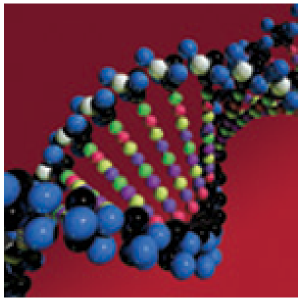
Vertical Transport of Ozone Over Complex Terrain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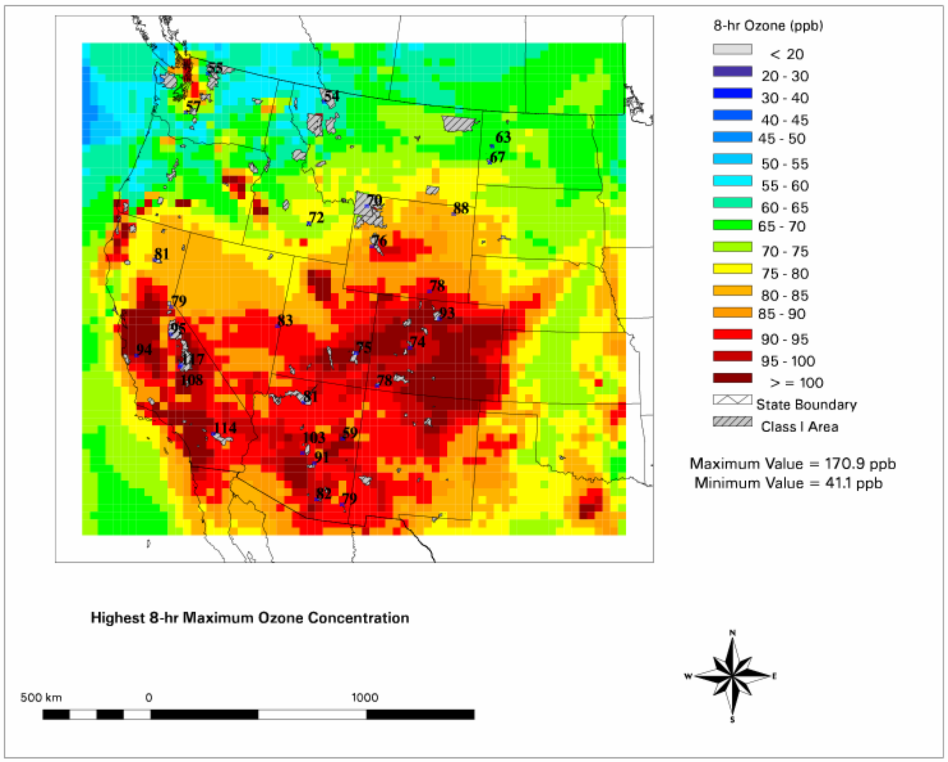
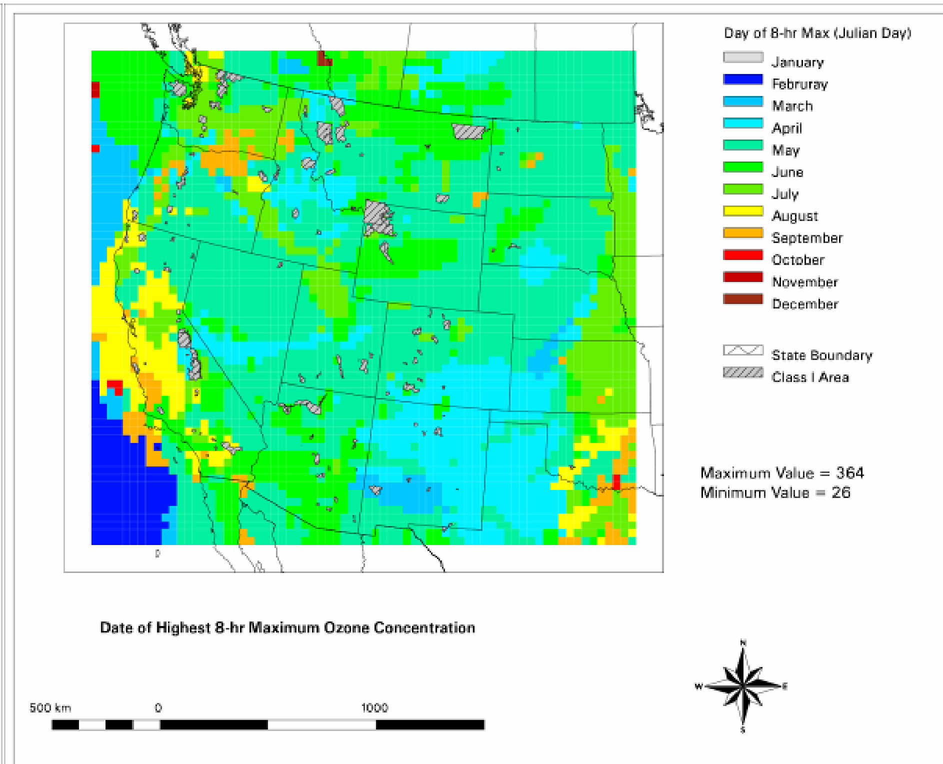
Introduction

- 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

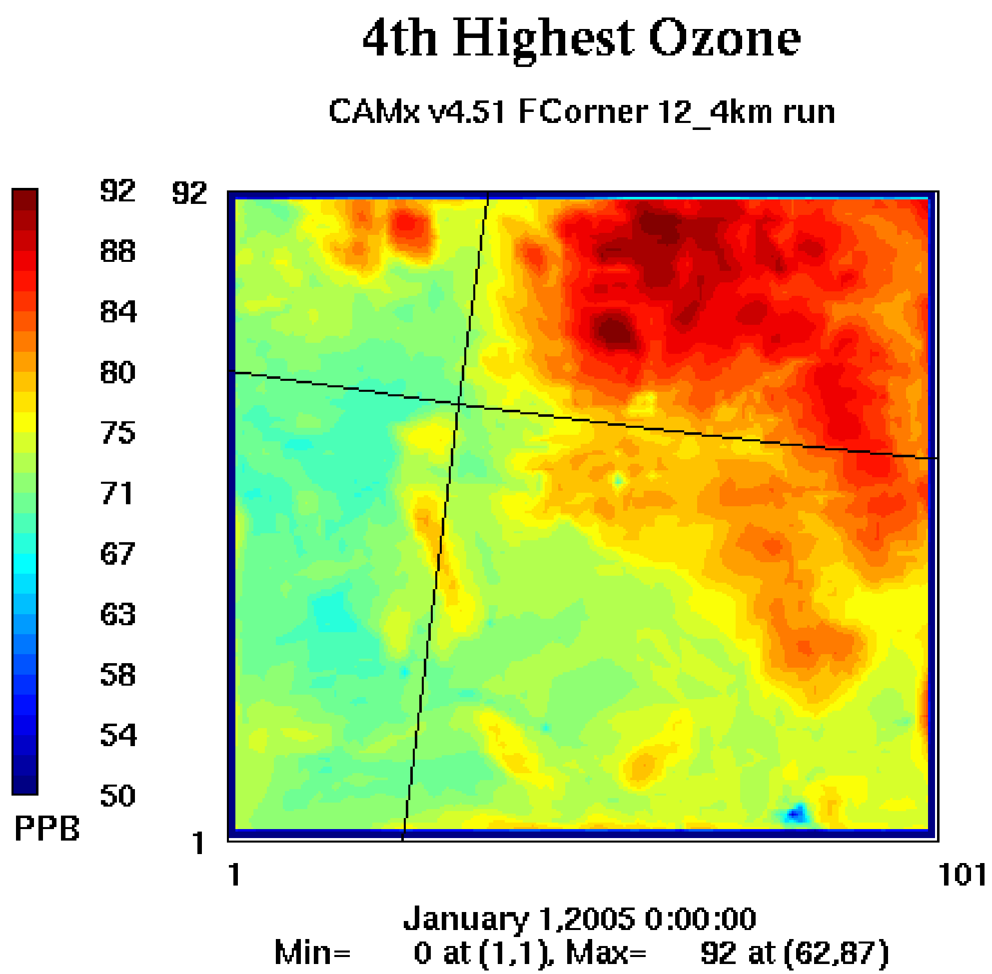
- Highest ozone in Rockies occurs in April-May



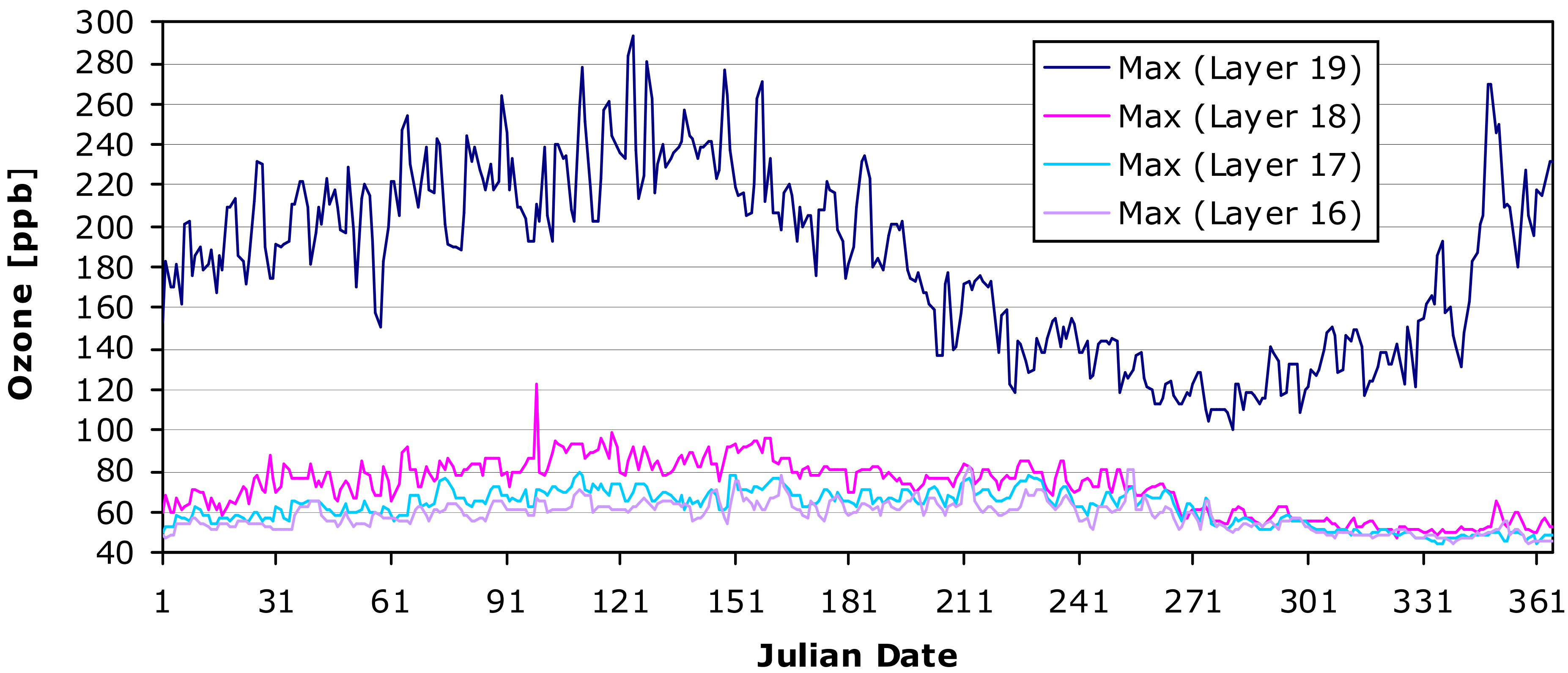


2005 Annual FCAQTF CAMx Results

- Highest ozone in San Juan Mountains occur in April



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 (AGL)
19	8-15 km
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

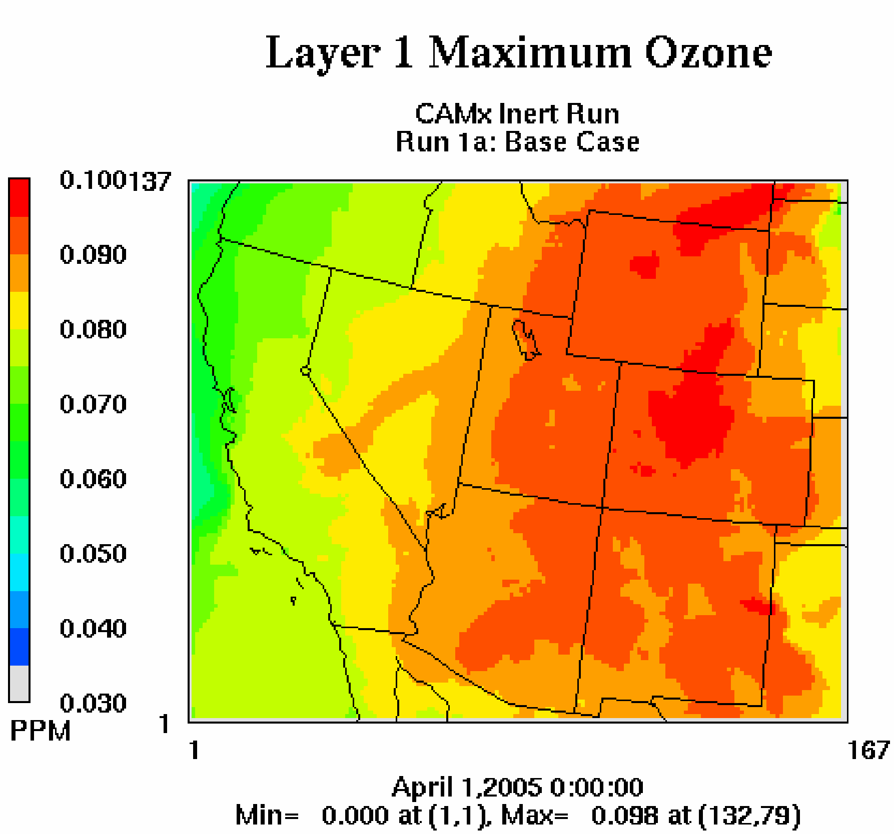
- Run CAMx in inert mode on 12-km western domain
  - Track inert ozone around from IC/BCs
    - Saves time and gas
  - Run for month of April 2005 (+ late March spinup)
  - All runs use same 2005 MM5 met
  - All runs use same 19 layer 2002 GEOS-CHEM BC
    - 19 layer BCs mapped to other layer structures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

Additional Layers

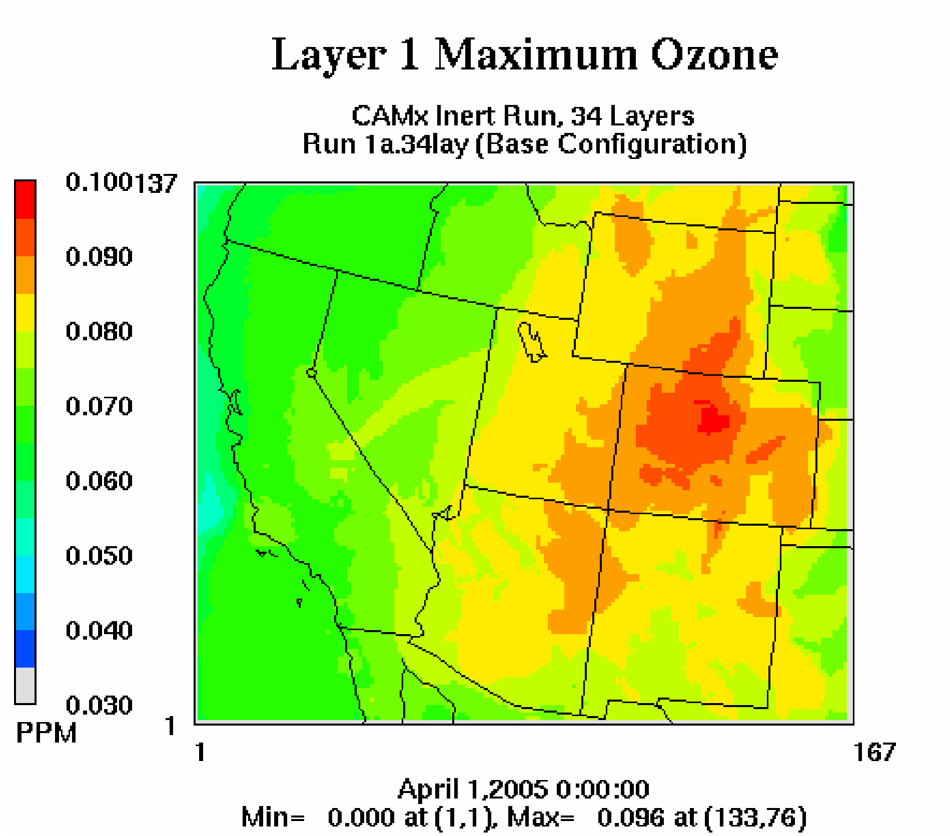
- Much of the problem can be attributed to vertical resolution
  - Layer 19 spans ~half the vertical domain
  - Poor resolution of upper winds, density and tropopause
  - Forces a lot of dynamics into one layer
  - “Instant” dilution through 7+ km
- MM5 met re-extracted for all 34 layers
- CAMx run used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

Additional Layers

19 layers



34 layers



Smoother-Desmoother

- Apply to horizontal wind fields
- Reduce small-scale (2-5Δx) 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

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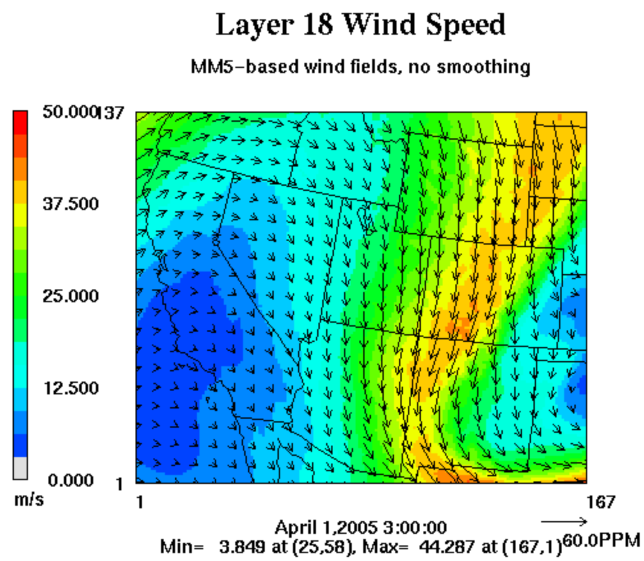
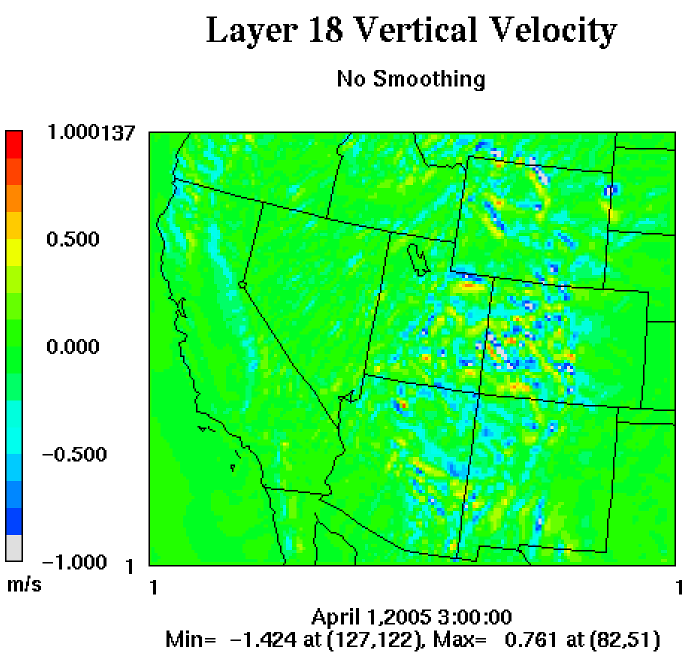
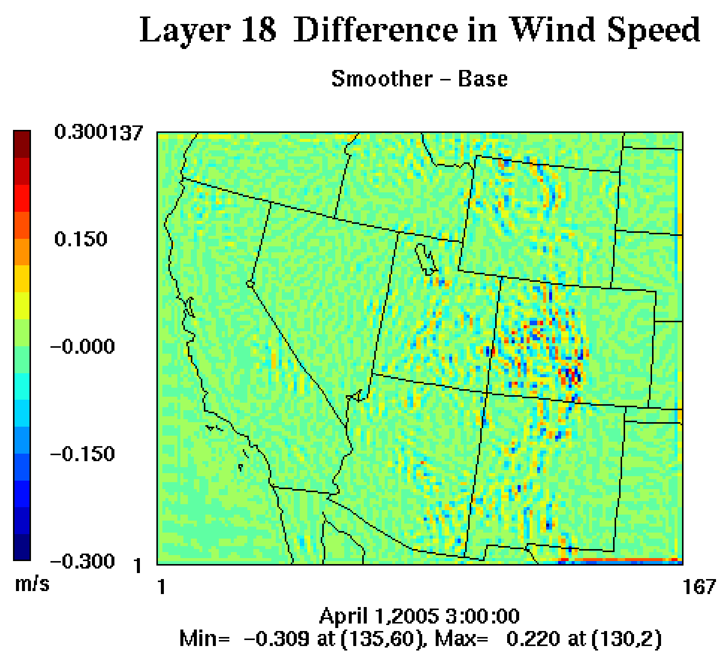
Smoother-Desmoother

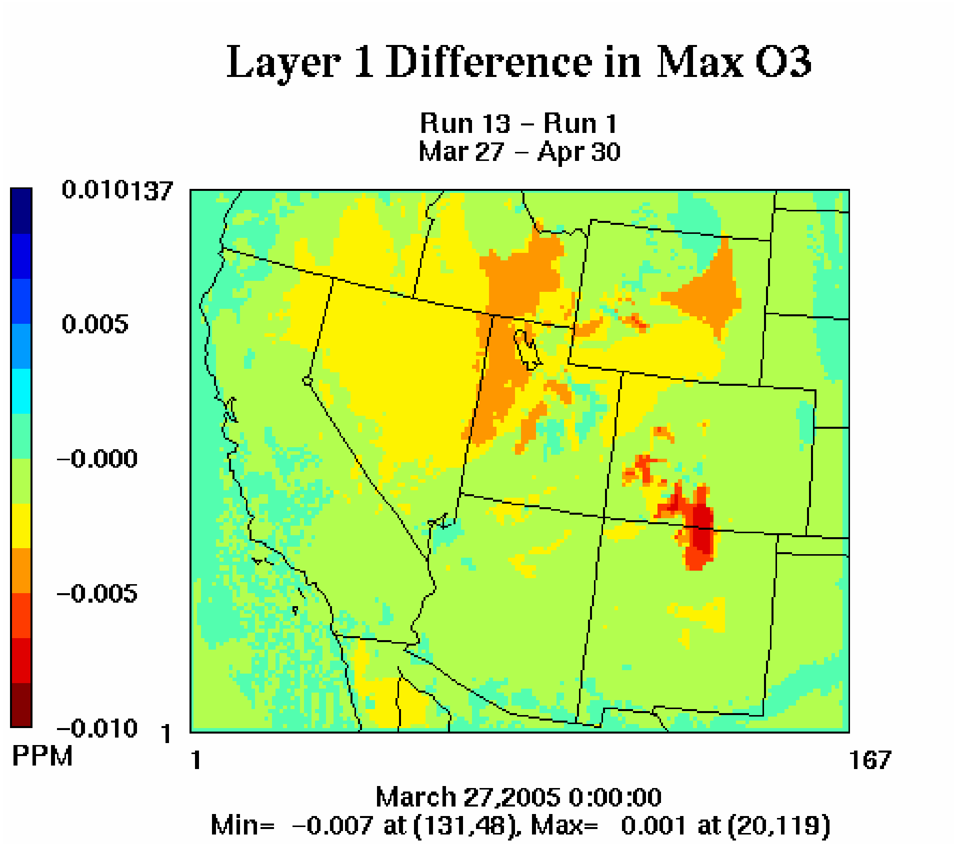






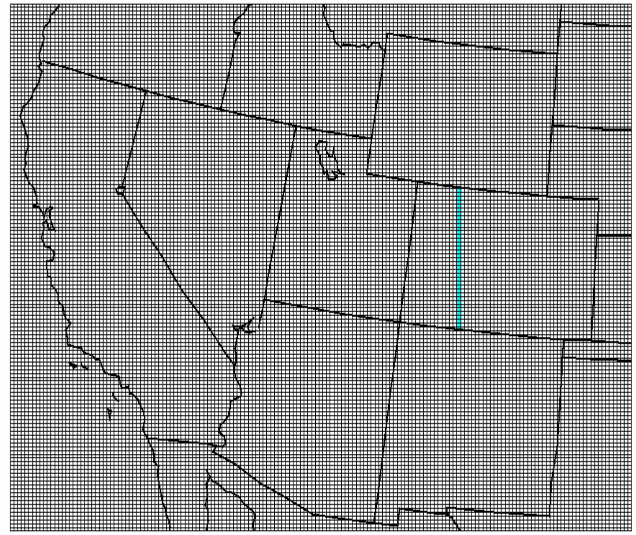
Smoother-Desmoother

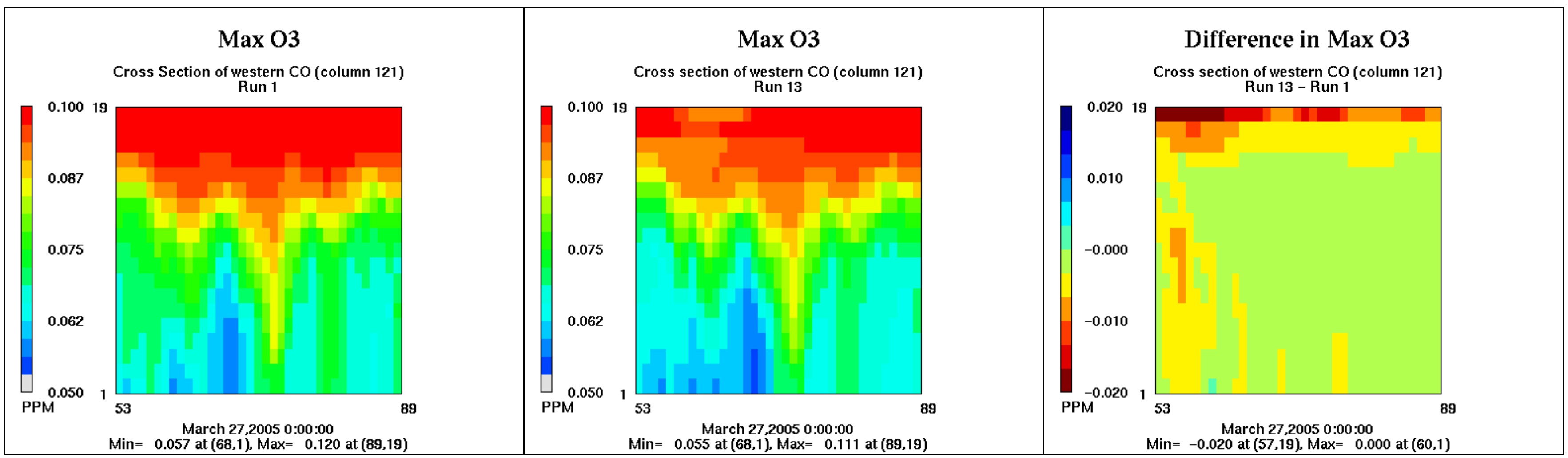
- Final run: Layer 16-19, heavy smoothing, no desmoothing, 5 passes



Smoother-Desmoother

- Vertical N-S cross-section through Colorado



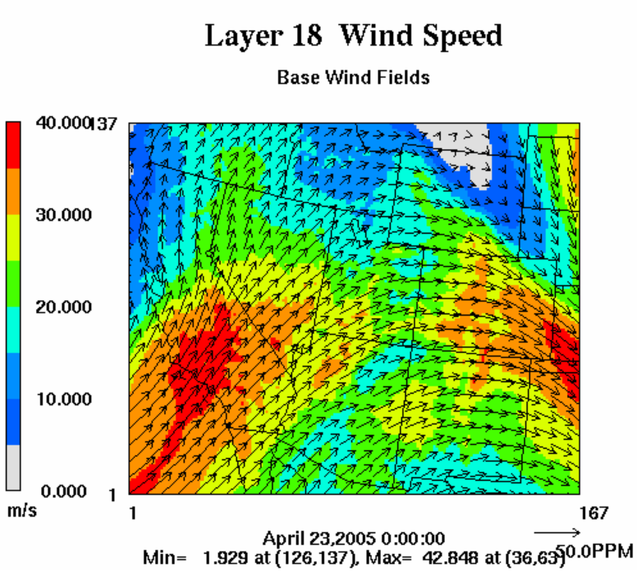


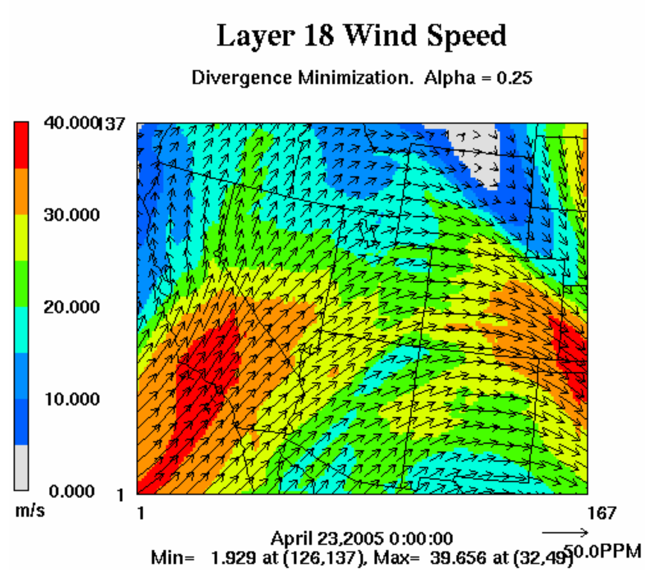
Divergence Minimization

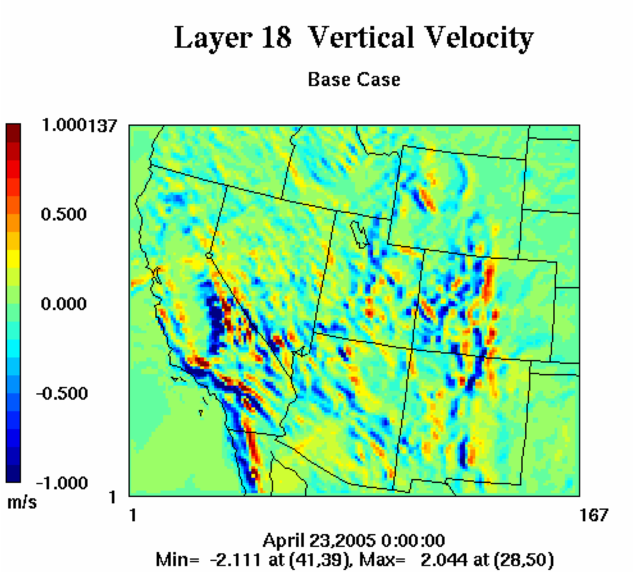
- Apply to horizontal wind fields
- Adapt CALMET algorithm to the CAMx grid stagger (Arakawa-C)
- Apply only to layers 16-19 (21-34)
- Test many attributes
  - Divergence minimization factor
  - Number of iterations
  - 19 vs. 34 layer configuration
  - Input vs. “zero-gradient” top BC

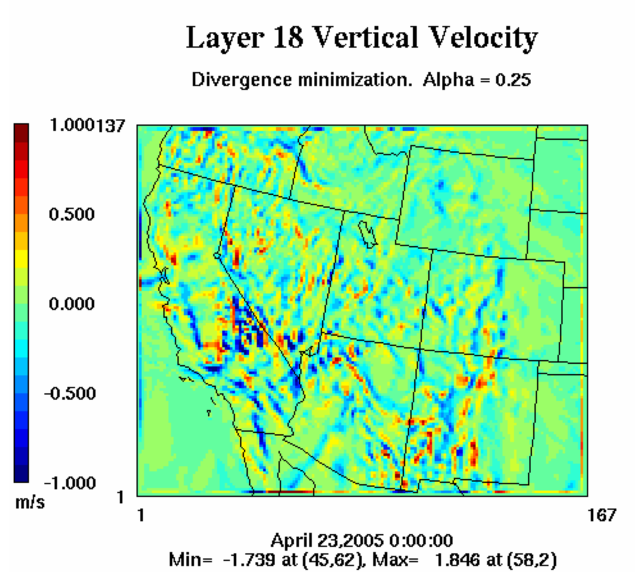
Divergence Minimization

Base / with DM

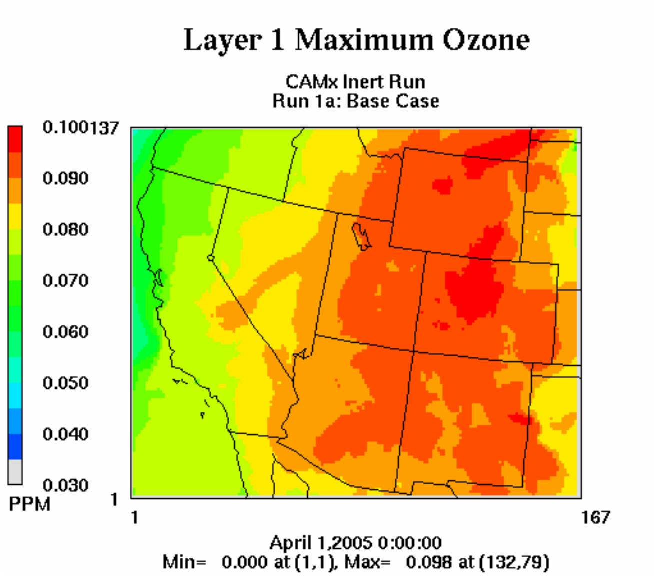


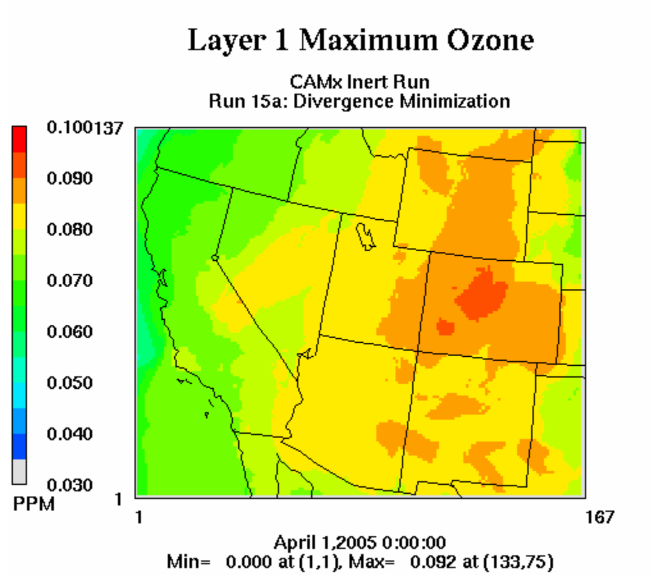


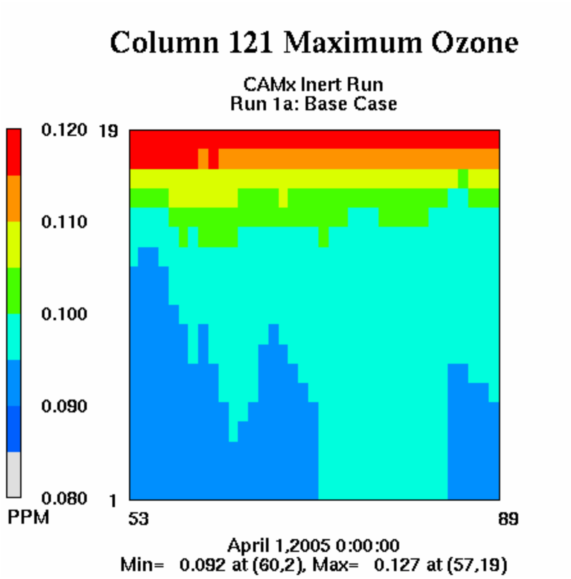


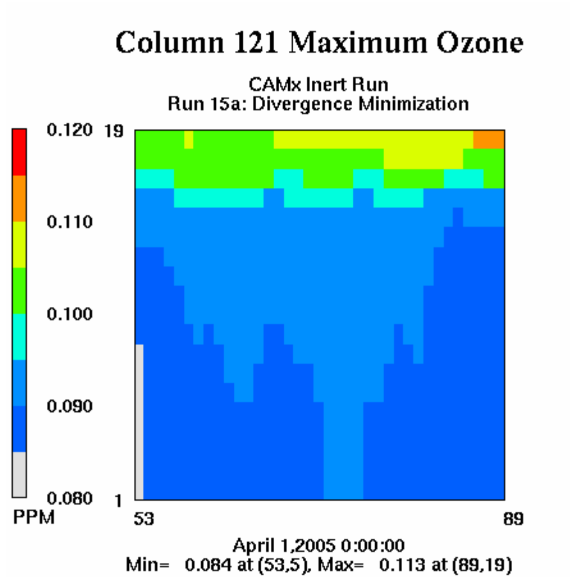


Divergence Minimization
19-layers, input Top BC

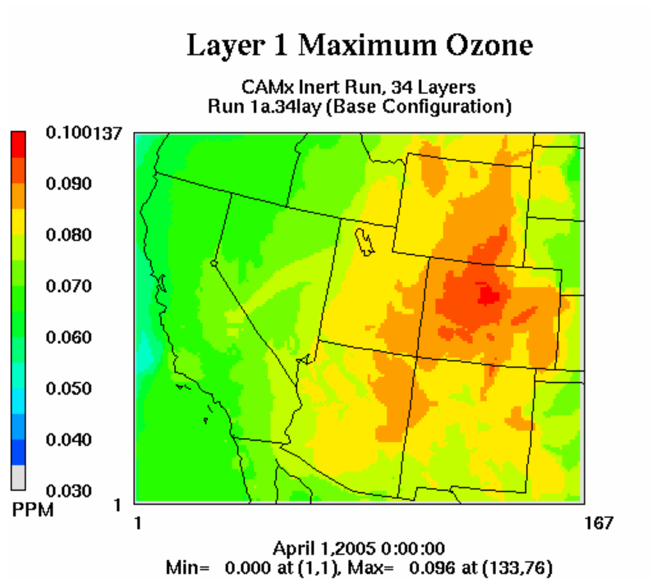


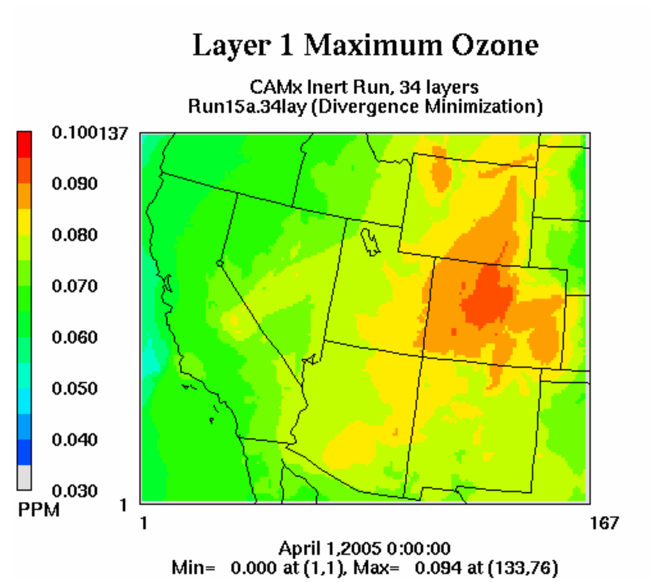


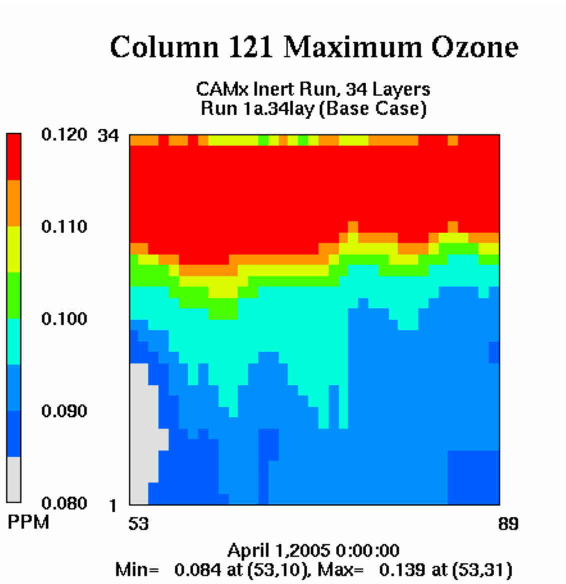


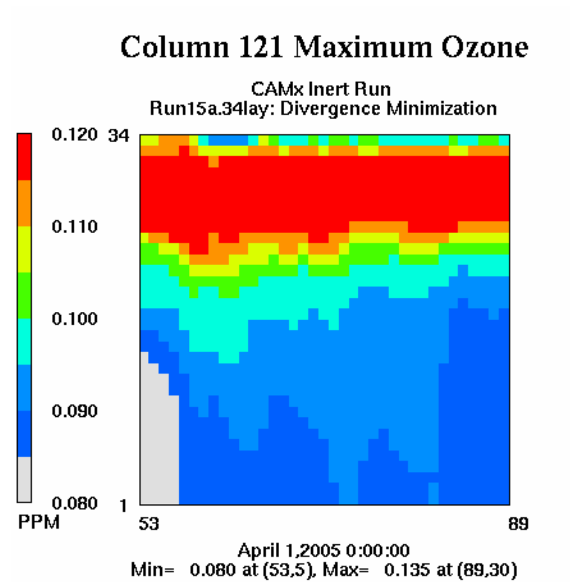


Divergence Minimization
34-layers, input Top BC

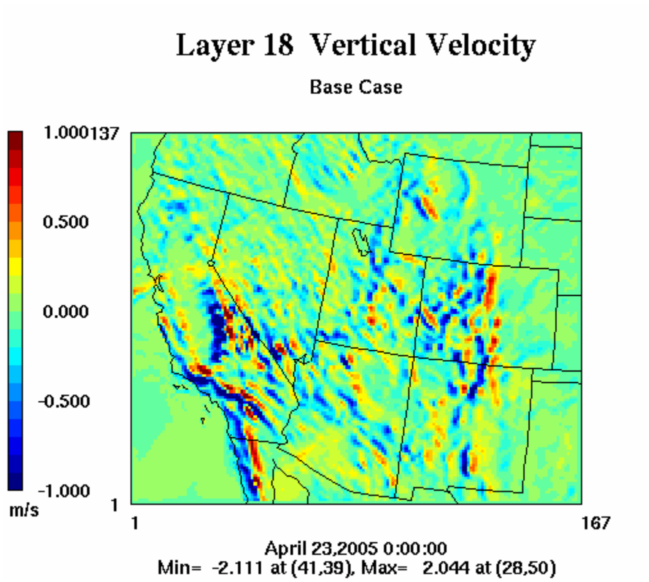


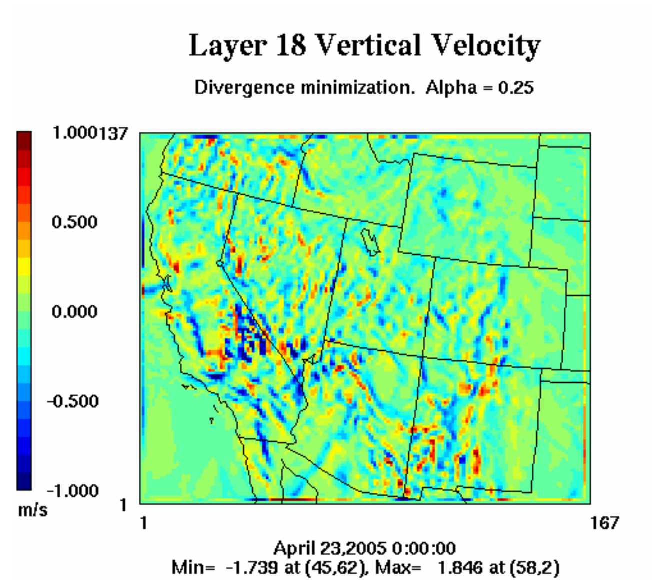






Divergence Minimization
Vertical Velocity: Layer 18 vs. Layer 19





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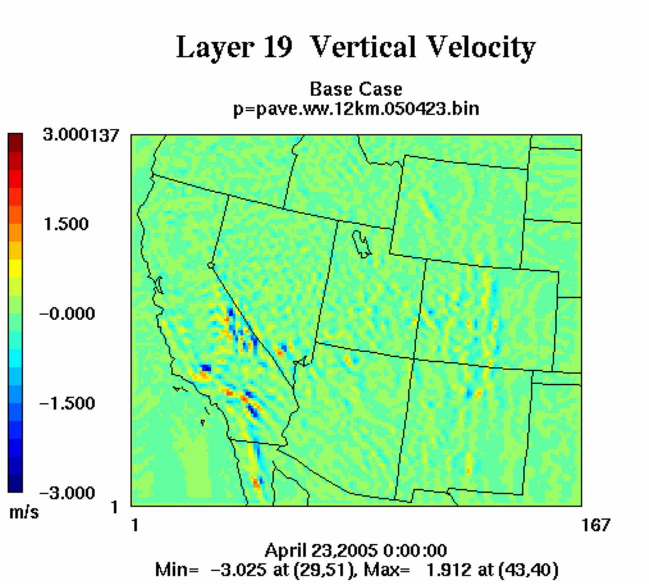
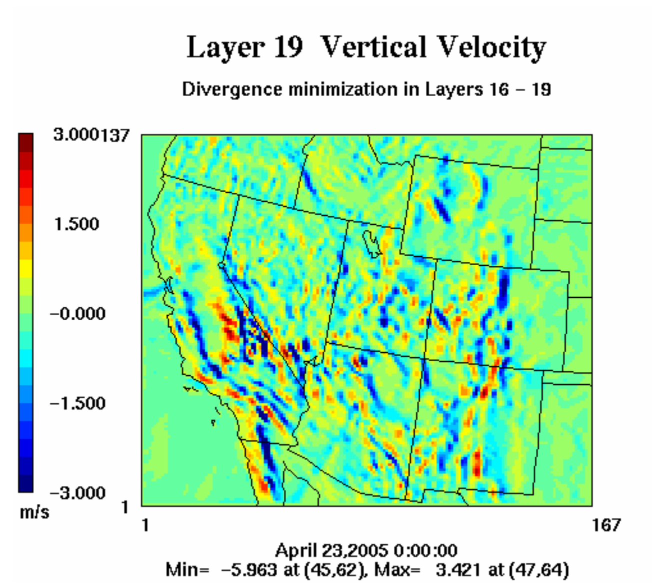
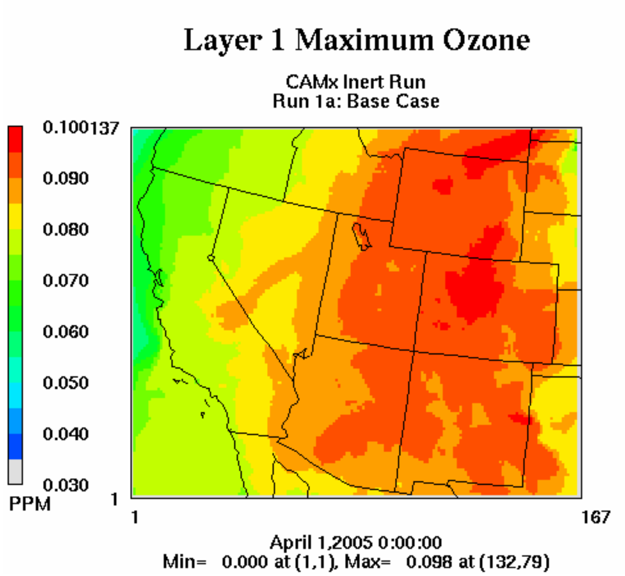
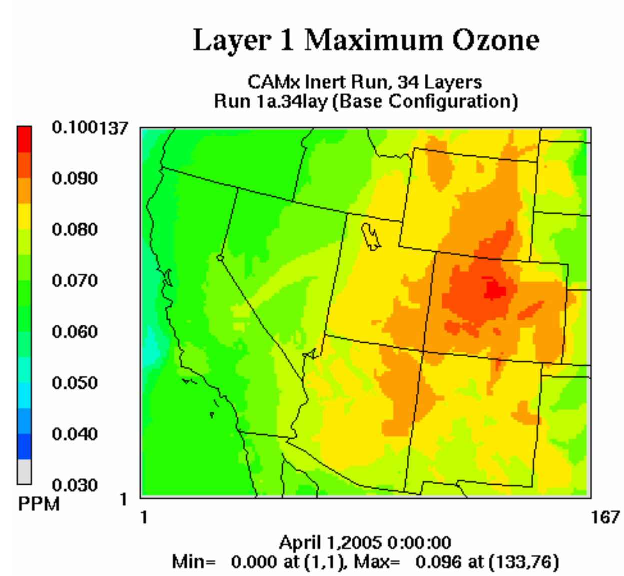




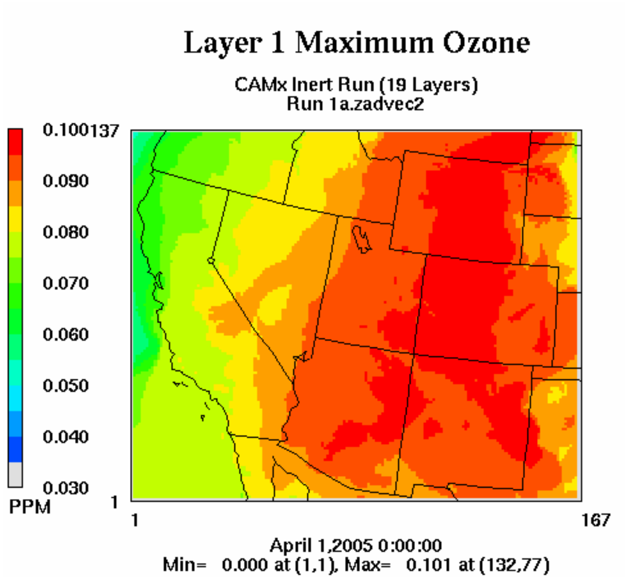
19

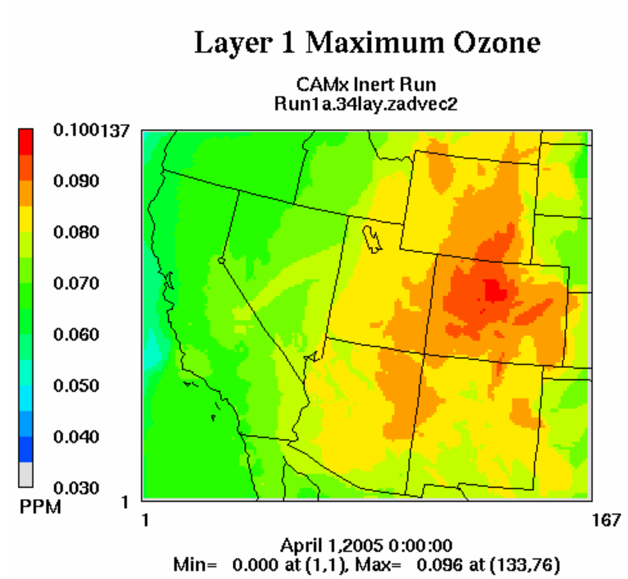
Zero-Gradient Top BC (no divergence minimization)





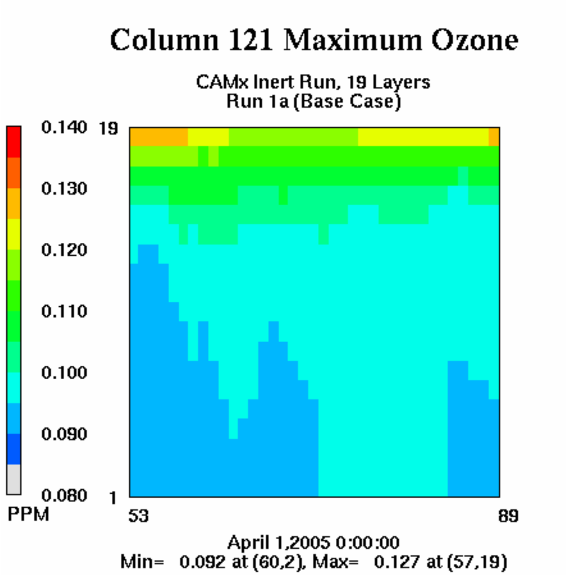
Orig

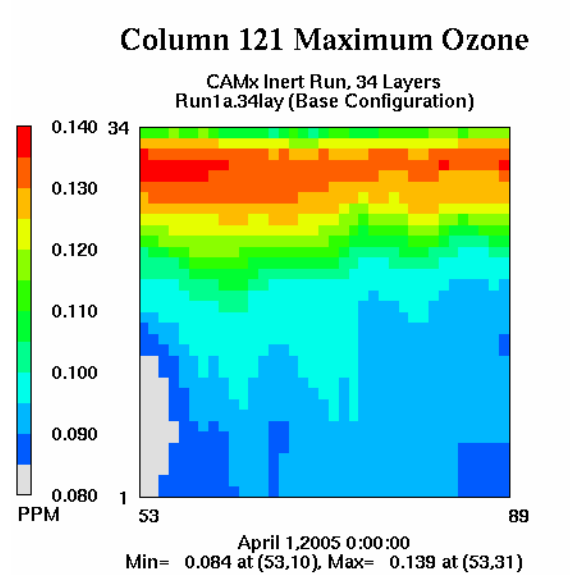




Zero-Grad

Zero-Gradient Top BC (no divergence minimization)





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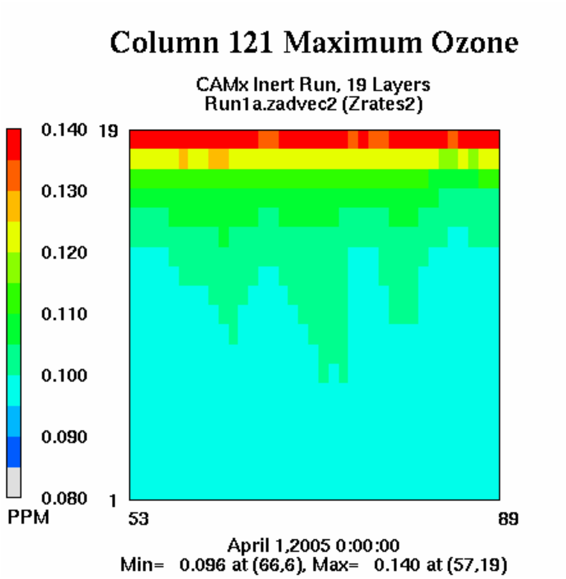
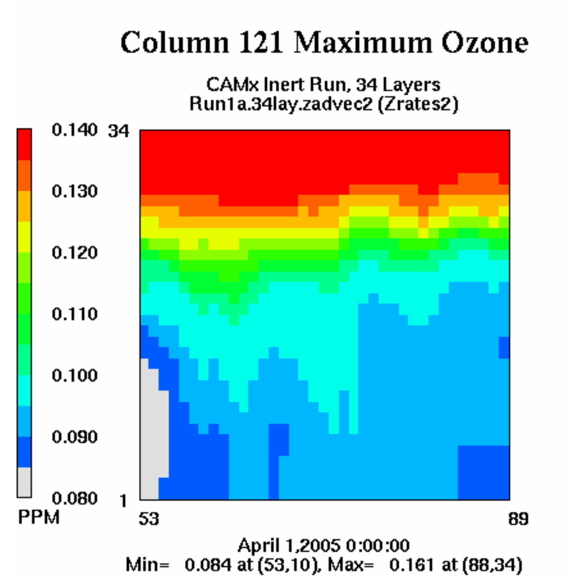




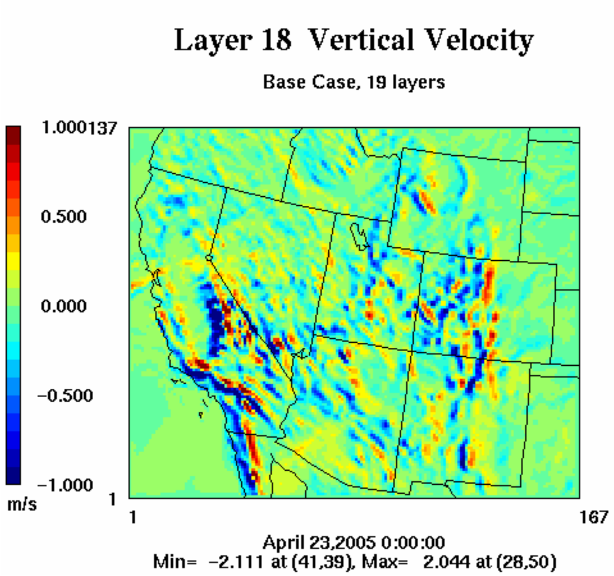
Zero-Grad

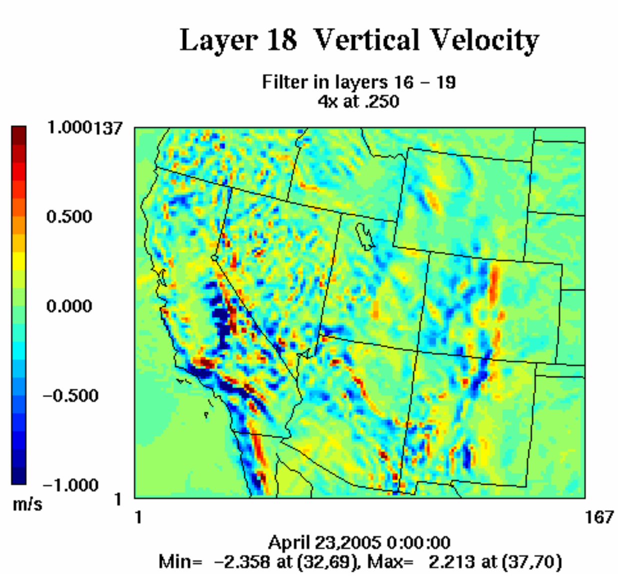
Mass Flux Filter

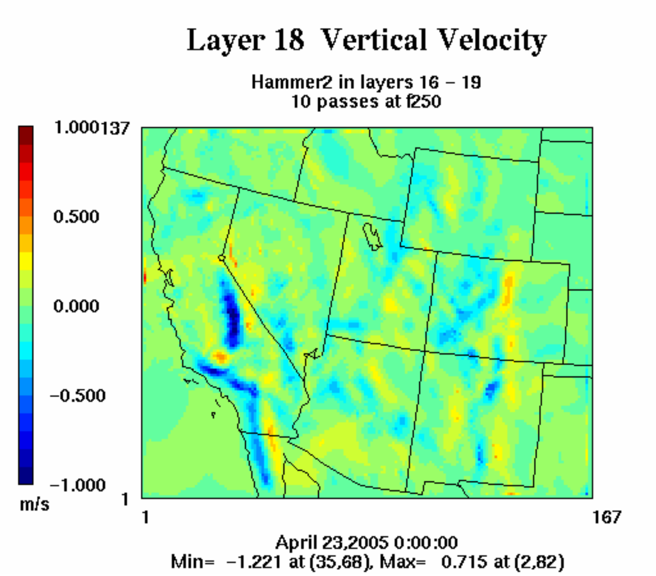
- Adapt from LLNL “pressure fixer”
- Adjust horizontal wind fields for column mass error
  - 19-layer zero-gradient top BC case only
  - Applied to layers 16-19, multiple passes
  - Mass buildup/loss due to horizontal advection is relaxed through
    - (1) modification of horizontal winds first
    - (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

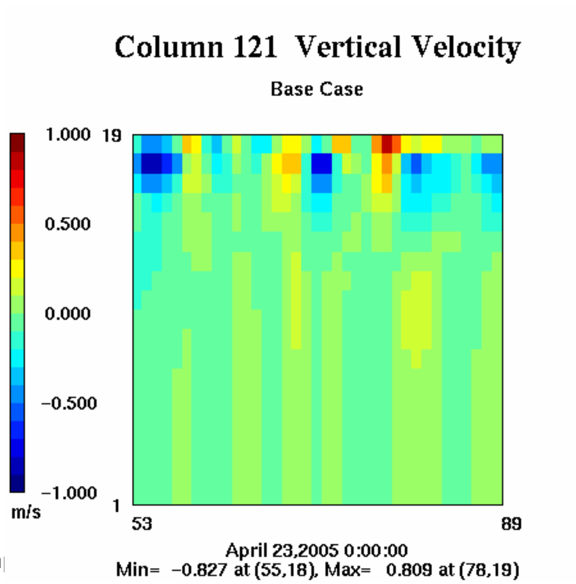
Mass Flux Filter – Vertical Velocities

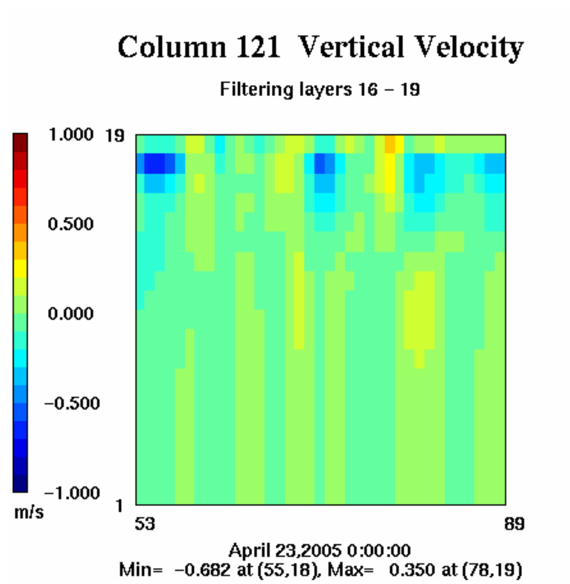
Base | Original Filter | Hammer

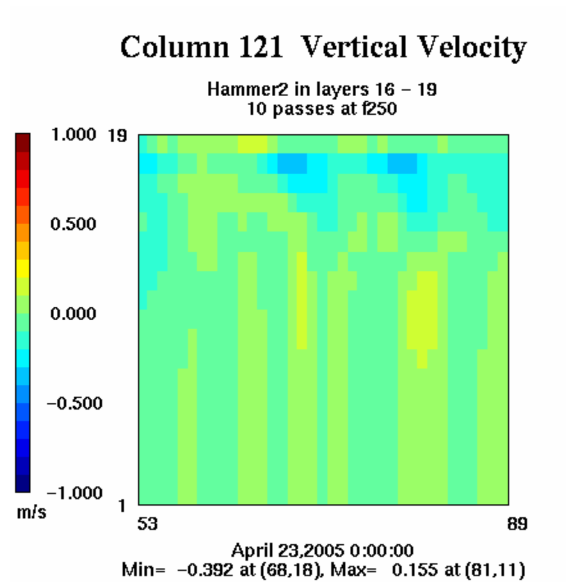












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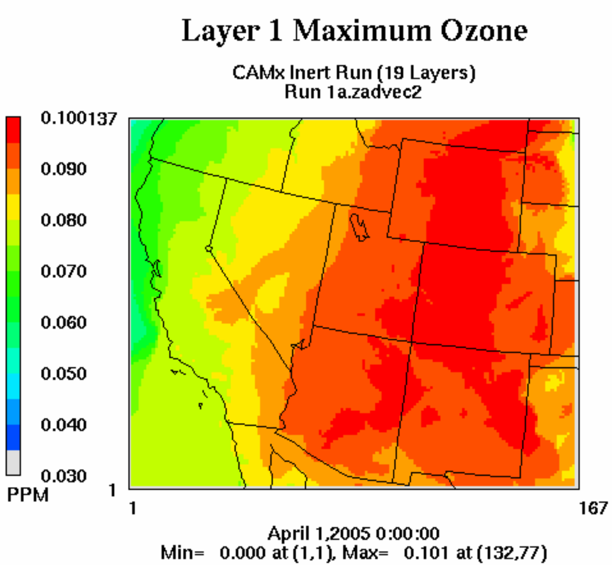
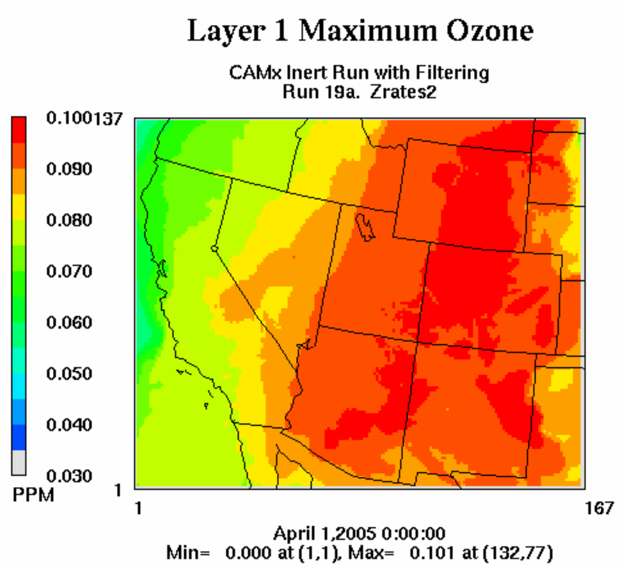
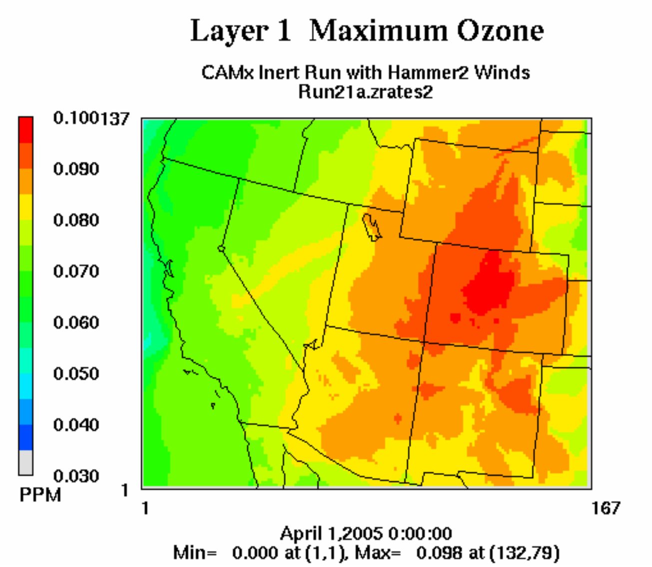
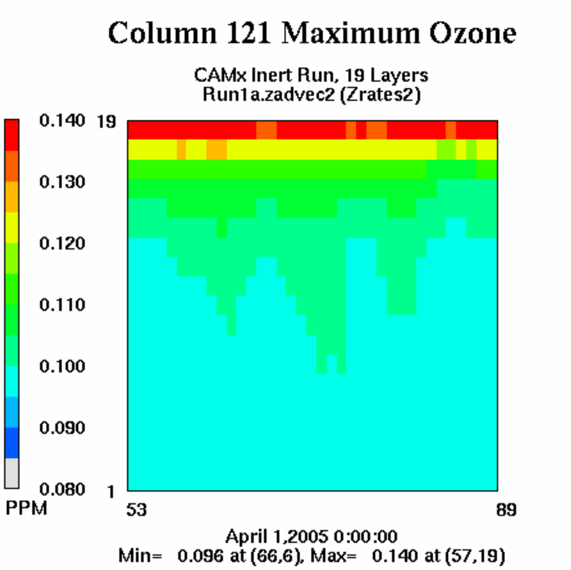
Mass Flux Filter – Max Surface Ozone

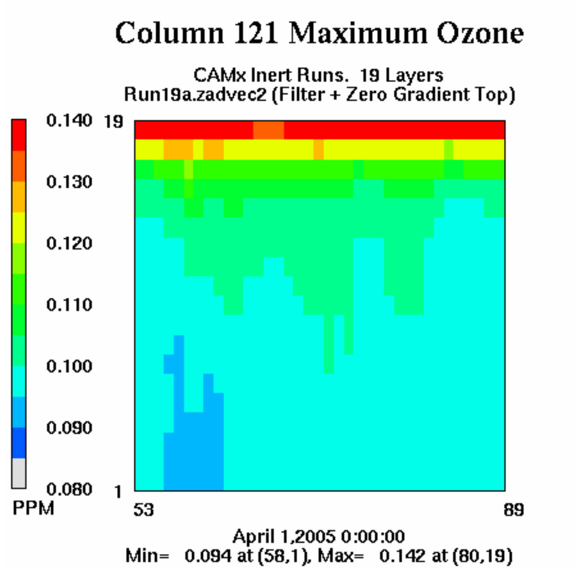
Base | Original Filter | Hammer

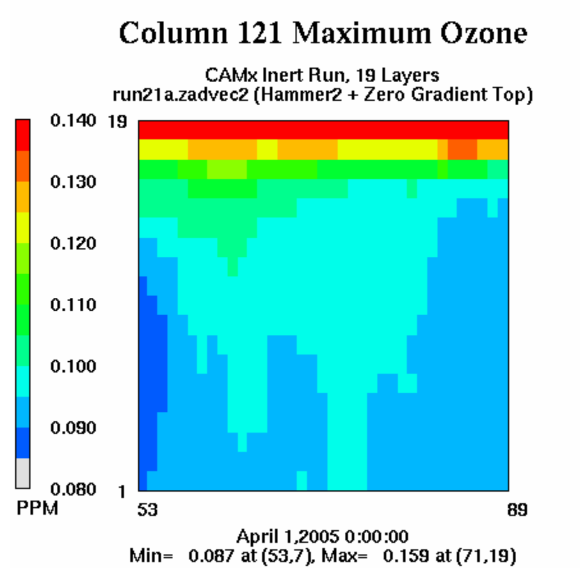












Summary

- 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 ≠ 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