A Closer Integration of Models and Observations across Air Quality/Weather/Climate Applications -- A Challenge and Opportunity for Improved Prediction & Analysis

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Today’s talk -

- Illustrate some multiscale air quality – weather feedbacks (aerosol focus)
- Their implications on air quality & NWP predictions and policy assessments.
- Observation/assimilation needs
- Help frame breakout discussions
Exploring Multiscale Air Quality – Weather Feedbacks

Current Applications: China, India, Chile, U.S.


- Aerosol direct effects (direct and semi-direct: Optical properties calculated by Mie theory [Fast et al., 2006] and then passed into the Goddard short wave radiative scheme.

- Aerosol indirect effects (1st & 2nd): Aerosol activation module to calculate activation of aerosols [Ghan and Easter, 2006, Abdul-Razzak and Ghan, 2002], and then passed to Lin et al. Microphysics and Goddard short wave radiation modules.
New BC (and PM2.5/10) Inventories Help Correct Previous Problems In Underestimating PM/BC Levels
Anthropogenic Radiative Forcing Analysis By Sector in Delhi Shows Warming Due to Transport, Domestic and Industry - Implications for Policy
Exploring Multiscale Urban Air Quality – Weather Feedbacks with WRF-Chem

Data: Tsinghua University

Data: Peking University
Simulating Continental Precipitation Events

Observations: Beijing Monitoring Center (Wang et al., 2010)

WRF-Chem captures the local daily time series of precipitation in Beijing.

Grell 3 cumulus scheme
Sensitivity runs with KF and GD cumulus schemes
Aerosol Feedbacks Lead To Better Precip Predictions

- a. Satellite
- b. WRF-Chem (colormap) vs WRF (contour)
- c. Cloud Water & CAPE
- d. SO₂
**The Southeast Pacific**

A Climate and Aerosol Modeling Challenge

The world’s most widespread, persistent subtropical low cloud regime.

Reference: Wood et al. (2011)

- WRF-Chem v3.3 CBMZ-MOSAIC/MYNN/Lin
- Fine vertical resolution: 75 levels, \( \sim 60\text{m} \Delta z < 3\text{km} \)
- Long spin-up: \( \sim 3-4 \text{ days} \)
Cloud Microphysics Comparison

- Observed aerosol #: Passive Cavity Aerosol Spectrometer Probe (PCASP)

- Observed droplet #: Cloud Droplet Probe (CDP)

- No wet dep model better for aerosol and for clouds (Indirect effects working OK)

Saide et al., ACPD, 2011
Linkage to Anthropogenic pollution

Continental sulfate pollution often seen at 75W, with clear influence on accumulation mode aerosol

TWO 4 DAY PERIODS OF RON BROWN AT 75W

WRF-Chem Base
WRF-Chem No Wet dep.

SO$_4$ 2$^{\text{nd}}$ BIN PLUME TRACKING

Date = 2008/10/29, time = 00UTC

SO$_4$ [µg/m$^3$]

N$_{\text{obs}}$ > 10 nm
N$_{\text{mod}}$ > 40 nm

Aerosol Number Concentration [#/cm$^3$]

0 100 200 300 400 500 600 700 800

Longitude

-82 -80 -78 -76 -74 -72 -70

Latitude

0.01 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 1.0

RonBrown WRF-Chem WRF-Chem NW

Observations
Cooling by smelters and power plants (coastal, brighter clouds) and Santiago/central Chile (offshore, longer cloud lifetime)

+ aerosol number concentration

- cloud effective radius
Challenge: Achieving A Closer Integration Of Observations And Models

- Need to Integrated Air Quality & Met. Model assimilation systems
- New requirements for NRT data, observing systems, and assimilation systems for chemical applications!!
Challenge: Observations Needed

MOST NEEDED:
- Height of the planetary boundary layer
- Soil moisture and temperature profiles
- High resolution vertical profiles of humidity
- Measurements of air quality and atmospheric composition above the surface layer
Idea – Constraining aerosols by assimilating cloud satellite retrievals

- Improving aerosol loadings improves cloud macro and micro physical properties.
- Data assimilation technique (4dVar) could be used to improve aerosol loadings given cloud satellite retrievals (*add info to AOD assimilation*)
- Optimize for aerosol number conc. and update mass conc. accordingly (same phase, same bin)
- Sensitivities are computed using the WRF-Chem adjoint (*we have several pieces*)
- 5D correlations: x,y,z,bins(1:8),phase(dry/wet)

\[ N_d = K \tau^{1/2} r_e^{-5/2} \]

- \( \tau \): Cloud optical Depth (COD)
- \( r_e \): Effective radius
- \( N_d \): Cloud Number of droplets

\( \tau \) and \( r_e \) can be obtained from MODIS or GOES

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Test case

- Extensive cloud cover to perform assimilation
- Remote zone with lower Nd, close to shore higher Nd

MODIS Terra $N_d$

Base WRF-Chem $N_d$
Impact of Assimilation: Sulfate mass 2nd bin (78-156 nm), 1st level

Assimilated WRF-Chem

Base WRF-Chem
Impact of Assimilation: Predicted Fields after 1 day of run

MODIS Terra | Base WRF-Chem | Assim WRF-Chem

$N_d$ | $\tau$

Legend: 0 - 1000
Closing Thoughts/Challenges

Need to continue to improve forward AQ and weather models (especially those aspect related to chemical weather e.g., pbl, clouds)

Need to continue to improve process understanding and key model inputs (e.g., emissions)

Need to evolve the observation infrastructure to help improve forward model and to support assimilation

Improve data assimilation techniques for AQ prediction improvements - and use also to define/design observational needs

Important to demonstrate the real benefits of better models and observing systems
Winter Time Nitrate Aerosol Prediction

Important implications for compliance

Models underestimate nitrate
PBL dynamics are crucial to model skill

Shallow model mixed layer and neg. bias in wind speed drive overprediction in primary and secondary PM2.5 concentrations during wintertime fine particle events. RH bias (snow melt), enhanced photolysis and nighttime chemistry are also important factors.
Challenge: Need to Estimate ALL Emissions at Appropriate Scales to Predict Chemical Weather (and they are constantly changing in space and time)

Anthropogenic: NE189
- Biomass burning: MODIS hotspot
- Dust (f(v))
- Volcanic: SO₂ estimated
- Biogenic: none at present

Domain 1
Δx = 12 km

Domain 2
Δx = 3 km

CO₂ emission rates:
- purple = low
- red = high
- nonlinear scale

Global Distribution of Lightning Activity

SOx Emissions
Rapid Updates of Emissions Are Needed

Scaling factors

We are developing new approaches to integrate satellite data with chemical transport models and emission inventories for improved AQM.

NASA: Argonne, Goddard SFC, Ulowa

Quantile-quantile plot

4D-Var setup:

Time window: July, 2004

Control:
Initial ozone, and NOx emissions

Observations:
Ozone from different platforms, and SCIAMACHY tropospheric NO2 columns

Emission changes over domain (ratio of new emission over NEI01)

<table>
<thead>
<tr>
<th>Case</th>
<th>Surface (level 1)</th>
<th>Elevated (2 &amp; above)</th>
<th>Total (all levels)</th>
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<tbody>
<tr>
<td>E only</td>
<td>0.934</td>
<td>0.849</td>
<td>0.920</td>
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<tr>
<td>E &amp; IC</td>
<td>0.928</td>
<td>0.881</td>
<td>0.908</td>
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<tr>
<td>OI</td>
<td>1.318</td>
<td>1.030</td>
<td>1.246</td>
</tr>
</tbody>
</table>

Chai et al., AE 2009
Other Physical Parameters Also Play Important Roles - Impact of Land Use Changes

Δ Urban area

Δ T–2 (K)

ΔPBL (m)

ΔO₃

ΔPM2.5 (µg/m³)

Daytime