Sahara: Adventures in vertically resolved aerosol products and assimilation

Jeffrey S. Reid and Juli I. Rubin; U.S. Naval Research Laboratory
Robert E. Holz, Amanda Gumber, and Willem Marais SSEC; U. of Wisconsin
With late breaking goodies from Melanie Ades; Copernicus/ECMWF

And thanks to numerous data providers for discussions and data:
Sophie Vandenbussche (RBISA); Jun Wang (Iowa); Peng Xian (NRL); Jianglong Zhang (North Dakota) and our friends at EUMETSAT

16th ICAP Working Group
Bonn, Germany
June 2026

Comments to
jeffrey.s.reid20.civ@us.navy.mil

EUMETSAT

Harmattan Surge 2026-03-30 08:00:00 UTC

Bottom Line Up Front: Vertical Products Assimilation

As has been our theme of recent ICAP meetings, aerosol forecasting emphasizes Aerosol Optical Thickness because its accessible, timely, & well characterized. What about the vertical?

- MAGPIE/CPEX give a great opportunity to play with the assimilation of vertically resolved products:
  - Lidar, notably now HSRL on many fronts
  - IR Sounder with potential for coupled dust, water vapor, and temperature profiles.
  - Vis hyperspectral products for aerosol centroid height.
  - Other network? Ceilometers, surface stations, etc
- Quality? All of the above exist in coverage-accuracy trade space. And with so many, product preparation/QA steps.
- For the vertical, **species dependent assimilation becomes implicit**.
- DA outcomes? Coverage still wins, but there are clear benefits to assimilation that don't always come out in raw scores. E.g., MAPIR improves speciation. Probably the same for 3MI.
- Discussion topic(s): Should we be striving for a harmonized integrated analysis for assimilation instead of assimilating a dozen products?

Adding dimensionality to data assimilation

The Past: Flatland

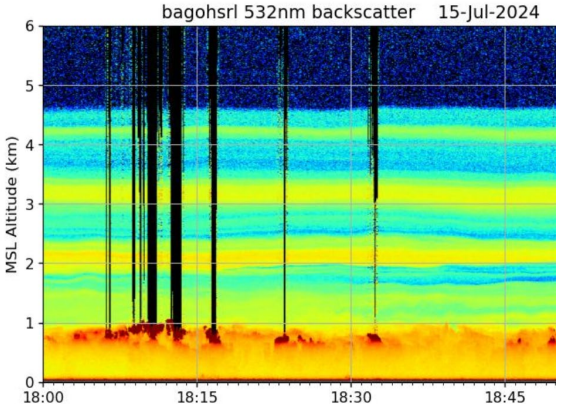
- Global aerosol monitoring & data assimilation is largely through satellite AOD & AOD/PM networks. Why? Coverage, ease, accessibility etc.
- Lots of demonstrations surface & airborne obs, lidar/ceilometer & CALIOP data is available, but the problem is more than data: More complex processing, information sampling, distribution/spreading, & error characterization. Oh, and the models need to get the physics right.

The Present: It's a good time to be an innovator.

- New observations and technologies are being developed. It is an exciting time to be in the business. But sensitivities to DFs are high.
- But, we still need to learn from flatland-especially accessibility and QA.

The future: Waiting for Moore's law.

- Processing and open data needs to catch up to ideas.
  - Easy to say "It will be all in the cloud" but getting there and making it all accessible is not straightforward.
  - Community tools are a must, as is thoughtful architecture and agency support
- Models & DA need to up their game, and perhaps change the current variational paradigm. Go object oriented w/ensemble & hybrid DA?

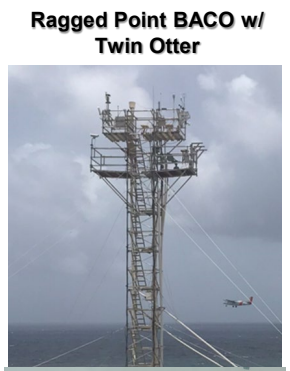


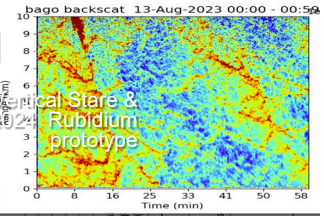
Vertical processes that need to be linked to observations; lets not talk about numerics.

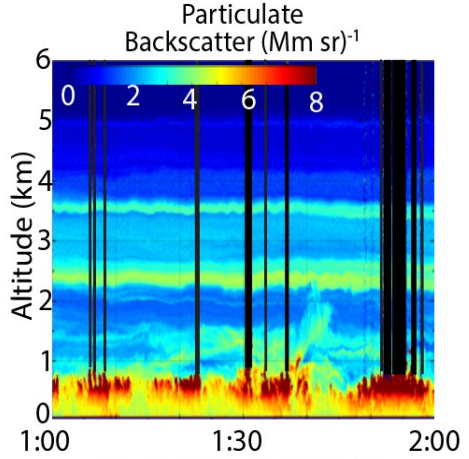
- **Planetary Boundary Layer:** The diurnal cycle is the aerosol system's heartbeat.
  - The persistent challenge of the surface layer. Not so much how it got there but how it gVerticets out.
  - The "Mixing" layer: Why do you assume it is mixed?
  - PBL clouds: Cloud turret injections into the FT and where much of the PBL's AOD variability resides
  - No man's land: Meso-γ interface, residual layers and PBL's nightly leftovers.
- **Free troposphere:** A more stratified nature compared with the PBL.
  - Injections: Plumes, clouds, and microfronts (sea/land breeze, cold pools etc.) and detrained precursors.
  - Shear and scavenging: How one big plume can become lots of little ones.
  - Synoptic: Poleward lifting, the warm conveyor, etc.
  - A host of misc. processes from gravity waves to cosmic ray particle nucleation.
- **Upper Troposphere/Lower Stratosphere:** Particles and precursor gases
  - Eruptions: Volcanic and PyroCb.
  - Convective detrainment and secondary particle production, e.g. single turrets and ascent within the Asian Monsoon anticyclone as transport pathway for ccn and precursor gases.
  - Folds? Danielson & Shapiro showed that while frequent, there may not be a significant net transfer of air.
- **Mid-Stratosphere**
  - Big eruptions + dynamics: Volcanic.
  - Secondary particle production and polar stratospheric clouds.
- **Higher????**
  - Meteor ablation, Cosmic rays, noctilucent and gravito/magneto-photophoretic processes, oh my.

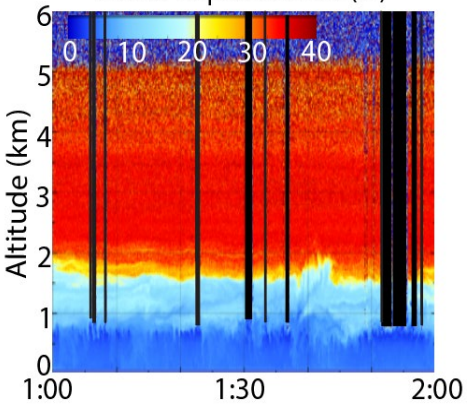
MAGPIE & CPEP-CV: Advance 4D obs & their application.

- MAGPIE and CPEX-CV created a wonderful opportunity to investigate vertical processes and model skill at work.
- CPEX (2021/2022) and MAGPIE (2023/2024) came online with new observing capabilities, including passive IR, hyperspectral UV/VIS, and now ATLID/EarthCARE.
- Take homes
  - New active remote sensors, including, lidar and SAR are game changers for mapping atmospheric variability and meteorological regimes.
  - SAL is really “SAL(s)”
  - Hygroscopic dust in the MABL.
  - Significant variability in light extinction due to cloud halos, detrainment, & individual updrafts/downdrafts from cloud base to the oceans surface
  - Processes are in two grey zones-meso to LES and LES to DNS.









MAGPIE: Ramifications of the Marine Boundary Layer Mixed and Surface Layer not being so well mixed

State of the Art: Drop/radiosondes and aircraft commonly measure the vertical state of the Marine Atmospheric Boundary Layer (MABL) and are used to infer processes like fluxes.

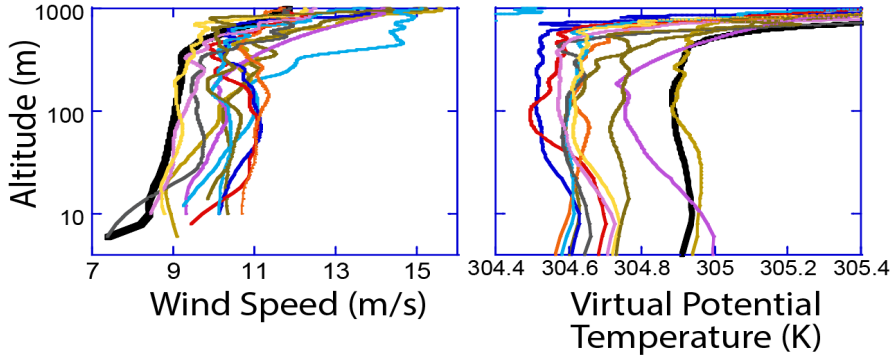
Challenge: The MABL can be inhomogeneous and ”little wiggles” in measurements from slight changes in the environment can bias model validation and significantly influence how processes are inferred.

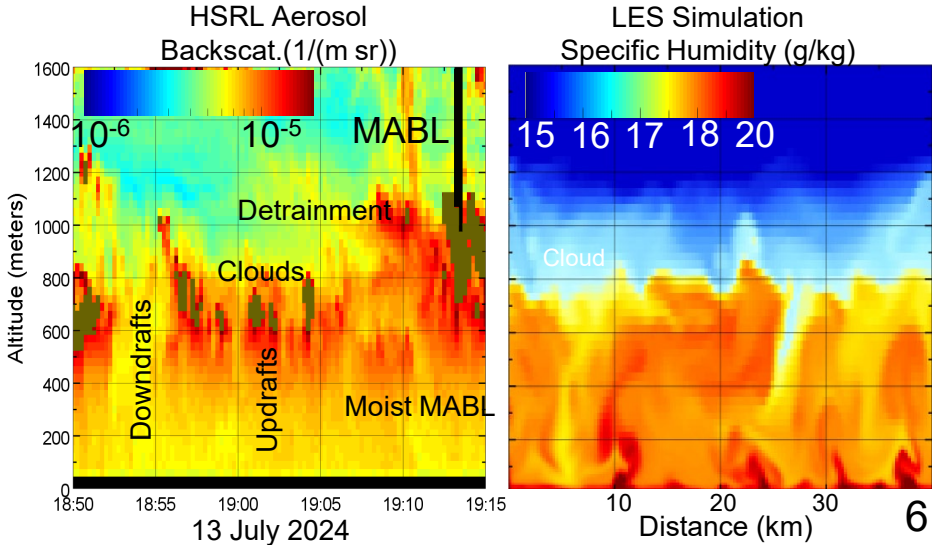
Demonstration of effect:

1) NOAA-P3 dropsondes over a large Saharan Air Layer Event (Avg in black), with 12 consecutive sondes just off of Barbados in color.

2) High Spectral resolution lidar aerosol backscatter is sensitive to humidity through particle hygroscopicity and then allows visualization of clouds, updrafts/downdrafts, and entrainment/detrainment. These fluxes can be traced through specific humidity.

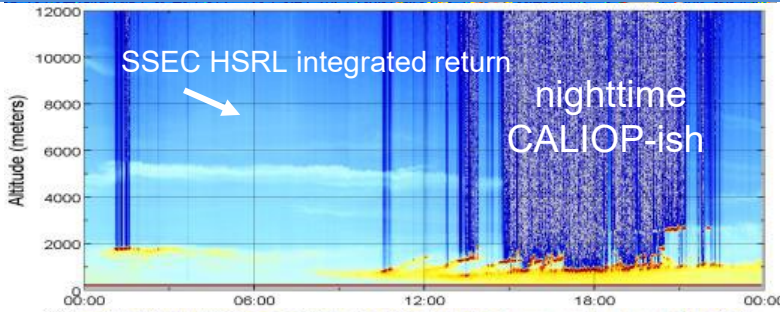
Ongoing: To close the system we are generating a MABL “Digital Twin using giga scale Large Eddy Simulations to better understand what an observation represents.

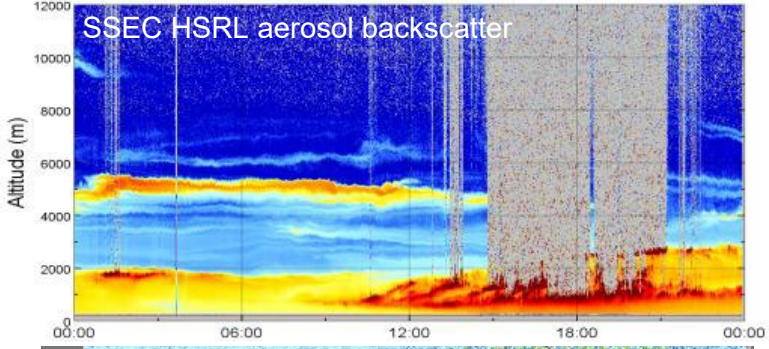


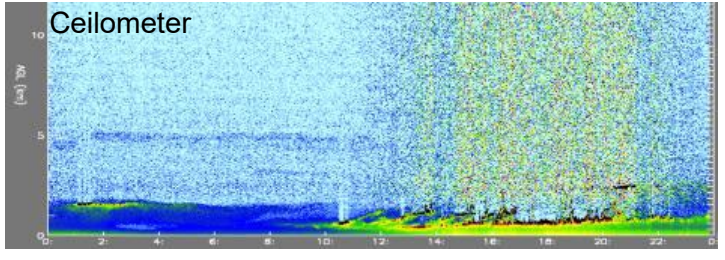


Where to find the vertical information: Lidars as an example of degrees of freedom

- **Elastic backscatter** lidars are the baseline: CALIOP and extensive ground lidar networks (e.g., MPLNET, NEIS, EARLINET). Inexpensive & numerous, uncertainty becomes less tractable with optical thickness from telescope. **Currently the US only has ICESAT2 in space.**
- **High Spectral Resolution Lidar**. More quantitative & easier error propagation. **ESA EarthCARE ATLID** & China ACHSRL in space.
- **Raman.** Can get some information…at night. Not sure where NASA+Italy LUCE project stands, or if it will evolve.
- **Ceilometer networks**: Qualitative, but plentiful & useful if we can work out the data flow.
- **All do well in the free trop, but persistent challenges:**
  - **PBL**
    - -Ground flash an issue looking down.
    - -Overlap zone looking up.
    - -Covariance with PBL cloud layers.
  - **Data integration** of the plethora of surface observations, including GALION and ACTRIS





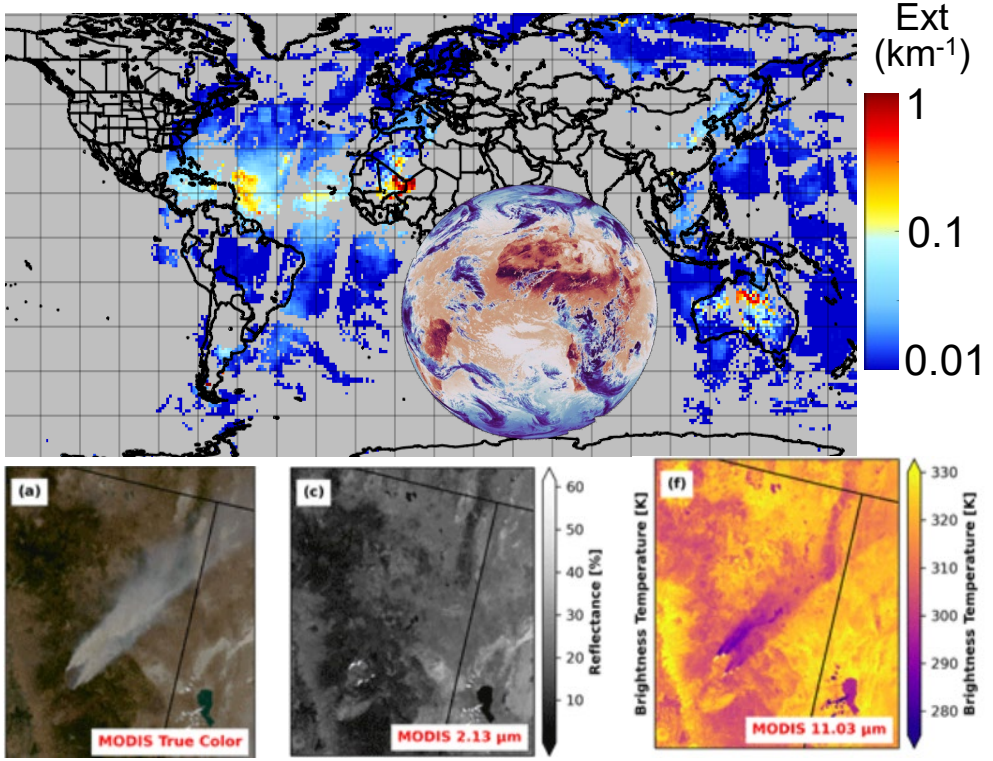


Where to find the vertical information: Infrared

Coarse mode degrees of freedom, with the potential of covarying T and RH.

- IASI, CrIS, show great promise for dust product operationalization AND diurnal coverage.
- Now with Infrared Sounder on MTG-S1, the door is wide open for unprecedented dust monitoring from the Red Sea to Barbados.
- Danger…complex error patterns. Still arguing over what IR signals from smoke-likely similar issues with dust, plus surface emissivity.
- But all of these are difficult to verify.
  - Extreme events are just that, atypical
  - High extinction challenge primary obs
  - Dusty regions have few obs to begin with.

METOP C IASI MAPIR 0-1 km Dust Extinction (550 nm)



Sorenson et al. Atmos. Chem. Phys., 24, 1231–1248, https://doi.org/10.5194/acp-24-1231-2024, 2024.

Where to find the vertical information: Emerging Passive Visible
Coverage over specificity, and a little more thought as to what it all means

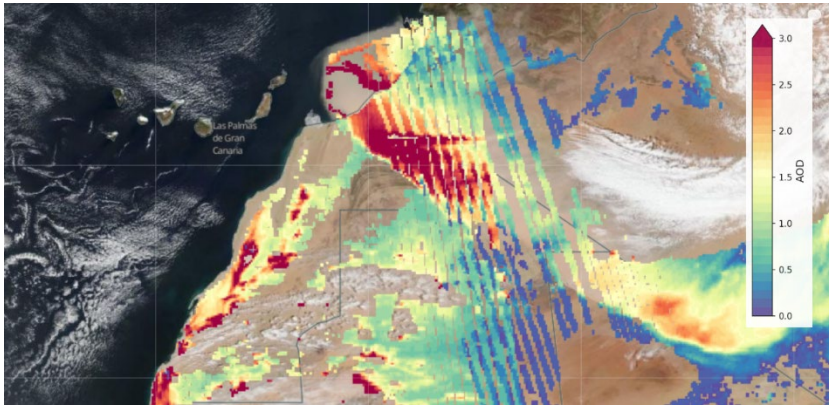
Spectral methods: The best coverage.
- Past: UV Aerosol Index dependencies: If it is 10, you know it is UTLS. Otherwise….
- Present: IR sounder dust profiles begin operationalized.
- Oxygen A&B + UV: Plume optical centroids TROPOMI, EPIC.
- Future: TEMPO usable geostationary products coming out soon?

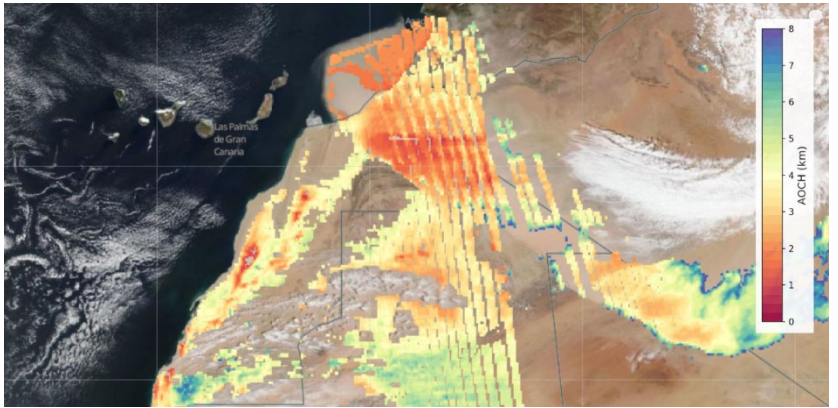
Stereography: Excellent bang for the buck for plume topography.
- MISR can easily pick out features, but on its way out.
- Can be adaptable from Geo to high resolution.
- Future? Multi angle polarimetry & cameras.

A good eye: Inference and machine learning.
- Sometimes just looking at an image or a loop can tell you a lot about the vertical nature of an aerosol feature-ripe for ML.
- Optical flow/feature track wind.
- Vertical wind shear is your friend.
- Hmm, maybe for dust with geo sounder…?

Iowa TROPOMI AOLH Product: 30 MAR2026

https://esmc.uiowa.edu/apps/tropomi_aoch/



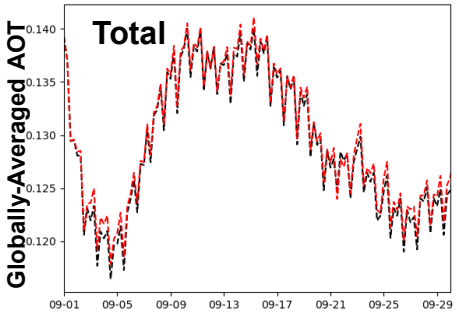


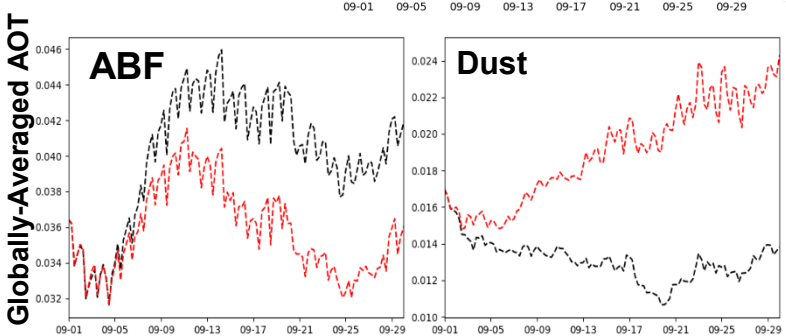
Pulling the String Through Rubin's MAPIR IR Dust AOT Product Assimilation

- Worked with EUMETSAT and SSEC to generate MAPIR products for Sept 2022 time period (CPEX mission). **Started with the dust AOT product.**
- Data assimilation experiments conducted in ENAAPS EAKF: 1) standard **MODIS + AERONET total AOT** 2) **MAPIR dust AOT + MODIS/AERO total AOT**

1. Negligible difference in total AOT, but positive shift in speciation:

MAPIR results in a shift from fine-mode aerosol (ABF) to more coarse-mode dust:



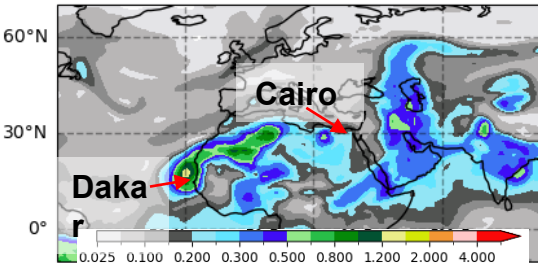


2. Coarse-mode aerosol verification indicates reduction in RMSE/bias and improved R^2 with MAPIR:

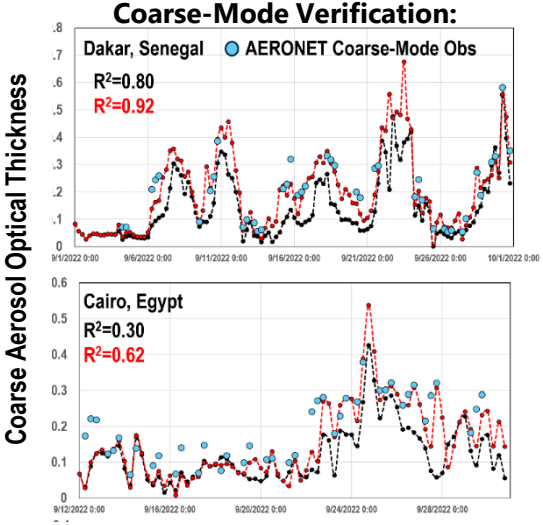
		RMSE		MAE	
Conditions:	# Obs	MODIS+AERO	+MAPIR	MODIS+AERO	+MAPIR
AOD>0.3, All Points	997	0.136	0.113	-0.079	-0.038
CAOD>0.3, All Points	120	0.306	0.250	-0.217	-0.142
CAOD>0.3 and >50% Coarse Fraction	113	0.093	0.062	-0.213	-0.139
CAOD>0.3 and >70% Coarse Fraction	89	0.097	0.064	-0.203	-0.135
CAOD>0.3 and >80% Coarse Fraction	54	0.095	0.067	-0.175	-0.126

Key Takeaway:

MAPIR Dust AOT assimilation improves Coarse-Mode AOT predictions and implicitly speciation.



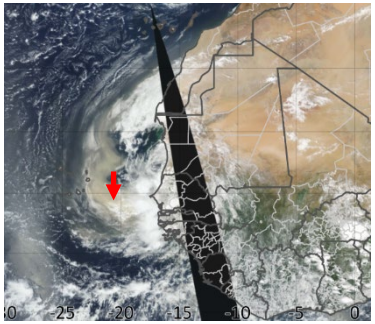
Coarse-Mode Verification:

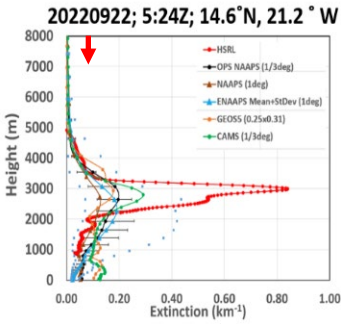


Noise-floor imposed of AOT>0.3. This limits MAPIR impact to large dust events.

Next, MAPIR Vertical Product Assimilation

Sept 22, 2022 was the most significant dust event during the CPEX campaign. All models were found to greatly low bias aerosol optical depth/extinction.





ENAAPS EAKF was successfully set up to take in MAPIR 1km vertical resolution dust extinction.

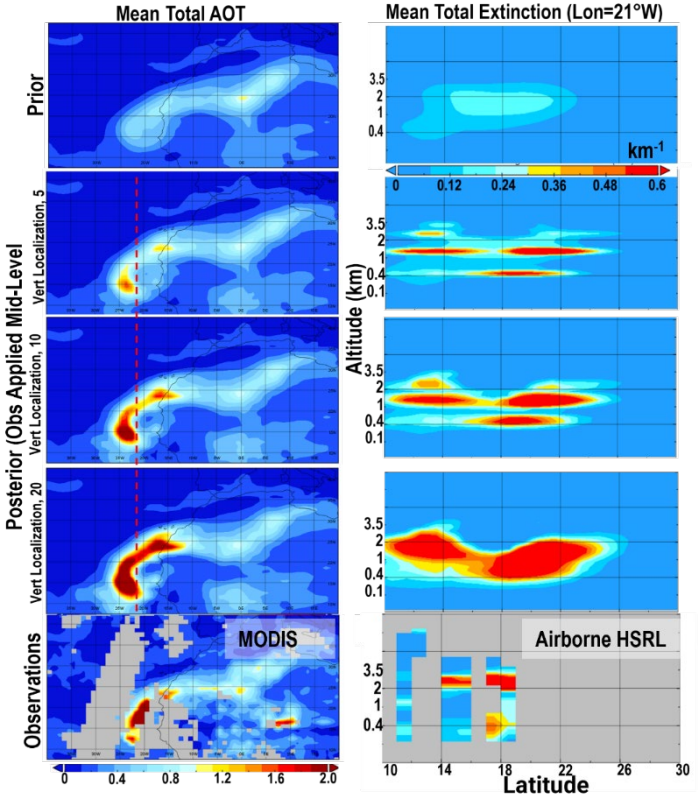
Initial data assimilation tests for evaluation were conducted for Sept 22.

Downside: Coarse vertical resolution (1km layers); Upside: Big positive impact. Day and night information. Plans to be operationalized.

Sensitivity Tests were conducted with varying Vertical Localization:

Noise-floor of Dust AOT>0.3 imposed based on observ evaluations. Limits impact to larger dust events.

- For these experiments, obs applied at mid-level (ie. 500, 1500, 2500m etc).
- Incorporation of MAPIR ext in all configurations greatly increases extinction/AOT.
- Results are sensitive to vertical localization settings.
- Very tight localization (5) results in very thin layers and broader localization (20) produces one large layer.
- Something in between seems more appropriate (10), although layer altitudes not quite right with the mid-level application.
- Preparing some cycling tests to see how the corrections play out and feed back on the model over longer time periods.



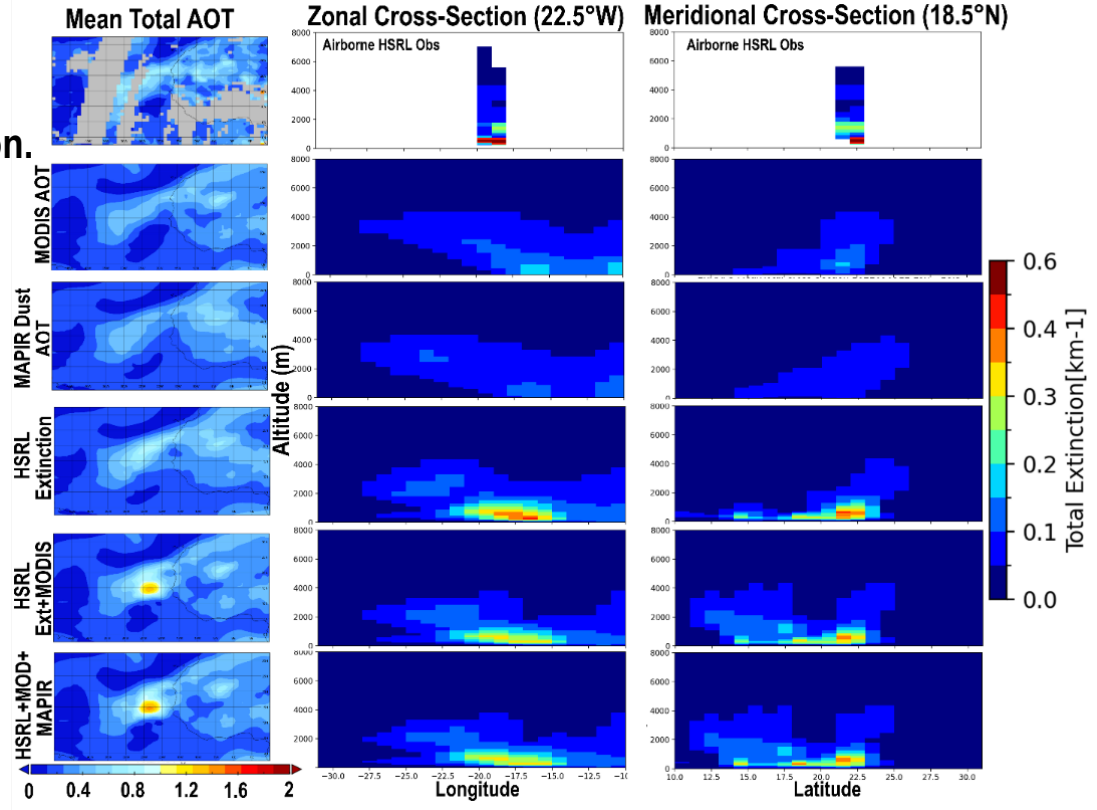
Vertical Product Assimilation (LaRC HSRL+Multi-Sensor)

- **Last year we conducted some initial tests with HSRL assimilation in ENAAPS.**
- **Since then, we have been able to conduct:**
  1. **Cycling tests of airborne HSRL assimilation.**
  2. **Multi-sensor assimilation tests with HSRL.**

ENAAPS EAKF was successfully set up to take in MAPIR 1km vertical resolution dust extinction.

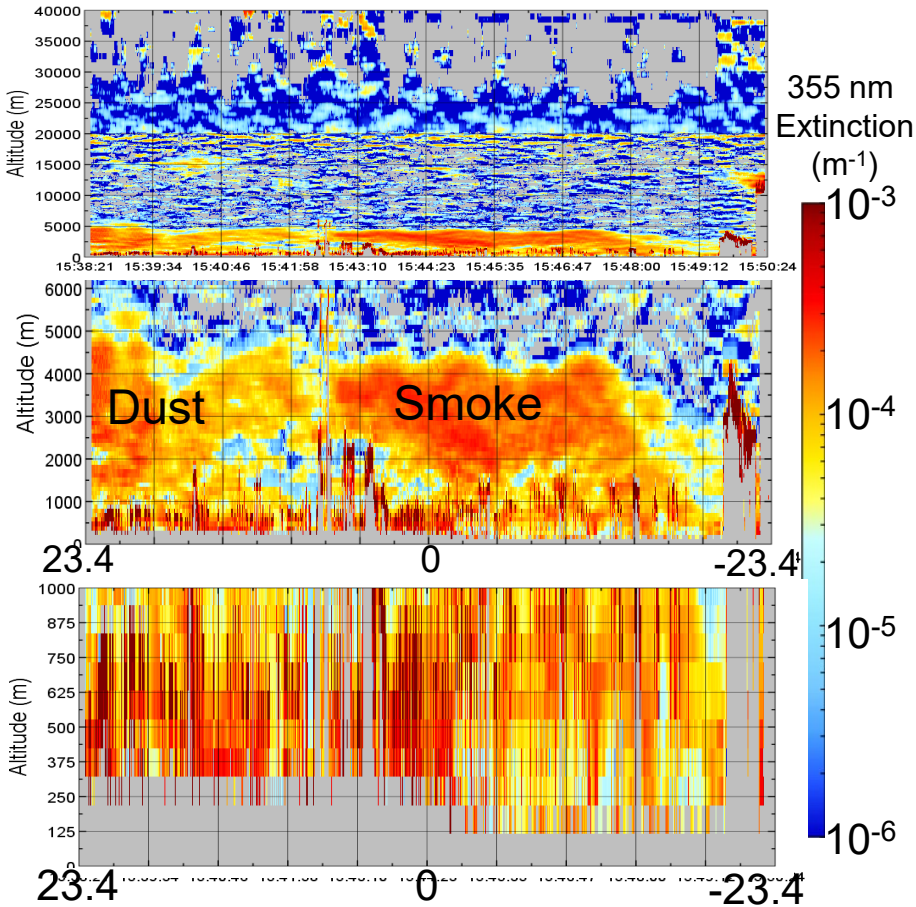
Initial data assimilation tests for evaluation were conducted for Sept 22.

Downside: Coarse vertical resolution (1km layers); **Upside:** Day and night information. Plans to be operationalized.

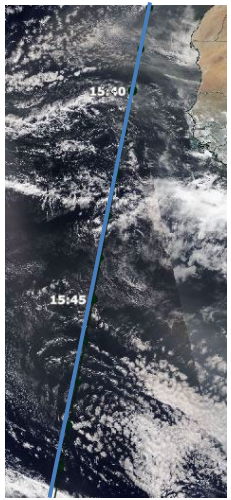


Next up! EarthCARE ATLID

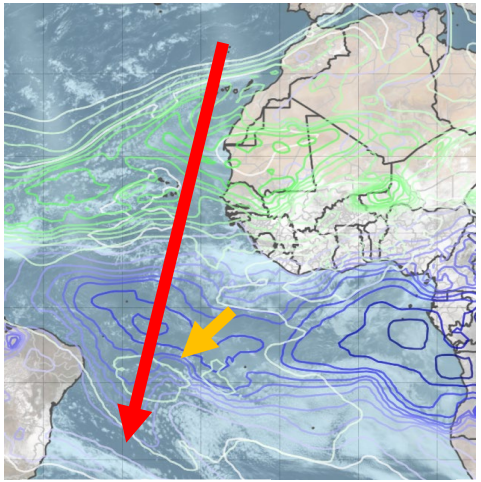
- Latest estimates on fuel and drag have EarthCARE operational until 2034+: Operationally viable- Woohoo!
- ATLID backscatter, lidar ratio, extinction, depol are at 355nm which complicates things. We need adjustments for DA and verification.
- Implicit for ATLID assimilation is some form of species assimilation. That means we also have to verify the ATLID speciation.
- Separate ESA and JAXA product lines. ESA more reusable but highly smoothed in both backscatter and extinction => Issues: Boundary layer and haloes around convection. High horizontal correlation versus vertical.
- ATLID has some production going back to 30July2024, and reported full production from 13AUG2024



13 Aug 2024



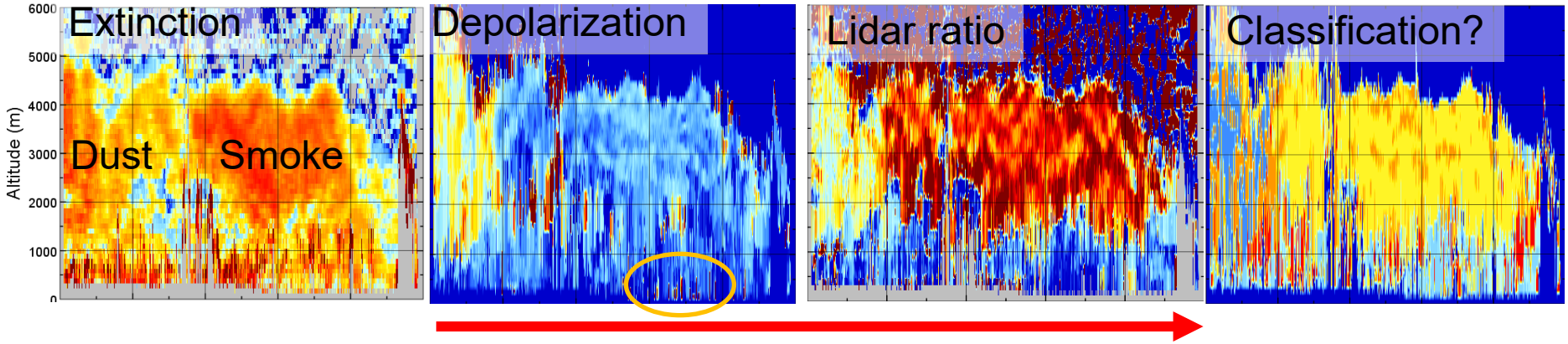
ATLID: Dealing with 355nm versus 532/550 nm



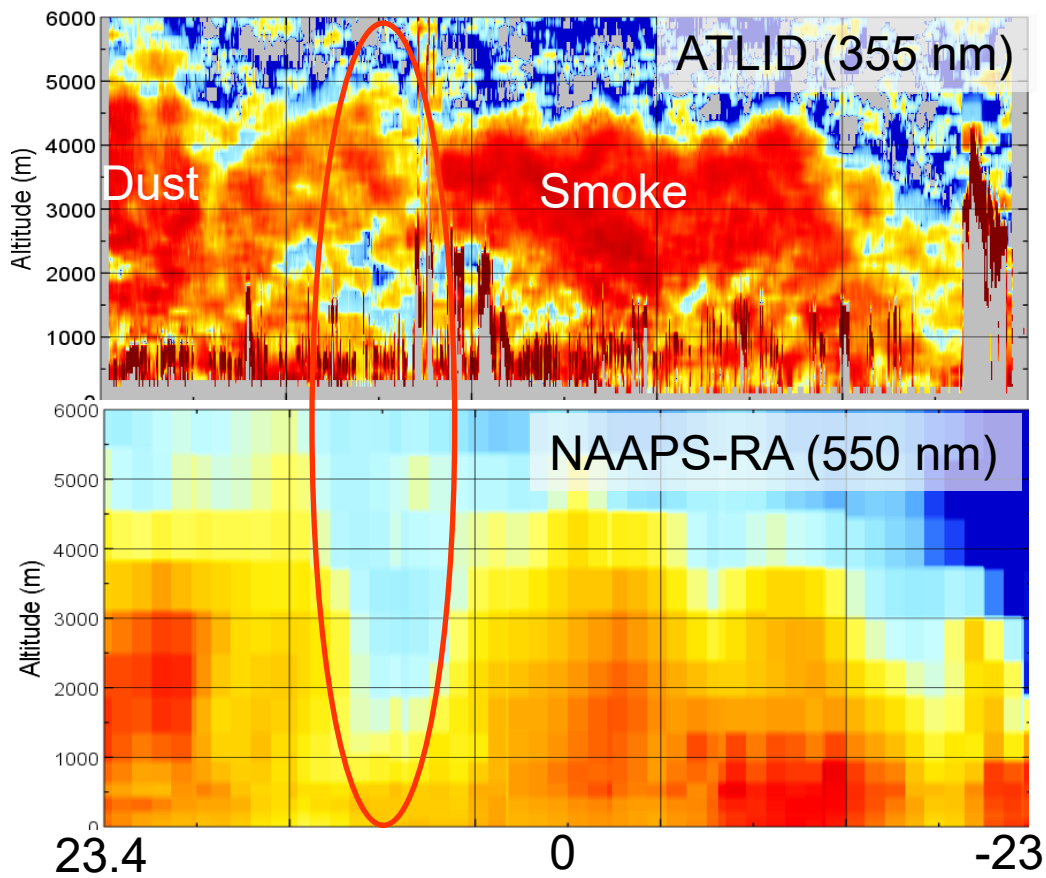
- Wavelength dependency dominated by fine particle size.
- Earlier attenuation (AOT~2). Noise floor ~0.04 km^{-1} ish…
- Dust has more variability in depolarization and lidar ratio.
- Smoke depolarizes more at 355 than 532 nm.
- Strong variable absorbers in UV (iron and Brown Carbon).
- Many of the native aerosol classes are ambiguous mixtures.

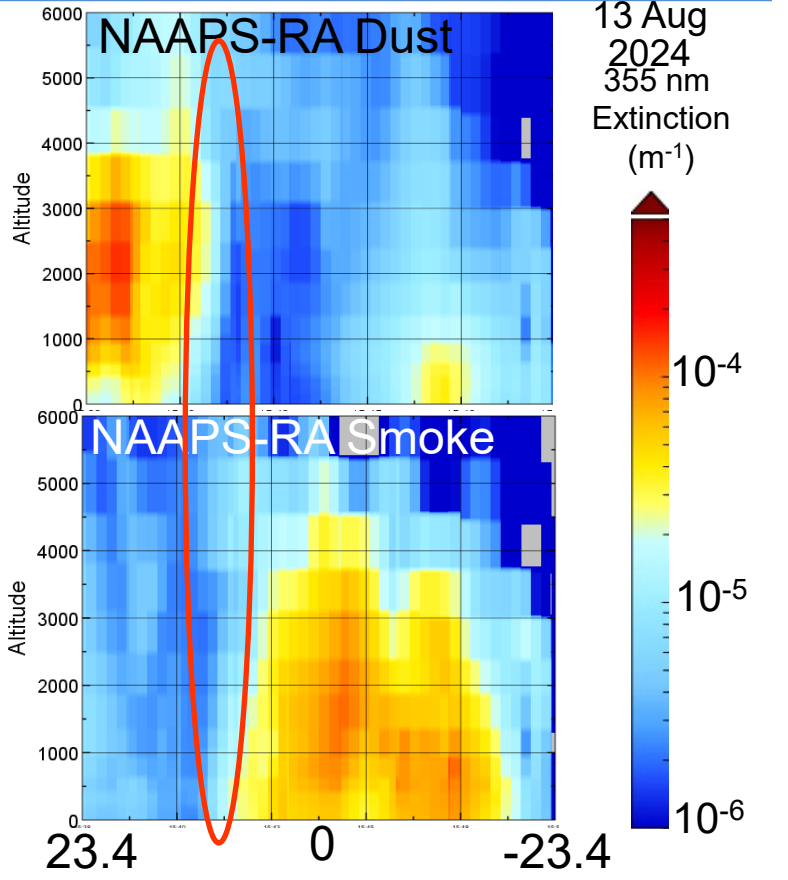
Good news: They map everything to aerosol backscatter.

⇒ Need to make the switch to species dependent assimilation.



First Comparison to NAAPS-RA: Low bias for big events and near the surface. No man's land for mixtures is complicated.

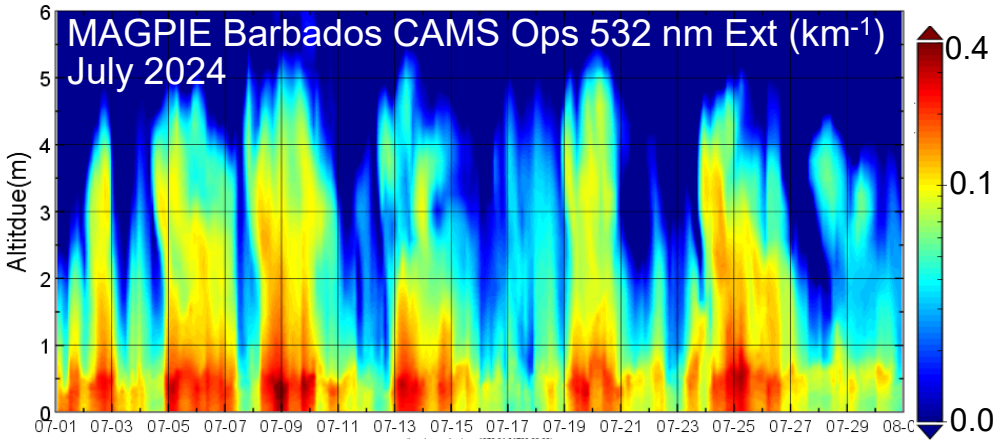


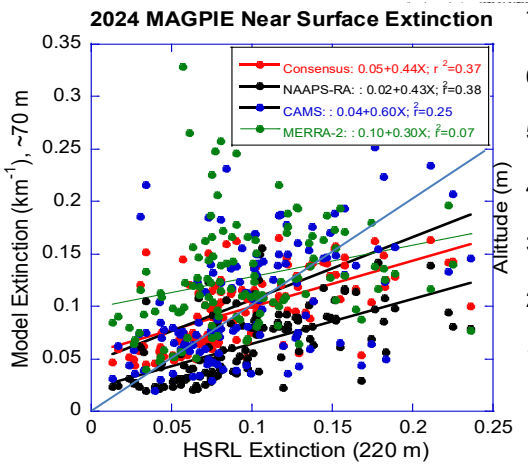


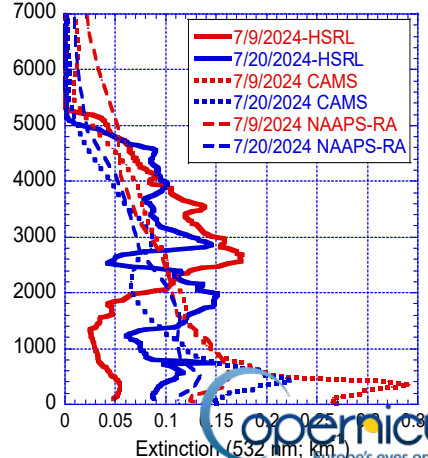
Switching Models: CAMS as a testbed on NWP impact

Late breaking goodies from Melanie Ades

- There are many things going on simultaneous in simulation-land, and the CAMS archive is a good place to look.
- Three runs in the archive: Full aerosol DA & aerosol diabatic effects; diabatic but no aerosol DA; no diabatic or aero DA.
- Questions:
  - What does AOT DA do to the vertical redistribution and speciation as a comparison to NAAPS/ENAAPS?
  - Does diabatic heating have a noticeable effect in temperature and humidity at analysis?
  - Does vertical distribution error translate to NWP feedback error?
- This is the start of a long process. But we need to start somewhere. Focus is on July 2024 MAGPIE Obs at Barbados







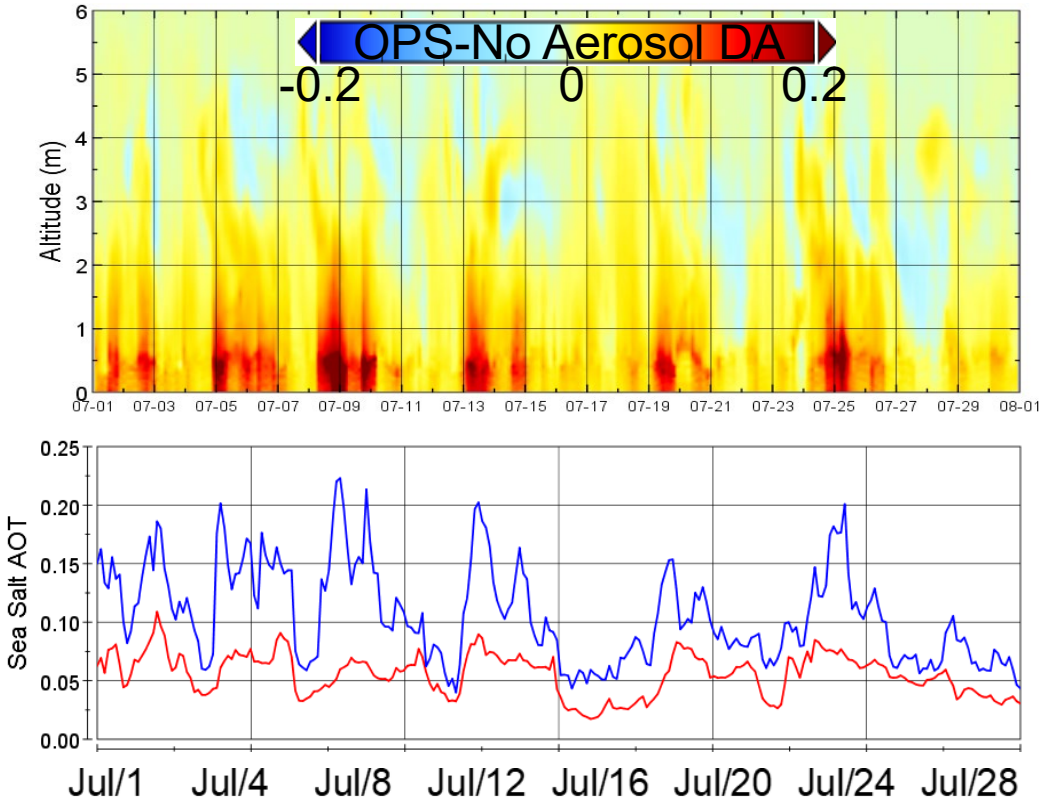
Effect of Aerosol DA With AOT DA- Without

Comparisons of what DA does to CAMS shows similar findings as Rubin in ENAAPS:

Good: AOT DA certainly improves AOT prediction.

Bad: AOT DA relies on the model, and the model doesn't do elevated plumes well so there is a net push of particles down. Its not all bad-concentrations do go in the right direction. But…

Ugly: Model priors in speciation likewise can lead to nonlinear error expansion, especially related to the MABL



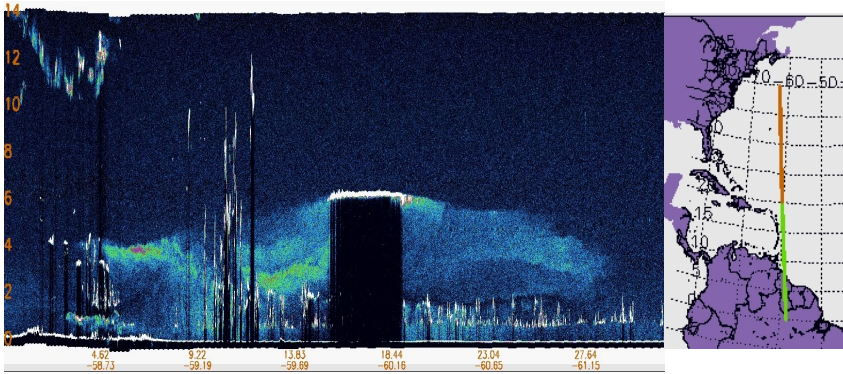
Where to get species information? 3MI?

- 3MI will give us information on:
  - AOT total, fine and coarse at 8 wavelengths
  - AAOD total, fine and coarse at 8 wavelengths
  - SSA total, fine and coarse at 8 wavelengths
  - Others such as fine mode fraction, aerosol layer height etc.
- This information can be used in assimilation to provide information on the different species present, i.e. fine and coarse tracers.
- However, the information needs to make it from observation space back to model space.
  - How to do this with many more or different tracers in the model compared to the observation information?
  - Operational constraints prevent all tracers being used directly in the assimilation?
  - Memory or speed of computations not possible in operations?
  - Cross-species covariances not available for all tracers? Dust versus sea salt?
  - Oh, did we mention observation error?
- How to combine total AOT, vertical profile, dust AOT/profile and speciation information in a single assimilation calculation, including size ?

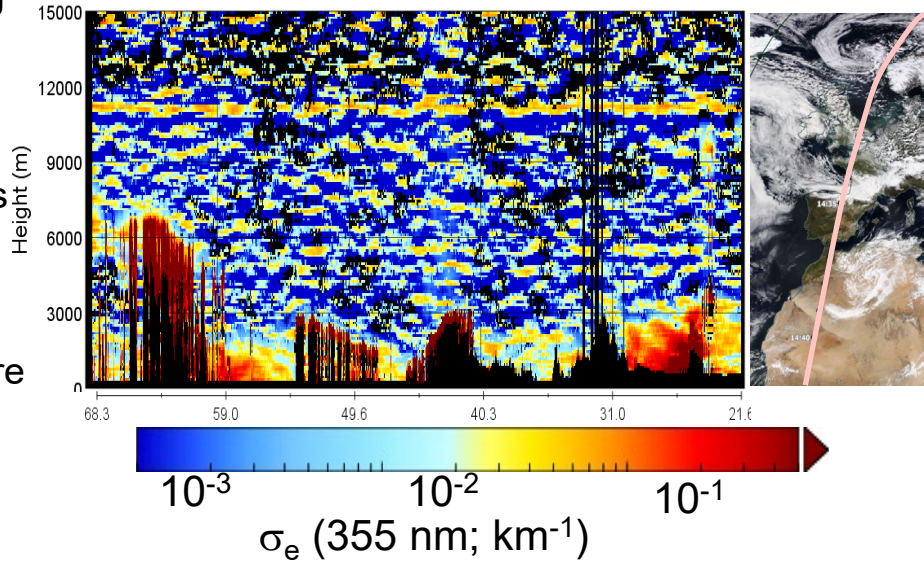
Closing thoughts and start of discussion

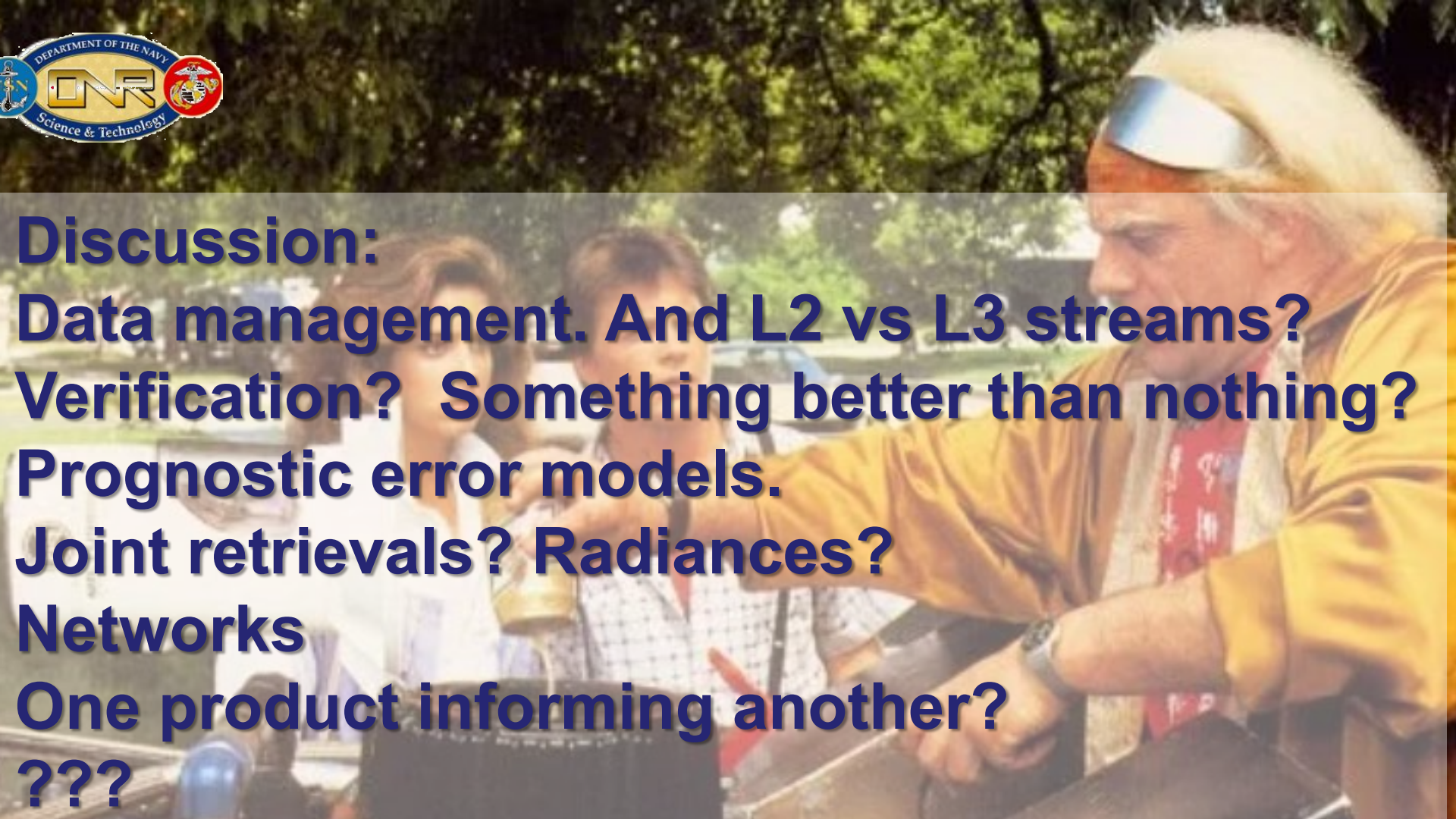
- Lots of new (dare I say exciting???) datasets out there that can add a vertical dimension, and yet we are still dealing with the MODIS->VIIRS transition.
- Africa-Caribbean corridor is a very good place to start.
  - Upside: Strong signal across spectrum; interesting physics; variability in surface characteristics.
  - Downside: Not nearly enough vertical obs to verify.
- Bigger data management issue coming. We already see verification issues with AOT (e.g., AERONET is necessary but not sufficient), but there is some proof in the puddling with assimilation tests. Current studies are encouraging.
- Speciation verification becomes a primary consideration.
- News: Miller (CSU) has a new ONR MURI on aerosol vertical distribution. Focus will be reconciling the physics with the obs.
- Question: At what point do we stop treating observations as independent?
  - EC/Copernicus biases corrected to Terra MODIS. There is no like benchmark for the vertical.
  - Models don't do well with the vertical in the first place.
  - Assimilate a multi sensor fusion?

ICESAT-2: 15AUG2023 MAGPIE Barbados



ATLID: 30MAR2026 Harmattan Event





Discussion:

Data management. And L2 vs L3 streams?

Verification? Something better than nothing?

Prognostic error models.

Joint retrievals? Radiances?

Networks

One product informing another?

???