MURI: Advancing littoral zone aerosol data assimilation in regime-dependent flows

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Outline

• Intro to Aerosols
• AOD forward operator
• Case study
• Assimilation results
Aerosols: suspended particles in air

Problems?

• Aerosols are short lived, have very large spatial and temporal variations in both their physical and chemical properties.

• Yet, aerosols have important climate impacts, and act as the “seeds” for cloud formation.

• Major aerosol types: smoke, dust, pollutant, and sea salt.
Why do we care?

- Aerosol particles affect climate
  - Scattering solar (SW) energy -- direct effect
  - Absorbing solar (SW) / earth emitted (LW) energy -- direct effect
  - Modify cloud properties (brighter clouds, longer cloud life time, indirect effects)
  - Absorbing aerosols heat air columns and evaporate clouds, semi-direct effect

- Aerosol particles affect air quality
  - E.g. Particulate Matter pollution (PM2.5 pollution)

- Aerosol particles affect visibility
  - E.g. diverting aircrafts, military applications

- Aerosol particles affect …
Aerosol Optical Properties:
Aerosol Optical Depth (AOD)

- **Extinction coefficient**: fractional depletion of radiance per unit path length (km\(^{-1}\)) due to scattering and absorption by aerosols

- **Aerosol optical depth** (AOD) or **thickness** (AOT): integrated extinction coefficient over a vertical column, \( I / I_0 = e^{-AOD} \)
  - AOD = 0  no aerosol effect
  - AOD ~ 1  “large”
  - AOD > 1  extremely high aerosol concentrations
Coupled aerosol-atmosphere data assimilation

- General multidimensional analysis solution (Kalman filter)

\[ x^a \quad x^f = P_f H^T \left( R + H P_f H^T \right)^{-1} [y \quad h(x^f)] \]

\[ x = \begin{pmatrix} x_{\text{atm}}^T \\ x_{\text{aer}}^T \end{pmatrix}^T \]

Standalone DA

\[ P_f = \begin{pmatrix} P_{\text{atm}} & 0 \\ 0 & P_{\text{aer}} \end{pmatrix} \]

Coupled DA

\[ P_f = \begin{pmatrix} P_{\text{atm}} & P_{\text{cross}} \\ P_{\text{cross}}^T & P_{\text{aer}} \end{pmatrix} \]

Cross-covariance between atmosphere and aerosol

(1) In standalone system: NEGLECT cross-covariance between atmosphere and aerosol

(2) In coupled system: USE cross-covariance between atmosphere and aerosol
Unconstrained adjustment in standalone aerosol DA

- Aerosol observations (AOD) are the main source of information for aerosol analysis
- Atmospheric observations have no impact on adjustment of aerosol guess

\[ P_{cross} = 0 \]

NEGLECT cross-covariance between atmosphere and aerosol
Aerosol observations (AOD) are the main source of information for aerosol analysis.
Atmospheric observations constrain adjustment of aerosol guess.
Together they form a more realistic analysis.

Constrained adjustment in coupled DA

\[ P_{\text{cross}} = 0 \]

USE cross-covariance between atmosphere and aerosol.
AOD Forward Operator

1. For each aerosol species split size distribution into logarithmically spaced bins.

2. Grow each diameter (each size bin) of the aerosol population hygroscopically to ambient RH (based on Petters and Kreidenweis (2007))

3. Adjust complex indices of refraction based on volume mixing rule assumption.

4. Generate the extinction efficiency for each bin using Mie Theory

5. Generate extinction coefficient for each bin by multiplying extinction cross section by number of particles in bin

6. Calculate extinction for each vertical grid box and sum across column to generate AOD.

7. Lookup Tables (LUT) created for 14 wavelengths and implemented into MLEF to calculate column AOD
GOCART aerosol module

- Georgia Tech/Goddard Global Ozone Chemistry Aerosol Radiation and Transport model (Chin et al., JGR, 2000)
  - **Bulk aerosol:**
    - Hydrophobic black carbon (fresh soot)
    - Hydrophilic black carbon (aged/coated soot)
    - Hydrophobic organic carbon (fresh burnt biomass)
    - Hydrophilic organic carbon (aged/coated burnt biomass)
      - Fresh $\rightarrow$ aged conversion time 2.5 days
    - Other GOCART primary PM2.5
    - Other GOCART primary PM10
    - Sulfate (only secondary aerosol species)
  - **Sectional scheme for dust and sea salt:**
    - Dust: 0.5, 1.4, 2.4, 4.5, 8.0 μm effective radius
    - Sea salt: 0.3, 1.0, 3.2, 7.5 μm effective radius
Hygroscopic Growth

- Each mode of the aerosol size distribution is grown independently to equilibrium with the ambient relative humidity.
- Kappa-Köhler calculation of growth factor for each mode and dry diameter

\[
\frac{RH(D)}{100} = \frac{D^3 - D_d^3}{D^3 - D_d^3(1 - \kappa)} \exp \frac{4\sigma_{s/a} M_w}{RT \rho_w D}
\]

\(RH\) – relative humidity
\(D\) – Droplet wet diameter
\(D_d\) – Dry diameter
\(\sigma_{s/a}\) – Surface tension
\(M_w\) – Molecular weight of water
\(\kappa\) – Particle hygroscopicity
\(R\) – Universal gas constant
\(T\) – Temperature
Adjust Complex Index of Refraction

- Volume mixing rule assumption for each mode and particle sized based on hygroscopic growth with water.
- For each mode, calculate complex index of refraction for each particle bin.

\[ V = \frac{1}{6} \pi D^3 \]
\[ V_d = \frac{1}{6} \pi D_d^3 \]
\[ V_w = V - V_w \]
\[ n = \frac{V_d}{V} n_d - \frac{V_w}{V} n_w \]

- \( V \) – Total particle volume
- \( n \) – Complex index of refraction (wavelength dependent)
- \( d \) – Dry component
- \( w \) – Wet component
Mie Theory

- Mie code is used for calculation of extinction efficiency for each mode and size bin.
- Based on wavelength, humidified particle diameter and complex index of refraction.
- Sphericity assumed for all particles.
AOD Observation Operator

AOD observation operator includes interpolation and transformation of the model guess (aerosol mixing ratio) to the AOD observation:

Transformation from aerosol mixing ratio to AOD:

\[ h(x, l) = \sum_{i=1}^{n} \sum_{k=1}^{K_{top}} E_{ext}(l, n_{r_i}, r_{eff_i}) x_k \cdot d_k \cdot d_k \]

- Wavelength
- Number of dust species
- Model top layer
- Refractive index
- Effective radius
- Aerosol mixing ratio
- Dry air density
- Model layer depth

Interpolation of AOD guess from model grid to observation location:

\[ h(x) = \sum_{j=1}^{J} w_j [h(x, l)]_j \]

- Interpolation coefficient
- Interpolation weight
Dust storm over Arabian Peninsula

- A plume originates in south western Oman on August 3, 2016.
- It advects over central Saudi Arabia, then extends out over the Persian Gulf by the morning of August 4\textsuperscript{th}.
- The plume remains in the region for the next few days as it slowly diffuses and thins.
- This case contains a strong plume that originates over land, moves over significant topography, and ultimately spreads over the region.
- MODIS (Aqua) image (right) of the dust plume.
Dynamic Enhancement Background Reduction Algorithm (DEBRA)

- A journal article describing the DEBRA algorithm has been submitted to the *Journal of Geophysical Research* (currently in review).

- DEBRA is being ported to various satellite sensors, including Himawari-8 AHI and GOES-16 ABI.

- Development of background files for DEBRA (as an alternative to estimates based on global surface emissivity) are ongoing.

- An F90 version of DEBRA has been coded, with the objective of folding into CLAVR-x processing.

- Evaluation of DEBRA for challenging case studies is ongoing, and beginning to entrain different complementary elements of the MURI Team.

→ *This talk details some of the progress and plans related to DEBRA as a stand-alone tool and in synergy with the MURI Team research.*
Case Study: A Tale of Two Dust Plumes

- What is accounting for the very different detection performance in DEBRA for these two dust plumes (P1 and P2)?
Assimilation of MODIS AOD observations

Experimental setup

- WRF-CHEM model with MOZART Chemistry and GOCART aerosols (MOZCART)
- 15 km / 50 layer
- MODIS AOD observations at 550 nm (AOD observation operator)
- NOAA atmospheric observations (forward GSI operator)
- 30 ensembles, 6-hour assimilation period
- Control variables include mixing ratios of GOCART dust species and atmospheric variables (pressure, temperature, winds, humidity)
- Case Study: Dust storm over Arabian Peninsula
  - WRF-Chem model initialized at 0Z on 4 August 2016
  - Data assimilation with conventional and AOD observations at 6Z
DA Analysis: Integrated Dust

- This analysis shows the DA impact of AOD observations
- Integrated dust of all 5 GOCART dust species
- Dust plume appears to be in the correct location at the correct time over the Persian Gulf
- Wind is seen to push the plume across the lower topography
- Drier dust plume over Saudi Arabia not quite as evident (yet)
Cross section of analysis increment for fine dust ($r_{\text{eff}}=0.5 \, \mu m$) at 25 N

Analysis increment for fine dust ($r_{\text{eff}}=0.5 \, \mu m$) at model level 5 (~740 m)

These analysis increments show how the observations are effecting the background (6 hour forecast) for fine dust in the area of the dust plume.

units: \(\mu g/kg\) dry air
Water Vapor

- Analysis from data assimilation experiment
- Water vapor plume in the same location as the dust plume
- Water vapor may be blocking the dust signal in DEBRA
- Sea breeze brings moisture into the Gulf
Conclusions

• Assimilating new AOD observations requires a forward operator

• Many assumptions made in development of operator

• An appropriate case study was chosen to evaluate the new operator

• Results show positive impact of new observations
Questions?