JEDI-Based Ensemble-Variational Data Assimilation System for Global Aerosol Forecasting at NCEP

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Outlines

- System Development
  - Near-Real-Time VIIRS 550 nm AOD Assimilation Experiment at NOAA/OAR/GSL
  - Development of Global Aerosol Reanalysis in 2016 from Assimilating MODIS 550 nm AOD Retrievals
Assimilation of 550 nm AOD retrievals in GEFS-Aerosols

- **Column-integrated AOD calculation** (Eq. 1 of Randles et al. 2017):
  \[
  \tau_f = \sum_{i,j} x_i \times b_{\text{ext},i}(\text{RH}, \lambda) \times \delta z,
  \]

  - \(\tau\): column-integrated AOD
  - \(x_i\): mass mixing ratio of aerosol species
  - \(b_{\text{ext},i}\): species-specific extinction coefficients as a function of wavelength (\(\lambda\)) and relative humidity (RH)
  - \(\delta z\): layer depth

  NOAA S-NPP VIIRS AOD retrievals at 550 nm (~ 50 km resolution)

- **AOD bias and uncertainty estimate:**
  \[
  \text{bias} = a_b + b_b \times \text{AOD}
  \]
  \[
  \text{uncertainty} = a_u + b_u \times \text{AOD}
  \]

GEFS-Aerosols 6-hour aerosol mixing ratio forecast at lowest model level

- **Dust**
  Dust at 2016061812 (ug/kg)

- **Sea salt**
  SeaSalt at 2016061812 (ug/kg)

- **Total black and organic carbon**
  OC+BC at 2016061812 (ug/kg)

- **Sulfate**
  SULF at 2016061812 (ug/kg)
JEDI-based Ensemble-Variational Aerosol Data Assimilation (DA) System for GEFS-Aerosols

- **JEDI**: Joint Effort for Data assimilation Integration -- a collaborative effort led by JCSDA;
- **AOD**: Aerosol optical depth (AOD) at 550 nm (currently from VIIRS and MODIS instruments);
- **IODA**: Interface for Observation Data Access (VIIRS/MODIS/AERONET AOD converters in Python available in JEDI/IODA);
- **UFO**: Unified Forward Operator (AOD forward operator and its tangent-linear and adjoint developed in JEDI/UFO using scattering lookup tables from CRTM and NASA);
- **EnVar/LETKF**: Ensemble-Variational solver/Local Ensemble Transform Kalman Filter (3D mass mixing ratios of 15 GOCART aerosol species are selected as control variables).
Stochastically-Perturbed Emissions (SPE, currently implemented in CCPP-based GEFS-Aerosols) based on ECMWF’s Stochastically Perturbed Parametrization Tendency (SPPT) Scheme to Account for Aerosol Emission Uncertainty

Emission scaling factor mainly to reduce modeled AOD bias

$\mathbf{f} = \mathbf{s}(1 + \mathbf{w}\mathbf{\sigma})$

Emission perturbation standard deviation to increase aerosol ensemble spread

Normally-distributed random noise used in SPPT

Innovation stats from one-month cycled assimilation of VIIRS AOD in June 2016

Spread of total sea salt mass mixing ratios at 1000 hPa from twenty-member GEFS-Aerosols 6-hour forecast

(a) No SPE

(b) Only scale sea salt emission in SPE

(c) Only perturb sea salt emission in SPE

(d) Scale and perturb sea salt emission in SPE
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The JEDI-based global aerosol DA system has been evaluated in near real-time (NRT) at NOAA/OAR/GSL since July 2021.

- Six-hourly assimilation of VIIRS 550 nm AOD retrievals derived from NOAA Suomi-NPP satellite;
- 3D-EnVar and LETKF for aerosol update;
- LETKF analysis recentered around EnVar analysis;
- NASA-LUTs for AOD forward operator calculation;
- Meteorological variables corrected by adding regridded increments from operational GDAS analyses;
- 1-control plus 20-member ensemble at C96 (~100km) using GSL’s CCPP version of GEFS-Aerosols model for aerosol forecasts.

### Study Design

<table>
<thead>
<tr>
<th>Feature</th>
<th>AOD DA</th>
<th>Ensemble members</th>
<th>Stochastically-perturbed emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>NRT-NODA</td>
<td>No</td>
<td>N/A</td>
<td>No</td>
</tr>
<tr>
<td>NRT-DA-SPE</td>
<td>Yes</td>
<td>20</td>
<td>Scaling factors /perturbation SD</td>
</tr>
<tr>
<td>Dust</td>
<td>1.2 / 2.0</td>
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<td></td>
</tr>
<tr>
<td>Sea salt</td>
<td>1.5 / 2.0</td>
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</tr>
<tr>
<td>Anthropogenic</td>
<td>1.2 / 2.0</td>
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<td></td>
</tr>
<tr>
<td>Biomass burning</td>
<td>1.0 / 2.0</td>
<td></td>
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</tbody>
</table>
Online Display of NRT Diagnostics (10/01/2021- present)

System description: https://ruc.noaa.gov/projects/nrt/
NRT diagnostics: https://ruc.noaa.gov/projects/nrt/Aerosol-DA/

AERONET 500 nm AOD

VIIRS/MODIS 550 nm AOD

NASA/GEOS and ECMWF/CAMS 550 nm AOD analysis
Innovation Statistics
(01/01 - 04/30, 2022)

Time Series of daily globally mean bias and RMSE against MODIS/Aqua 550 nm AOD

(a) Bias wrt MODIS/AQUA 550 nm AOD
- NRT-NODA 6h fcst (-0.090)
- NRT-DA-SPE 6h fcst (-0.066)
- NRT-DA-SPE analysis (-0.066)

(b) RMSE wrt MODIS/AQUA 550 nm AOD
- NRT-NODA 6h fcst (0.180)
- NRT-DA-SPE 6h fcst (0.160)
- NRT-DA-SPE analysis (0.144)
Bias and RMSE against independent AERONET 500nm AOD (01/01 - 04/30, 2022)

- Benefit of AOD assimilation against AERONET 500 nm AOD is more pronounced in Oct. – Dec. 2021, e.g., $R^2$ of NRT-DA-SPE analysis is about 0.24 higher than NRT-NODA 6-hour forecast (Huang et al., 2022 under review in JAMES).
Averaged 550nm AOD bias against NASA/GEOS and ECMWF/CAMS analyses (01/01 - 04/30, 2022)

- RMSE difference is similar to bias difference (not shown).

- NRT-DA-SPE 6h fcst show very similar bias and RMSE as NRT-DA-SPE analysis (not shown).

- When against NASA/GEOS AOD analysis, larger negative bias in NRT-DA-SPE analysis in northern Africa is mainly because VIIRS AOD is smaller than MODIS AOD in this region that is assimilated in NASA/GEOS.
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- VIIRS (left) and MODIS (right) 550 nm AOD aggregated on July 4, 2022.
AERONET AOD@500 nm Statistics for Year 2016

noDA

bias=-0.036
$r^2=0.50$

DA

bias=+0.012
$r^2=0.68$
Comparison of Profiles in MERRA-2, CAMSiRA, and GEFS-Aerosols in August, 2016
Ongoing and Future Efforts

- Extending the JEDI-based aerosol DA system to UFS-Aerosols that will replace GEFS-Aerosols for operations at NCEP/EMC in the future;

- Developing a 2018-2022 global aerosol reanalysis using UFS-Aerosols (funded by WPO/CTB);

- Addressing the limitations and deficiencies of the current DA System
  - Non-Gaussian distributions of observation (for retrievals typically $\delta \text{AOD} = \alpha \cdot \text{AOD} + \beta$) and model errors (which requires transformation of variables);
  
  - Undetermined magnitudes of observation errors (which requires diagnosis and further development of tools for thinning/super-obbing);
  
  - Insufficient ensemble spread (which requires further development of stochastic parameterizations);
  
  - No account for systematic model biases (which requires a systemic approach);
  
  - Significant uncertainties in aerosol scattering/absorbing properties (especially important for aerosol-radiation interactions, current GOCART may be intrinsically deficient).
Thanks for your attention!

Questions?

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