Using the Relationship Between Mean 500-Millibar (Mb) Heights and Mean Surface Ozone Concentrations in Colorado to Decompose Ozone Times Series and Evaluate the Impacts of Changes in Precursor Emissions

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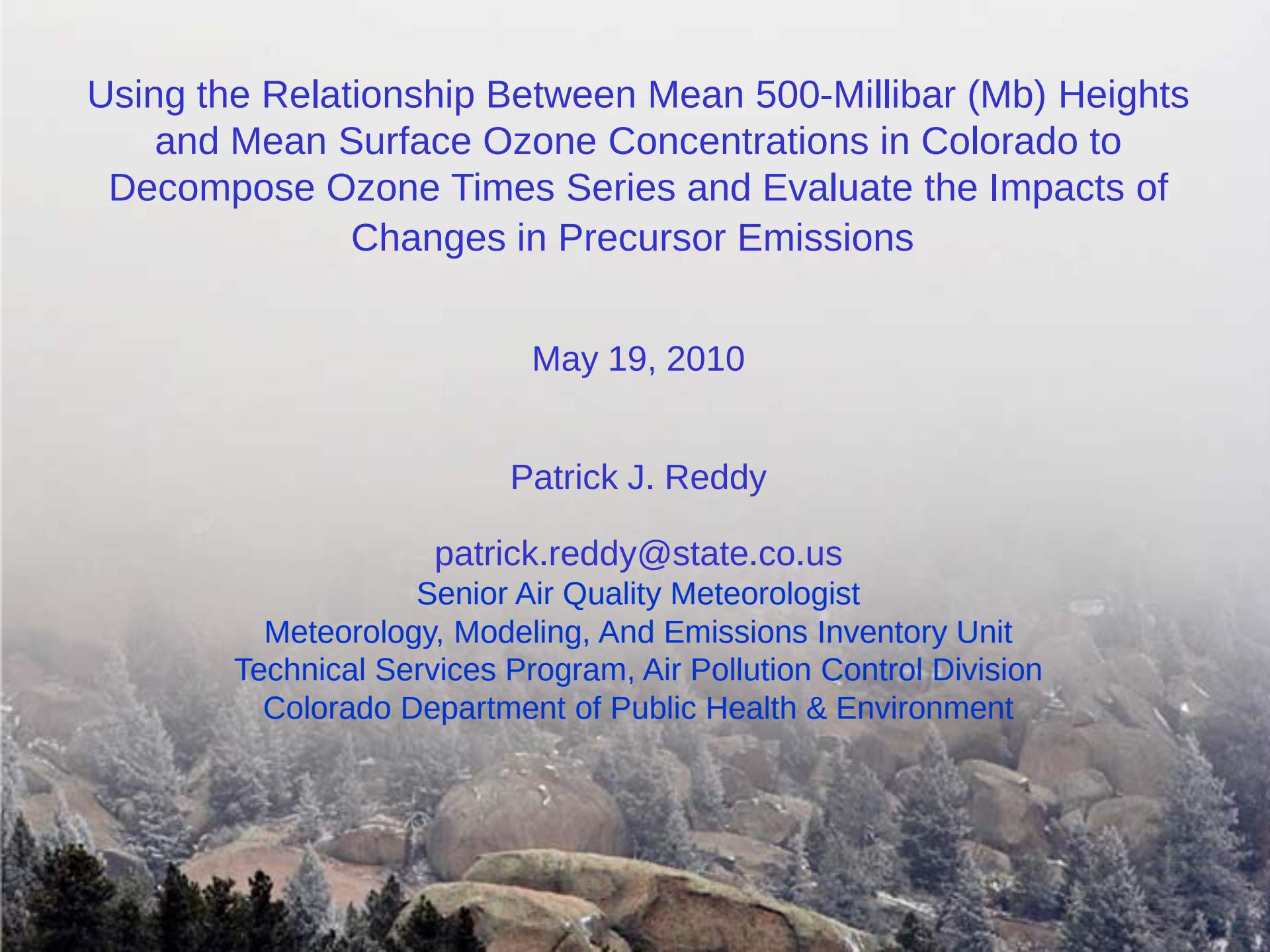
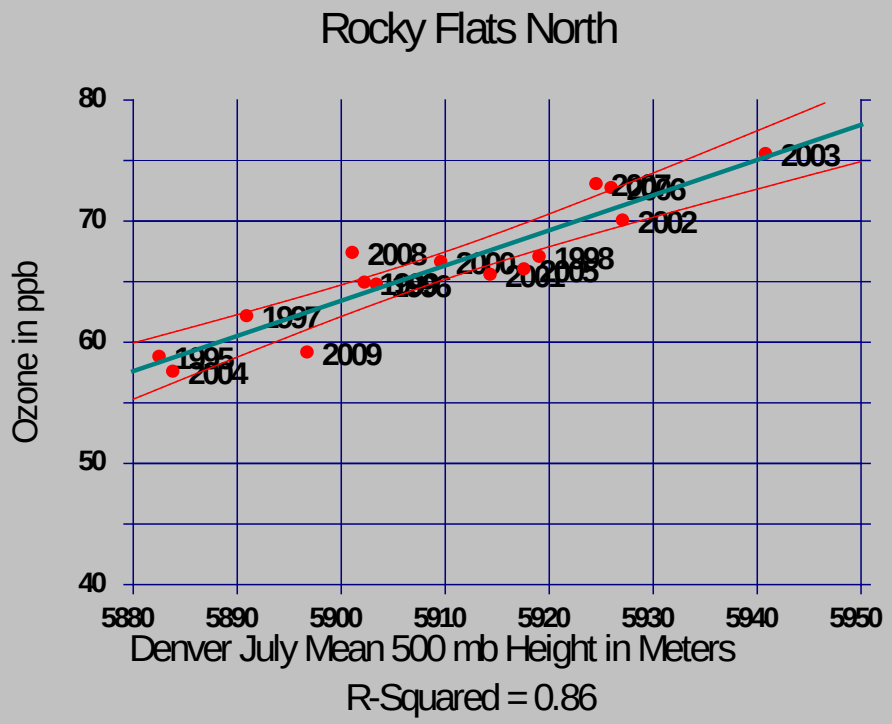


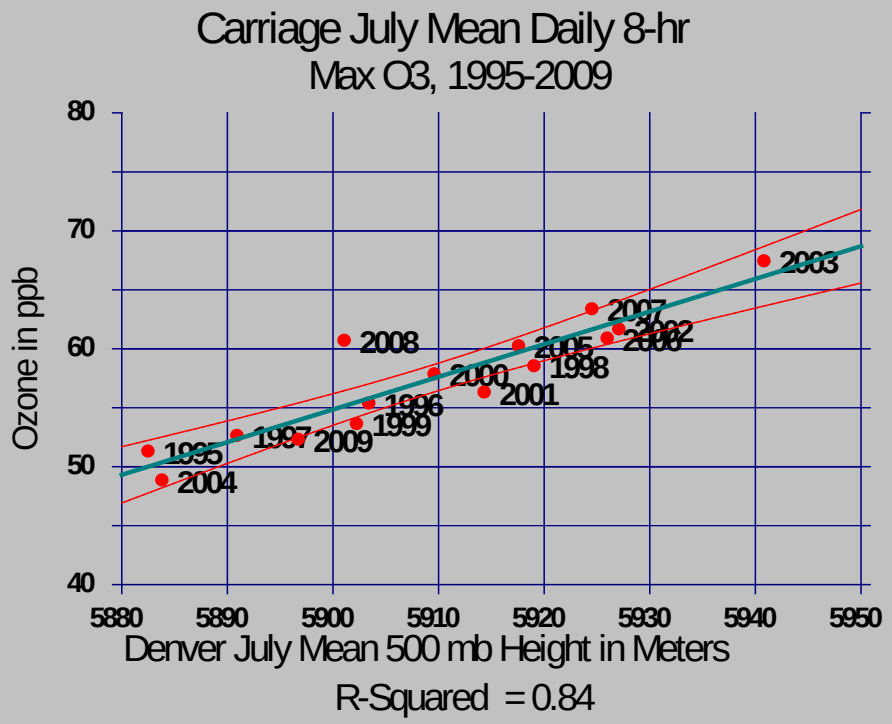
- In Colorado, **local** mean July 500-mb heights are the single best predictor for July mean daily max 8 hour O3 (R-squared values of about 0.6 to 0.9). Several dozen variables tested.

- This makes sense since large heights are caused in part by high temperatures in the column below about 19,000 feet, and are associated with light winds, local and regional re-circulation, limited cloud cover, and the buildup of local/regional background concentrations.

- Correlations between short-term ozone and short-term heights are weak. Correlations between monthly means for June and August are weak.

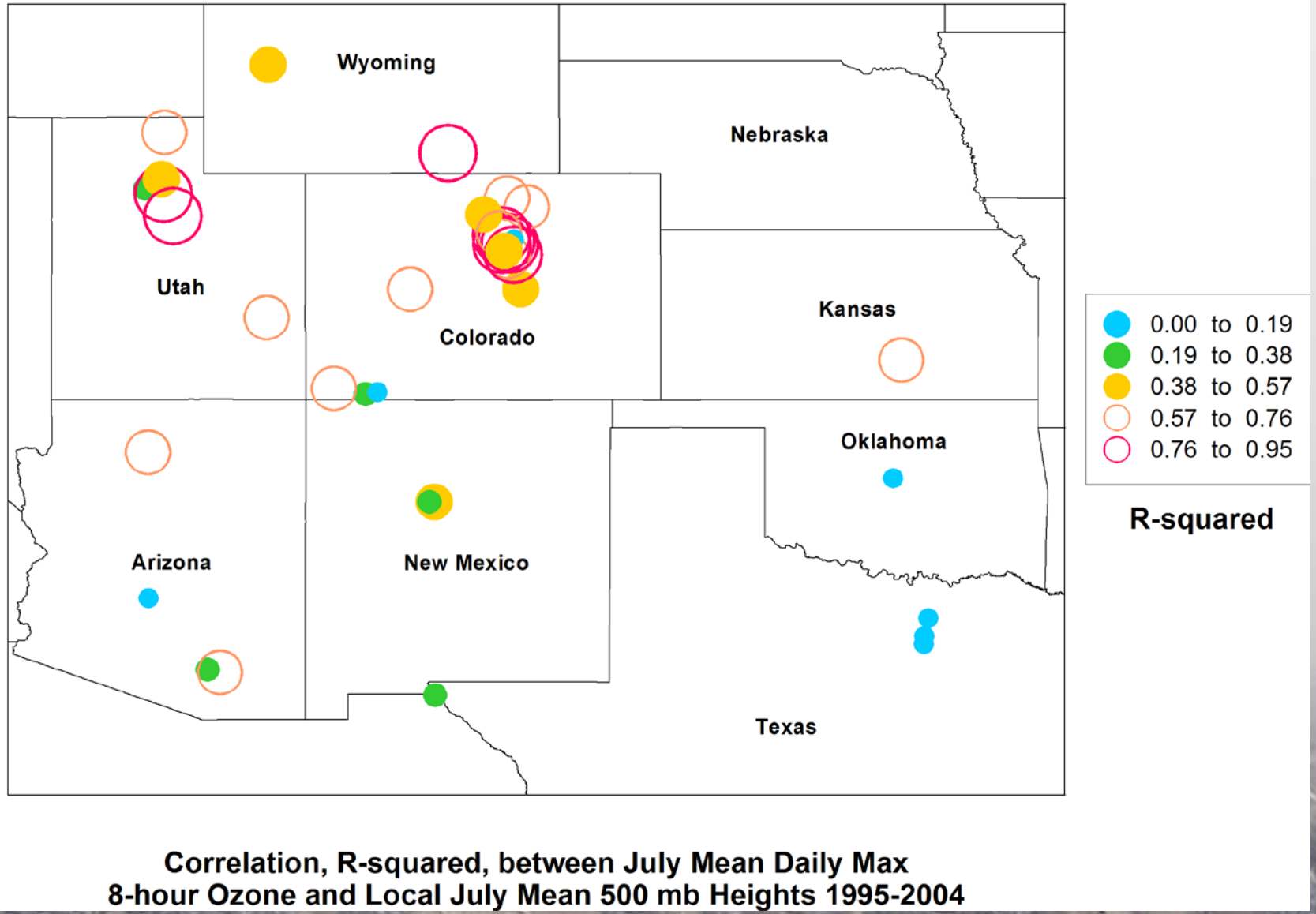
- The correction for weather in the ozone time series consists of nothing more than the calculation of the residuals from the linear regression of ozone with 500-mb heights.





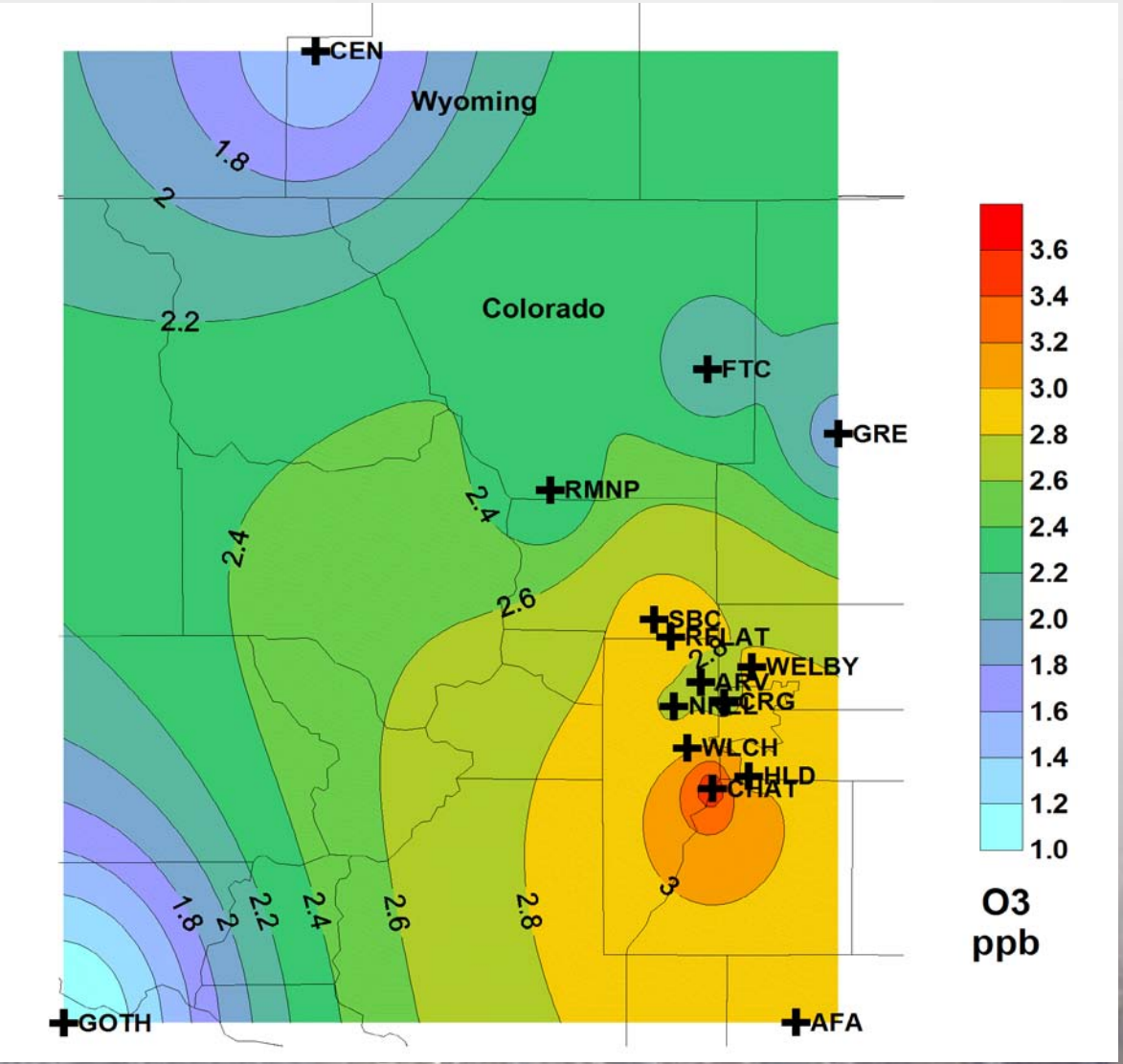
Linear regressions between Rocky Flats North and Carriage July mean daily max 8-hour O3 and July mean 500-mb heights from the NCAR/NCEP Reanalysis[1] data set for the Front Range grid cell, essentially the northern Front Range and north central mountains of Colorado. Rocky Flats is the Front Range high-concentration site; Carriage is a lower-concentration site just west of downtown Denver.

1 Kalnay, E. and Coauthors, 1996: The NCEP/NCAR Reanalysis 40-year Project. Bull. Amer. Meteor. Soc., 77, 437-471.

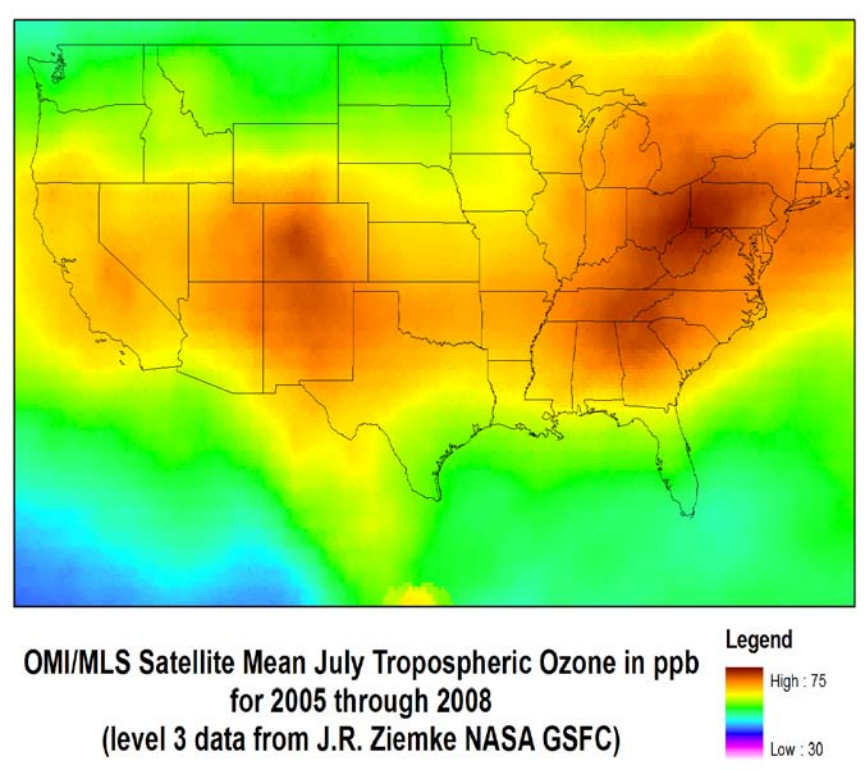


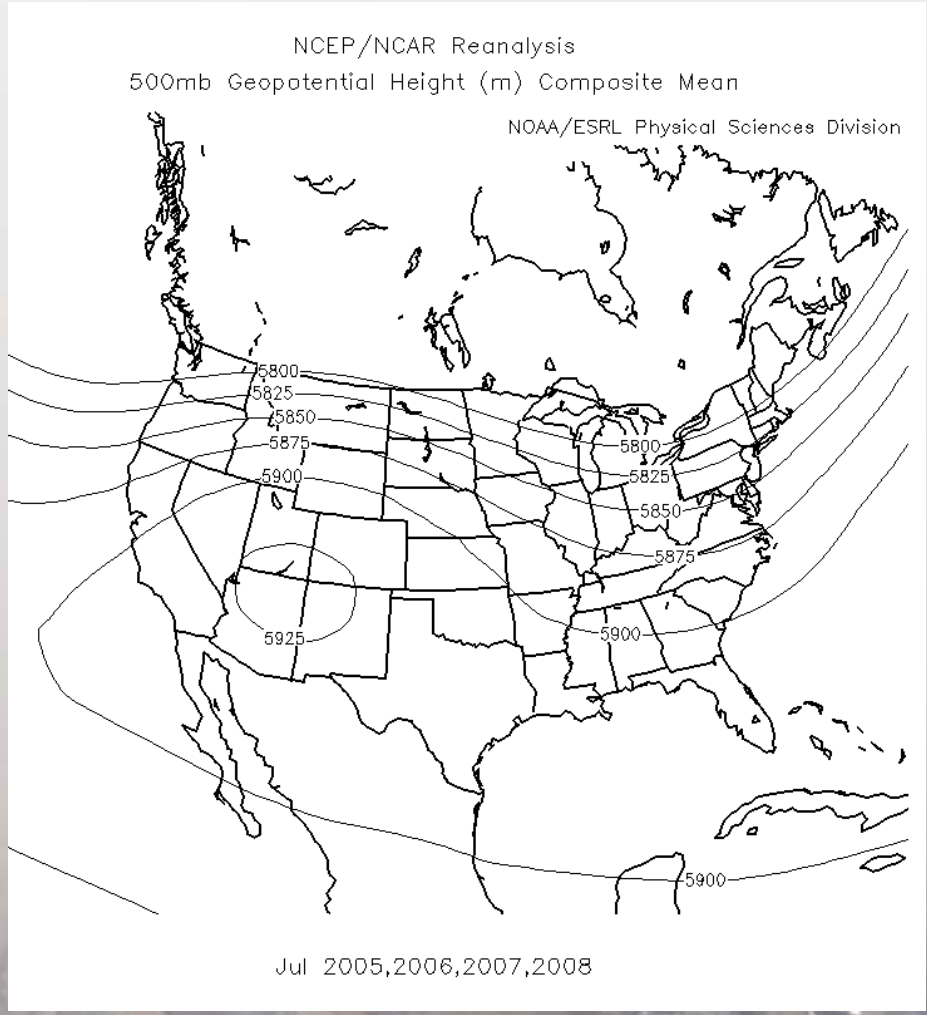
Correlation, R-squared, between July Mean Daily Max 8-hour Ozone and Local July Mean 500 mb Heights 1995-2004

The relationship between mean daily max O3 and 500-mb heights is strongest along the Wasatch Front of Utah and Front Range of Colorado, and in UT, NM, AZ, WY, and CO. These are areas where average afternoon mixing heights are often 17,000 to 25,000 MSL



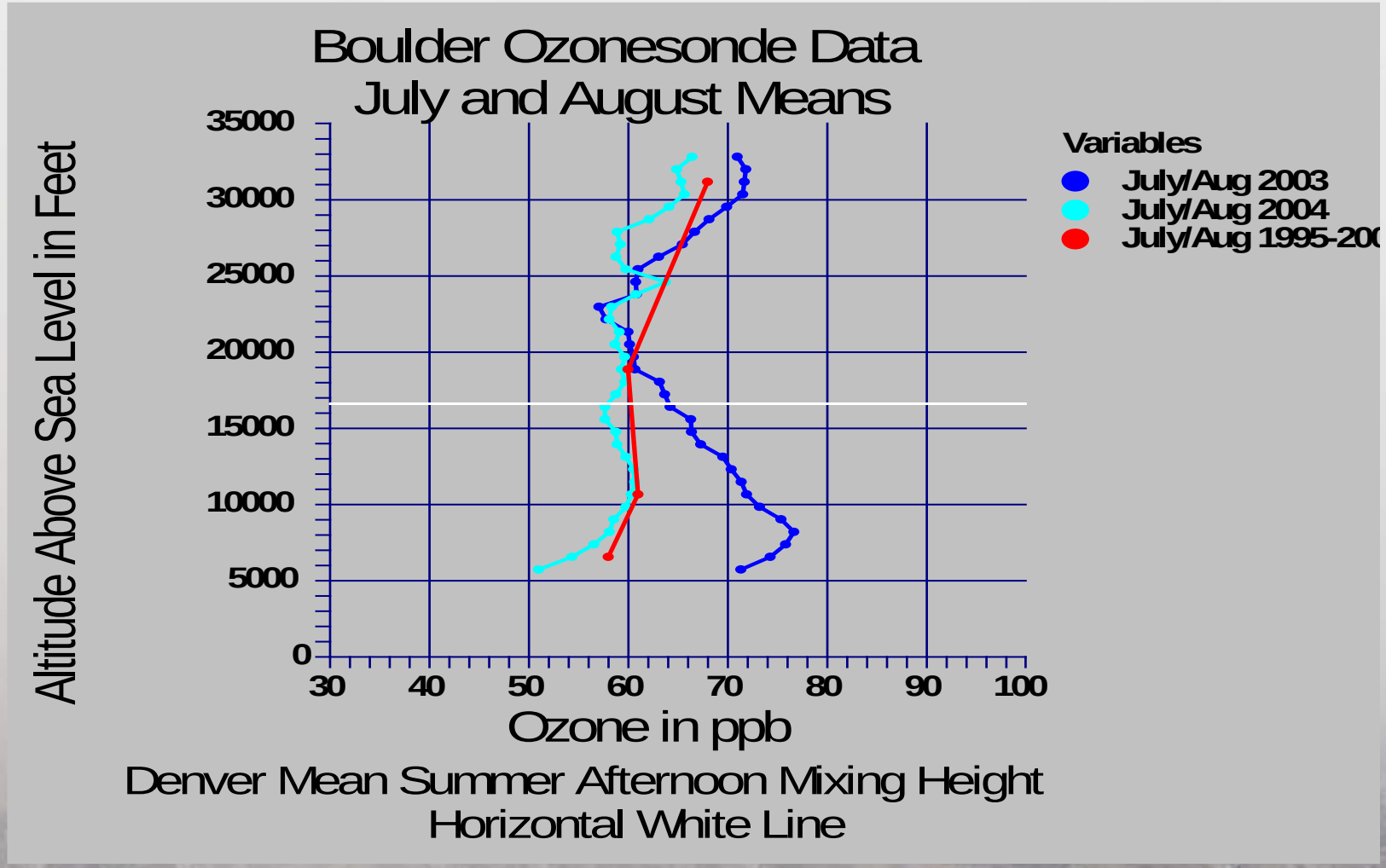
1995-2009: Response in O3 to 500-mb heights ranges from 1.0 to 3.5 ppb per decameter in and near Colorado's Front Range: 6 to 21 ppb over the range of heights observed. Increases in local background with persistent high pressure? Response in other high-impact areas of AZ, UT, WY is about 1.5 to 2.5 ppb per decameter.





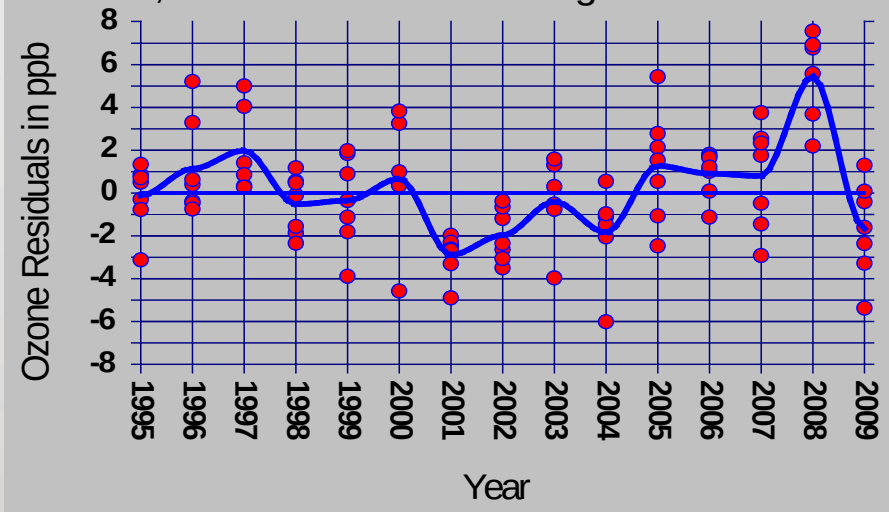
Is the correlation between mean July O3 and 500-mb heights related to the upper tropospheric enhancement described by Owen Cooper and coauthors[2,3]? Four Corners high typically blocks the monsoon; regional lightning NOx may not be major factor when this upper-level high is strong.

2. "Large upper tropospheric ozone enhancements above midlatitude North America during summer: In situ evidence from the IONS and MOZAIC ozone measurement network," Owen Cooper et al., ***Journal of Geophysical Research***, 2007.
3. "Evidence for a recurring eastern North America upper tropospheric ozone maximum during summer," Owen Cooper et al., ***Journal of Geophysical Research***, 2006.

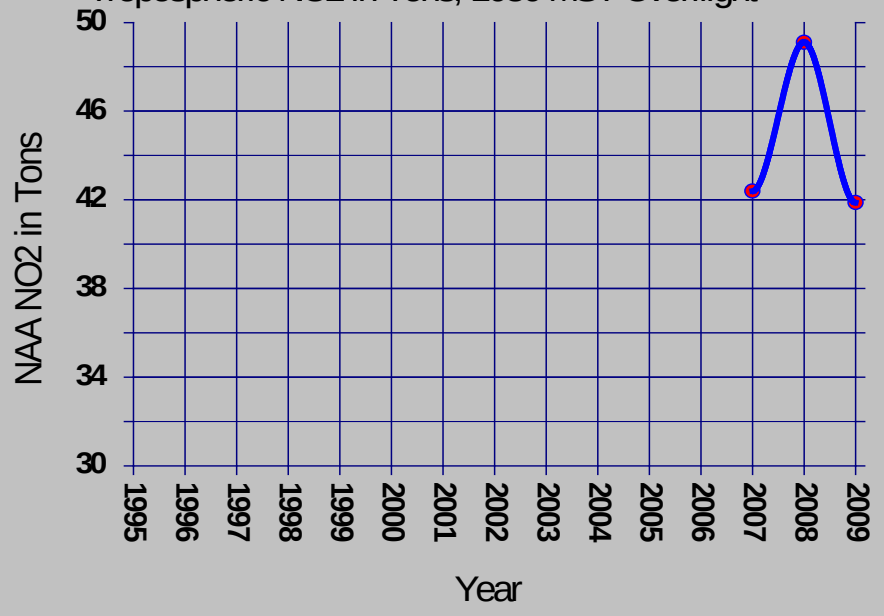


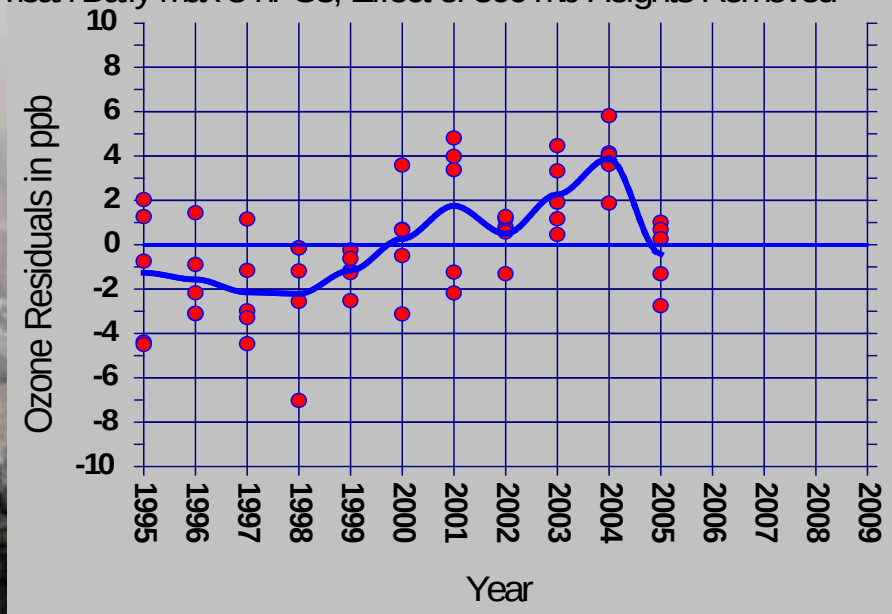
NOAA ESRL/GMD Boulder ozonesonde mean profiles for July and August: 2003 in dark blue, 2004 in light blue, climatology for 1995-2001 in red.[4] 2003 represents worst-case O3 concentrations; 2004 was a low-concentration summer. July of 2003 and 2004 also represent the extremes for 500-mb heights for 1995-2009.

4. Newchurch, M. J., M. A. Ayoub, S. Oltmans, B. Johnson, and F. J. Schmidlin, *Vertical distribution of ozone at four sites in the United States*, ***Journal of Geophysical Research***, VOL. 108, NO. D1, January 15, 2003.



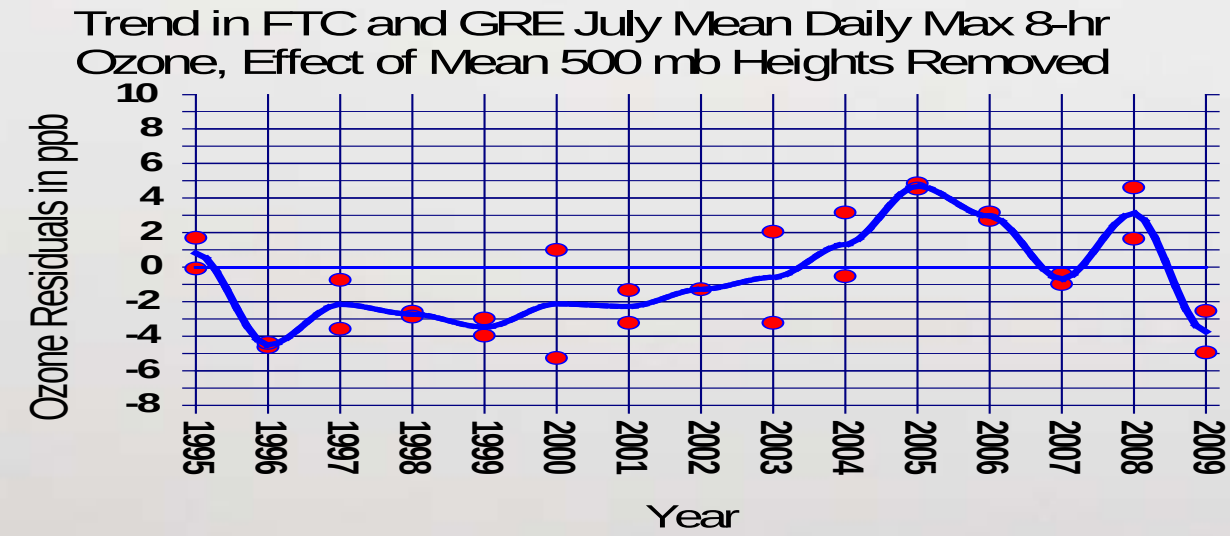
(Residuals are differences between actual and weather-predicted ozone. CHAT outlier removed.)



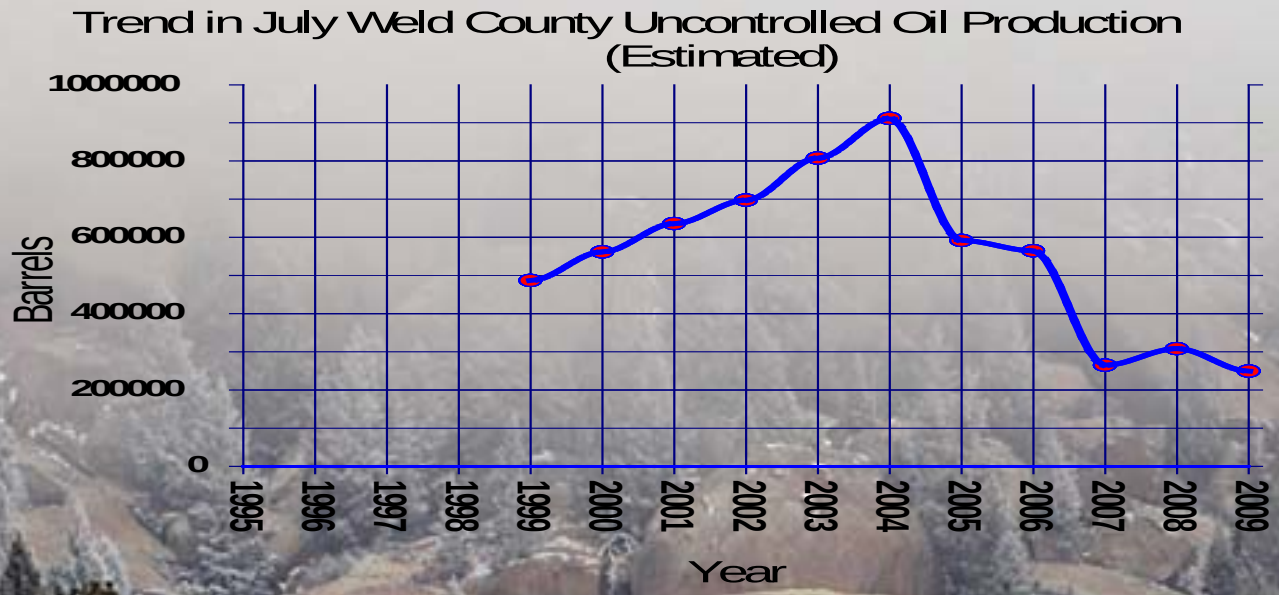


The Denver-area peak in corrected O3 in 2008 matches GOME2 tropospheric NO2. The decline in both in 2009 is consistent with the Recession.

Huge reductions in power plant & smelter SO2 and modest reductions in power plant NOx occurred in AZ and NM in the late 1990s. Is the O3 signal (left) related to sulfate-O3 interactions?

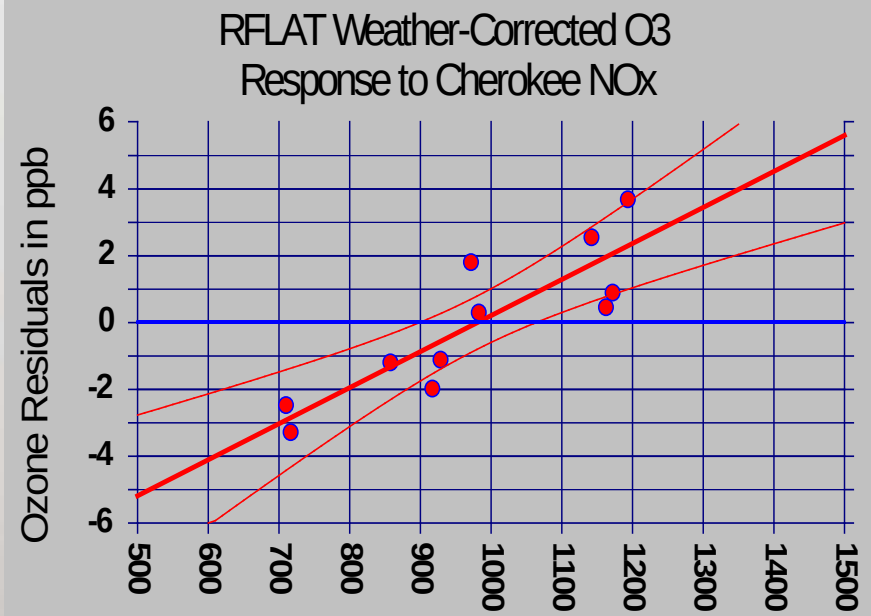


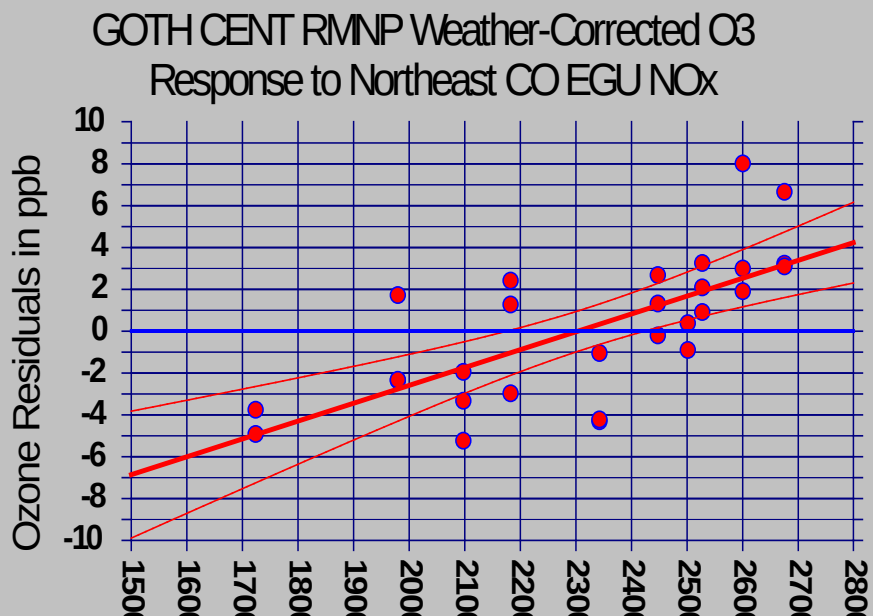
(Residuals are differences between actual and weather-predicted ozone.)



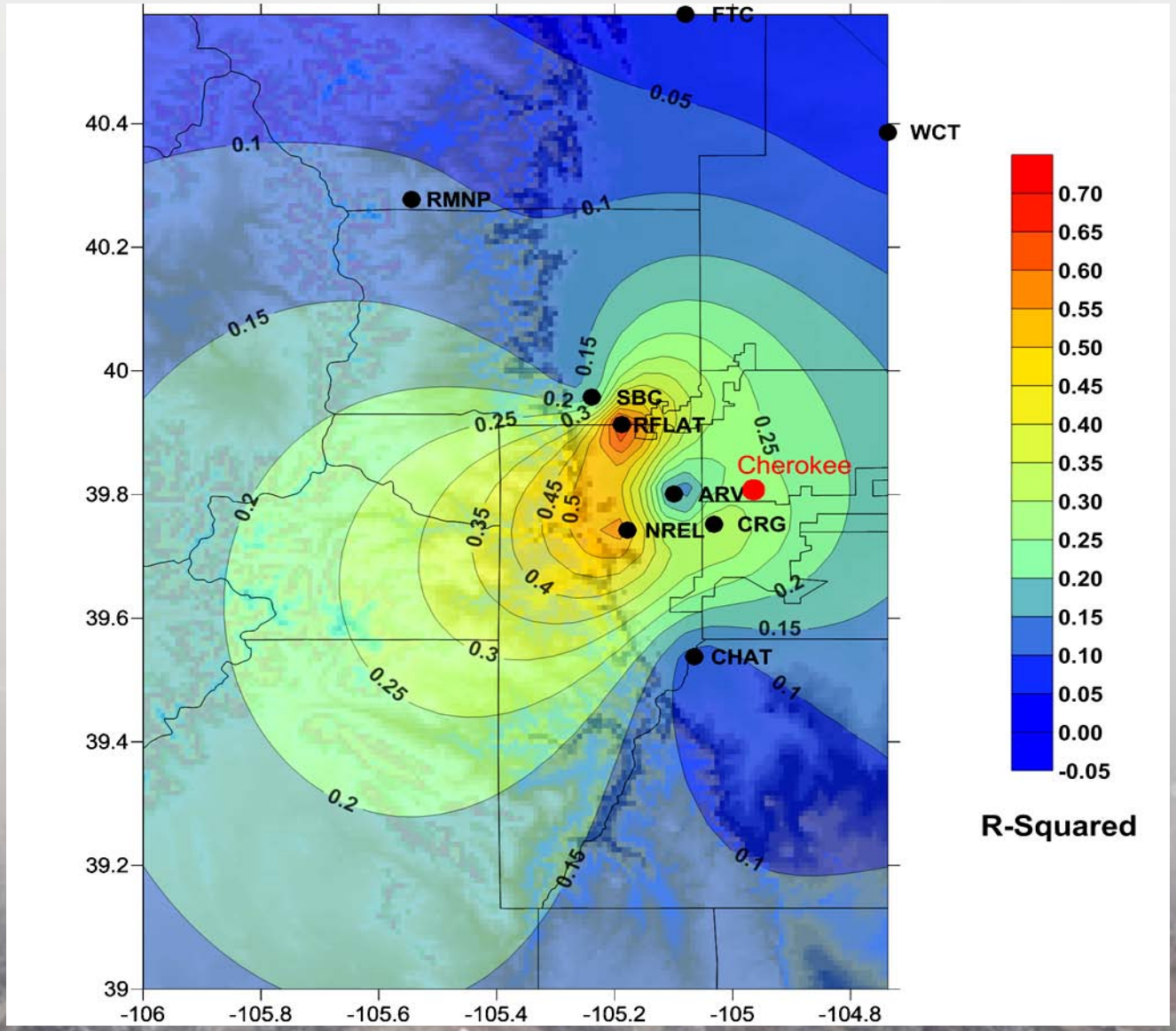
The ozone time series for FTC and GRE seem to show the influences of oil and gas field changes, changes in NOx, and the Recession.

The lower plot is an estimate of oil production without full VOC emissions controls. The estimate is based on regulations, not compliance.





Correlations among Colorado July Power Plant (EGU) NOx and weather-corrected O3 are generally weak. There are, however, strong statistically significant relationships between RFLAT and Cherokee Power Plant NOx and Centennial WY, Gothic & RMNP and Front Range EGU NOx. (Power Plant emissions not well-correlated with heights, r-squared < 0.05.)



These are contours of the R-squared values in a regression of weather-corrected station O3 and Cherokee EGU NOx emissions (2000-2009). The close-in, downwind pattern of high r-squared values is consistent with typical daytime transport from Cherokee toward the foothills.

Author's Conclusions (not official positions of the State of Colorado)

- The relationship between mean 500-mb heights and mean daily max O3 in July along Colorado's Front Range and at most sites examined in the Four Corners states is robust. R-squared values: 0.4 to 0.9. 500-mb heights were more predictive than dozens of other variables; 700-mb temperatures were second.

- The response along the Front Range is 2 to 3.5 ppb per decameter, and it is 1.5 to 2.5 ppb per decameter in neighboring high-altitude states. There was a 3 to 5 ppb increase in O3 along Front Range per degree C at 700 mb for 1995-2009.

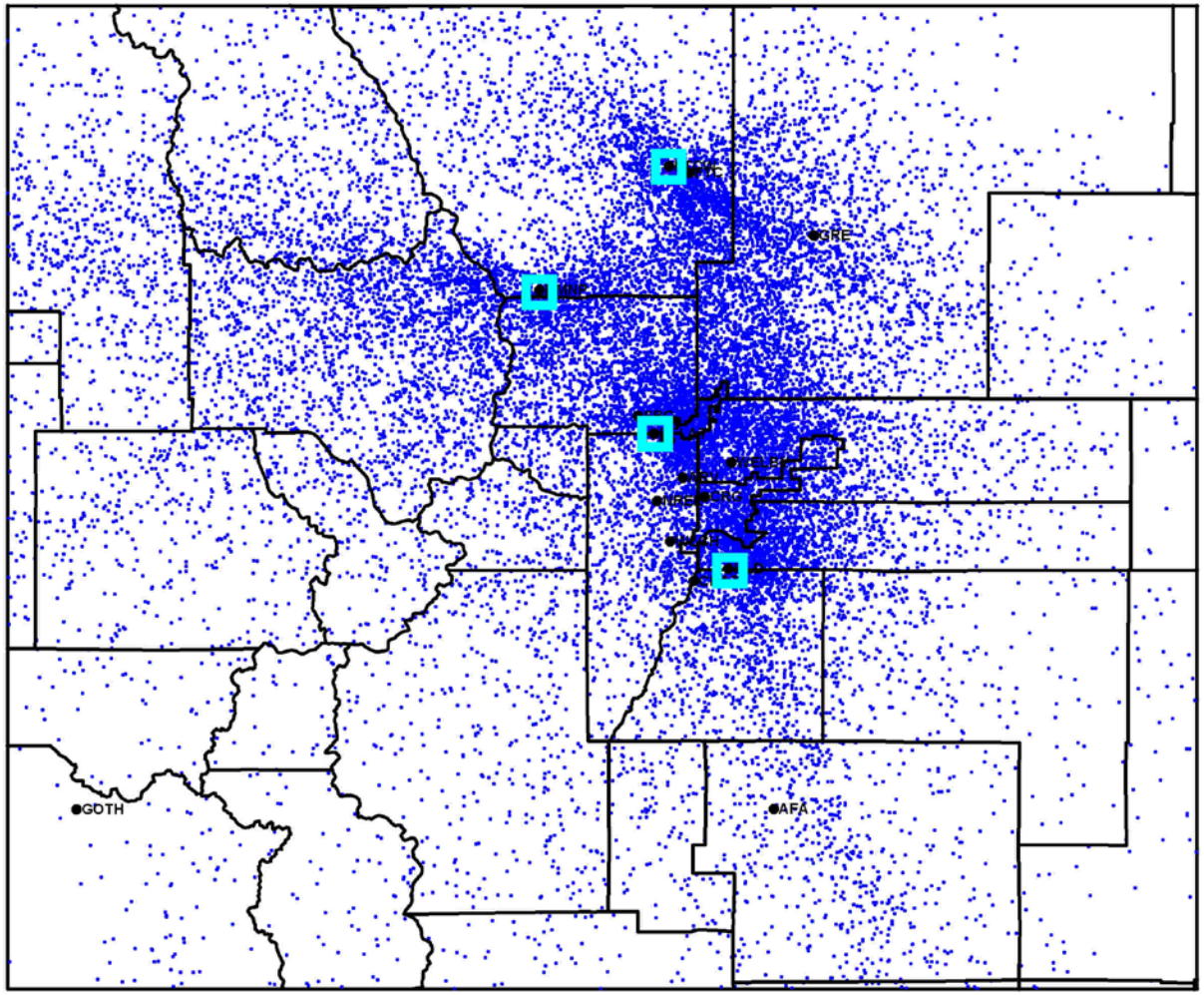
- A 4 to 6 ppb drop in weather-corrected ozone per 500 tons decrease of July power plant emissions has been observed at several, but not all, Front Range sites. The Front Range is not uniformly VOC-limited as has been asserted. A uniform drop of about 6 to 7 ppb in northern Colorado in 2009 points to the Recession.

Hypotheses

- Temperature, recirculations, stagnation, and other weather factors enhance ozone as heights increase. This may be due in part to local/regional accumulations within the middle troposphere and residual layer. Local accumulations are associated with terrain-driven circulations, and regional are associated with broader circulations within the high-pressure system.

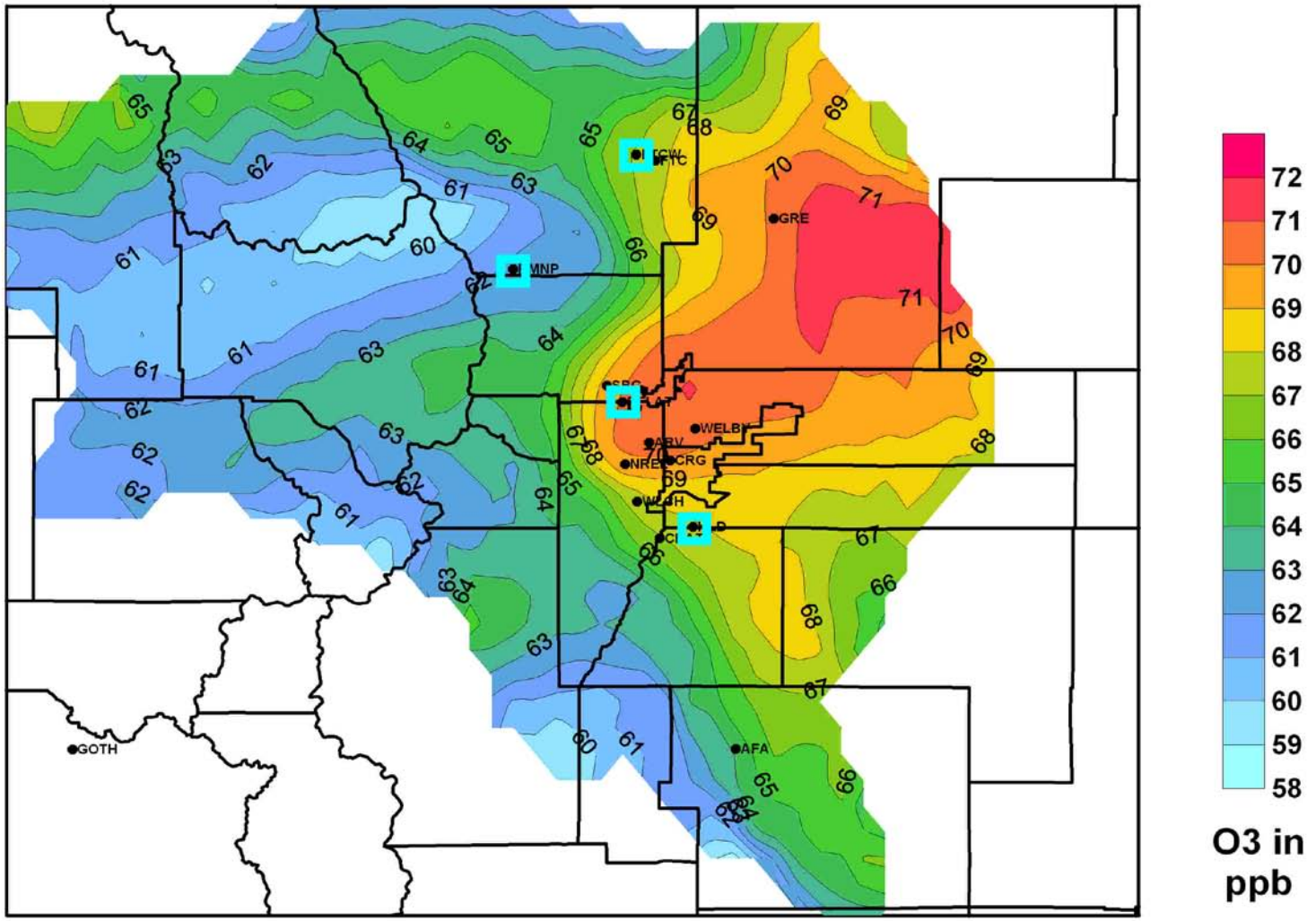
- A preliminary look at Boulder ozonesondes suggests that the upper troposphere may not play a major role - but what exactly are the roles of upper tropospheric enhancement, lightning NOX, long-range transport, or other factors not considered here?

Extra Slides

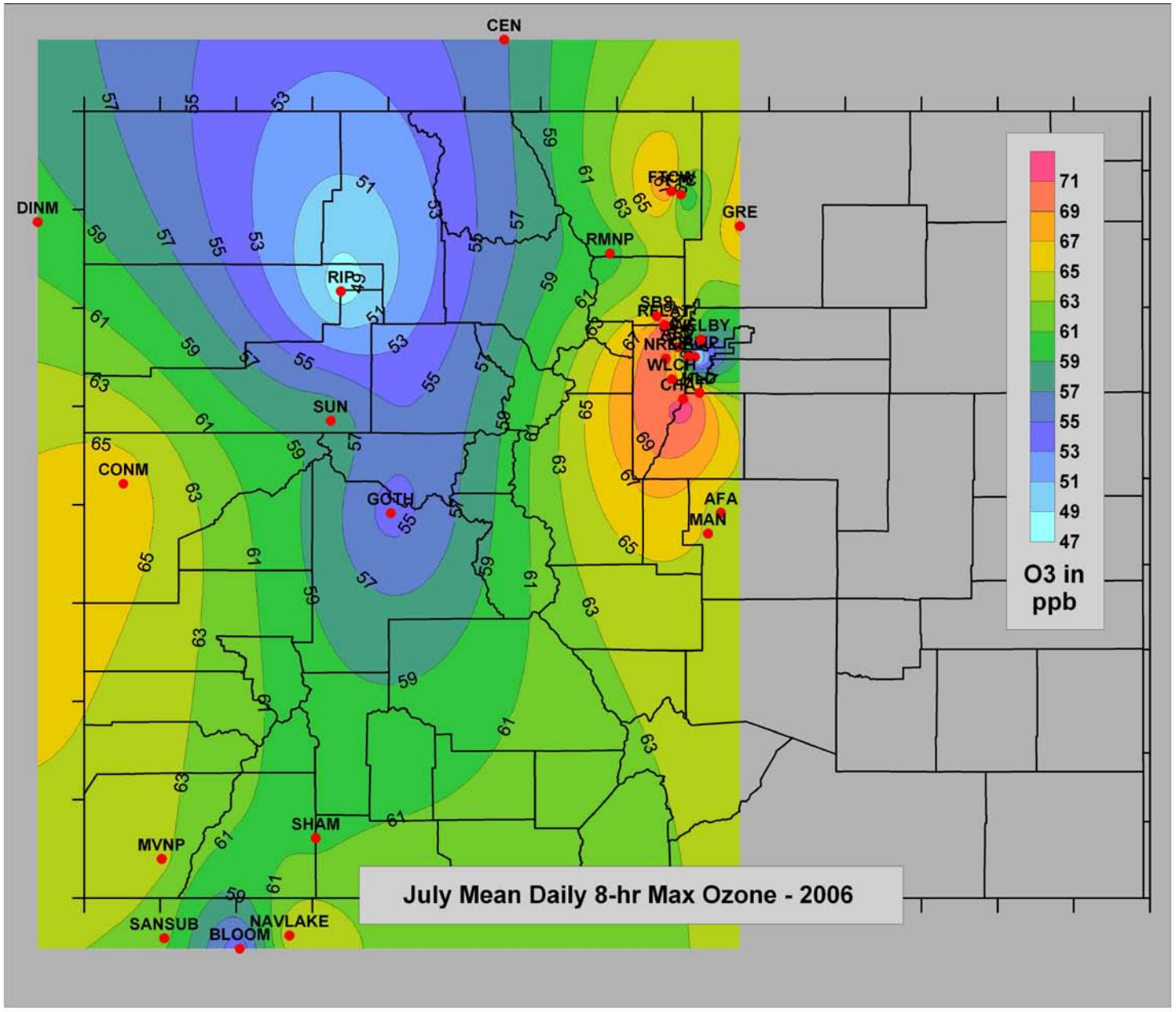


SAME-DAY AIR TRANSPORT ROUTES

NOAA HYPLIT back trajectory model points for FTCW, RMNP, RFLAT and HLD using EDAS40 40 kilometer meteorological data for May 17 through August 15, 2006. Back trajectories up to 12 hours in length for each of the 8 hours associated with daily 8-hour max O3 with an average start time of 6:30 AM MDT. Roughly 25,000 points filtered and analyzed for source area impacts.



A map of the average daily max 8-hour O3 associated with air parcels arriving from source regions in and near the Front Range (based on HYSPLIT back trajectories for FTCW, RMNP, RFLAT, and HLD monitoring sites, Summer 2006).***This shows what concentrations are caused at these monitors by air originating in a given area***. Urban sources and oil and gas activities are in the key source region.


CEN
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GRE
RMNP
RIP
SUN
CONM
GOTH
AFA
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MVNP
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BLOOM
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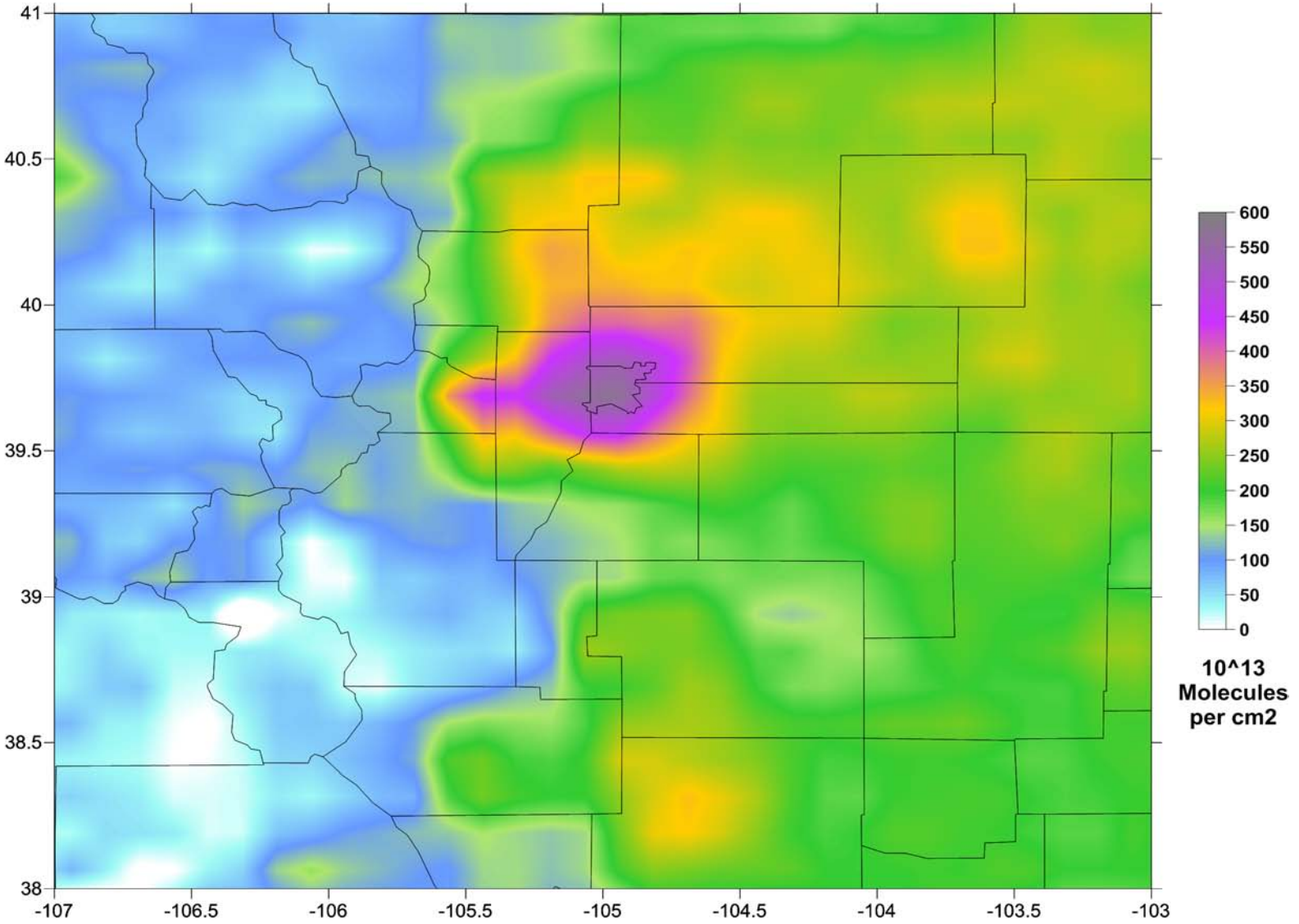
O3 in ppb
July Mean Daily 8-hr Max Ozone - 2006



Mean July 2006 Tropospheric OMI NO2.

Boersma, K.F., H.J. Eskes, J.P. Veefkind, E.J. Brinksma, R.J. van der A, M. Sneep, G.H.J. van den Oord, P.F. Levelt, P. Stammes, J.F. Gleason and E.J. Bucsela, Near-real time retrieval of tropospheric NO2 from OMI, *Atm. Chem. Phys.*, 2013-2128, sref:1680-7324/acp/2007-7-2103, 2007