Improving Air Quality (and weather) Predictions via Closer Integration of Observations and Models

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- Trend toward closer linkages of weather, atmospheric composition, and climate related services
- Information needed at higher resolution (and longer lead times) to address societal needs
- Further improvements require advances in observing systems, models and assimilation systems
Atmospheric Composition Matters: To Air Quality, Weather, Climate and More

Disasters

Visibility

Ozone layer

Volcanic ash, dust & smoke

Urban smog

Regional smog

Climate forcing

Plume dispersion

Acid rain

Biogeochemical cycles

LOCAL < 100 km

REGIONAL 100-1000 km

GLOBAL > 1000 km
Current Air Quality Models have appreciable prediction skill

Itahashi et al., ACP, 2020
Major sources of uncertainty in AQ Model

- Emissions (anthropogenic and natural (e.g., biomass burning, wind blown dust))
- Meteorology
  - Clouds (photolysis rates, aqueous chemistry, redistribution)
  - Precipitation (removal by scavenging)
  - Planetary boundary layer height
- Process understanding (chemistry, dry deposition, etc.)
PM is most important in AQ – AOD assimilation is the current focus. Testing the Impact of GOCI AOD Assimilation

UIOWA/UCLA WRF-Chem forecasting system

- WRF-Chem with MOSAIC aerosols and a Reduced Hydrocarbon chemistry (Pfister et al. JGR 2014), including simplified SOA formation (Hodzic and Jimenez, GMD 2011)
- GFS and CAMS meteorological and chemical boundary conditions
- KORUS-AQ anthro (Jung-Hun Woo) and QFED fire emissions
- AOD data assimilation using GSI (Saide et al., ACP 2013). MODIS and GOCI data were assimilated simultaneously every three hours (Saide et al., GRL, 2014)
- Four days of forecasts were available for the outer domain, 2 days for the inner domain
- Output available to other users: All species and meteorology along DC-8 flight track on KORUS-AQ repository, full model outputs available by request (saide@ucar.edu)

Saide et al., GRL, 2014 Fractional Bias reduction
Air Pollutants also Impact Weather & Climate -- Aerosol composition matters

- Aerosols mask about 50% of the forcing of GHGs.
- BC acts like CO2 with about 50% of forcing as CO2, but with a much shorter atmospheric lifetime.
- Aerosols impact atmospheric stability, PBL height – absorption plays a critical role.

Overarching Objective - Improve Prediction Capabilities via Incorporating/Integrating Composition, Weather and Climate

Earth Systems Modeling Approach

Global societal needs

Research

Data processing Modeling Forecasting

Weather services

Climate services

Hydrological and water management services

Environmental services

Research findings

Disaster risk reduction

Safety and economic operation of air, marine and land transport

Resilience to climate variability and change

Sustainable use of natural resources

Economic growth

ENABLERS

Standards, quality management, risk management, efficiency, effectiveness
Capacity development
Partnerships

Seamless Prediction Across all Relevant Temporal and Spatial Scales (GDPFS)
Up to 1 K cooling of 2m Temperature because of Dust Transport in Europe (June 2019)

Difference in RMSE of temperature at 1000 hPa against analysis between prognostic and climatological aerosol and ozone. Blue areas indicate an improvement with prognostic aerosols and ozone.

V-H Peuch, ECMWF private comm, 2020
Aerosol impacts at the S2S scales

Results summarized in Benedetti and Vitart, MWR, 2018

Aerosol impacts on the monthly forecasts: Rank probability skill scores
Models Constrained With Observations Play Increasing Important Roles In Research and Applications

- Need for More aerosol and atmospheric composition data for use in assimilation
- New observations streams are in the pipe-line ...
- Need to improve our forward models

Little experience with coupled models!
Putting the pieces together
Emission inversion and feedbacks (UCLA/IOWA)

WRF with aerosol-aware microphysics (AAM): 96 hrs

- Based on Thompson and Eidhammer (JAS, 2014) and Saide et al. (JGR, 2016), 12km resolution
- Smoke emissions constrained in near-real time using Saide et al. (GRL 2015) over 6 regions for 8 hour intervals
- Simulations turning on and off fires to assess aerosol-cloud-radiation interactions
- Source identification
- Full chemistry (gases and aerosol composition)
Vertical information is needed to test/improve predicted aerosol properties important to weather and climate.

Doherty et al., in prep.

Shinozuka et al., ACP, 2022
There is also the issue of improving predictions of aerosol composition.

Model evaluation: Olympic park

Observational constraints for assimilation:
- Absorption
- Size (fine model)
- Shape
- Actual composition

Park et al., Elementa, 2021
Source Attribution (sector/region/anthropogenic) is Becoming an Important Component of Air Quality Predictions

Sobhani et al., ACP, 2018
Improving Air Quality Predictive Capabilities

Exciting Times Ahead!!

- Trend toward closer linkages of weather, atmospheric composition, and climate related services
- Information needed at higher resolution (and longer lead times) to address societal needs
- Further improvements require advances in observing systems, models and assimilation systems
- Need to continue to develop Earth System approach
- Atmospheric composition observing system is expanding in important ways (e.g., GEMS, TEMPO)
- ACCP offers a great opportunity to advance our capabilities to understand and model aerosol processes and their interactions with weather and climate
Backup slides
Application #5. Severe Storm (tornado) Prediction

Saide et al., 2014 in review

Biomass burning smoke before and during the severe weather outbreak of April 27 and modeled impacts on tornado parameters. Left: 42 hour back trajectories from the beginning of violent tornado tracks, with circles marking 24 hour, observed AOD over ocean on 27 April, and fire locations for the day before. Top-right: Statistics of Significant Tornado Parameter (STP) used in tornado forecasting (Thompson et al., 2003) from WRF-Chem simulations with fire emissions and data assimilation (blue) and without fire emissions (red). Statistics are computed for the mean near-storm environment for each tornado, with numbers on top of each panel representing the number of tornadoes that go into the statistics and * showing significant differences at the 5% p-value level. Bottom-right: Map of mean STP differences for the outbreak period between the two simulations.
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, ~60m Δz < 3km
- Long spin-up: ~3-4 days
Assimilation results: + & - biases reduced

• Assimilate MODIS Terra $N_d$
• Aerosol mass and number are changed

WRF-Chem Guess

WRF-Chem Assimilated

MODIS Obs

Ref. Saide et al., PNAS 2012
Daytime $N_d$ after assimilation vs GOES and in-situ aerosol

- Large improvements during the first 2 days for all domain
- GOES Assimilation improves agreement with VOCALS-REx C130 aerosol number and mass observations

A single MODIS $N_d$ Assimilation

Ref: Saide et al., PNAS 2012
Daytime $N_d$ after assimilation vs GOES and in-situ aerosol

Saide et al., PNAS, 2013

• Large improvements during the first 2 days for all domain

• GOES Assimilation improves agreement with VOCALS-Rex-C130 aerosol number and mass observations

If necessary, you can also translate the table and the legend of the graphs mentioned in the text. This text provides a clear summary of the improvements in aerosol number and mass observations following assimilation with GOES and other data sources. The diagrams illustrate these improvements over time, showing a significant reduction in fractional bias after assimilation.
Coupled Size-Resolved Model Configuration to Study New Particle Formations

Figure 2. Visualization of the result from D19 on aerosol-cloud interactions in the nucleation explicit variant of WRF.

**Impacts of New Particle Formation on Short-term Meteorology and Air Quality Determined by the NPF-explicit WRF-Chem in the Midwestern United States**

Can Dong, Hitoshi Matsui, Scott Spak, Alicia Kalafut-Pettibone, Charles Stanier
How observations are used for atmospheric composition applications?

**Real-Time**
- **< 2-3 hours**
  - Applications:
    - Primary: assimilation/forecast
    - Secondary: inverse modelling of emissions and fluxes
  - QA/QC: Automated Filtering, flagging

**Near-Real-Time**
- **< 2-3 days**
  - Applications:
    - Primary: Verification of products
    - Secondary: assimilation, inverse modelling of surface emissions and fluxes (for Delayed-Mode applications)
  - QA/QC: Semi-automated

**A posteriori**
- **< 1 month**
  - Applications:
    - Primary: Verification of products
    - Secondary: assimilation, inverse modelling of surface emissions and fluxes (for Delayed-Mode applications)
  - QA/QC: Manual, Expertise Semi-validated

**Final**
- **1-2 year**
  - Applications:
    - Primary: Validation of models and products, interim reanalyses
    - Secondary: R&D
  - QA/QC: Expertise+ Validated

- reanalyses
- Climate Data Records
- Assessments
- Validation of models and products
- R&D
Scarcity of data --
common need to enhance observing system

Good News: The global observing systems for atmospheric composition are growing
An overarching goal of research is to enable **Predictive Capability (S4S; R2O)**.
FIREX-AQ: Fire Influence on Regional to Global Environments Experiment - Air Quality

Objective:
Provide comprehensive observations to investigate the impact on air quality and climate from wildfires and agricultural fires across the continental United States.

More info: https://esrl.noaa.gov/csd/projects/firex-aq/
Impacts of plume rise process
NASA - Aerosol, Clouds, Convection and Precipitation (A-CPP) Study

Absorption, direct and indirect effects redistribution

Cloud & Precipitation Development & Evolution

Low Cloud Climate Feedback

Transporting Cloud And Precipitation Water To Upper Troposphere

Determining Extreme Precipitation

High Cloud Climate Feedback

Collocated Water Vapor, Cloud and Precipitation Observations Vertical Motion in Severe Storms

ACCP provides transformative space-based and suborbital observations of essential cloud, precipitation and aerosol processes, leading to improved predictions of weather, air quality, and climate for the benefit of society.