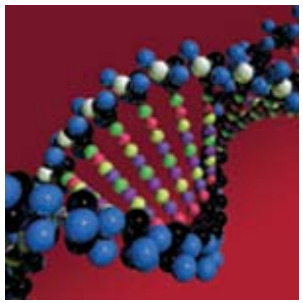
Improving Cloud Impacts on Photolysis Rates in Off-Line AQMs



Chris Emery
ENVIRON Corporation

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Acknowledgements: K. Baker, B. Timin, EPA/OAQPS

ENVIRON

Introduction

- Photochemistry is strongly influenced by clouds
  - Attenuate or enhance irradiance of ultraviolet (UV) bands
  - Depends on: cloud location/depth, water content, water phase
- Clouds are difficult to accurately simulate
  - Widely varying spatial and temporal scales
  - Often ill-suited for Eulerian models (esp at AQ model scales)
- Meteorological models can adequately characterize:
  - Large-scale cloud patterns, well-resolved weather systems
- But rely on parameterizations for sub-grid processes
  - Account for bulk characteristics
  - Cloud impacts are uncertain and sources of poor performance
  - Translate to large errors/uncertainties in photochemical models

Introduction

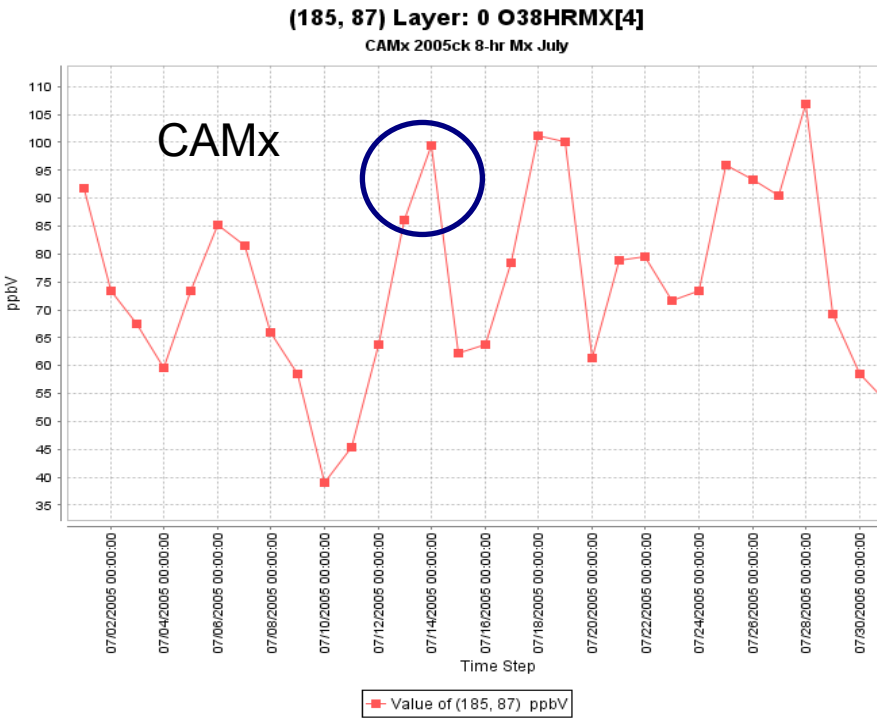
- EPA applies CMAQ and CAMx on a large eastern U.S. domain
  - Dolwick (2006) investigated role of clouds from MM5
  - Even relatively thin clouds can have large effects on ozone
  - These models differ greatly in their cloud impacts
    - CMAQ generates thicker clouds than CAMx
    - Occasionally large differences in ozone patterns
- EPA recently expanded their inter-model cloud comparison
  - Evaluated cloud parameterizations
  - Explained significant ozone differences on certain cloudy days
    - CAMx underestimates clouds attenuation
    - CMAQ probably overestimates cloud attenuation

Introduction

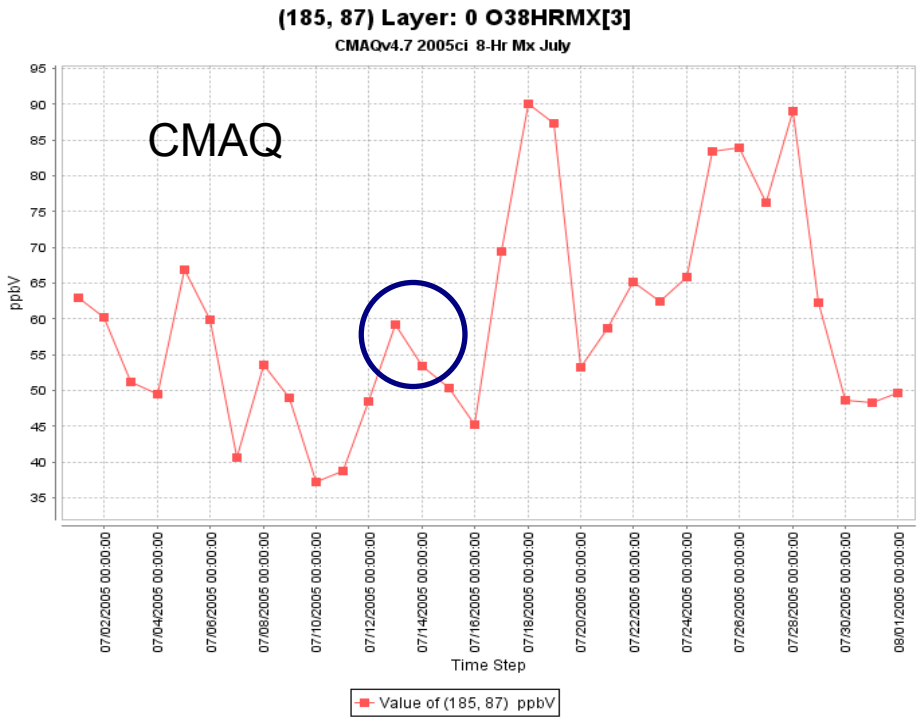
- In 2009, EPA and ENVIRON developed some near-term recommendations
  - Further tests with both models
  - Develop improvements to the MM5CAMx interface processor to help reduce the cloud shortfall in CAMx
  - Review additional methodologies to improve cloud characterization in off-line photochemical models

EPA CMAQ/CAMx July 2005 Simulations

CAMx

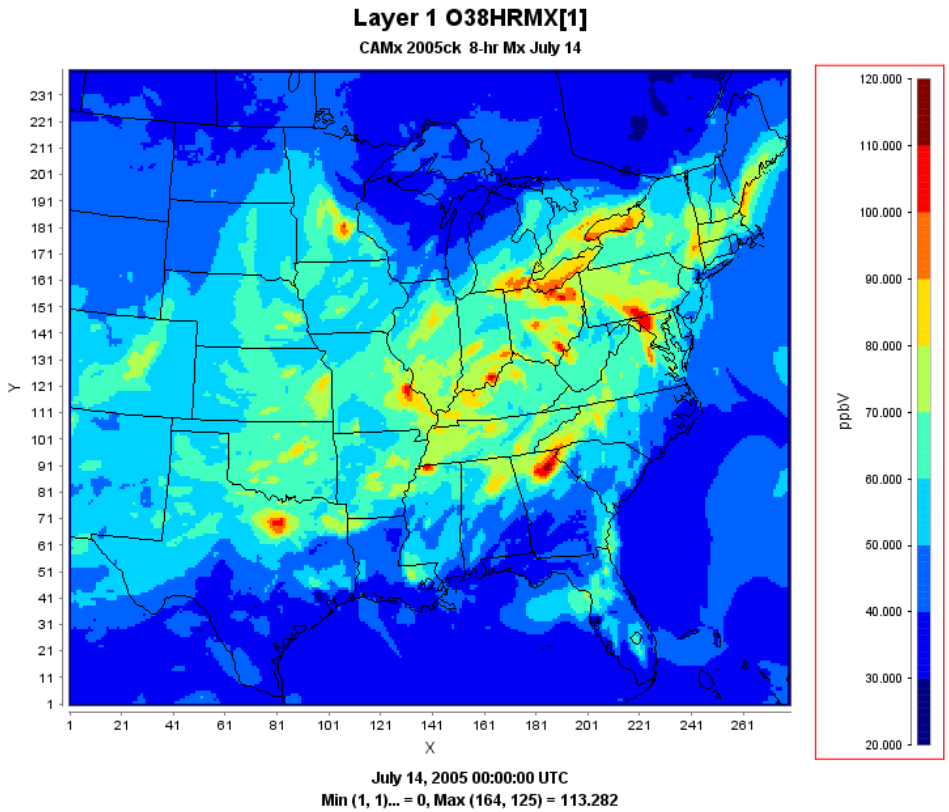


CMAQ

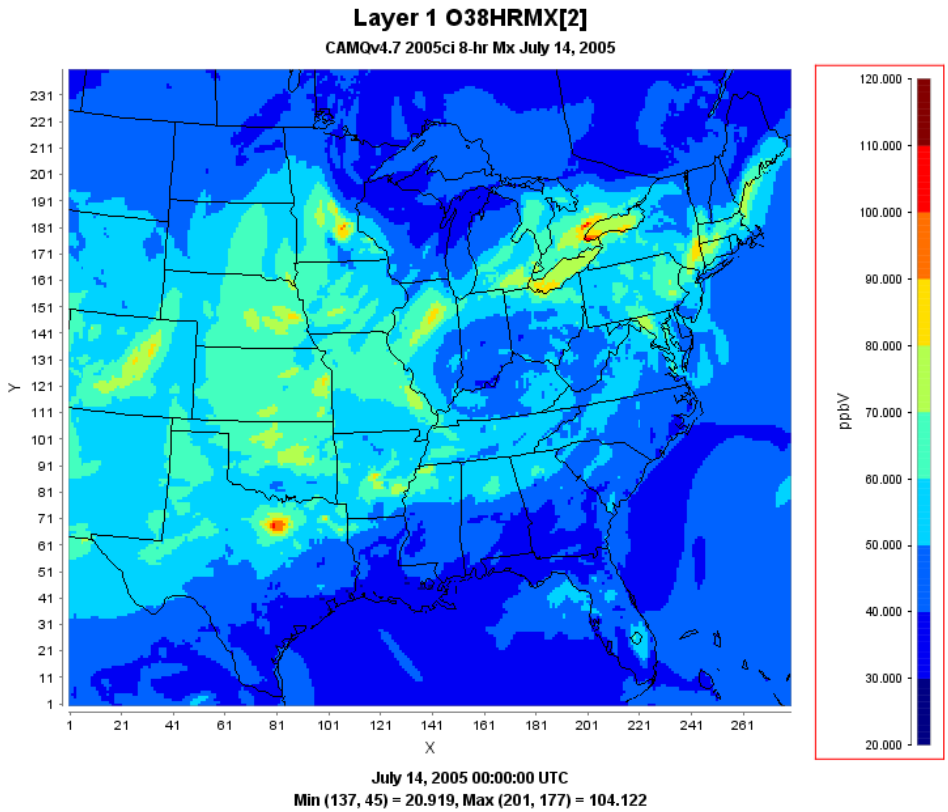


EPA CMAQ/CAMx July 2005 Simulations

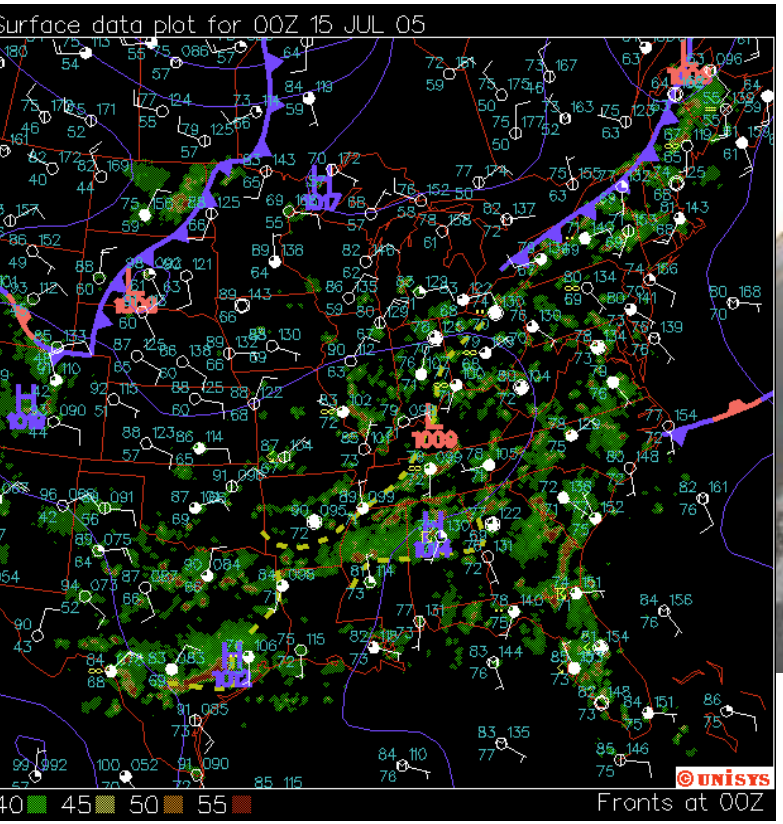
CAMx

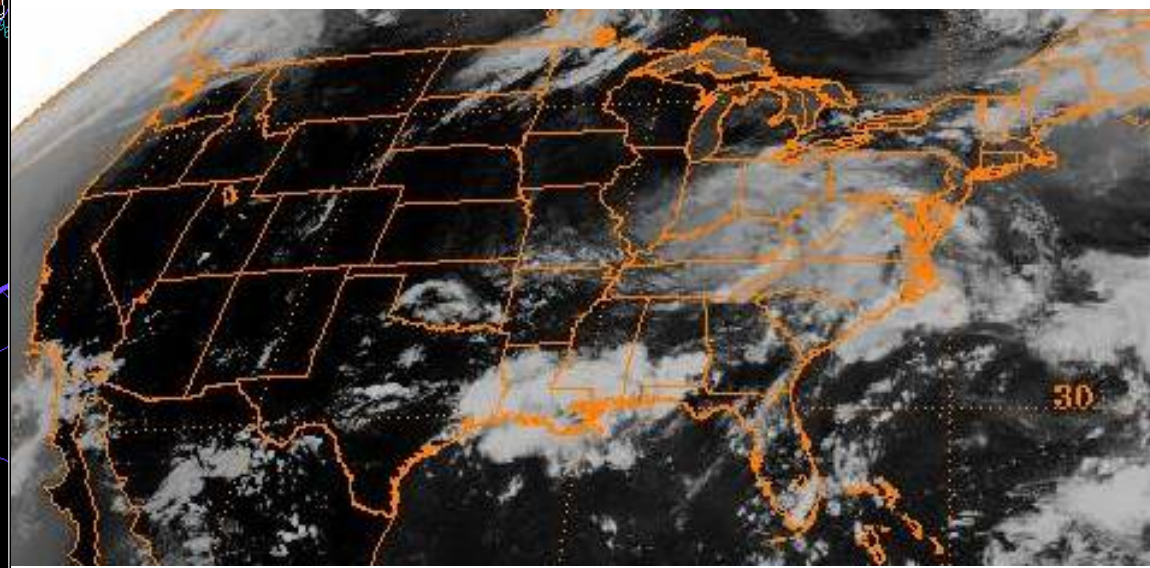


CMAQ



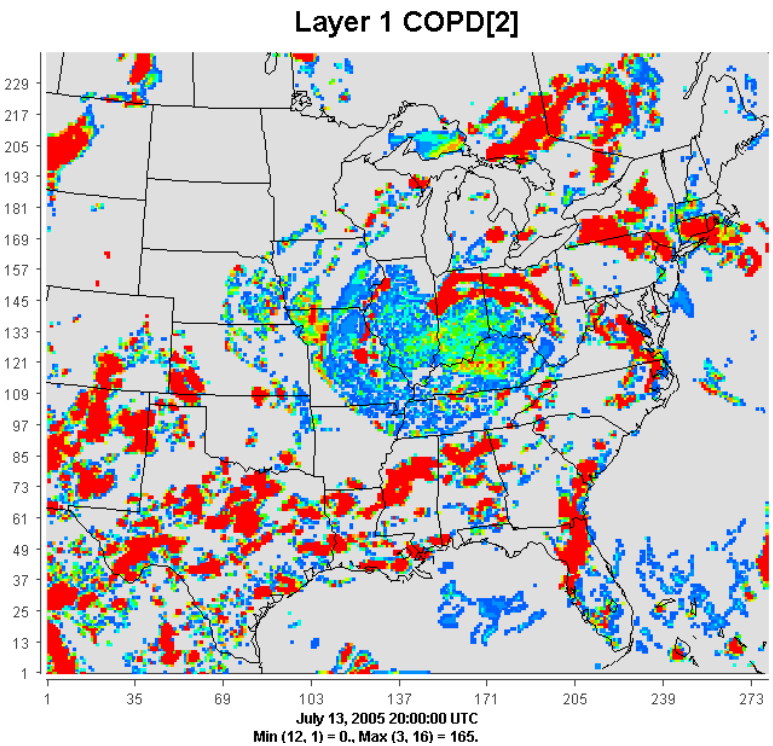
Meteorology on July 14, 2005



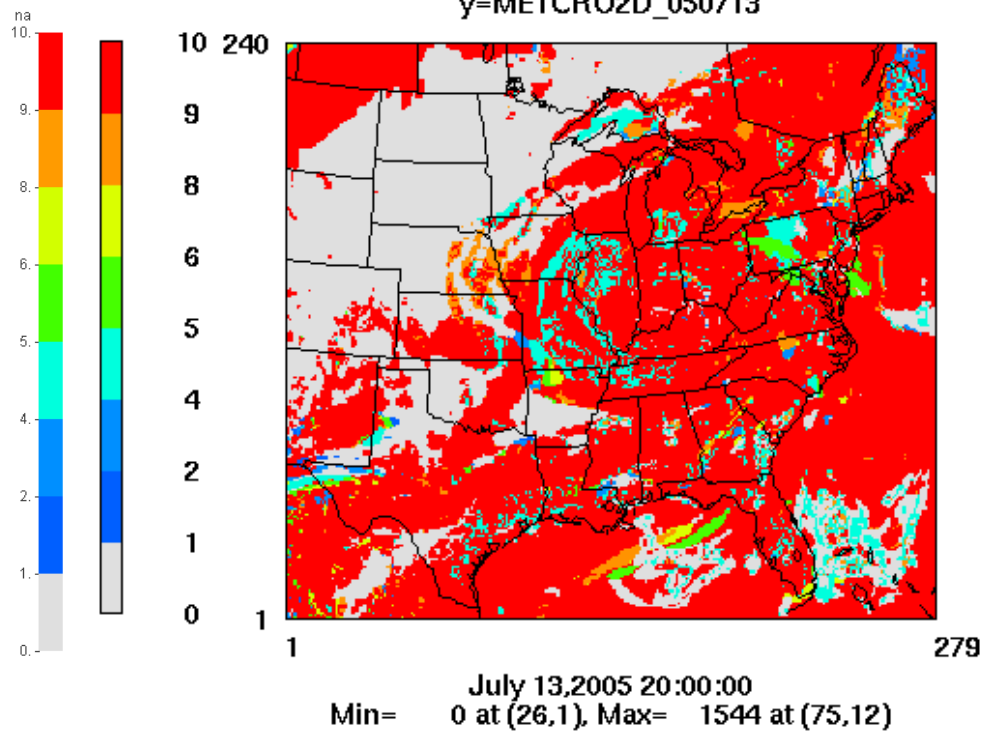


Modeled Cloud Optical Depth

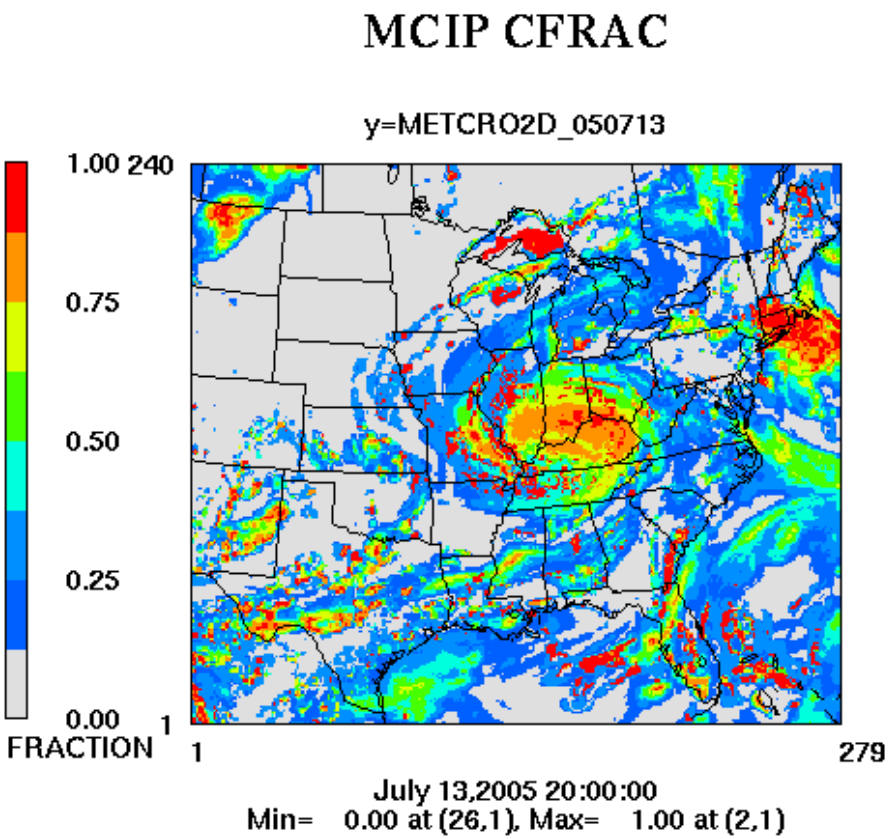
CAMx

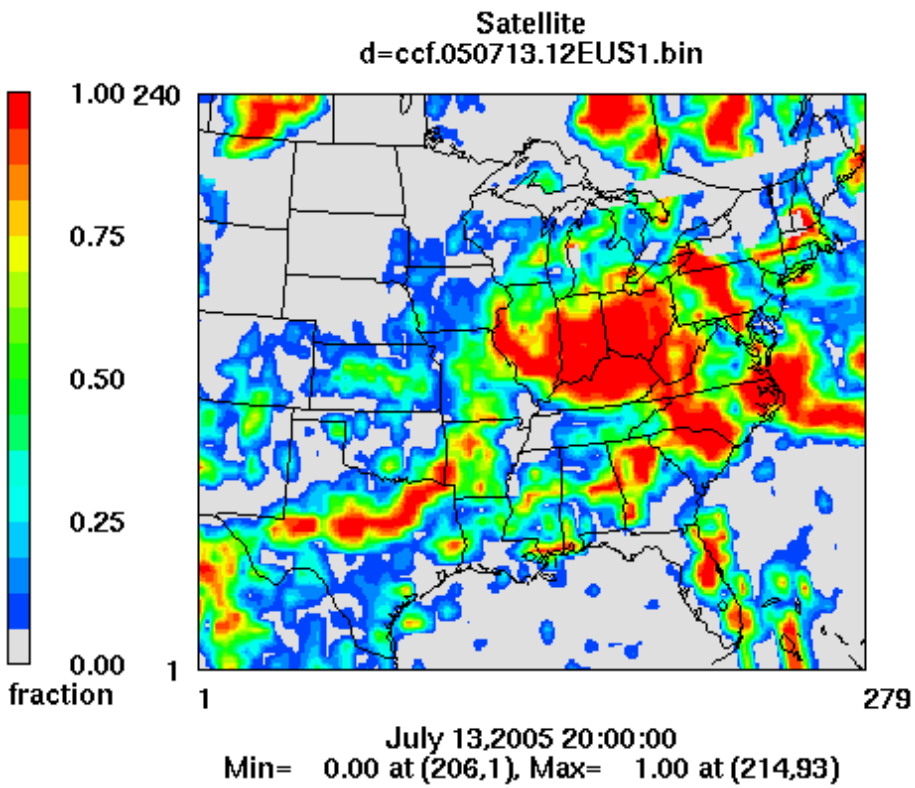


CMAQ/MCIP



CMAQ Cloud Fraction vs. Satellite





Evaluation Results

- Obs: heavy OVC/BKN cloud cover, some light rain
- CMAQ has more cloud photolysis attenuation
  - Significant difference in cloud cover, same MM5 run
  - Different cloud optical depth (COD)
    - But CAMx and CMAQ COD calculations are similar
  - Different cloud cover fraction
    - CAMx: only grid-resolved clouds (i.e., MM5 resolved clouds)
    - CMAQ: grid-resolved clouds (MM5) and diagnosed sub-grid (MCIP)
- MM5 generated little resolved cloudiness, and too thin
- MM5 likely generated much more sub-grid cloudiness
  - Impossible to verify (MM5 does not output sub-grid cloud info)
  - We conclude lack of CAMx COD due to lack of clouds

Comparison of CAMx/CMAQ Cloud Attenuation

- RADM cloud adjustment to clear-sky photolysis rates (Chang et al, 1987):

$$J = J_{clear}\left[1 + F_{cloud}\left(A_{cloud} - 1\right)\right]$$

- Below-cloud attenuation factor:

$$A_{cloud} = 1.6\, t_r \cos\varphi$$

- Cloud transmission coefficient:

$$t_r = \frac{5 - e^{-\tau}}{4 + 3\tau\left(1 - f\right)}$$

Comparison of CAMx/CMAQ Cloud Attenuation

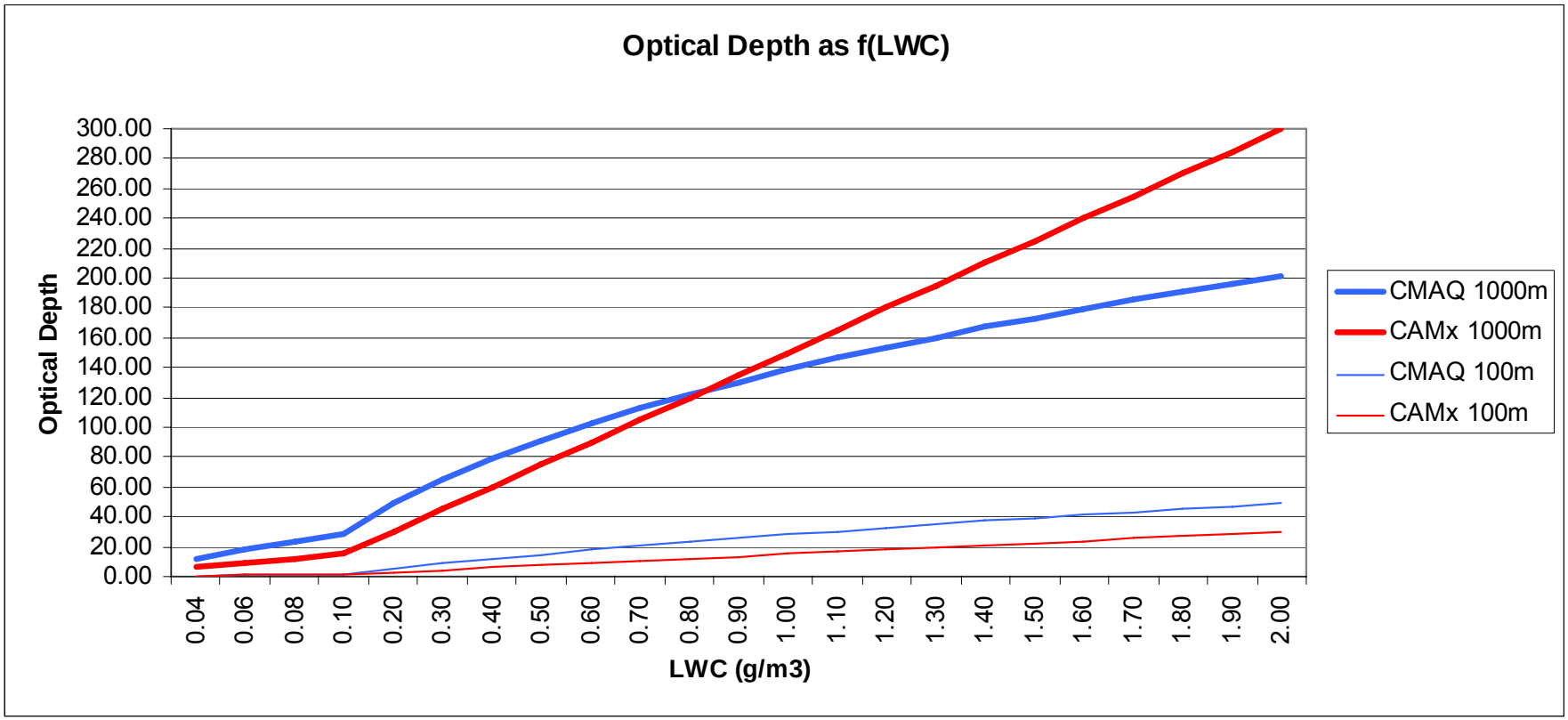
- CAMx COD (RADM)

$$\tau = \frac{3 L \Delta z_{cloud}}{2 \rho_w r_d}$$

- CMAQ COD (Stephens, 1978)

$$\tau = 10^{0.2633 + 1.7095 \ln\left(\log_{10} LWP\right)}$$

Analysis of COD Equations



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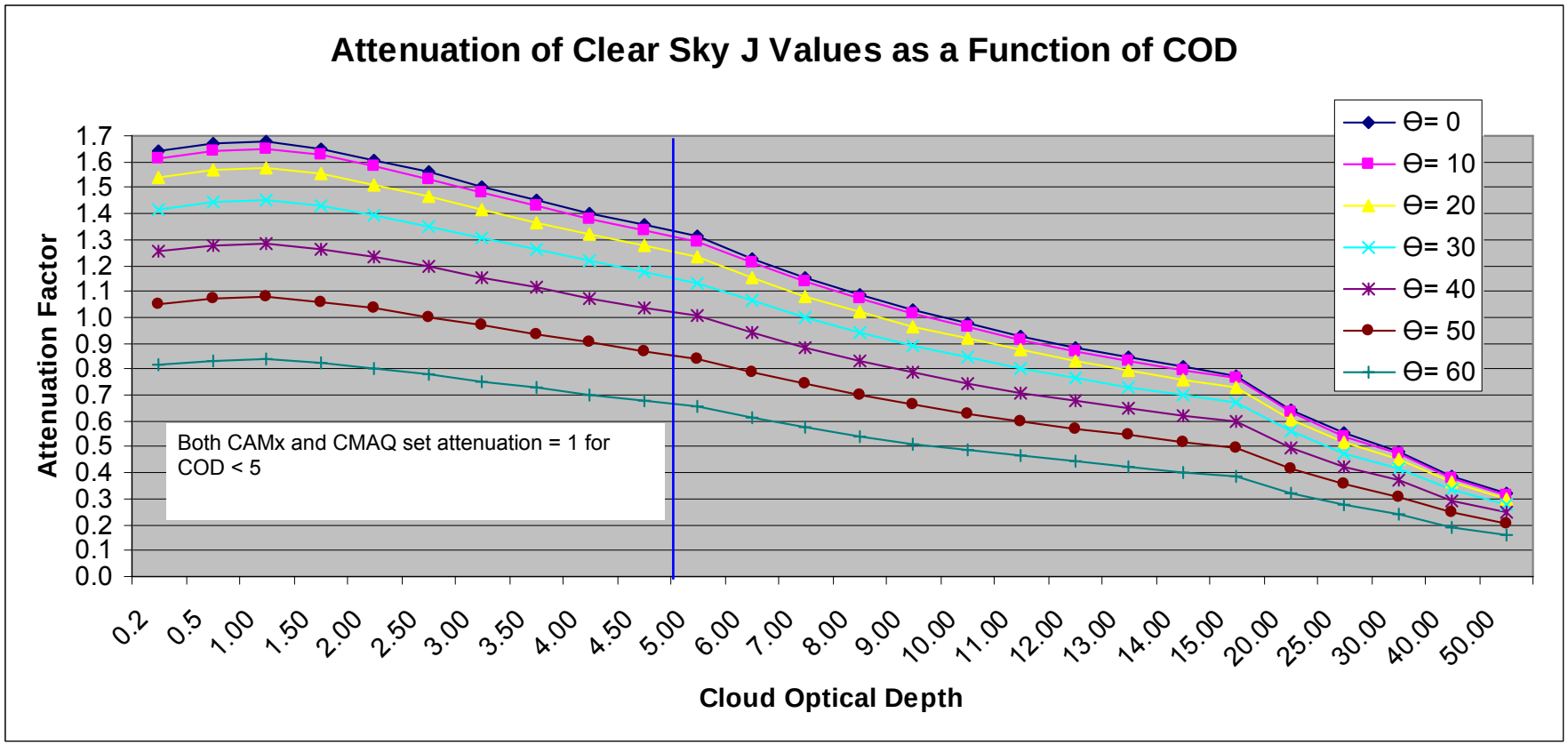


CAMx Cloud Sensitivity Tests

- EPA/ENVIRON performed sensitivity tests increasing the COD:
  - 1: arbitrarily increase COD by x10
    - Largest increases in COD, no change in cloud spatial pattern
    - Ozone results similar to CMAQ and observations
  - 2: add sub-grid precipitating clouds to COD calculation
    - Some areas of higher COD, but little spatial increase in cloud patterns
    - Minimal areas of MM5 sub-grid precipitation
    - Minor ozone reductions
  - 3: As in 2, but scale COD to match Stevens (1978) equation
    - Negligible change to COD pattern
    - Negligible change to ozone
- CAMx COD equation is not a factor
- CAMx needs more clouds

Interim Cloud Improvement

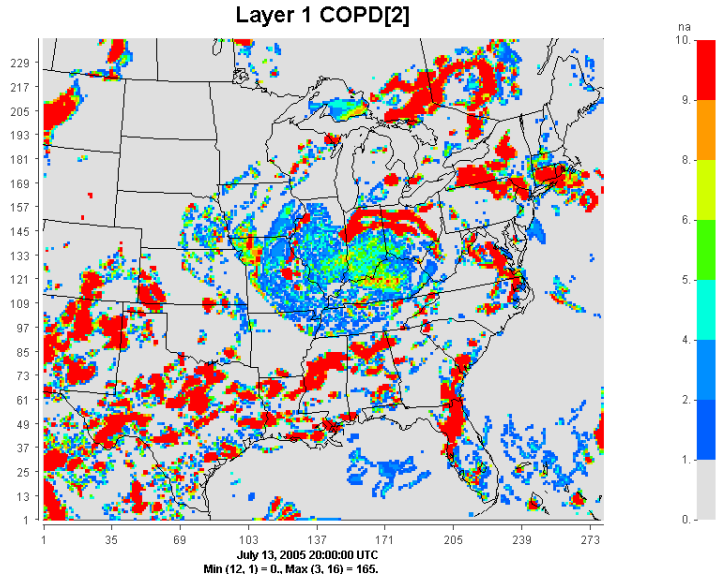
- MM5CAMx interface program was further modified:
  - 3-D cloud fields determined for several cloud types:
    - Resolved L from MM5 (as before)
    - Sub-grid "stratiform" Fcloud and L according to RHc profile (following MCIP)
    - Sub-grid convective Fcloud and L (following CMAQ)
  - COD equation according to DelGenio et al. (1996) and Voulgarkakis et al. (2009):

$$\tau = \frac{3 L \Delta z_{cloud}}{2 \rho_w r_d} \left(F_{cloud}\right)^{3/2}$$

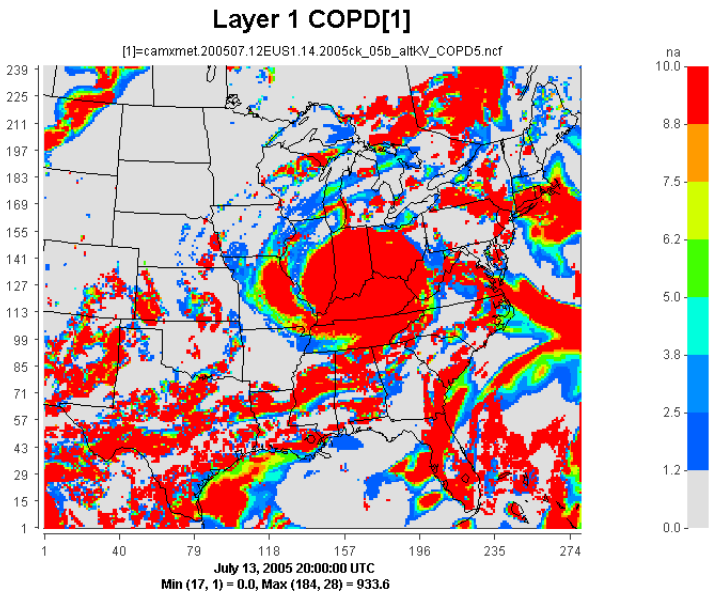
- EPA tested this modification on their 2005 12-km CAMx simulations

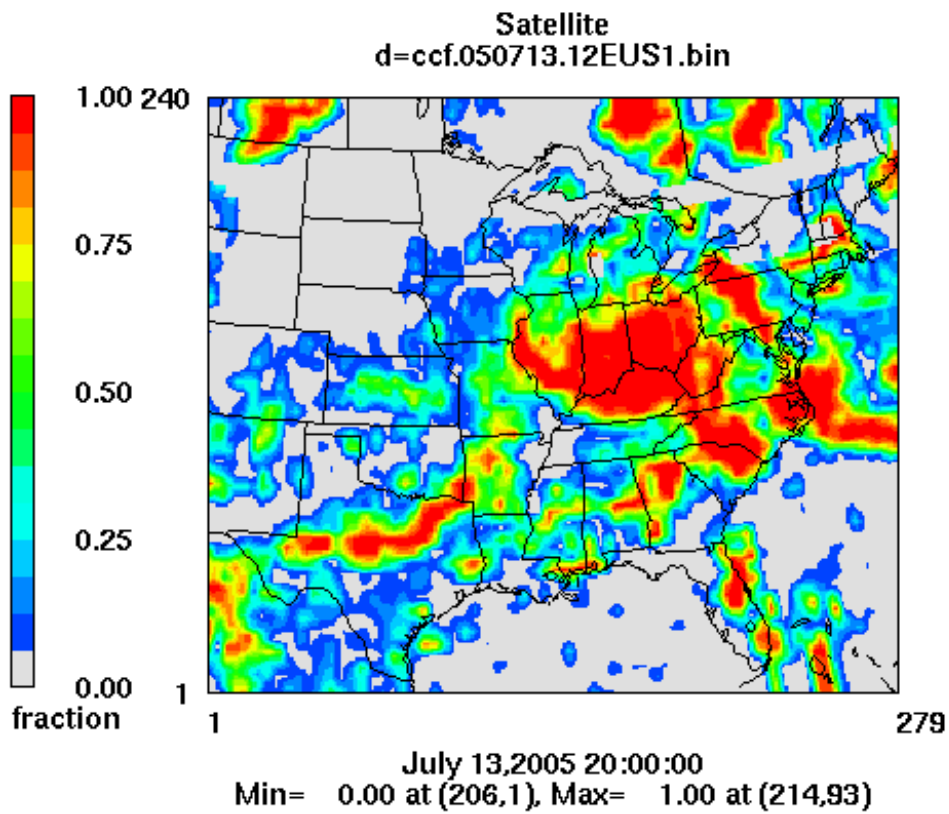
Interim Cloud Improvement

Old

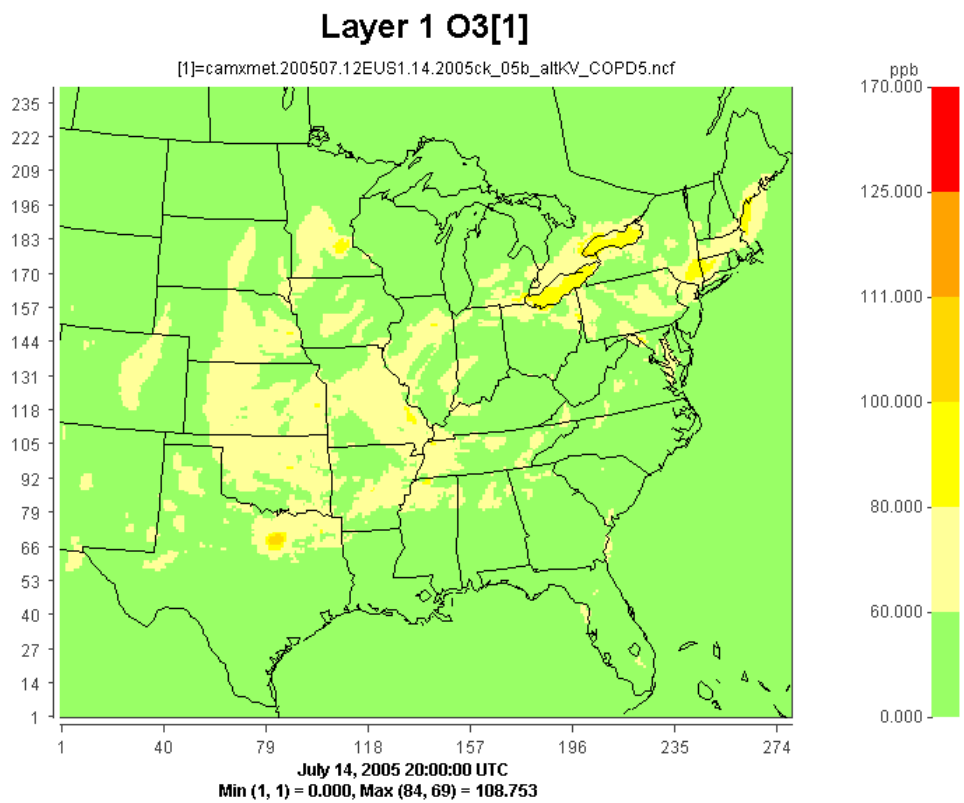


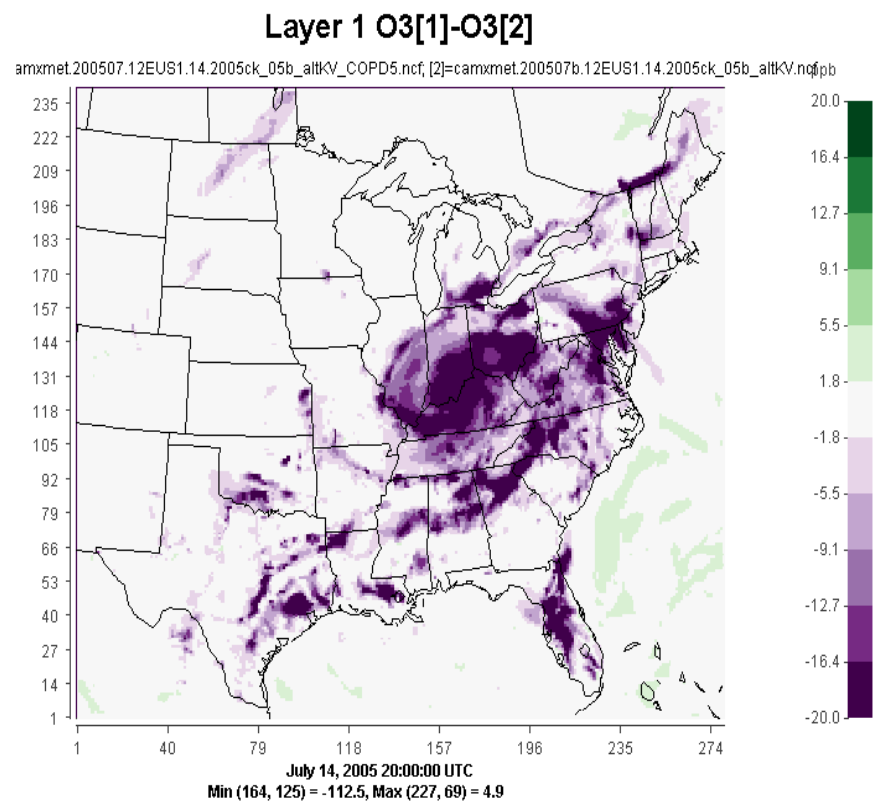
New





Interim Cloud Improvement

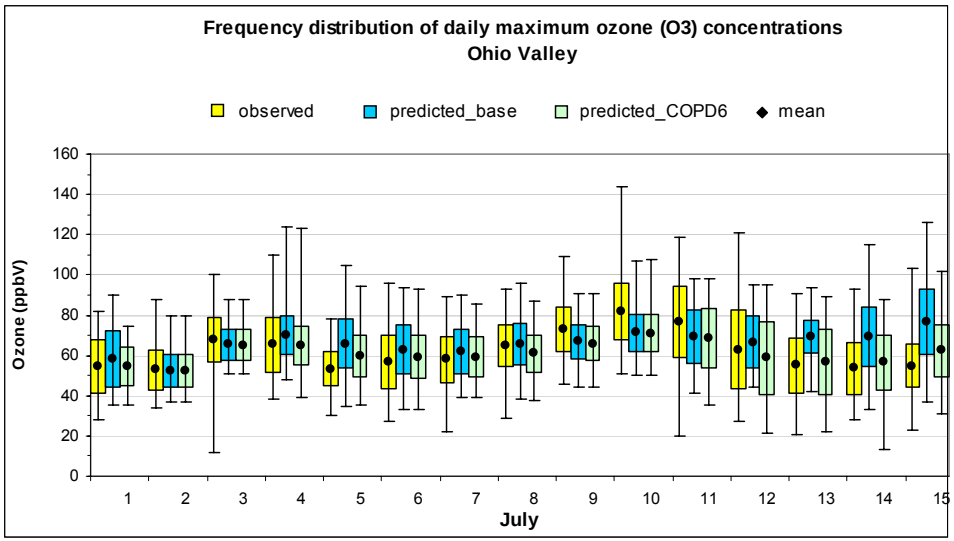


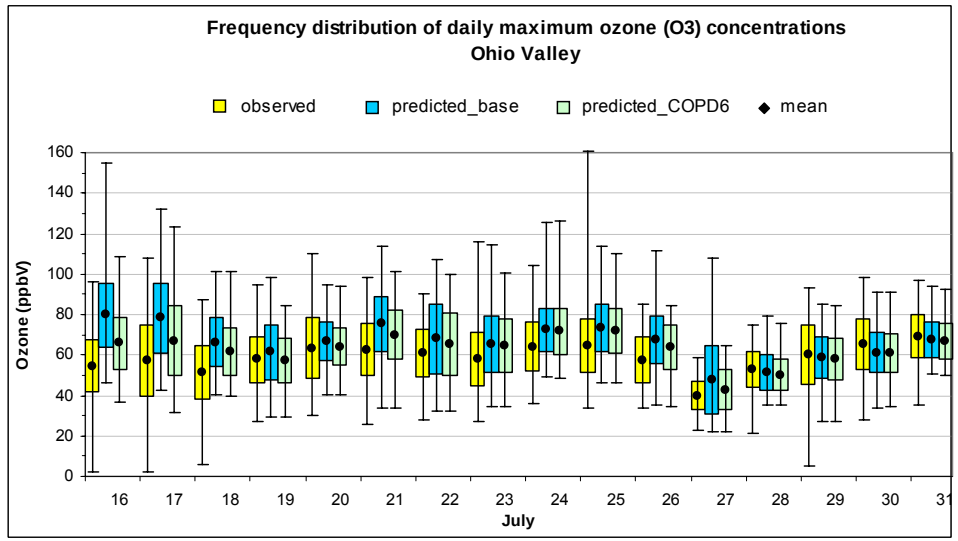


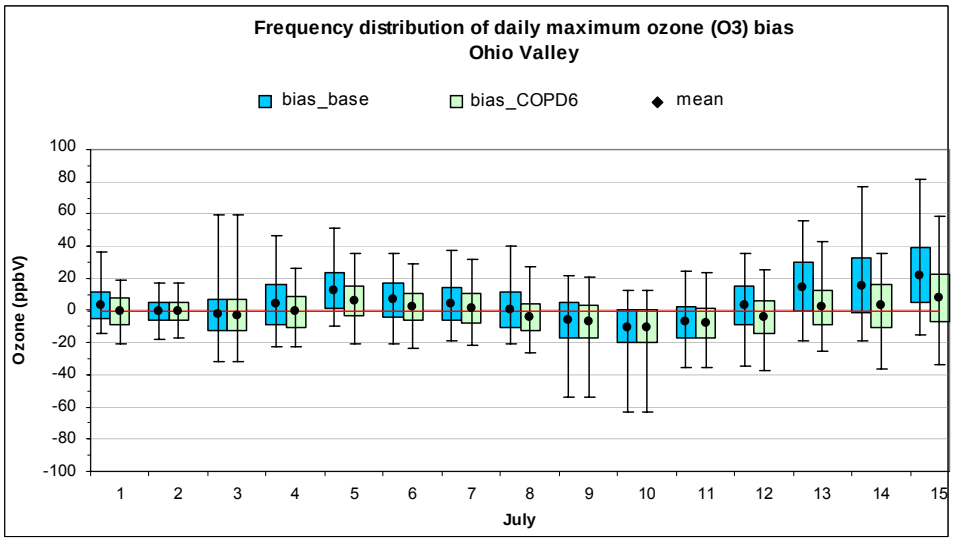
Interim Cloud Improvement

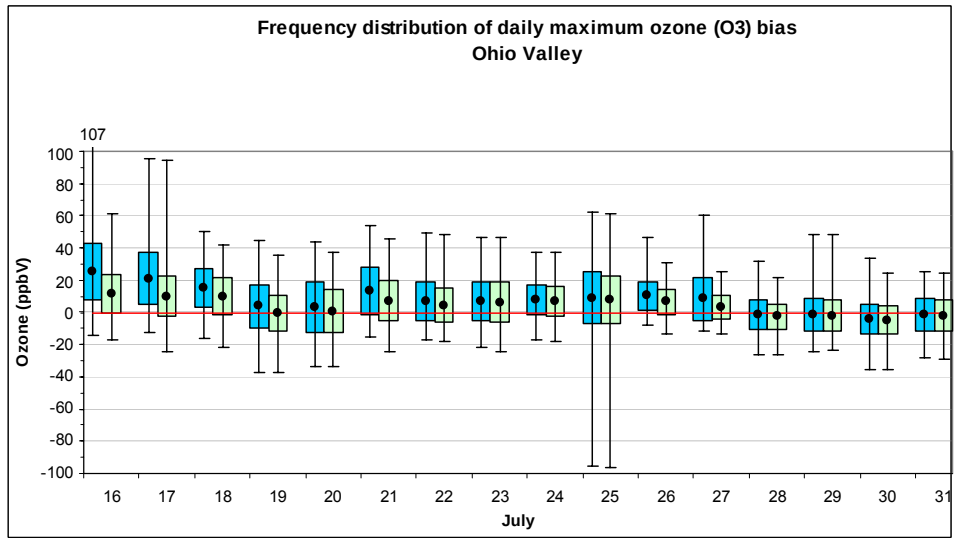
- Significantly more cloudiness (and COD) was added by including fractional cloud cover
- Large reduction in Ohio Valley ozone
  - Similar to the case with CODx10
  - Similar to the observed and CMAQ fields
- EPA ran CAMx for Jan/July 2005
  - ENVIRON conducted in-depth MPE
  - Daily maximum ozone
  - 24-hour averaged sulfate (SO4)

July Ozone Performance – Ohio Valley

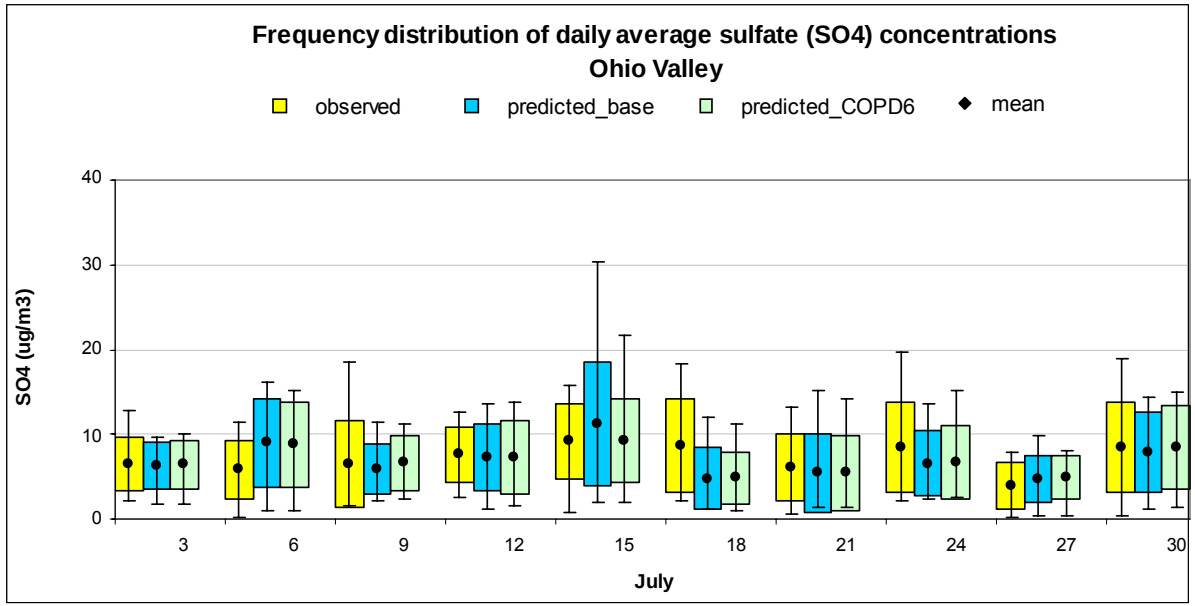


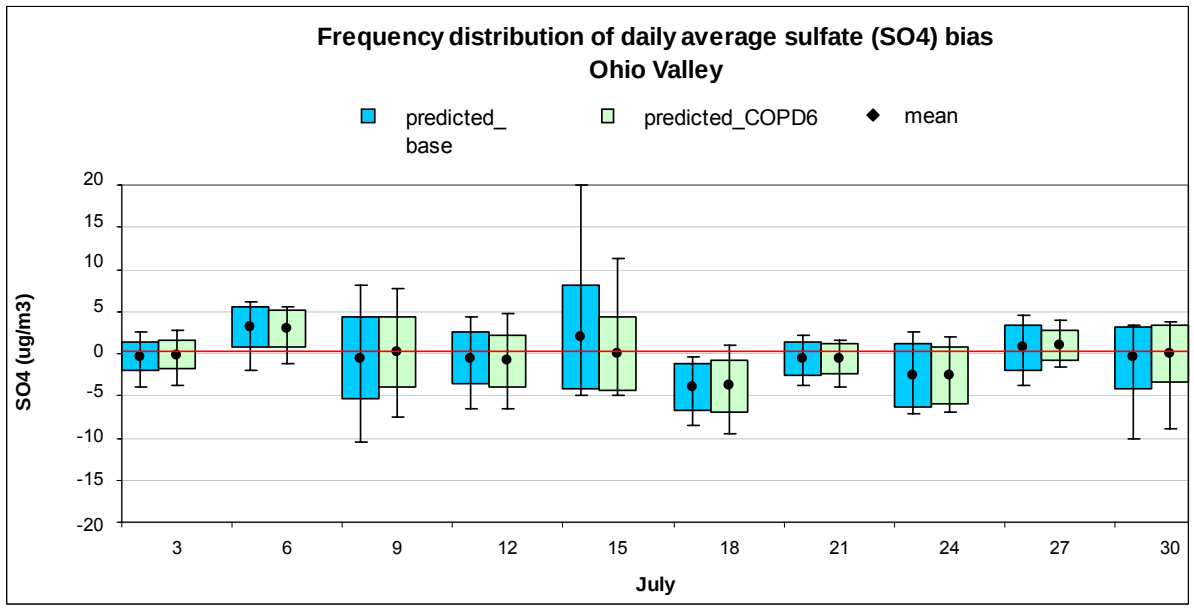






July Sulfate Performance – Ohio Valley





Summary of MPE Impacts

- Good overall ozone bias, except July 13-18:
  - Mean bias jumps to 20 ppb, peak bias 107 ppb on July 16
  - New run greatly improved model performance
    - 20-40 ppb bias improvement
- Cloud changes negligible in January across domain
  - Likely lack of sub-grid convection during this season
- Good overall sulfate bias throughout July
  - New run performed equally well
  - Greatest change on July 15, when tropical clouds lingered
    - CAMx over predicted highest sulfate by 20 μg/m3
    - New run reduced peak bias by 8 μg/m3
- Sulfate differences in January were subtle

Improving Cloud Impacts on Photolysis

- Errors in cloud predictions and simplicities in parameterized cloud attenuation both adversely impact ozone predictions
- Lack of sub-grid cloud data available to off-line air quality models exacerbates inconsistencies between the modeling systems
- We reviewed three techniques:
  - Supplementary cloud outputs from meteorological models
  - Use of satellite data to adjust clear-sky photolysis
  - Use of simplified on-line radiative transfer models within air quality models

Additional Output from Met Models

- MM5 and WRF output 3-D resolved cloud/precip water
  - Easily transferred to the air quality models
  - Support photolysis rate adjustments, aqueous chemistry, wet deposition
- Significantly more cloud/precip can be generated by sub-grid cumulus schemes
  - Relative contribution increases with coarser resolution
  - But no detailed cloud information is saved
  - Only gridded precipitation rates are accumulated
  - AQ models must re-diagnose cloud properties
  - Leads to inconsistencies between met and AQ models

Additional Output from Met Models

- We recommend that sub-grid cloud algorithms output additional data, for example:
  - Cloud base and top
  - Cloud fractional horizontal coverage
  - Cloud liquid and ice water profile
  - Precipitation liquid, snow, graupel water profile
  - Ambient air entrainment/detrainment fluxes
  - Vertical convective/mixing rates
- Met-AQ interface programs would need to be updated to utilize this information

In-line Radiation Models

- RADM cloud photolysis attenuation parameterization is crude and inaccurate
  - Esp. at larger zenith angles
- Introduction of simpler fast RTMs into AQMs
  - McHenry & Coats (2003): SIM into MAQSIP-RT
    - Report significant forecast ozone improvements
  - More recently:
    - Fast-J into CMAQ
    - Fast-TUV into WRF-CHEM
  - Account for sub-grid cloudiness, fractional cover, stacked and staggered cloud patterns, above/within/below cloud impacts

Satellite Adjustments

- McNider et al. (1998) used satellite-derived broadband cloud transmittance to correct photolysis rates within RADM
  - Over predictions of simulated clouds significantly reduced photolysis relative to the satellite-derived cloud data
- Pour-Biazar et al. (2007) used satellite-derived cloud data to correct photolysis rates within CMAQ
  - MM5 poorly predicted clouds location, timing, coverage
  - Improved cloud photolysis impacts using hi-res GOES data
    - Focus on improving cloud patterns, not RADM parameterization
  - Tested in CMAQ for Houston August 2000 TexAQS
  - Improved intensity, location, timing of ozone patterns
- This only improves impacts on photochemistry
  - No effect on mixing/transport, aqueous chemistry, wet dep

Discussion

- Use of satellite-derived cloud information and in-line RTMs are both innovative and promising
- Important limitations:
  - Satellite techniques cannot modify, shift, add, or remove all cloud-related processes within air quality models
    - Photolysis improved at the expense of exacerbated inconsistencies in cloud representation
  - In-line RTMs are simplified for efficiency
    - Clear-sky calculations are not as accurate as the input lookup tables generated by the full-spectrum offline RTMs

Discussion

- EPA has released "beta" versions of CMAQ v4.7 that include:
  - Satellite cloud adjustment (with UAH)
    - New techniques for GOES data assimilation in MM5 and WRF, and for use in CMAQ
    - Satellite adjustment scheme only applies to the standard clear-sky photolysis rate lookup table option
  - In-line photolysis model techniques (Fast-J)
    - Input cloud fields
    - CMAQ aerosols for extinction and scattering
    - Grid specific surface albedo
    - Modeled meteorological and chemical profiles

Discussion

- ENVIRON's current work with the TCEQ
  - Modifying Grell cumulus scheme (WRF v3.2) to output sub-grid cloud water profiles and cloud fraction
    - Supplying WRF/Grell-generated sub-grid cloud data to CAMx
    - Keeping "interim" modifications for non-Grell applications
  - Adding an in-line (simplified) version of the TUV RTM
    - Start with accurate full TUV clear-sky photolysis lookup table
    - Run TUV in-line to get profiles of clear/cloud flux ratios
    - Apply clear/cloud ratios to clear-sky lookup values