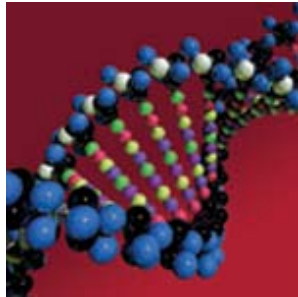
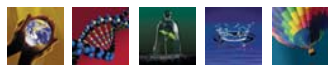


CAMx Vertical Transport Over Complex Terrain



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ENVIRON International Corporation
Novato, California

August 25, 2009



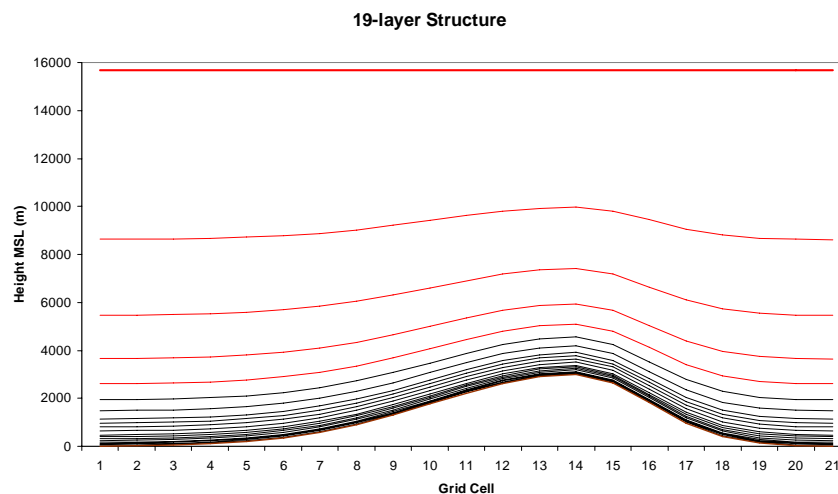
Introduction

- CMAQ (2002 WRAP) and CAMx (2005 FCAQTF) simulate high springtime ozone over Rocky Mountains
 - Typically ~20 ppb higher than remote measurements
- Result from stratospheric ozone levels in top layer
 - Generated by lateral boundary conditions (BCs)
 - Derived from output of GEOS-CHEM global chemistry model
- Stratospheric ozone is rapidly transported to surface over high/complex terrain
 - Sierras, Cascades, Rockies

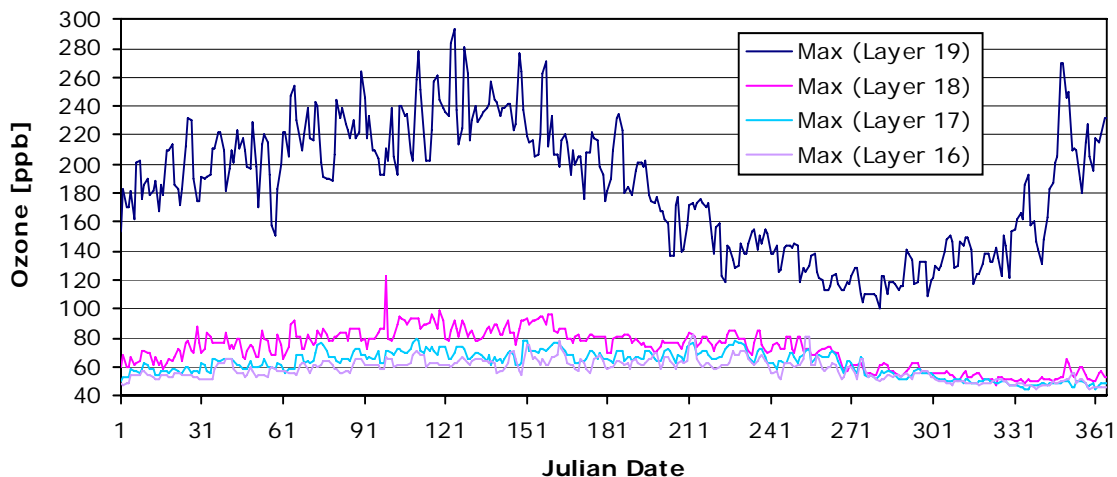


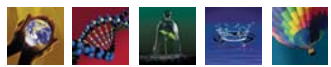
Introduction

- Both of these CMAQ and CAMx runs use 19 layers
 - Top layer spans 8-15 km



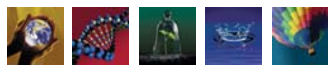
- 2002 ozone BCs in layer 19 range 100-300 ppb





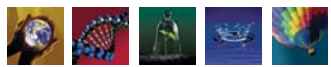
Introduction

- **Contributors to high ozone over the Rockies:**
 - High surface altitudes (2-3 km)
 - Surface is closer to stratosphere
 - Deep PBL mixing and convection (through 4-6 km)
 - Couple surface to mid-troposphere
 - Vigorous resolved vertical circulations (through 4-8 km)
 - Transport layer 19 ozone downward
- **API funded study to investigate this issue that found the following problems:**
 - Coarse vertical grid structure (more aloft layers help)
 - GEOS-CHEM BC interface (better interpolation helps)
 - Vertical velocities (filtering/smoothing helps)
 - CAMx vertical solver technique (alternative approach helps)
 - Does CMAQ have similar vertical advection solver issues?



Approach

- **CAMx 2005 FCAQTF run**
 - Inert, ozone only, no sources/sinks
 - Single 12-km regional grid covering western U.S.
 - Track ozone IC/BC over April 2005
 - Original IC/BC from 2002 GEOS-CHEM extraction (WRAP)
 - New IC/BC from 2005 GEOS-CHEM extraction
- **API-funded work**
 - Task 1: Test smoother-desmoothing (memo 2/18/09)
 - Task 2: Test divergence minimization (memo 4/20/09)
 - Task 3: Test density/wind filter (completed)
 - Task 4: Test best of 1-3 on full photochemical FCAQTF run
 - Task 5: EPA interaction/transfer technology to MCIP/CMAQ



Approach

- ENVIRON in-kind investigations
 - Improved treatment of CAMx top boundary condition
 - Zero flux top BC rather than set BC top concentration aloft
 - Tested alternative vertical grid structures/resolution
 - Implemented alternative (2005) lateral BCs
 - Use 2005 GEOS-CHEM global model output
 - Reviewed GEOS-CHEM interface and improved technique
 - Correct GEOS-CHEM BC interpolation program
 - Implement revised CAMx vertical advection solver



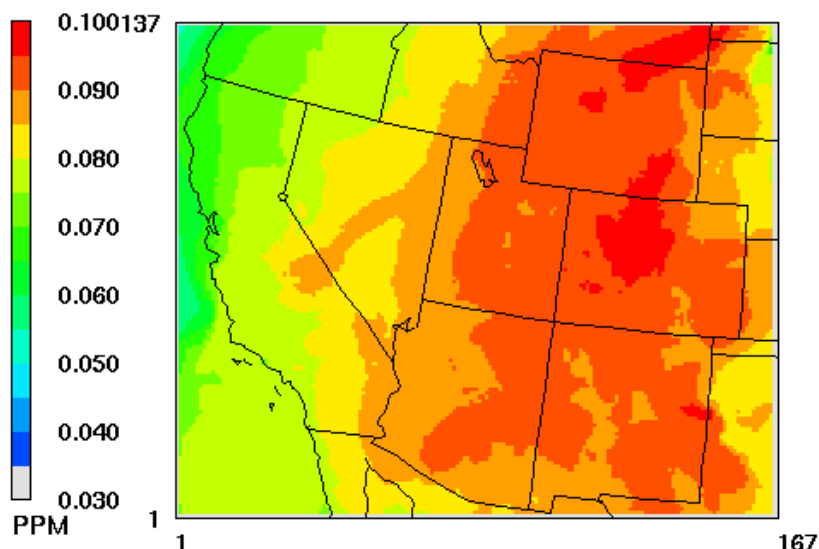
Smoother-Desmoother

- Approach of Yang and Chen (2008)
 - Applied to input horizontal winds to calm vertical velocity
 - Applied aggressively to upper layers only
 - Results in <5 ppb change in April maximum ozone

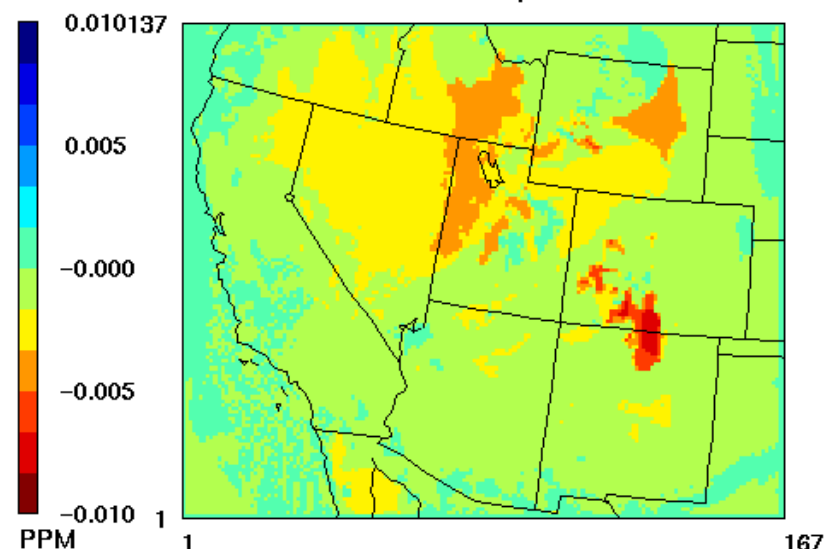
BASE

DIFFERENCE FROM SMOOTHING

Layer 1 Maximum Ozone

CAMx Inert Run
Run 1a: Base CaseApril 1, 2005 0:00:00
Min= 0.000 at (1,1), Max= 0.098 at (132,79)

Layer 1 Difference in Max O3

Run 13 - Run 1
Mar 27 - Apr 30March 27, 2005 0:00:00
Min= -0.007 at (131,48), Max= 0.001 at (20,119)



Divergence Minimization

- Adapted from CALMET
 - Applied to input horizontal winds to reduce vertical velocity
 - Applied aggressively to upper layers only
 - Results in <10 ppb change in April maximum ozone

BASE

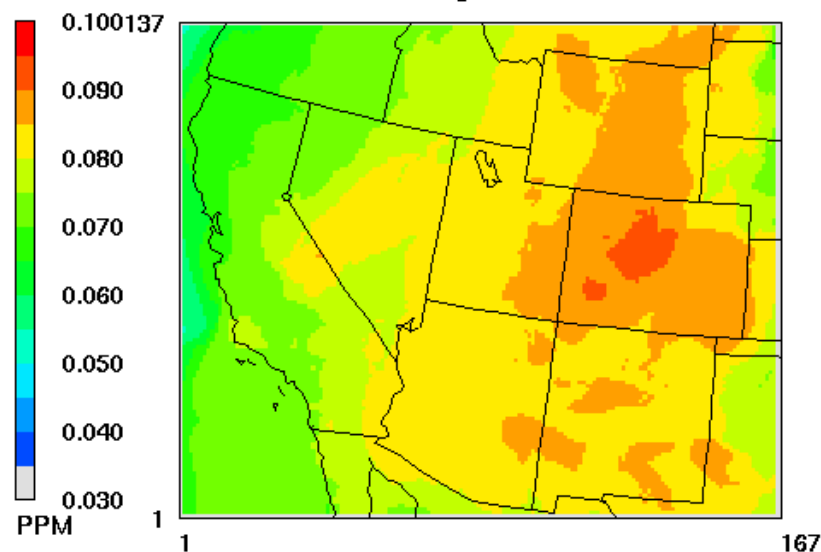
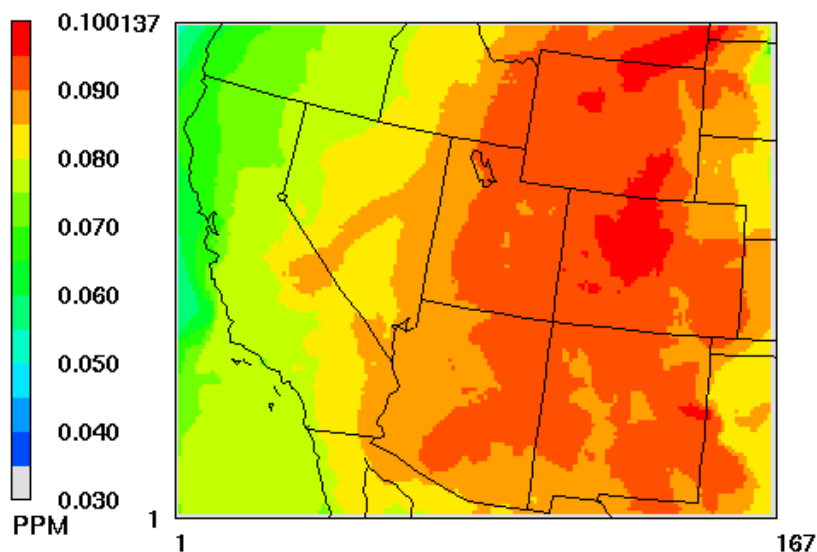
DIV-MINIMIZED

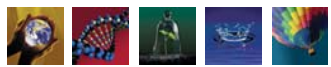
Layer 1 Maximum Ozone

Layer 1 Maximum Ozone

CAMx Inert Run
Run 1a: Base Case

CAMx Inert Run
Run 15a: Divergence Minimization





Divergence Minimization

- **Puzzling/troubling results for vertical velocity profiles in upper layers**
 - Led to big dilution of layer 19 ozone
 - Associated with use of much lower ozone top boundary conditions (70 ppb) than in CAMx top vertical layer (Layer 19)
- **CAMx was revised to use “zero-gradient” top boundary conditions for all subsequent tests**
 - Ignores top boundary condition input
 - Removes artificial dilution of top layer

More Model Layers

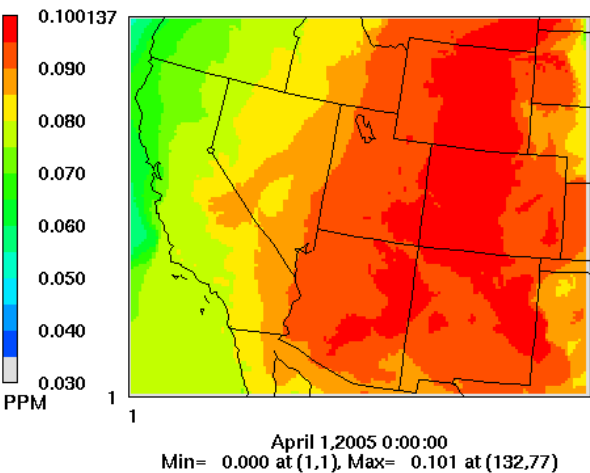
- Reprocess input meteorology, no smoothers/filters
 - Zero-gradient top boundary condition
 - Full 34 MM5 layer structure
 - Runs ~2x slower than 19 layers, 10-15 ppb ozone reduction
 - Intermediate 22 layers to improve resolution aloft
 - Runs ~1.1x slower than 19 layers, ~10 ppb ozone reduction

19-layer

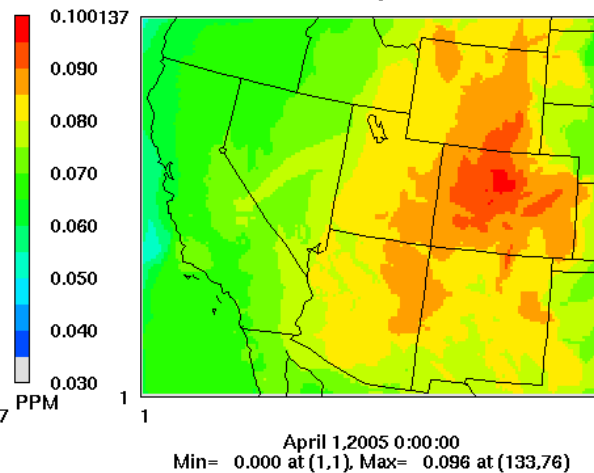
34-layer

22-layer

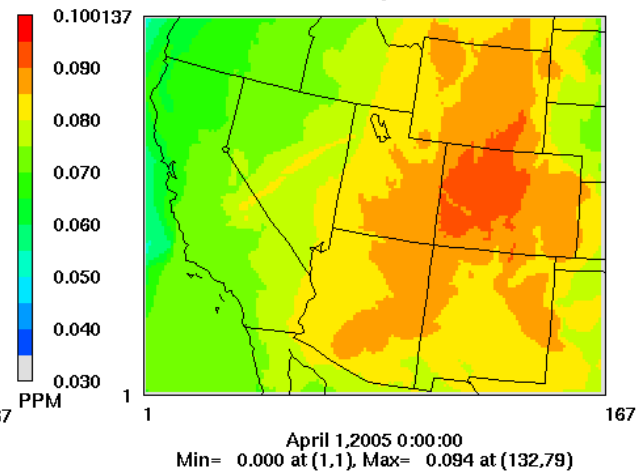
Layer 1 Maximum Ozone

CAMx Inert Run (19 Layers)
Run 1a.zadvec2

Layer 1 Maximum Ozone

CAMx Inert Run
Run1a.34lay.zadvec2

Layer 1 Maximum Ozone

CAMx Inert Run,
Run1a.22lay.zadvec2



2005 Day-Specific BCs

- New BCs, original met inputs, no smoothers/filters
 - Zero-gradient top boundary condition
 - Higher stratospheric ozone, higher surface ozone, different patterns
 - 2002 monthly averaging removed day-specific ozone variations
 - NOTE CHANGES TO COLOR SCALE!

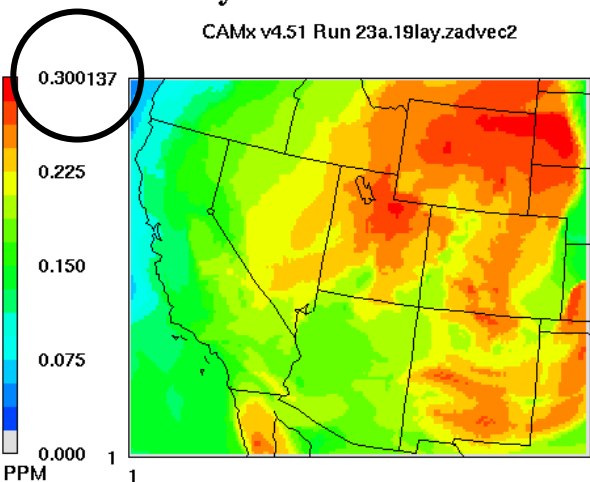
19-layer

22-layer

34-layer

Layer 1 Maximum Ozone

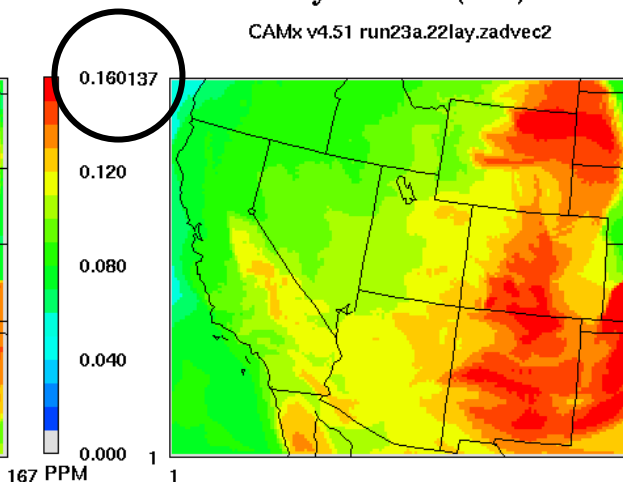
CAMx v4.51 Run 23a.19lay.zadvec2



April 1, 2005 0:00:00
Min= 0.000 at (1,1), Max= 0.299 at (154,122)

Layer 1 max(o3b)

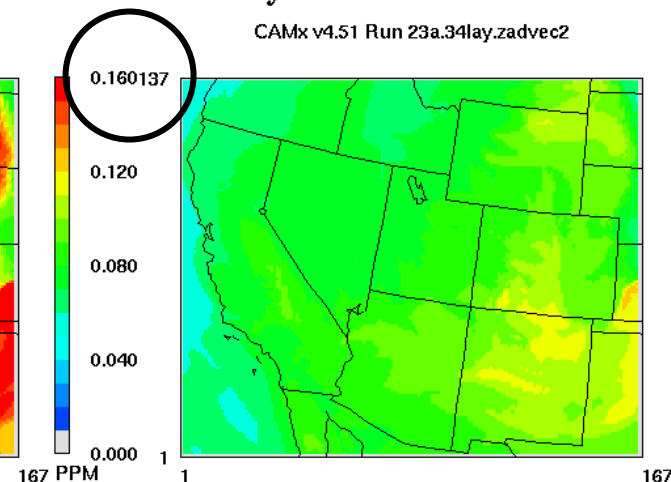
CAMx v4.51 run23a.22lay.zadvec2



April 1, 2005 0:00:00
Min= 0.000 at (1,1), Max= 0.166 at (162,59)

Layer 1 Maximum Ozone

CAMx v4.51 Run 23a.34lay.zadvec2

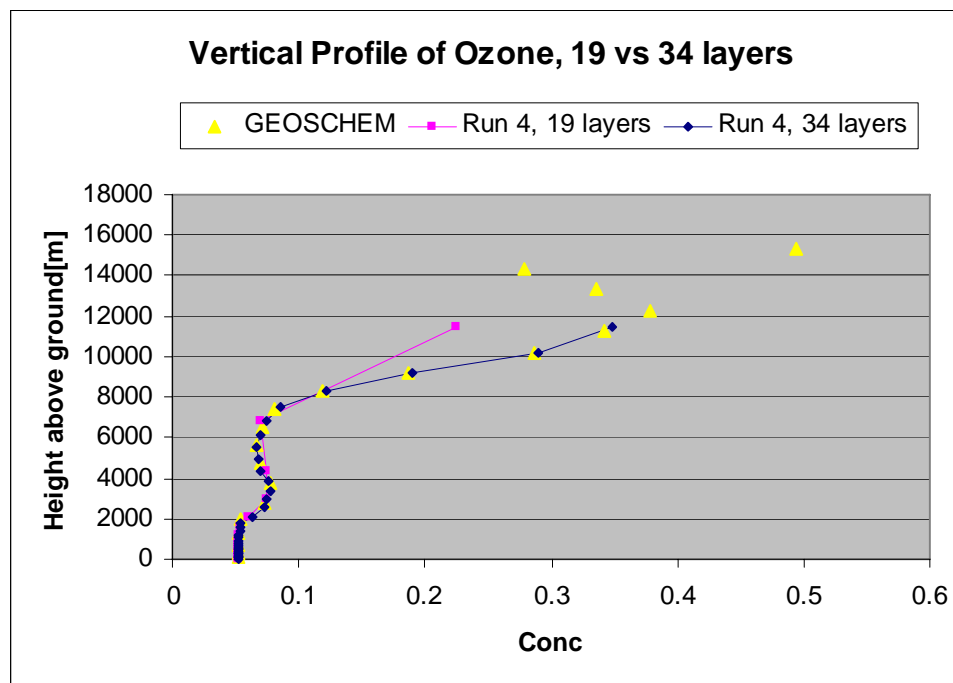


April 1, 2005 0:00:00
Min= 0.000 at (1,1), Max= 0.123 at (163,61)



2005 Day-Specific BCs

- Problem found in GEOS-CHEM interface program
 - Vertical interpolation was not consistent with CMAQ or CAMx layer structure definitions
 - Did not account for deep CMAQ/CAMx layers
 - Resulted in same ozone levels in 19, 22 and 34 layer cases
 - Fixed by converting to layer-weighting technique (compare profiles below)



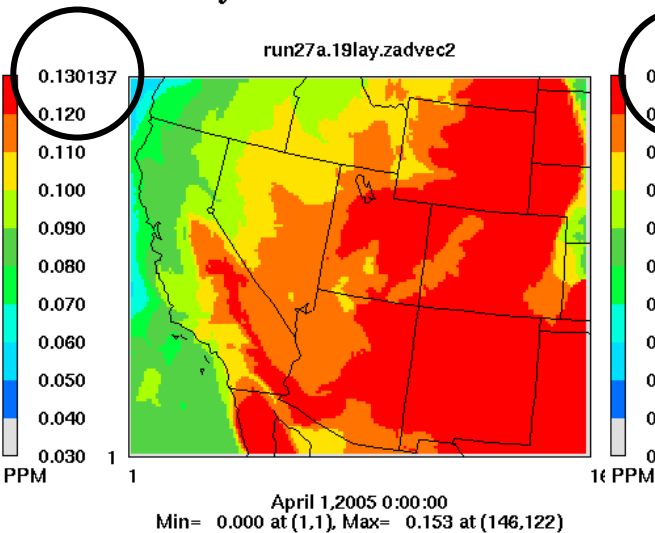
Improved 2005 BCs

- Fixed BCs, original met inputs, no smoothers/filters
 - Zero-gradient top boundary condition
 - Lower stratospheric ozone, lower surface ozone
 - Ozone still higher than with 2002 BCs

19-layer

Layer 1 Maximum Ozone

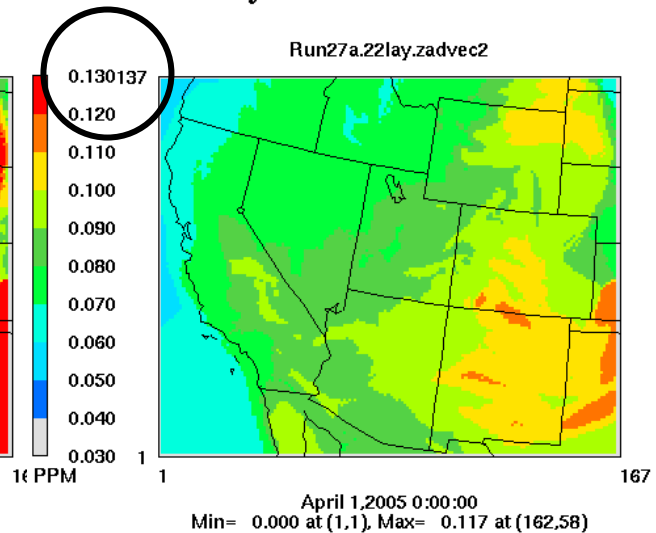
run27a.19lay.zadvec2



22-layer

Layer 1 Maximum Ozone

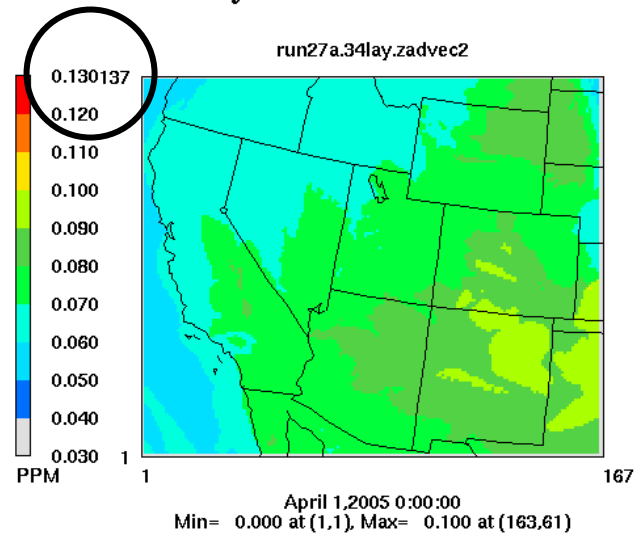
Run27a.22lay.zadvec2



34-layer

Layer 1 Maximum Ozone

run27a.34lay.zadvec2



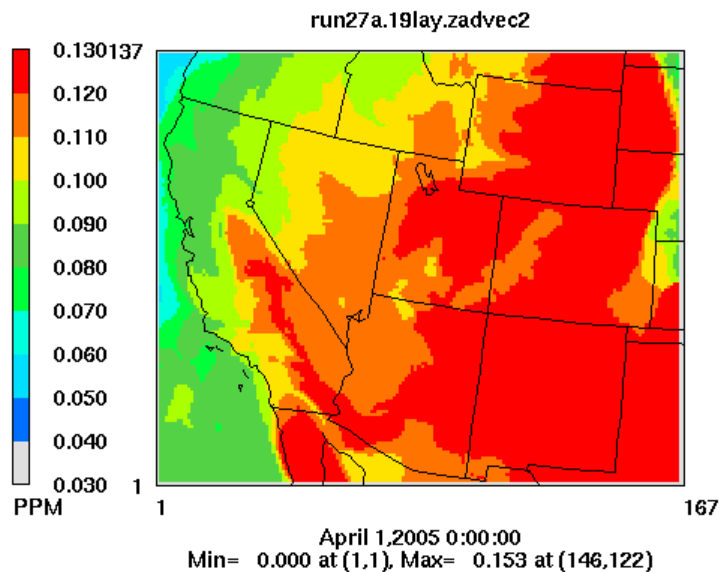


Density/Wind Filtering

- “Pressure Fixer” of Rotman et al. (2004)
 - Zero-gradient top BC, fixed 2005 lateral BC
 - Applied to input horizontal winds to reduce vertical velocity
 - Applied aggressively to upper layers only
 - Results in 10-20 ppb change in April maximum ozone

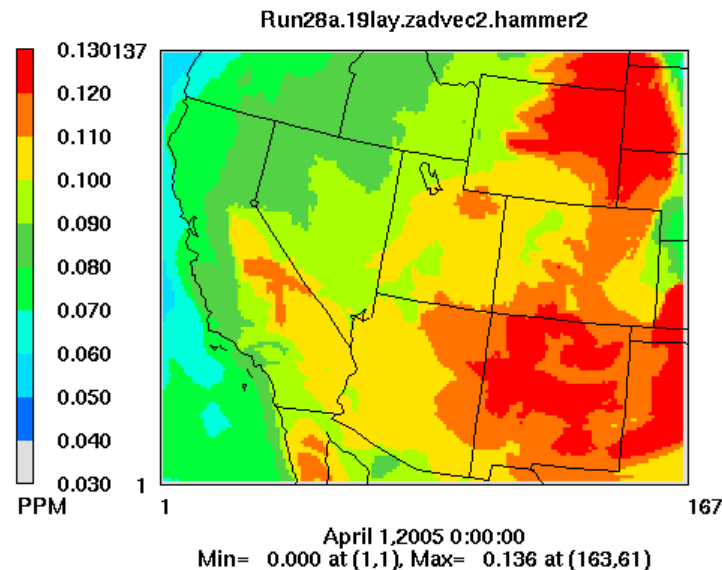
19-layer BASE

Layer 1 Maximum Ozone



FILTERED

Layer 1 Maximum Ozone



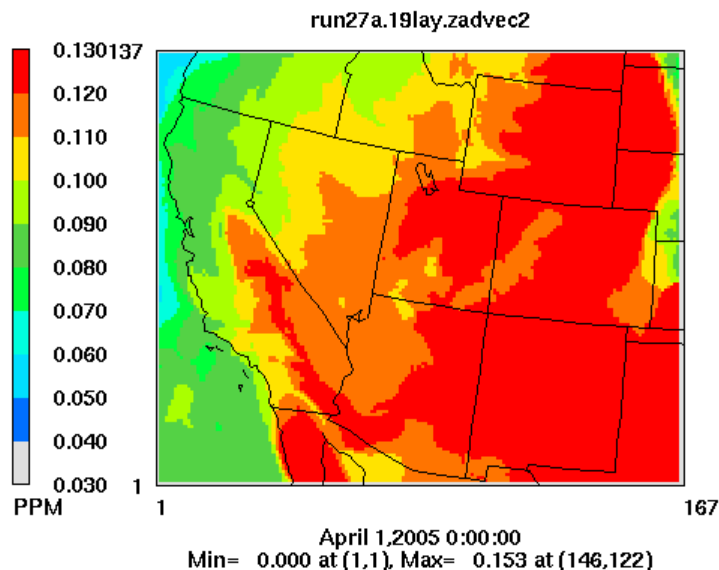


Revised Vertical Advection

- Original input meteorology, no smoothers/filters
 - Zero-gradient top BC, fixed 2005 lateral BC
 - Revised vertical velocity calculation to remove downward bias
 - Revised vertical solver to be consistent
 - Results in 40-70 ppb change in April maximum ozone

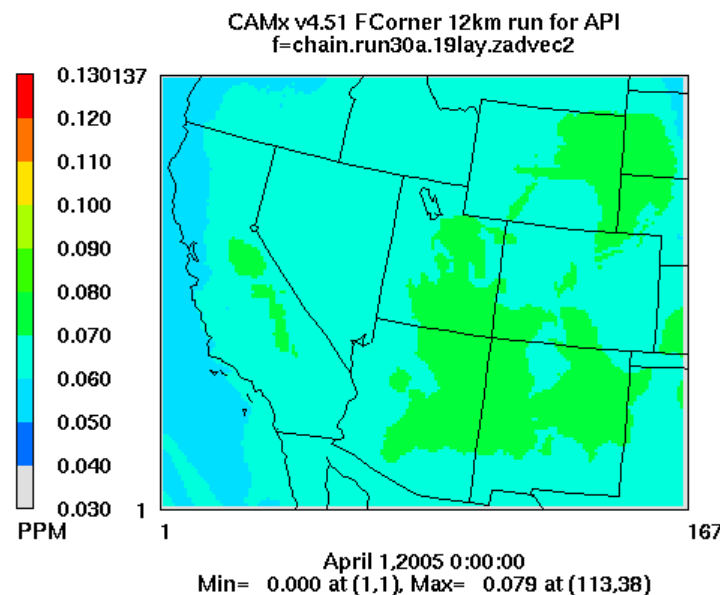
19-layer BASE

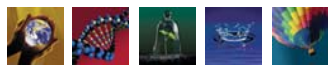
Layer 1 Maximum Ozone



MODIFIED ADVECTION

Layer 1 max(O3f)





Revised Vertical Advection

- Comparison of 19, 22, and 34-layer configurations
 - Maximum surface ozone of 79, 75 and 75 ppb using 19, 22 and 34 vertical layers

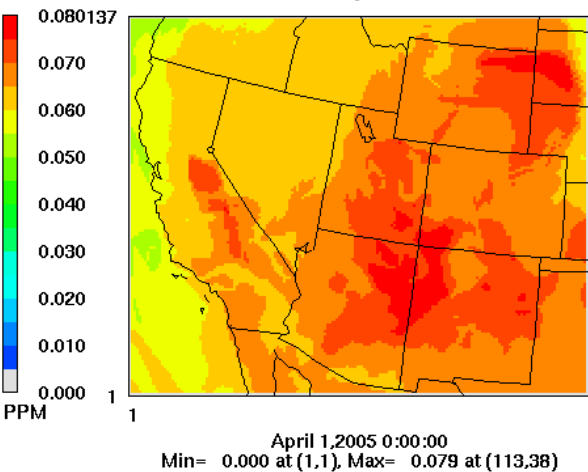
19-layer

22-layer

34-layer

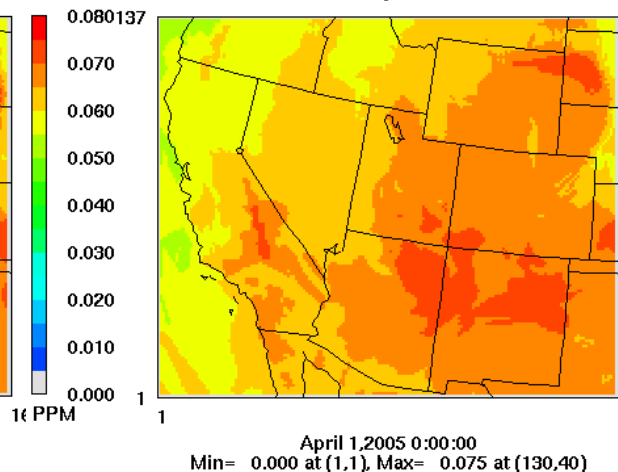
Layer 1 Maximum Ozone

CAMx Inert Run, 19 Layers
Run30a.19lay.zadvec2.fix2



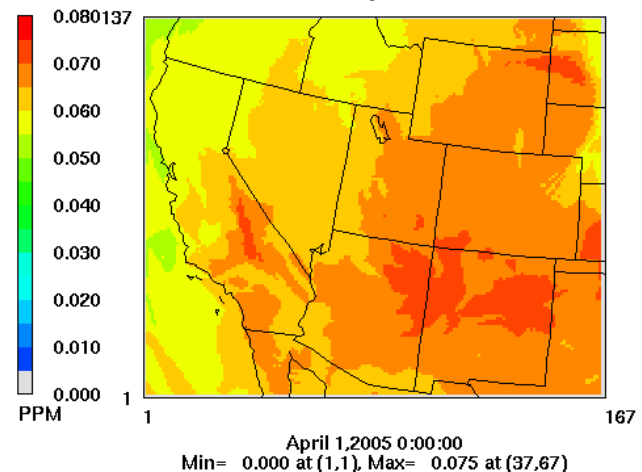
Layer 1 Maximum Ozone

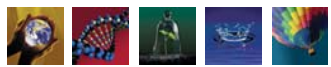
CAMx Inert Run, 22 Layers
Run30a.22lay.zadvec2.fix2



Layer 1 Maximum Ozone

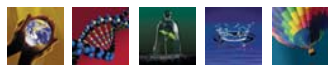
CAMx Inert Run, 34 Layers
Run30a.34lay.zadvec2.fix2





Recommended Further Work for API Study

- Test modified CAMx for full photochemical applications
 - 2005 FCAQTF Database
 - O&G projects in Rocky Mountains
 - Evaluate spring and summer performance changes
 - Is external smoothing/filtering still necessary?
 - Evaluate photochemical results before developing a recommendation
- Document all results in summary report and conference paper
- CMAQ exhibits similar problems
 - Recommend reviewing vertical advection in CMAQ
 - If possible, integrate similar change and test on WRAP
 - Interact with EPA/ORD



Recommendations for Denver Modeling

- Don't believe a 36/12/4 km ozone source apportionment is needed given recent findings
 - Will just identify GEOS-CHEM BCs as main component of ozone transported into Denver NAA
- Instead recommend revised CAMx base case using latest vertical velocity algorithms and corrected 36 km GEOS-CHEM BCs
 - Process 2006 GEOS-CHEM output to make day-specific BCs for 36 km domain (with correct interpolation scheme)
 - Revised CAMx 36 km base case Jun-Jul 2006 using new VertVel
 - Revised CAMx 12/4 km base case Jun-Jul 2006 using new VertVel
 - Ozone model performance evaluation
 - Also desirable to update vertical layer structure (22 layers), but requires reprocessing MM4 data