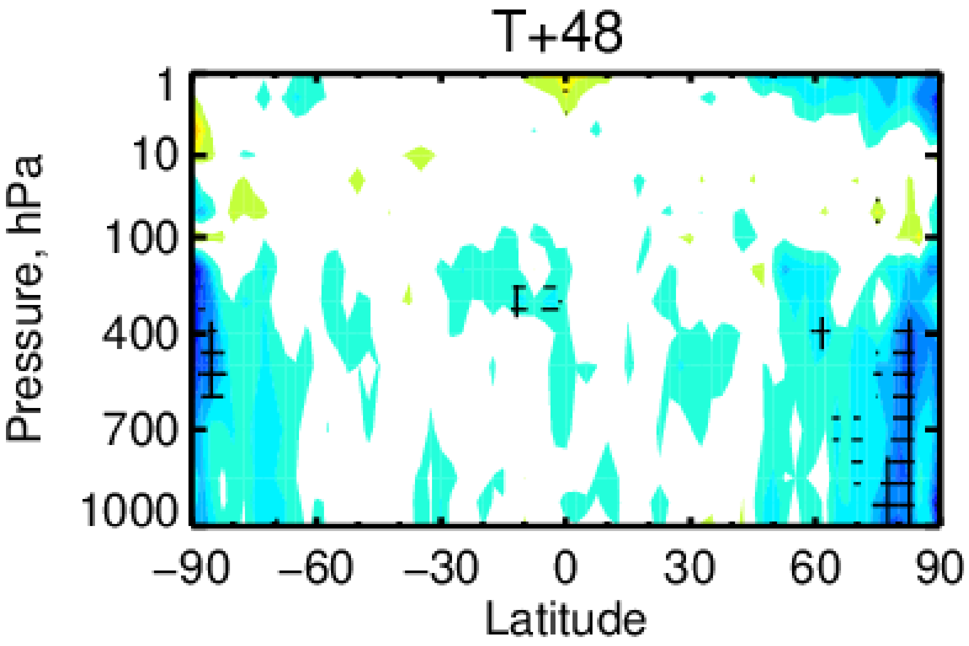
Recent results – **Mie impact can be increased** with improved assignment of observation error (including representativeness error)

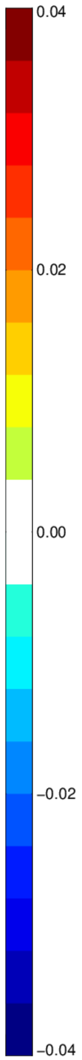
Mie-only impact on vector wind for 2 August to 26 December 2019

Observation errors as in current operations at ECMWF



Improved Mie observation error model





+4%

Better with Mie

-4%

Summary of Aeolus NWP impact assessment at ECMWF (*so far!*)

- Aeolus impact assessment
  - OSEs have shown statistically significant positive impact in tropics and at poles
  - FSOI from operations shows Aeolus is a useful contribution to Global Observing System
    - Shows **benefit of direct winds**
  - Aeolus is only <1% by number of obs assimilated (more wind profilers needed)
  - Rayleigh winds are providing most of the tropical impact (OSE and FSOI agree), but Mie impact is improved by more realistic observation error modelling
  - Early FM-B (with more signal) shows larger impact than in late FM-A period
    - Smaller wind errors hence more weight in data assimilation
    - Suggests if we could somehow get back some of the missing factor 2-3 of photon counts, **impact would be much greater, especially when solar background noise is large**
    - Good impact had relied on bias correction using the model as a reference (particularly for Rayleigh channel)
    - However upcoming operational processor (telescope temperature dependent bias correction) reduces the model reliance
  - ***There is still plenty of scope to improve the impact, both in processing the observations and in the assimilation methods***