From Dust to Volcanic Ashes: Lessons learned from the development of NCEP's global in-line aerosol model

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With acknowledgments to many colleagues and collaborators
NGAC Overview
(NEMS GFS Aerosol Component)
What is NEMS?

- NEMS stands for NOAA Environmental Modeling System
- A shared, portable, high performance software superstructure and infrastructure
- Employ Earth System Modeling Framework (ESMF)
- For use in operational prediction models at National Centers for Environmental Prediction (NCEP)
- National Unified Operational Prediction Capability (NUOPC) with Navy and Air Force
- Eventual support to community through Developmental Test Center (DTC)
- [http://www.emc.ncep.noaa.gov/NEMS/](http://www.emc.ncep.noaa.gov/NEMS/)
- NEMS implementation Plans
  - 2011 implementation: NMMB with nests
  - 2012 implementation: NEMS GFS Aerosol Component (NGAC)
Earth System Modeling Framework

Modeling framework for the geo-science community

• A software infrastructure that enables different weather, climate, and data assimilation components to operate together on a variety of platforms
• Earth system models that can be built, assembled and reconfigured easily, using shared toolkits (e.g., data communications, time management, message logging, re-gridding, and error handling) and standard interfaces
• A growing pool of Earth system modeling components that, through their broad distribution and ability to interoperate, promotes the rapid transfer of knowledge.
• Community effort, partially supported by NOAA
• ESMF superstructure (grid component, state, and coupler) required for all NEMS components
• ESMF infrastructure optional

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NEMS Component Structure

All boxes represent ESMF components.

From Mark Iredell & Tom Black presentation (2010 AMS/NWP conf.)
Team efforts toward building global aerosol forecast capability at NCEP

Mark Iredell (NEMS team lead)  
Sarah Lu (aerosol modeling)  
Shrinivas Moorthi (physics)  
Yu-Tai Hou (radiation-aerosol)  
Henry Juang (dynamics)  
Jun Wang (I/O and ESMF infrastructure)  
Hui-Ya Chuang (post)  
Weiyu Yang (ESMF infrastructure)  
Perry Shafran, Fanglin Yang (verification)  
Eugene Mirvis (DTC support)  
Nicole McKee (documentation/web)  
Ho-Chun Huang (aerosol data assimilation)  
Jeff McQueen (coupling with regional AQ)  
Youhua Tang (coupling with regional AQ)  
Xu Li (SST-aerosols)

Collaborators
GSFC (Arlindo da Silva and Mian Chin) for aerosol modeling  
NESDIS (Shobha Kondragunta and Xiaoyang Zhang) for biomass emissions  
ECMWF (Angela Benedetti and Jean-Jacques Morcrette) for volcanic ash capability  
NRL (Jeff Reid, Walter Sessions) for model inter comparison
NEMS GFS Aerosol Component

- NCEP Annual Operating Plan milestone for Q4 FY12
- NGAC will be the first global in-line aerosol forecast system at NCEP
- NGAC will be the first global NEMS implementation and the second NEMS implementation at NCEP
- NGAC configuration:
  - Forecast model: Global Forecast System (GFS) based on NOAA Environmental Modeling System (NEMS), NEMS-GFS
  - Aerosol model: NASA Goddard Chemistry Aerosol Radiation and Transport Model (GOCART)
  - Simulate atmospheric aerosols including dust, sulfate, black carbon (BC), organic carbon (OC), and sea salt.
Developing an interactive atmosphere-aerosol forecast system

• **In-line chemistry advantage**
  – **Consistent**: no spatial-temporal interpolation, same physics parameterization
  – **Efficient**: lower overall CPU costs and easier data management
  – Allows for feedback to meteorology

• **NEMS GFS Aerosol Component**
  – NEMS GFS and GOCART are *interactively* connected using ESMF coupler components
  – **Concurrent development**: The coupler components can be modified to incorporate on-going and future changes in NEMS and/or GOCART

![Diagram of Atmospheric Dynamics and Physics with Color Key]

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Goddard Chemistry Aerosol Radiation and Transport Model (GOCART)

Arlindo da Silva (GSFC)

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Outcomes of the aerosol component

• Enable NCEP to produce global short-range chemical weather forecasts
• Provide lateral aerosol boundary conditions for regional air quality forecast system
• Create aerosol information needed for atmospheric correction in satellite retrievals
• Provide a first step toward an aerosol data assimilation capability at NCEP
• Allow NCEP to explore aerosol-chemistry-climate interaction in the climate system
Near-Real-Time NEMS GFS Aerosol Component

Current State
• Near-real-time experimental system
• The first global in-line aerosol forecast system at NCEP
• AGCM : NCEP’s NEMS GFS
• Aerosol: GSFC’s GOCART
• 120-hr dust-only forecast once per day (00Z), output every 3-hr
• ICs: Aerosols from previous day forecast and meteorology from operational GDAS
• Operational Implementation targeted for Q4 FY12

Ongoing Activities and Future Plans
• Use near-real-time smoke emission from satellites
• Plan toward full package implementation (dust, sea salt, sulfate, and carbonaceous aerosols)
• Refine the prototype volcanic ash capability
• Provide aerosol information for potential downstream users (e.g., NESDIS’s SST retrievals, CPC-EPA UV index forecasts; aerosol lateral boundary conditions for CMAQ)
Beyond dust forecasting
Aerosol Lateral Boundary Conditions: Trans-Atlantic dust transport

MODIS onboard Terra, from Giovanni online data system (developed and maintained by NASA DISC)

Dust influx at CMAQ boundaries from NGAC simulations

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Aerosol Lateral Boundary Conditions: Trans-Atlantic dust transport

**NAM-CMAQ simulations using LBCs from NGAC**

Baseline CMAQ with static LBCs versus experimental CMAQ with dynamic LBCs from NGAC, verified against AIRNOW PM observations

<table>
<thead>
<tr>
<th></th>
<th>CMAQ Baseline</th>
<th>CMAQ Experimental</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whole domain July 1 – Aug 3</td>
<td>MB = -2.82 Y = 1.627 + 0.583*X R = 0.42</td>
<td>MB = -0.88 Y = 3.365 + 0.600*X R = 0.44</td>
</tr>
<tr>
<td>South of 38° N, East of -105° W July 1 – Aug 3</td>
<td>MB = -4.54 Y = 2.169 + 0.442*X R = 0.37</td>
<td>MB = -1.76 Y = 2.770 + 0.617*X R = 0.41</td>
</tr>
<tr>
<td>Whole domain July 18 – July 30</td>
<td>MB = -2.79 Y = 2.059 + 0.520*X R = 0.31</td>
<td>MB = -0.33 Y = 2.584 + 0.795*X R = 0.37</td>
</tr>
<tr>
<td>South of 38° N, East of -105° W July 18 – July 30</td>
<td>MB = -4.79 Y = 2.804 + 0.342*X R = 0.27</td>
<td>MB = -0.46 Y = -0.415 + 0.980*X R = 0.41</td>
</tr>
</tbody>
</table>

Youhua Tang (EMC, now at NESDIS)

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Atmospheric Correction

‘Dust-Free’ vs. ‘Dusty’ Granule Retrievals
07/28/2011, 08/01/2011 IASI and CrIMSS

Date: 08/01/2011 Dusty
No Dust flag Used:

- IASI Retrievals: Solid Blue (82%) Dotted Blue (82%)
- CrIMSS Retrievals: Solid Green (59%) Dotted Green (59%)

With Dust flag, new REG:

- IASI Retrievals: Solid Red (53%) Dotted Red (53%)

Dusty IASI RET ‘ACCEPTED CASES’ were used to get CrIMSS Cases.

Notice: Skin Temperature Improvement with AVHRR use (2.7K to 1.4K).

Dust Flag: De-Souza Machado’s recipe; AVHRR: Eric Maddy’s, IASI Team Research at NOAA.
Aerosol-radiation feedback: Impact of aerosols on weather forecasts

Verification against analyses and observations indicates a positive impact in temperature forecasts due to realistic time-varying treatment of aerosols.

- T126 L64 GFS/GSL# experiments for the 2006 summer period
- PRC uses the OPAC climatology (as in the operational applications)
- PRG uses the in-line GEOS4-GOCART% dataset (updated every 6 hr)

#: 2008 GFS package
%: In-line GEOS4-GOCART

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Aerosol-radiation feedback: Impact of aerosols on weather forecasts

- T382 L64 GFS/GSI# experiments for the 2008 summer period
- PRC uses the OPAC climatology (as in the operational applications);
- PRG uses the off-line GEOS4-GOCART% monthly dataset

# : 2010 GFS package
% : off-line GEOS4-GOCART
NGAC dust module has been modified to forecast volcanic ashes. Results from the prototype ash system are qualitative, as the focus is on plume transport pattern.

Left panel: Ash forecast from London VAAC
Right panel: NGAC ash forecast at level 32 (corresponding to FL200/FL350 [green dash] on the left)
Volcanic Ash Modeling

Volcanic ash modeling study (thanks to support from EMC and ECMWF)

• Case: The eruption of Eyjafjallajökull volcano, Apr-May 2010
• Prototype volcanic ash forecast systems:
  – NGAC (NEMS GFS Aerosol Component): NCEP global in-line aerosol system by coupling NCEP’s NEMS/GFS with GSFC’s GOCART
  – MACC (Monitoring Atmospheric Composition and Climate): ECMWF global in-line aerosol system by coupling ECMWF’s IFS with LOA/LMD-Z
• The London VAAC at UKMO is responsible for monitoring and forecasting the dispersion of Eyjafjallajökull ashes.
• Neither NGAC and MACC are tasked officially to provide volcanic ash forecasts. The goal of the NGAC-MACC ash modelling study is:
  – An opportunity to examine the capability and limitation of the NCEP/NGAC and ECMWF/MACC
  – Explore the sensitivity of ash dispersion to meteorology, emission, and physical processes, which may provide some insight on the ensemble approach
  – Assess whether the NCEP/NGAC and ECMWF/MACC can provide some useful information on volcanic ash dispersion
Volcanic Ash Modeling

- While the short-range plume dispersion is dominated by the meteorological conditions, other factors also affect the spreading of the ash plume:
  - Both NCEP/NGAC and ECMWF/MACC modelling studies found that ash dispersion is affected by the specification of ash emissions
  - ECMWF/MACC modelling study found that the ash dispersion is sensitive to sedimentation, and is not sensitive to the assumed aerosol optical properties.
  - NCEP/NGAC modelling study found that the ash dispersion is sensitive to the specification of plume profile

Profile 1

```
col_mass (g m^-2) 2010041606
```

Profile 2

```
col_mass (g m^-2) 2010041606
```

Time series of column mass over Leipzig (51.4N, 12.4E) by NCEP/NGAC

```
Blk(h,i) Crn(cir) Yu(hv) Lgn(opt) Rd(opt)
```

Ashes arrived over Leipzig at 5 UTC and peak at 12-15 UTC (Lidar retrieval)
Volcanic Ash Modeling

Discussions

• The 2010 eruption event provides an unique opportunity to test the model’s capability and limitation. For instance, Gibbs phenomenon (spurious oscillation in the vicinity of sharp gradients) are found in NCEP/NGAC results.

• More studies are needed to understand the interaction between volcanic ash particles and the atmosphere.

• Reasonable estimate of emissions in near-real-time is needed to develop a global ash plume forecast system

• It appears better to have a volcano ash forecast system with only a few parameters that could be adjusted to give a reasonable agreement with observations such as MODIS AOD considering the following:
  • Each volcano eruption is different and the behaviour of the volcanic ash plume likely depends on many parameters.
  • Detailed plume profile information is not likely to be available in near-real-time.

• Ensemble with perturbation in meteorology and emissions can be done and could provide useful information on tracking ash dispersion
Challenges and Issues
Challenges for incorporating aerosol component into NEMS

• NWP vs CTM modeling
  – Different focus for the same parameter
    • High wind speeds and heavy precipitation for NWP versus stagnant conditions and low intensity rain for CTM
  – Different approaches are needed for emission estimates
    • Climate simulations versus NRT forecasts
  – Are experiences in NWP applicable to chemistry modeling?
    • Multiple model ensemble
    • Verification and evaluation
• The use of NWP model to transport chemical species
  – Need mass conserving, positive definite advection scheme
• Requirements in operational environments
  – Code optimization
  – Concurrent code development
  – Near-real-time global emissions
Dust AOD for 24-hr forecast valid 2011-07-21 00Z

Modeled dust AOD, 120-hr forecast, initialized from 2011-07-20 00Z

• ICAP activities: Collaborations among NCEP, NRL, GSFC, ECMWF, and JMA
• Total aerosols (DU, SS, SU, OC/BC) with data assimilation except for NCEP (dust forecasts only) and JMA (total aerosols forecasts only)

Walter Sessions (NRL)

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Aerosol Verification

Rational for International Cooperative for Aerosol Prediction 2nd workshop: Aerosol Verification
While the NWP community has over 30 years of experience with the definition of internationally accepted verification measures to quantify model skill, the aerosol forecasting community is still at the stage of defining suitable “scores” that can fulfill a similar function.

Conclusion from my ICAP presentation:

- NCEP is performing routine verification of PM predictions for the US.
- The goal is to ensure that the NAQFC meets the needs of local and state AQ forecasters and provides timely and accurate information to the general public.
  - Verification is based on the accuracy w.r.t. the PM standard (currently 35 µg/m³)
  - Near-real-time verification relies on AIRNOW surface PM measurements
- Issues faced by NCEP for verifying/evaluating global aerosol forecasts
  - Verification goal and performance metrics TBD
  - Data Sources
    - Analysis data (aerosol data assimilation in development)
    - Independent observations (limited observations on composition and profiles)
Aerosol Verification

Verification for CONUS PM using EPA AIRNOW PM observations
Threat Score (TS), 1-h aerosols
Jan 2009 - Jun 2010, Th = 35 ug/m³

Verification for Alaska smoke using NESDIS GOES-W GOES GASP
Critical Success Index (CSI), daily avg smoke
July 2009, Th = 1 ug/m³

2x2 contingency table

<table>
<thead>
<tr>
<th>Observed</th>
<th>yes</th>
<th>no</th>
</tr>
</thead>
<tbody>
<tr>
<td>forecast</td>
<td>a</td>
<td>b</td>
</tr>
<tr>
<td></td>
<td>c</td>
<td>d</td>
</tr>
</tbody>
</table>

FC = (a + d)/(a + b + c + d)
TS = a / (a + b + c) (2)
POD = a / (a + c) (3)
FAR = b / (a + b)

Verification for Alaska smoke using NESDIS GOES-W GOES GASP
Critical Success Index (CSI), daily avg smoke
July 2009, Th = 1 ug/m³

GASP: GOES Aerosol Smoke Product
(Shobha Kondragunta, NESDIS)

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FC with respect to the alert threshold of 35 µg/m³ (the standard for daily max of the 24-hr averaged PM2.5) is most relevant to AQ forecasters.
Aerosol Verification

AOD from NGAC forecasts versus in situ observations (AERONET) and satellite measurements (MODIS) at Key Biscayne and Izana (by Luke Jones of ECMWF)

We thank Philippe Goloub and Kenneth Voss for the efforts in establishing and maintaining Izana and Key Biscayne site, respectively.

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NMM-B’s new advection scheme is shown to be mass conservative.

Youhua Tang (EMC, now at NESDIS)
• Flux-limited vertical advection reduces (but does not eliminate) negative tracer values caused by spectral transform.

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Simulation of Grimsvotn ashes

Gibbs phenomenon in NGAC, spurious oscillation in the vicinity of sharp gradients

High resolution run won’t help.
Need for Near-Real-Time Emissions

**Dust Source Function**: Function of surface topographic depression, surface wetness, and surface wind speed (Ginoux et al. 2001)

\[
\text{Source Flux}_p = \begin{cases} 
Ss_p u_{10}^2 (u_{10} - u_t) & u_{10} > u_t \\
0 & \text{otherwise}
\end{cases}
\]

- **S**: C * Source function
- **s_p**: fraction of clay and silt size
- **u_{10}**: wind speed at 10 m
- **u_t**: threshold wind velocity

\[
u_t = \begin{cases} 
A \sqrt{\frac{\rho_p - \rho_a}{\rho_a}} g \Phi_p \left(1.2 + 0.2 \log_{10} w_t\right) & \text{if } w_t < 0.5 \\
\infty & \text{otherwise}
\end{cases}
\]

- **A**: constant=6.5
- **w_t**: surface wetness
- **\Phi_p**: particle diameter
- **\rho_p, \rho_a**: particle and air density

**Global annual total aerosol emissions for dust species (in Tg/yr)**

<table>
<thead>
<tr>
<th>Year</th>
<th>Range</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1789</td>
<td>[541-4036]</td>
<td>Average range from AeroCom models</td>
</tr>
<tr>
<td>1970</td>
<td></td>
<td>GEOS4-GOCART on-line simulations (Colarco et al., 2010)</td>
</tr>
<tr>
<td>3242</td>
<td></td>
<td>Off-line GOCART (Chin et al., 2009)</td>
</tr>
<tr>
<td>664</td>
<td>[3126]</td>
<td>NGAC using C as GOES4 [off-line GOCART]</td>
</tr>
</tbody>
</table>

C is 0.175e⁻⁹ and 1.0e⁻⁹ for GEOS4-GOCART and off-line GOCART, respectively.

Dust emissions for GEOS4, off-line GOCART, and AeroCom are based on Calarco et al. (2010)
Satellite observations provide a choice of near-real time and global fire emissions dataset for operational forecasting

- **NASA Quick Fire Emission Dataset version 1 (QFED)** using MODIS fire counts onboard Aqua and Terra. PI: Arlindo da Silva (NASA GSFC)
- **NOAA/NESDIS Global Biomass Burning Emissions Product (GBBEP)** using Fire Radiative Power observed from a constellation of geostationary satellites (GOES, MetoSAT, and MTSAT). PI: Shobha Kondragunta (NOAA NESDIS)
- QFED has smaller area of detected fires but with stronger carbon emissions.
- There is a limited coverage for geostationary satellites at high latitudes.
Need for Near-Real-Time Emissions

• For an aerosol data assimilation system without any information on volcano emissions, the signal in the assimilated aerosol observations is likely aliased into elevated level of aerosol loading of different composition at different vertical levels.
• For the case of 2010 Eyjafjallajokull eruption, a sea salt plume near the surface is shown in the pre-operational MACC aerosol analysis when volcanic ash is not known in the background conditions

Sea salt plume off the coast of Iceland on April 19, 2010 at 0300 UTC (ECMWF Tech Memo 653)
• Version control system is needed to manage code development among groups
• NCEP uses SVN (SubVersion). Other options are available, i.e., CVS
• Version control system alone does not guarantee productive code development:
  – Solid ground rule
  – Well designed regression test
  – Shared Infrastructure that can be assembled and reconfigured
  – Revision log that makes sense
  – Effective/efficient communication among developers
  – Ensure these above can help rather than hurt the code development
In Conclusion

- NCEP has adopted NASA GOCART model in NEMS GFS for global aerosol modeling. The NEMS GFS Aerosol Component now has the capability to forecast dust, sulfate, sea salt, and carbonaceous aerosols.

- Capabilities and limitation of NEMS GFS to predict aerosols [NWP models to predict chemical species ] are discussed
Thank You.