Recent Progress in Developing A Global-Through-Urban Weather Research and Forecast Model with Chemistry (GU-WRF/Chem)

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Presentation Outline

• Background and Motivation
• Development and Application of GU-WRF/Chem
  • Model Development Highlights
  • Current-Year Simulations
    • Model Application and Evaluation
    • Chemistry-Aerosol-Cloud-Radiation Feedbacks
      – Direct Effects on Shortwave Radiation and NO₂ Photolysis
      – Semi-Direct Effects on Planetary Boundary Layer (PBL) Meteorology
      – Indirect Effects on Cloud Condensation Nuclei (CCN), Cloud Droplet Number Concentration (CDNC) & Precipitation
  • Future-Year Simulations
    • Impact of Projected Emissions and Climate Change on Air Quality
    • GU-WRF/Chem vs. Community Climate System Model (CCSM)
• Major Findings and Future Work

• Hypothesis
  – Climate change (CC) - air quality (AQ) feedbacks are important

• Objectives and Tasks
  – Develop a unified online-coupled model for integrated CC-AQ modeling
  – Conduct global-through-urban simulations for current/future scenarios
  – Replicate/quantify CC-AQ feedbacks and examine model uncertainties
  – Guide the win-win strategy for integrated CC mitigation and AQ control

• Scientific Questions
  – What are the important feedbacks of urban/regional air pollutants to CC?
  – How can CC and emission control affect urban/regional AQ?
  – What are key uncertainties associated with predicted effects/feedbacks?
Model Development and Application Activities

- **Key Model Development**
  - Globalize WRF/Chem
  - Compile global emissions (MOZART4, RETRO, IPCC, AeroCom); project future-year emissions based on IPCC A1B
  - Develop/improve model treatments for global-through-urban applications
    - Incorporate SAPRC99/CB05/CB05_GE, MADRID, FN05, & nucleation
    - Couple gaseous mechanisms with default and new aerosol/cloud modules
    - Add/improve other treatments (e.g., FTUV, dust, SOA, plume-in-grid)

- **Model Evaluation of Current-Year (2001) Simulations**
  - Met: T, QV, Precip, Radiation from NCEP/NCAR, NCDC, CMAP, TRMM, BSRN
  - Chem: O₃ and PM₂.₅ from CASTNET, STN, IMPROVE, AIRS-AQS, SEARCH
    column CO, NO₂, and TOR from MOPITT, GOME, OMI, TOMS/SBUV
  - Other: AOD, CCN, CDNC, Cloud Fraction, COT, CER from MODIS

- **Model Intercomparison and Trend Analysis of Future-Year Simulations**
  - Intercomparison: 2050 GU-WRF/Chem vs. 2046-2055 10-yr average CCSM
Development and Incorporation of CB05 for Global Extension (CB05_GE) into GU-WRF/Chem

- A Total of 120 New Reactions in CB05_GE
  - 5 stratospheric reactions (O₂, N₂O, O¹D)
  - 78 reactions for 25 halogen species (48 for 14 Cl and 30 for 11 Br species)
  - 4 mercury reactions (Hg(0) and Hg(II))
  - 13 heterogeneous reactions on aerosol/cloud and 20 reactions on PSCs
  - H₂O, CH₄, CO₂, O₂ and H₂ are treated as chemically-reactive species

- Box Model Test
  - Four conditions: urban, upper troposphere, lower stratosphere, and Arctic
  - Several scenarios: NoClBr – no halogen chemistry (blue), ClBr – with full halogen chemistry (red), NoBr – with chlorine chemistry (green)

Arctic (March)

- [Graphs showing O₃, Hg(0), Hg(II) over time for different scenarios]
Simulated Aerosol Activation Fractions as a Function of Parcel Temperature and Updraft Velocity: Uncertainty in Aerosol Activation Parameterizations

- Two Activation Parameterizations
  - Abdul Razzak-Ghan 2000 (AR-G00) (Default in WRF/Chem)
  - Fountoukis-Nenes 2005 (F-N05)

- Box Model Test
  - Single aerosol type (sulfate), with a modal representation with 3 modes
  - Identical CCN spectrum in AR-G00 and F-N05
  - 3 conditions: Marine (Type 1), Continental (Type 2), Remote Marine (Type 3)

Aerosol activation fractions differ by up to a factor of 4
Simulated Nucleation Rates as a Function of $N_{H_2SO_4}$

Uncertainty in Nucleation Parameterizations

Nucleation rates differ by > 16 orders of magnitude
Nested GU-WRF/Chem Simulations
(Base Configurations: FTUV/CB05GE/MADRID/CMU/AR-G, 27 layers from 1000-50 mb)

- Period: Met only: 2001/2050, at 4° × 5° & 1° × 1°, w different physics options
- Domain: D01: 4° × 5°, 45 (lat.) × 72 (long.) (Global)
  D02: 1.0° × 1.25°, 44 × 192 (Trans-Pacific)
  D03-CONUS: 0.33° × 0.42°, 84× 168 (CONUS)
  D03-China: 99× 177 (China)
  D04: 0.08° × 0.10°, 136× 144 (E. US)

Gas and PM:
1. 2001 Jan/Jul over D01-D04, w and w/o PM
2001 Monthly Mean Daily Precipitation (mm/day)

Observation (CMAP)  Simulation

Jan.

NMB = 11.5%

Jul.

NMB = 5.7%
PM$_{2.5}$ decreases shortwave radiation domainwide by up to -45% (global mean: -10%)
Semi-Direct Effects of PM$_{2.5}$ on Temperature at 2-m

PM$_{2.5}$ decreases T2 over most areas up to -546% (global mean: -1.6%)
Indirect Effects of PM$_{2.5}$ on Precipitation

PM$_{2.5}$ decrease precipitation over polluted regions by up to -82% (global mean: -5%)
PM$_{2.5}$ enhances CCN domainwide by up to 3340% (global mean: 478%)
**Major Findings and Future Work**

- **GU-WRF/Chem demonstrates promising skills in reproducing observations**
- **Aerosol feedbacks to radiation, meteorology, and cloud microphysics**
  - Aerosols decrease shortwave radiation by up to -45% (global mean: -10%)
  - Aerosols decrease NO₂ photolysis rate by up to -52% (global mean: -11%)
  - Aerosols decrease near-surface temperature by up to -546% (global mean: -1.6%)
  - Aerosols decrease PBL height by up to -39% (global mean: -1.7%)
  - Aerosols increase to CCN by up to 3340% (global mean: 478%)
  - Aerosols increase to CDNC by up to 5751% (global mean: 318%)
  - Aerosols decrease precipitation by up to -82% (global mean: -5%)
- **Simulated aerosol, radiation, and cloud properties exhibit small-to-high sensitivity to nucleation and aerosol activation parameterizations**
  - Higher sensitivity to nucleation parameterizations: PM mass and number, CCN, Precip
  - Higher sensitivity to activation parameterizations: AOD, COT, CDNC, LWP, $R_{eff}$
  - Small sensitivity: OLR, GLW, GSW, SWDOWN, RSWTOA, CF
- **Observations are needed to verify feedbacks, improve models, and reduce the uncertainties in simulated aerosol direct and indirect effects**
- **Use feedbacks to guide win-win emission control strategies for CC/AQ**
  - Isolate and quantify complex speciated feedbacks: GHGs, cooling and warming PM
  - Assess the effectiveness of O₃ and PM attainment plans under different future emission scenarios and a changing climate
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