The impact of assimilating AEOLUS wind data on regional Aeolian dust model simulations using WRF-Chem

Kiriakidis Pantelis[3], Gkikas Antonis1,*, Papangelis George[1], Drakaki Eleni[1], Proestakis Emmanouil[1],Gialitaki Anna[1,2], Marinou Eleni[1], **Kushta Jonilda**[3], **Christoudias Theodoros**[3], Spyrou Christos[1], Benedetti Angela[4], Rennie Michael[4], Kampouri Anna[1], Straume Anna Grete[5], Retscher Christian[6],Dandocsi Alexandru[6], Sciare Jean[3] and Amiridis Vassilis[1]

[1]Institute for Astronomy, Astrophysics, Space Applications and Remote Sensing, National Observatory of Athens (IAASARS/NOA), Athens, Greece

[2]Laboratory of Atmospheric Physics, Aristotle University of Thessaloniki (AUTH), Thessaloniki, Greece

[3]The Cyprus Institute (CyI), Nicosia, Cyprus

[4]European Centre for Medium Range Weather Forecasts (ECMWF), Reading, UK

[5]European Space Agency (ESA/ESTEC), Noordwijk, Netherlands

[6]European Space Agency (ESA/ESRIN), Frascati, Italy

Outline

- Winds determine aeolian dust emission and atmospheric transport: **representation of wind fields crucial for numerical models to capture mineral dust mobilization and transport**.

- **ESA project NEWTON** (ImproviNg dust monitoring and forEcasting through Aeolus Wind daTa assimilatiON): Investigate potential improvements on regional dust simulations attributed to the assimilation of Aeolus wind profiles.

- **WRF/Chem (**Weather Research and Forecasting regional atmospheric coupled model) used to simulate the airborne dust concentrations for **two month-long periods in the spring and fall season of 2020**, with focus on October 2020 dust event.

- The model is **driven by ECMWF IFS outputs** with (hel4) and without (hel1) **assimilation of Aeolus** quality-assured Rayleigh-clear and Mie-cloudy wind profiles over broader **Eastern Mediterranean region**:
  - subjected frequently to dust transport,
  - encompassing the major natural erodible dust sources of the planet.

- Model performance (extinction coefficient, atm. optical depth and PM concentrations) evaluated against:
  - AERONET sun photometers, PollyXT ground-based lidar, EMEP station network in situ observations.
  - LIVAS and MIDAS satellite-derived datasets providing vertical and columnar dust optical properties, respectively.

WRF-Chem regional dust simulations

- Encompassing the major dust sources at the East Mediterranean-Middle East (EMME) region
- Horizontal resolution: 20x20km
- Two periods of interest:
  - **Spring 2020**: 04/04 - 31/05s
  - **Autumn 2020**: 01/09 - 04/11

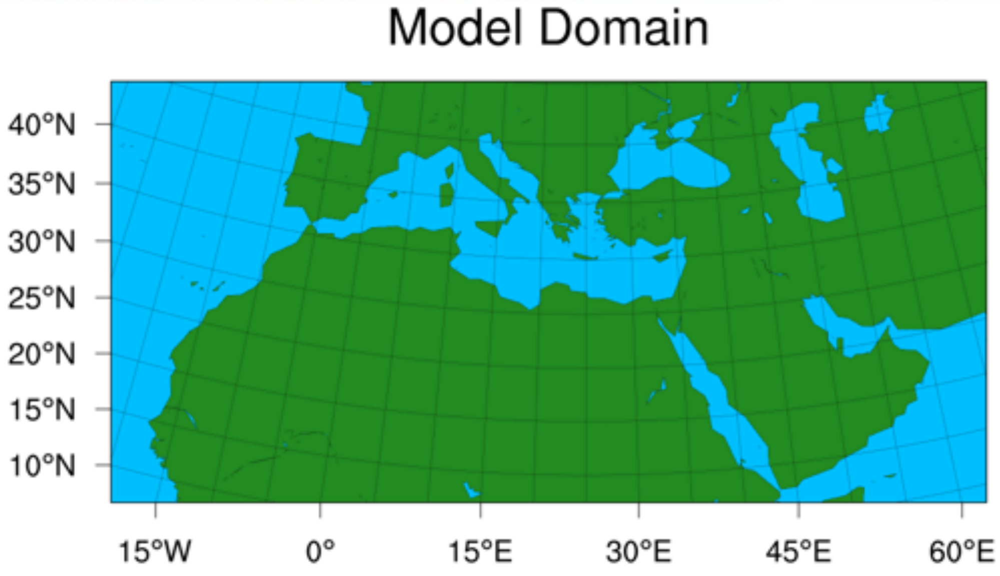

Figure 1. Model domain used in the WRF-Chem simulations.

- **ECMWF IFS provides** meteorological conditions (Cf. previous talk):
  - **hel1** = **Control** dataset (IFS re-analysis).
  - **hel4** = Experimental dataset **with Aeolus Data Assimilation** (Rayleigh-clear and Mie-cloudy winds).

- WRF-Chem simulations (WRFv3.9.1 and WPSv4.2) nudged towards the two datasets, both with:
  - The chemistry option RADM2/MADE - SORGAM (Gas Phase Chemistry with Secondary Organic Aerosol Formation).
  - The Anthropogenic emissions inventory EDGARv5 (Species; SO_2, CO, NOx, NH_3, OC, BC, NMVOC, PM2.5, PM10).

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Observation datasets used for the evaluation

Ground-based:

- **AERONET [columnar]** - Sunphotometer instruments retrieve the **Aerosol Optical Depth (AOD),** a unitless measure of aerosol load in the total atmospheric column. We make use of 87 stations within the study region.

- **EMEP (DLI) [near-surface in situ]** - Pan-European database of ground-based aerosol concentration observations. We make use of hourly retrievals of **coarse particulate matter** (**PM10) concentrations** at the Ayia Marina Background station in Cyprus.

- **Polly^{XT} [profiling]** - **Dust mass concentration**, lidar products from PANGEA observatory in Antikythera, Greece.

Satellite-based:

- **MIDAS [columnar]** – Satellite **AOD retrievals** of spatial resolution 0.1 x 0.1 degrees.

- **LIVAS [profiling]** - LIdar climatology of **Vertical Aerosol Structure** for space-based lidar simulation studies, providing the pure-dust product in 5km horizontal and 60m vertical resolution.

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Seasonal Differences

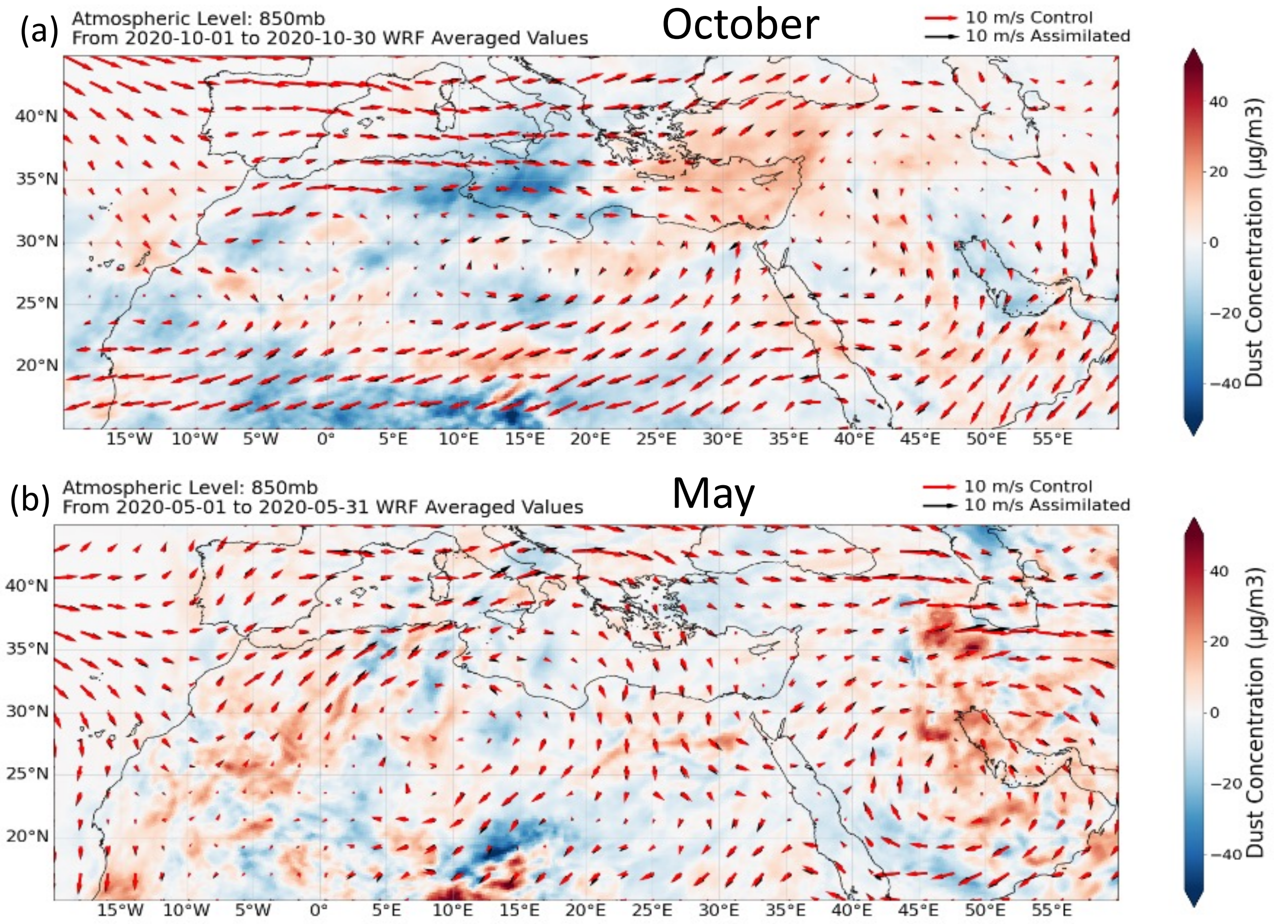


Figure 2. Averaged dust concentration differences (assimilated - control) and wind fields at the atmospheric level of 850mb of the WRF-Chem simulations for the months of October (a) and May (b), where the red arrows represent the control wind vectors and the black arrows the assimilated ones.

- Use of the assimilated dataset has small difference between the two datasets during the spring months, while a difference is observed for autumn:
  - In spring (2b) the differences in dust concentration within the EMME and central Mediterranean regions are less than 20 μg/m^3.
  - In autumn (2a) the differences are more pronounced, and a dipole seems to prevail with hel1 transporting dust in the Central Mediterranean and hel4 over the EMME region.
- Indication of temporal (seasonal) dependence of assimilation effect for the region under investigation?

Periods of interest (EMEP station DLI)

- Small divergence of the two runs for spring season (b)
- Autumn Period 14 – 27 October selected for further analysis.

Table 1. **Change in statistical metrics** with introduction of assimilated dataset.

Highlighted Period	Correlation Coefficient	IOA
07/10 - 10/10	0.06	0.16
10/10 - 14/10	- 0.21	- 0.01
18/10 - 23/10	0.34	0.06
28/10 - 02/11	0.17	0.15

Index of Agreement (IOA) between two variables is a unitless metric comparing the magnitude of values, with range 0 to 1, where 1 indicates perfect agreement.

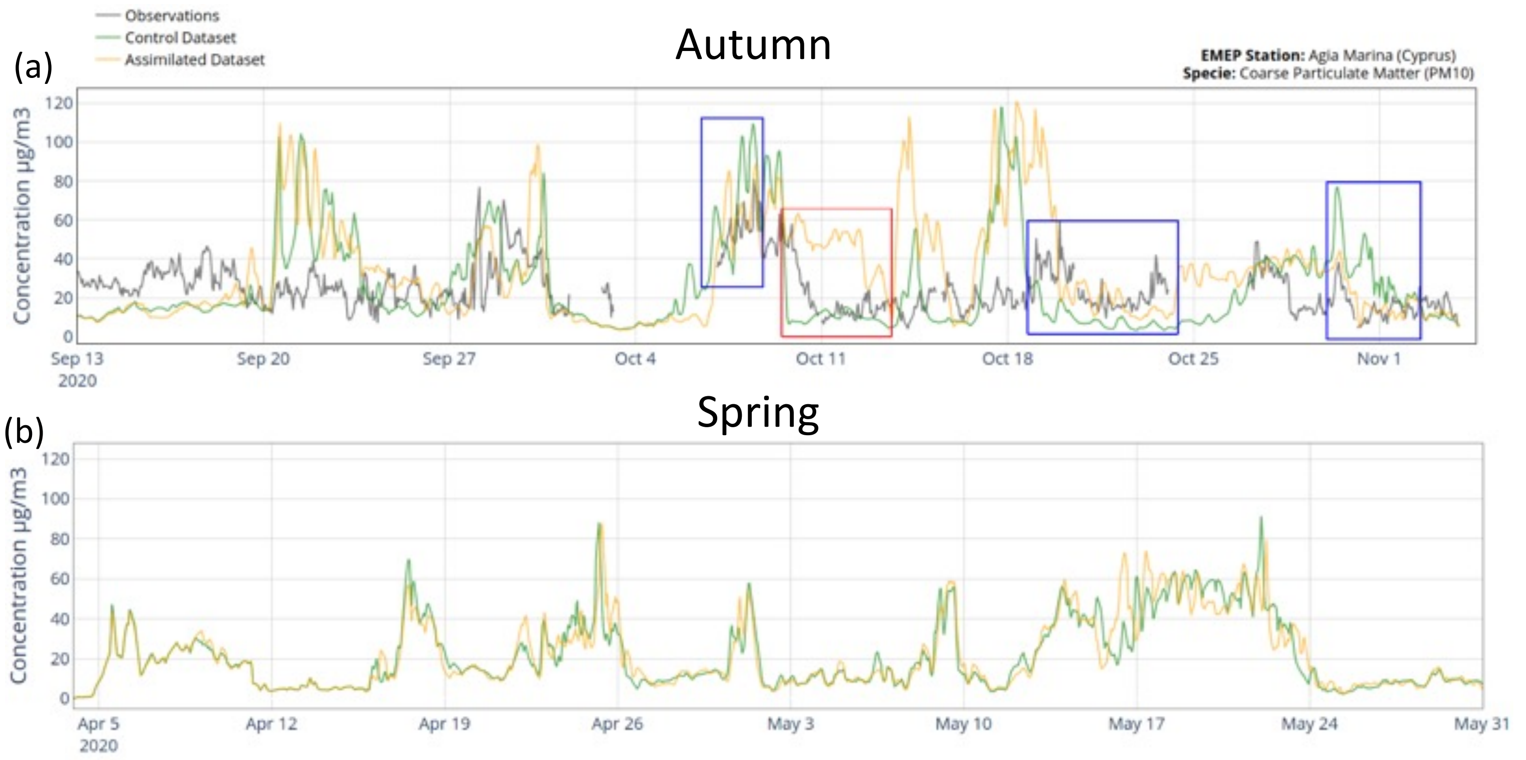


Figure 3. Timeseries of PM10 concentration at Ayia Marina, Cyprus, for autumn (a) and spring (b). **Green:** control run, **Yellow:** assimilated run, **Black:** observed values.
Blue highlighted boxes represent periods where the assimilated run outperforms the control run and the **Red** box represents the opposite.

Meteorological Conditions in Autumn

Analysis period split into two distinct time frames:

14/10 - 19/10

- **A high-pressure cell developed in both simulations** on the north-eastern tip of Libya, with minor differences.
- This produced an anticyclone just north of the great sand sea desert, in the Sahel region, 30N and 25E.

20/10 - 25/10

- In the latter period the **high-pressure system moves westwards:** in the control run it remains more defined while for the assimilated run it weakens and dissipates.
- This leads to the **formation of a second anticyclone in the control run that does not appear in the assimilated run**.

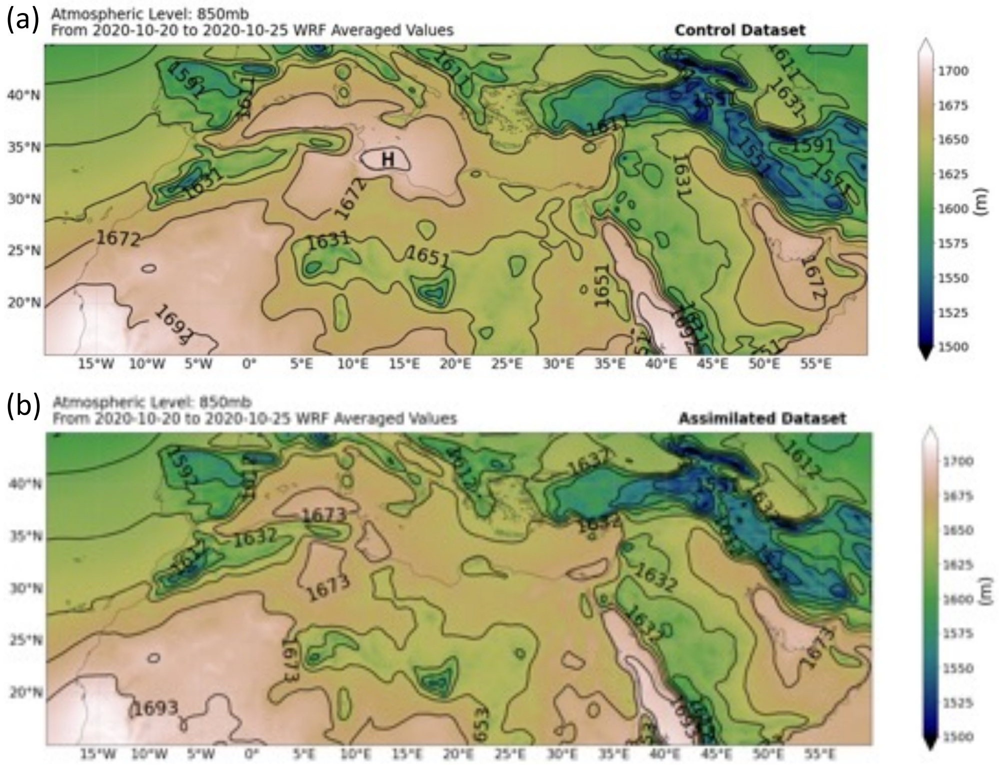
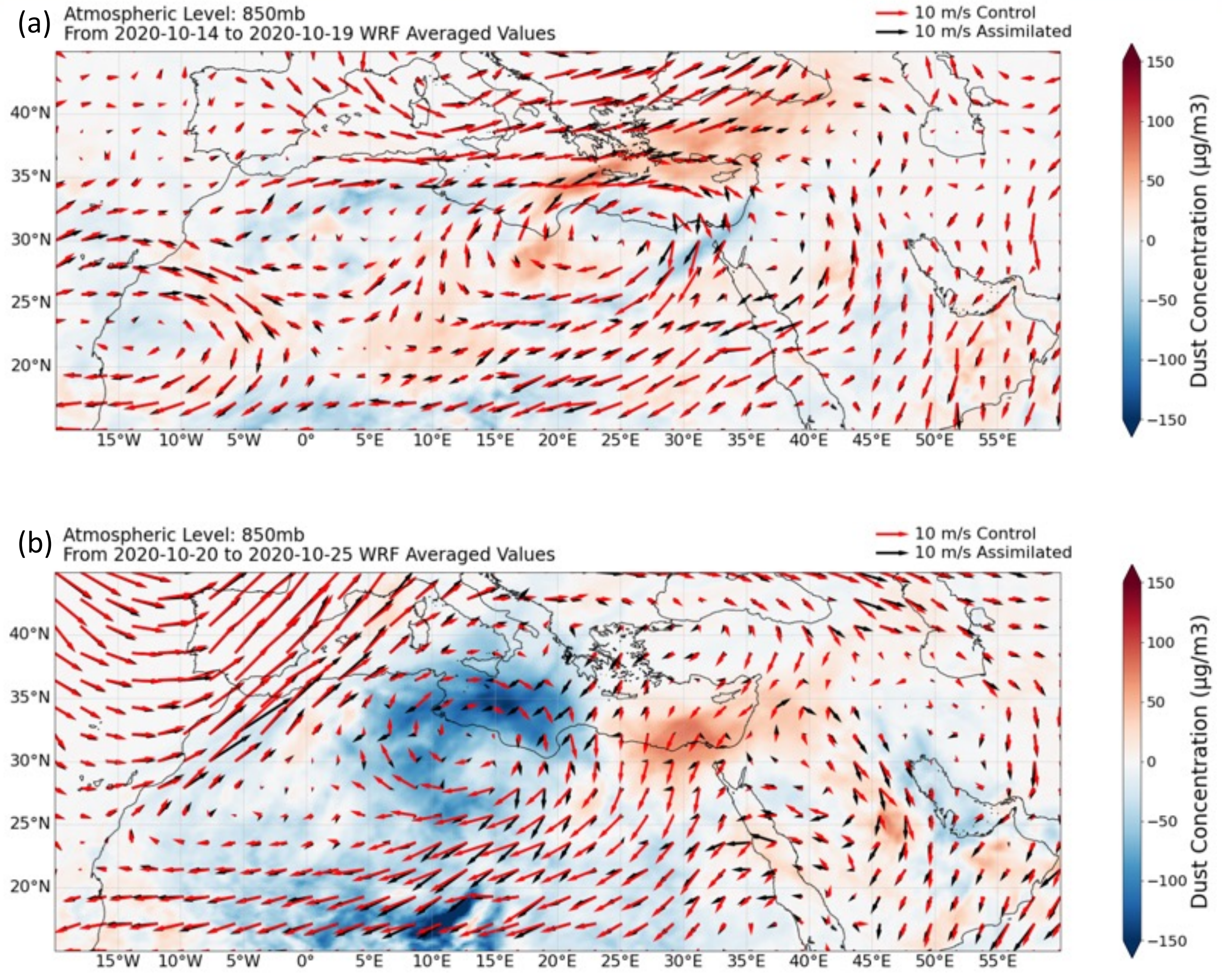


Figure 4. **850 hPa geopotential height** averaged 20-25 October for **control run (a)** and **assimilated run (b)**

Dust Transport



- Anticyclogenesis on the 14th to 19th lifts and transports dust through the gulf of Sidra into the Mediterranean basin.
- Deviation leads to dust transport North-East for the assimilated run, while South-West for the control run.
- During 20th to 25th the second anticyclone in the control run mobilises dust from the Saharan desert towards the Central Mediterranean.
- More stagnant conditions observed in the assimilated run over the Eastern Mediterranean lead to higher values over Egypt and the Middle East.

Figure 5. Averaged dust concentration differences (assimilated - control) and wind fields at the atmospheric level of 850mb for the time averaged periods; 14-19 of October (a) and 20-25 of October (b) where the red arrows represent the control wind vectors and the black arrows the assimilated ones.

FLEXPART Trajectories (NOA)

- **Lagrangian dispersion model (A. Kampouri):** 5-day backwards trajectory of 10,000 tracer particles arriving at Ayia Marina, Cyprus, on the 19th of October at 02:00am.

- Deviations in meteorological fields for the 14-19th of October lead to aerosols received at the Ayia Marina Cyprus station to be of different origin.

- At a height of 0.5km (6a) in the assimilated run they originate from dust source regions, while for the control run from mainland Europe.

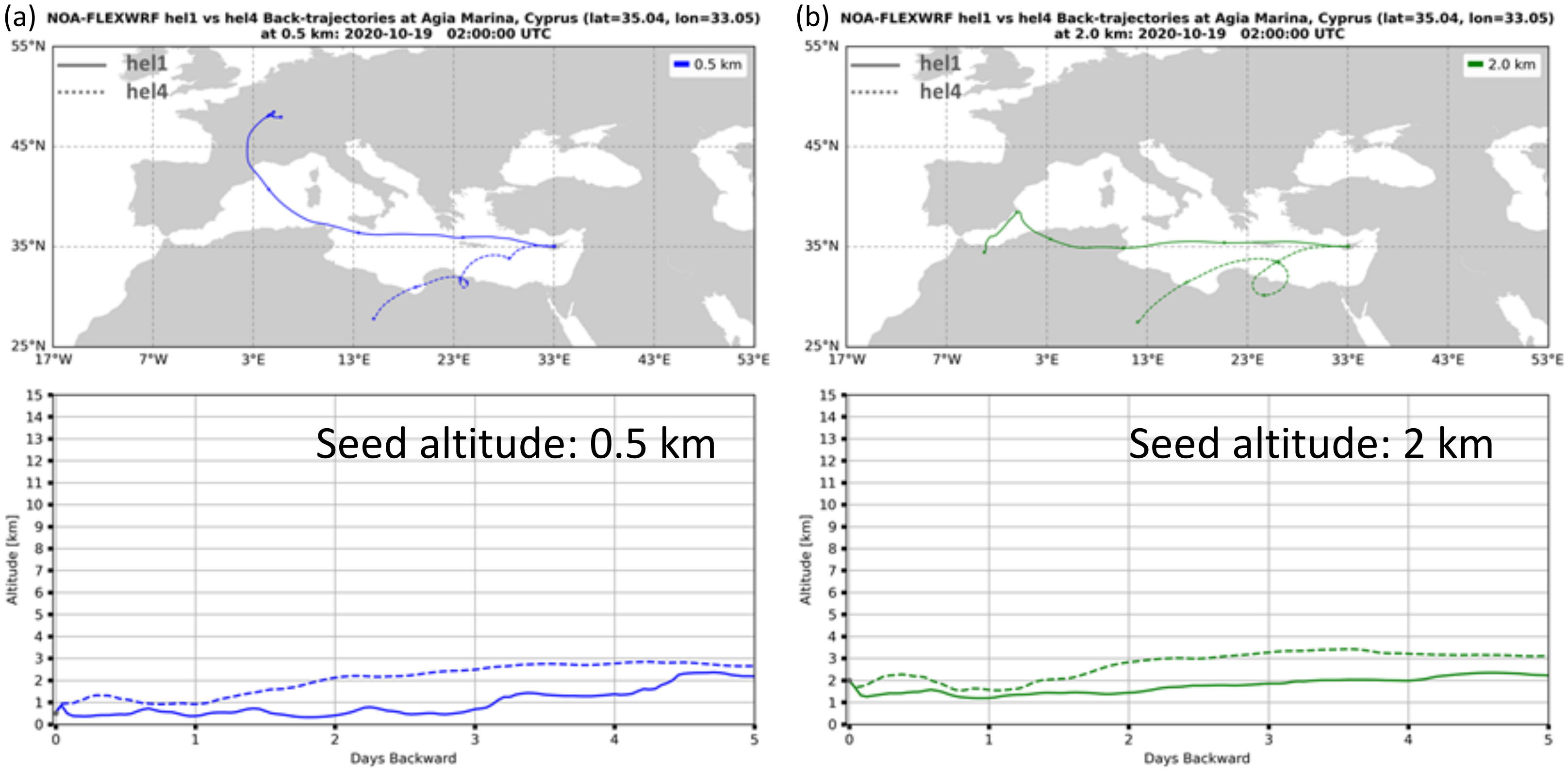
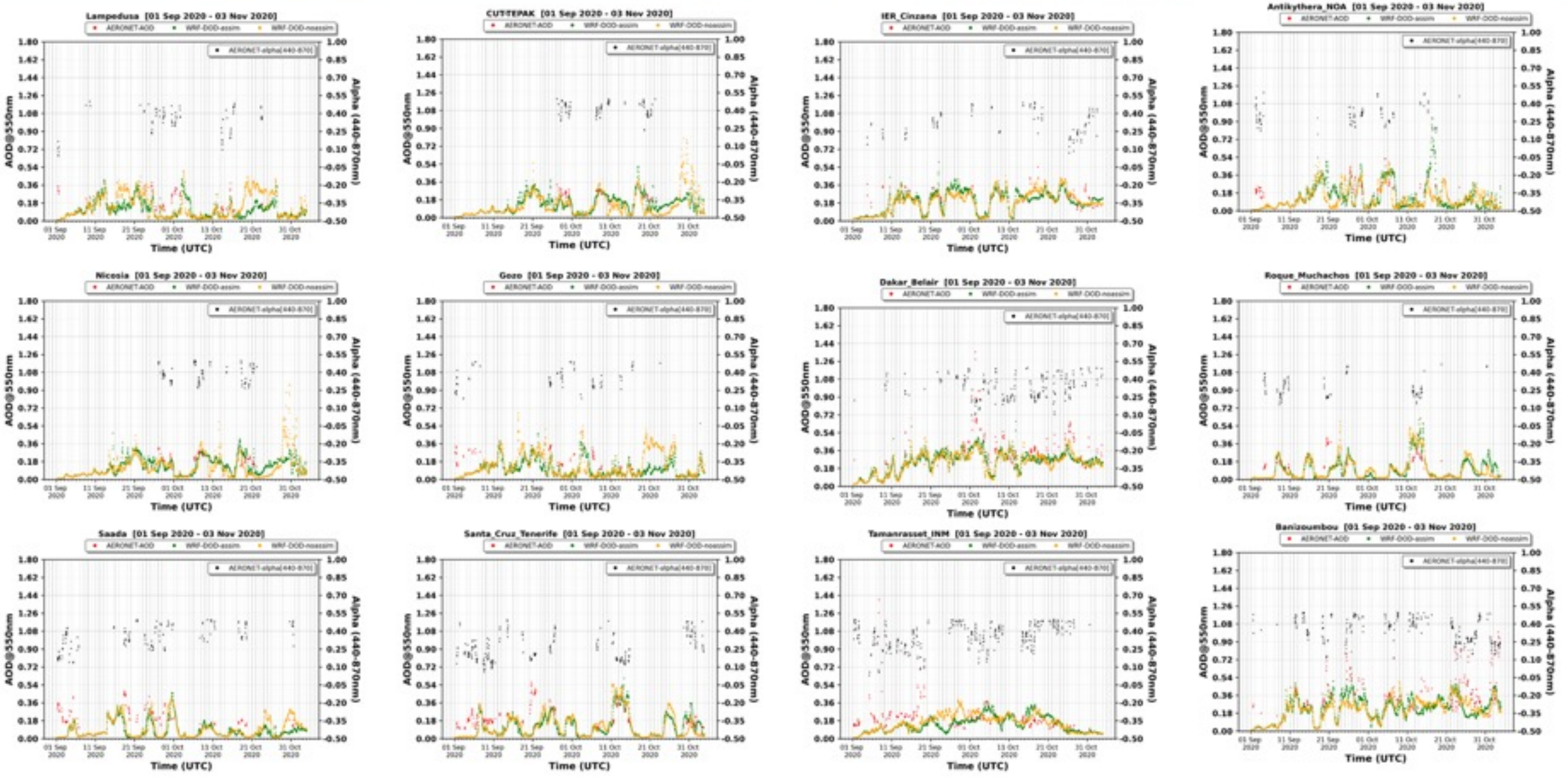


Figure 6. Five-day backward trajectories of particles arriving at the Ayia Marina station, Cyprus, on the 19th of October at 02:00am (a) at 0.5km and (b) at 2.0km.

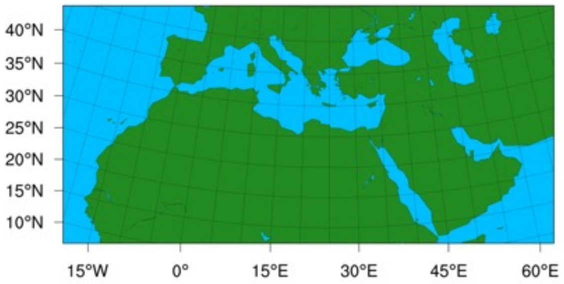
WRF-Chem vs AERONET

esa



1 September – 3 November 2020

Model Domain



AERONET alpha (440-870nm)
AERONET AOD
(AOD≥ 0.1)
Assimilated (hel4)
Control (hel1)

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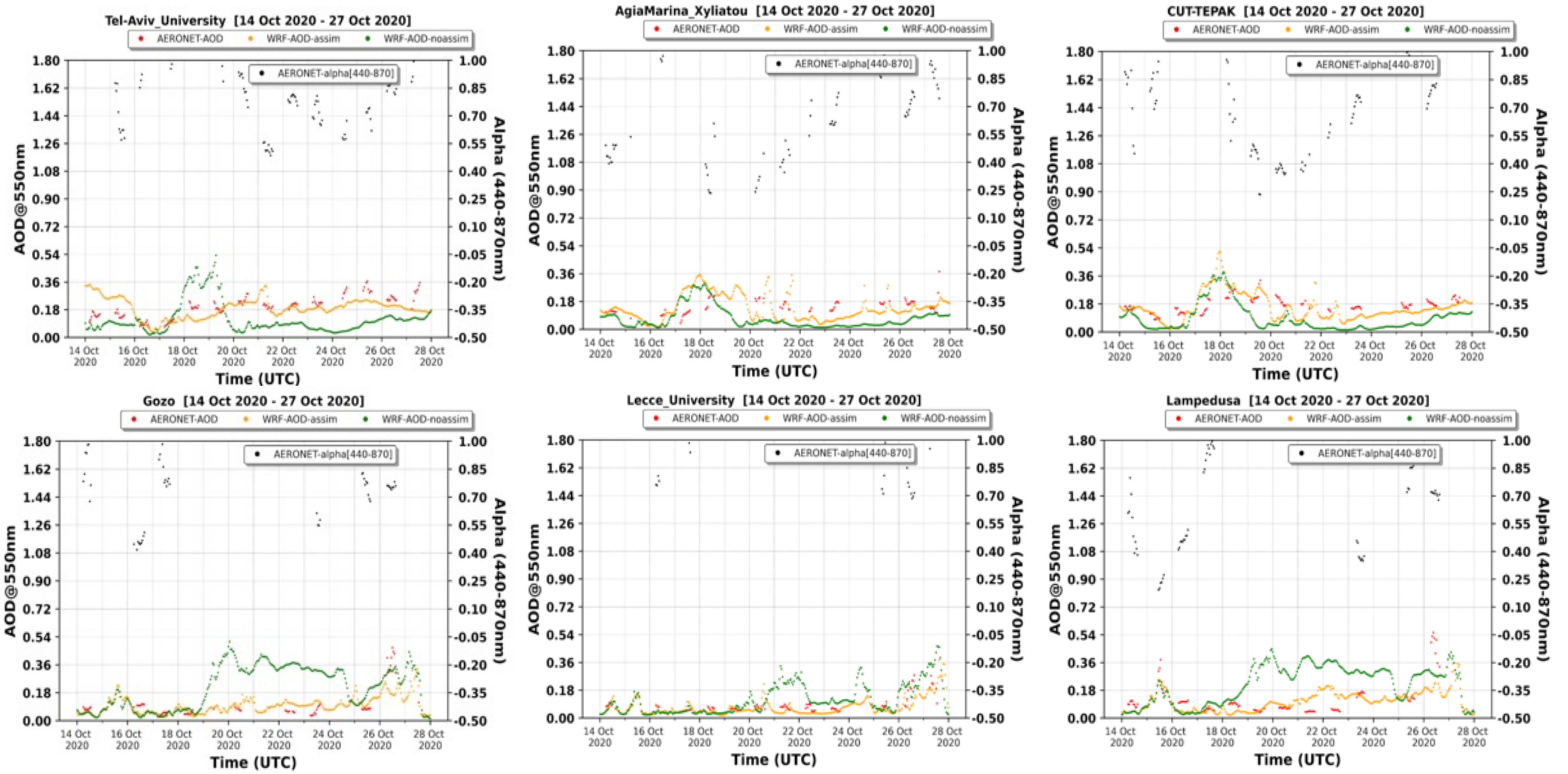
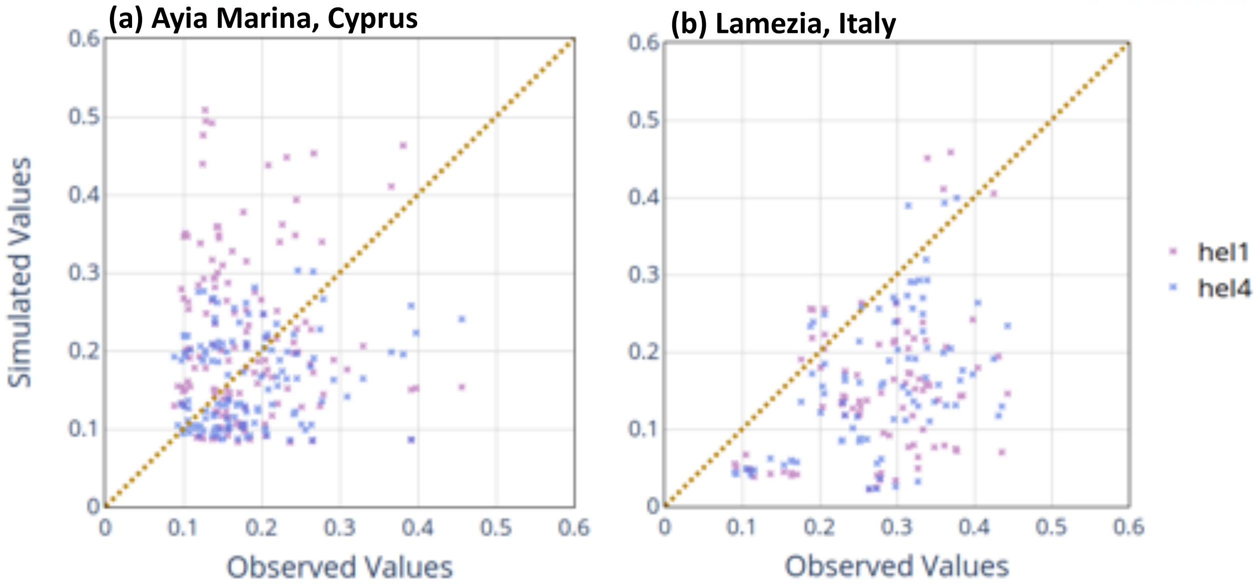
WRF-Chem vs AERONET



AERONET alpha (440-870nm)
AERONET AOD
(AOD≥ 0.1)
Assimilated (hel4)
Control (hel1)

- 6 stations situated in the **EMME and Central Mediterranean** for the period 14 – 27 October
- Overall **hel4 scores a correlation coefficient and IOA**, on average 0.20 and 0.13 **higher than hel1** respectively

WRF-Chem vs AERONET



	Selected Stations 14-27/10/2020		Selected Stations 14-19/10/2020		Selected Stations 20-25/10/2020		All Stations 14-27/10/2020	
Datasets	**hel1**	**hel4**	**hel1**	**hel4**	**hel1**	**hel4**	**hel1**	**hel4**
Counts	489 (9.7%)		226 (4.5%)		263 (5.2%)		5033 (100%)	
R	0.10	0.30	0.23	0.43	0.22	0.44	0.45	0.50
IOA	0.40	0.53	0.48	0.59	0.37	0.52	0.43	0.46

- **Reduction of bias** with introduction of hel4.
- Synoptic analysis of all stations within the defined time-period may dilute the improvement.
- Focusing on the **stations within the Central and Eastern Mediterranean** results in overall marked improvements from the incorporation of hel4.

Figure 7. Scatter plots of hel1 (purple) and hel4 (blue) against observations for two stations, one in Cyprus (a) and one in Italy (b). Additionally, the table depicts statistical metrics for the comparison of hel1 (control run) and hel4 (assimilated run) to observed AERONET AOD for the aforementioned stations, within defined timeframes.

WRF-Chem vs MIDAS

- **Columnar aerosol optical depth (AOD) at 550 nm**
- **Spatial/Temporal resolution:** 0.1° x 0.1° / Daily
- **Glonal Spatial coverage** (over land and ocean)

- **hel4: Reduction of positive bias**
- Attributed to the control run simulating an anticyclone, which does not materialise in the assimilated run.

Table 3. Statistical metrics for the comparison of hel1 (control run) and hel4 (assimilated run) to observed MIDAS AOD for the whole period and for selected regions

	Whole Domain		0E,30N to50E,40N		Syria		Central Mediterranean	
Datasets	hel1	hel4	hel1	hel4	hel1	hel4	hel1	hel4
Counts	20606 (100%)		3773 (18.3%)		1060 (5.1%)		1421 (6.9%)	
R	0.52	0.54	0.33	0.61	0.51	0.62	0.56	0.71
IOA	0.71	0.72	0.51	0.72	0.54	0.64	0.71	0.80
NMB	57%	52%	51%	28%	-43%	-35%	67%	22%

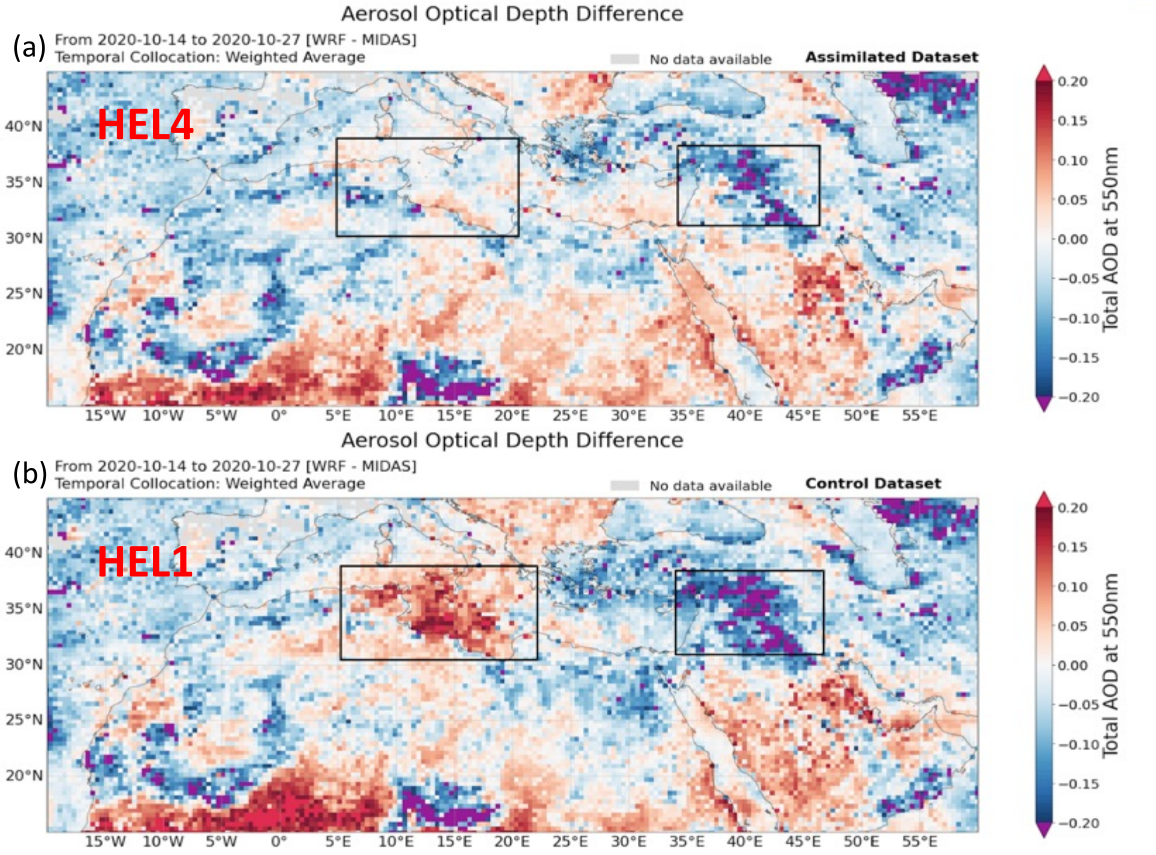


Figure 8. Representation of the time averaged differences in AOD (WRF-MIDAS) for the assimilated run (a) and the control run (b), where the black boxes indicate regions of significant improvement when simulating conditions using hel4.

Evident improvement of the simulated AODs, thanks to Aeolus wind data assimilation, in areas with dust presence

WRF-Chem vs LIVAS

- **Dust Mass Concentration remote sensing**
- **Vertical resolution:** 60 m.
- **Spatial resolution:** 1° × 1°.

- Both hel1 and hel4 are overestimating vertical dust concentrations, but with the highest difference of 500 and 300 µg/m3 relative to LIVAS

Table 4. Statistical metrics for the comparison of hel1 (control run) and hel4 (assimilated run) to observed LIVAS vertical dust concentration.

Dataset	hel1	hel4
Counts	20606	
R	0.36	0.40
IOA	0.54	0.62
NMB	48%	22%
RMSE	90	68

- At (32.5N, 15.5E) in the control run, the pronounced anticyclonic activity mobilises dust, which is not present neither in hel4 nor in LIVAS

- Introduction of hel4 reduces positive bias by 26% and improves r by 0.04

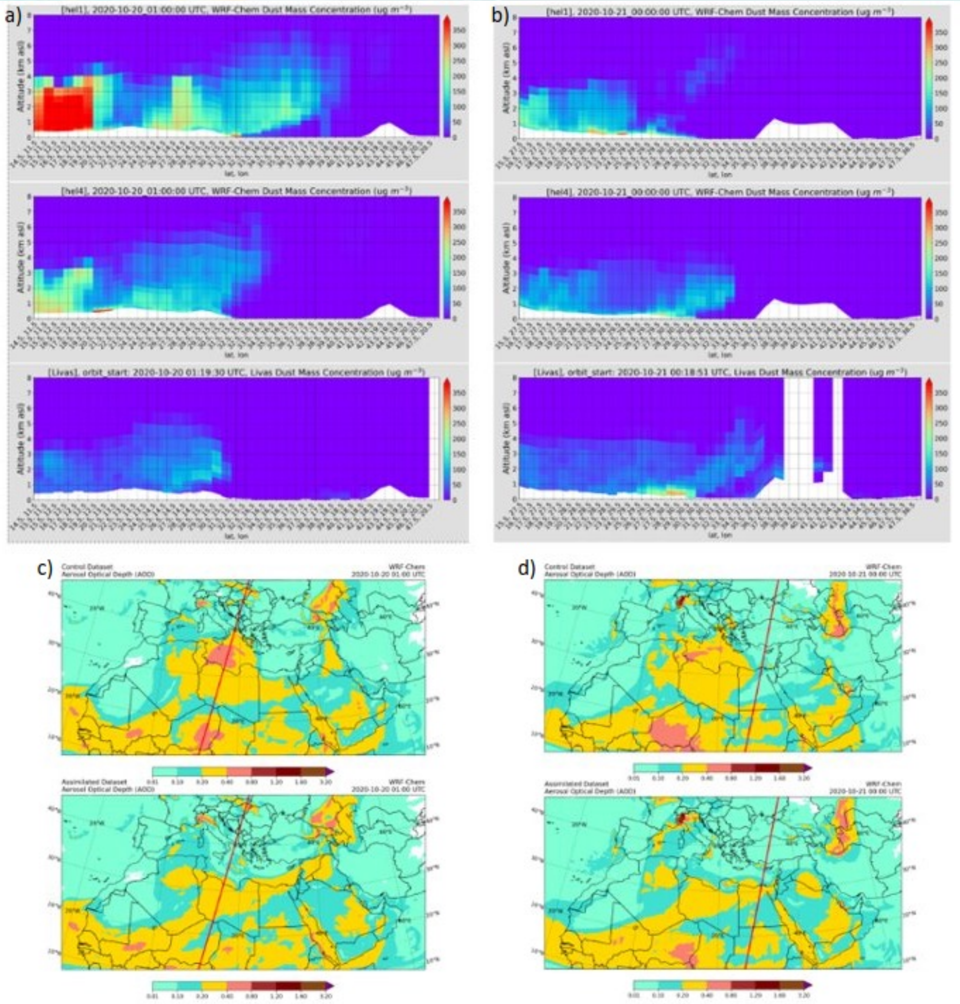
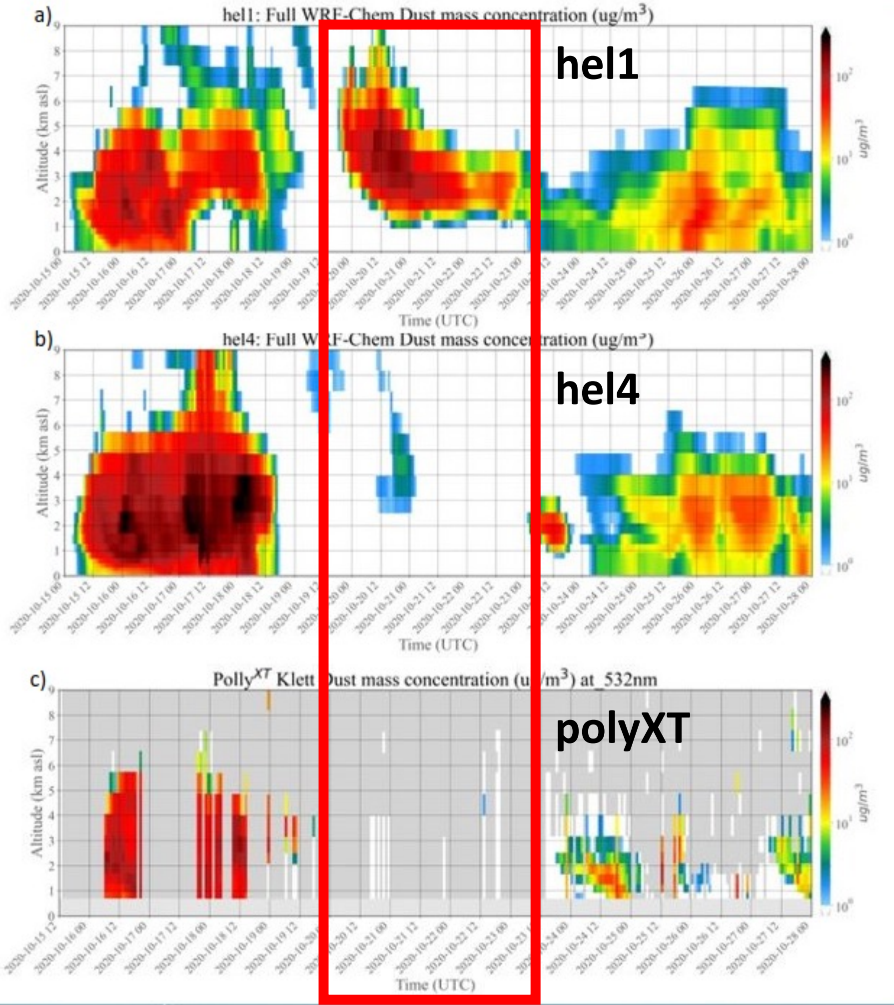


Figure 9. Collocated hel1 and hel4 to LIVAS depicting vertical dust concentrations for the dates; 2020-10-20-01:00 (a) and 2020-10-21-00:00 (b) along the CALIPSO tracks represented by the red lines in the horizontal AOD simulated values for hel1 and hel4 (c, d).

WRF-Chem vs PollyXT

- **Dust Mass Concentration above Antikythera, Greece station**
- **Ground-based Lidar Vertical resolution:** 60 m
- October 2021

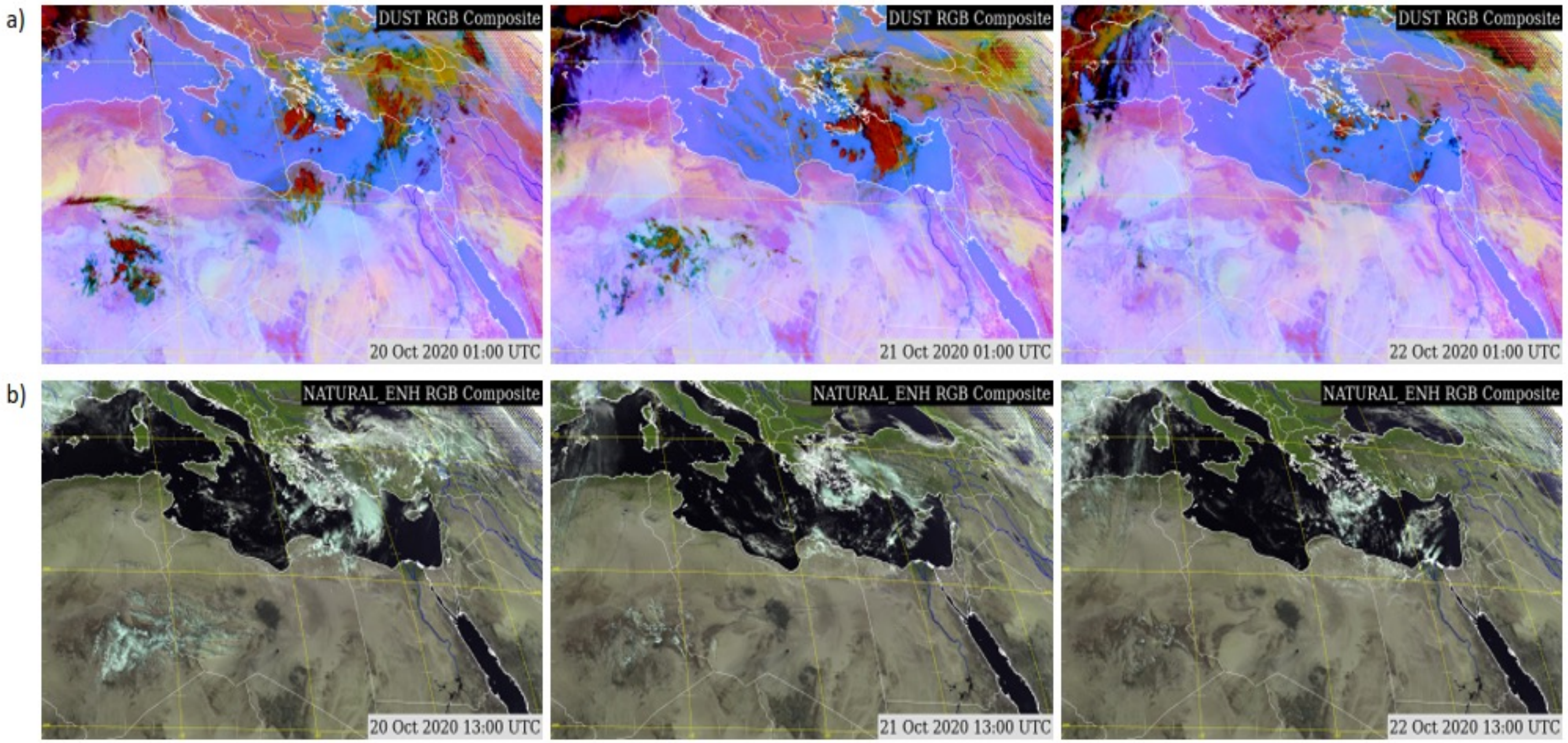
- ***15th to the 19th***: hel1 underestimates, hel4 overestimates, with better fit.
  - Note: 20-30% uncertainty in the lidar product (Ansmann et al., 2019).
- ***20th to 22nd***: hel1 simulates a dust plume over Antikythera, not in hel4!
  - Attributed to the pronounced anticyclonic motion in simulation.
- ***23rd to the 28th:***
  - hel4 simulates a dust plume arrival earlier than observed, whereas hel1 simulates lower values of a different vertical structure



WRF-Chem vs PollyXT

- ***20th to 22nd Oct*:**
  hel1 simulates a dust plume over Antikythera, Greece not in hel4:

- hel4 in clearly **better agreement with complementary observations from MIDAS dataset and SIVIRI**



Satellite imagery over Antikythera from the 20th to the 22nd of October

(a) Dust RGB composite colour is shown for night-time imagery at 01:00 UTC

(b) Natural enhanced imagery is shown for 13:00 UTC.

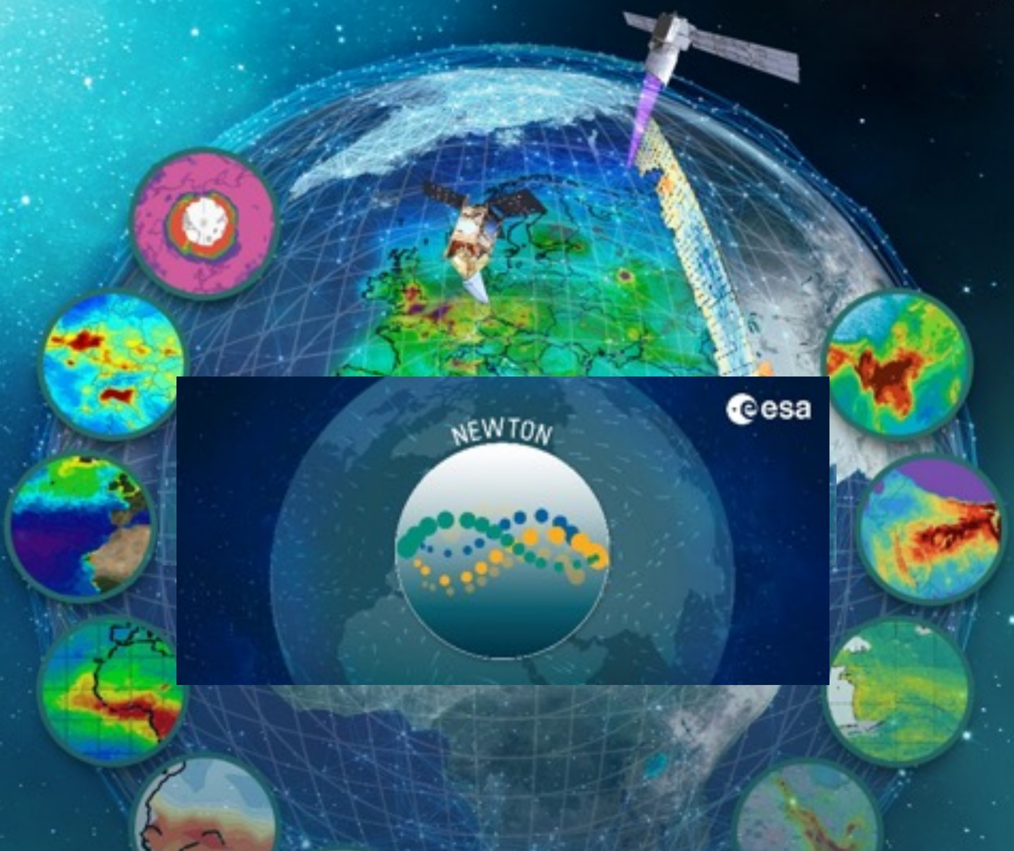
Conclusions

Synopsis

- Upstream assimilation of the Aeolus products improves skill of WRF-Chem model of aeolian dust over the East Mediterranean and Middle East regions for the autumn period.
- Statistical metrics: Marked reduction of positive bias and underestimates.
- Quantitative benefits: source of dust emissions, arrival of plumes, vertical structure of transport corroborated by multiple instruments/modalities.

Outlook

- Effect of assimilated dataset on the WRF-Chem may vary seasonally:
    - Inclusion of the Aeolus products during the spring months leads to an small divergence of meteorological conditions from the control products in the study region.
- Initial model findings to be confirmed/strengthened as more AEOLUS data is amassed



Thank you for your attention!

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