
# The impact of Aeolus satellite wind lidar observation in the global NWP system of DWD

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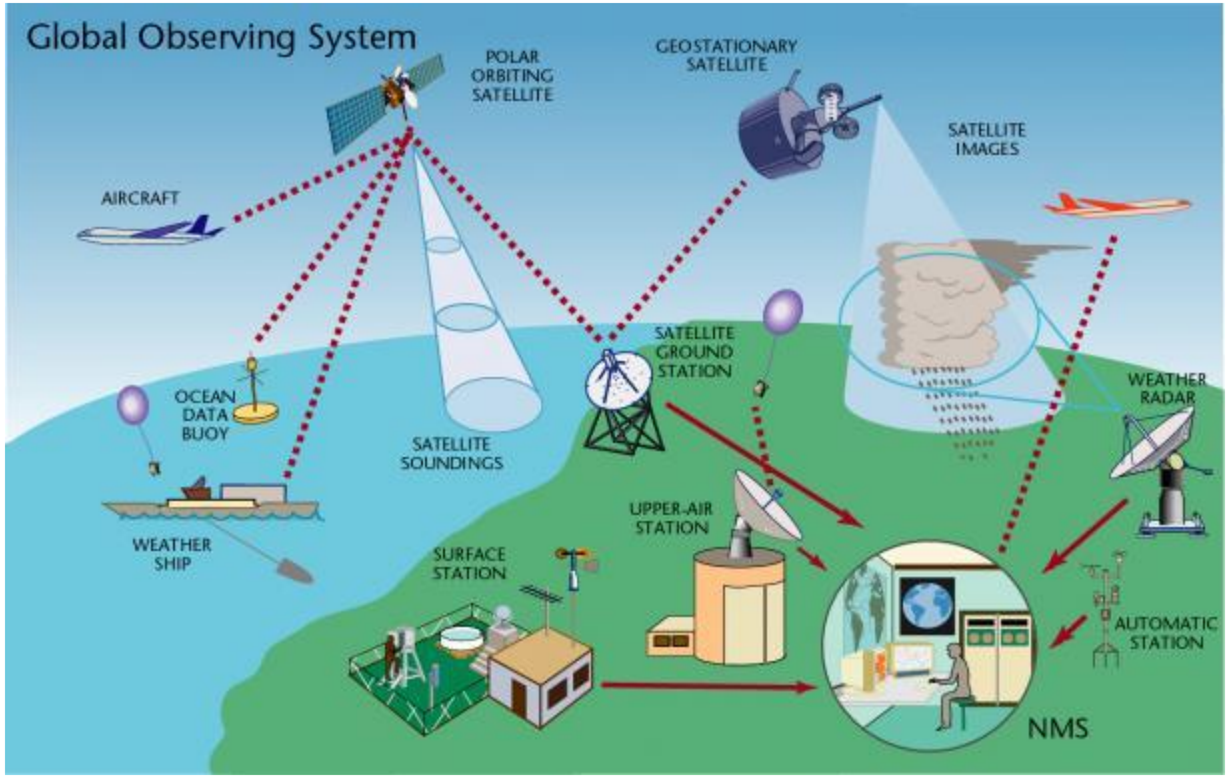
KIT Karlsruher Institut für Technologie
LMU MIM

# The global observing system for NWP




https://public.wmo.int/en/programmes/global-observing-system

Major NWP centres nowadays assimilate on the order of 10 - 100 million observations per day

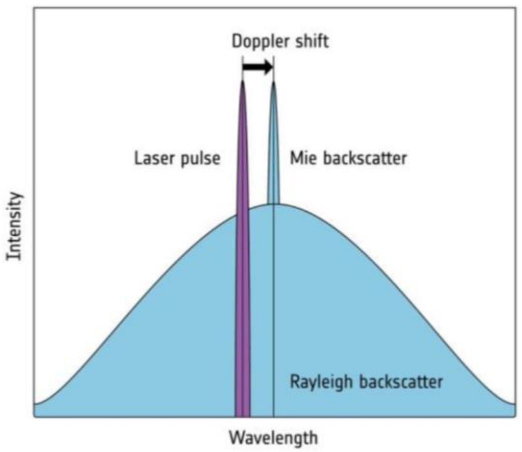
But the vast majority of these observations are satellite radiances that are related to temperature, humidity and trace gases (i.e. mass information)

Wind observations are still very sparse in many regions of the world and constitute only a few percent of the assimilated observations

To overcome this deficiency, European Space Agency (ESA) selected Aeolus as an Earth Explorer mission for a satellite wind lidar in 1999

Technological challenges significantly delayed the mission, but finally in 2018 the Aeolus satellite with a lidar that provides global wind profiles was launched and delivered observations until spring 2023

# The Aeolus satellite




## Doppler Wind Lidar ALADIN:

- operates in the ultraviolet spectral region (354.8 nm)
- doppler shift of backscattered signal ( $\Delta f = 2f_0 \; v_{LOS} / c$ ) is analyzed by a dual channel receiver
    - **Rayleigh channel**: scattering from air molecules
    - **Mie channel:** scattering from aerosols and water droplets

## Aeolus Measurement Geometry:

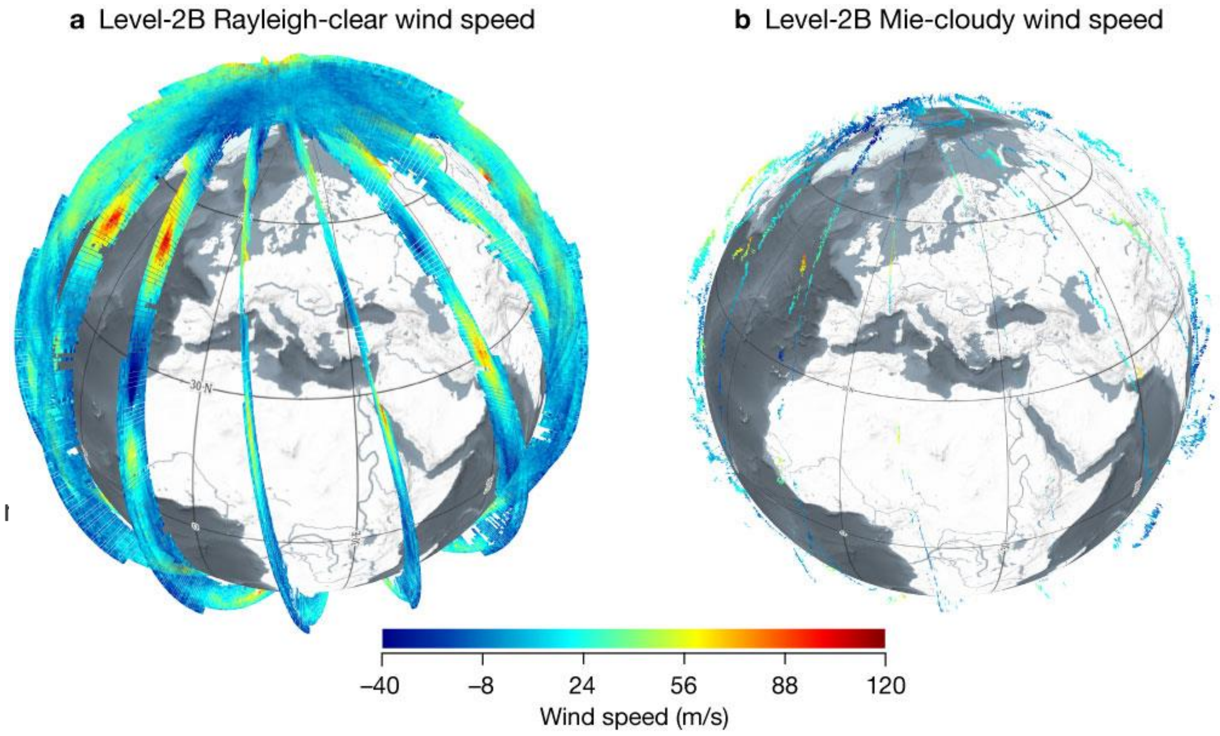
- polar, sun- synchronous orbit
- 7 days repeat cycle
- profiles of the line-of-sight (LOS) winds perpendicular to the satellite's velocity

  —> data product usable in NWP: **Level 2B Horizontal LOS (L2B HLOS)** winds, r

  —> from ground up to 30 km accumulated in vertical range bins (0.5 - 2 km)
- horizontal resolution

  Rayleigh: 87 km

  Mie: 87 km —> 10 km (since 5 March 2019)




12-h observation coverage
Rennie, Healy, Abdalla, McLean & Henry, 2022 (ECMWF newsletter 173)

# Experimental set up – DWD OSE

To investigate the impact of Aeolus on NWP, we conducted two an Observing System Experiment for three months:

**NWP model:** deterministic version of the global DWD model ICON based on R3B07 grid ($\Delta x \approx 13$ km)

**—>** hybrid DA method: Local Ensemble Transform Kalman Filter (LETKF) to estimate uncertainty from an ensemble state, coupled to a 3D variational algorithm (3D-VAR) to achieve a deterministic analysis

**Time period:** July 2020 – September 2020 (M1 temperature bias correction operational)

**—>** small bias: < 1 $ms^{-1}$, but height dependent

Empirical **bias correction** based on departures of preceding two weeks for Rayleigh as function of latitude for different height levels for ascending and descending orbit

(surface - 850 hPa | 850 hPa - 500 hPa | 500 hPa - 200 hPa | 200 hPa - 70 hPa | 70 hPa - 5 hPa)

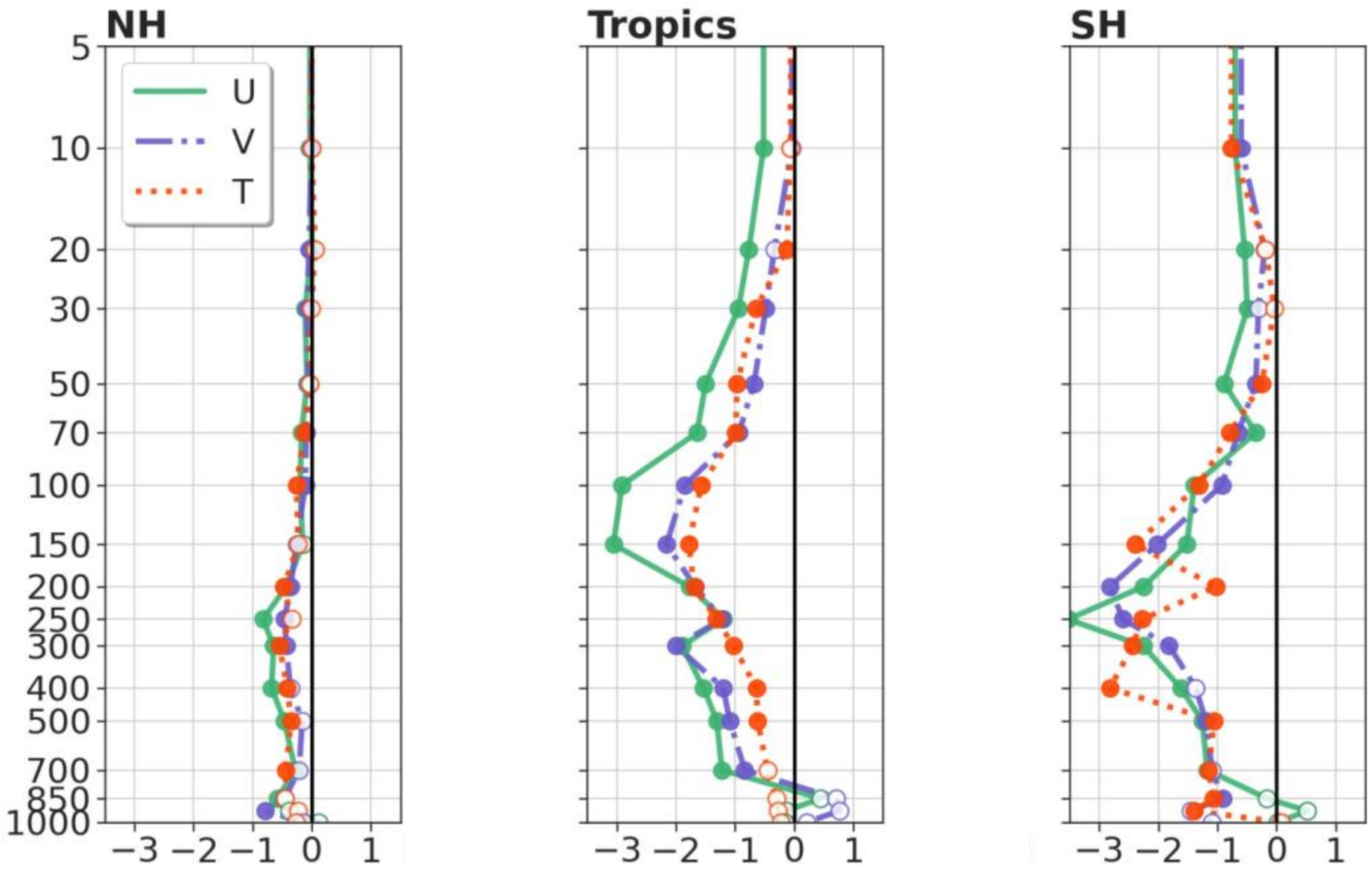
**Observing system experiment (OSE):**

**—> Control run (CTRL):** all operational observations **with the exception of Aeolus**

**—> Experiment AEOLUS** (**EXP AEOLUS**): all operational observations **including Aeolus Rayleigh clear** and **Mie cloudy** wind observations

**Model verification** against: ERA5 reanalysis (ECMWF system without Aeolus)

# Verification of short-term forecasts (3 - 36 h) with radiosondes




**Relative error reduction of EXP compared to CTRL**

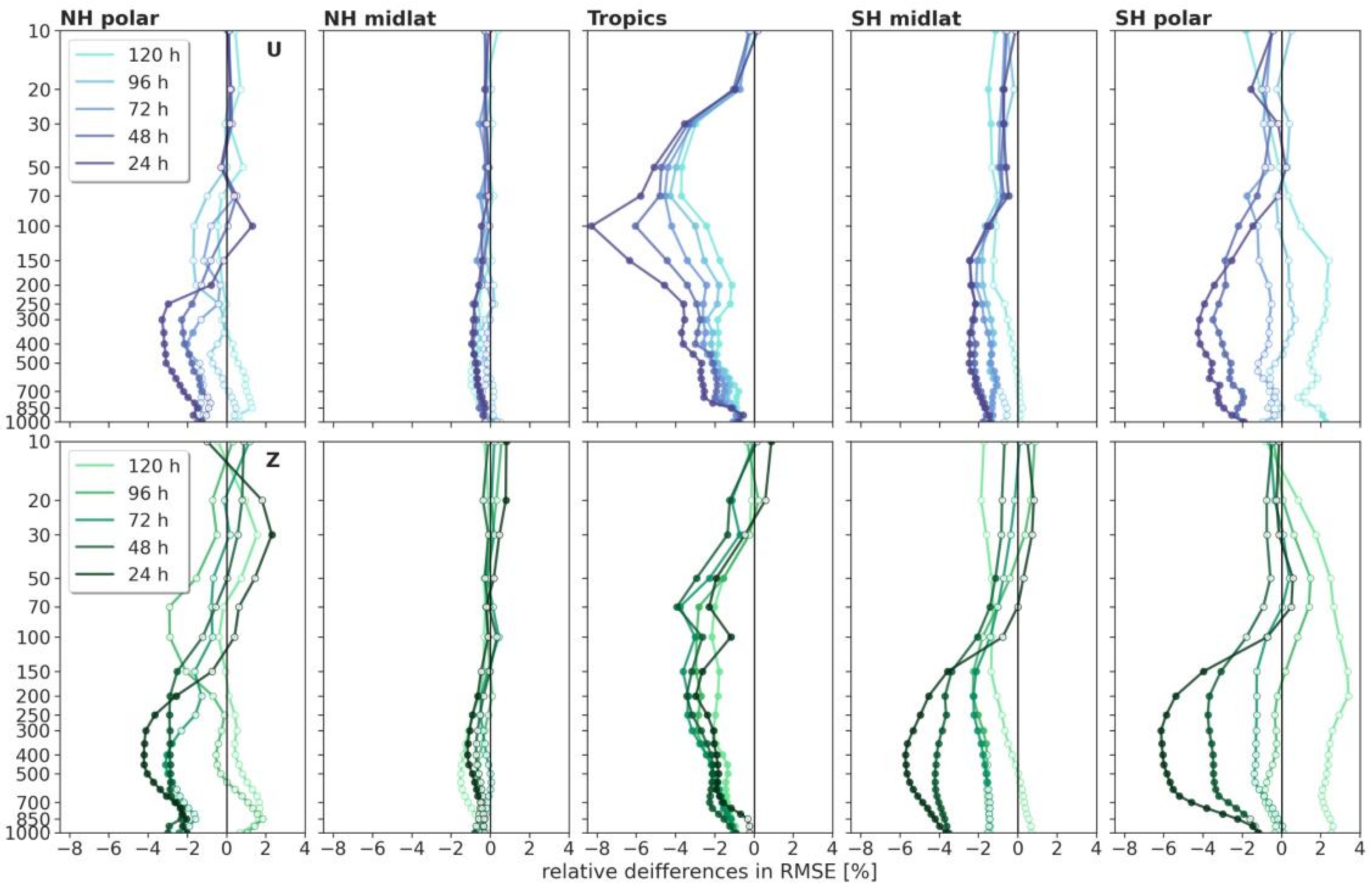
**Filled circles = significant differences**

- Aeolus leads to an error reduction of several percent
- Largest error reduction in tropics
- Second largest on southern hemisphere
- But also significant improvements on northern hemisphere → This is where most of us live and this is harder to achieve by other means



(Martin, Weismann & Cress, QJRMS, 2023)

# Verification of medium-range forecasts (24 - 120 h) with ERA reanalysis




**Relative error reduction of EXP compared to CTRL**

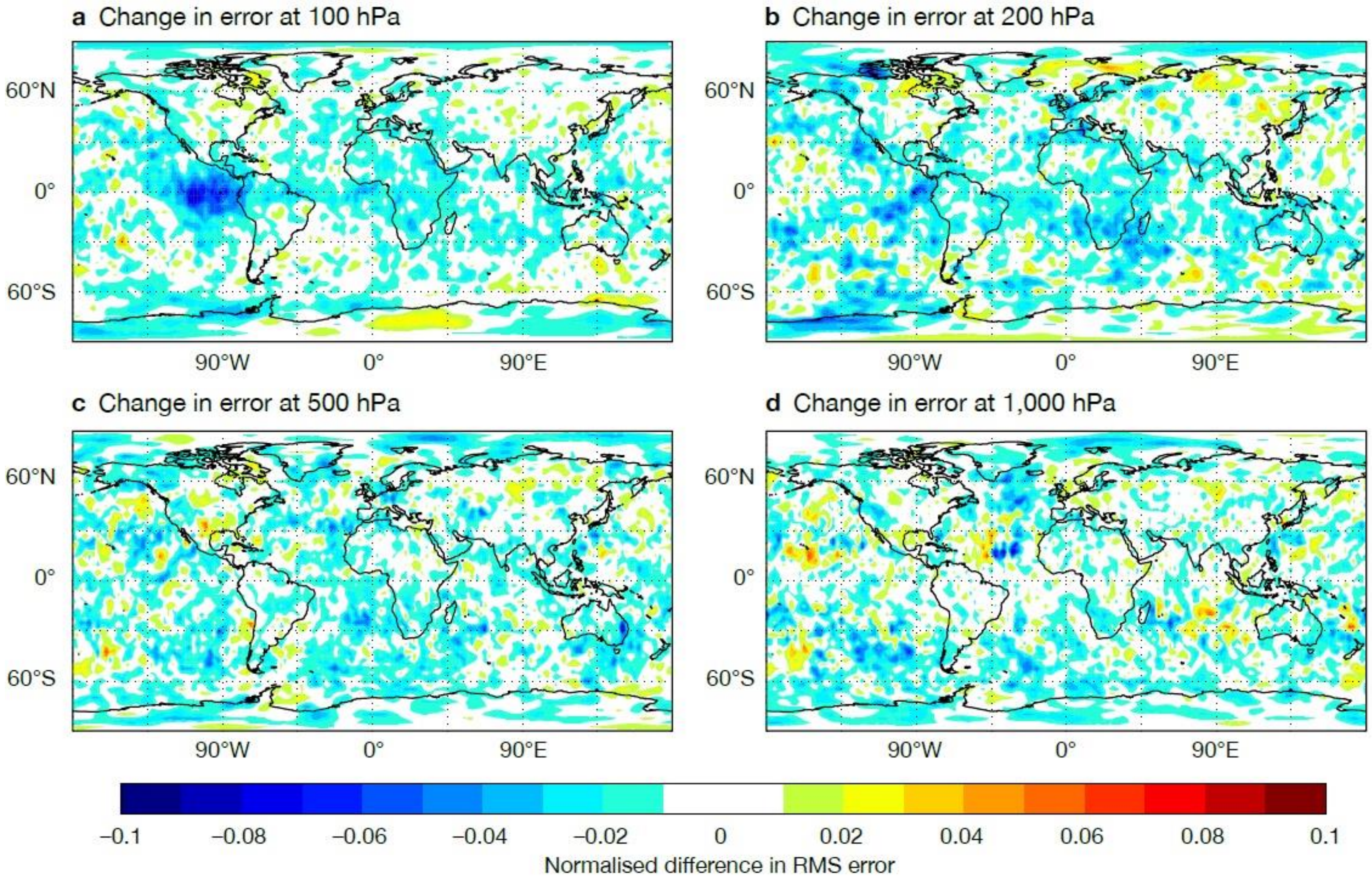
**Filled circles = significant differences**

- Aeolus leads to an error reduction of several percent
- Largest error reduction in tropics
(signif. values up to 8%!)
- Second largest on southern hemisphere
(signif. values up to 6%!)
- But also significant improvements on northern hemisphere → This is where most of us live and this is harder to achieve by other means
(signif. values up to 1.5%!)
- Large improvement in polar areas, but more variable (smaller area)



(Martin, Weismann & Cress, QJRMS, 2023)

# Aeolus impact at ECMWF (15-month period)




- Consistent global improvement by Aeolus also found by ECMWF
- Smaller in magnitude than in DWD system, but still very remarkable
- Largest impact per satellite

Rennie, Healy, Abdalla, McLean & Henry, 2022 (ECMWF newsletter 173)

# Some thoughts on the impact of Aeolus…

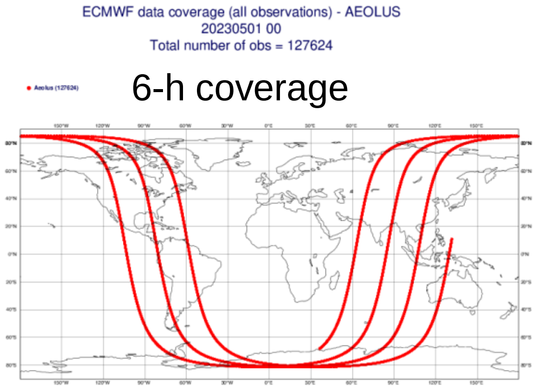
Aeolus has a remarkable impact on short- to medium-range NWP, which was shown in studies by several NWP centers

But actually, Aeolus is only adding 2% of additional observations in DWD system (and ~ 0.2% in ECMWF system)

Aolus random errors of most observations (i.e. Rayleigh) are comparably high (similar magnitude as AMVs)
See e.g. Martin, Weissmann, Reitebuch, Rennie, Geiss & Cress (2021, AMT)

And additionally, the observations have some remaining biases

**Which essential dynamical features are observed by Aeolus that lead to such a high impact of relatively few observations with a relatively high error?**



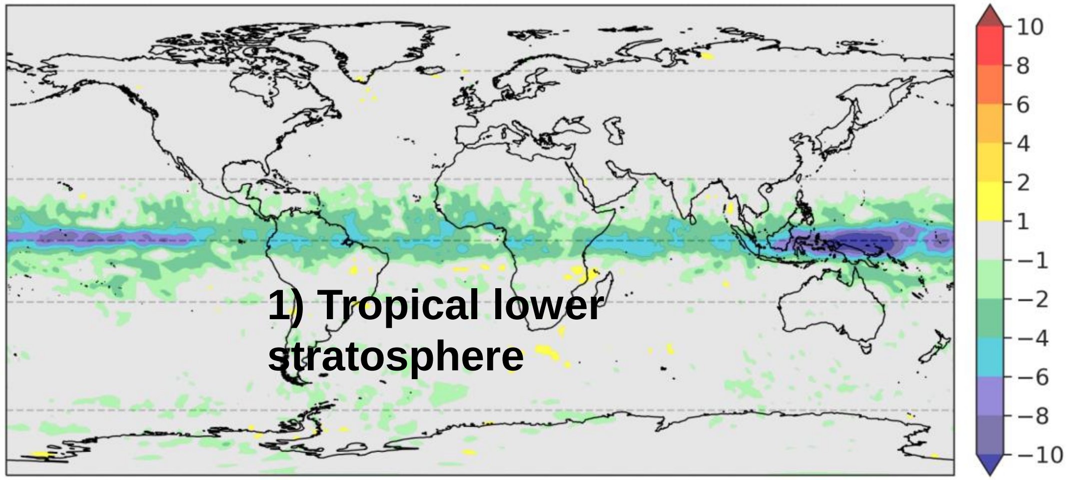

Assigned errors of Aeolus Rayleigh channel winds

| level [hPa] | 1000 | 850 | 700 | 500 | 400 | 300 | 250 | 200 | 150 | 100 |
|---|---|---|---|---|---|---|---|---|---|---|
| $\sigma(\epsilon_{O\_ass})$ [m $s^{-1}$] | 5.50 | 5.00 | 4.50 | 4.50 | 4.75 | 5.00 | 5.00 | 5.25 | 5.25 | 5.50 |

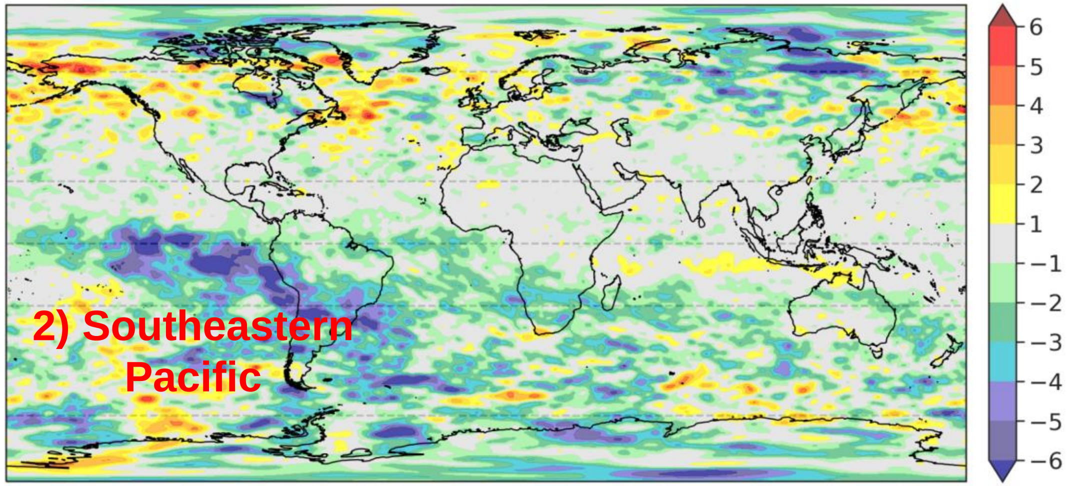
## Further investigation of three atmospheric regions with particularly large improvements

Mean relative differences in 24 - 120 h forecast RMSE between the EXP_A and the CTRL run [%]

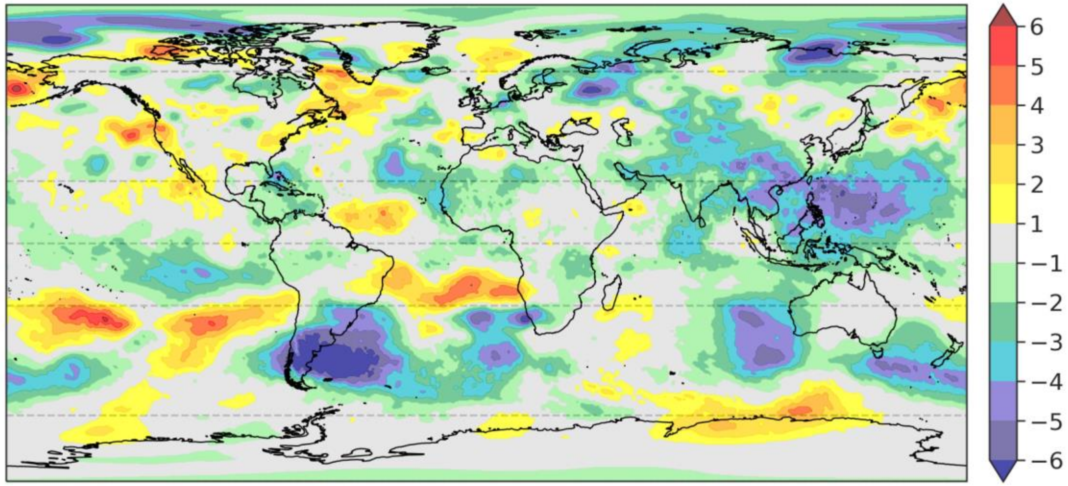
(a) U 50 hPa



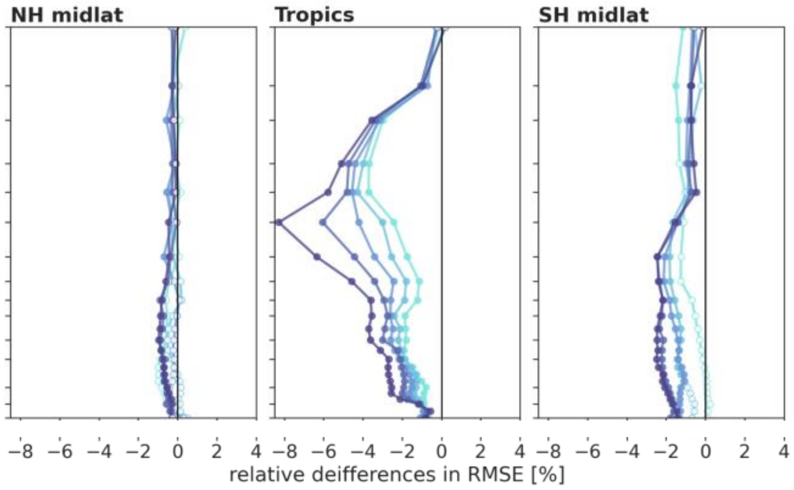

(b) U 300 hPa




(c) Z 500 hPa




**3) Improvements in SH storm track and maybe also systematic mid-latitude improvements in NH that are hidden by variability of the jet-stream?**

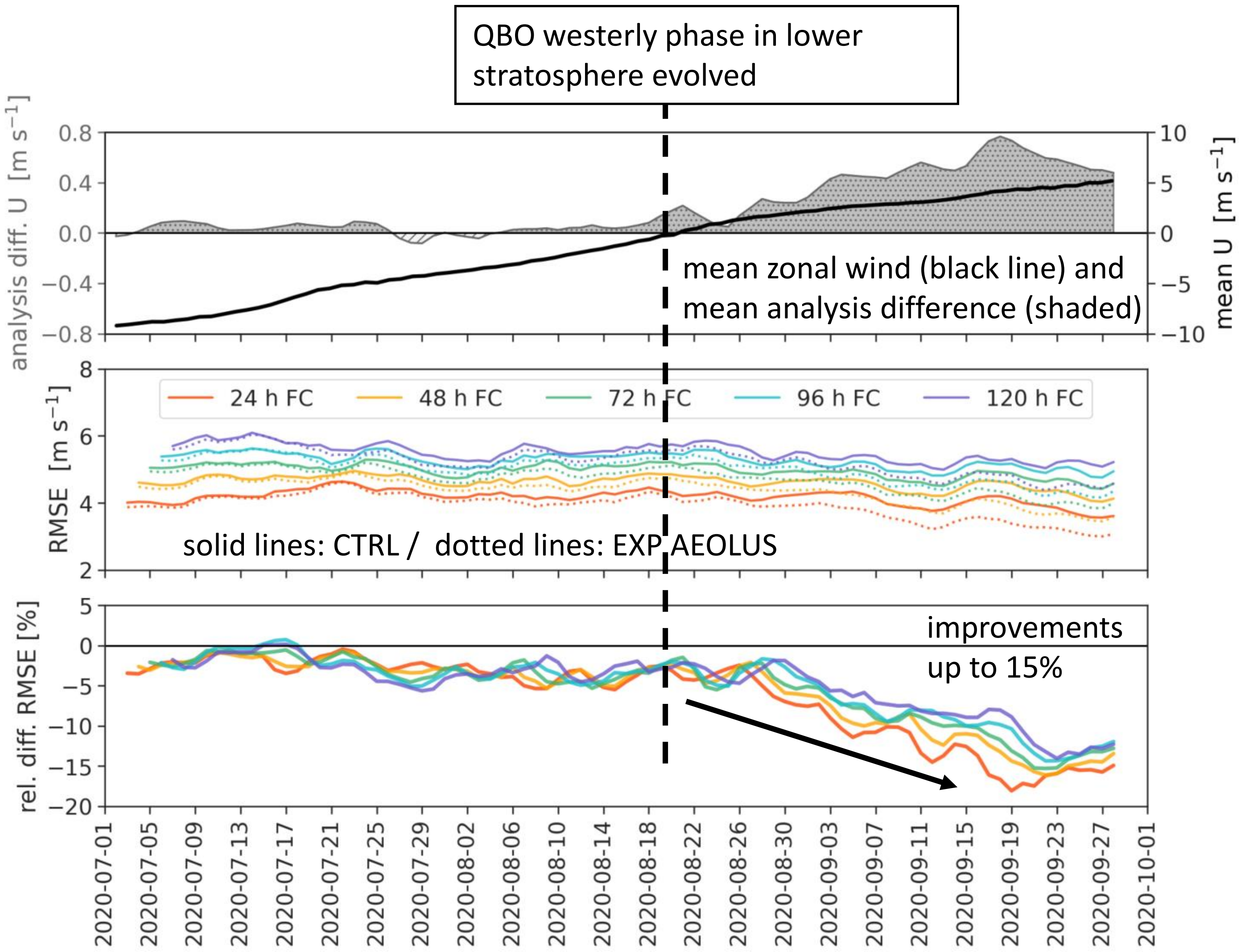


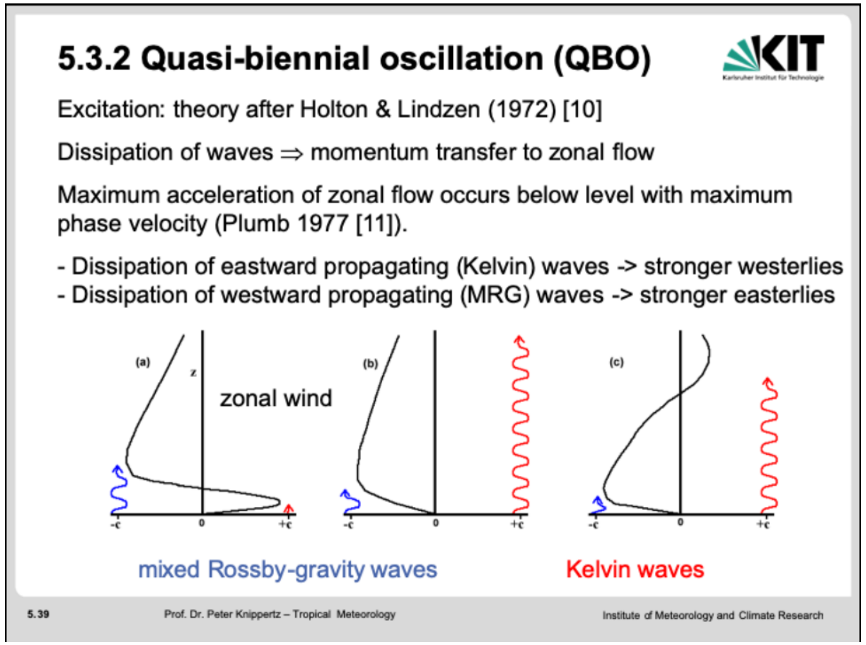



(Martin, Weismann & Cress, QJRMS, 2023)

# 1) Tropical stratosphere: Improvement around phase change of Quasi-Biennal-Oscillation (QBO)

Time series for the tropical belt ±10◦ latitude between 30 and 50 hPa



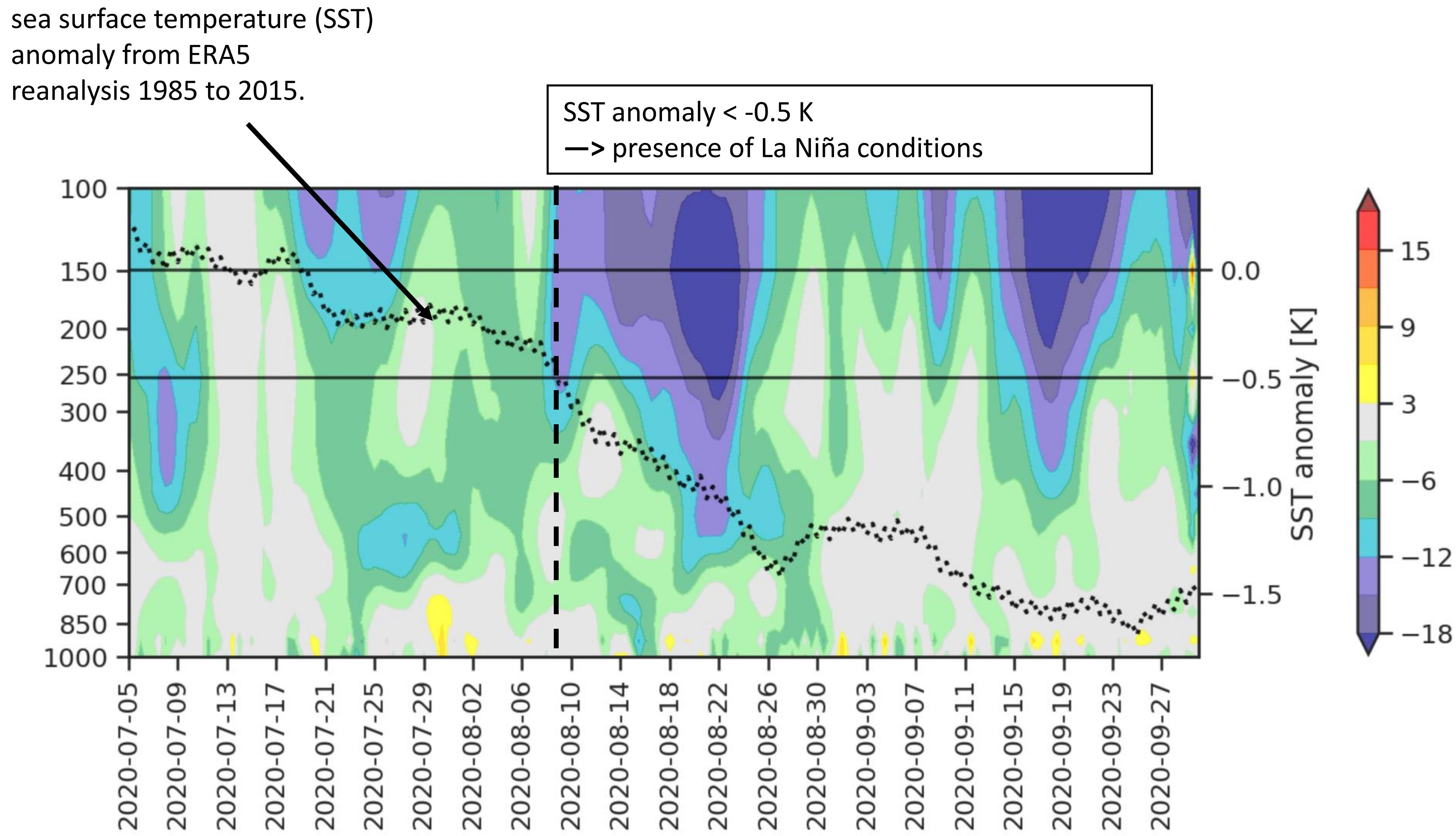




- QBO is due to **vertically propagating waves** that deposit momentum in the stratosphere
- Vertical wave propagation is determined by atmospheric stability **and vertical wind shear**
- Except very sparse radiosondes and aircraft ascents/descents, **Aeolus is the only instruments that observes vertical wind shear in tropics**

(Martin, Weismann & Cress, WCD, 2023)

# 2) Southeastern Pacific: ENSO phase change from El Niño to La Niña

Relative differences in 48 h forecast RMSE of the zonal wind component [%] between EXP_A and CTRL [5°S - 5°N, 90°W - 160°W] as function of forecast time and pressure [hPa]




Largest error reduction in the 48 h forecast occurs about 48 h after the strongest negative increase in the SST anomaly

But the largest anomaly of ENSO occurs at the sea surface

The upper-level flow is coupled to the surface by the Walker circulation

But Aeolus does not observe the surface branch and vertical velocity

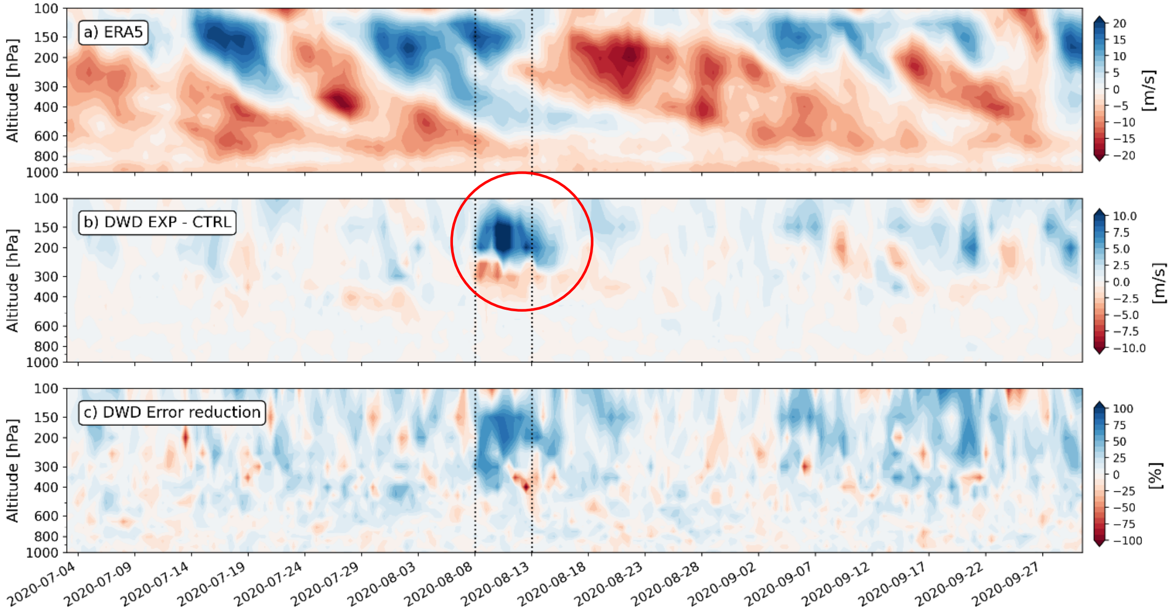
Can the assimilation system change the whole circulation consistently with upper-level wind info by error covariances and cycling?

Or again indication that shear and vertically propagating waves play a role?

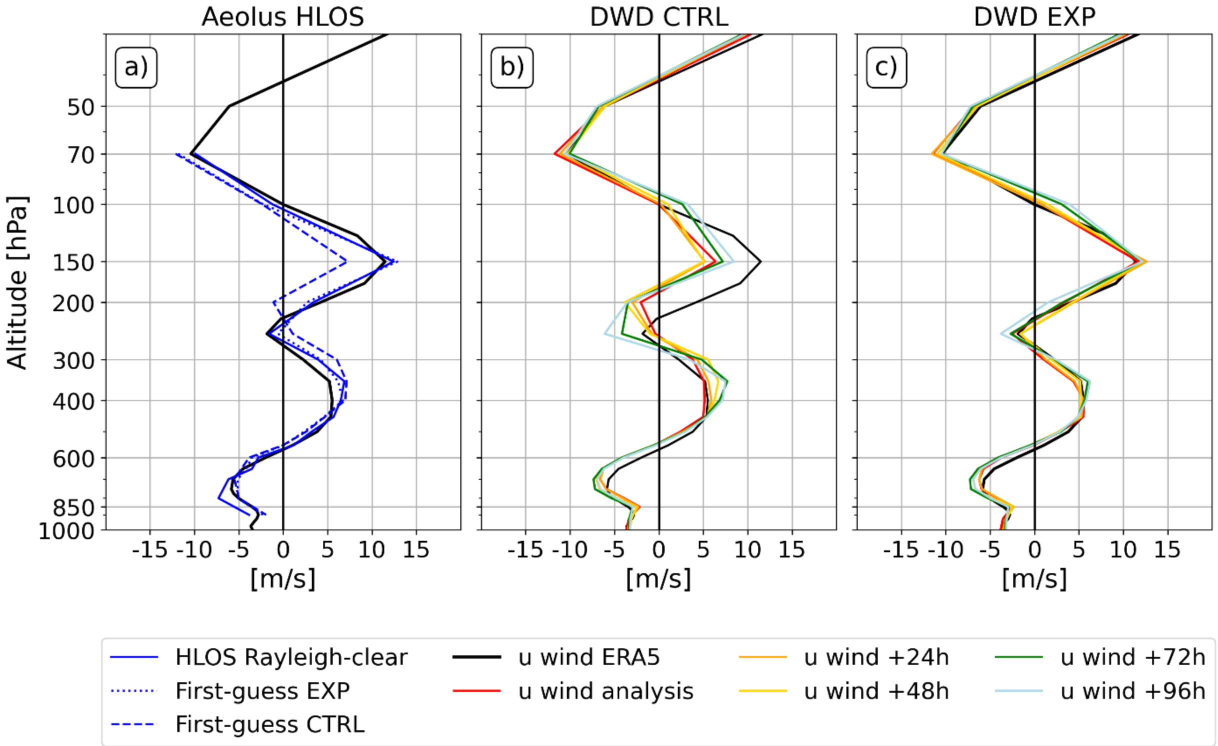
(Martin, Weismann & Cress, WCD, 2023)

# 2) Southeastern Pacific: ENSO phase change from El Niño to La Niña

Mean zonal wind in the area / period of largest improvement




Mean wind profile (8-13 August 2020)




Structure of vertically propagating wave in wind field (top panel)?

Dipole in differences (middle panel) marks systematic change to vertical wind shear during period of largest improvement (bottom panel)

CTRL: Systematic differences of zonal wind to Aeolus and ERA reanalyses

EXP Aeolus: Good agreement of mean wind profile in the analysis and forecast

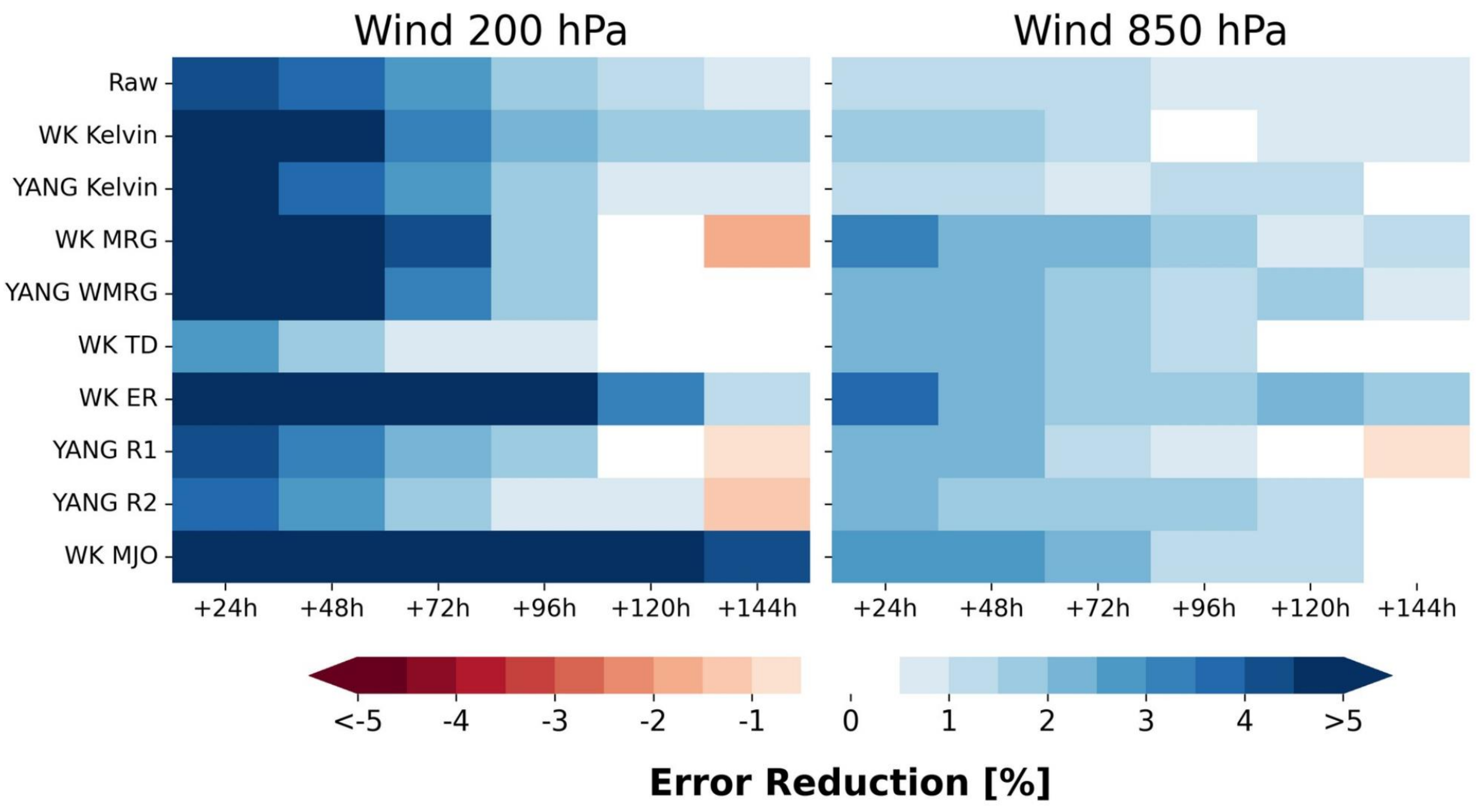
## Waves identified using Wheeler & Kiladis (1999, WK) (Freq.-Wavenumber Filtering using FFT) and Yang et al. (2003) (2D Spatial Projection using Parabolic Cylinder Functs.) methods (preliminary results)

MRG: Mixed Rossby Gravity waves )

WMRG: Westward moving MRG
TD: Tropical Disturbance

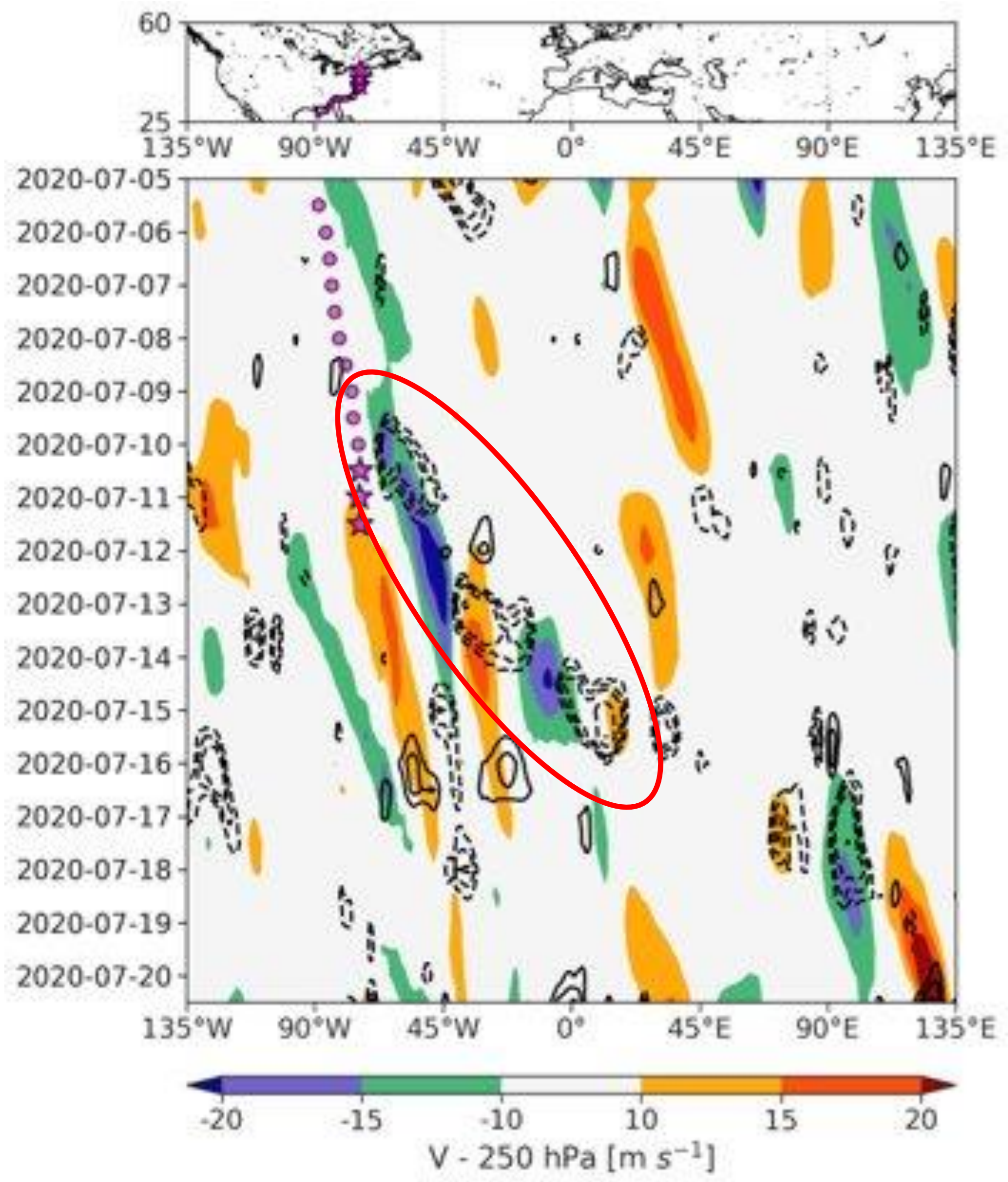
ER: Equatorial Rossby wave

R1/2: Equatorial Rossby wave with meridional mode number 1/2




There seems to be a clear improvement of various tropical waves → further investigation ongoing…

# 3) Midlatitudes: Extratropical Transition of Hurricane Fay and excitation of Rossby wave




----- largest reduction in forecast error due to assimilation of Aeolus

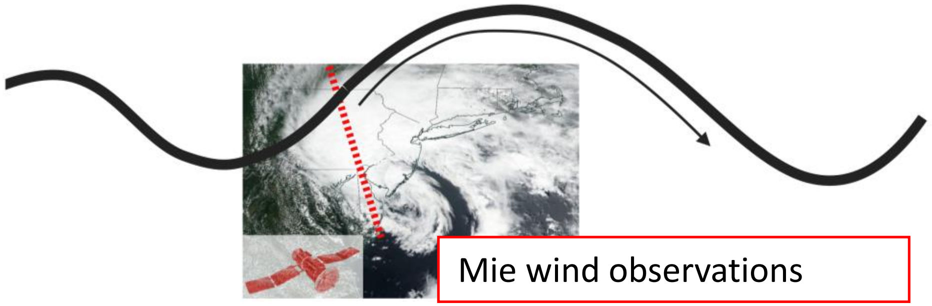
★ extratropical transition of Hurricane Fay

Excitation of Rossby Wave Packet by Hurricane Fay

The largest improvement follows the interaction of Hurricane Fay with the mitlatitude Rossby wave and seems to propagate with the Rossby wave group velocity

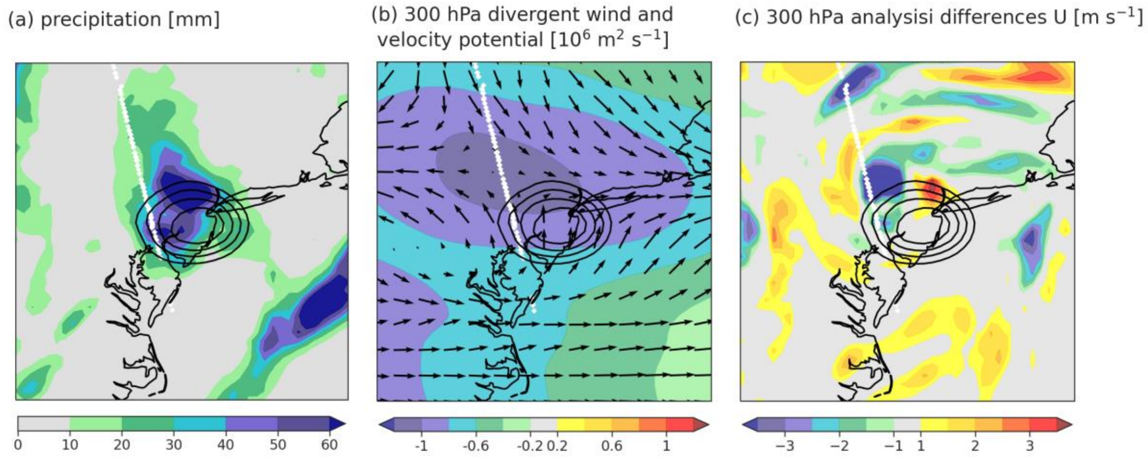
(Martin, Weismann & Cress, WCD, 2023)

# 3) Midlatitudes: Extratropical Transition of Hurricane Fay and excitation of Rossby wave




Interaction of hurricane with Rossby Wave:

- Upper-level divergent outflow interacts with the jet stream
- The Aeolus Mie channel provides observations of this cloudy outflow region with **comparably high accuracy (estimate error ~2 m/s) and high horizontal resolution (10 km)**




Not shown: Indication that cases with large improvements coincide with cases where the Aeolus track was well located over regions of upper-level divergence (e.g. outflow of tropical cyclones)

(Martin, Weismann & Cress, WCD, 2023)

# Conclusions

- Aeolus led to a large significant reduction of short- and medium-range forecasts by several percent in the NWP system of DWD
- Significant improvements by Aeolus also found by other NWP centres (largest impact per satellite @ECMWF)
- Largest improvement in the tropics, followed by the southern hemisphere
- But also significant improvements in the northern hemisphere
- Largest tropical improvement coincides with phase change of two large-scale circulation systems: QBO and ENSO
- Largest midlatitude improvement after the extratropical transition of Hurricane Fay and similar events that are characterized by upper-level divergence

In addition to simply more winds, Aeolus observes two key atmospheric features that are largely unobserved by other systems:

- Vertical wind shear in the tropics (Rayleigh)
- Upper-tropospheric divergence in midlatitudes (Mie)

i.e. observations of unbalanced parts of the flow

In contrast:

- AMVs have poor horizontal resolution due to thinning to mitigate correlated errors arising from errors in height assignment
- Aircraft usually avoid regions of vertical motion that exhibit upper-level divergence

→ Aeolus has died unfortunately, but there is a plan for follow-on wind lidar satellites by EUMETSAT

→ Perfect timing to investigate these processes further to optimize observations from Aeolus II

# References

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Rennie, Healy, Abdalla, McLean & Henry, 2022 (ECMWF newsletter 173): https://www.ecmwf.int/en/newsletter/173/earth-system-science/aeolus-positive-impact-forecasts-second-reprocessed-dataset

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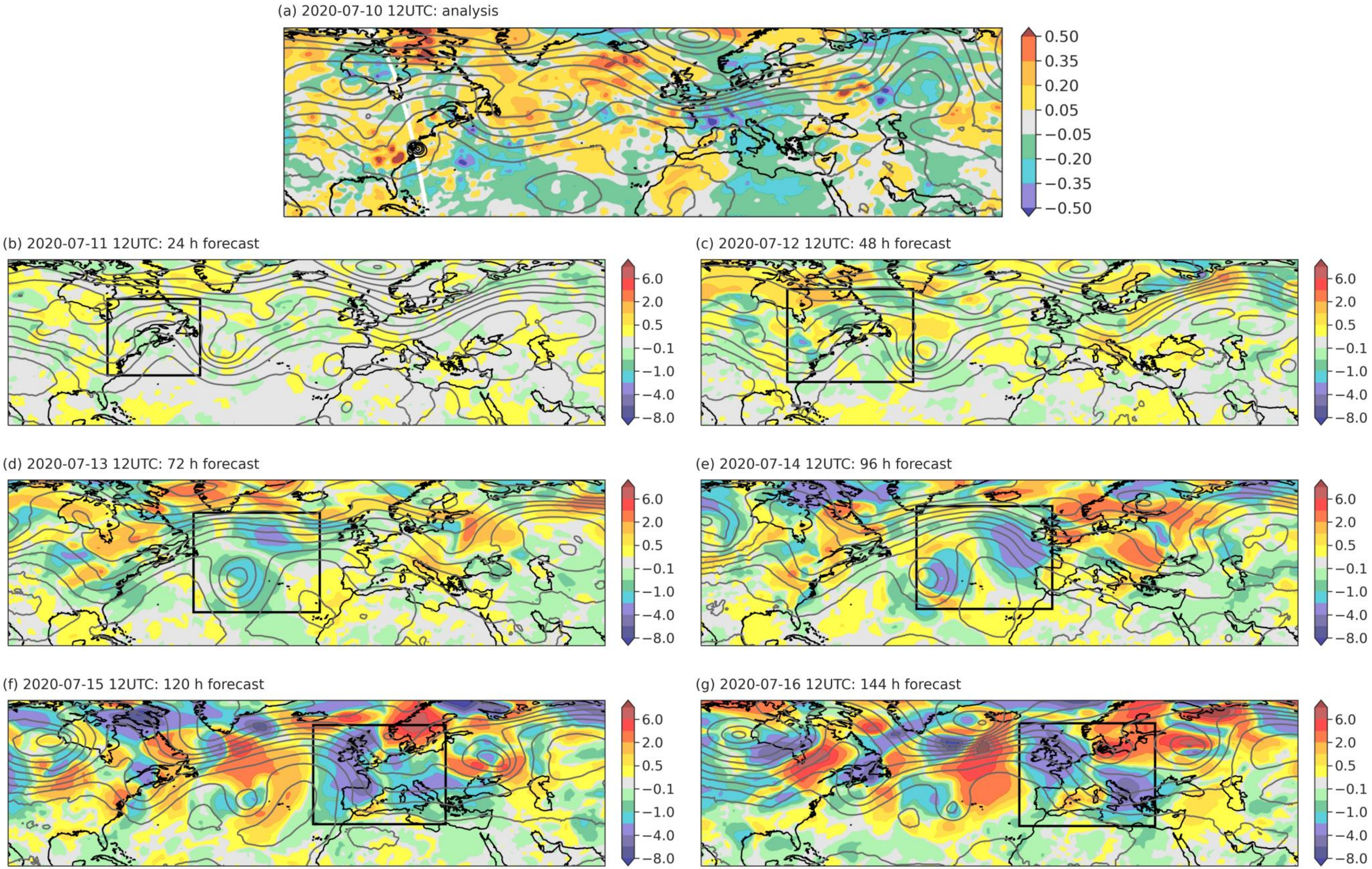


**Forecast error difference EXP_AEOLUS – CTRL**

**Cold colours = improvement**

(Martin, Weismann & Cress, WCD, 2023)