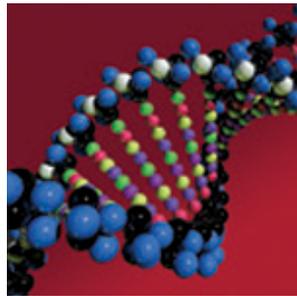


Vertical Transport of Ozone Over Complex Terrain



Chris Emery
ENVIRON International Corporation
Novato, CA
June 25, 2009



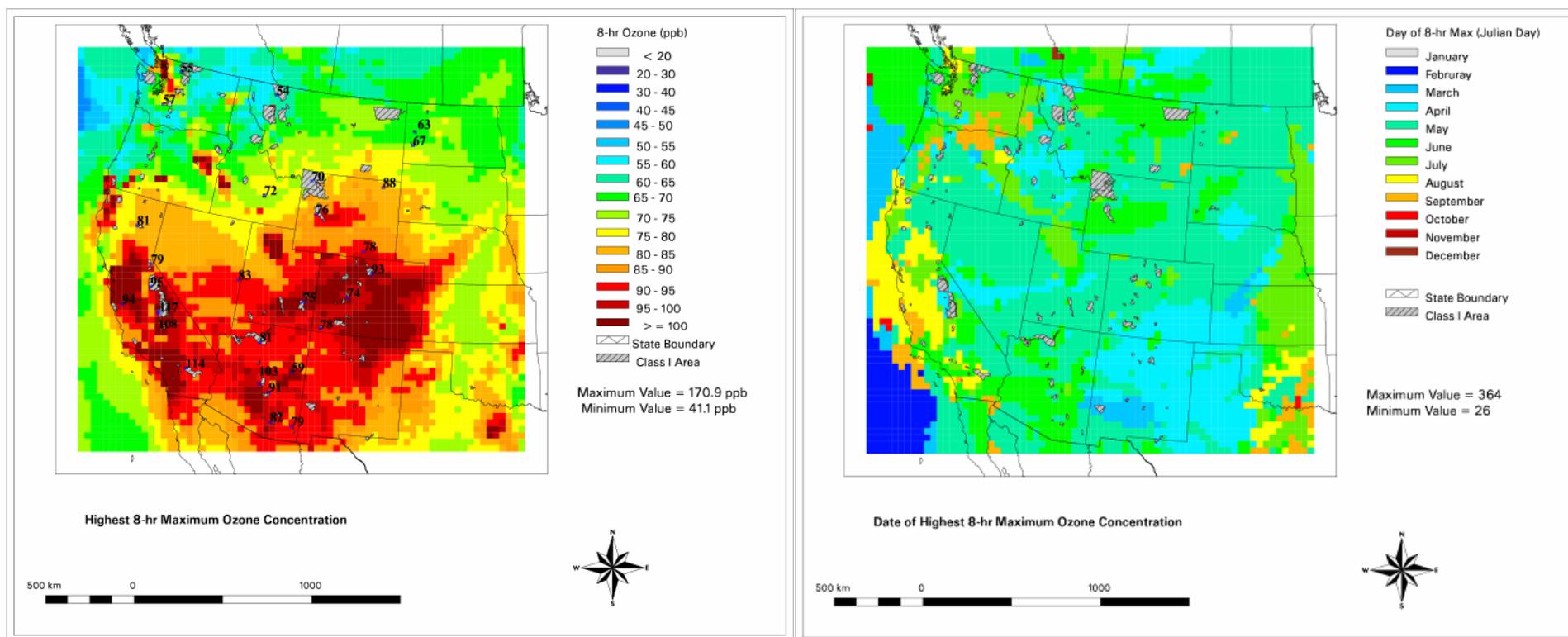
Introduction

- **Issue:**
 - Regional CMAQ & CAMx modeling of the western U.S. result in high ozone predictions over the Rocky Mountains in spring
 - Rural measurement data show both models over predict ozone by 20+ ppb
- **Apparent Cause:**
 - Large ozone lateral boundary conditions in the upper layers are excessively circulated downward over complex terrain
 - BCs derived from Harvard GEOS-CHEM global chemistry model
 - Maximum ozone exceed 200 ppb in the top model layer (8-15 km)
 - Such concentrations are reasonable at these altitudes in the spring



2002 Annual WRAP CMAQ Results

- Highest ozone in Rockies occurs in April-May



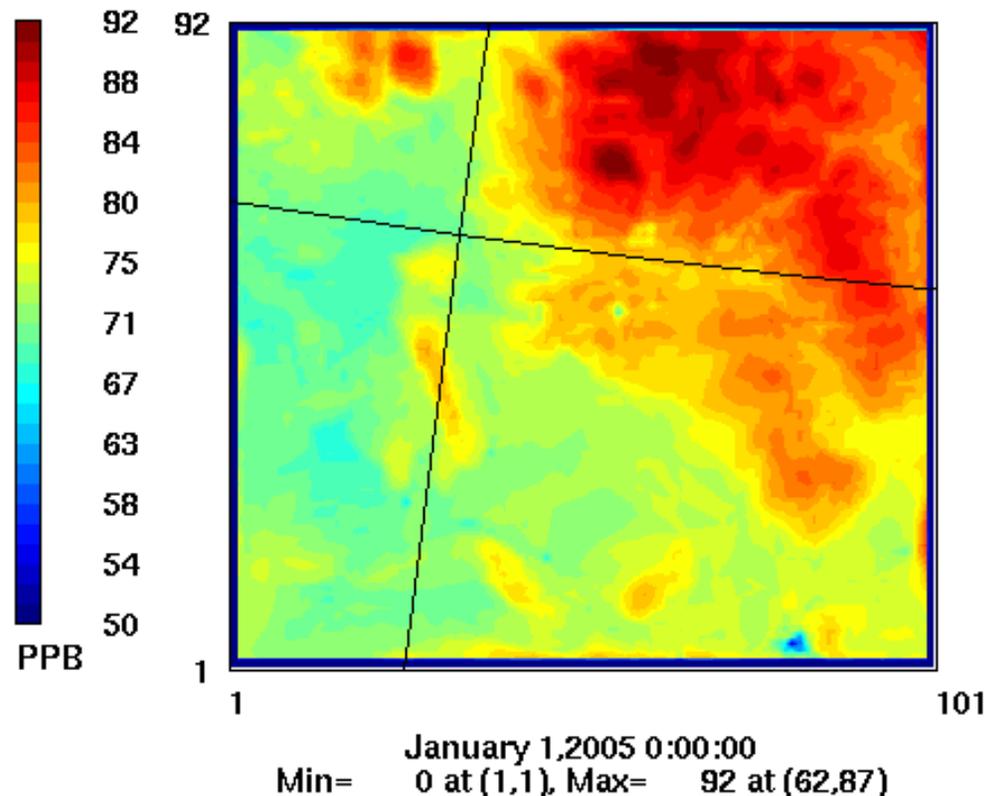


2005 Annual FCAQTF CAMx Results

- Highest ozone in San Juan Mountains occur in April

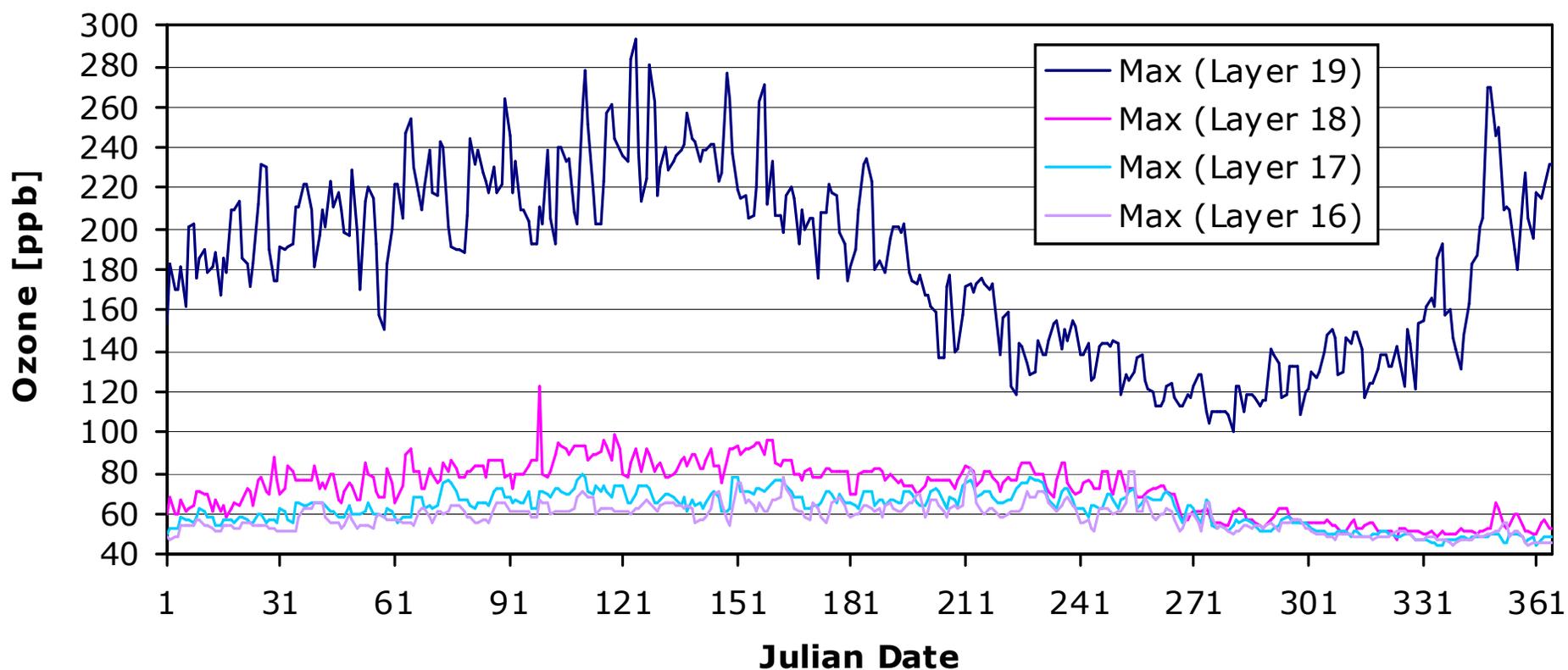
4th Highest Ozone

CAMx v4.51 FCorner 12_4km run





2002 Boundary Conditions from GEOS-CHEM





2002 CMAQ vs. 2005 CAMx

- Different meteorology
- Same regional grid structure (RPO)
- Same 2002-based GEOS-CHEM BCs
 - CMAQ: 3-hourly, day-specific
 - CAMx: Monthly-average diurnal profile

Layer	Altitude Range
19	8-15 km (AGL)
18	5-8 km
17	3.5 – 5 km
16	2.5 – 3.5 km



Problem

- Both CMAQ and CAMx internally diagnose vertical velocity from horizontal mass flux divergence
 - Maintain mass conservation and consistency
 - Deviations from MM5 physics, coordinate system, & numerical methods lead to differences in vertical velocities
 - Numerical artifacts from MM5 might be transferred to the PGMs and possibly magnified
- CAMx diagnostics show:
 - Largest vertical velocities occur in the uppermost and thickest layers
 - Over high terrain, vertical transport is needed in only a few upper layers to efficiently transport aloft ozone to the surface
 - Can we shut the gate on vertical transport in aloft layers?



Approach

- ENVIRON is examining, implementing, and testing methodologies in CAMx to reduce vertical transport over complex terrain:
 - Use more layers (← no-brainer)
 - Modify input horizontal winds
 - Smoother-desmoother applied on horizontal winds
 - Yang and Chen (2008)
 - Divergence minimization
 - From CALMET (really, believe it)
 - Adapt “pressure fixer” from LLNL’s IMPACT model
 - Rotman et al (2004), Prather et al (1987), Heimann and King (1989)



Approach

- Run CAMx in inert mode on 12-km western domain
 - Track inert ozone around from IC/BCs
 - Saves time and gas
 - Run for month of April 2005 (+ late March spinup)
 - All runs use same 2005 MM5 met
 - All runs use same 19 layer 2002 GEOS-CHEM BC
 - 19 layer BCs mapped to other layer structures
- Test effect of input top BC vs. “zero-gradient” top BC



Additional Layers

- Much of the problem can be attributed to vertical resolution
 - Layer 19 spans ~half the vertical domain
 - Poor resolution of upper winds, density and tropopause
 - Forces a lot of dynamics into one layer
 - “Instant” dilution through 7+ km
- MM5 met re-extracted for all 34 layers
- CAMx run used input Top BC
 - Standard CAMx formulation



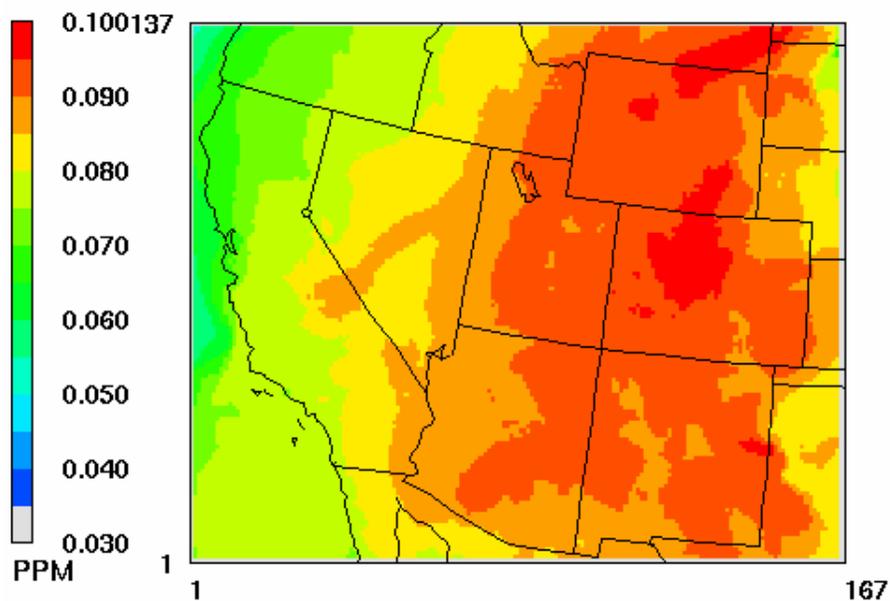
Additional Layers

19 layers

34 layers

Layer 1 Maximum Ozone

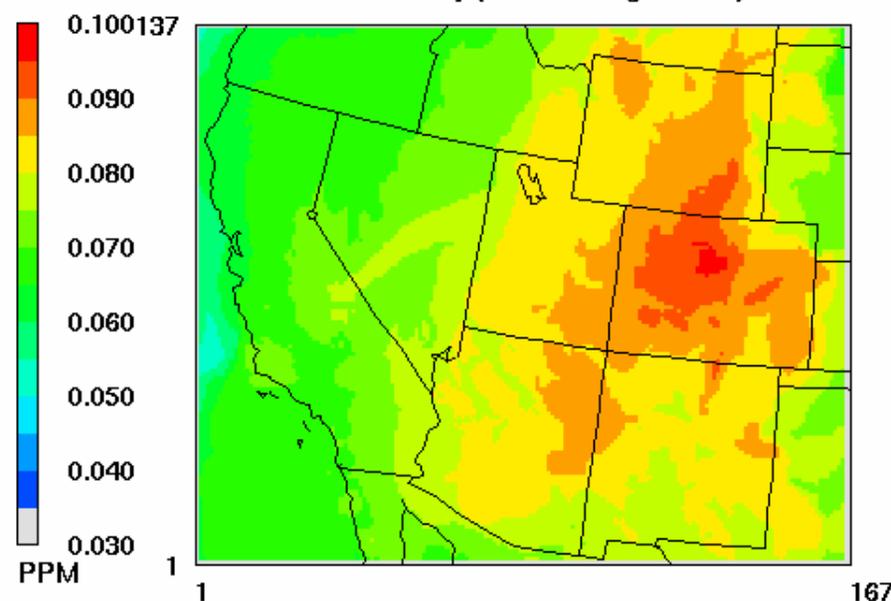
CAMx Inert Run
Run 1a: Base Case



April 1, 2005 0:00:00
Min= 0.000 at (1,1), Max= 0.098 at (132,79)

Layer 1 Maximum Ozone

CAMx Inert Run, 34 Layers
Run 1a.34lay (Base Configuration)



April 1, 2005 0:00:00
Min= 0.000 at (1,1), Max= 0.096 at (133,76)



Smoother-Desmoother

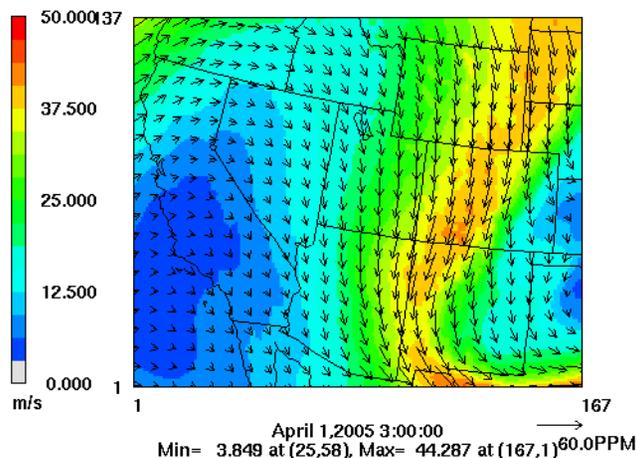
- Apply to horizontal wind fields
- Reduce small-scale ($2-5\Delta x$) variations
 - Generated by noise and small-scale terrain effects
- Test many attributes
 - Smoother/desmoother factors
 - Number of passes
 - Winds only, and winds + temperature + pressure
 - Layers to be smoothed
- All runs use 19 layers + input Top BC
 - Standard CAMx formulation



Smoother-Desmoother

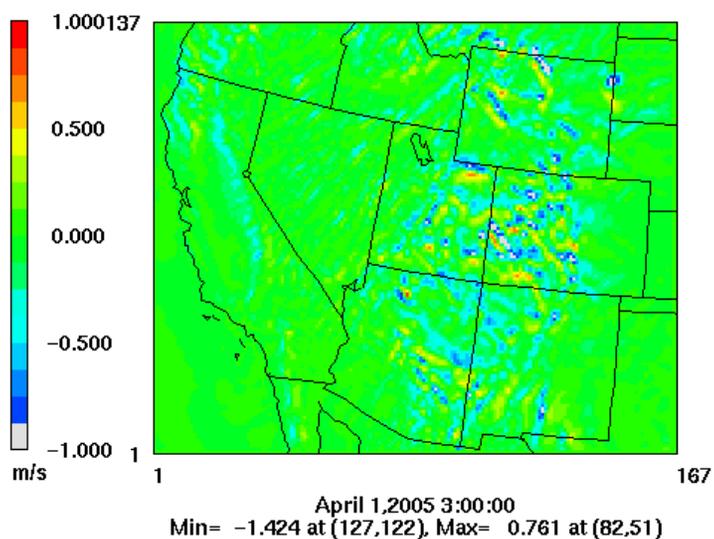
Layer 18 Wind Speed

MMS-based wind fields, no smoothing



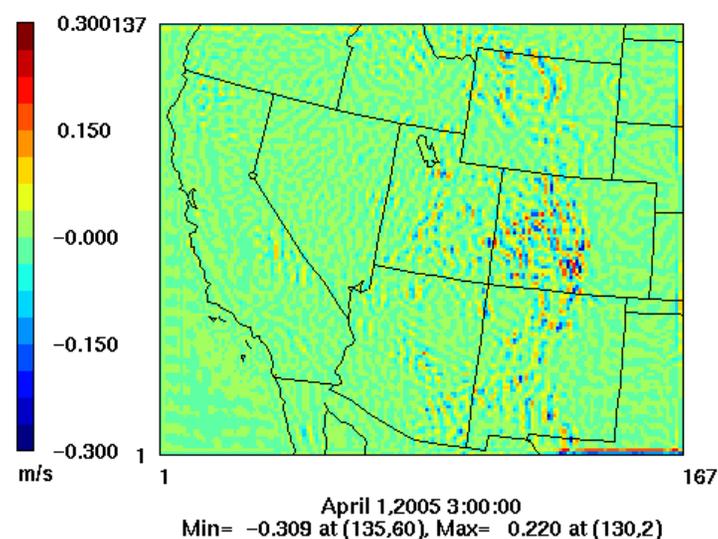
Layer 18 Vertical Velocity

No Smoothing



Layer 18 Difference in Wind Speed

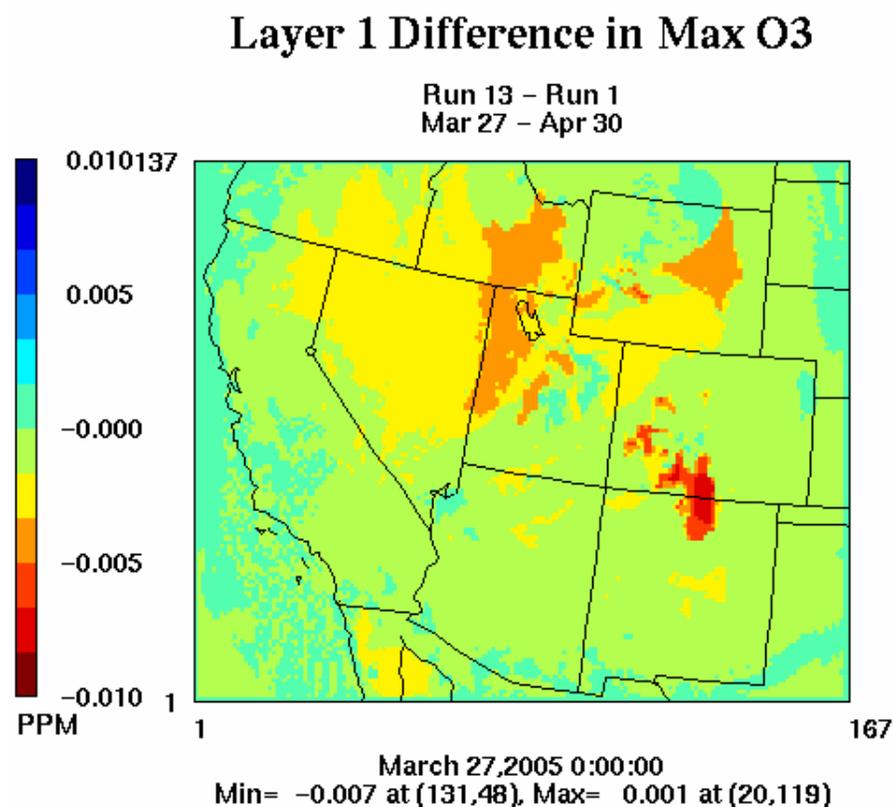
Smoother - Base





Smoother-Desmoother

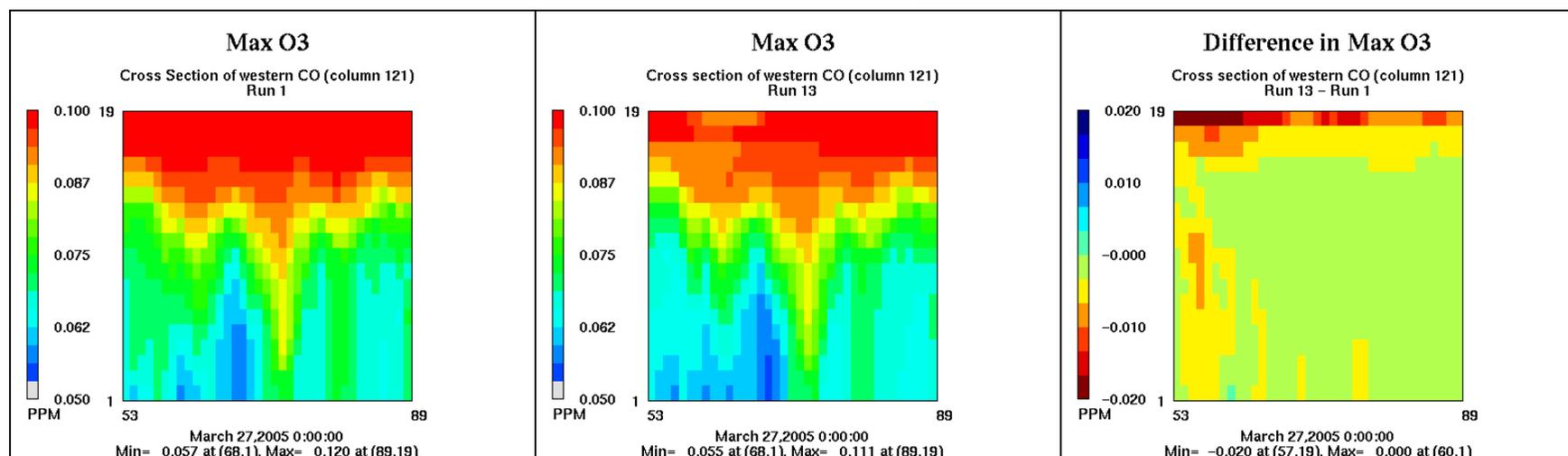
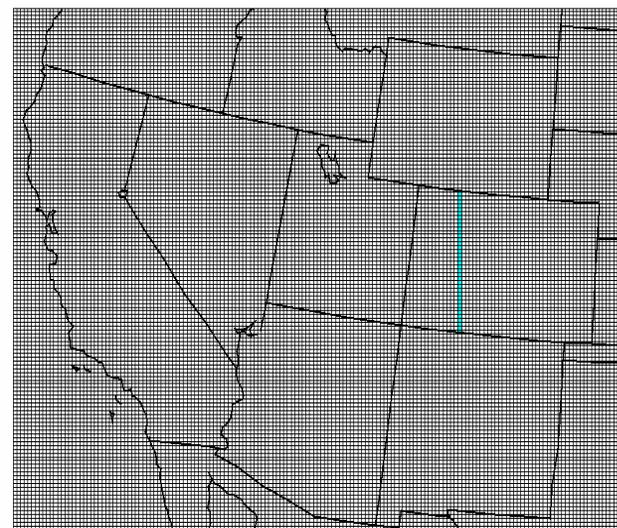
- Final run: Layer 16-19, heavy smoothing, no desmoothing, 5 passes





Smoother-Desmoother

- Vertical N-S cross-section through Colorado





Divergence Minimization

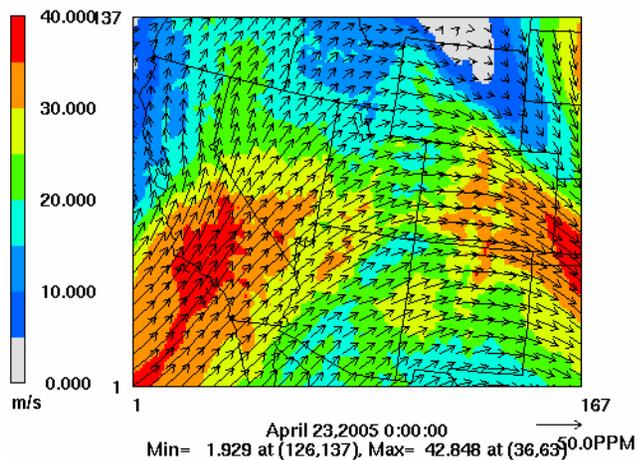
- Apply to horizontal wind fields
- Adapt CALMET algorithm to the CAMx grid stagger (Arakawa-C)
- Apply only to layers 16-19 (21-34)
- Test many attributes
 - Divergence minimization factor
 - Number of iterations
 - 19 vs. 34 layer configuration
 - Input vs. “zero-gradient” top BC



Divergence Minimization Base with DM

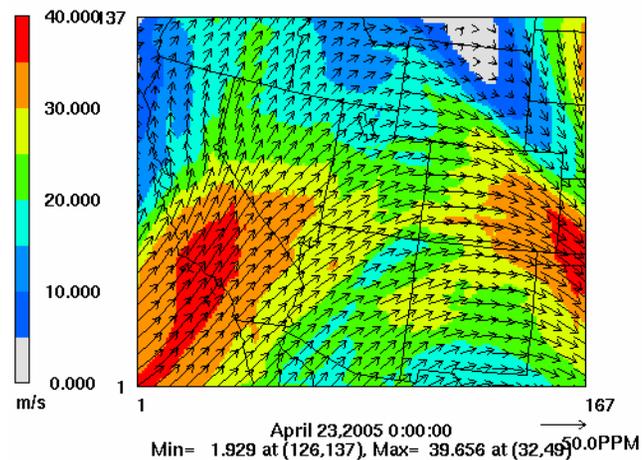
Layer 18 Wind Speed

Base Wind Fields



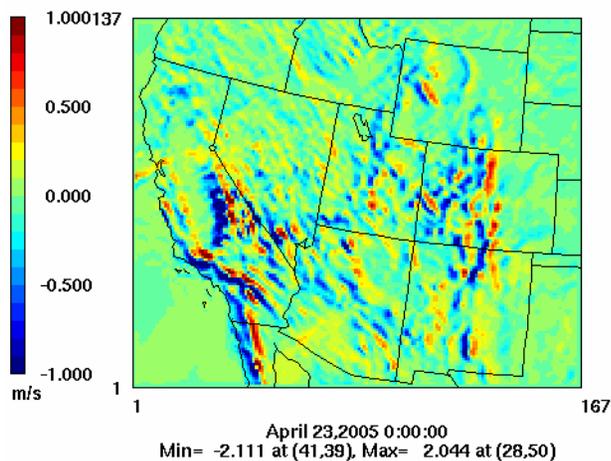
Layer 18 Wind Speed

Divergence Minimization. Alpha = 0.25



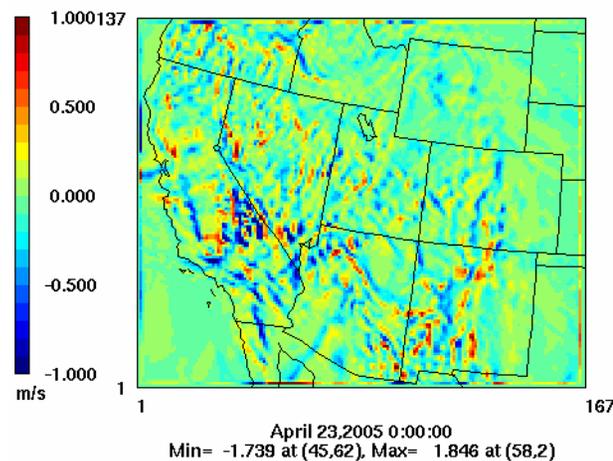
Layer 18 Vertical Velocity

Base Case



Layer 18 Vertical Velocity

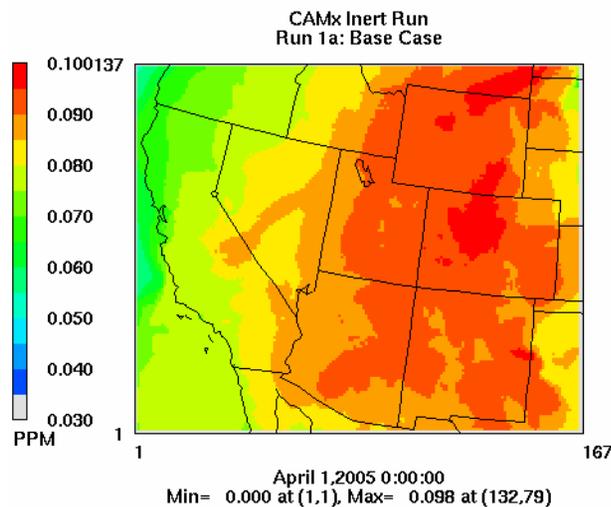
Divergence minimization. Alpha = 0.25



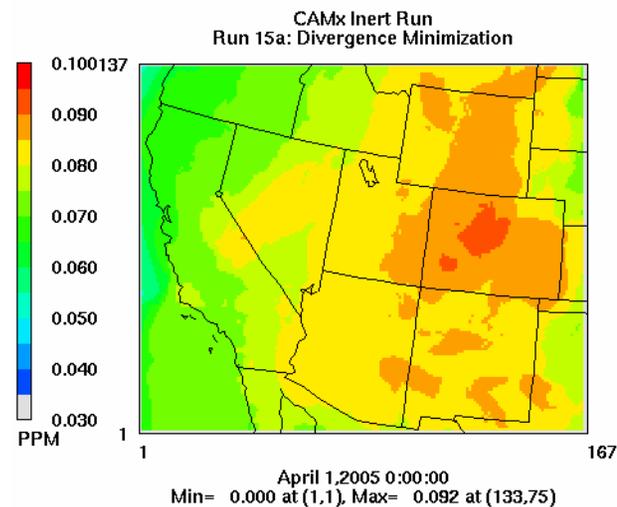


Divergence Minimization 19-layers, input Top BC

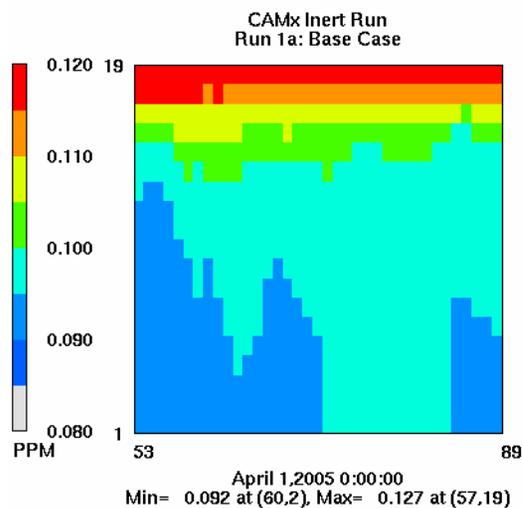
Layer 1 Maximum Ozone



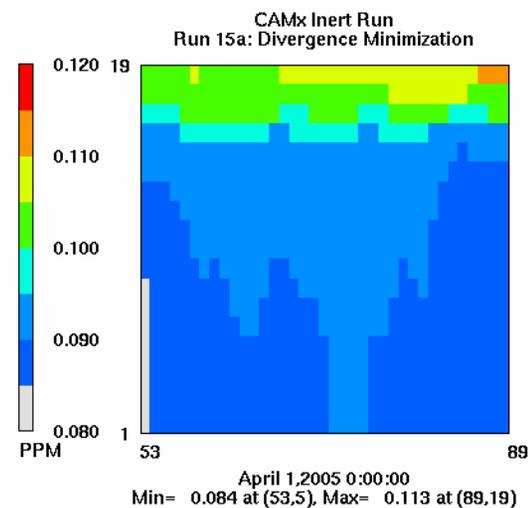
Layer 1 Maximum Ozone



Column 121 Maximum Ozone



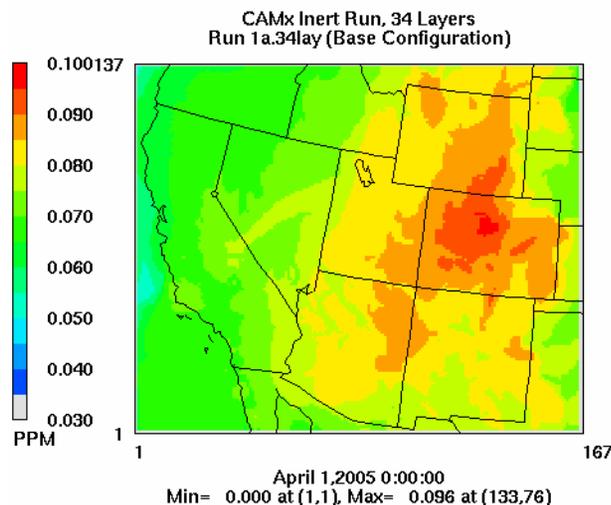
Column 121 Maximum Ozone



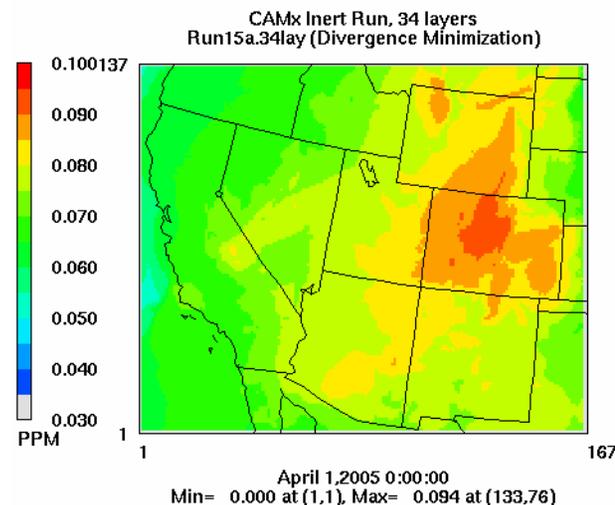


Divergence Minimization 34-layers, input Top BC

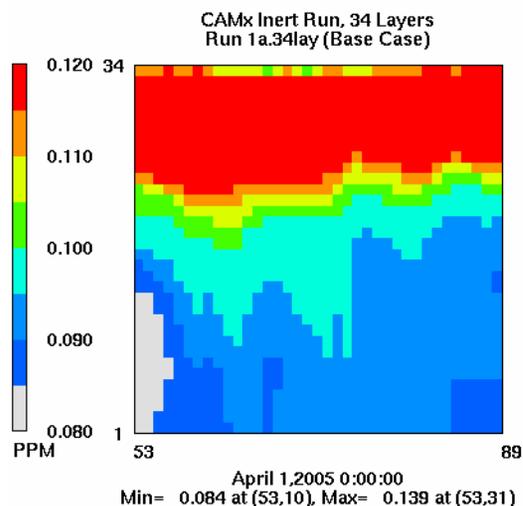
Layer 1 Maximum Ozone



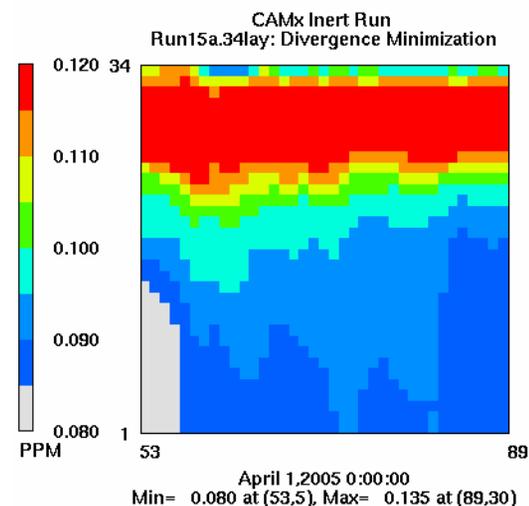
Layer 1 Maximum Ozone



Column 121 Maximum Ozone



Column 121 Maximum Ozone



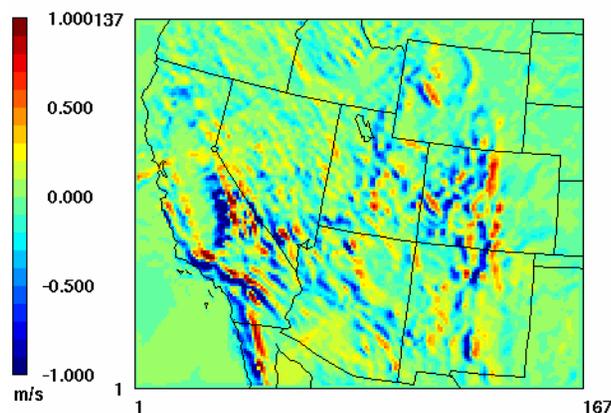


Divergence Minimization

Vertical Velocity: Layer 18 vs. Layer 19

Layer 18 Vertical Velocity

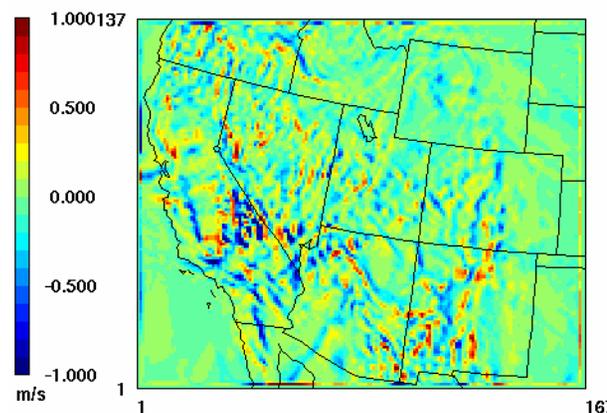
Base Case



April 23,2005 0:00:00
Min= -2.111 at (41,39), Max= 2.044 at (28,50)

Layer 18 Vertical Velocity

Divergence minimization. Alpha = 0.25

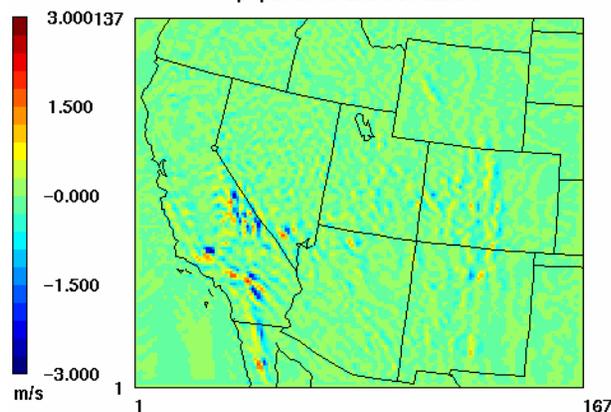


April 23,2005 0:00:00
Min= -1.739 at (45,62), Max= 1.846 at (58,2)

18

Layer 19 Vertical Velocity

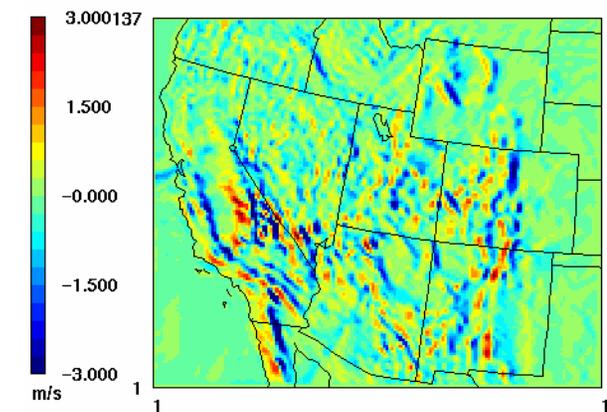
Base Case
p=pave.wv.12km.050423.bin



April 23,2005 0:00:00
Min= -3.025 at (29,51), Max= 1.912 at (43,40)

Layer 19 Vertical Velocity

Divergence minimization in Layers 16 - 19



April 23,2005 0:00:00
Min= -5.963 at (45,62), Max= 3.421 at (47,64)

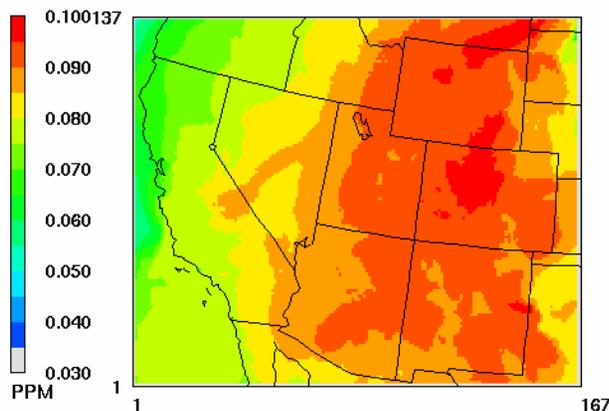
19



Zero-Gradient Top BC (no divergence minimization)

Layer 1 Maximum Ozone

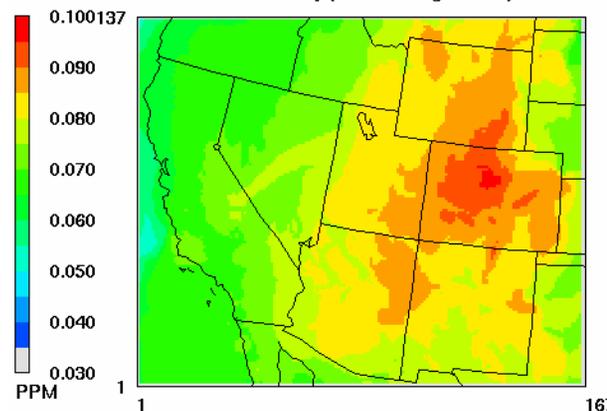
CAMx Inert Run
Run 1a: Base Case



April 1, 2005 0:00:00
Min= 0.000 at (1,1), Max= 0.098 at (132.79)

Layer 1 Maximum Ozone

CAMx Inert Run, 34 Layers
Run 1a.34lay (Base Configuration)

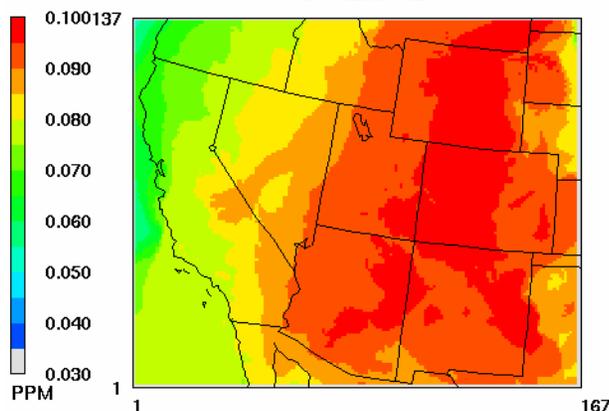


April 1, 2005 0:00:00
Min= 0.000 at (1,1), Max= 0.096 at (133.76)

Orig

Layer 1 Maximum Ozone

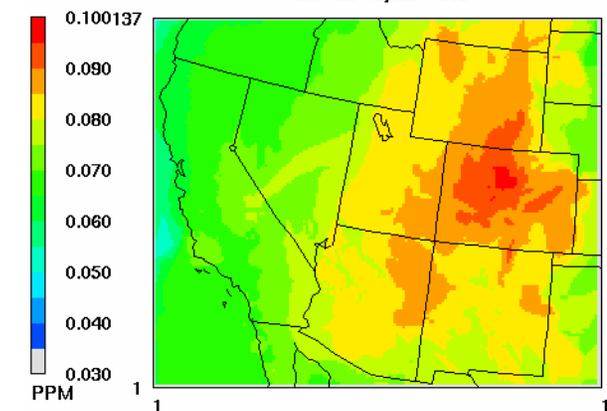
CAMx Inert Run (19 Layers)
Run 1a.zadvec2



April 1, 2005 0:00:00
Min= 0.000 at (1,1), Max= 0.101 at (132.77)

Layer 1 Maximum Ozone

CAMx Inert Run
Run 1a.34lay.zadvec2



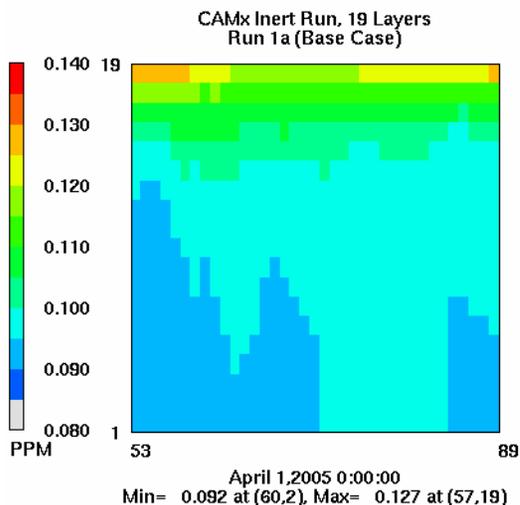
April 1, 2005 0:00:00
Min= 0.000 at (1,1), Max= 0.096 at (133.76)

Zero-Grad

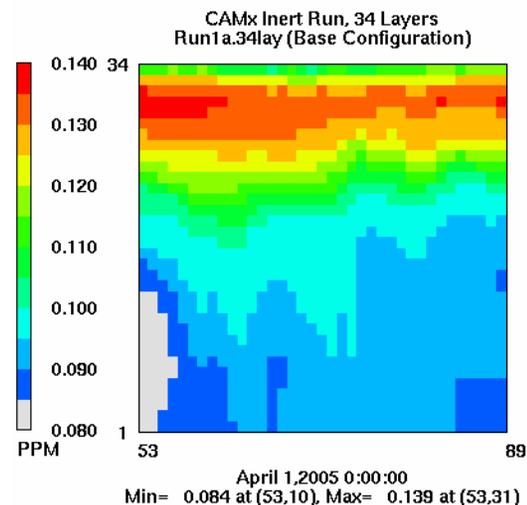


Zero-Gradient Top BC (no divergence minimization)

Column 121 Maximum Ozone

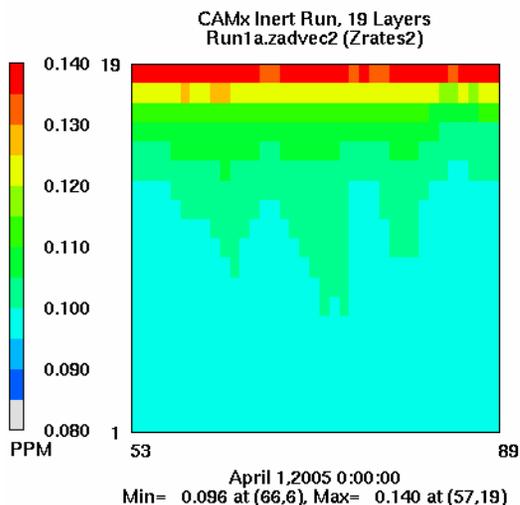


Column 121 Maximum Ozone

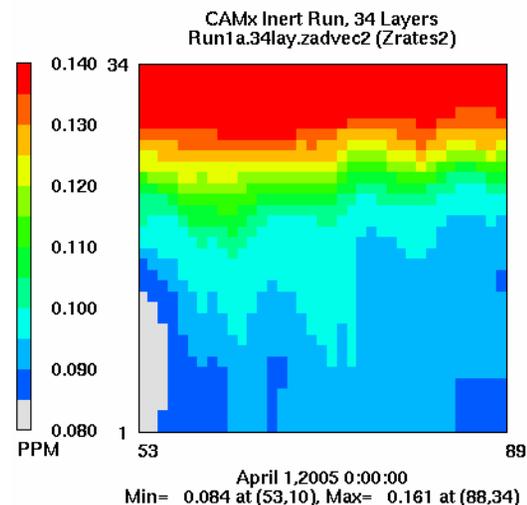


Orig

Column 121 Maximum Ozone



Column 121 Maximum Ozone



Zero-Grad



Mass Flux Filter

- Adapt from LLNL “pressure fixer”
- Adjust horizontal wind fields for column mass error
 - 19-layer zero-gradient top BC case only
 - Applied to layers 16-19, multiple passes
 - Mass buildup/loss due to horizontal advection is relaxed through
 - (1) modification of horizontal winds first
 - (2) then calculation of vertical winds
- Test a few variants
 - Adjust winds between columns with different mass errors (“Original”)
 - Adjust winds for any mass error (“Hammer”)
 - Hybrid of both

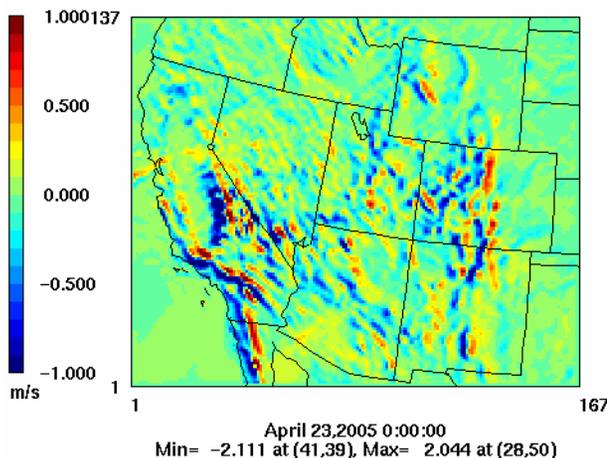


Mass Flux Filter – Vertical Velocities

Base Original Filter Hammer

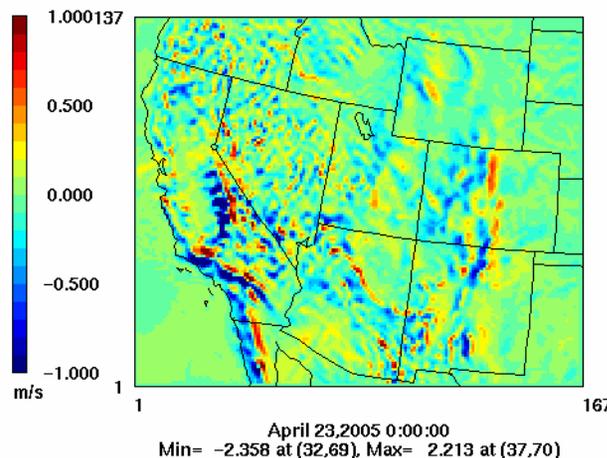
Layer 18 Vertical Velocity

Base Case, 19 layers



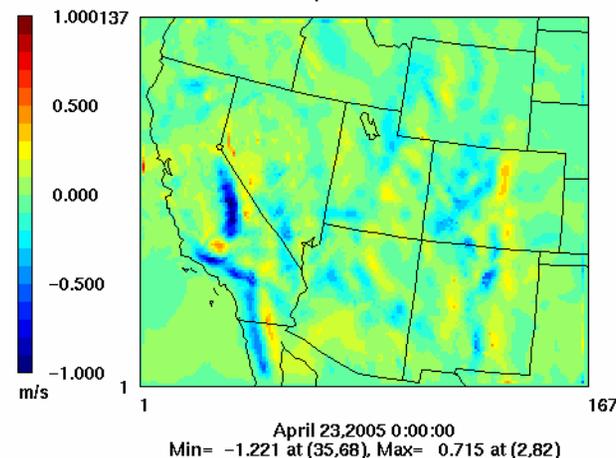
Layer 18 Vertical Velocity

Filter in layers 16 – 19
4x at .250



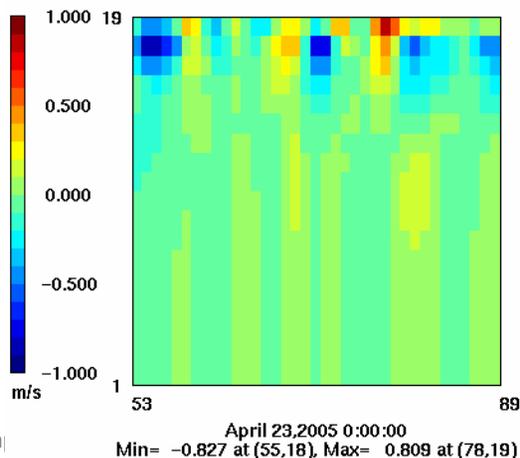
Layer 18 Vertical Velocity

Hammer2 in layers 16 – 19
10 passes at f250



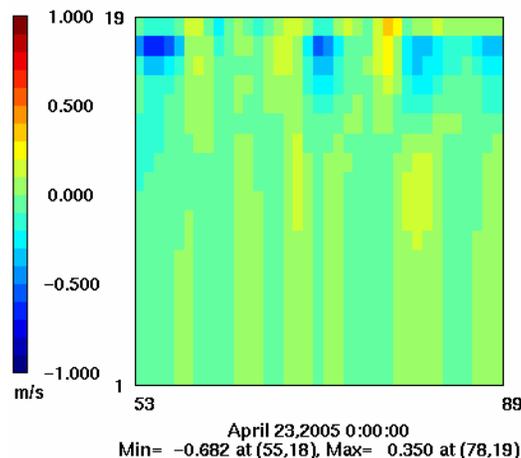
Column 121 Vertical Velocity

Base Case



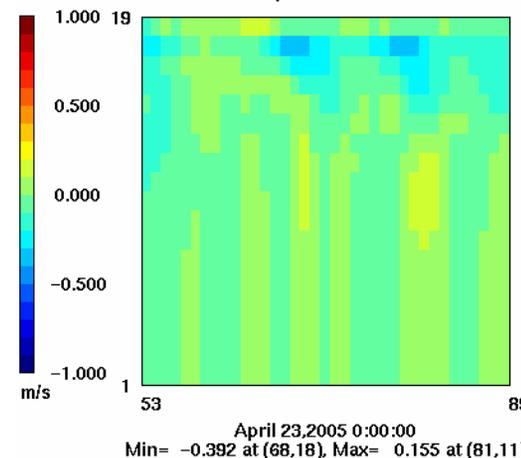
Column 121 Vertical Velocity

Filtering layers 16 – 19



Column 121 Vertical Velocity

Hammer2 in layers 16 – 19
10 passes at f250





Mass Flux Filter – Max Surface Ozone

Base Original Filter Hammer

Layer 1 Maximum Ozone

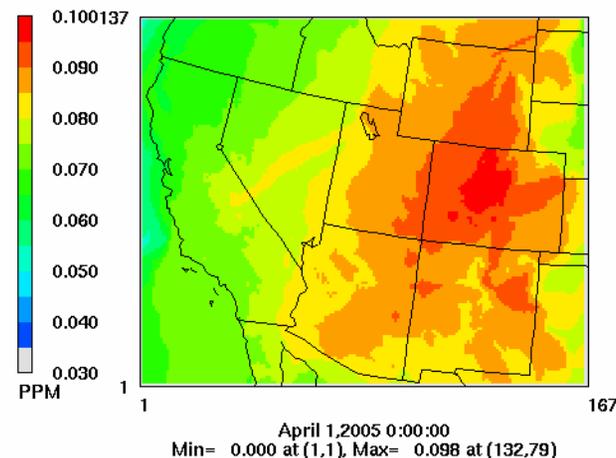
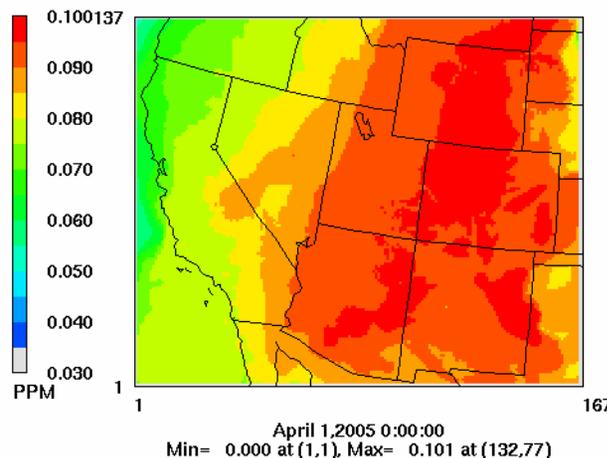
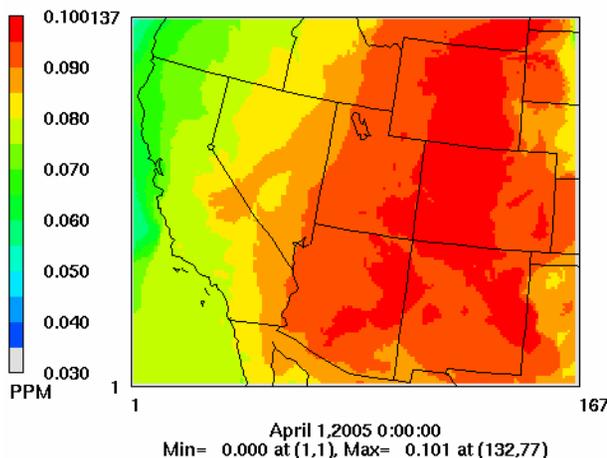
Layer 1 Maximum Ozone

Layer 1 Maximum Ozone

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

CAMx Inert Run with Filtering
Run 19a. Zrates2

CAMx Inert Run with Hammer2 Winds
Run21a.zrates2



Column 121 Maximum Ozone

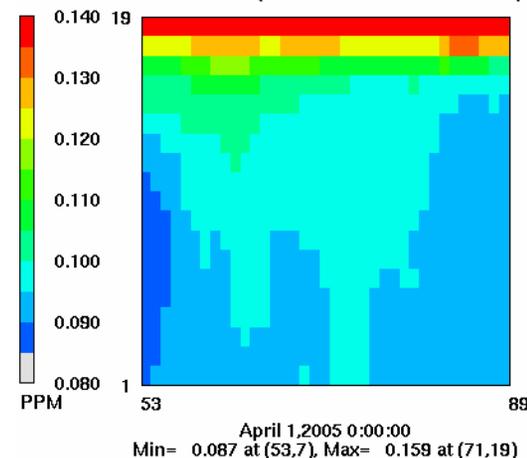
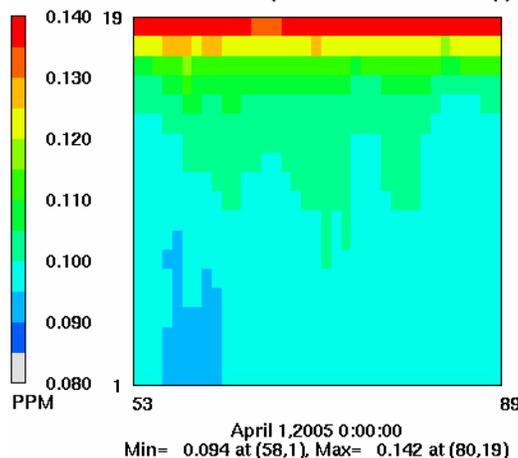
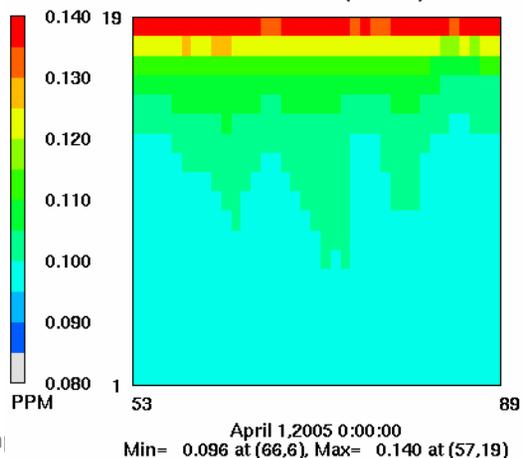
Column 121 Maximum Ozone

Column 121 Maximum Ozone

CAMx Inert Run, 19 Layers
Run1a.zadvec2 (Zrates2)

CAMx Inert Runs, 19 Layers
Run19a.zadvec2 (Filter + Zero Gradient Top)

CAMx Inert Run, 19 Layers
run21a.zadvec2 (Hammer2 + Zero Gradient Top)





Summary

- Using all 34 MM5 layers
 - Helps a lot, but expensive & not always viable solution
 - Basic problem still persists over Rockies
- Smoother-desmoother
 - Some minor improvement
- Divergence minimization
 - Found issues with input top BC approach (artificial dilution)
 - Zero-gradient top BC better approach (but takes away a mitigating effect)
 - Unexpected and inconsistent numerical features
 - Troubling and difficult to understand
 - Wind divergence minimization \neq mass flux divergence



Summary

- **Mass flux filter**
 - Technically more sound
 - Much improvement to vertical velocity fields
 - Potentially large impacts to surface ozone
 - But not where we need it (Rockies are least impacted)



Continuing Work

- Intermediate layer structure
 - 22 layers, add in upper domain
 - Balance need for more layers against resources
- Modified lateral BCs
 - Use of 19-layer BCs for higher-resolution runs is a problem
 - Concentrations in layer 19 mapped to layers 30-34
 - No change in “effective” stratospheric definition
 - Extract new 2005 GEOS-CHEM data to 19, 22, 34 layer structure
 - Compare results and repeat mass filter experiments