Summary
Day 2 – NWP impact assessment

Jean-Francois Mahfouf (Météo-France), Mike Rennie (ECMWF), Ad Stoffelen (KNMI), Stephane Laroche (ECCC),
Anne Grete Straume and Jonas von Bismarck (ESA)

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Summary Aeolus mission NWP impact reporting (1/3)

- Aeolus exceeded its nominal lifetime of 3 years + 3 months commissioning end November 2021. It has reached its main scientific objective, to improve atmospheric dynamics modelling and operational weather forecasts. Five NWP centers operationally assimilate Aeolus L2B winds with good impact. The data quality, however, slowly decreases with time e.g. due to transmission loss (likely Laser-Induced Contamination).
- ECMWF is running a long Observing System Experiment (OSE) at high resolution ($T_{CO}639$) for the 2nd reprocessing dataset (July 2019-December 2021), where overall impact as well as special investigations of tropical cyclones and extreme weather predictability are investigated
  - Results from first 6 months show larger impact than 1st reprocessed dataset, with largest impact in the tropical Upper Troposphere and Lower Stratosphere (UTLS) and polar areas. The forecast fit to other observations improve, and positive impact in all regions is seen up to medium-range (in some cases up to 10 days). One contributor may also be the higher model resolution for this second OSE. Positive impact for wind, temperature, humidity fields and geopotential.
  - Temperature dependent biases detected and probably due to imperfect Rayleigh-Brillouin scattering correction in L1B-L2B processing. Tests with improved temperature information gives improved short-term forecasts, and mixed impact on medium term.
  - Forecast Sensitivity and Observation Impact (FSOI) of Aeolus ~5% in July 2019, and decreasing with time due to slowly increasing random errors. ~2% in November 2021, but some positive forecast should continue.
- DWD investigated impact of Aeolus in ICON from July 2020 – September 2020. Aeolus is amongst instrument types with the most impact. Own bias correction scheme still implemented. Forecast improvements in Tropical UTLS (up to 10% w.r.t. GNSSRO) and Polar areas.
  - Main changes to ICON model zonal winds in Tropical UTLS (convectively active areas in Inter-Tropical Convergence Zone (ITCZ)). Positive impact still in December 2021 and expected for coming year. Positive impact for wind, temperature and humidity fields.
- Météo-France NWP monitoring since Jan 2020 confirms slow random error increase with time. Now 7.5 m/s (O-B) statistics for Rayleigh clear. Operational assimilation since July 2020. FSOI statistics showing decrease of impact from 5% (June 2020) to 4% (now). Aeolus amongst instrument types with largest impact, and on wind, temperature and humidity fields.
  - 3 OSEs for 1st reprocessed dataset (July-October 2019) with different bias corrections tested. Improved fits to other observations seen except from polar and tropical Atmospheric Motion Vectors (AMVs). Largest impact in tropical UTLS, with Rayleigh clear impact larger than Mie cloudy up to day 4. It was suggested to increase representativeness error for Mie winds to increase impact.

Summary Aeolus mission NWP impact reporting (2/3)

- Met Office assimilates operationally Mie winds since Dec. 2020. Rayleigh winds tested in May-July 2021 (0.22% improvement in O-B fits and forecast improvements to 4 days in tropics and SH) and in September-November 2020 (0.3% improvement in (O-B) fits and impressive 7-day impact in Northern Hemisphere (NH)). FSOI: Aeolus second best after drifting buoys. Rayleigh winds show larger impact than Mie winds.
- NCMWRF assimilates operationally Aeolus winds since May 21, 2021. Tests with two systems (GDAS and NCUM). Positive impact of tropical wind and temperature scores (around 100 hPa) up to day-6. Smaller positive impact in SH and neutral impact in the NH. FSOI: Aeolus represents around 3% - similar in July 2020 and July 2021. Mie contribution is about 1/3 of Rayleigh contribution and is located in the lower troposphere. Case studies on tropical cyclones over India: Aeolus improves pressure deepening and reduces positioning error
- ECCC presented OSEs with Near Real Time (NRT, i.e. within 3 hours of sensing) B06 and reprocessed B10 Aeolus winds in August-September 2019. The NRT winds have been bias corrected using mean(O-B) values (depending upon location and orbital phases) and reprocessed wind uses the M1 temperature bias correction. Positive forecast scores have been obtained with better results using reprocessed data (enhanced impacts in polar regions). Enhanced positive impact of Aeolus when AMVs are withdrawn (40 %). Impacts of AMVs is twice that of Aeolus in extra-tropics, but Aeolus dominates in the tropics.
- The impact of Aeolus winds was examined in the Korean global model (KIM) from 15 June to 31 July 2020. A 300 km thinning is applied to the Mie-cloudy and Rayleigh-clear Horizontal Line-of-Sight (HLOS) winds. The prescribed observation errors for the Aeolus winds are the L2B estimated errors inflated by a factor of 1.5. Significant impacts (up to 2% error reduction) are obtained in the Southern Hemisphere and tropics for the first 3 days forecasts. The impact is smaller in the Northern Hemisphere.
- The impact of Aeolus winds was assessed in the NOAA FV3GFS forecast system from 20 November to 31 December 2019. M1 telescope mirror temperature bias corrected data are used. A total-least-square bias correction scheme is also applied to the data for removing residual biases. Based on summary forecast assessment metrics, the impact of Aeolus is significant in both tropics and extra-tropics regions up to day 5. The largest forecast error reduction (~4%) is obtained in the UTLS over the tropics. Aeolus data have a significant impact on medium-range forecasts of two blizzard events in central and eastern United-States during the period examined.

Summary Aeolus mission NWP impact reporting (3/3)

- The impact of Aeolus winds in the Harmonie-Arome model over the Scandinavia region in autumn 2018 (during the operation of Aladin Flight Model-A (FM-A) laser) and spring 2020 (during operation of Aladin Flight Model-B (FM-B) laser) was investigated. A 3D-Var with a 3-h data assimilation cycle is used. Aeolus data in that region are available only at 03 and 06 UTC descending orbits and 15 and 18 UTC ascending orbits. When Aeolus data are present in the domain, the DFS is comparable to those of aircraft and radiosonde data. The impact of Mie-cloudy data is significant on analyses. However, the impact of Aeolus is neutral on forecasts. Preliminary results from 4D-Var look promising.
- Explanations have been provided by N. Zagar (U. of Hamburg) regarding the largest positive impact of Aeolus tropical tropopause layer. ECMWF forecasts with and without Aeolus have been compared. Impacts appear to be coupled to the Quasi Biennial Oscillation (QBO) and to a better propagation of equatorial waves (Kelvin) with Aeolus.
- T. Banyard (U. of Bath) has shown the importance of improved bin range setting of the lidar that took place in June 2020 for the description of the QBO by Aeolus (comparisons with the Singapore radiosoundings and ECMWF ERA5 reanalysis). The signature of the QBO disruption (associated by an Eastward propagation of Kelvin waves) has been shown in the three data sets.
- M. Borne (KIT) has studied the representation of the West African Monsoon (summer 2019/2020) by ECMWF forecasts with and without Aeolus compared against ERA5. He showed that the temperature bias correction (linked to RBC) improves Rayleigh winds, whereas Mie wind biases are still present and more complex (linked to the diurnal cycle). An additional understanding of the remaining biases could further improve NWP forecasts over Africa.

Plenary discussion (1/4)

Aeolus NWP impact assessment (1/2):

- It has been shown that Aeolus has reached its main scientific objective, to improve atmospheric dynamics modelling and operational weather forecasts. Currently, five NWP centers operationally assimilate Aeolus L2B winds. Aeolus impact has been shown to be among the largest when compared to other weather observation data types, especially for the initial period of the redundant FM-B laser operation.
- Some evidence of reducing NWP impacts with time, due to the slow increase in Aeolus L2B wind random errors, have been shown by timeseries of FSOI results available during the period 2020-2021 from various operational NWP centres (ECMWF, Météo-France). However, NCMRWF did not see a similar degradation over time (found similar FSOI scores). The fractional FSOI impact at Météo-France has decreased from 5 % mid-2020 to around 2-3 % end 2021; ECMWF saw a decrease from 3-4% to 2% over the same period. DWD has seen a decrease of EnVar “weights” from Rayleigh clear winds since July 2021, whereas impact of Mie cloudy winds remain unchanged.
- OSEs should be undertaken over a recent period to reassess the NWP impact with larger random errors to see if this agrees with the FSOI trends. ECMWF are in the process of doing this.
- Current WMO OSCAR random error thresholds seem a bit pessimistic given the impact obtained with relatively noisy Aeolus data.
- Systematic errors are less a problem since model background (and also collocated radiosoundings) can be used to identify and correct them (as experienced by several NWP centres before M1 temperature correction: ECCC, DWD, Météo-France).
- NWP improvements in the short-range have been shown at ECMWF using a temperature correction for the remaining bias due to the Rayleigh-Brillouin Correction (RBC) - but neutral in medium range. DWD tested switching off their own additional bias correction which gave similar results – suggesting that the current bias correction methods do a good job.
- Improved NWP impacts from the reprocessing data have been demonstrated (2nd reprocessing better at ECMWF than the first one, but could also be due to increased model resolution - which is interesting if Aeolus has more impact in higher resolution models). Comparisons over the 2019 period reveal that improvements come from a more efficient bias correction method (ECMWF, Météo-France).

Plenary discussion (2/4)

Aeolus NWP impact assessment (2/2):

- Contrasting relative impacts have been shown between NWP centers, showing that the impact depends on the models and their assimilation methods and data use. Individual FSOI are similar between Rayleigh Clear and Mie Cloudy at ECMWF, whereas they are much smaller at Météo-France for Mie Cloudy. At DWD, the “EnVar” weights are larger from Mie than for Rayleigh. At Météo-France the overall NWP impact of Aeolus is dominated by Rayleigh Clear. ECMWF OSE results from a year ago also showed Rayleigh-clear more important than Mie-cloudy, so this may be caused by an FSOI issue at ECMWF? Met Office show more impact from Rayleigh-clear than Mie-cloudy in both FSOI and OSEs. Positive impacts from Mie Cloudy winds are located in the lower troposphere and near polar regions (Météo-France, ECCC, ECMWF). This may explain the dominance of Mie winds in the HARMONIE-AROME model having its domain located at high latitudes.

- Experience from NWP centres show that the fit of the model short-range forecasts is improved against many independent observing systems such as radiosoundings or GNSS-RO data. Regarding AMVs, a reduced model fit has been noticed by several centres (Météo-France, ECMWF) at ~500 hPa, whereas improvements have been noticed at DWD and Met Office. ECCC has shown that when excluding AMVs Aeolus impacts are larger, particularly over polar regions.

- The impact on tropical cyclones forecasts has been examined by several centres, e.g. case studies at NCMWRF, and over a 6-month period at ECMWF. Both studies show improved trajectory and reduced forecast error of minimum central pressure. Two US winter storms have been studied at NOAA/NCEP (November-December 2019) with positive impact in the medium range due to an improved moisture transportation from the Pacific region to the East-coast, leading to better precipitation forecast skill scores.

Recommendations for Aeolus operations:

- All met centers still see positive impact of Aeolus winds. The Aeolus Mission Manager asked when centers think that more drastic measures should be taken in Aeolus operations, such as change to FM-A laser or lowering of the orbit. DWD and ECMWF indicated that positive impact of Aeolus still looks to be reasonable from FSOI scores. However, it was suggested to confirm this with a recent OSE. S. Laroche proposed to perform OSE tests with increased random errors to check the sensitivity, as was done by the paper of Horanyi (2014). A. Cress proposed a possible criterion for change in operation being FSOI scores below 0.8%.

Plenary discussion (3/4)

DWL/Aeolus-2 preparations and expectations (1/2):

- The 3-year lifetime of this novel satellite type, and the time (more than a year) needed to obtain a stable dataset with an efficient bias correction suitable for operational assimilation, is probably the reason why a number of NWP centres did not considered operational implementation (ECCC, NOAA, KMA, JMA). Another reason may be the instrument degradation issues. Experience gained with Aeolus is currently used to ensure fast availability of stable products for NWP needs for the candidate DWL/Aeolus-2 follow-on. Moreover, the mission is designed to last longer and to have a better signal quality and horizontal/vertical sampling, which makes it worth the preparation investment by NWP centres.

- It is likely that a DWL will remain unique and highly complementary to the rest of the global observing system by providing vertical resolved wind profiles in data void areas, particularly in clear air. Moreover, a much improved atmospheric return for Aeolus-2 would further enhance NWP impact compared to Aeolus. It could be well complemented by a mission like WIVERN (cloud Doppler radar), an ESA candidate Earth Explorer Mission, providing winds in clouds. Aeolus improvements in the tropical UTLS come from a better description of *vertical wind shear* that has a critical role in the propagation of Kelvin and gravity waves and consequently on tropical variability (diagnostic studies from Zagar, Banyard and Borne). OSSEs should be undertaken with the 2030 observing system in order to further quantify these statements.

- So far, only few studies have been undertaken with LAM models. The one from Hagelin et al. (2021) shows neutral forecast impacts. They could be enhanced by the use of 4D-Var (this is currently planned), additional overpasses (more than one instrument), and better vertical and horizontal resolutions. Improved observation operators in order to better match model and observation resolutions (such as supermodding) should be developed.

- The impact of degradation of random errors between 2019 and 2021 on forecast skills gives some first input for the preparation of Aeolus-2, but needs further work. At Météo-France, the increase in STDEV(O-B) values from 4.3 m/s to 6 m/s induced a 1 % degradation of tropical scores. The impact of different random errors on forecast skills (e.g. as shown by Horanyi et al in 2014) should be assessed for the follow-on mission e.g. by performing OSSEs. The experiments should also include GNSS-RO constellations, which having a large NWP impact.

- Improved description of the stratosphere (up to 30 km) is important to better represent interactions with the troposphere, particularly in the tropics as evidenced by diagnostics studies. Better initial states in the stratosphere are known to enhance the predictability of the troposphere.

Plenary discussion (4/4)

DWL/Aeolus-2 preparations and expectations (2/2):

- Any further mitigating action on Aladin, leading to a reduction of random errors on Rayleigh Clear winds, would be useful to assess in terms of corresponding impact in NWP forecast skill scores.
- Defining a common experimental framework (period, dataset) for OSEs/FSOI of all interested NWP centers would help to convey the most robust conclusions in terms NWP impact at the 2022 DWL/Aeolus-2 meeting at EUMETSAT. The Aeolus NWP impact workshops have been organized since May 2018, for this purpose, and should be continued in 2022. ESA, EUMETSAT and the Aeolus DISC should continue to lead this effort together.
- The Aeolus mission manager recommended the NWP/science community at the workshop to write a letter to the director of Earth Observation at ESA and the EUMETSAT DG, strongly recommending an Aeolus follow-on given the positive impacts found. This was also done following the Aeolus NWP impact workshop in September 2019. The letter should include thoughts on what could be achieved with significantly improved Rayleigh random errors as should be expected with Aeolus-2. The conveners of the NWP impact session (day 2) were encouraged to do this.