Maximum Surface Ozone, Satellite NO2 and Meteorological Variables in Colorado; CDPHE Forecasting Support for FRAPPE & DISCOVER-AQ

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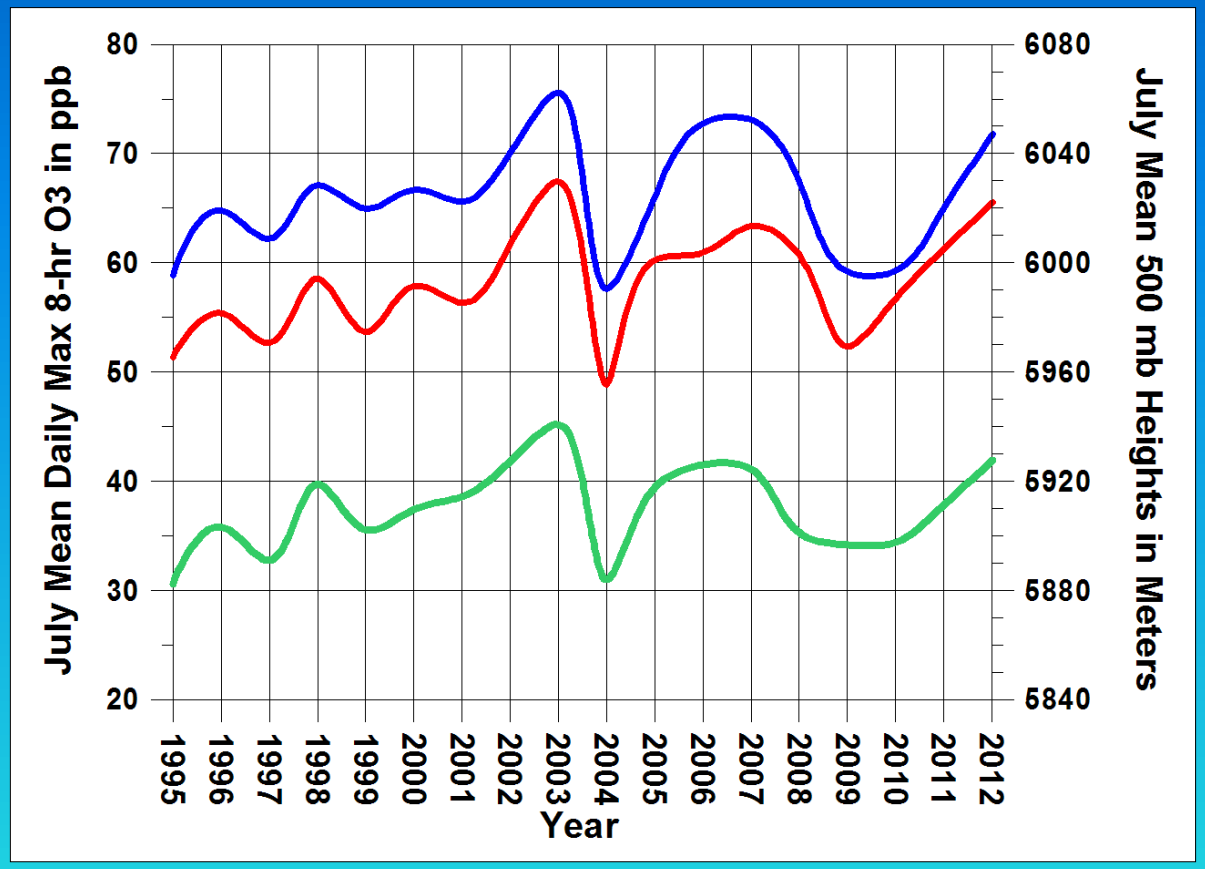
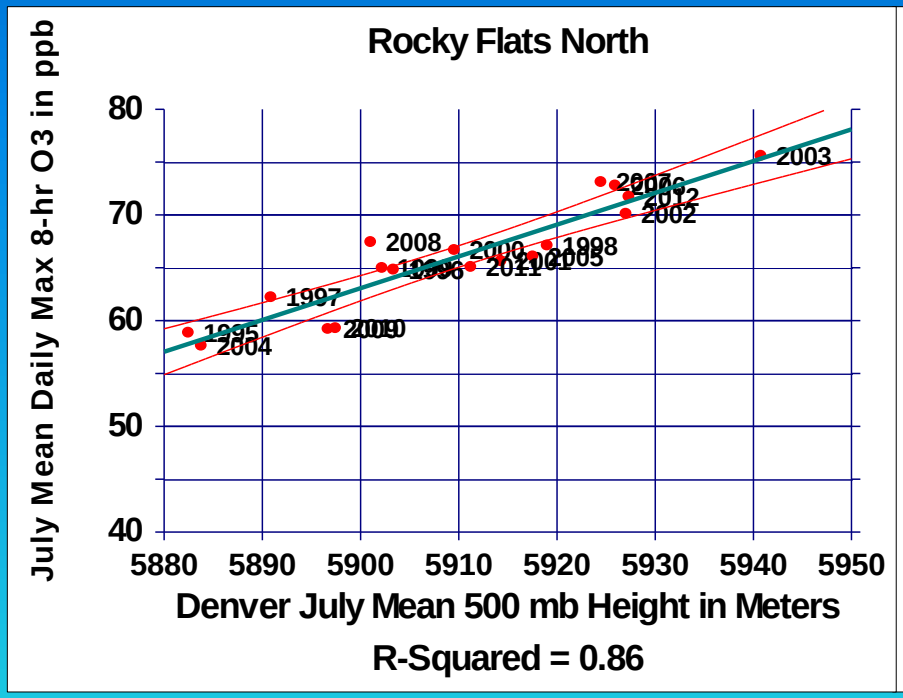
- There is a very strong relationship between July mean 500 mb heights and July DMAX 8-hr O3 in Colorado and other western states.
- Under the influence of an upper high, skies are often clear, temperatures are elevated, and westerlies are reduced in strength.
- These conditions promote the formation of mountain-plains solenoid circulations and westward propagating density currents along the Colorado Front Range and in the mountainous terrain of central Colorado.
- Mid-day PBL often extends to 6 to 8 km levels over Front Range and mountains to the West.
- These circulations appear to enhance O3 and NO2 and lead to many of the highest concentration events.

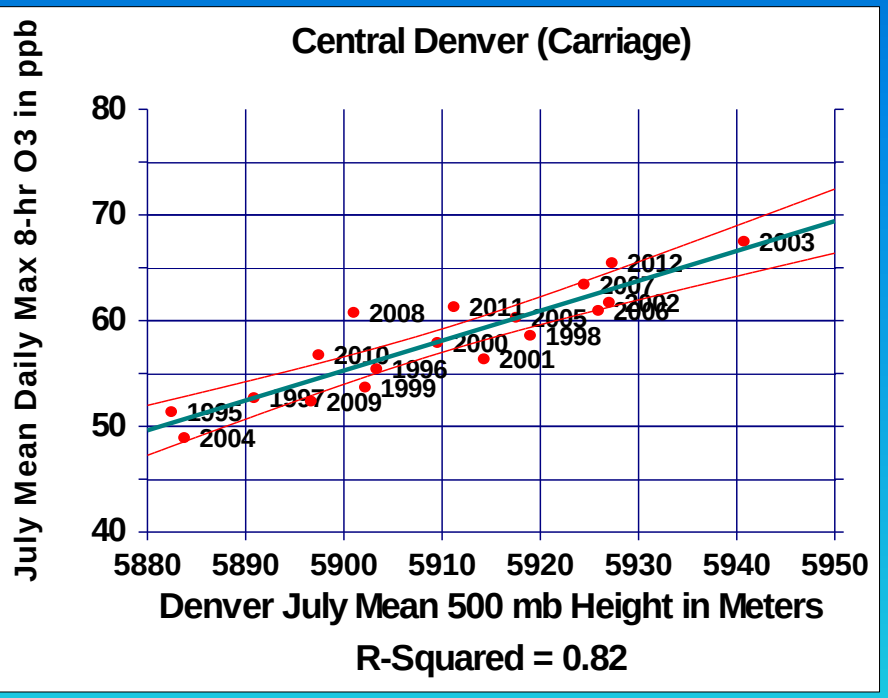
Mean July Daily Max O3 Tracks with Mean July 500 mb Heights



Large decline in surface O3 in 2004 after worst O3 in decades in 2003. Exploration of ~ 100 variables (time scales 1 day to 1 month) showed that mean July 500 mb heights had the greatest predictive power, followed by mean July 700 mb temperatures and mean July surface temperatures.

Very High Correlations Between July Means for Daily Max O3 and 500 mb Heights

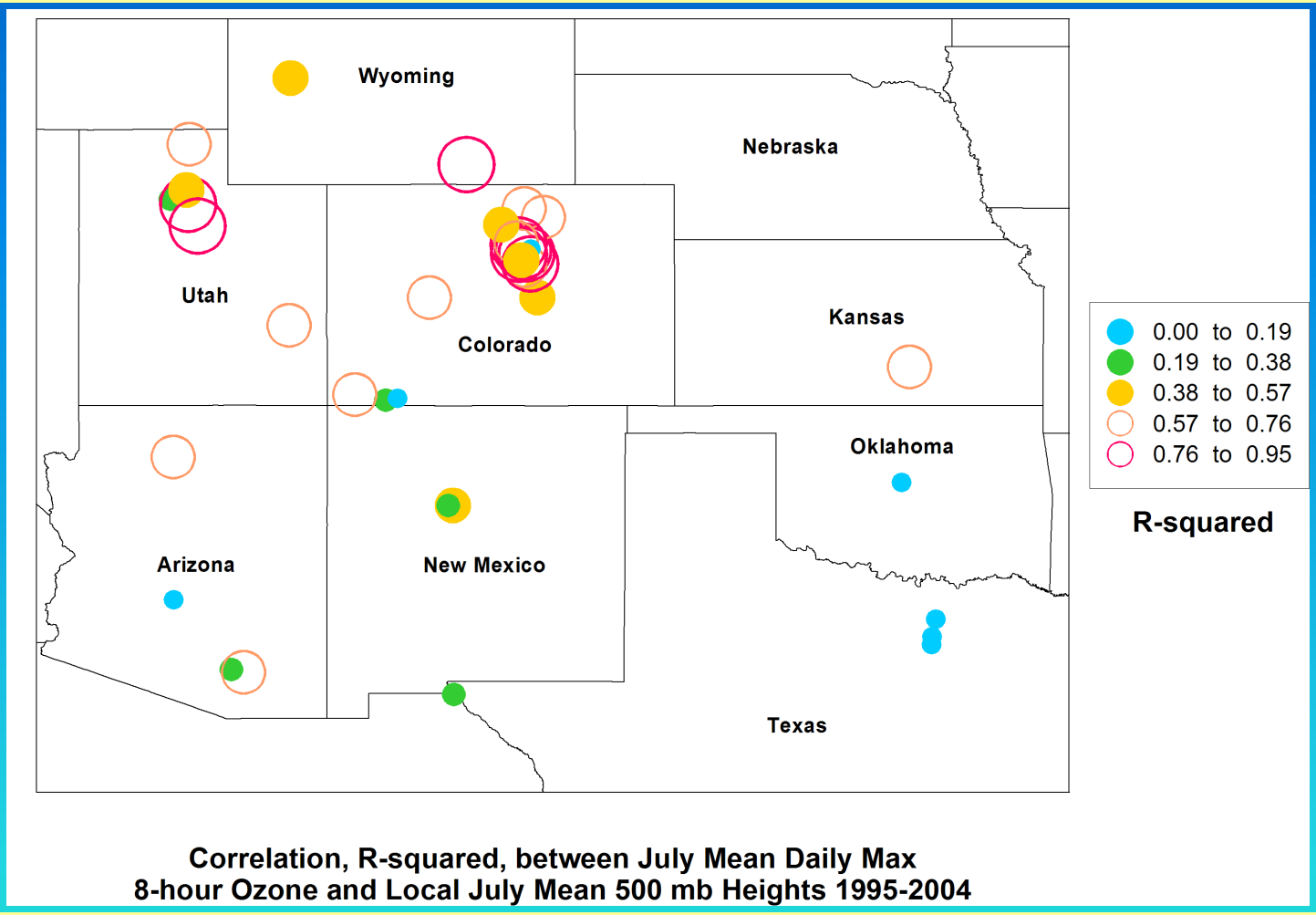




Linear regressions: Rocky Flats and Carriage July mean daily max 8-hour O3 and July mean 500-mb heights. **Rocky Flats is a high-concentration site; Carriage is a low-concentration site west of downtown Denver**.

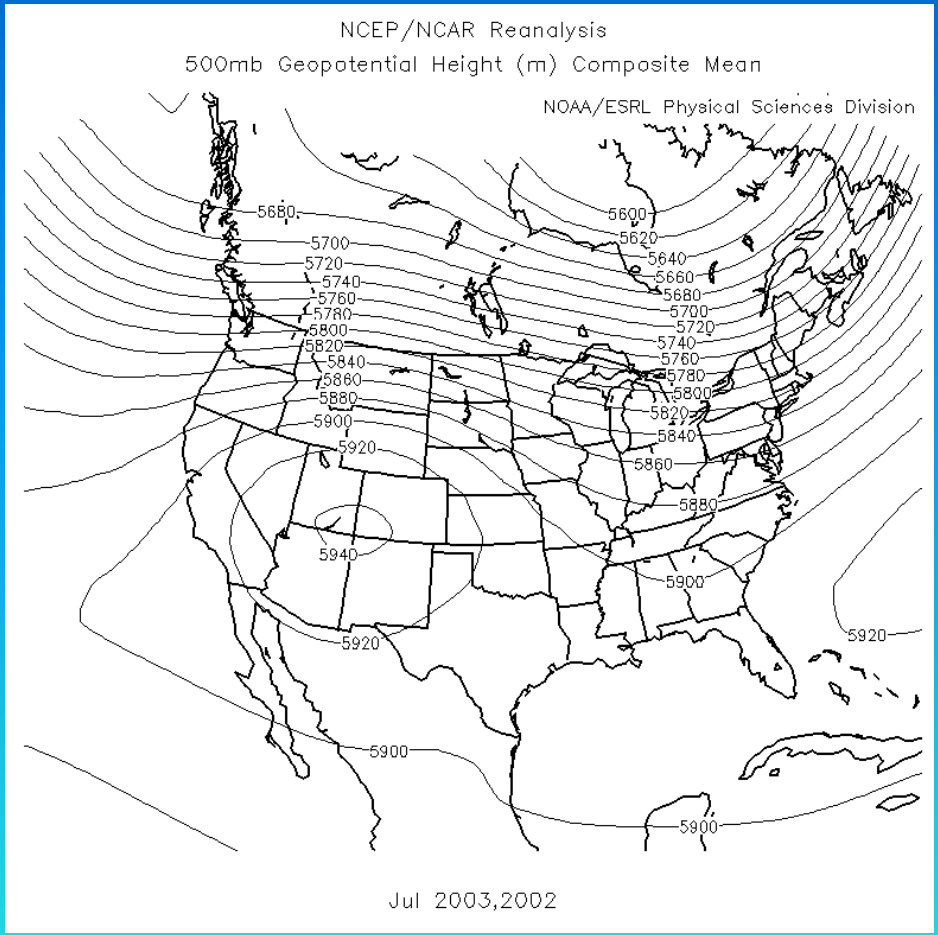
500-mb heights from the NCAR/NCEP Reanalysis data set (Kalnay et al. 1996)

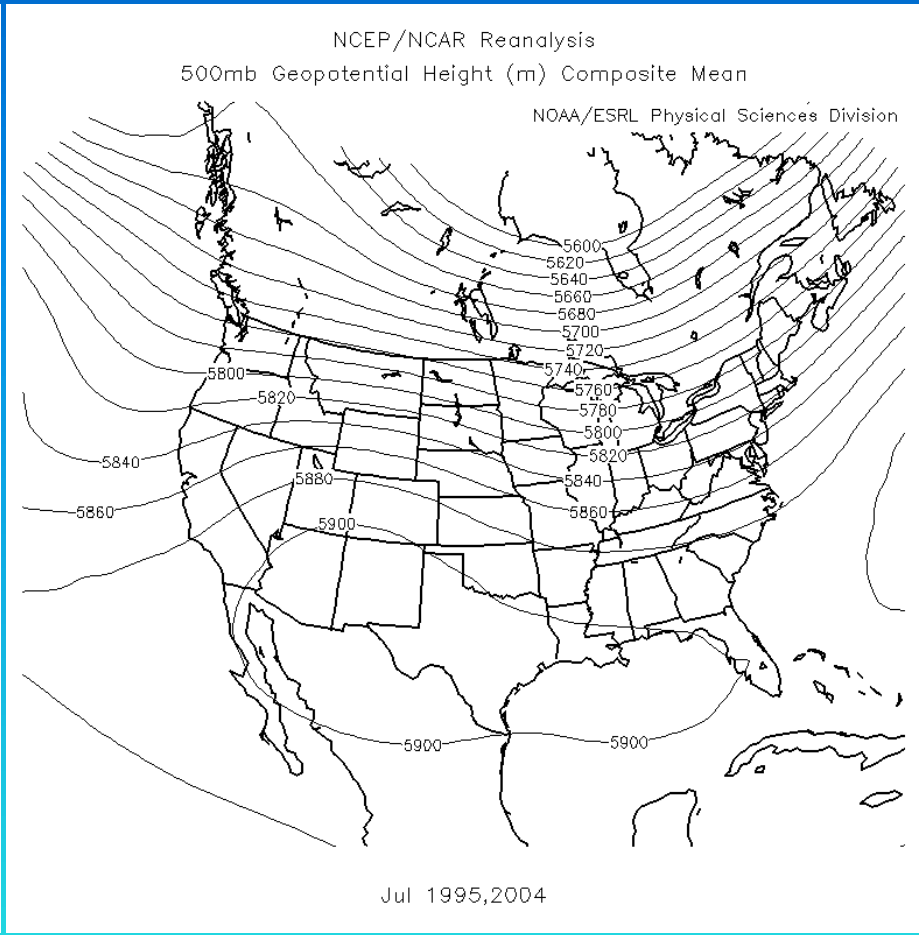
Analyses for Many Sites in CO, UT, AZ, WY, & NM Show Similar Correlation.



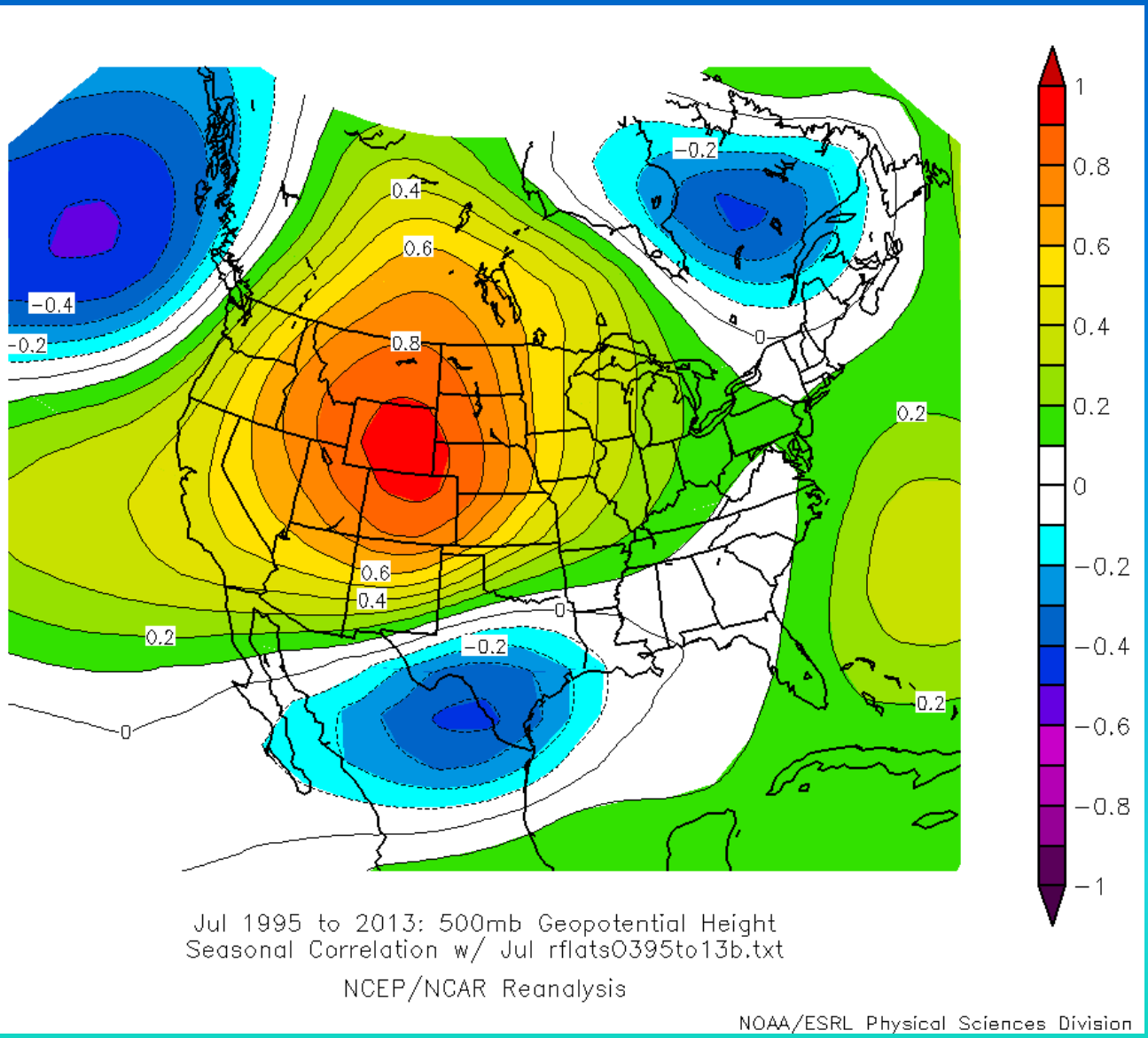
Correlation, R-squared, between July Mean Daily Max 8-hour Ozone and Local July Mean 500 mb Heights 1995-2004

Relationship between July mean daily max O3 and 500-mb heights is strongest in Utah and Front Range of Colorado, and in NM, AZ, and WY. 500 mb heights have much weaker influence in LA and Houston.



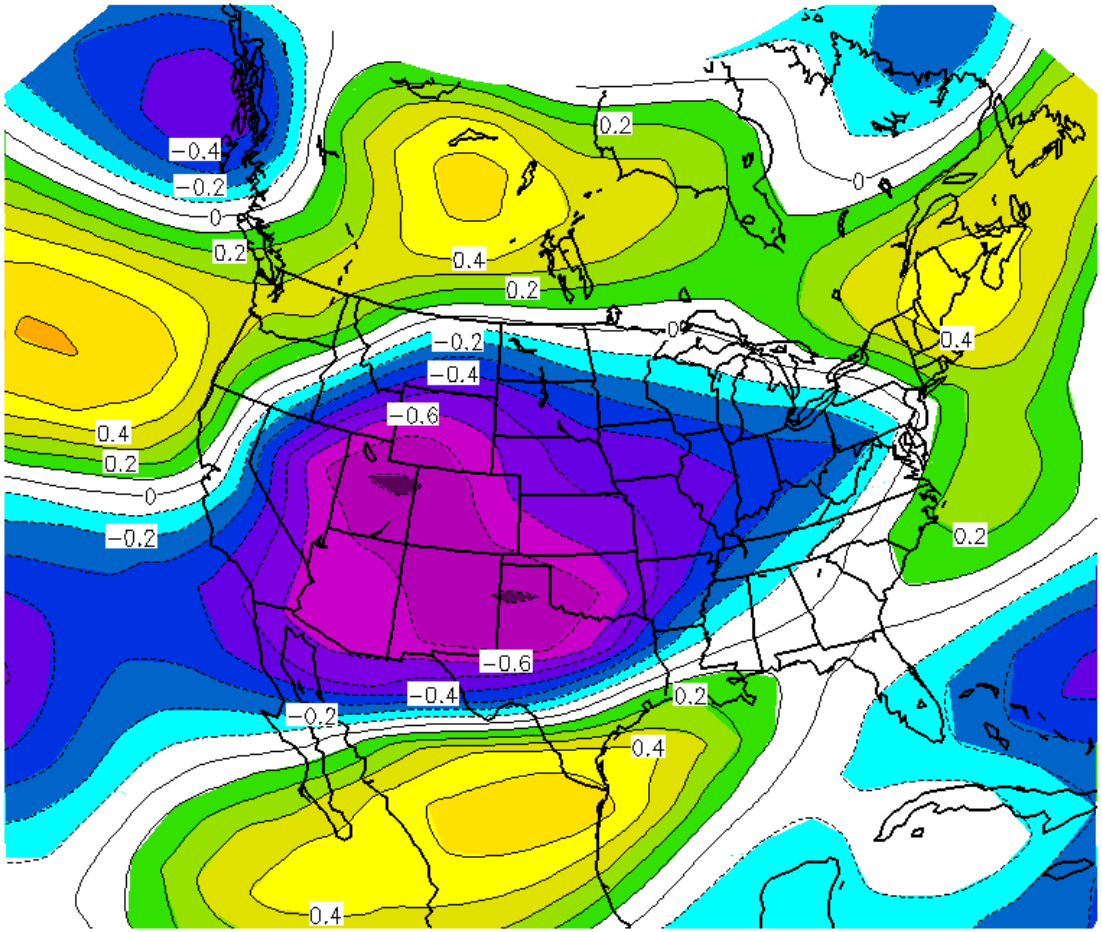


July mean NCEP/NCAR Reanalysis 500 mb heights in 2002 &2003, high O3 years **left**, and 1995 & 2004, low O3 years **right**, showing a northward intensification in 2002 & 2003 and the establishment of Four Corners high in 2002 & 2003.



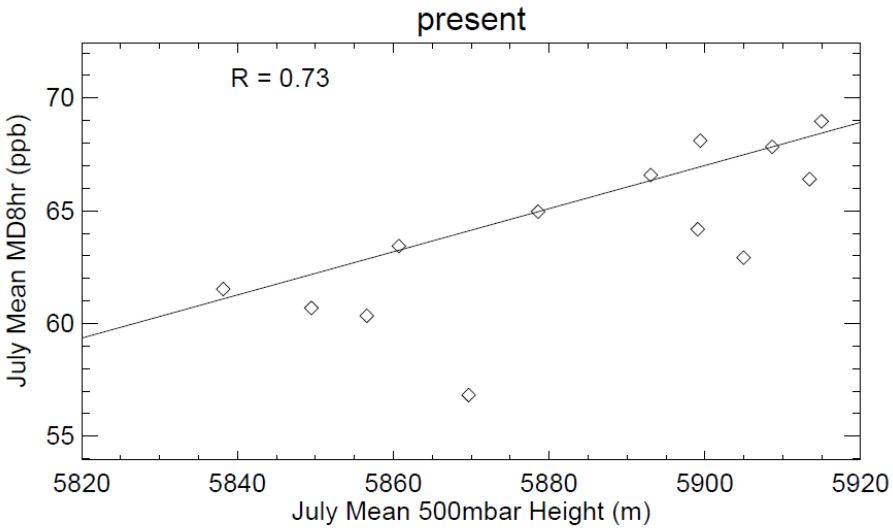
Based on 1995-2013 July mean NCEP/NCAR reanalysis data: Rocky Flats July mean DMAX 8-hr O3 is sensitive to an increase in heights in WY and northern CO.

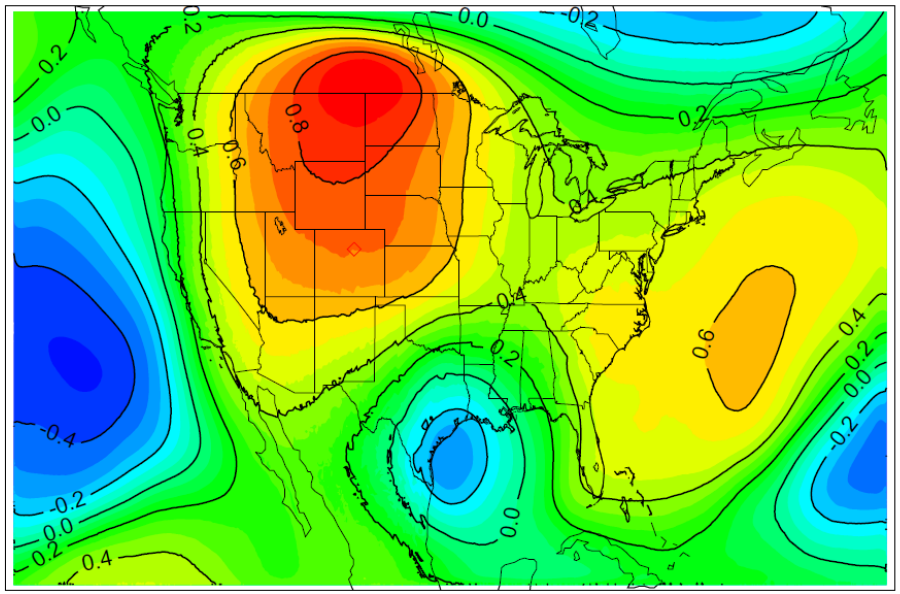
This is consistent with a northward expansion of ridge and a build-up of high pressure at 500 mb in the 4 Corners states.



Based on 1995-2013 July mean NCEP/NCAR reanalysis data: Rocky Flats July mean DMAX 8-hr O3 is anti-correlated with 700 mb zonal flow in 4 corners states.

This is consistent with a northward expansion of ridge and a build-up of high pressure at 500 mb in the 4 Corners states.





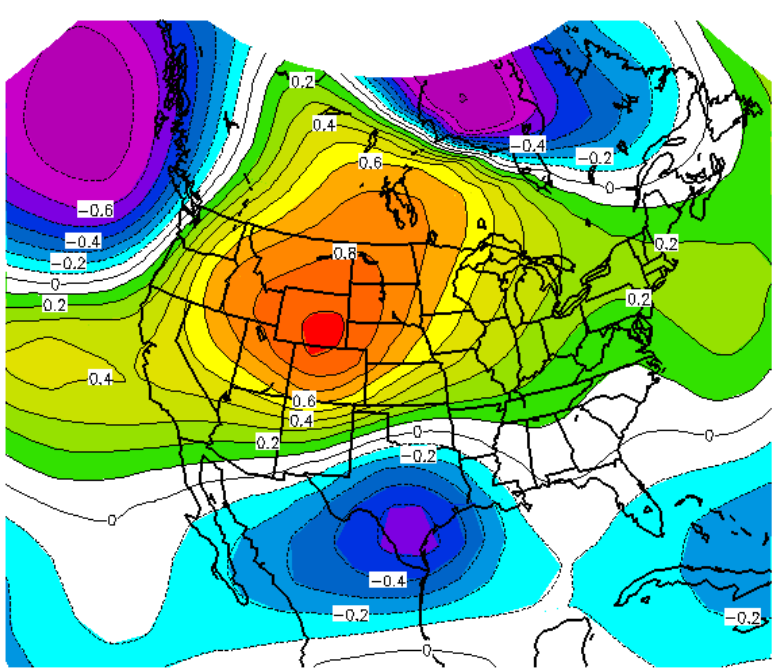
Lat: 39.8092 Lon: -105.109 Elev: 1720.78m

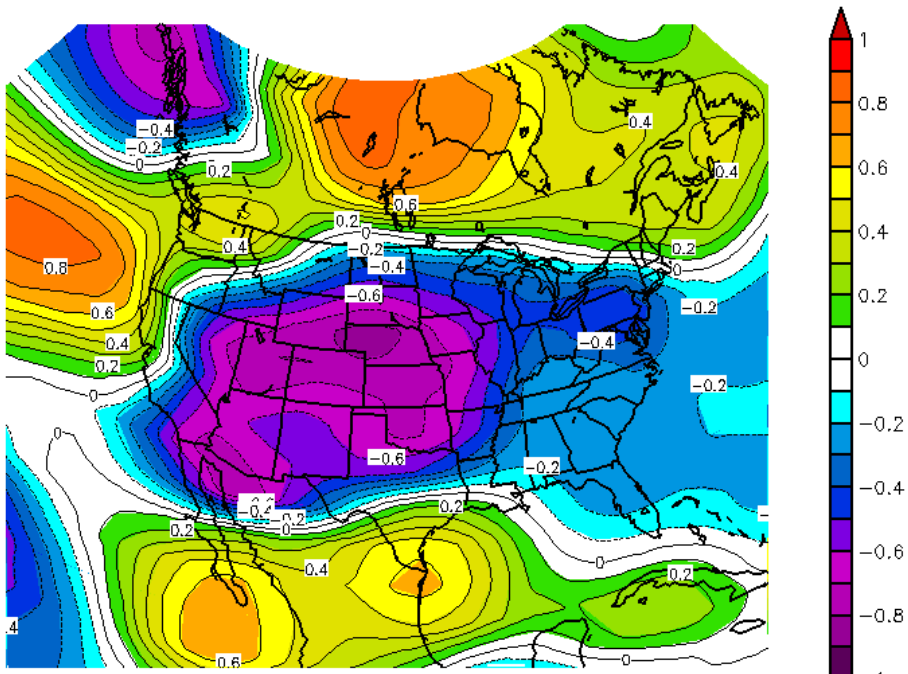
Preliminary Results:

Gabi Pfister (NCAR) has completed 12 km NRCM-Chem model runs based on the CCSM 3 climate model running for 13 years under present era emissions scenarios.

In the modeled atmosphere, July mean daily max 8-hour O3 and mean local 500 mb heights show an approximately linear relationship at RFLAT with an R value of 0.73. The pattern of correlation with North American 500 mb heights is very similar to the pattern for 1995-2013 data for RFLAT in slide 7.

Using the RCP8.5 future climate scenario with 50% reductions in NOx, background increases but local contributions decrease, and the correlation drops to 0.26 with much reduced slope.

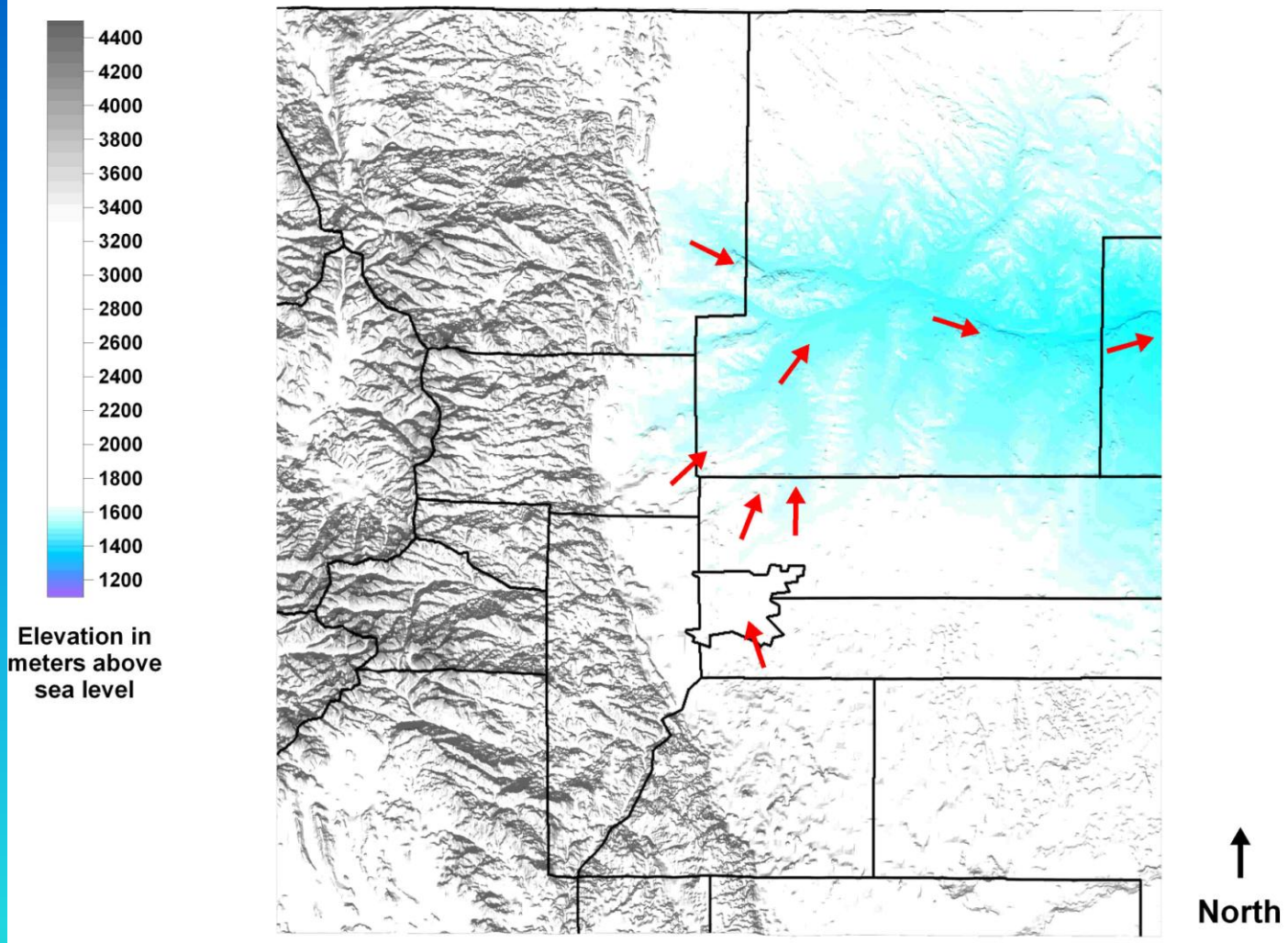




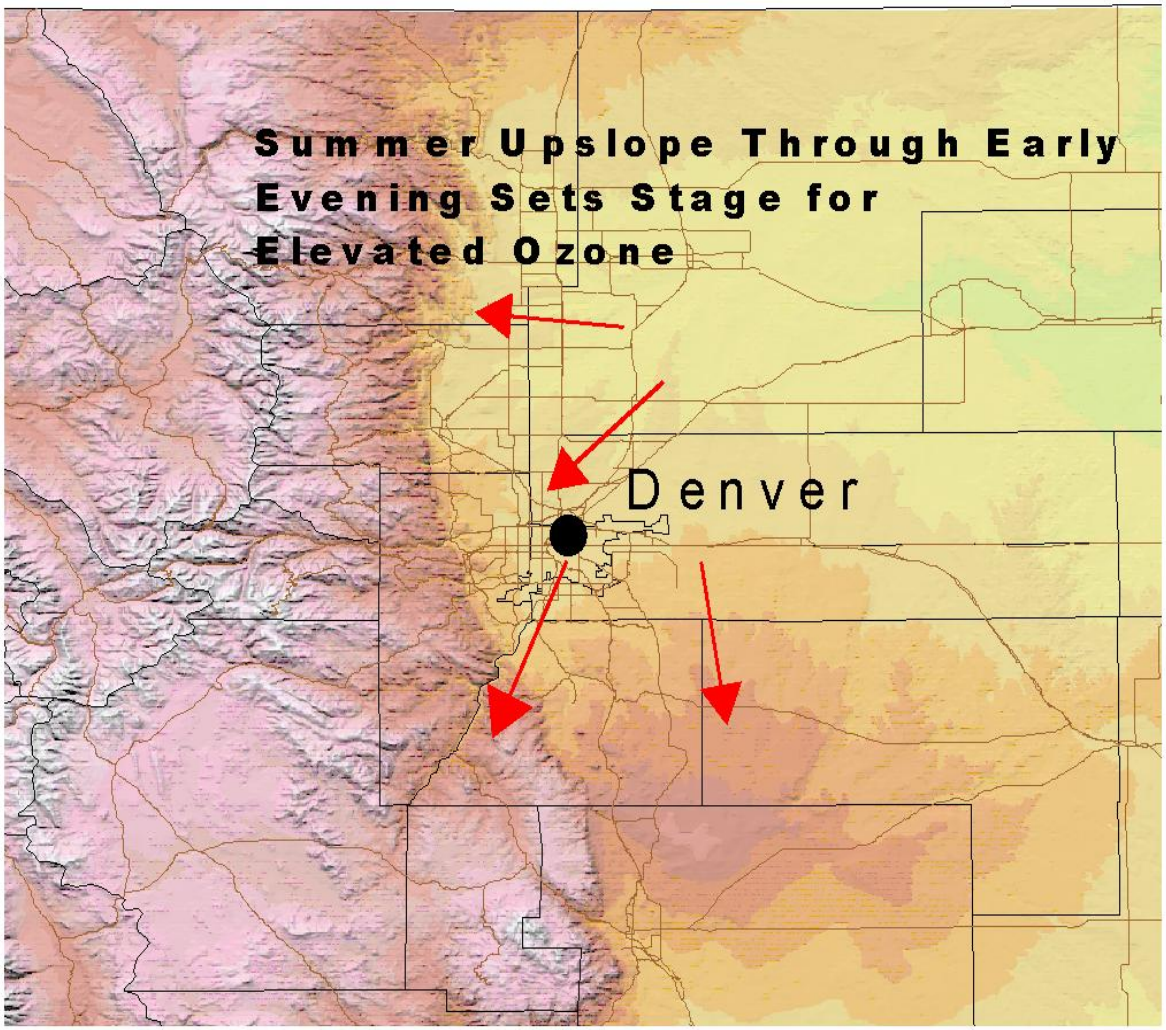
July mean northeast Front Range quadrant (see slide 23) OMI level 3 tropospheric NO2, like O3, is strongly sensitive to increases in 500 mb heights in Colorado and Wyoming and strongly anti-correlated with zonal flow at 700 mb over Colorado – 2005 through 2013 data.

Why is all of this important?

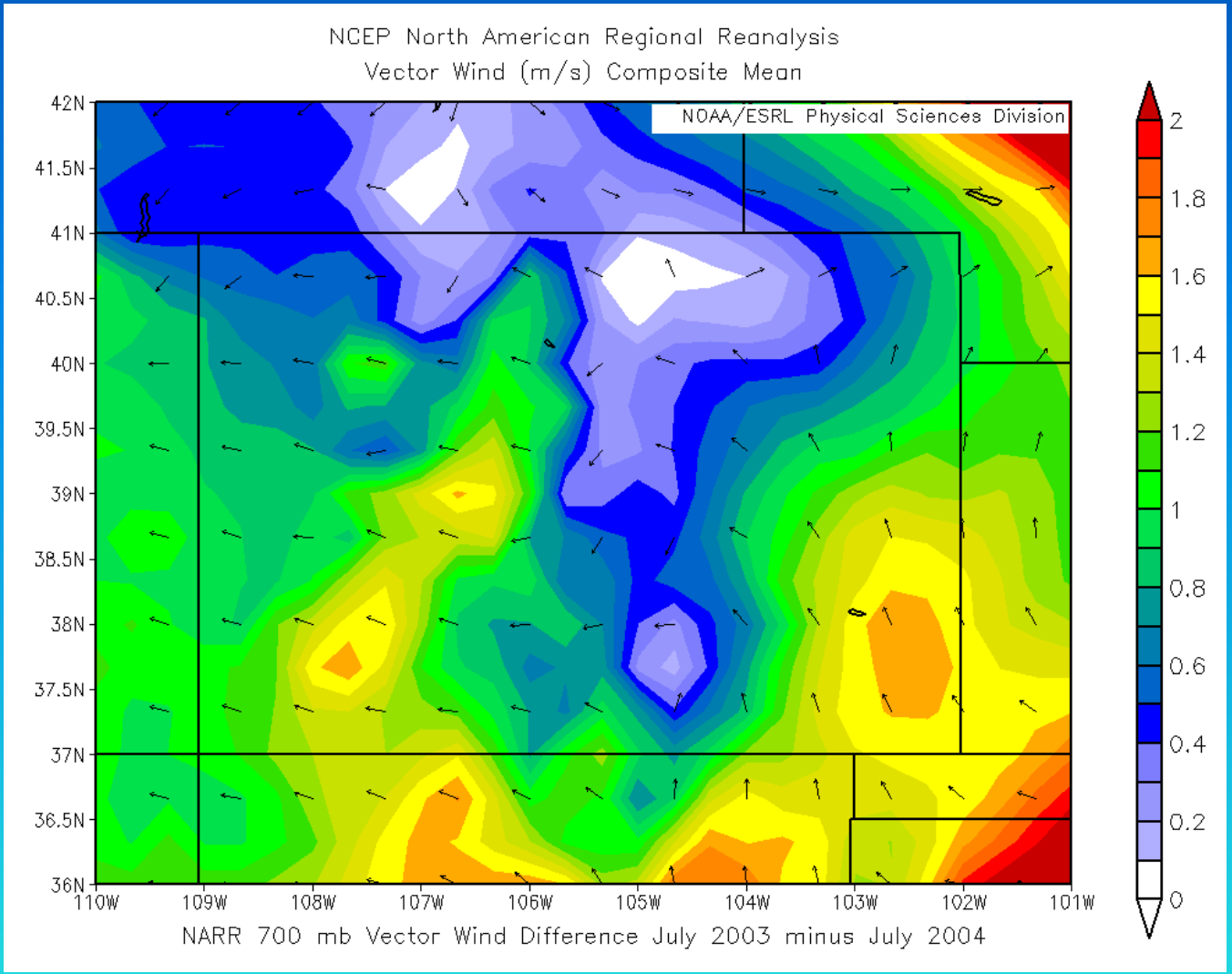
- The July climatology of mean O3 and NO2 point to the roles of terrain and geography in increasing local and sub-regional concentrations when a persistent upper level high is present.
- Under an upper-level ridge, synoptic scale circulations may recycle pollutants within the region.
- An upper-level ridge favors unimpeded thermally-driven upslope flow and mountain-plains solenoid circulations that recycle pollutants locally.
- Unimpeded mountain-plains solenoid circulations allow for evening and nighttime “westward propagating density currents” which can transport Front Range pollutants westward to points well past the Continental Divide.



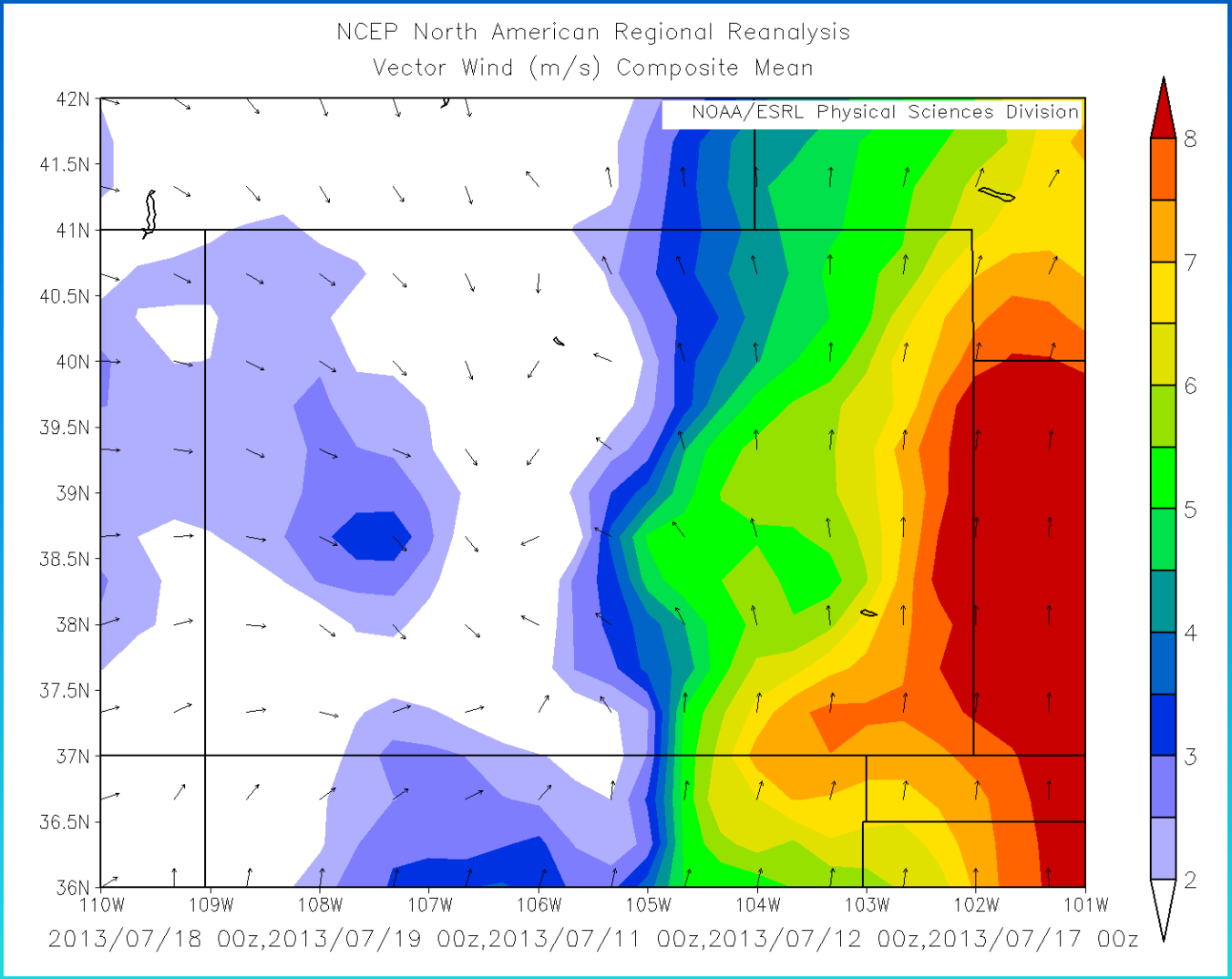
Cool air moves down-valley at night within an inversion. Emissions follow this flow and pool in lower terrain. Emissions trapped in the morning Platte Valley cool pool turn out to be a key source for ozone.



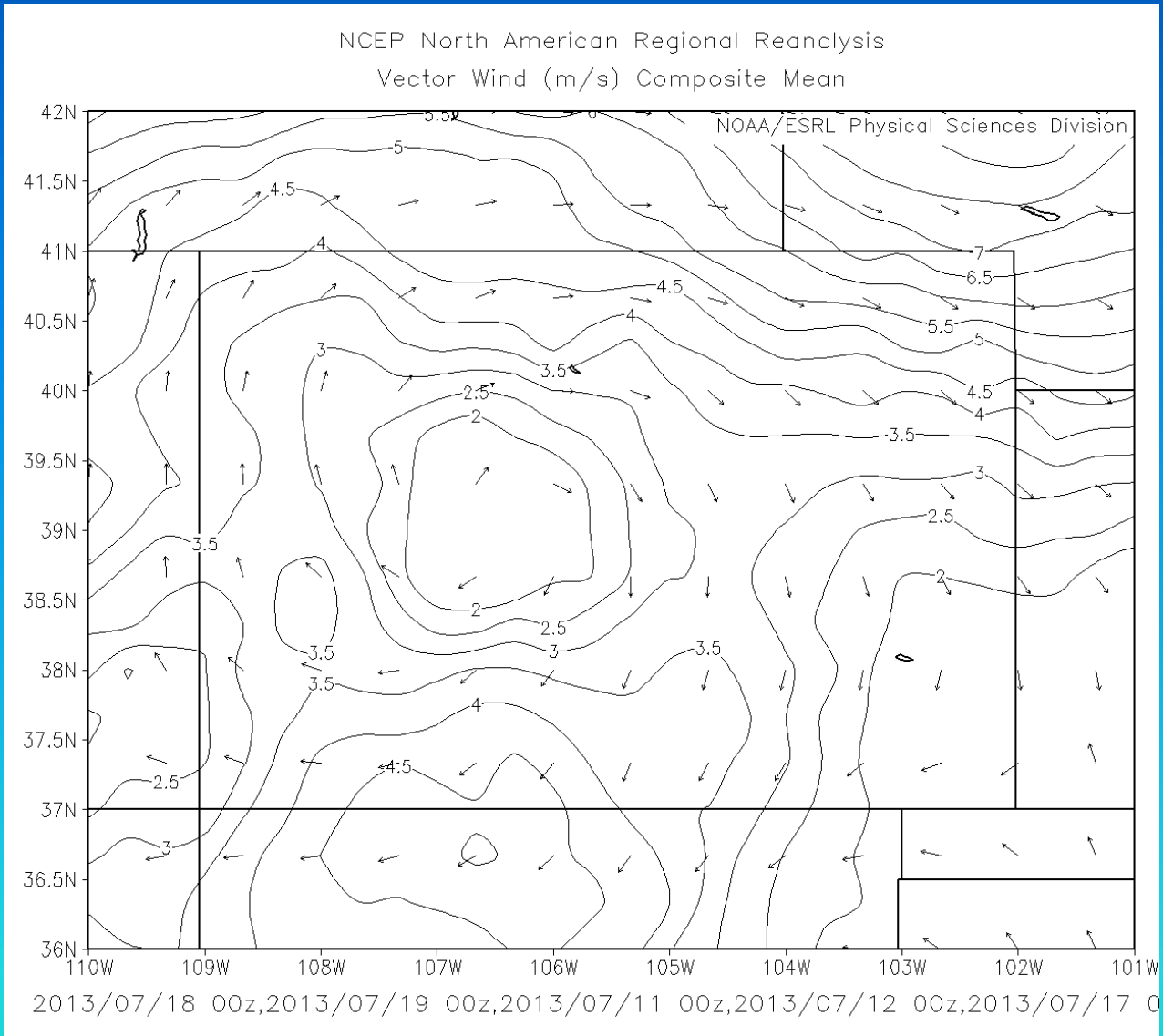
Daytime thermally-driven upslope pulls air on the plains westward into the mountains. In the upper part of the boundary layer, the flow is often westerly and back towards Denver. Deep mixing can bring the air back to the surface on the plains. This circuit is the mountain-plains solenoid.



The 2003 minus 2004 vector difference in 700 mb winds shows a peak reduction in westerlies or increase in easterlies of ~2 m/s over mountains. The pattern suggests that the solenoid circulation is present in both years, with further westward extent during high-height, high-ozone 2003.



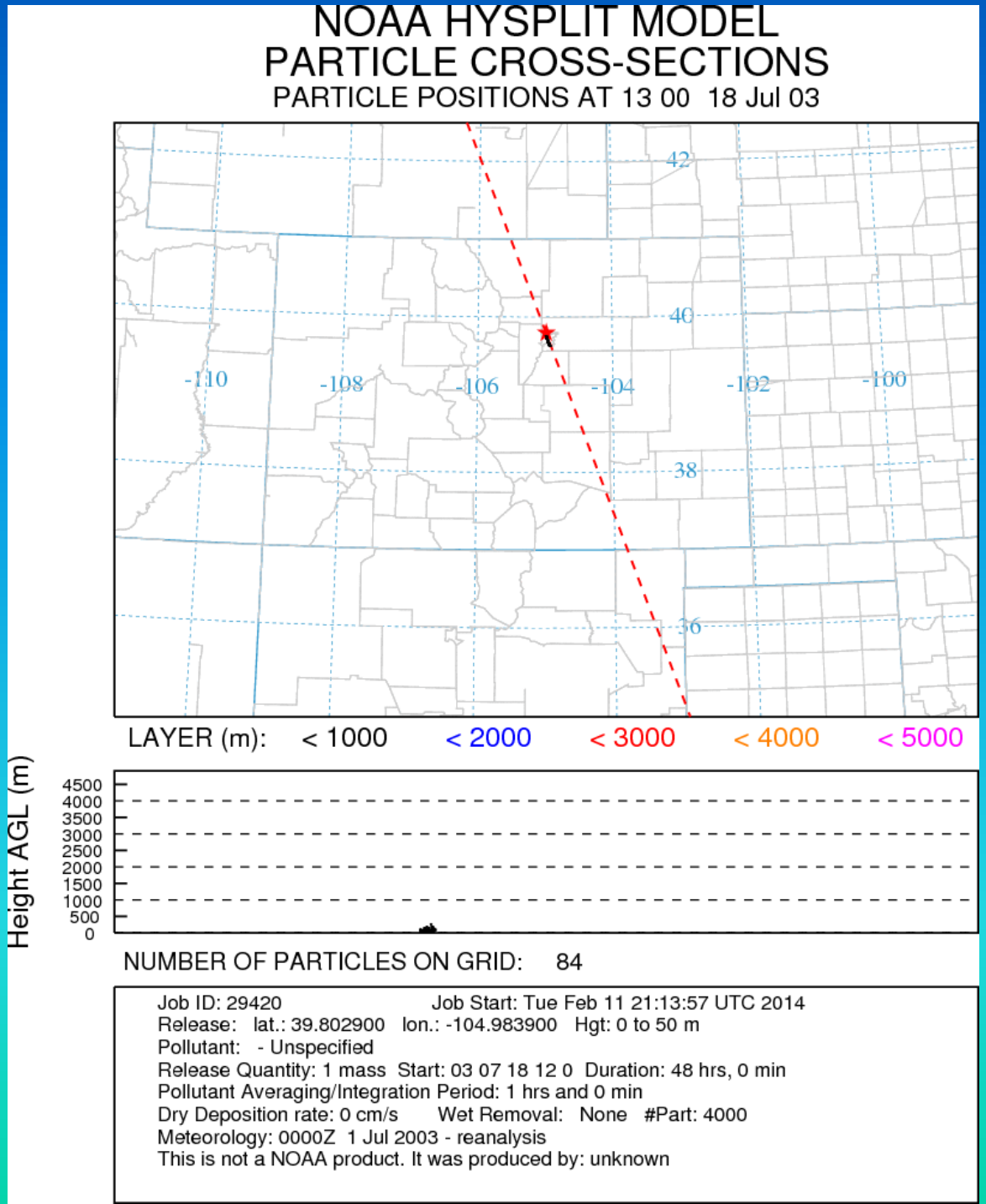
A composite of reanalysis data for 5 PM MST on 5 high O3 days in 2013 shows easterly flow at 700 mb as far west as Leadville CO, data for later times show easterly flow as far west as Aspen and Gothic CO.



A composite of reanalysis data for 5 PM MST on 5 high O3 days in 2013 shows clockwise circulation at 500 mb over west-central Colorado. In general, the flow aloft in this case is often counter to the flow at 700 mb.

Running the NOAA HYSPLIT dispersion model in particle mode for a 3-day, high-O3 episode in 2003 illustrates how the interplay of synoptic-scale flows and terrain-driven flows can keep pollutants re-circulating within the Front Range region and the mountains to the west.

More time for Oil and Gas emissions to contribute to local Ozone?



This HYSPLIT dispersion model animation for the O3 episode of July 18 through 20, 2003, shows transport deep into the mountains, easterly flow at low levels, weak westerlies aloft, mixing to 3.5 km above ground and a mountain plains solenoid keeping particles “trapped” in looping flow along the Front Range.

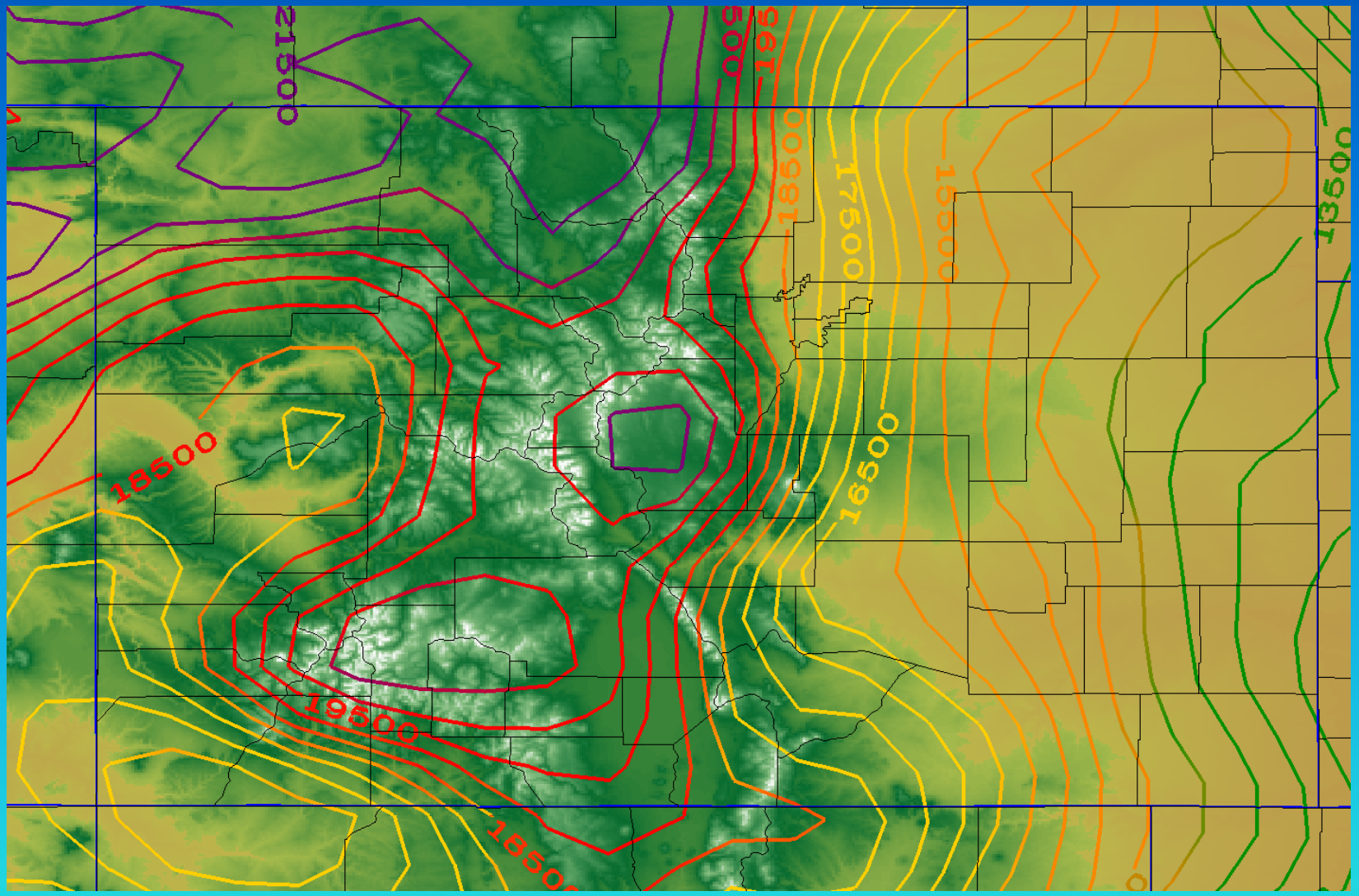
Upper level high pressure favors the development of this kind of recirculation. 5990 meter high centered over CO on July 18.

Does satellite NO2 tell us anything about the spatial extent of this pattern?

7/18: 95 ppb CHAT, 93 ppb HLD
7/19: 86 ppb CHAT, 82 ppb RFLAT
7/20: 74 ppb NREL & HLD

Afternoon mixing heights for the first day of this episode show deep mixing over the plains and much deeper mixing over the mountains. The thermal low over the mountains leads to upslope from the east and west and lower evening air densities over the mountains and high basins.

An evening “cold front” forms at mountain-top levels moving air into the mountains from both the east and west of the Rockies.

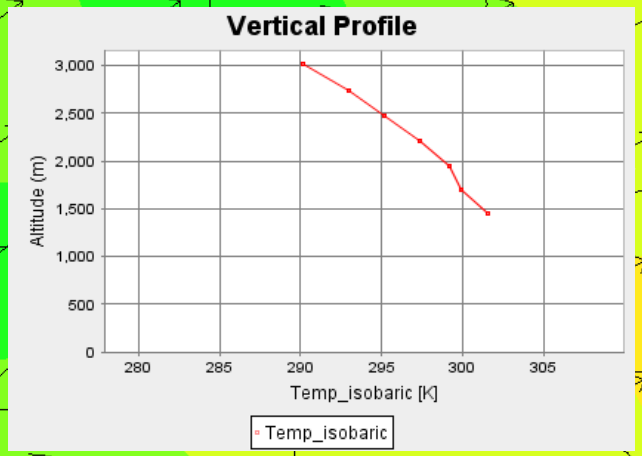


North American Regional Reanalysis (NARR) mixing heights (MSL) in feet at 21Z on July 18, 2003, a day in the previous HYSPLIT simulation – mixing heights >20,000 feet MSL over Divide and high basins, 18,000 feet MSL over Denver, 13,500 feet MSL on the eastern CO border.

Some fraction (30 to 40% ??) of high O3 episodes are associated with plains mixing heights that are well below mountain-top level.

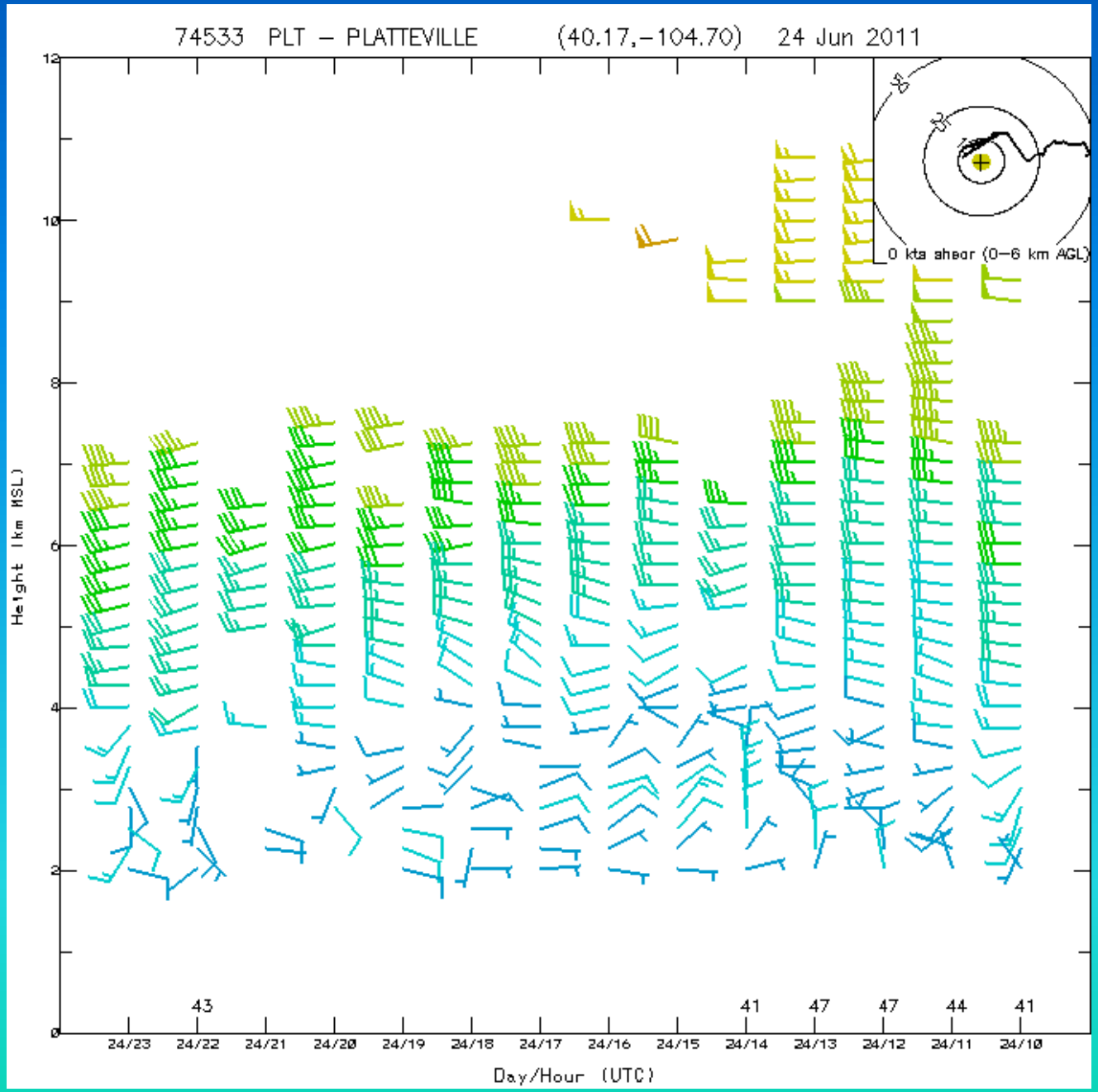
These are often associated with the “thin western edge” of a modified Canadian high over the plains states, a Denver Cyclone, or remnants of the Greeley cool pool caught up in thermally driven upslope.

A subset of high O3 days show limited vertical mixing, minimal solenoid, and a cap below mountain top level: 21Z June 24, 2011.



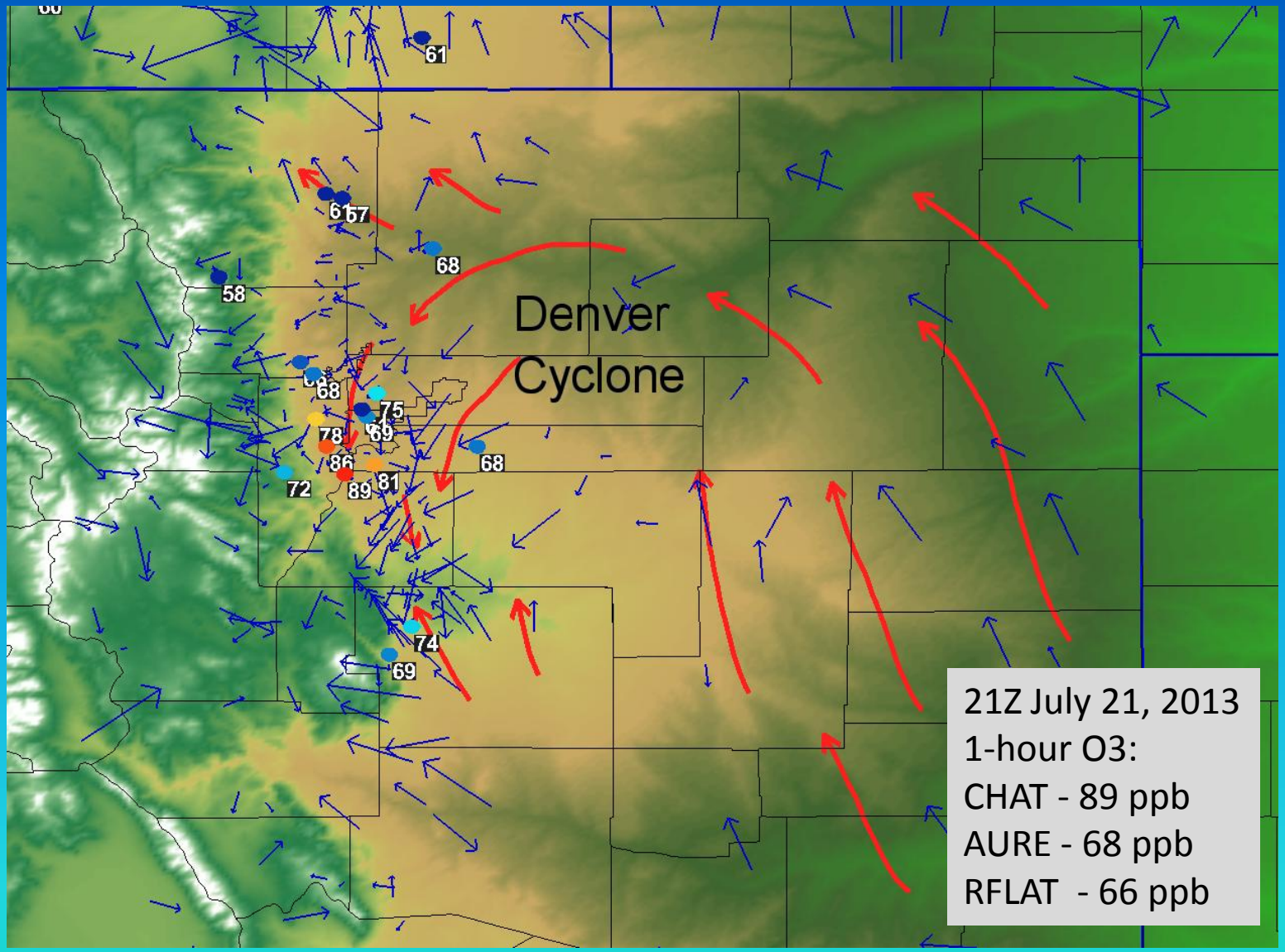
RFLAT DMAX 8-hr O3: 105 ppb
CHAT DMAX 8-hr O3: 100 ppb
AURE DMAX 8-hr O3: 78 ppb

North American Regional Reanalysis (NARR) surface potential temperatures (color shading) surface winds, and 1-hour O3 in ppb for 21Z June 24, 2011. NARR temperature profile for RFLAT shows cap ~ 500 meters AGL along stationary front. Local “Denver Cyclone” northerlies influenced CHAT.

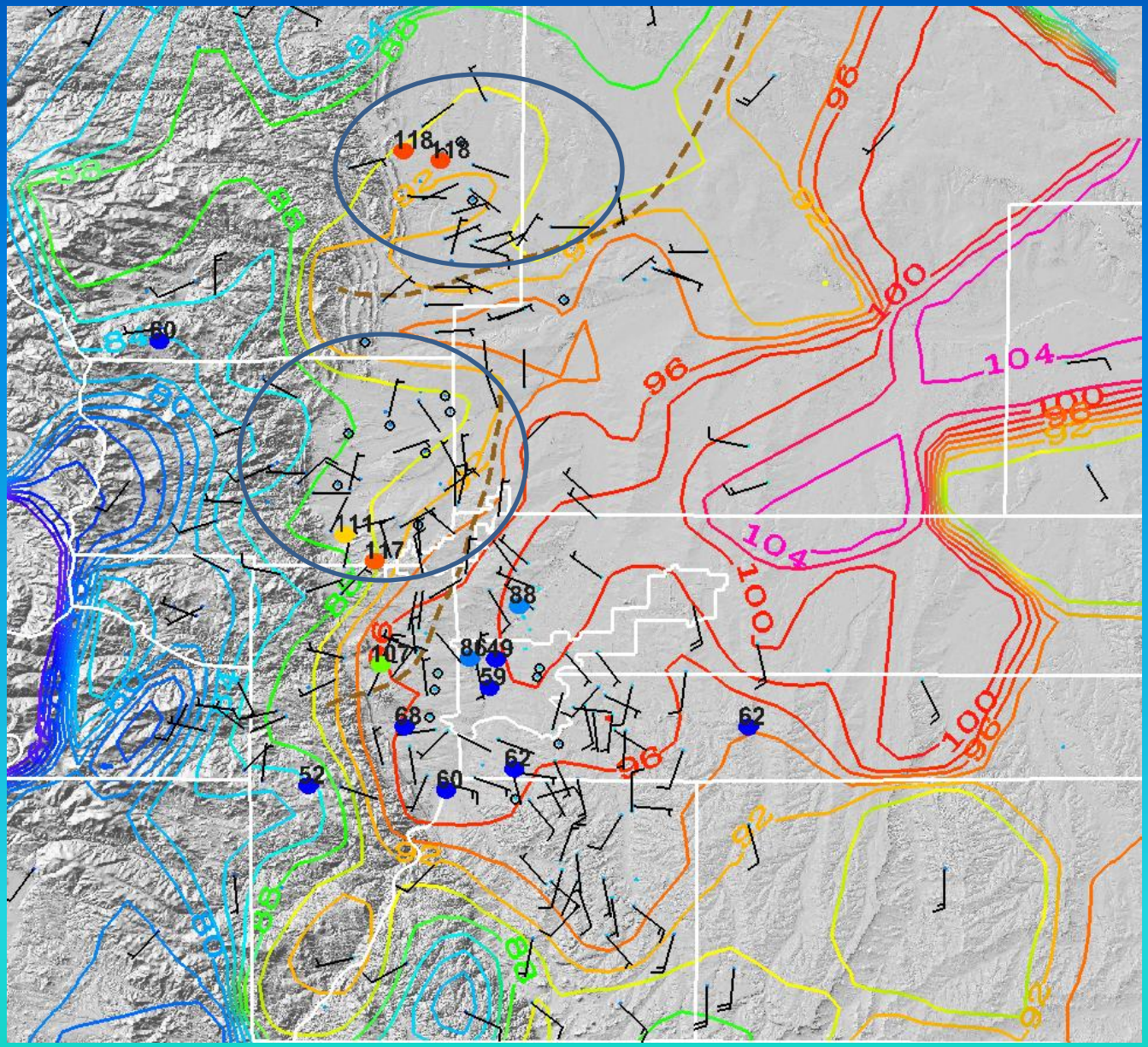


June 24, 2011 Continued:

Platteville profiler data for June 24, 2011, show easterlies below 3 km and brisk westerlies above .



A cap or stable layer below 700 mb or about 3 km MSL and southeasterly winds across the palmer Divide will lead to a Denver Cyclone circulation in the boundary layer with peak O3 south and southwest of Denver



June 22, 2012, MesoWest surface temperatures in degrees F, winds, and 1-hour O3. Cool pockets RFLAT to FTC.

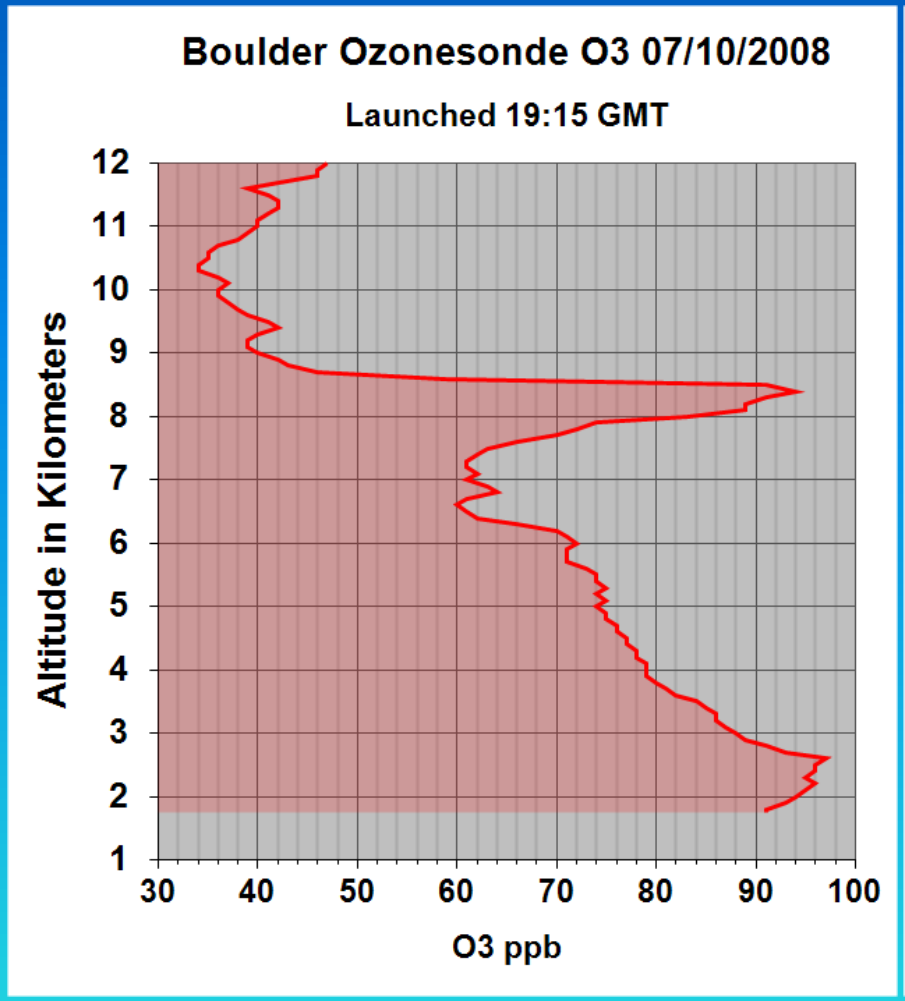
The center of the Platte Valley AM Cool Pool near Greeley is often the last place where the surface inversion breaks.

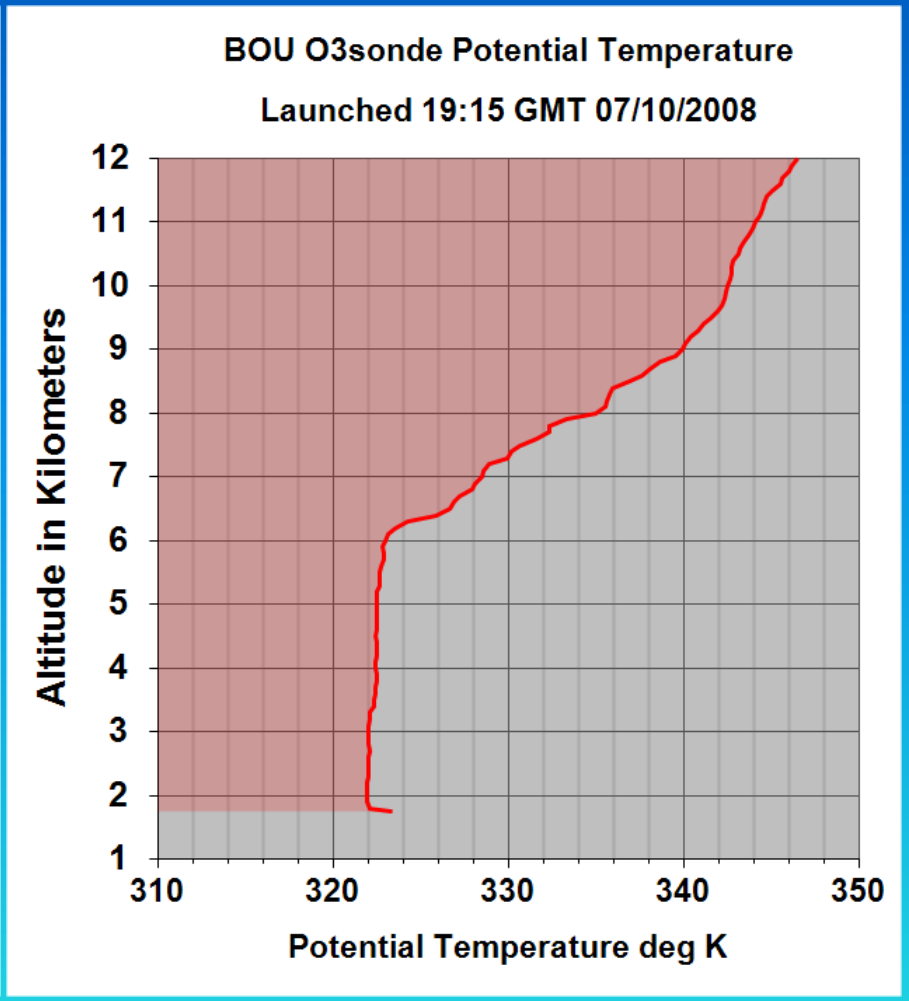
Remnants of this cool pool often persist and are carried in upslope flow up against the foothills. High O3 often forms in these pockets of shallow mixing.

1-hour O3 at 20Z on 6/22/12 in pockets:
FTC: 118 ppb
FTCW: 118 ppb
RFLAT: 117 ppb

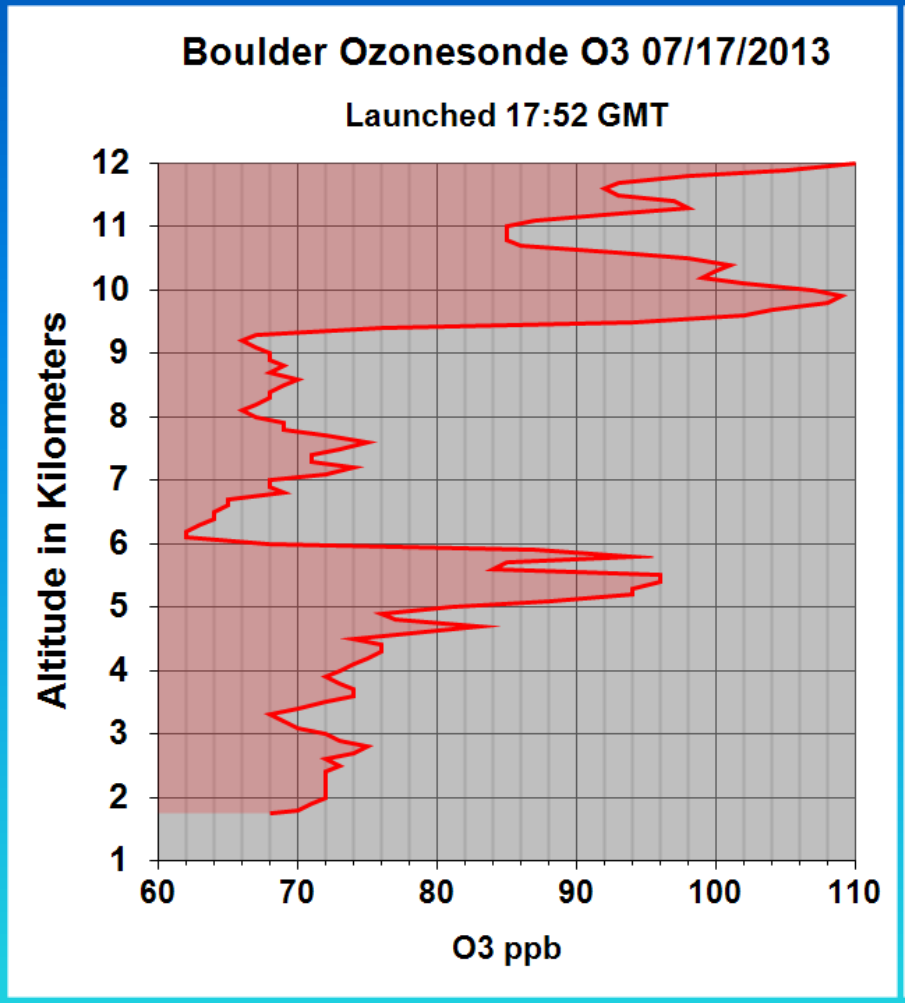
Elsewhere:
HLD: 62 ppb
CHAT: 60 ppb
AURE: 62 ppb

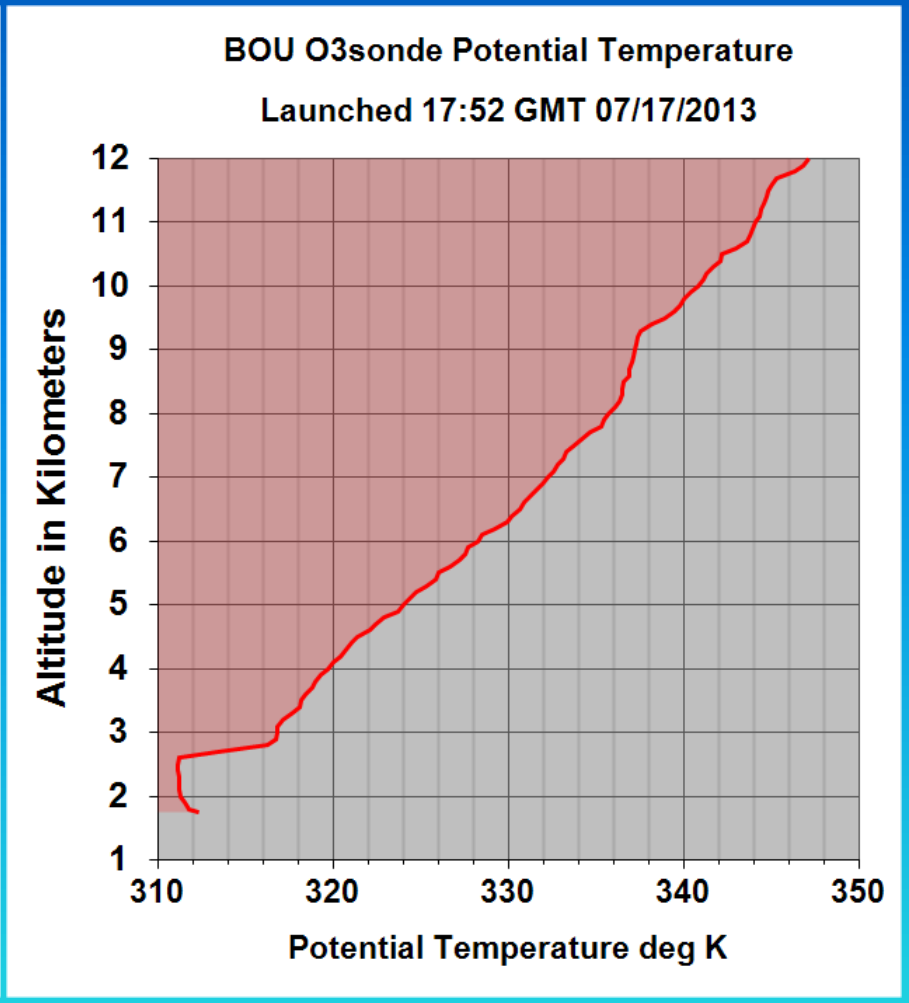
Boulder ozonesonde data (courtesy of NOAA GMD) provide examples of the vertical distribution of O3 on high-O3 days.



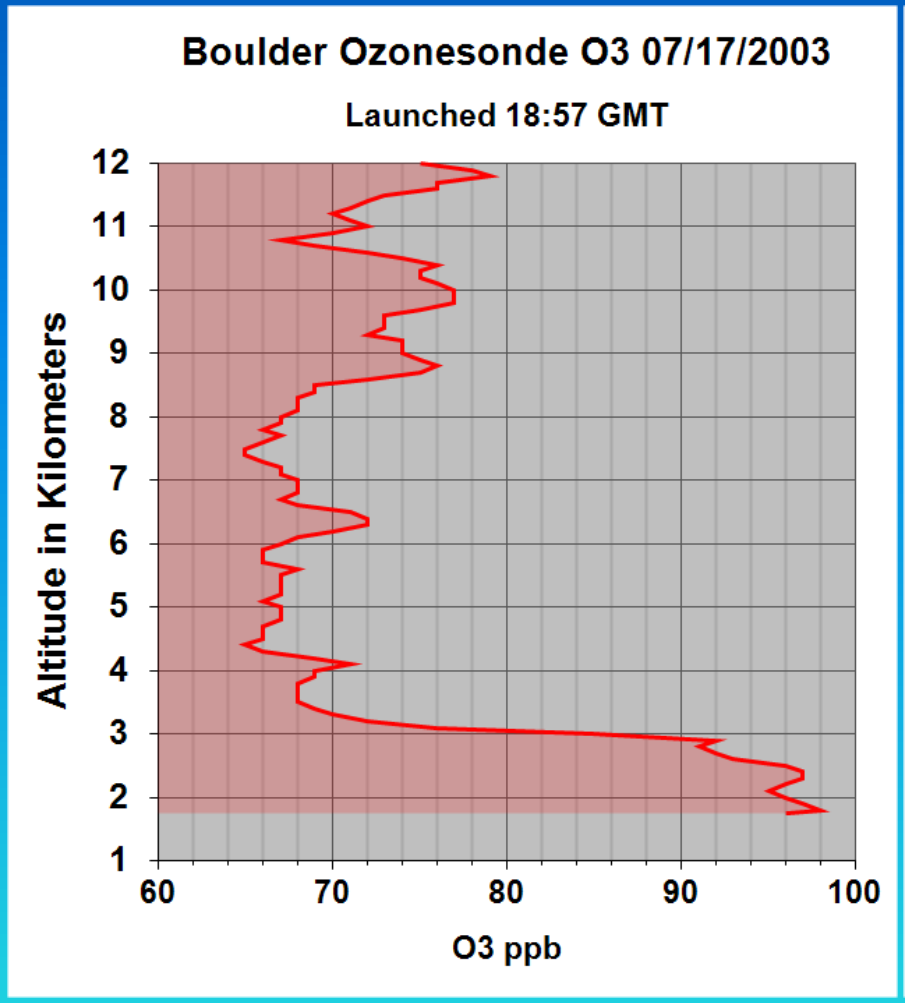


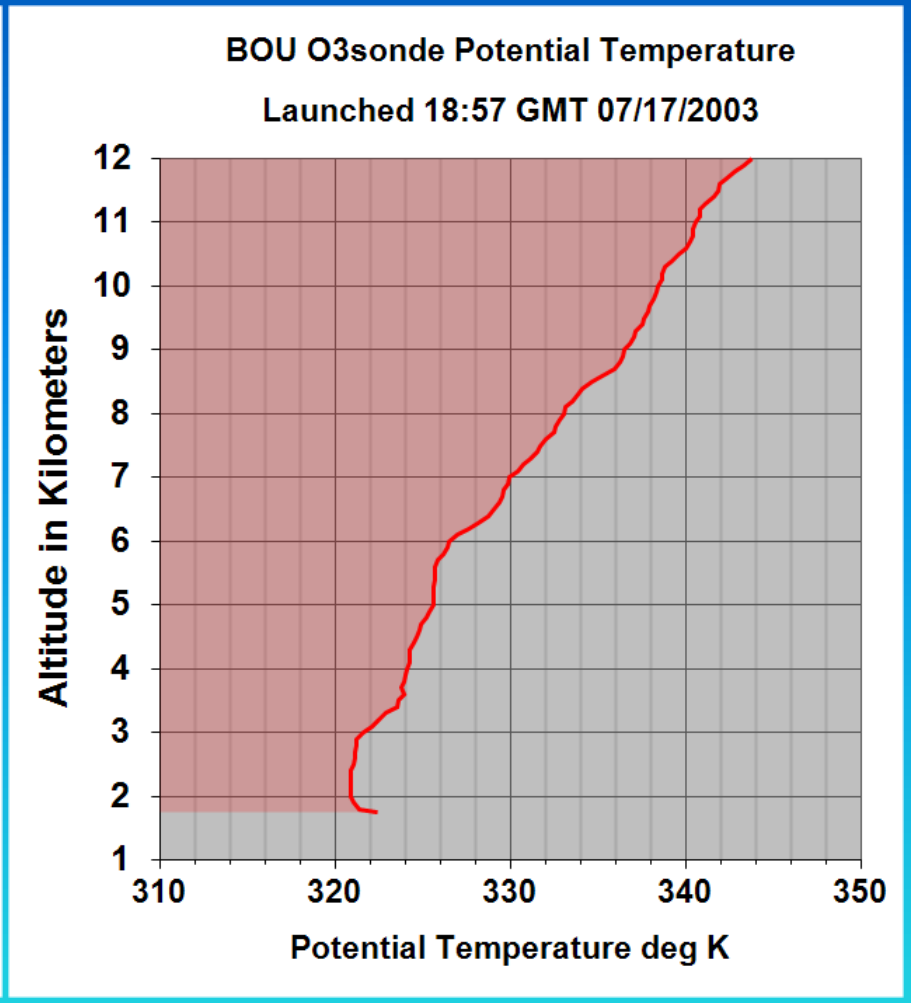
Boulder ozonesonde for 19Z, 7/10/2008, shows mixing to just above 6 km, O3 of 72 to 97 ppb in the boundary layer and some sort of residual O3 at ~ 8 km. DMAX 8-hr O3 of 95, 83, 86, and 91 ppb at Welch, RFLAT, NREL, and CHAT, respectively. NARR 21Z showed mixing to 6.5 km over Welch and ~ 7 km over north Denver.





Boulder ozonesonde for 18Z, 7/17/2013, shows mixing to 2.6 km, O3 of 72 to 75 ppb in the boundary layer and a residual O3 layer at 5-6 km. DMAX 8-hr O3 of 93, 90, and 91 ppb at RFLAT, NREL, and FTCW, respectively. NARR 21Z showed mixing to ~ 5 km level over RFLAT area.

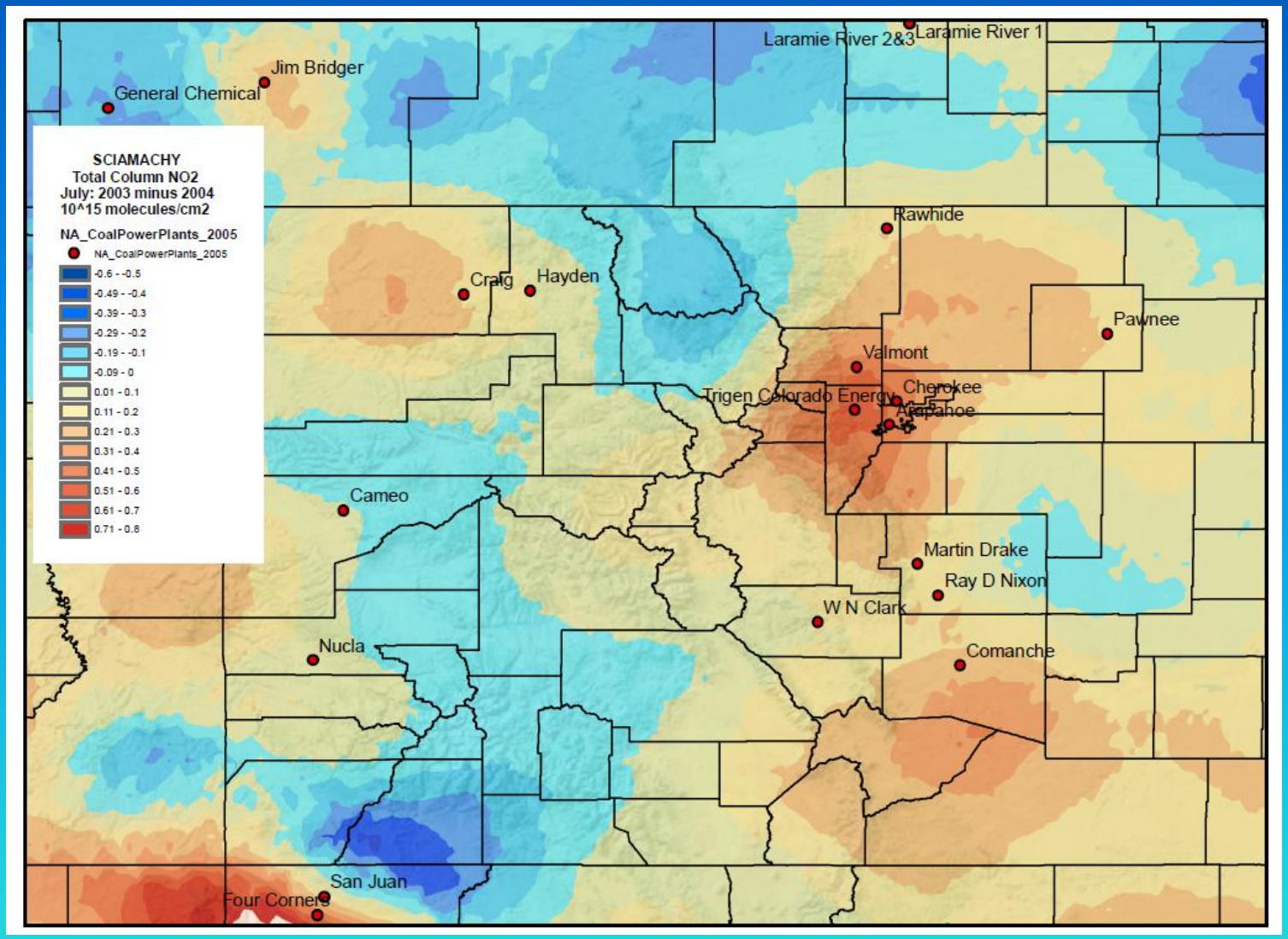




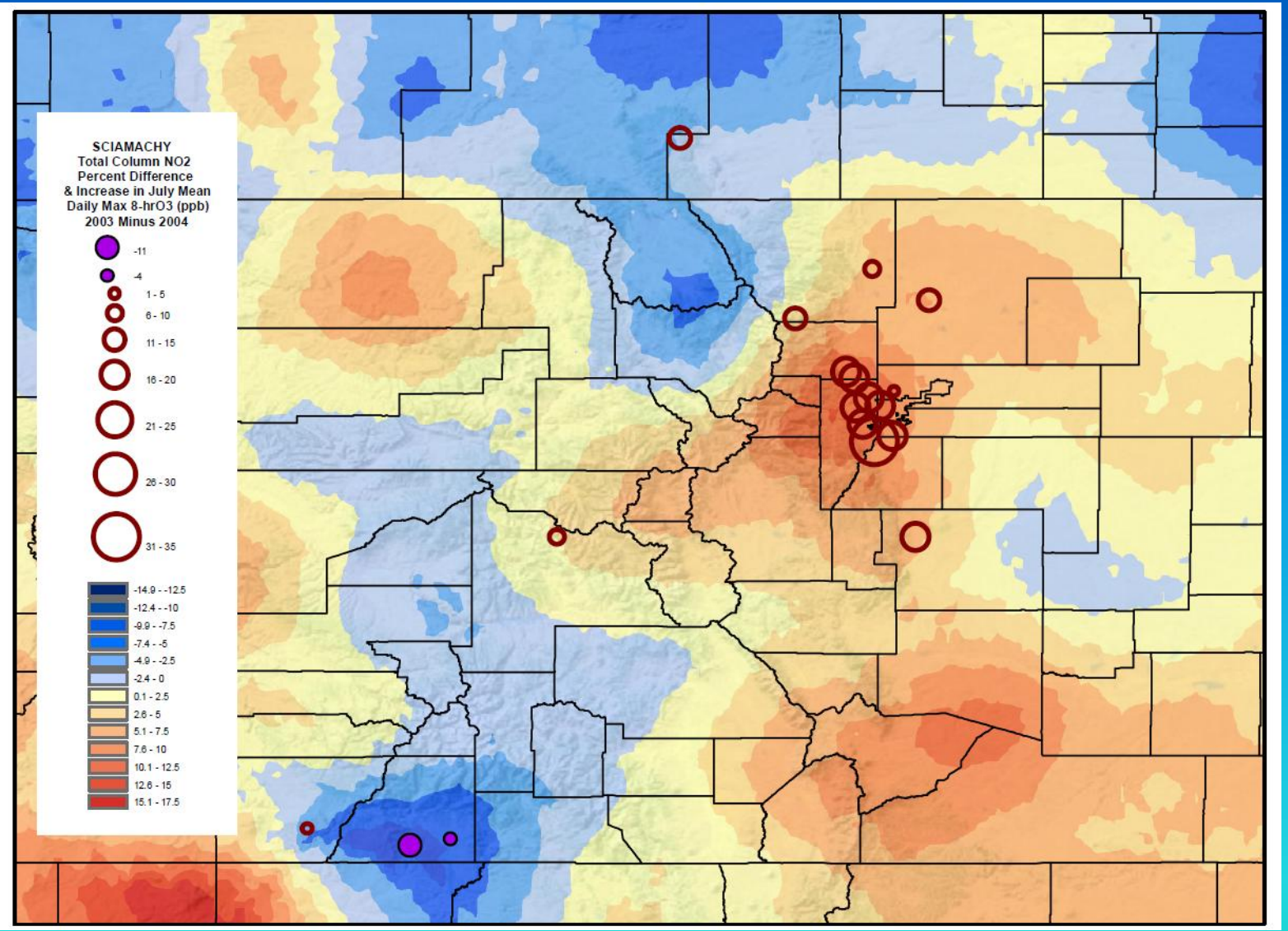
Boulder ozonesonde for 19Z, 7/17/2003, shows mixing to just above 6 km and O3 of 90 to 98 ppb in the boundary layer. DMAX 8-hr O3 of 95, 93, and 86 ppb at RFLAT, NREL, and CHAT, respectively. NARR 21Z showed mixing to 6.5 km at RFLAT.

SCIAMACHY, OMI, and BEHR NO2 data provide insights into the effects of local and regional circulations on O3 and its precursors. These point to the need for sampling in the foothills and mountains west and especially southwest of Denver.

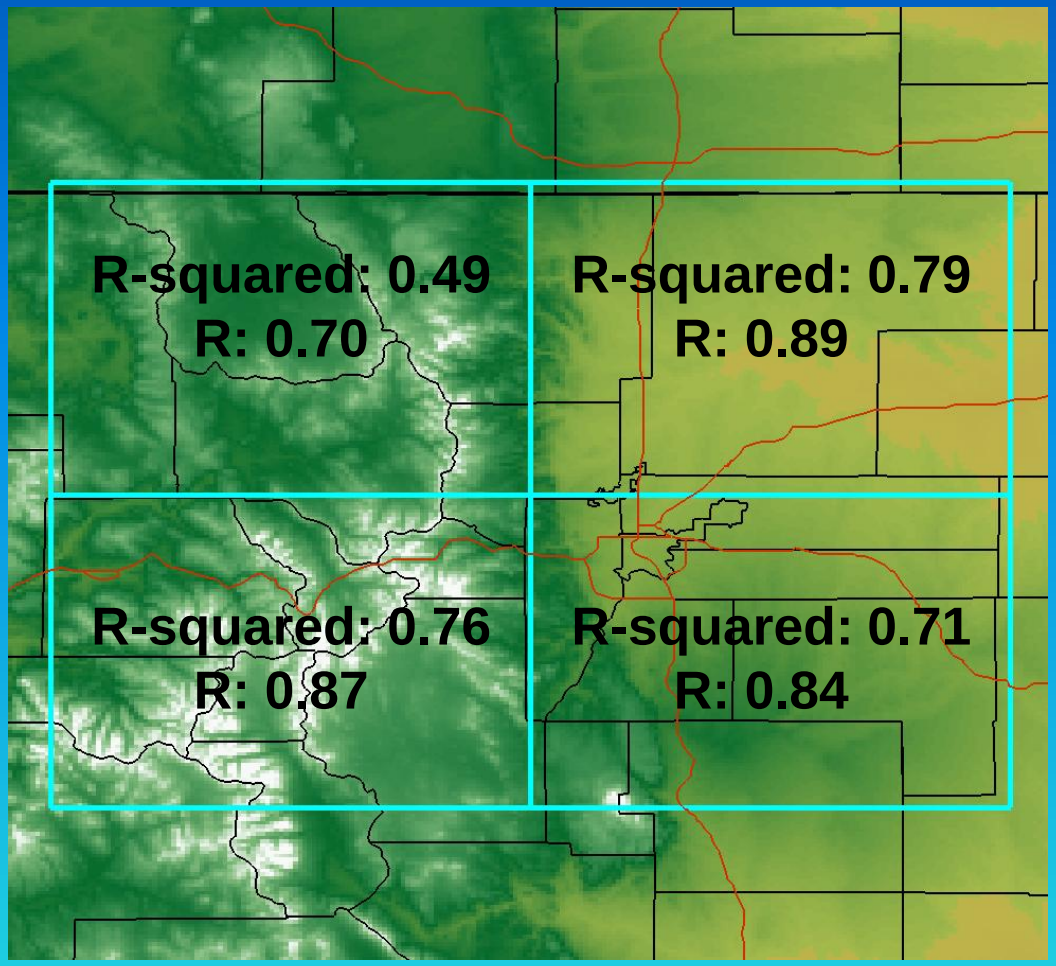
What does the re-distribution of tropospheric NO2 look like under the influence of a strong Four Corners high?



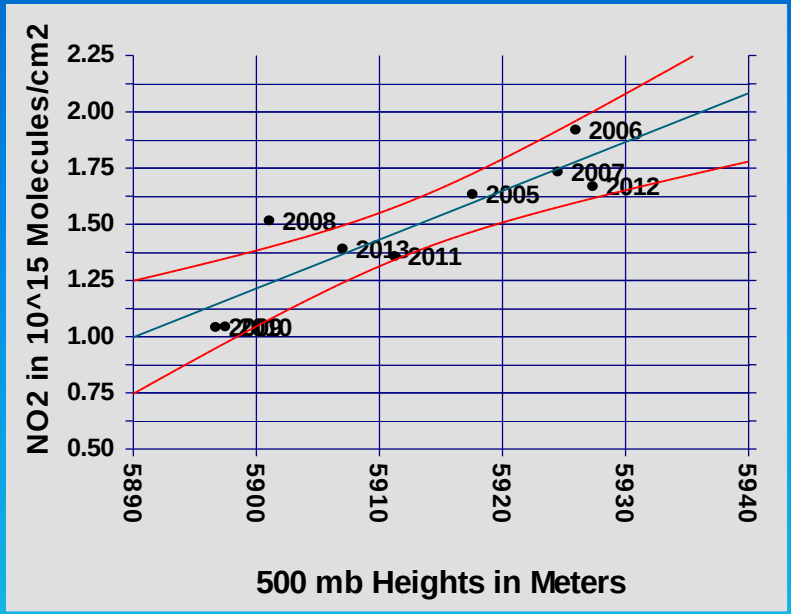
The difference between SCIAMACHY July mean total column NO2 (2003 minus 2004) gives us an idea of where NO2 increases and decreases when mean upper level high pressure is strong. NO2 penetration deep to the southwest, enhancements along the Platte River to the northeast of Denver. At 10 MST thermally-driven upslope has typically not crossed the Divide.



Circles show increases or decreases in July DMAX 8-hr O3 (2003 minus 2004) along with SCIAMACHY NO2 (2003 minus 2004). Increases in NO2 in central Colorado likely represent NO2 emissions from previous day(s).

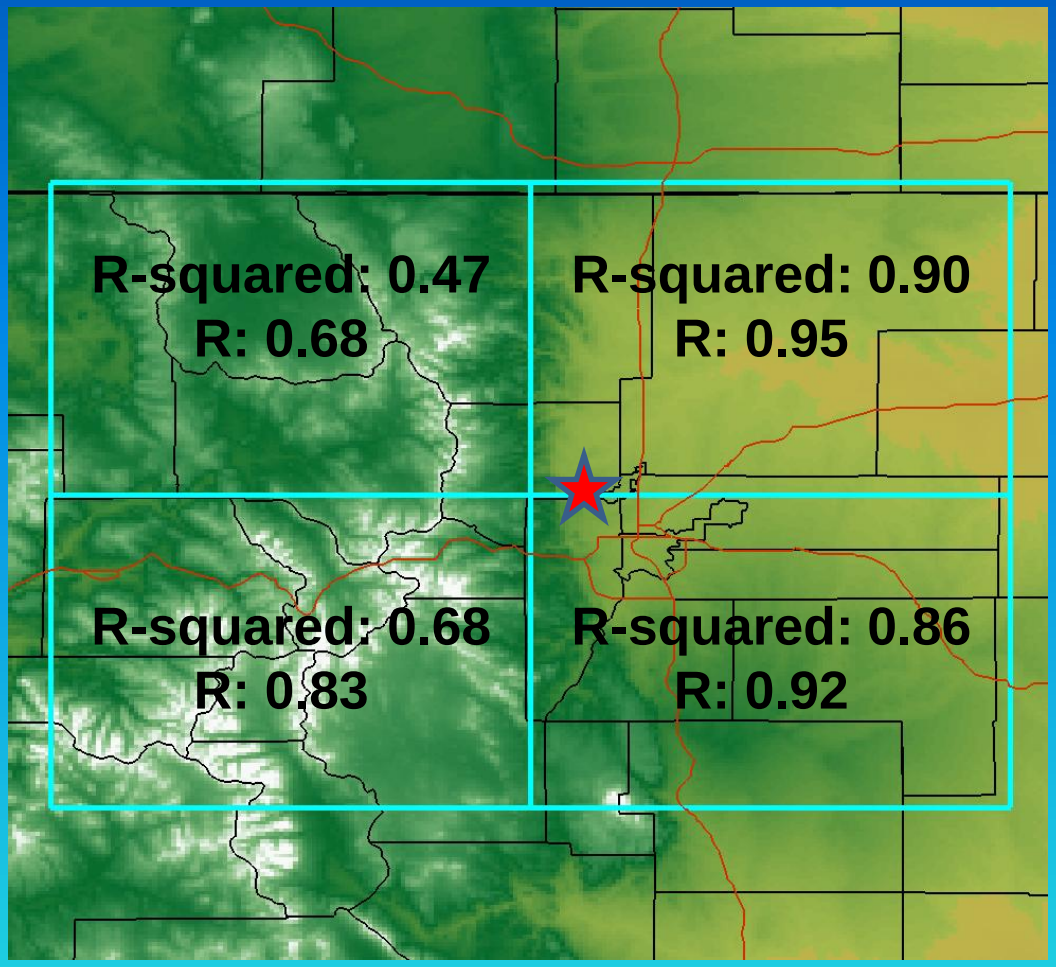


OMI NO2 vs 500 mb Heights

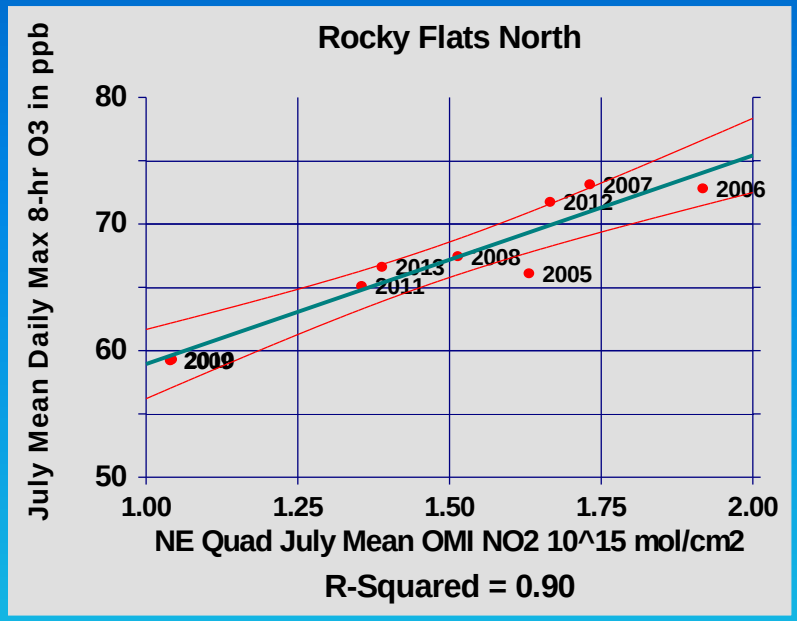


Northeast quadrant level 3 July mean OMI tropospheric NO2 versus July mean 500 mb heights, R-squared 0.79.

2005 through 2013 July mean level 3 OMI tropospheric NO2 is strongly correlated with July mean monthly 500 mb heights, with the highest correlations in the northeast (0.89) and southwest (0.87) quadrants and the lowest (0.70) in the northwest quadrant - based on quadrant mean NO2.

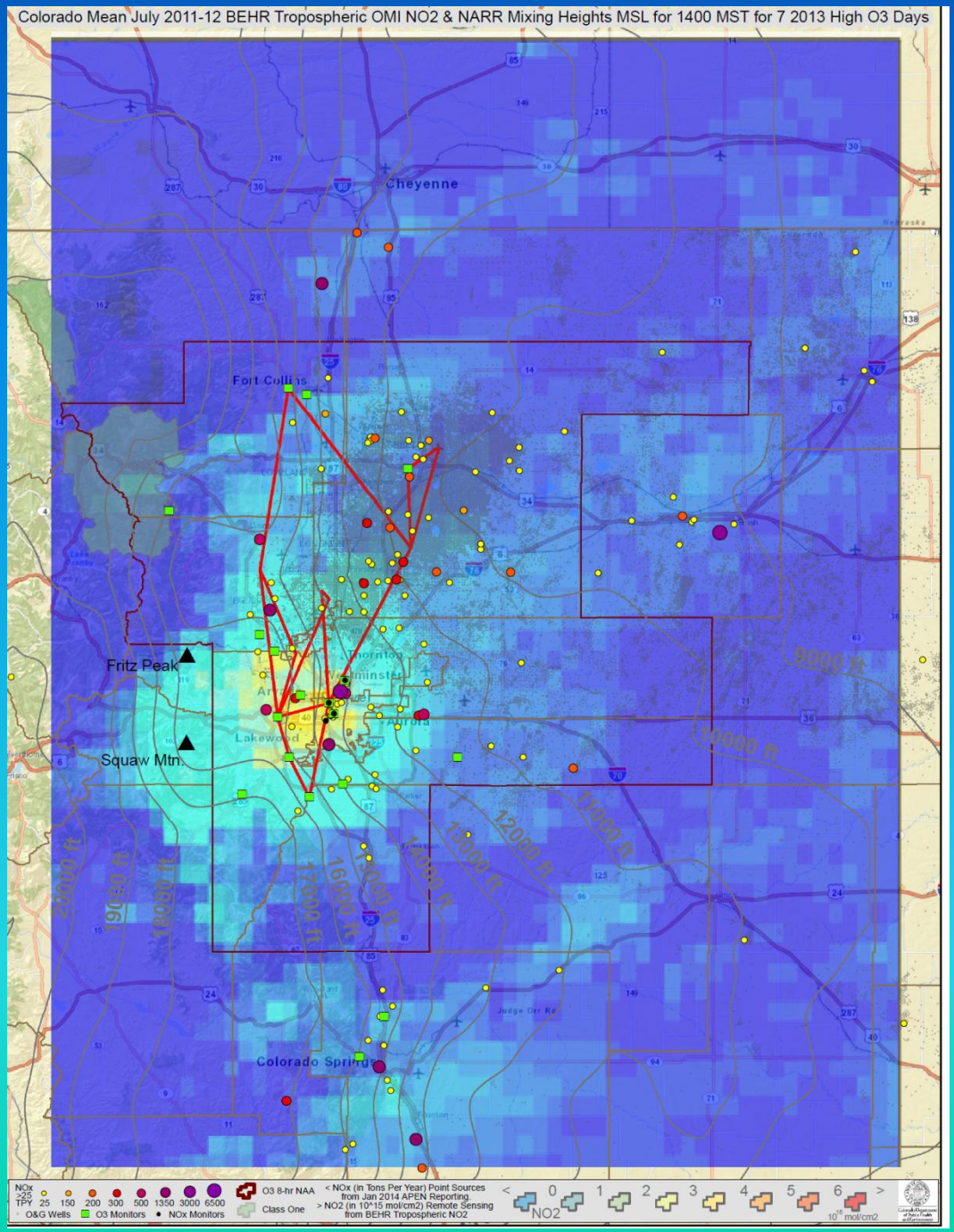


RFLAT O3 vs OMI NO2



RFLAT July mean DMAX 8-hr O3 versus Northeast quadrant level 3 July mean OMI tropospheric NO2.

2005 through 2013 July mean RFLAT DMAX 8-hr O3 is strongly correlated with level 3 OMI tropospheric NO2, with the highest correlations in the northeast (0.95) and southeast (0.92) quadrants and the lowest (0.68) in the northwest quadrant - based on quadrant mean NO2. **Chatfield O3 has an r-squared of 0.93 and correlation of 0.96 with southeast quadrant OMI NO2**.



BEHR mean July tropospheric NO2 For 2011-2012 shows early afternoon Plume moving west and southwest Of Denver.

Data courtesy of the Berkeley Satellite group: http://behr.cchem.berkeley.edu/Home.aspx

Some sort of daily measurements of O3 and precursors in the vertical would be advised for Squaw Peak or Fritz Peak. The C-130 may not be able to complete enough flights in the southwestern portion of the solenoid circulation which climatology suggests may be a source region.

Conclusions

- There is a very strong relationship between July mean 500 mb heights and July DMAX 8-hr O3 in Colorado and other western sates. Under the influence of an upper high, skies are often clear, temperatures are elevated, and westerlies are reduced in strength.

- These conditions promote the formation of mountain-plains solenoid circulations and westward propagating density currents along the Colorado Front Range and in the mountainous terrain of central Colorado.

- These circulations appear to enhance O3 and NO2 and lead to the highest concentration events. Deep mixing and terrain-driven circulations set this region apart from many low-altitude and coastal areas.

- A fraction of high O3 events do have shallow PBL heights below the 3 km MSL level with brisk westerlies aloft. Same-day emissions may contribute to high O3 within a relatively shallow boundary layer.

- Satellite NO2 and HYSPLIT runs provide evidence for extensive and persistent re-circulations of Front Range emissions under strong ridging aloft.

- More monitoring in the hills and mountains southwest of Denver?

The Air Pollution Control Division (APCD) of the Colorado Department of Public Health & Environment (CDPHE) Will Provide O3 Forecast Support

- 4 meteorologists at the APCD will continue to issue statewide and Front Range forecasts for O3 and other pollutants 7 days a week.

- These will include a 9 AM MDT update, a 24-36 hour forecast by 3 PM MDT, and a multi-day outlook (crafted specifically for FRAPPE and DISCOVER-AQ.)

- Meteorologist will also issue advisories for blowing dust, wildland fire smoke, stratospheric O3 intrusions, and any air quality event in Colorado.

- Forecasts are based on several synoptic and mesoscale meteorological models, a variety of satellite products, observations, in-house regression tools, and more than 7 decades of combined staff Colorado air quality forecasting experience. RAP HRRR best tool for 15-hour convection outlook.

- Forecasts and advisories are currently disseminated on our web pages and via listserves, AIRNow, local media, and hotlines. We can arrange for project-specific methods of distribution. A large number of wildfires will absorb much of our time.