Dry deposition of ozone: Intercomparison and evaluation across chemical transport models in the Air Quality Model Evaluation International Initiative (AQMEII)

photo source: David Foster

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The Air Quality Model Evaluation International Initiative (AQMEII)

- Since 2009, AQMEII has focused on evaluating regional CTMs used for research and regulatory applications
- Fourth phase focuses on wet & dry deposition – I’ll focus on ozone in this talk
- Two activities guided by steering committees
  - Activity 1 – regional CTMs
  - Activity 2 – single-point models
AQMEII4 Motivation: Ozone deposition velocities vary strongly across global CTMs

- All but two use schemes based on Wesely [1989]
- Factor of 2-3 variation suggests sensitivity to implementation of a given scheme
- Uncertainty w/r/t model land use/land cover (LULC) distributions confounds understanding of spread
- Deposition pathways driving spread are uncertain due to lack of process-level diagnostics

Annual averages from SRI models used in TF HTAP intercomparison

-ozone deposition velocity (cm s\(^{-1}\))
-Latitude

Hardacre, Wild, & Emberson, ACP, 2015
AQMEII4 Motivation: Ozone deposition velocities also vary strongly across **different** dry deposition schemes

Intercomparison using single-point modeling driven by same site-specific forcing at Borden Forest

- Large spread highlights a role for process representation & parameter choice

*Wu et al., JAMES, 2018*
‘Effective conductances’: contribution of a given pathway to the deposition velocity in velocity units

LULC-specific output eases process-oriented comparison among models with differing LULC distributions

Paulot et al. ACP 2018; Clifton et al. RoG 2020
• Annual simulations with common emissions & boundary conditions over NA & EU for 2 years each
• Archive concentrations, met fields, deposition velocities & fluxes (including process- & LULC- specific output)
• Common process & LULC categories for reporting diagnostics
Activity 1 – Goals

1. Quantify performance and variability of dry and wet deposition simulated by multiple state-of-the-science regional AQ models

2. Identify and quantify causes of differences in model-generated deposition fluxes by using detailed ancillary diagnostic fields added to deposition algorithms and common LULC categories

3. Investigate methods for using simulated meteorological, concentration, and deposition fields from multiple models with observations to estimate maps of total dep and impacts

Galmarini et al., 2021
Activity 1 – Ongoing & completed publications

- Galmarini et al., 2021 – AQMEII4 & Activity 1 intro [published in ACP special issue]
- Hogrefe et al. – diagnostic analysis of US EPA CMAQ sims [submitted to ACP special issue]
- Kioutsioukis et al. – multi-model evaluation & analysis [in preparation]
- Makar et al. – critical load model ensemble analysis [in preparation]

Technical note: AQMEII4 Activity 1: evaluation of wet and dry deposition schemes as an integral part of regional-scale air quality models

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Here we show examples from the model outputs currently in the AQMEII4 database; all results are preliminary.
Activity 1 – Observed & modeled seasonal & diel cycles

Comparison to extensive observational datasets of ambient concentrations is the first step of Activity 1, to attribute/isolate sources of errors (e.g., precursors, transport, dry deposition)
Activity 1 – Annual North America averages by depositional pathway

- Model-to-model differences in deposition velocities and totals as well as absolute and relative contributions of the different pathways
- Model spread in deposition velocity often but does not always correspond to deposition total (due to other process differences modulating concentrations)

**no water included in domain averages**
Activity 1 – North America July mean diel cycles

- Model differences in magnitude & degree of diel variation
Activity 1 – North America July mean ozone effective conductance (cm s\(^{-1}\)) diel cycles

\[\text{sum of effective conductances} = \text{ozone deposition velocity}; \text{note differences in y-axis ranges across panels}\]

- Soil and stomatal pathways tend to dominate
- Relative pathway contributions similar across models

Note different y-axis ranges
Activity 1 – LULC-specific ozone deposition velocities and effective conductances

Deciduous Broadleaf Forest, July, North America

- Model-to-model differences even for same LULC type & deposition pathway
Activity 1 – Takeaways so far

- Domain average comparisons suggest modest model spread in ozone deposition velocities and fluxes.
- Perhaps some spatial offsetting in domain averages; stronger variability across models for one LULC.
- More differences in magnitude of deposition velocities and fluxes than contributions from pathways.
- Both stomatal and nonstomatal pathways key for domain average, as well as specific LULC domain average for one LULC, across models.
How do we evaluate the dry dep schemes in AQMEII4?
A couple of considerations …

- Unreproducible strong interannual variability suggests model evaluation with limited site-based observational data is inadequate
- Abundant short-term ozone flux datasets (103 sites), but missing long-term datasets (11 sites with > 5 years; none with >15 years)

*Clifton et al. GRL 2017; Clifton et al. RoG 2020*
How do we evaluate the dry dep schemes in AQMEII4?

A couple of considerations …

Intercomparison using single-point modeling driven by same site-specific forcing at Borden Forest

- Simulated meteorology does not necessarily capture local site conditions, posing challenges for understanding strengths & weaknesses of dry dep schemes using flux observations
Activity 2 – Methodology & Models

**Single Point Model Intercomparison: Activity 2**
Co-leads: O. Clifton, D. Schwede, C. Hogrefe, C. Holmes

- Extract dry dep schemes from host models as standalone single point models
- Drive the models with the same site-specific forcing datasets
- Compare & evaluate simulated deposition velocities

Inputs: observed LAI, meteorology, soil & canopy characteristics, etc.

**Standalone dry dep scheme**

Site with observed ozone fluxes

Output: modeled deposition velocity

<table>
<thead>
<tr>
<th>Group</th>
<th>Host model</th>
<th>Scheme(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECCC</td>
<td>GEM-MACH</td>
<td>Wesely, Zhang</td>
</tr>
<tr>
<td>U.S. EPA</td>
<td>CMAQ</td>
<td>M3DRY, M3DRY-psn, STAGE</td>
</tr>
<tr>
<td>Technical University of Madrid</td>
<td>WRF-Chem</td>
<td>Wesely</td>
</tr>
<tr>
<td>ECMWF</td>
<td>IFS</td>
<td>Wesely, two configurations</td>
</tr>
<tr>
<td>Florida State University</td>
<td>GEOS-Chem</td>
<td>Wesely</td>
</tr>
<tr>
<td>Chinese University of Hong Kong</td>
<td>GEOS-Chem coupled to TEMIR</td>
<td>Wesely and Zhang, with three stomatal options (standard, Medlyn, Ball-Berry)</td>
</tr>
<tr>
<td>University of York</td>
<td>EMEP</td>
<td>DO$_3$SE with two stomatal options (standard, psn)</td>
</tr>
<tr>
<td>Wageningen University</td>
<td>EMAC/SCM</td>
<td>MLC-CHEM</td>
</tr>
</tbody>
</table>

Eighteen single-point models

Models participating in Activity 1
Coupling to photosynthesis
### Activity 2 – Sites

<table>
<thead>
<tr>
<th>Site</th>
<th>Land use/land cover</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auchencorth Moss, UK</td>
<td>Peat bog</td>
</tr>
<tr>
<td>Borden Forest, Canada</td>
<td>Temperate mixed forest</td>
</tr>
<tr>
<td>Bugacpuszta, Hungary</td>
<td>Grass</td>
</tr>
<tr>
<td>Easter Bush, UK</td>
<td>Grass</td>
</tr>
<tr>
<td>Ispra, Italy</td>
<td>Deciduous broadleaf forest</td>
</tr>
<tr>
<td>Harvard Forest, US</td>
<td>Temperate mixed forest</td>
</tr>
<tr>
<td>Hyytiälä, Finland</td>
<td>Evergreen needleleaf forest</td>
</tr>
<tr>
<td>Ramat Hanadiv, Israel</td>
<td>Shrub</td>
</tr>
</tbody>
</table>

Five out of eight sites at least three and up to twelve years of ozone fluxes.
Activity 2 – Goals

1. Quantify the performance of a variety of dry deposition schemes under identical conditions

2. Understand how the different deposition pathways contribute to the intermodel spread

3. Probe the sensitivity of schemes to environmental factors, & variability in the environmental sensitivities across schemes

4. Understand the differences in dry deposition simulated in the regional models in Activity 1
Activity 2 – Ongoing Publications

- Clifton et al. – intro to Activity 2 and initial results focusing on multiyear seasonality [submitted to ACP special issue]
- Bash et al. – use of ozone flux measurements in AQMEII4 database for optimization of select STAGE resistances [in preparation]
- Lee, Makar, et al. – use of cluster analysis for identifying met conditions leading to model biases [planning stages]
- Lee, Makar et al. – physics-informed machine learning for refining parameter values [planning stages]
- Toyota, Makar et al. – improving the GEM-MACH dry dep scheme [planning stages]
- Khan, Clifton, et al. – investigate model differences in stomatal uptake using observational constraints on stomatal conductance from carbon and water fluxes [planning stages]

Here we show results on how the models differ in capturing observed multiyear mean seasonality in ozone deposition velocity, and the contribution of different deposition pathways.
Activity 2 – Evaluation of monthly ozone deposition velocities across ensemble of single-point models

- Factor of 1.2 to 1.9 spread across models (excl. outliers) for ann. averages
- Model ensemble (excl. outliers) captures observed values reasonably well
- Performance varies by model, season, & site; no model always within 50% of obs. across sites & seasons

Clifton et al., submitted to ACP
Activity 2 – Multiyear monthly mean effective stomatal conductance across single-point models

- Large variation in magnitude & seasonality in stomatal uptake across models
- Work led by Anam Khan (UW-Madison) to use this diagnostic to pinpoint strengths & limitations of different types of stomatal conductance models

Clifton et al., submitted to ACP
Activity 2 – Nonstomatal uptake also contributes to model spread

- Models can disagree in relative contributions from the pathways, even when they predict similar deposition velocities, or agree in the relative contributions but predict different deposition velocities.

Clifton et al., submitted to ACP
Activity 2 – Takeaways so far

• Decent ensemble model performance & modest model spread (when ignoring outliers) with respect to multiyear average seasonality in ozone deposition velocities

• Individual model performance is site & season dependent
• Both stomatal and nonstomatal uptake contribute to model spread during growing season

• Models differ in magnitude & relative contribution of individual pathways, even when they agree on the magnitude of the deposition velocity
Activity 1 & 2 – Takeaways so far

- A lot of iterations – model set-up, input, & diagnostic issues. But, reruns are complete & analysis is back on track

- Documenting dry dep schemes is key – not only facilitates intercomparison & our ability to push the science forward, but we found bugs!

- Activity 2 suggests more model variation in ozone deposition velocities, especially in fraction of pathway contributions
  - May be due to initial focus on domain averages (spatial offsetting), or that Activity 2 has more & more different dry dep schemes

- Still a lot to explore in Activity 1 & 2 databases – please get in touch if you’d like to lead analyses of results!

Thanks for your attention!