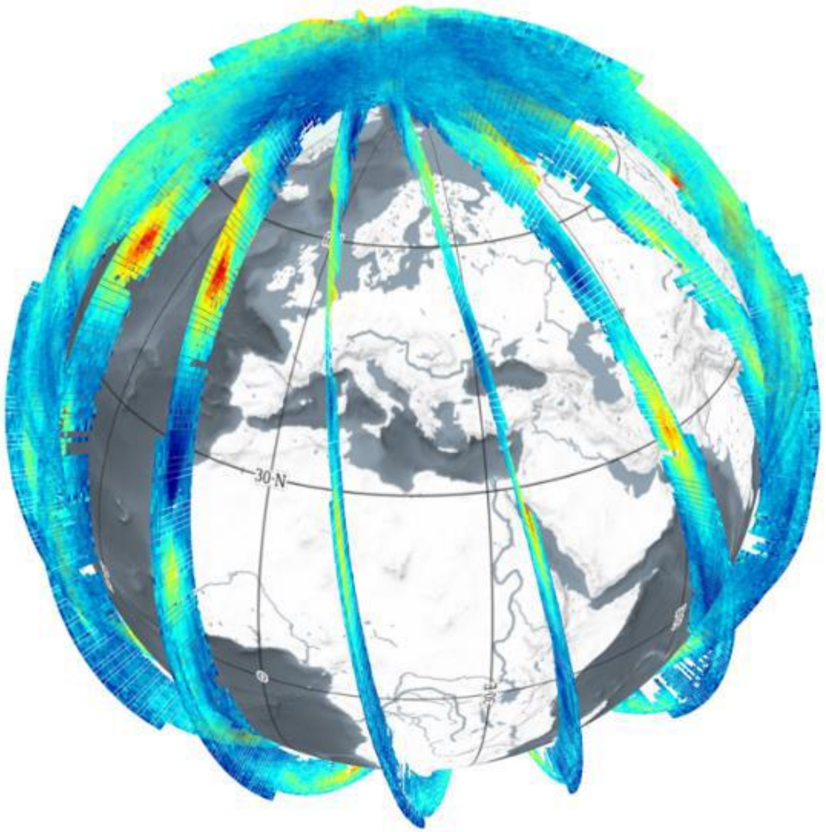
Royal Netherlands Meteorological Institute
Ministry of Infrastructure and the Environment

esa

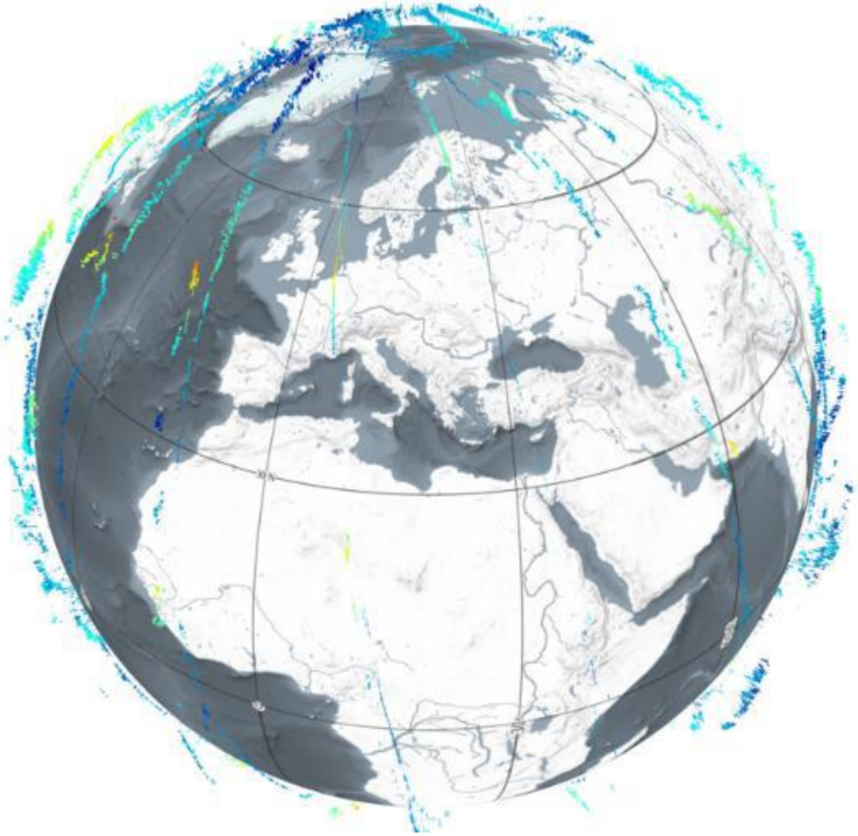
Bracketing EPS-Aeolus impact expectations

Ad.Stoffelen@knmi.nl, Gert-Jan Marseille, NOAA OSSE team, Mike Rennie, Sean Healy (ECMWF), Vivien Pourret (MF)

Aeolus clear air and cloudy winds



Signal quality
2-3 times lower
than specified



Rayleigh winds from molecules
- No humidity, no aerosol needed
- ~ 70% of atmospheric volume, depending on height

Mie winds from clouds
- Not many aerosol winds for Aeolus-1 (in PBL)
- ~10% of atmospheric volume, depending on height

Adopted by CGMS 49th plenary:

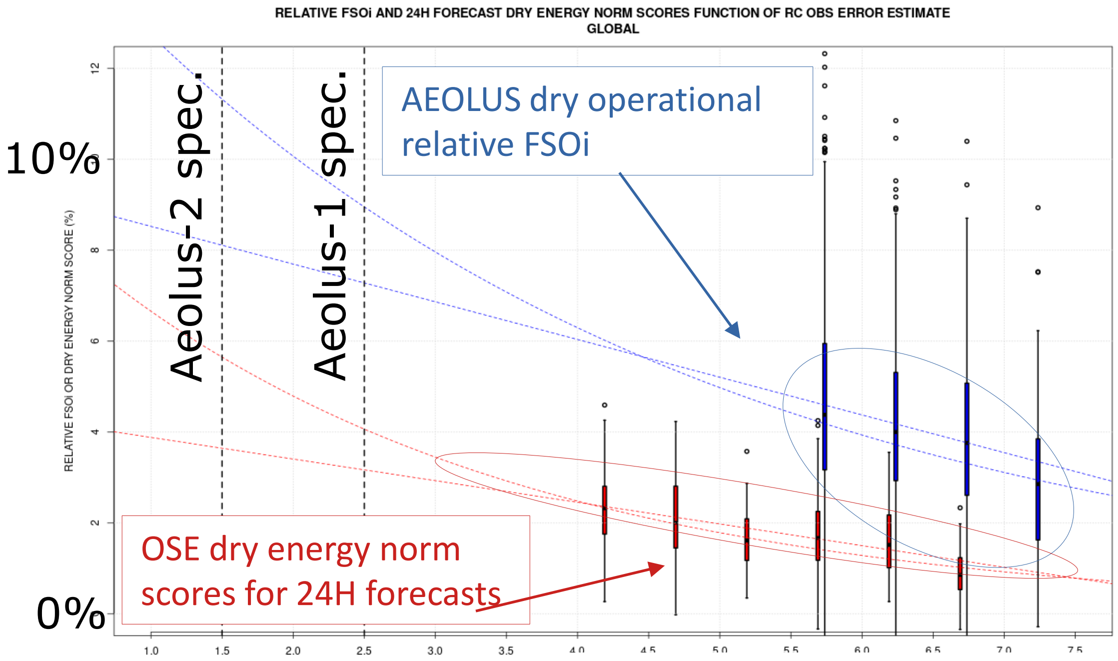
- **Recommendation 1: For consideration by CGMS Plenary the IWWG recommends space agencies to address the gap of global 3D wind profile observations with high priority. Based on the Aeolus experience, a combination of lidar & IR missions can provide complimentary wind observations which look to be very promising.**

- **Aeolus shows significant positive impact on global NWP models as shown by ECMWF, Météo-France, Met Office, DWD, NOAA, JMA, NCMRWF and ECCC and is better than expected prior to launch.**
- **Operational assimilation at ECMWF, Météo-France, DWD, the Met Office and others.**
- **Strength within the entire assimilation scheme.**
- **Valuable as an AMV intercomparison dataset.**

24H forecast dry energy norm scores (comparing FSOi and OSE scores)

- Monthly **AEOLUS FSOi** **vs** **RC σ_{Oe}** (from monthly oper monitoring, 07/2020 to 06/2022)
- Monthly **AEOLUS dry energy norm score S** **vs** **RC σ_{Oe}** (from OSEs with first reprocessed data, pre-oper OSE with oper data and ARPEGE toy OSEs with oper data)

Following the linear fit:
AEOLUS (RC + MC) FSOi inference for low observation error lead to an improvement of 7 % for initial AEOLUS specifications and of 8 % for AEOLUS 2 ones.
For OSEs (RC + MC) dry energy scores, it leads to lower impacts: 3 and 3.5 %

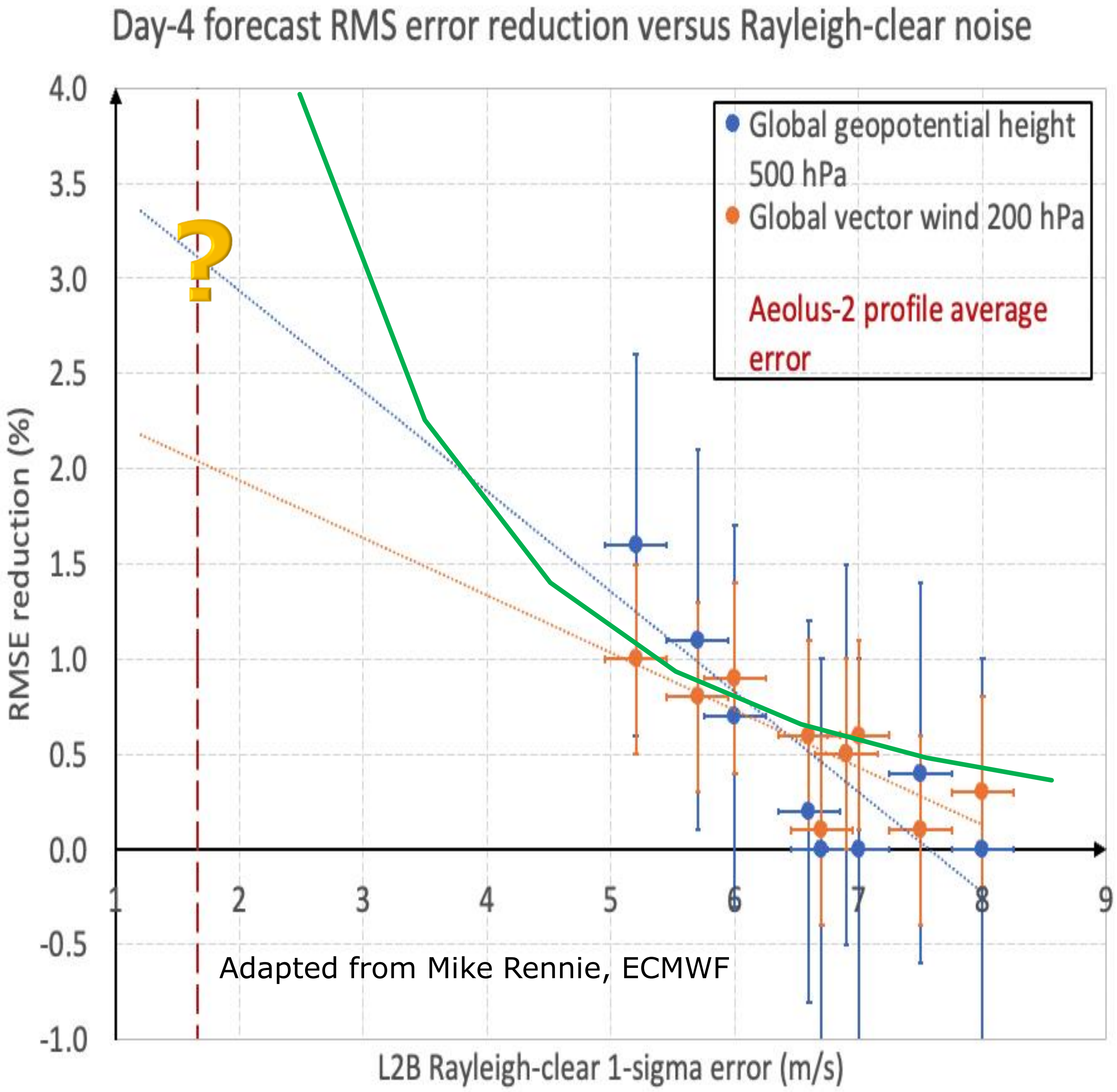


σ_{Oe} (RC) [m/s]

$\sigma_{Oe}^2=\sigma_{O-B}^2-\sigma_B^2$, σ_B=2.4 m/s, T_r=300K

Main reasons differences:

- Linear assumptions for FSOi
- FSOi is the part of the change of the total norm explained by the AEOLUS observing system, whereas for OSE scores, it is the change of the norm between the control EXP (no AEOLUS) and the EXP (with AEOLUS).
- In FSO, guesses take advantage of all the cycled previous analyses with AEOLUS, In OSEs, the control experiment does not.
- OSE scores are for 0H and 12H base hours, whereas FSOi is computed for all base hours (0, 6, 12 and 18).
- FSOi resolution is T1798+T224, for OSE it is T1798 projected on a 0.25° x0.25° grid
- Atmospheric references are own analyses for FSO vs an independent one (IFS analyses) for OSE scores



Improved Aeolus-2 OSE expectation ?

Following DAS paradigms:

- Dynamical error growth is linear in first 24 hours (Bengtsson, 1978) and beyond (Megner et al., 2015)
- Simplified analysis error at DWL sampling:

  $\sigma_A^2 = \sigma_O^2 * \sigma_B^2 / (\sigma_O^2 + \sigma_B^2)$
- x = observation error σ_O, Background error σ_B is about 2 m/s
- y = initial improvement or c.[1 – $(\sigma_A / \sigma_B)^2$]: fitted green line
- Ignores changes in sampling w.r.t. σ_O (more Mie for Aeolus2, higher resolution)
- How to address this extrapolation? => NOAA OSSE, ECMWF EDA, . .

EUMETSAT

WORKSHOP

EPS-STERNA AND EPS-AEOLUS

IMPACT ASSESSMENT WORKSHOP

19-20 APRIL 2023
DARMSTADT, GERMANY

LIPAS simulation of Aeolus and EPS-Aeolus

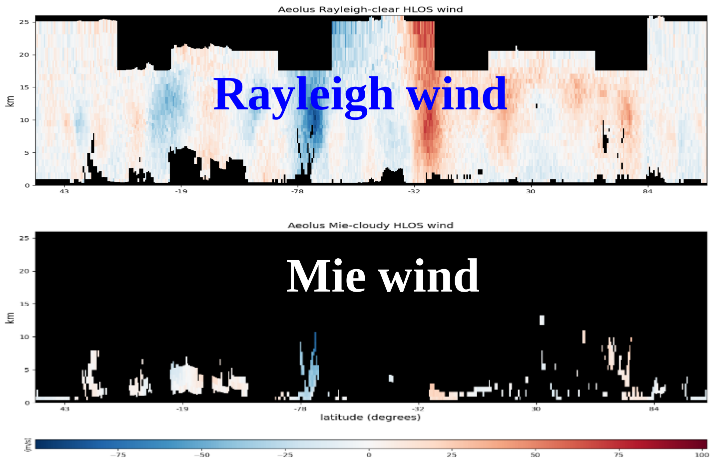
LIPAS – Lidar In-space Performance Atmospheric Simulator

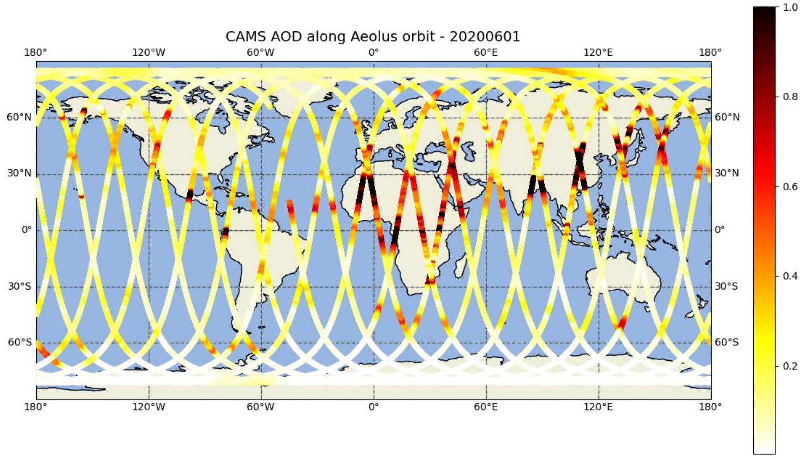
- Used in many ESA pre-launch impact studies
- Simulates Aeolus Rayleigh and Mie channel HLOS wind and wind errors

Nature Run
(P,T,u,v,q,cc,ciwc,clwc)

LIPAS

CAMS (Copernicus Atmospheric Monitoring Service
(aerosol backscatter and extinction)



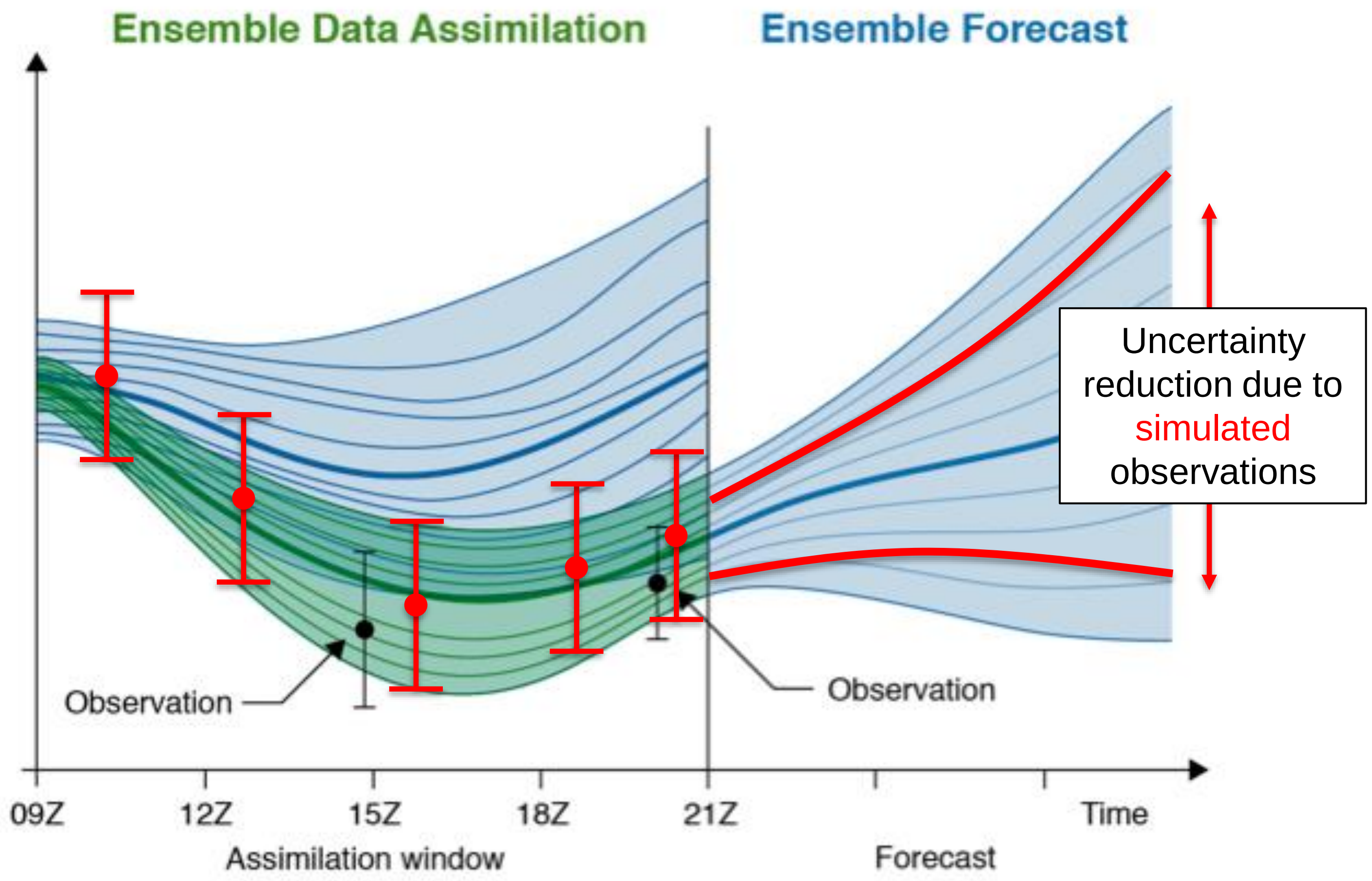


- 2 months simulation, June/July period
- KNMI responsible for LIPAS tuning
- LIPAS code transferred to NOAA for uptake in OSSE system

aeolus

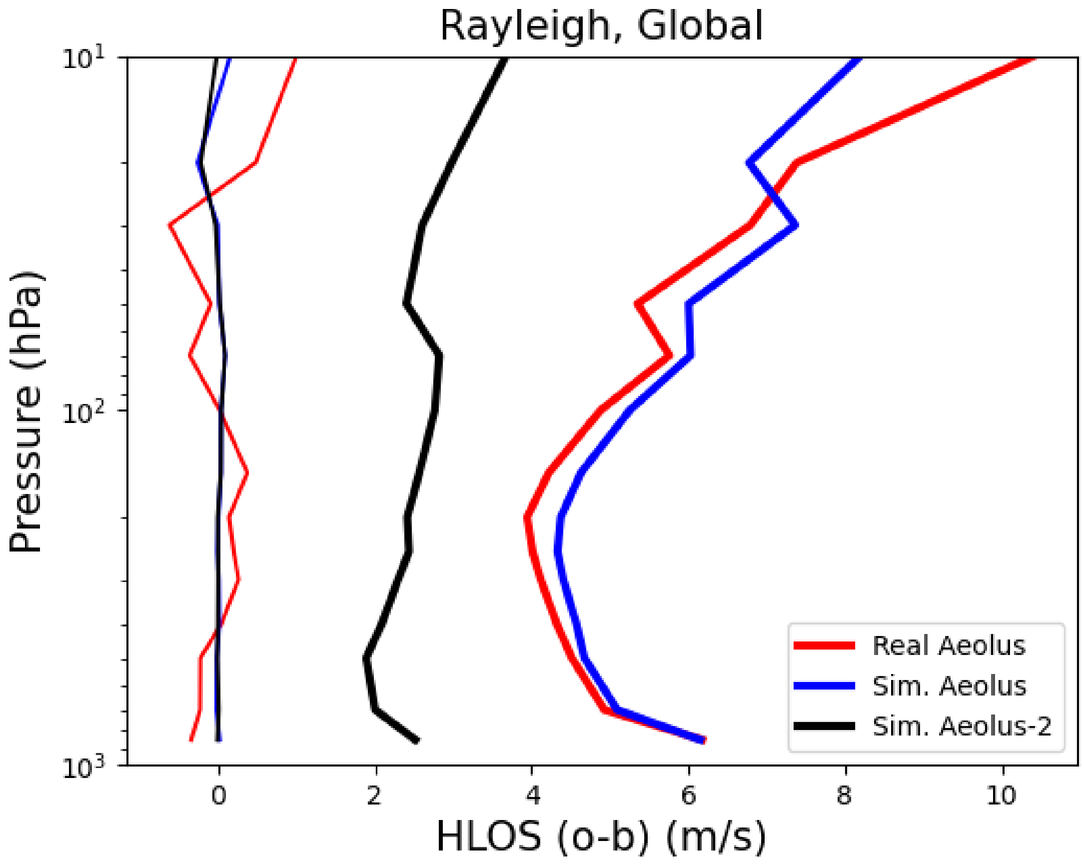
The Ensemble of Data Assimilations (EDA) method to assess future observations

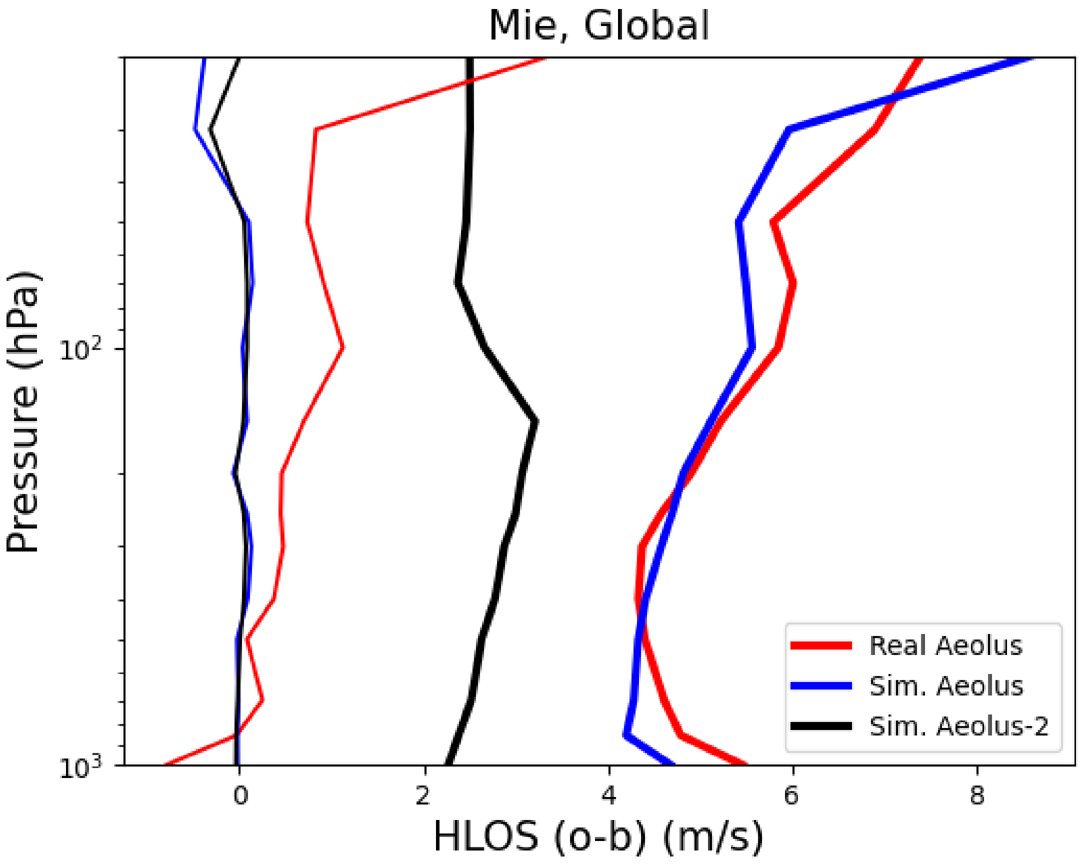
- EDA consists of:
  - Finite number of independent cycling assimilation systems
  - Uses real and added simulated observations
  - Observations, forecast model and SSTs perturbed to generate different inputs for each member
- Benefit of additional data measured by reduction in variation across different members – “EDA spread” → reducing forecast/analysis uncertainties
- Assumes errors of the simulated observations are realistic
- Focus on spread changes at 12-hour forecast range



Used for previous ESA and EUMETSAT studies for future impact of first Aeolus, Radio Occultation and to investigate broad questions on constellation design for small sats carrying MW sounders.

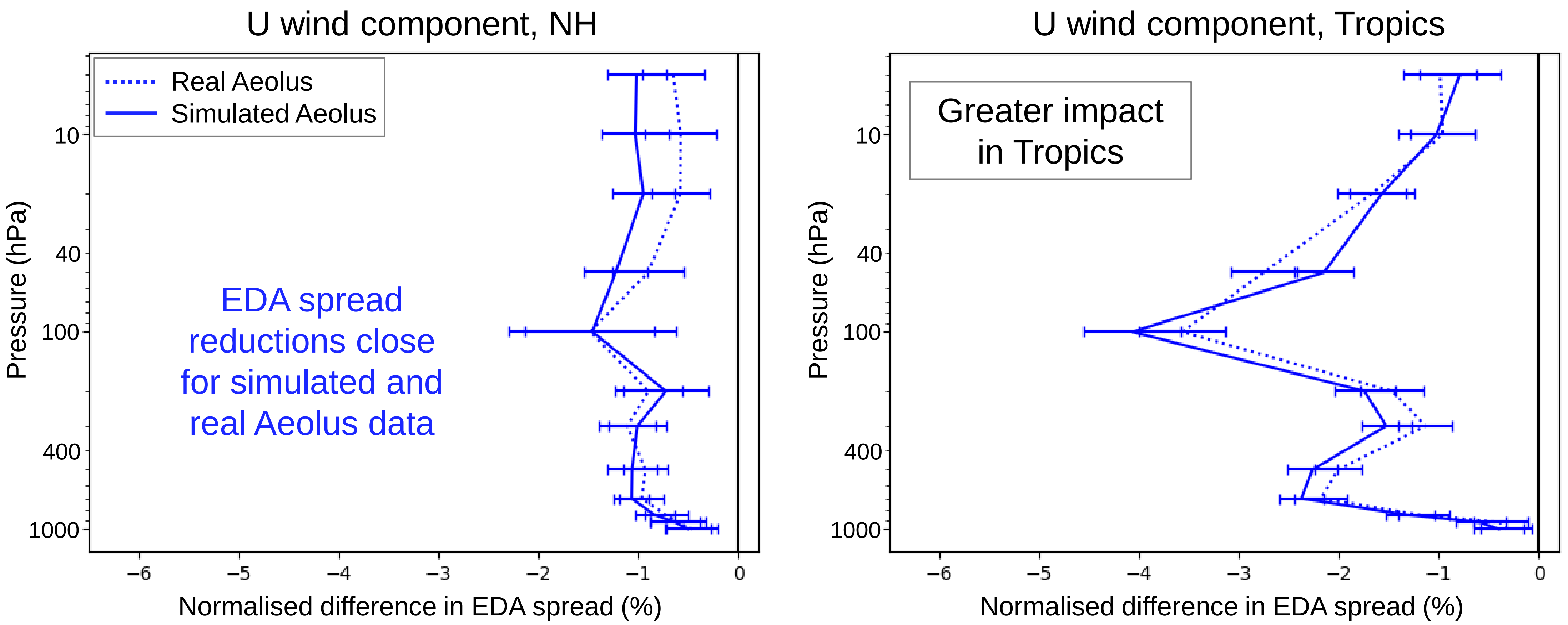
Departure statistics for real and simulated data: July 1-10, 2019
Globally averaged



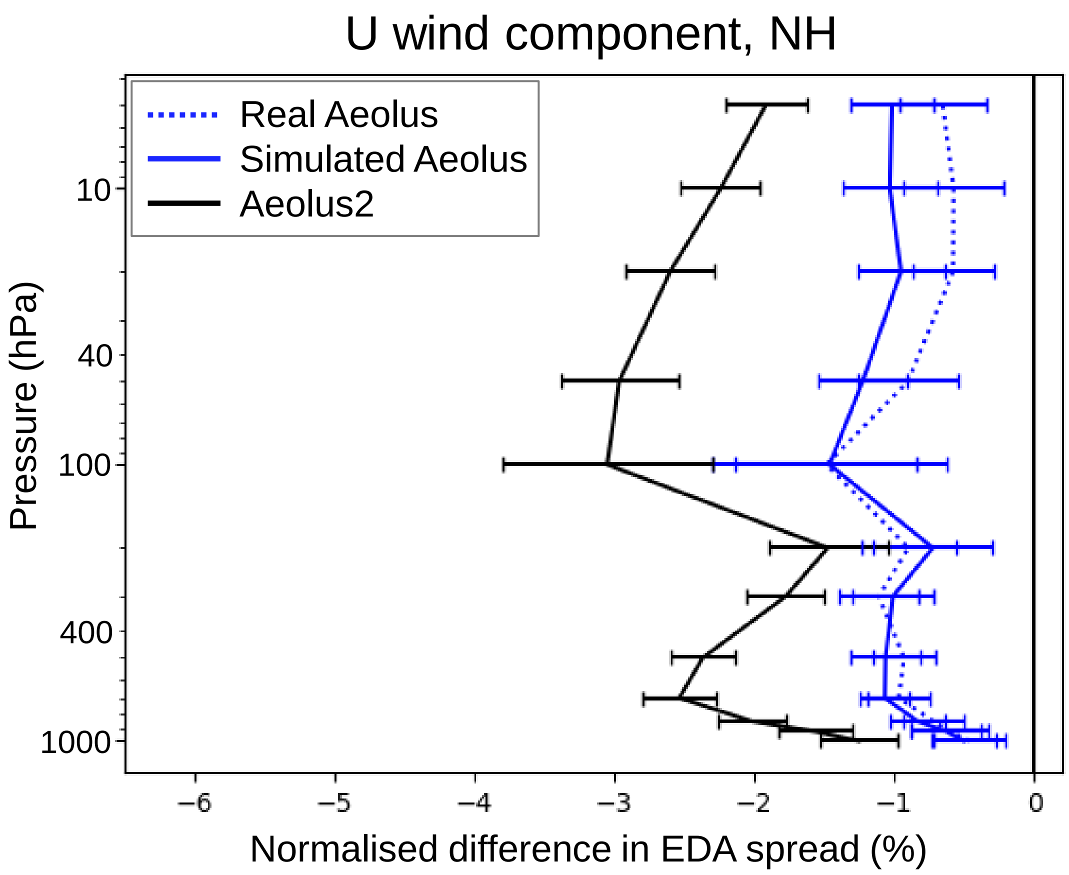


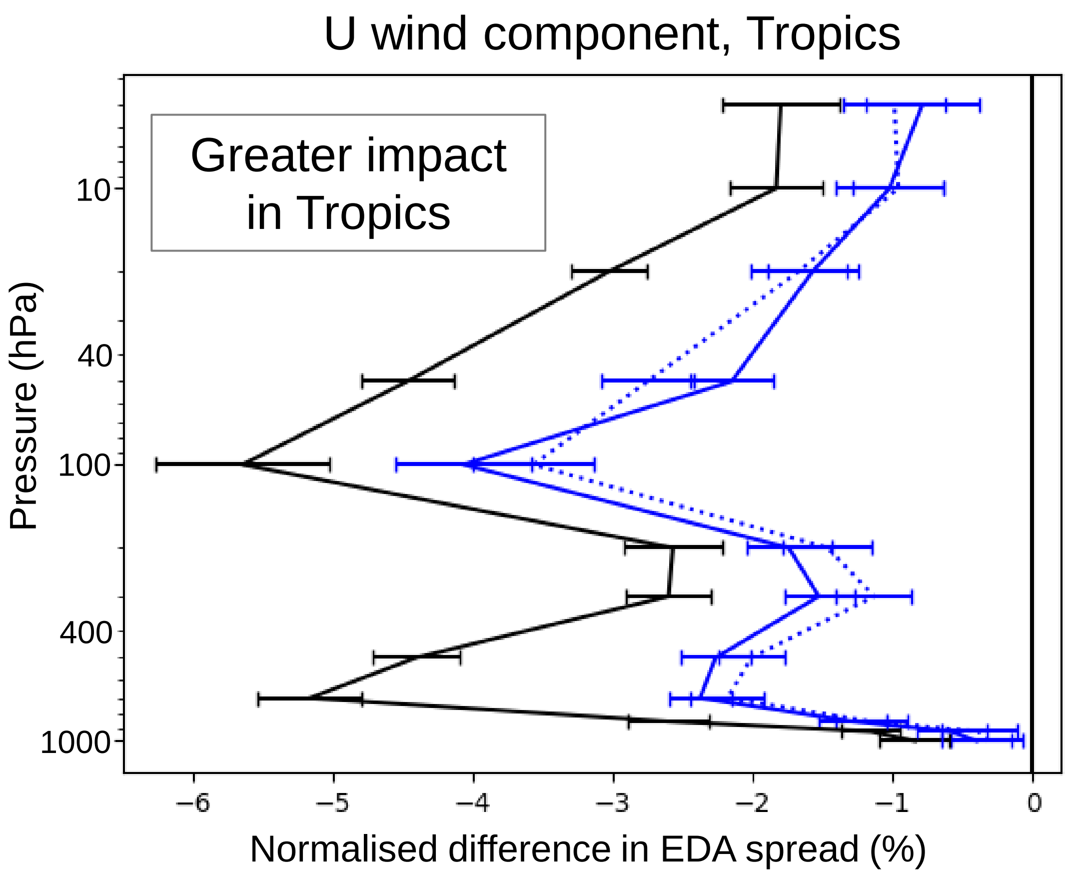
Agreement between real and simulated Aeolus illustrate the accuracy of Mike Rennie's uncertainty model. But simulated data has much smaller biases

Good agreement between real and simulated Aeolus impact in EDA



Significant additional benefit for Aeolus2





In general, Aeolus2 is ~2-3 x impact of current Aeolus

Key points

- We produce realistic (o-b) departure statistics for simulated Aeolus data. Confidence in simulation system
- EDA spread reductions obtained with **real** and **simulated Aeolus** measurements consistent
- **Aeolus2 spread reductions ~2-3 times bigger than Aeolus** with improved uncertainty specifications
  - Just completed two new experiments: Aeolus2 Rayleigh clear **only**/Mie Cloudy **only**
- **ECMWF also showed combined impact of Aeolus2 and Sterna in Darmstadt workshop**

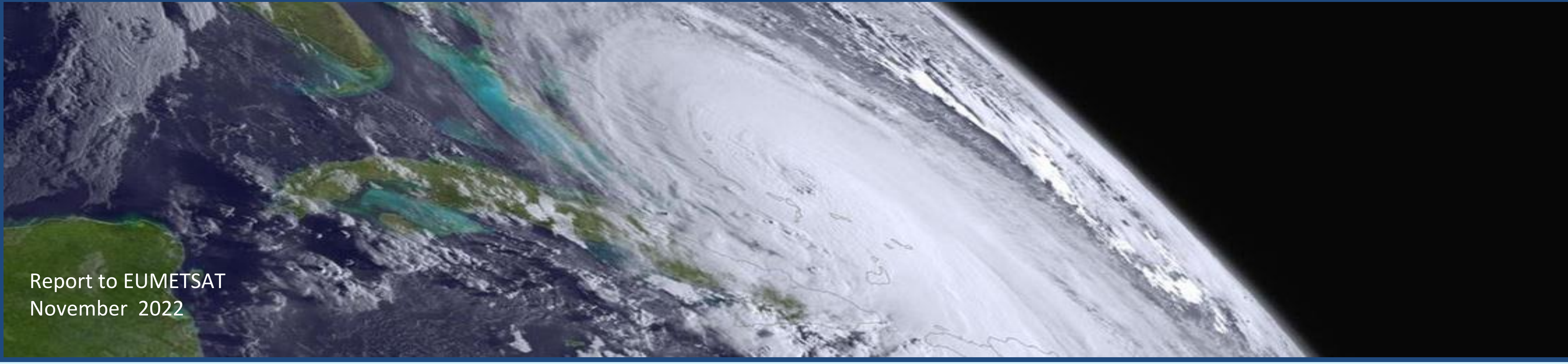
Impact Assessment of Aeolus/Aeolus-2 with the global NOAA OSSE system – Final Report

Lidia Cucurull

Chief Scientist and Deputy Director

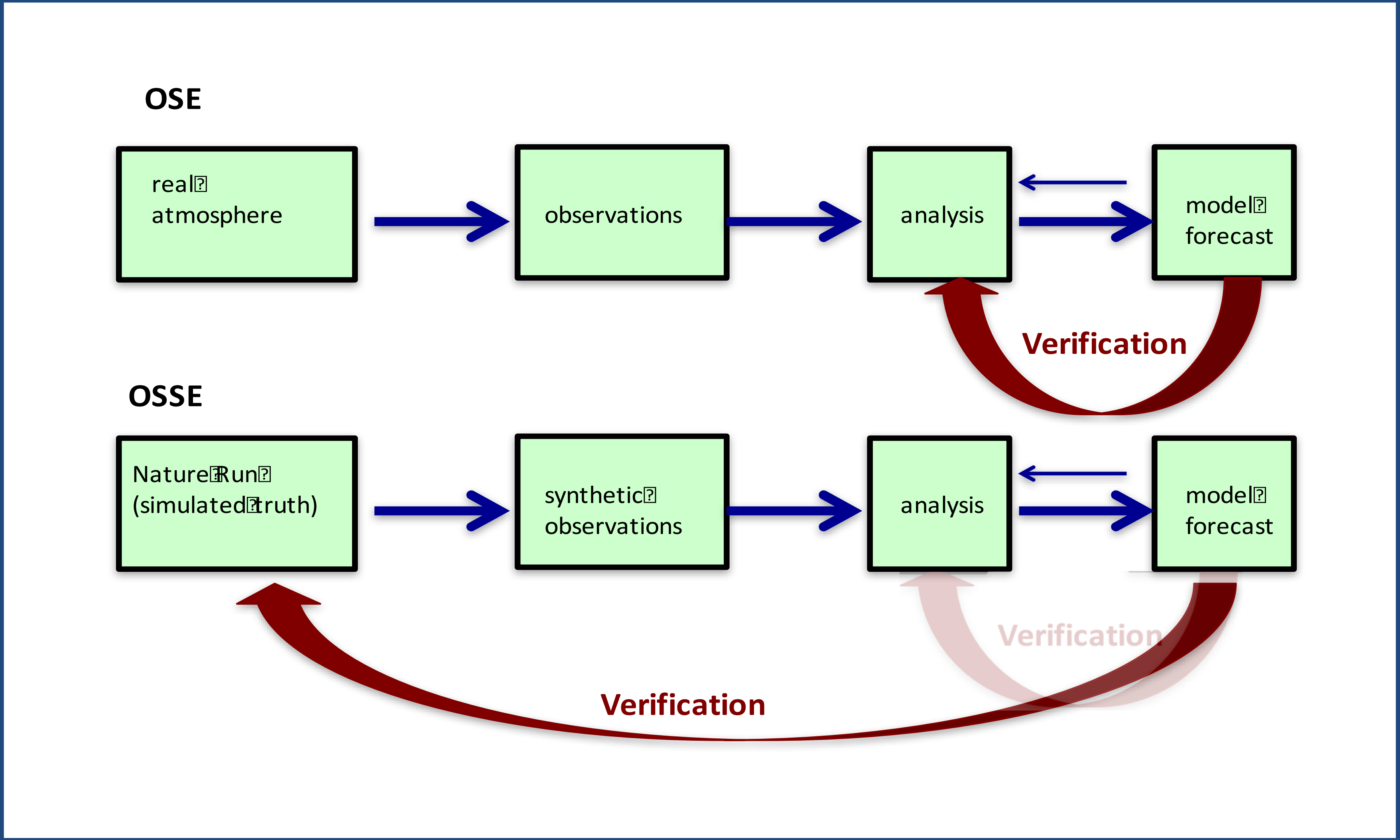
NOAA Quantitative Observing System Assessment Program (QOSAP)

QOSAP Team: A. Lim, M. Mueller, S. Casey, A. Vidal, and P. Paz.
In collaboration with Ad Stoffelen and Gert-Jan Marseille (KNMI)



Report to EUMETSAT
November 2022

OSE (real) vs. OSSE (simulated)



The truth is unknown

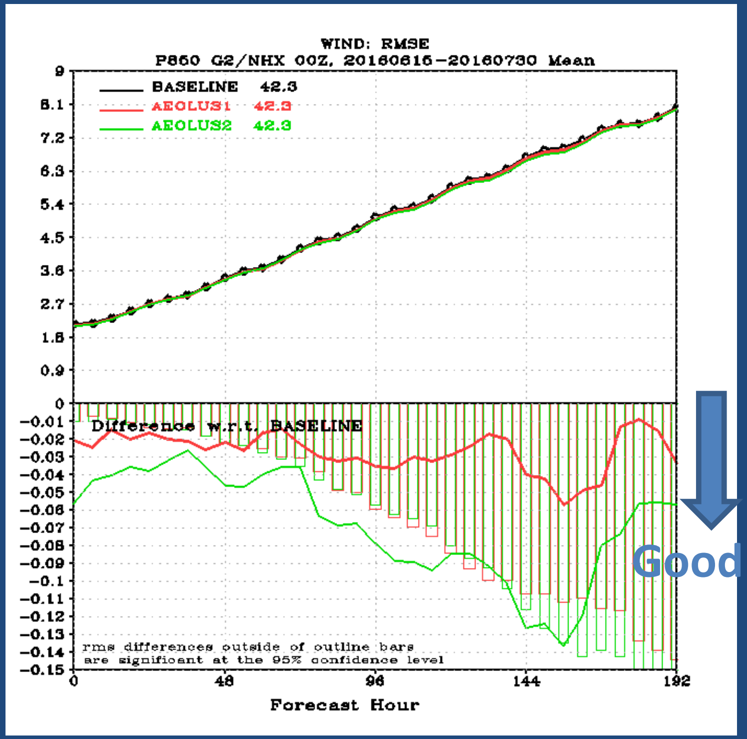
The truth is known

OSSE with Aeolus/Aeolus-2

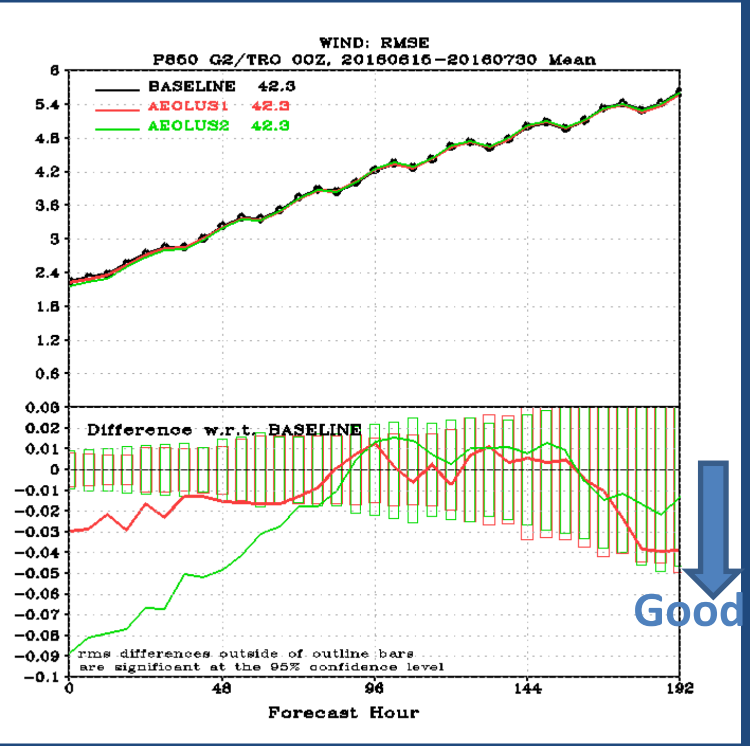
BASELINE = Baseline control configuration
AEOLUS1 = Baseline + Aeolus-1
AEOLUS2 = Baseline + Aeolus-2

850 hPa RMS Wind error

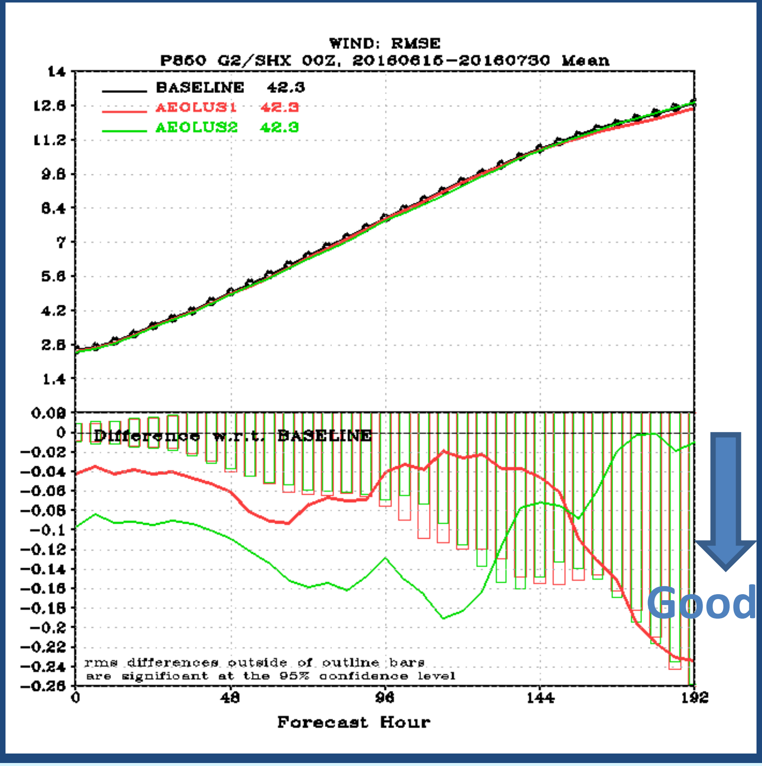
Northern Hemisphere extra-tropics



Tropics



Southern Hemisphere extra-tropics

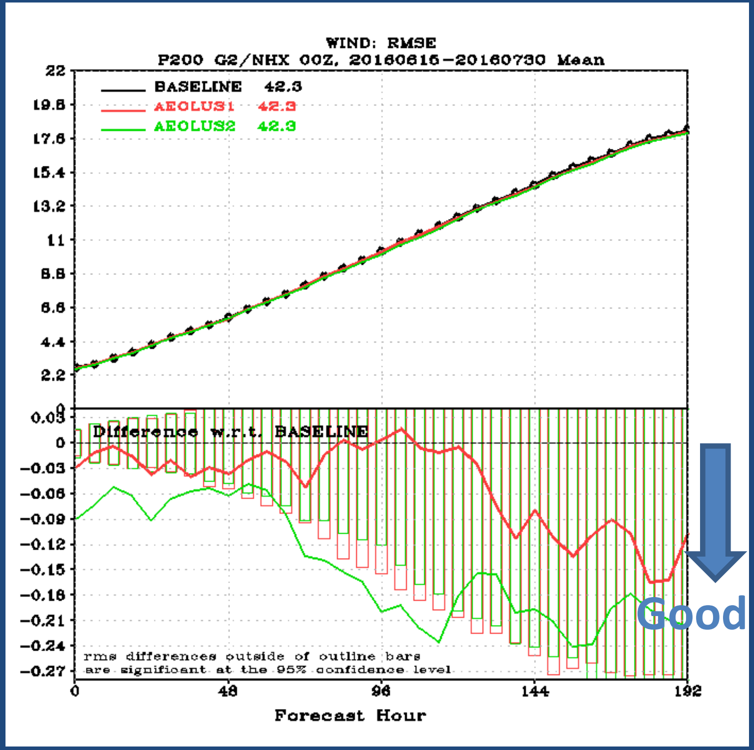


OSSE with Aeolus/Aeolus-2

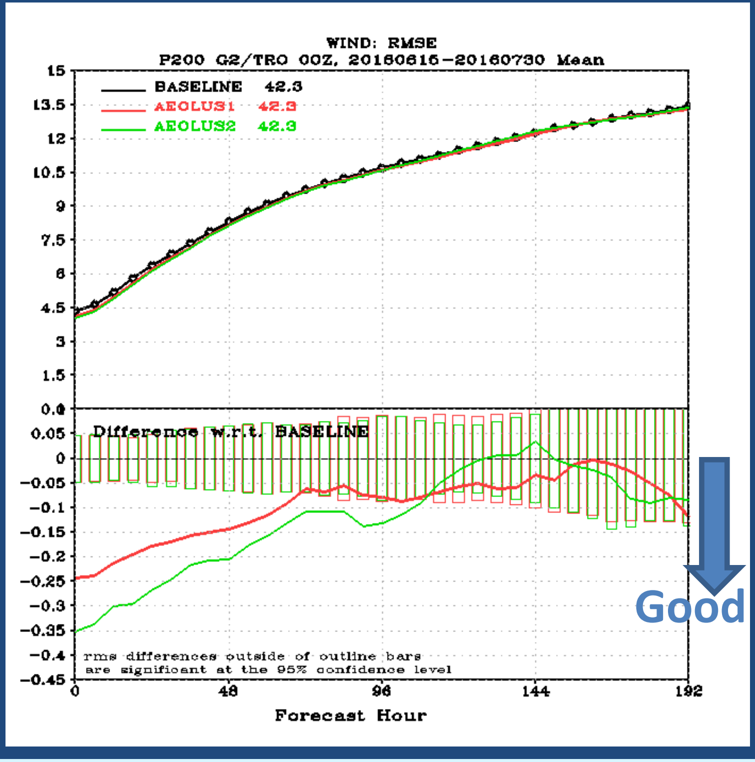
BASELINE = Baseline control configuration
AEOLUS1 = Baseline + Aeolus-1
AEOLUS2 = Baseline + Aeolus-2

200 hPa RMS Wind error

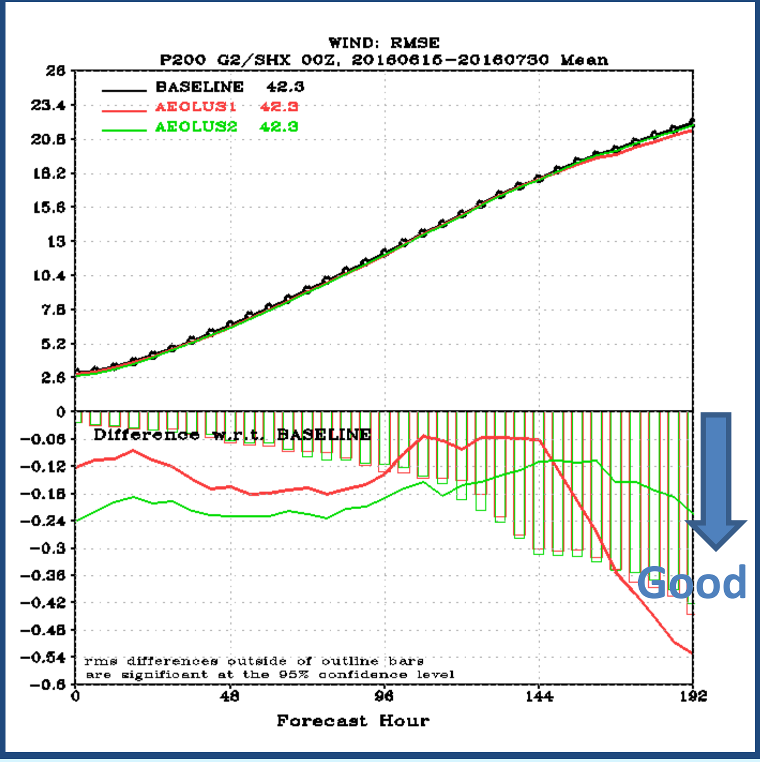
Northern Hemisphere extra-tropics



Tropics



Southern Hemisphere extra-tropics

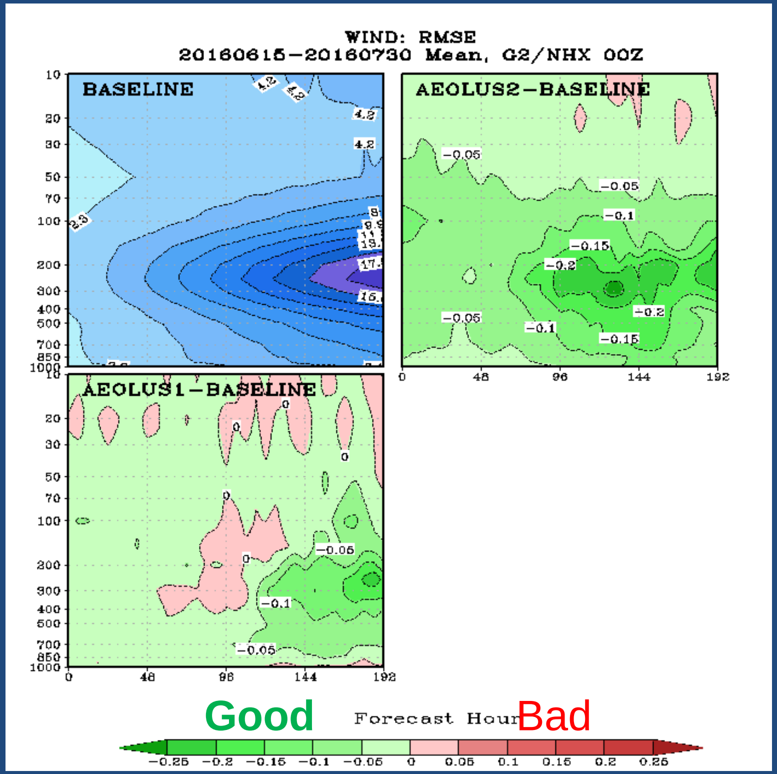


OSSE with Aeolus/Aeolus-2

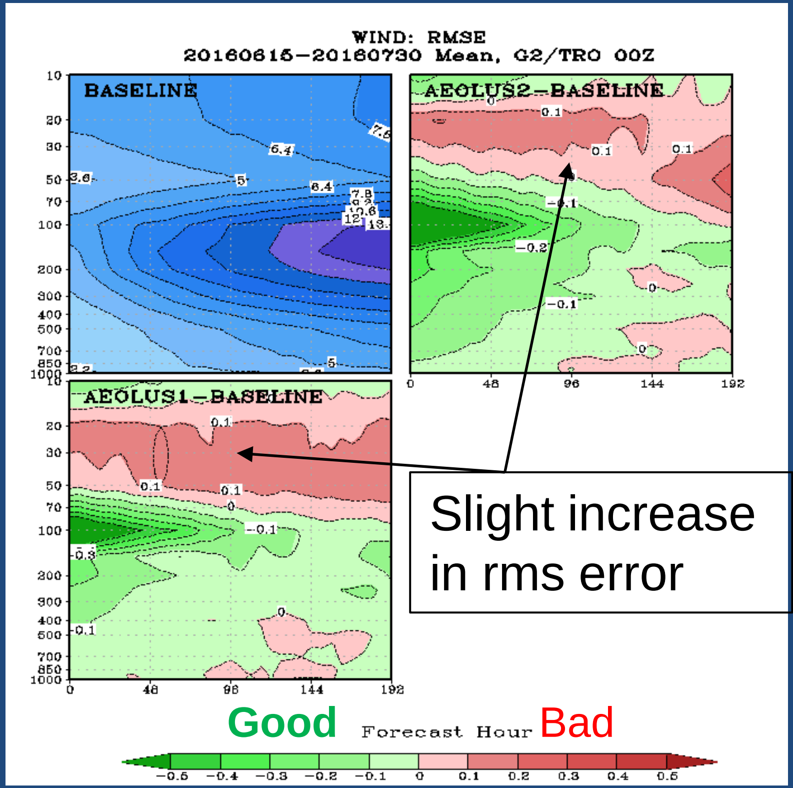
BASELINE = Baseline control configuration
AEOLUS1 = Baseline + Aeolus-1
AEOLUS2 = Baseline + Aeolus-2

RMS Wind error Cross Section

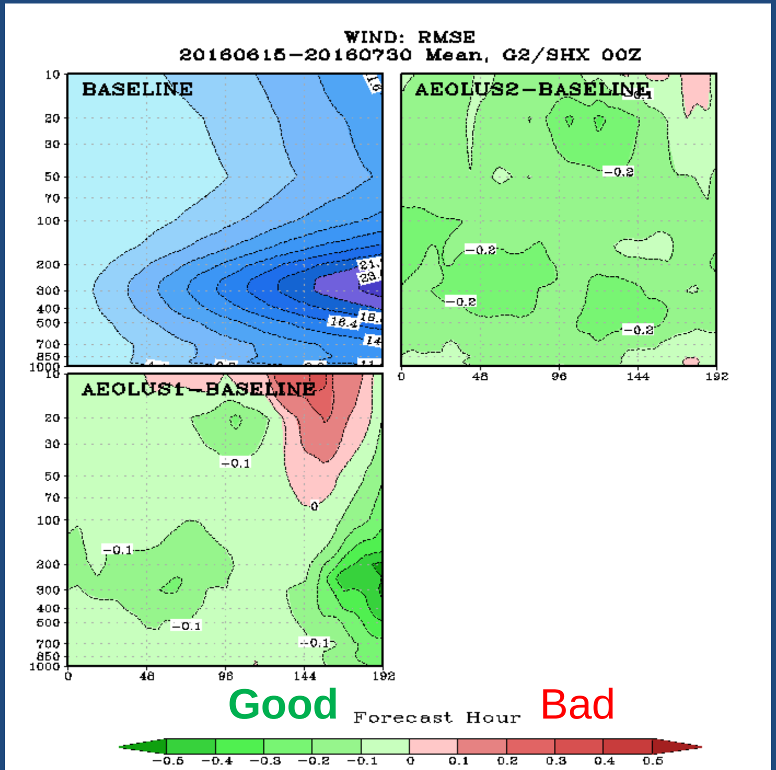
Northern Hemisphere extra-tropics



Tropics



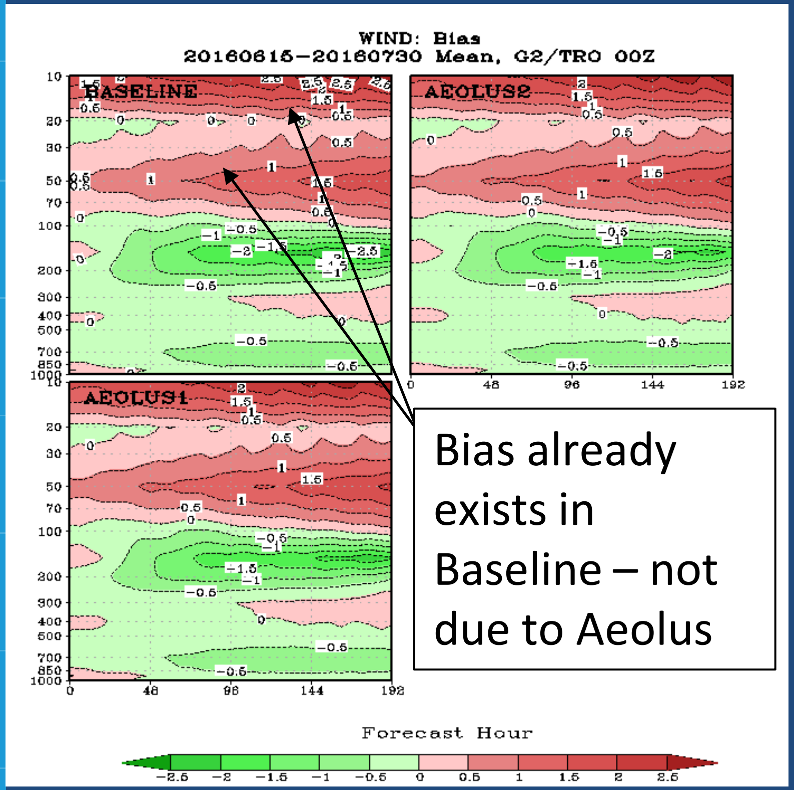
Southern Hemisphere extra-tropics



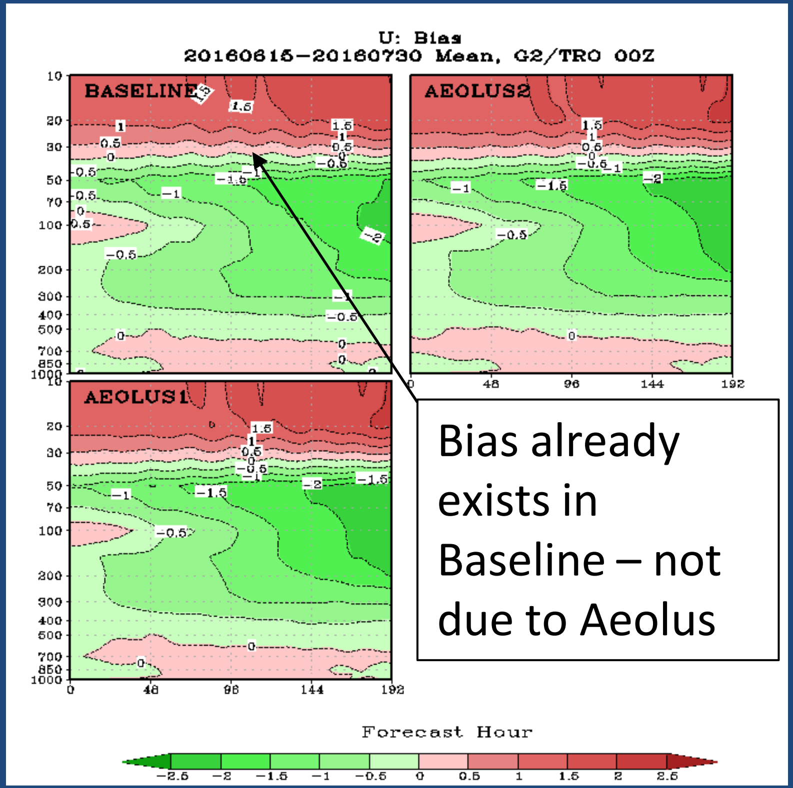
Tropics - Wind Bias cross section

Investigation of the causes of the bias in the Baseline experiment is ongoing work

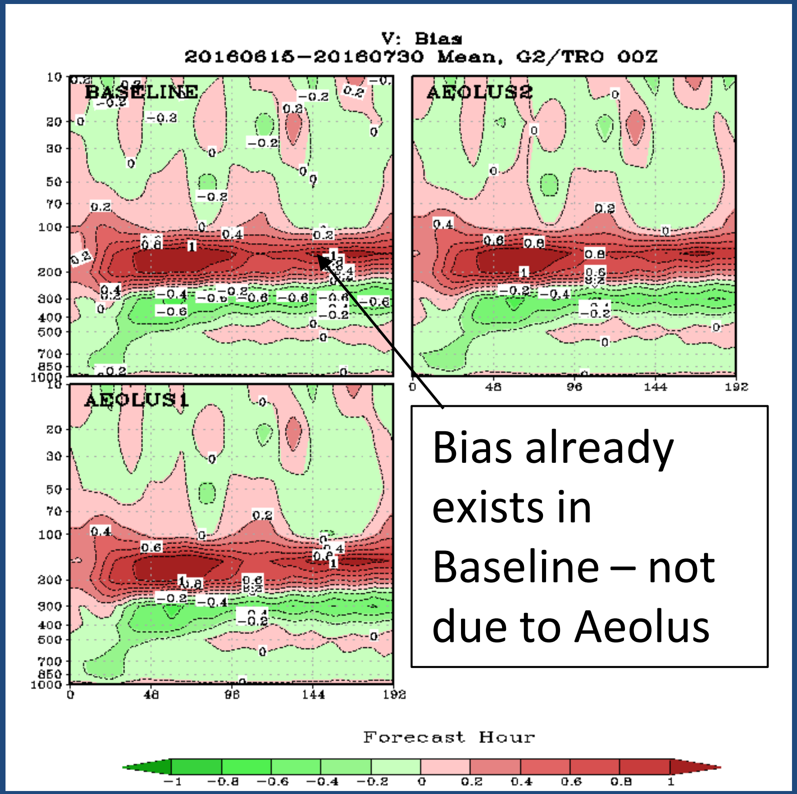
WIND



U-WIND

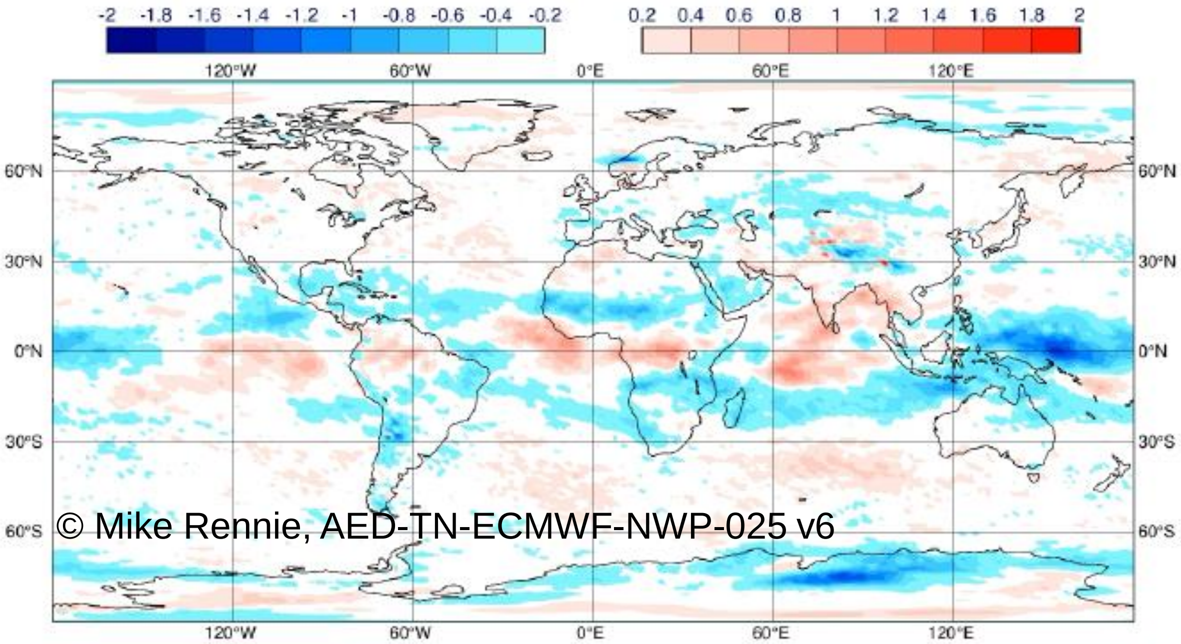


V-WIND

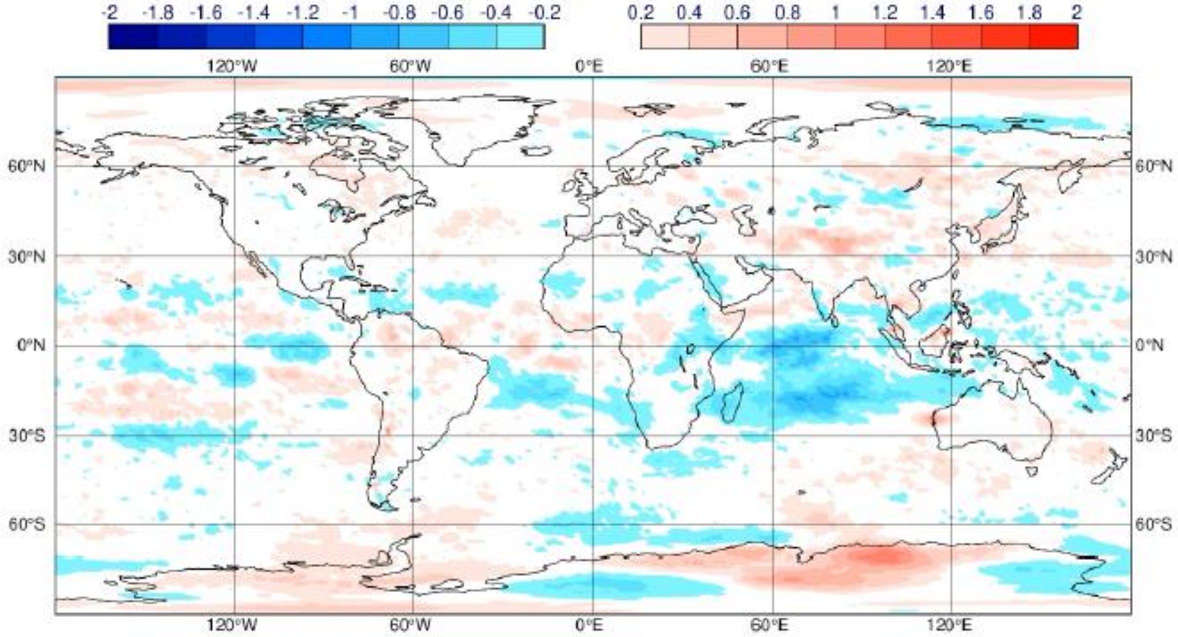


Some observed model wind biases

- Biases exist in model winds due to dynamical closure and parameterization errors
- Biases are detrimental in data assimilation and hinder beneficial impact (BLUE paradigm)
- Identical twin OSSEs or EDA are not sensitive to biases (in contradiction to OSE and proper OSSE)
- Model biases are **not** easily corrected (e.g. spectral deficits), but some may be adjusted by for example VARBC or ML (under test for scatterometer winds by NUIST/KNMI/ECMWF)



Mean differences between ECMWF and Met Office for 1 Jan to 20 Feb 2023



Summary

- Aeolus impact is much larger than anticipated in earlier OSSE, SOSE and EDA. The much larger Aeolus noise does not decimate impact; models may be poorer than anticipated
- Aeolus-2 remains unique in providing clear air winds to depict atmospheric dynamics (Stoffelen et al., 2020)
- More cloud/humidity winds will emerge in the 2030-2040 decade
- Data assimilation theory predicts much larger impact when the ratio of observation and background error covariance goes to one (B error is about 2 m/s; Aeolus mission Rayleigh error more than 4 m/s generally)
- ECMWF EDA and NOAA OSSE show indeed much increased impact for Aeolus-2 w.r.t. Aeolus-1
- NOAA OSSE shows the detrimental effect of biases in data assimilation
- Model biases do exist, but are (currently) ignored in EDA
- Better observations may not help that much in data assimilation in case of model biases
- Better observations do help in reducing model biases through model improvement (in principle)

The first Aeolus wind profile; questions ?

Launch 22 August 2018

Thanks!

Wind profile satellite observation requirements and capabilities

Ad Stoffelen, Angela Benedetti, Régis Borde, Alain Dabas,
Pierre Flamant†, Mary Forsythe, R. Michael Hardesty, Lars Isaksen,
Erland Källén, Heiner Körnich, Tsengdar Lee, Oliver Reitebuch, Michael Rennie,
Lars-Peter Riishøjgaard, Harald Schyberg, Anne Grete Straume,
Michael Vaughan

✓ Published in the Bulletin of the American Meteorological Society, 2020

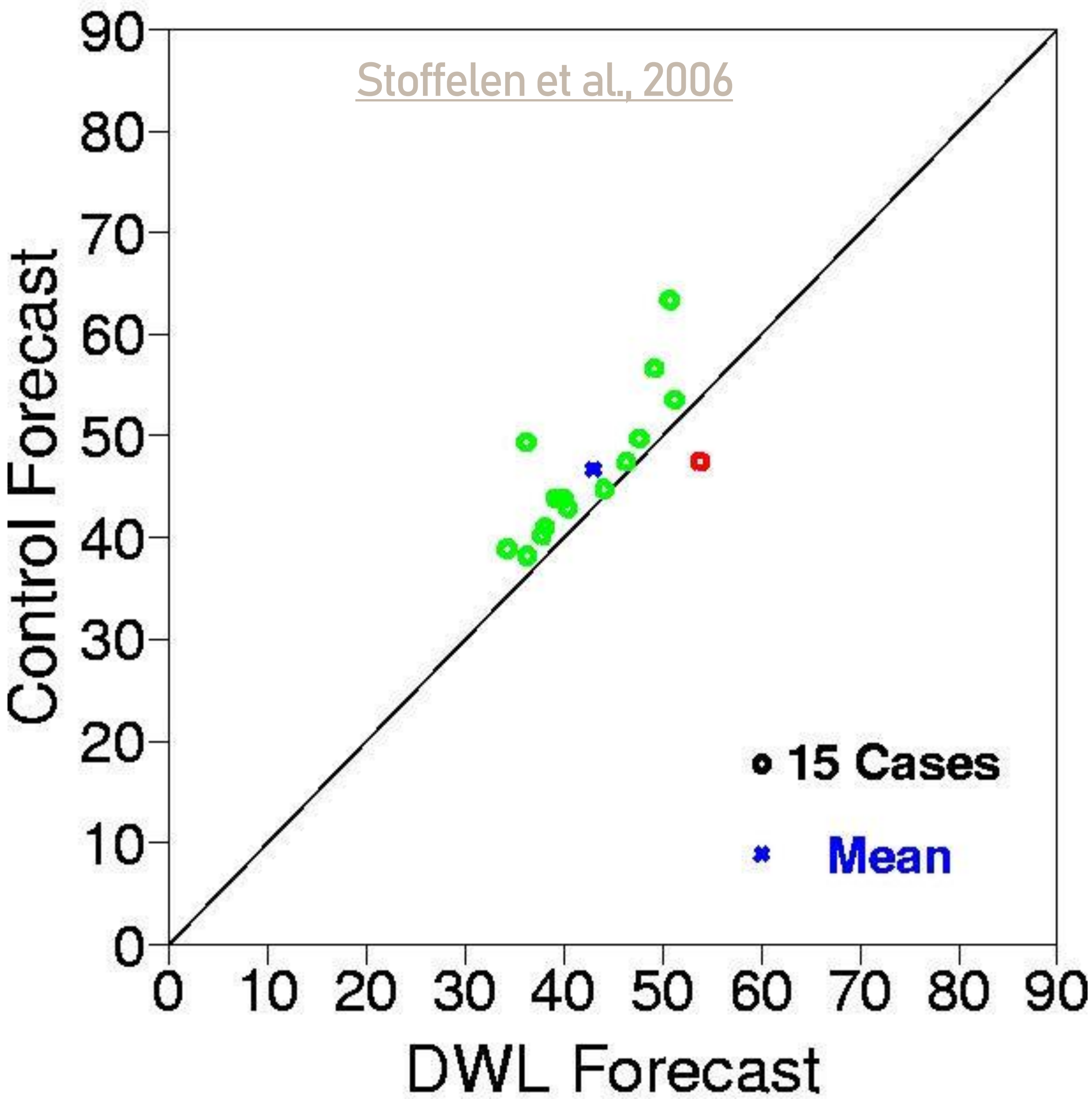
Following Aeolus success, looks forward to future vertical wind profiling capability in operational meteorology.

Addresses the need for high-quality wind and profile information to capture and initialize small-amplitude, fast-evolving and mesoscale dynamical structures, as the resolution of global NWP improved well into the 3D turbulence regime on horizontal scales smaller than 500 km.

Recognizes the transport and dispersion of atmospheric constituents and improved depiction of circulation on climate scales.

Direct wind profile observations over the oceans, tropics and Southern Hemisphere are not provided by the current global observing system. Looking to the future most other wind observation techniques rely on cloud or regions of water vapour and are necessarily restricted in coverage. Therefore, after its full demonstration, an operational Aeolus-like follow-on mission obtaining globally-distributed wind profiles in **clear** air by exploiting molecular scattering remains unique.

Aeolus (ADM) OSSE in 1999



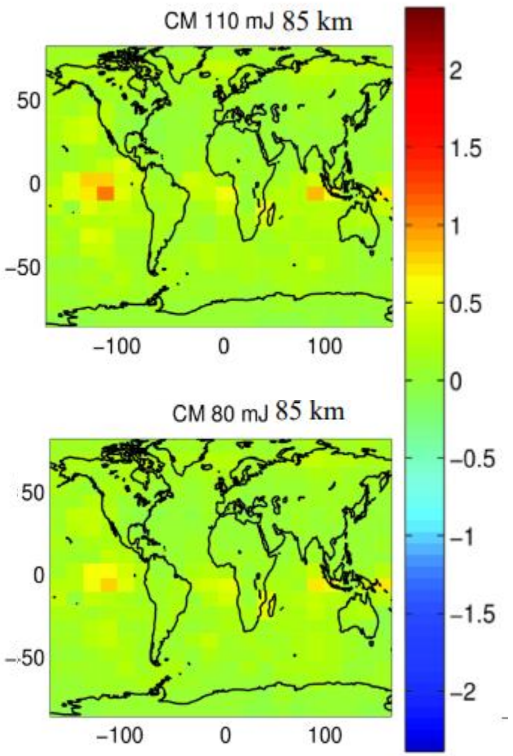
- ❖ Nature Run = old ECMWF model version
- ❖ 60-km grid
- ❖ Before the satellite era
- ❖ Impact comparable to radiosonde inclusion

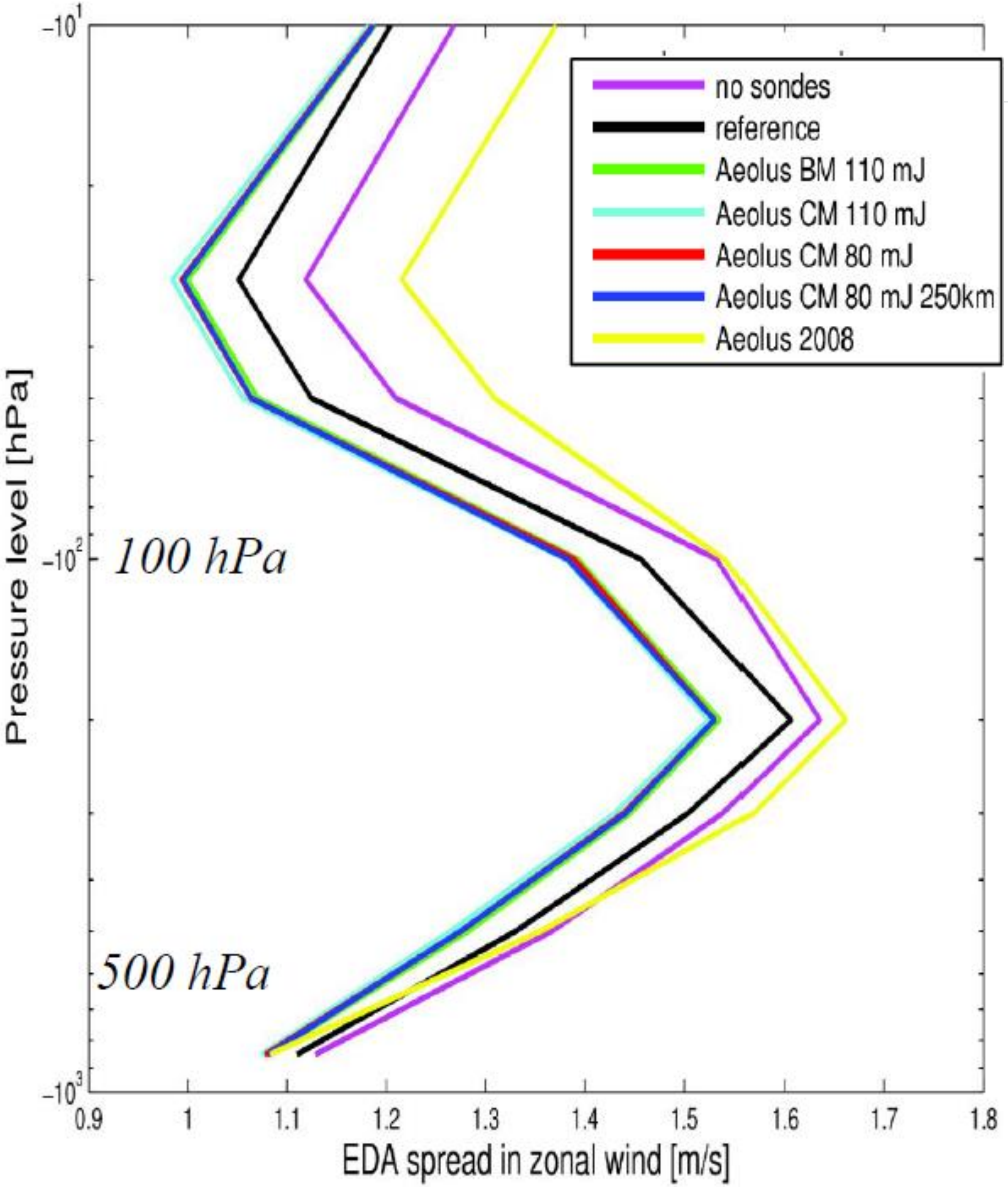
➢ Aeolus achieves more than radiosonde impact today with much lower data quality and in the presence of more advanced models and substantial uptake of satellite data; why ?

EDA ~10 years later

- Ensemble spread is reduced by better initialization by observations
- Taking out radiosondes increases spread
- Adding simulated Aeolus reduces spread
- Radiosonde and Aeolus effects are similar
- The real Aeolus is much less powerful, while it still matches radiosonde impact

➢ Are model winds much poorer than assumed in OSSE and EDA ?





Aeolus

Strategic goals

- Match radiosonde quality in terms of number of profiles and accuracy
- Require stable instrument that is well characterized
- Demonstrate NWP impact

Preparations

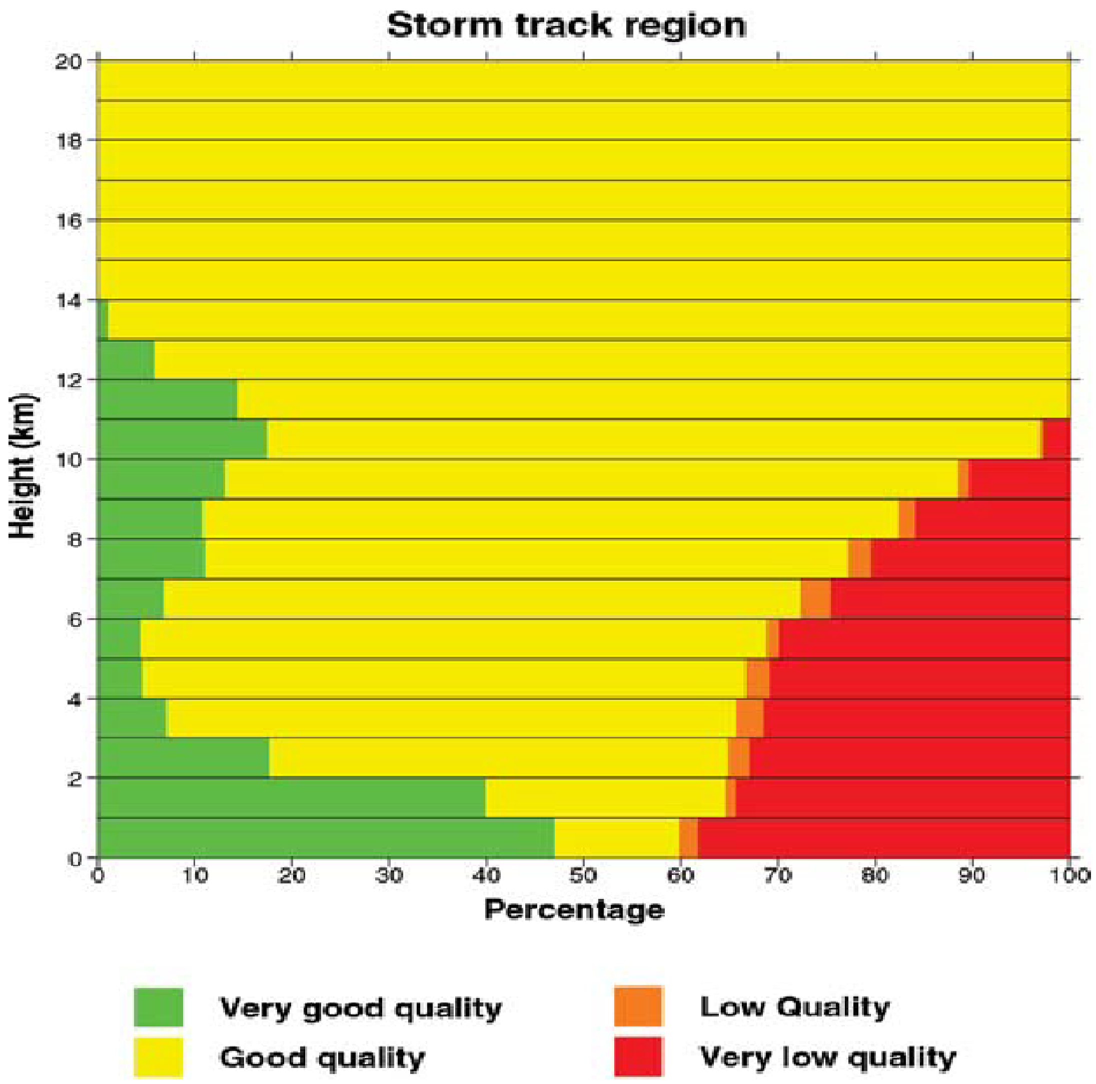
- Lidar In-space Performance Assessment Simulation (LIPAS) of global atmospheric error statistics, accounting for aerosol, wind and cloud distributions (since 1995 by Gert-Jan Marseille et al.)
- KNMI data base of detailed aerosol, wind and cloud distributions (models, LITE, CALIPSO, in situ)
- Trade-off studies on profile biases in data assimilation, shear assimilation
- Consider atmospheric heterogeneity for laser beam, in wind processing and in data assimilation

Lesson learned

✓ Succeeded with relatively stable instrument and NWP calibration by “reverse engineering” of instrument biases

✓ For ESA Earth Explorer mission unique swift shift to “nominal” operations, allowing operational NWP

What did we expect in 1999?

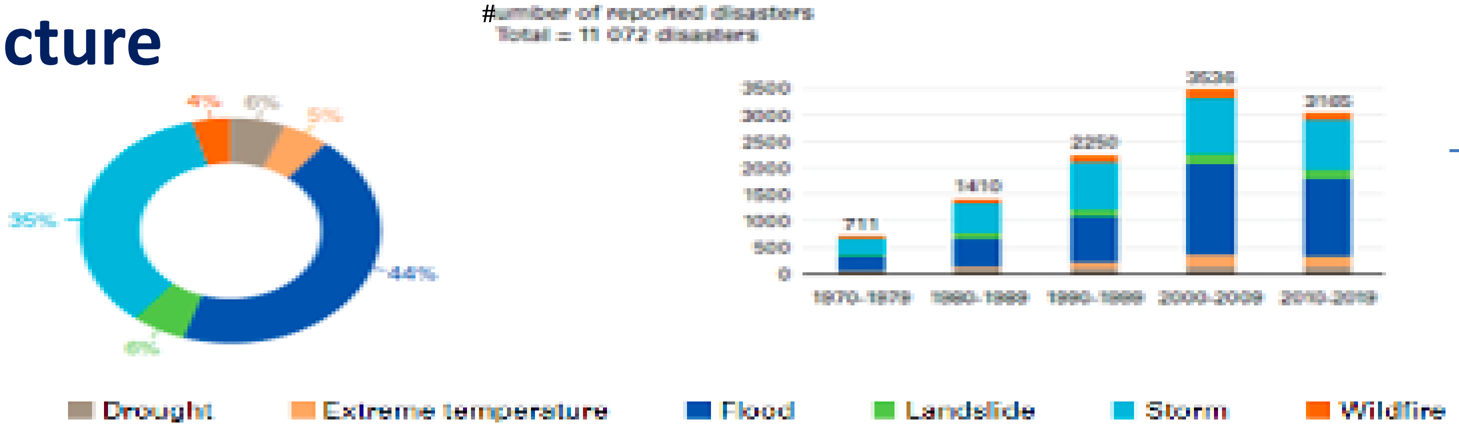


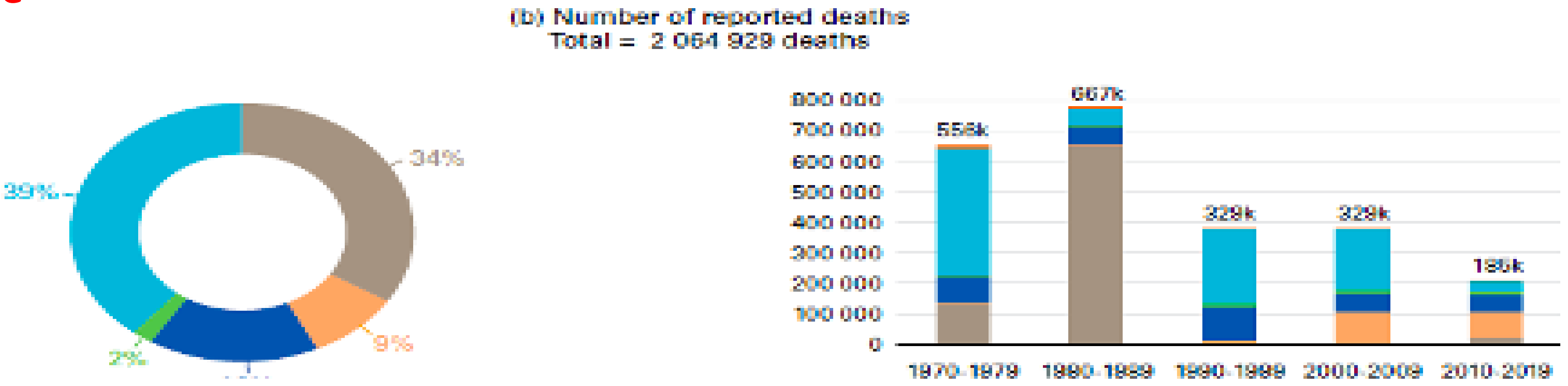
- ❖ Molecules most of the time (largely yellow)
- ❖ Particles part of the time (largely green)
- ❖ Not much under dense clouds (red)
- ❖ Radiosonde quality winds, height resolved
- ❖ Improved NWP, 3D turbulence, circulation
- ❖ Tropics, UTLS
- ❖ Reference for improving satellite winds

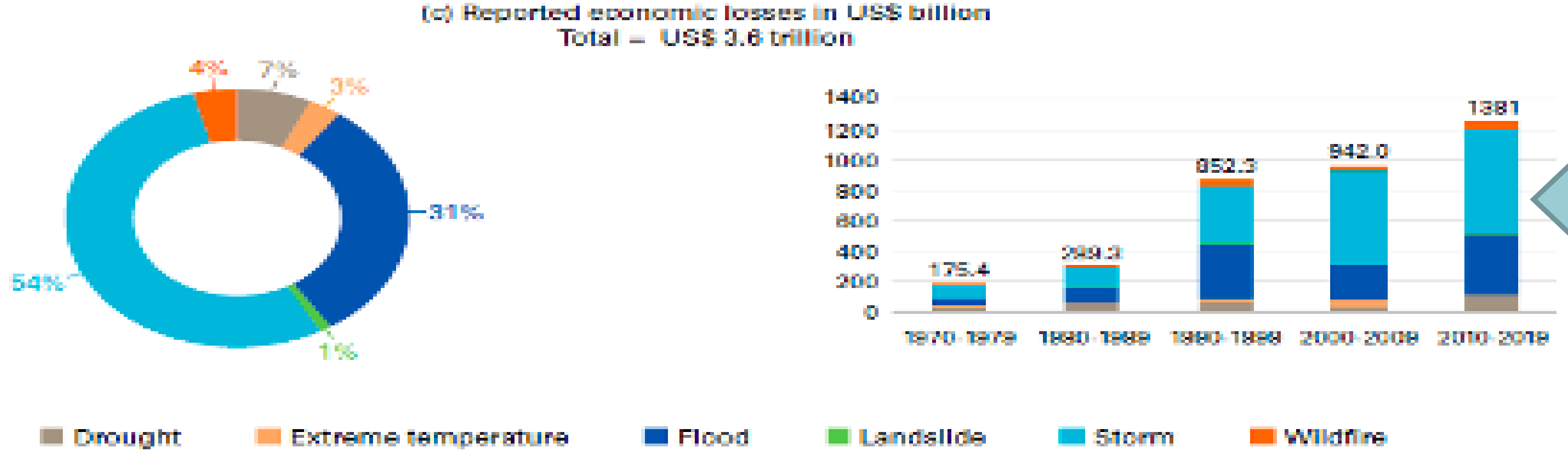
- ➢ Why would this 1999 vision still work 20 years later, after a “silent revolution” in NWP?

Protecting people and infrastructure

- Weather losses are frequent, deadly and costly global disasters
- Subject to climate change
- More vulnerable infrastructure
- Lives and costs are saved by weather warnings







- More losses

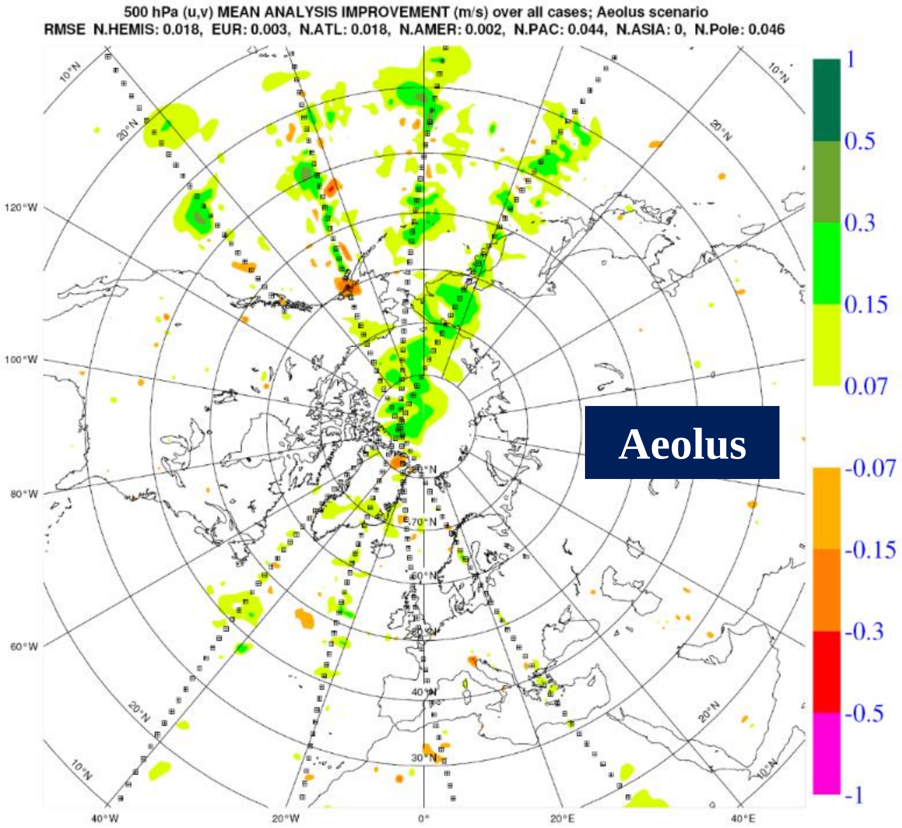
- Improved warnings
- More heat

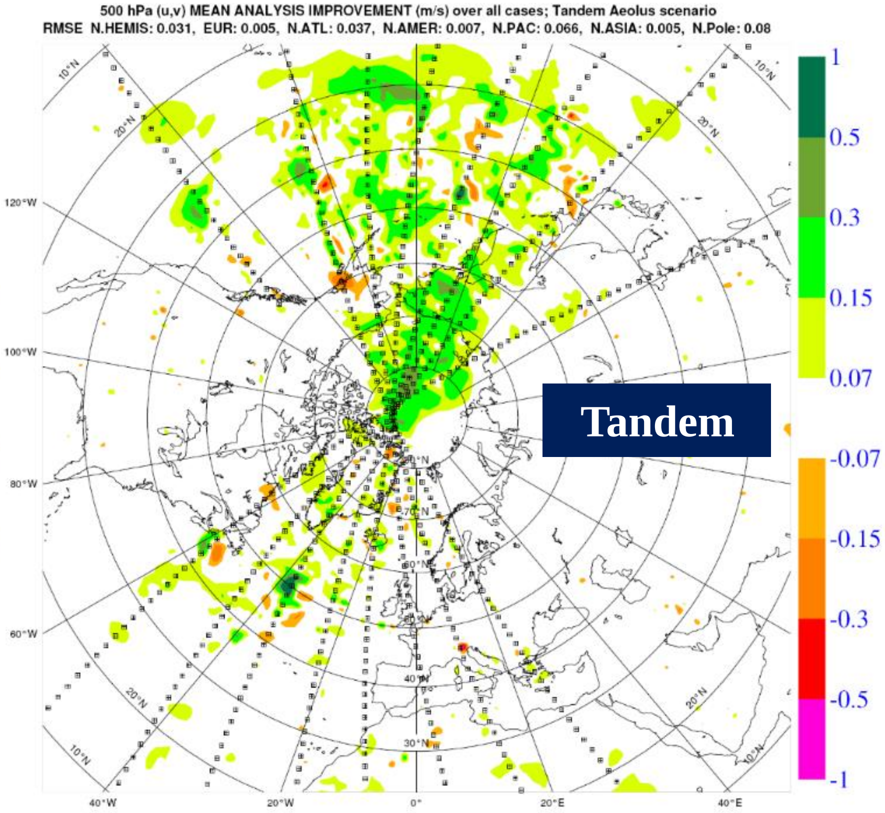
Optimum DWL configuration

- Aeolus FO missions in dawn-dusk orbit, i.e., at about 6:00 and 18:00 Local Solar Time (LST)
- Tandem (and trio) DWLs deliver spatial filling in of DWL curtains within 45 minutes
- Sampling mostly the instantaneous large-scale wind field over distances of 500-2000 km;
- Wind profile voids over the oceans, tropics and southern hemisphere are at least this large
- While dawn-dusk orbits have their advantages for a UV DWL, the temporal coverage gap is not addressed
- From scatterometer studies we know that wind instruments separated by 2.5 hours in LST overpass, provide independent NWP impact. Hence, DWL constellations at 9:00 LST, 12:00 LST, 15:00 LST and 18:00 LST would be very useful too for NWP (E.g., Stoffelen et al., https://www.knmi.nl/kennis-en-datacentrum/publicatie/research-and-development-in-europe-on-global-application-of-the-oceansat-2-scatterometer-winds)

aeolus

DWL analysis impact – 500 hPa wind

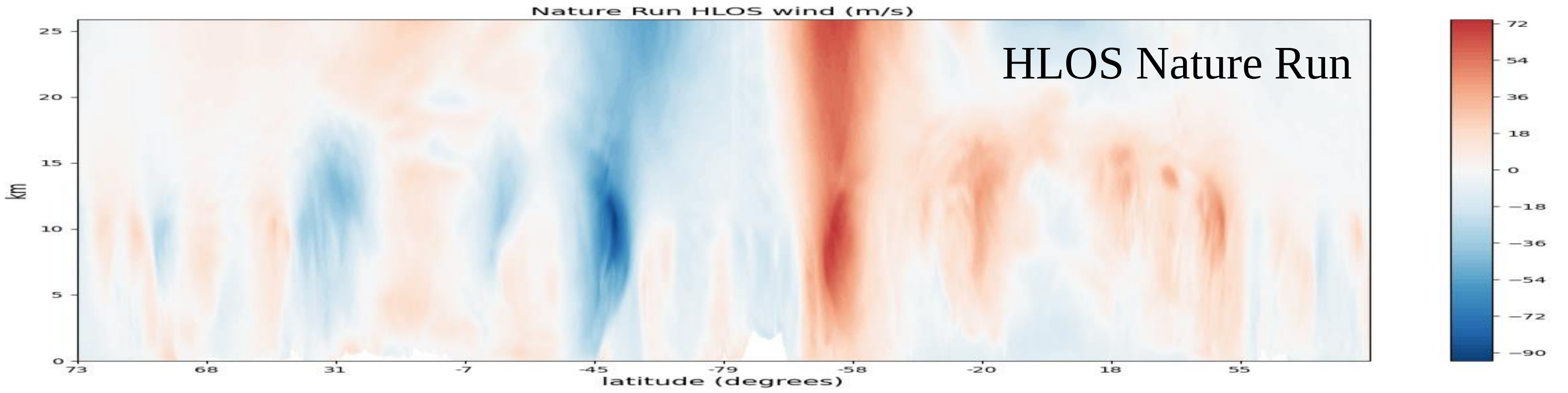


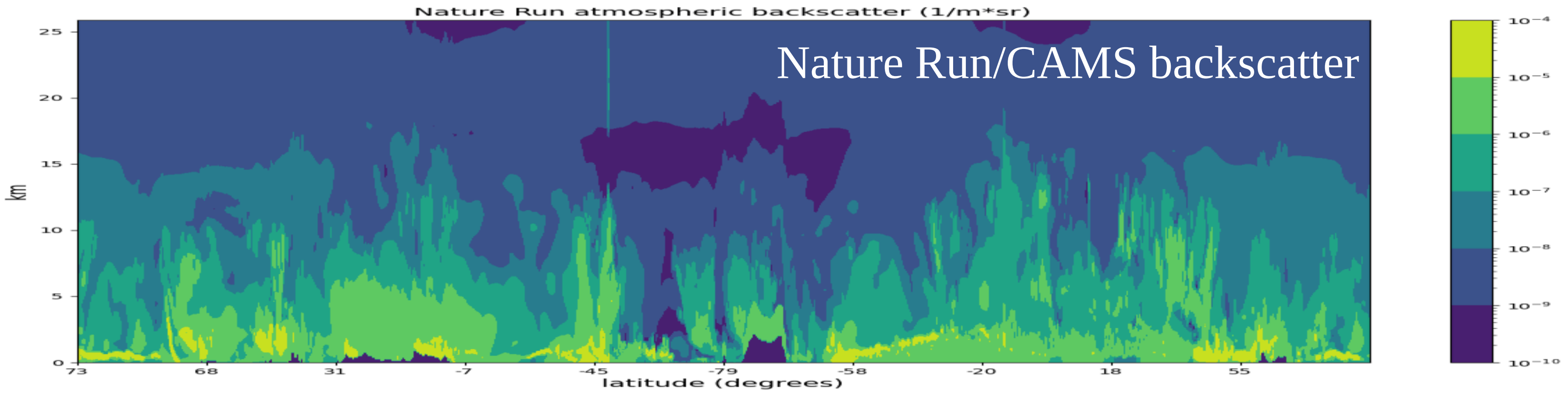


- Tandem-Aeolus scenario recovers large scale structures

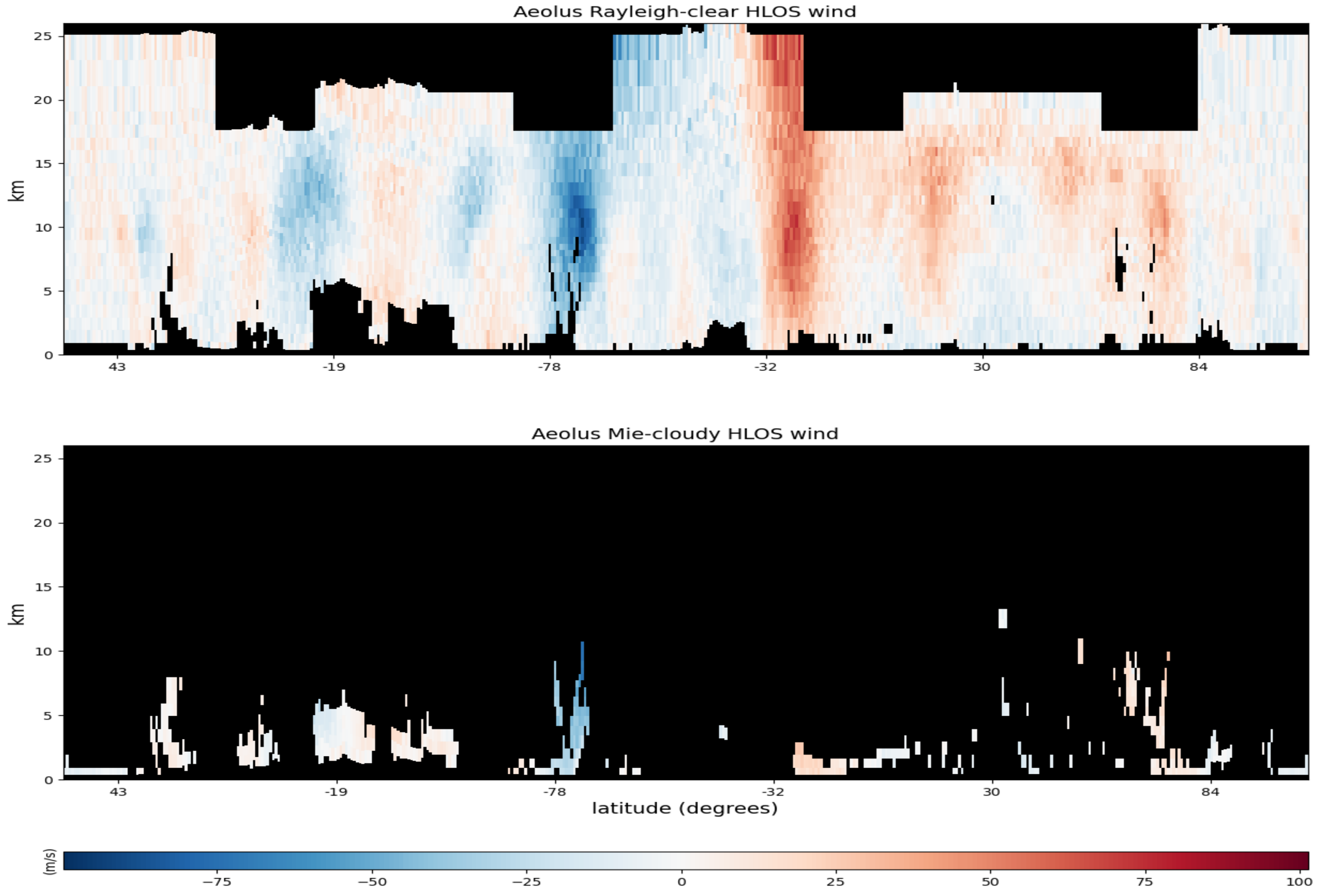
Nature Run truth – 1 orbit

Koninklijk Nederlands Meteorologisch Instituut
Ministerie van Verkeer en Waterstaat





LIPAS simulated Aeolus winds

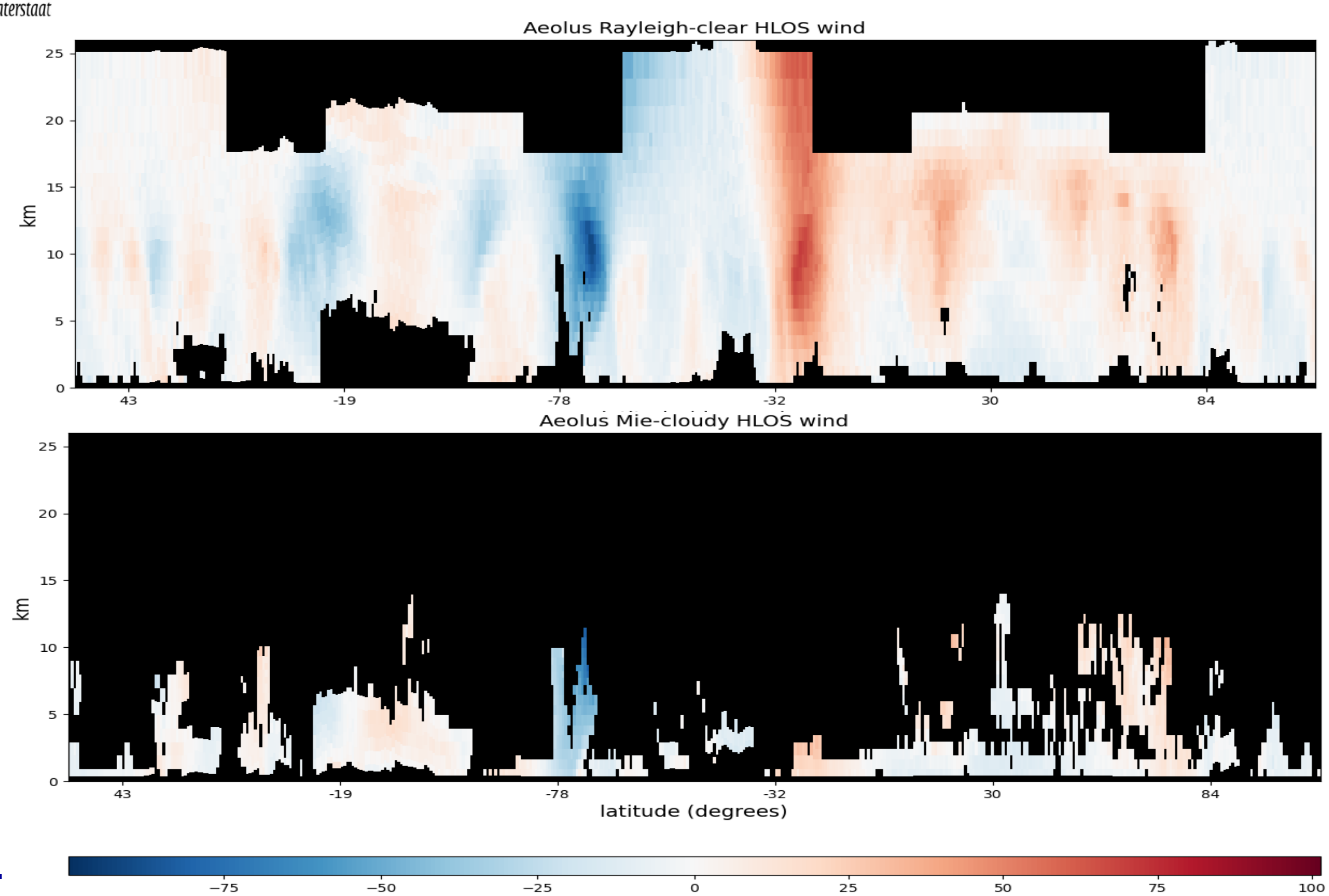


Rayleigh wind

Mie wind

Koninklijk Nederlands
Meteorologisch Instituut
Ministerie van Verkeer en Waterstaat

LIPAS simulated EPS-Aeolus winds

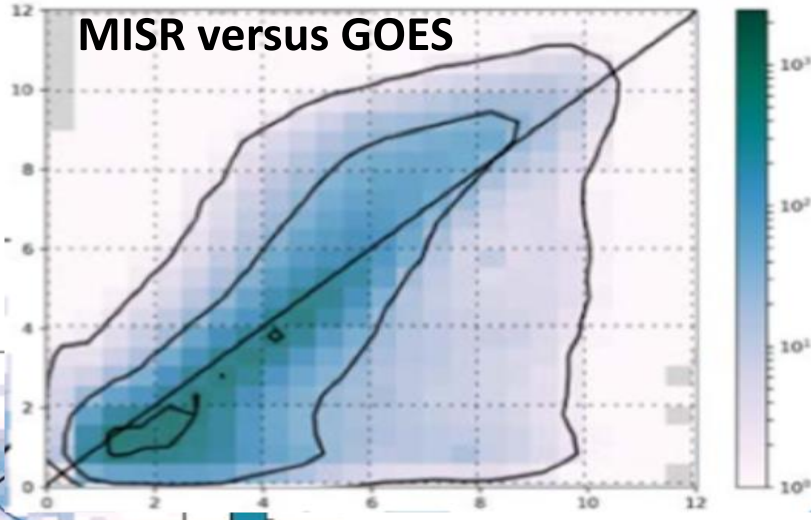


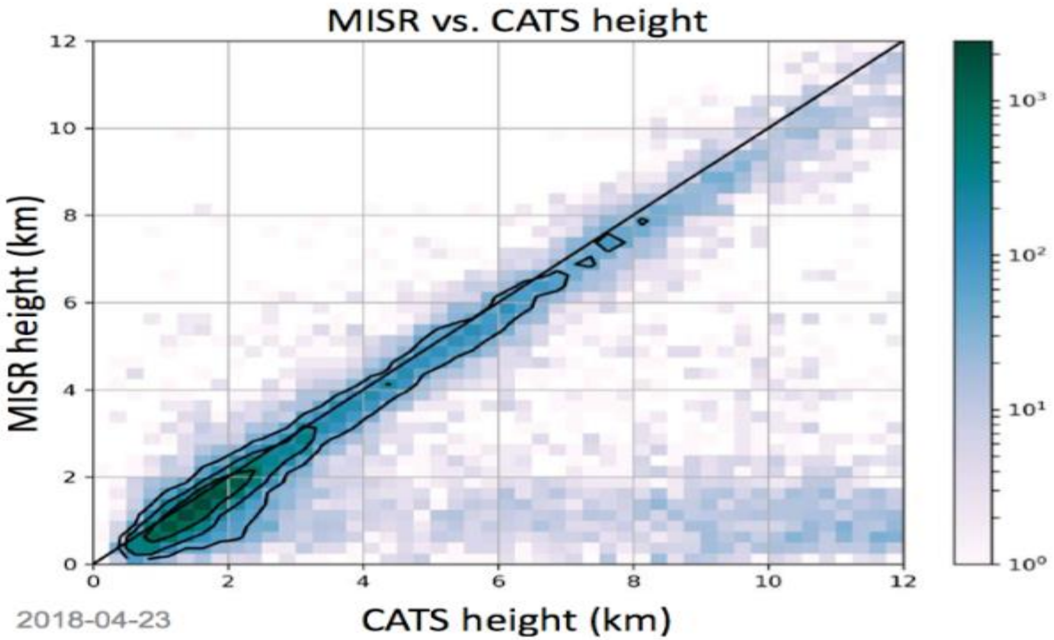
Rayleigh wind

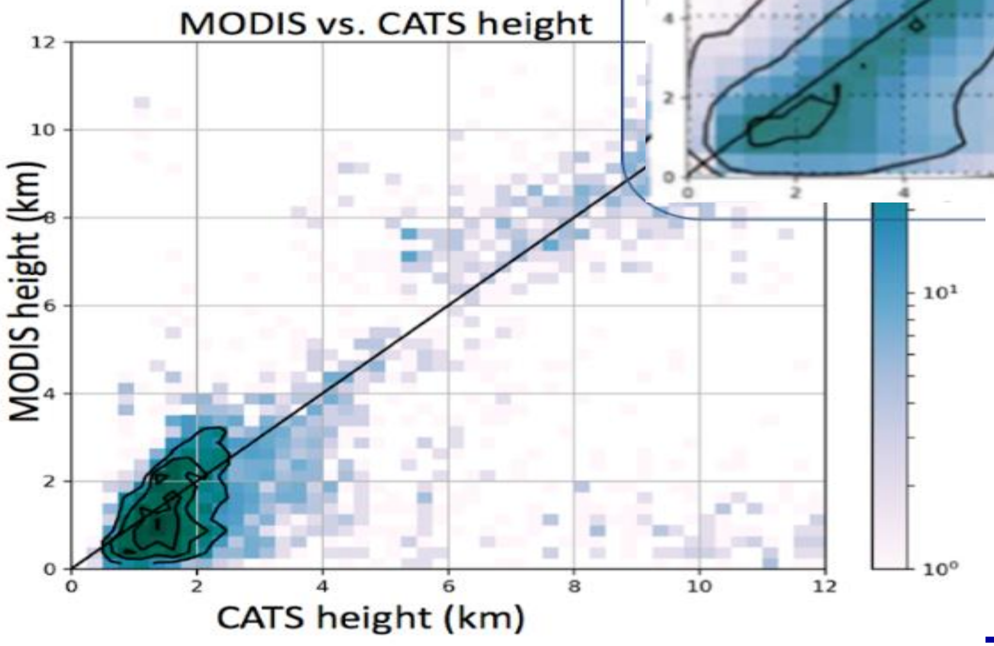
Mie wind

How does Aeolus complement feature tracked winds?

- Atm. waves, convergence, cloud dynamics and wind; do observed features move with the wind?
- Do we know the height of these features?
- Height uncertainty detriments wind accuracy with average shear of 4 m/s per km up to 30 km; 2 m/s accuracy implies σ_z = 500 m
- Accurate geometrical height assignment is needed, e.g., Aeolus



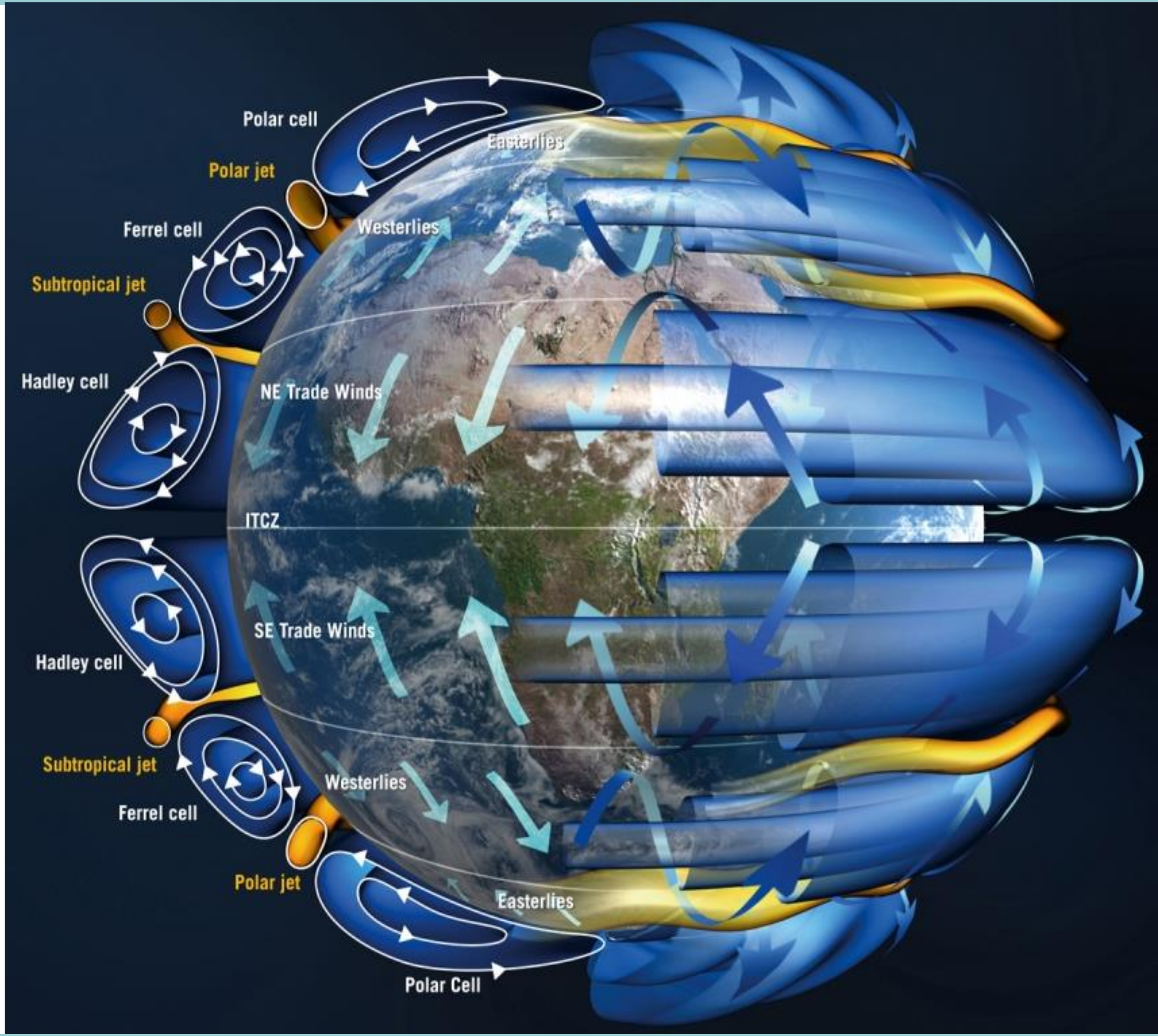




Atmospheric dynamics

- Climate change
  - Temperature/radiation?
  - Atmospheric stability?
  - Humidity/clouds/rain?
- Dynamics change?
  - Hurricanes/tornado's ?
  - Jet streams?
  - El Nino, MJO, NAO, .. ?

➢ Often determine local change



WMO OSCAR database

https://www.wmo-sat.info/oscar/

The "threshold" is the minimum requirement to be met to ensure that data are useful

The "goal" is an ideal requirement above which further improvements are not necessary

The "breakthrough" is an intermediate level between "threshold" and "goal" which, if achieved, would result in a significant improvement for the targeted application. The breakthrough level may be considered as an optimum, from a cost-benefit point of view, when planning or designing observing systems.

Wind; global NWP (PBL/FT/UTLS)	Goal	Breakthrough	Threshold
Uncertainty	1 (m/s)	3 (m/s)	5 (m/s)
Horizontal resolution	15 (km)	100 (km)	500 (km)
Vertical resolution	0.5 (km)	1 (km)	3 (km)
Observing cycle	60 (min)	6 (hr)	12 (hr)
Timeliness	6 (min)	30 (min)	6 (hr)

Aeolus
(along track only!)

EPS-Aeolus

Strategic goals

- Require stable and well-characterized instruments for swift operations
- Operational NWP data assimilation

Challenges

- Possibly bi-static set-up and new interferometer, including adaptive controls
- Less discriminative for molecular responses
- Study possible particle biases in Rayleigh winds (at improved random observation error)
- Interference of particle biases with dynamic weather is very likely and the EPS-Aeolus instrument can and **must** resolve this (TBD)

Preparations

- LIPAS simulations of global atmospheric error statistics with new instrument characteristics
- Simulate possible detrimental interaction of atmospheric and instrument variabilities
- Globally and in more detail for expected detrimental cases (e.g., PSC in wind shear, S in stratosph.?)