Front Range Ozone

FRAPPÉ results and current state of research

Presentation to the Legislative Interim Committee on Ozone Air Quality

8 November 2023

Frank Flocke

Atmospheric Chemistry Observations and Modeling Laboratory

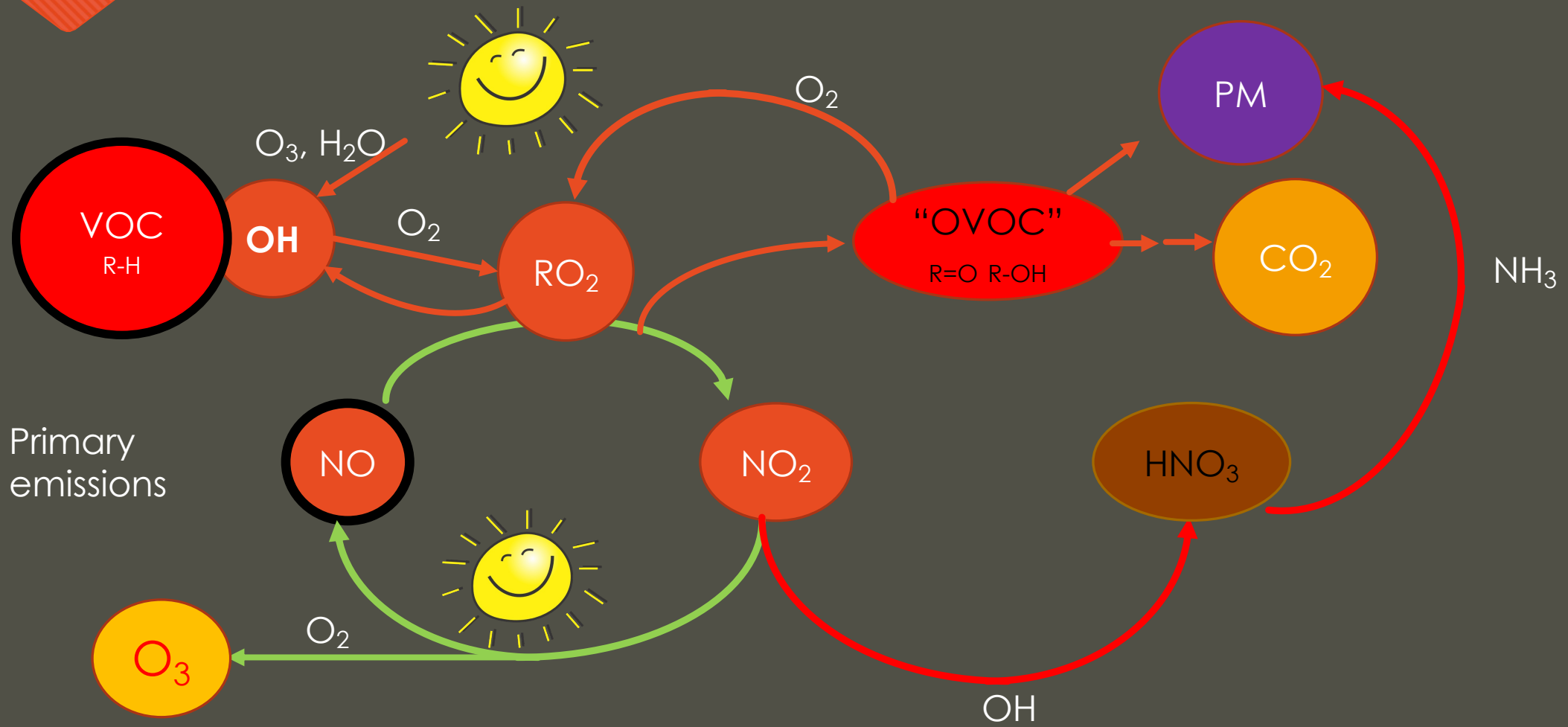
National Center for Atmospheric Research, Boulder, Colorado

This material is based upon work supported by the National Center for Atmospheric Research, which is a major facility sponsored by the National Science Foundation under Cooperative Agreement No. 1852977.

Outline

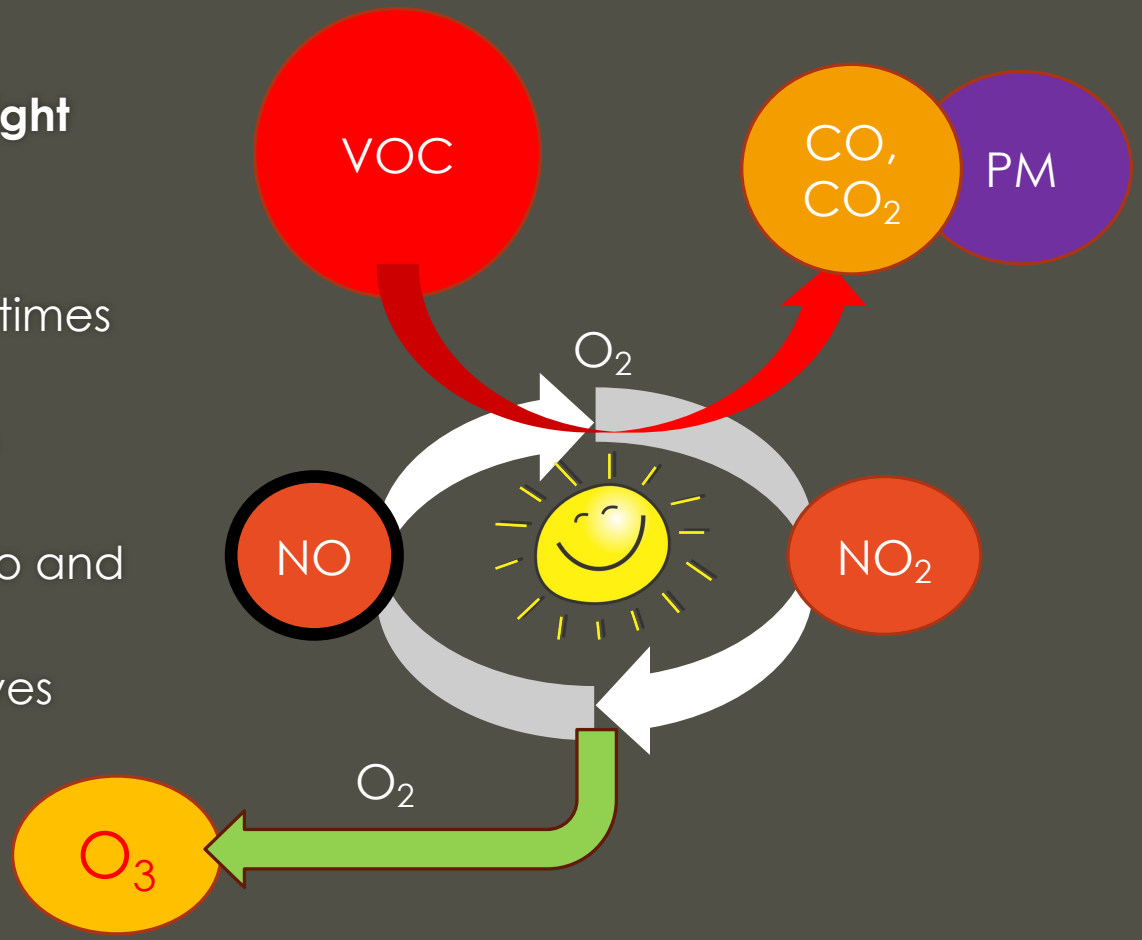
- Quick ozone primer
- FRAPPÉ results
- 9 years later – what's different
- How can NCAR help?

Ozone formation chemistry (troposphere)



Ozone chemistry boiled down

- To make ozone in the troposphere, **NOx, VOC**, and **sunlight** are needed
- Each cycle between NO_2 and NO spits out one ozone
- VOC "burn" in the process, turn into CO, CO_2 and sometimes PM
- NOx is the catalyst, only removed in process termination reactions (see previous slide)
- Ozone formation efficiency depends on VOC / NOx ratio and VOC reactivity
- VOC reactivity changes (typically decreases) as air moves away from emission sources
- NOx is removed at time scales of ~ 1 day
- The "ozone machine" runs at time scales of minutes

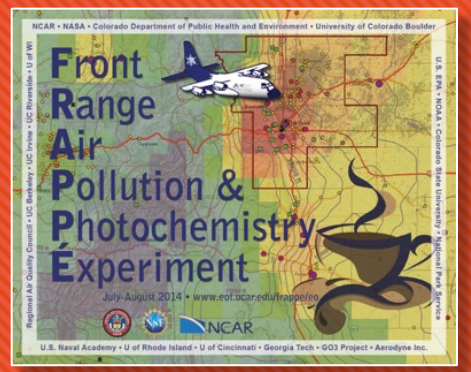


Primary vs. secondary pollutants

- Primary pollutants are directly emitted, such as
  - CO, NO, SO_2, NH_3, many VOC, black carbon and dust particles
- Secondary pollutants are not emitted but formed in the atmosphere by chemical and physical processes
  - Ozone
  - OVOC (oxygenated VOC)
  - Many types of aerosols

Drivers of Air Quality

- AQ is driven by three parameters
  - Emissions
  - Meteorology (dispersion)
  - Chemical and physical processes
- The Front Range has
  - Diverse emission sources (transportation, industry, energy, livestock, agriculture)
  - Complicated meteorology driven by the proximity to the mountains (and their orientation)



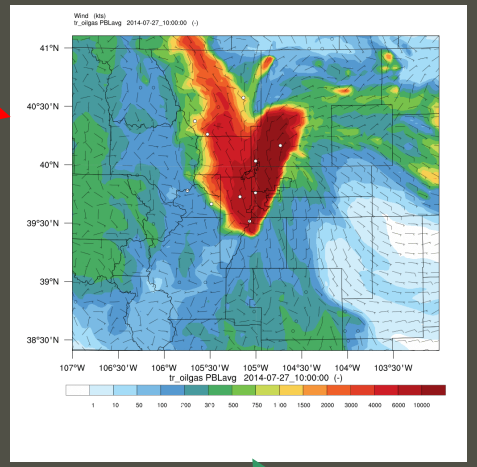
FRAPPÉ 2014

- Goal: Quantify individual emission sector contributions to ozone production in the Northern Colorado Front Range Metro Area (NFRMA).
- The non-compliance status of the NFRMA with the ozone NAAQS was primary motivation
  - Large population (traffic) increase and boom in oil and natural gas extraction
- Raise awareness of NCAR in public and stakeholder community
- FRAPPÉ attracted NASA's DISCOVER-AQ[1] team to participate in a joint campaign
- Teamed up with Gabi Pfister (AQ modeling), went on a crusade to find funding
- Success securing funding from the State of Colorado (CDPHE[2]) and NSF
- **Mobilized a large fraction of the AQ community, both academic and regulatory, with many local groups participating on ground and aircraft**

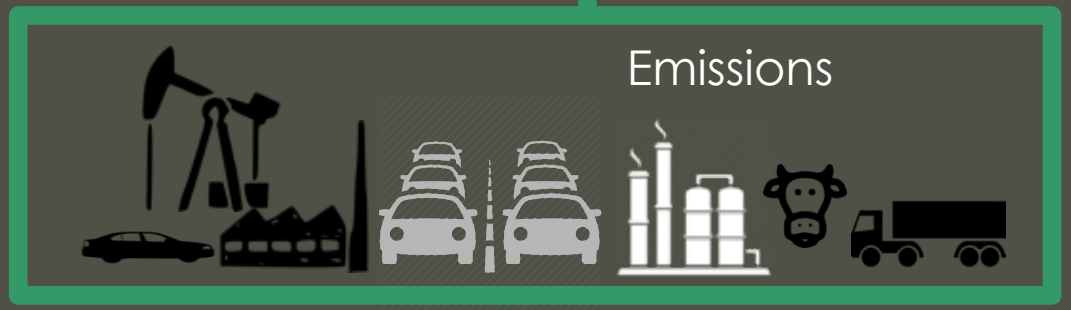
[1]Deriving Information on Surface conditions from Column and Vertically Resolved Observations Relevant to Air Quality
[2]Colorado Department of Public Health and Environment

Operational measurements and AQ planning

Very limited, ground-based observations



Rigid modeling systems

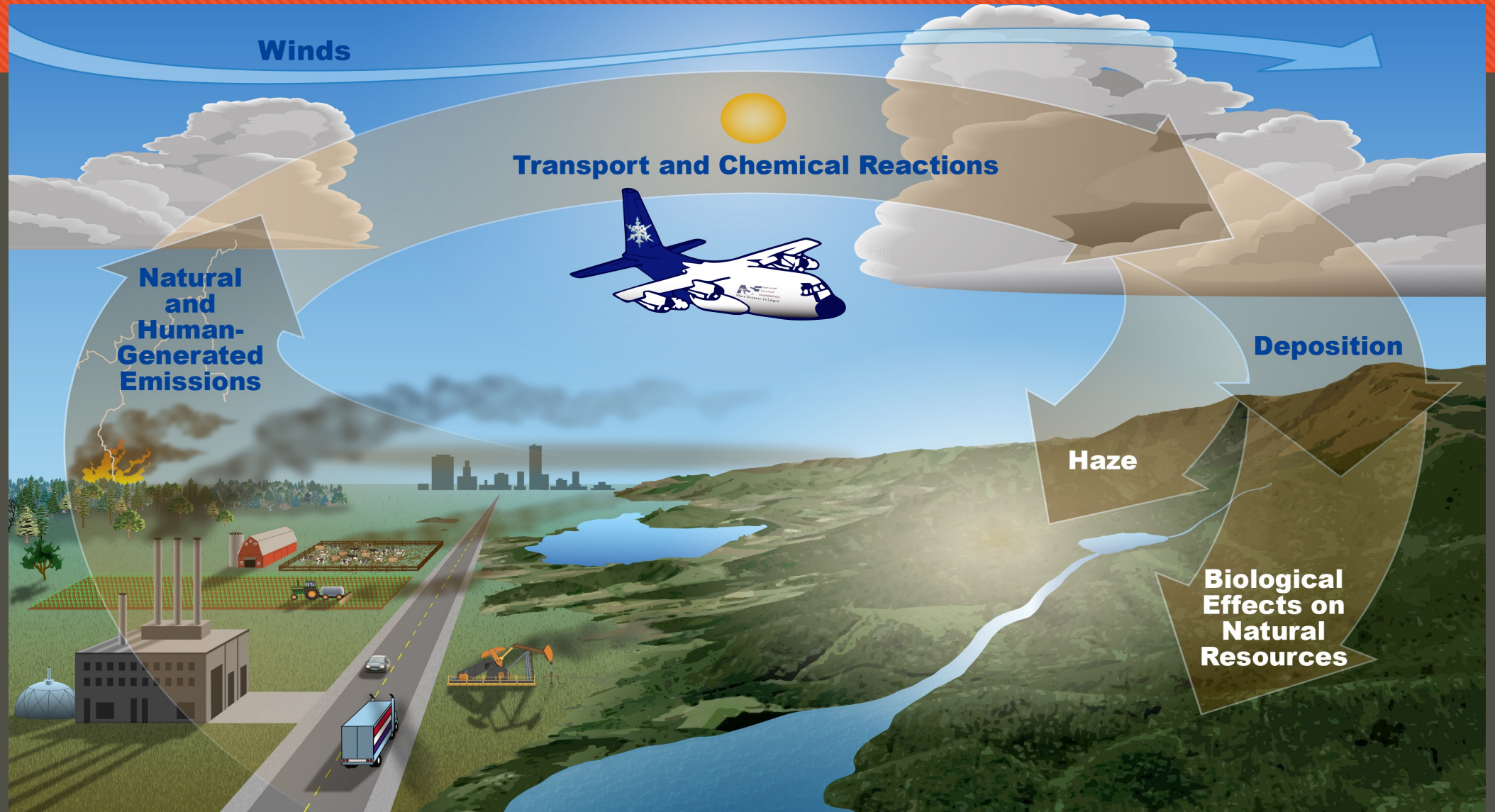


Limited capacity to evaluate emission inventories

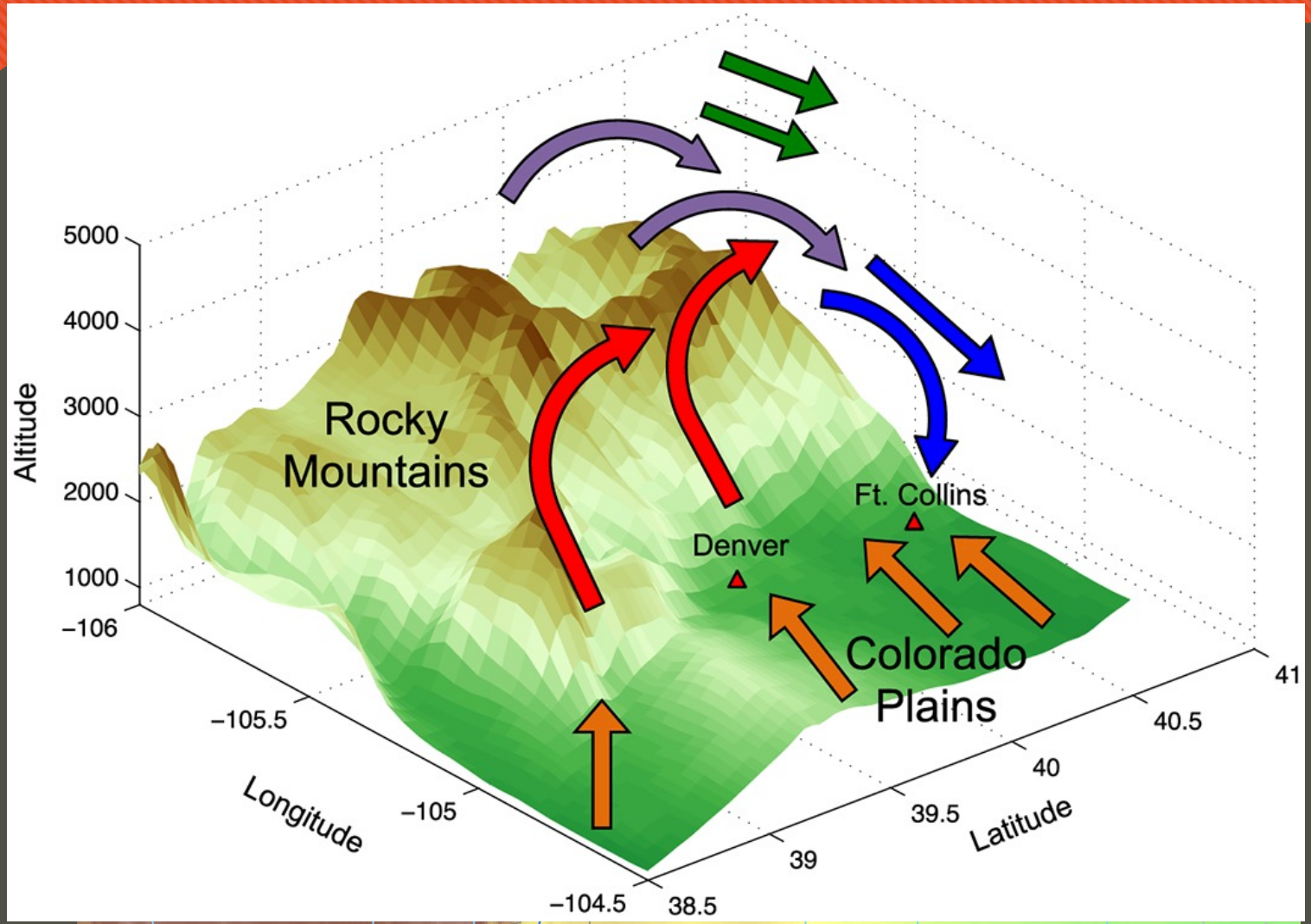
Ground observations can't tell the complete picture

- Regulatory ground-based monitoring is limited in coverage and diversity of species measured (typically few or no intermediates or photochemical products except ozone itself)
- They provide no information on vertical distributions of pollutants

The utility of aircraft measurements



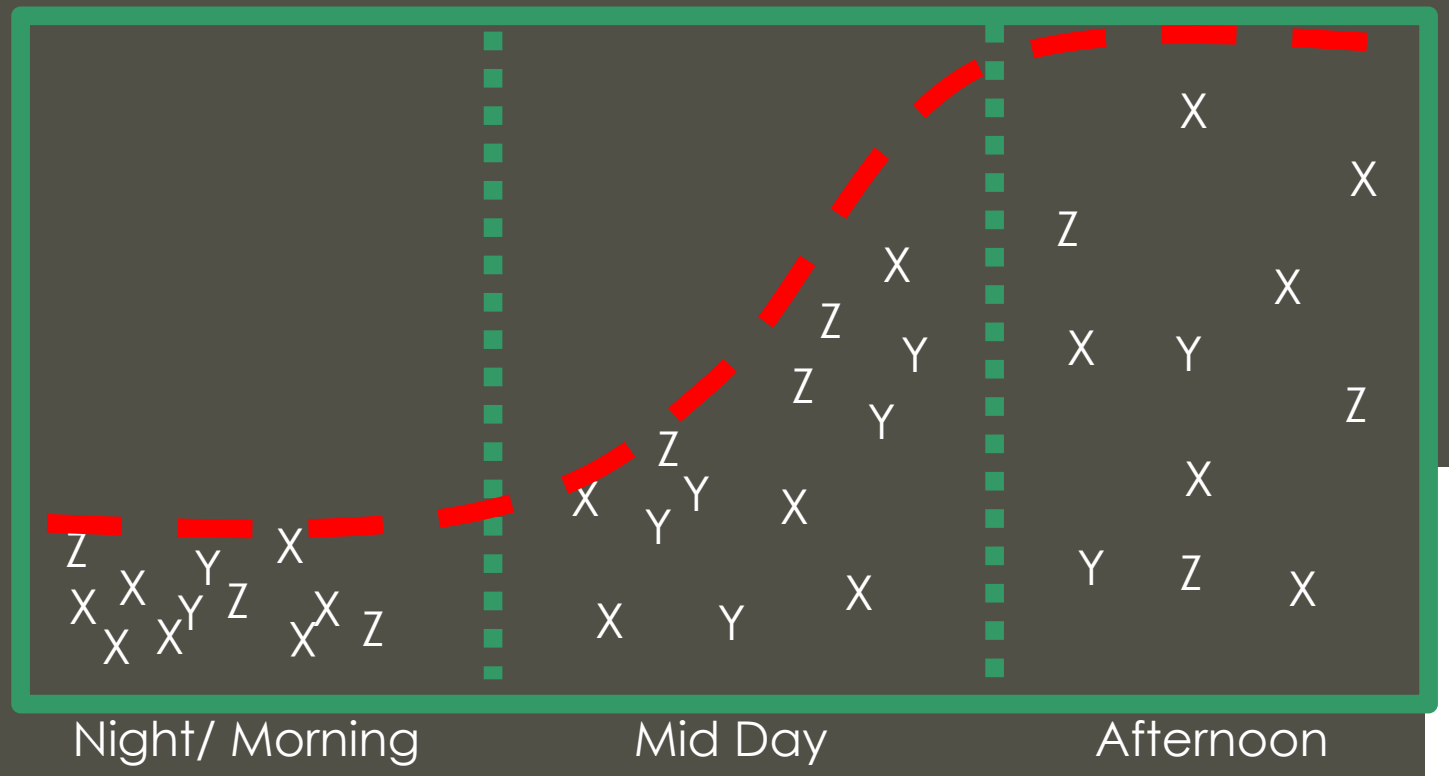
The NFRMA has a very diverse mix of emissions and complex meteorology



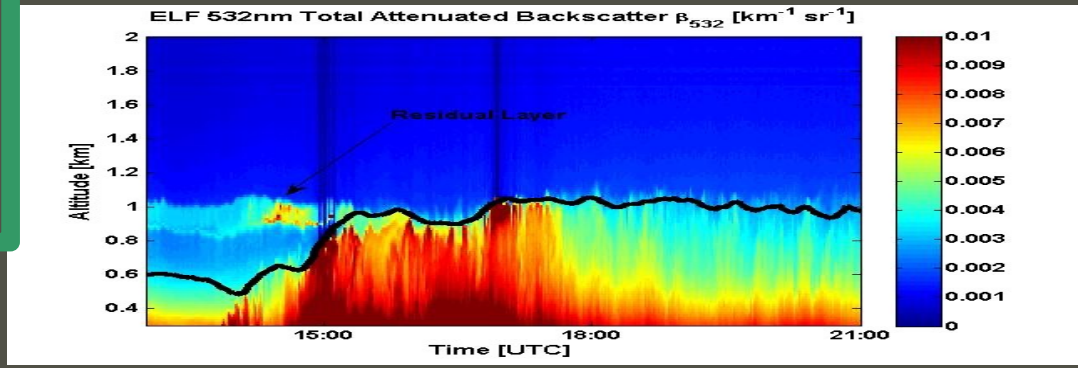
The atmospheric boundary layer

Source: Wikipedia

The planetary boundary layer (PBL) expands in depth through the course of the day

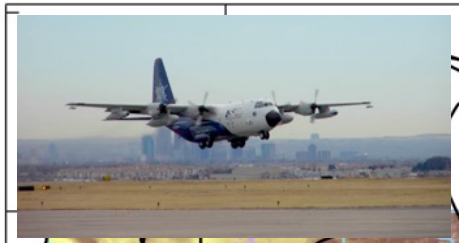


- This increases the volume that emissions are diluted into
- Models have trouble correctly simulating the PBL
- Many chemical processes are non- linear



Remote sensing measurements during FRAPPÉ

Coordinated FRAPPÉ + DISCOVER-AQ research flights maximized scientific return



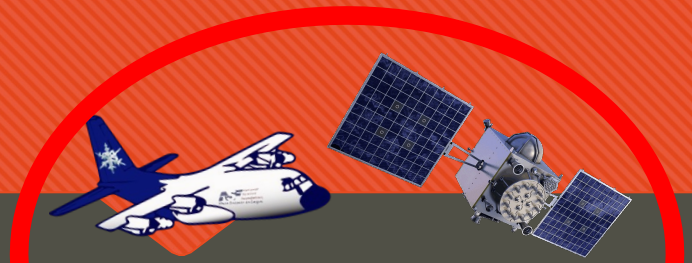
NASA P-3 flight tracks:

- focus on non-Attainment area
- repetitive flight pattern to investigate diurnal variability
- Vertical profiling over selected ground sites 1,000agl-18,000asl
- Link to satellite observations

NCAR/NSF C130 flight tracks:

- larger region with targeted flights
- emission sources in the NFRMA and upwind areas (urban, O&NG, agriculture, EGUs, …)
- Mixing, outflow, upslope events,…

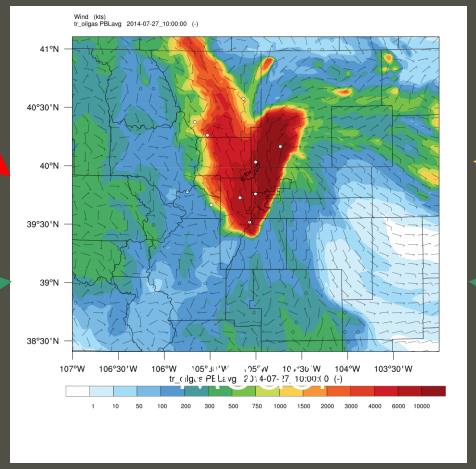
The synergy of detailed observations and research grade tools



Observations

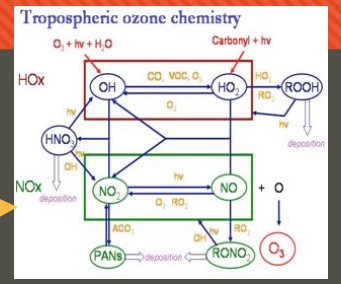
Measure hundreds of species at high precision and time resolution

Simulate full chemistry using chemical transport models



refine

evaluate

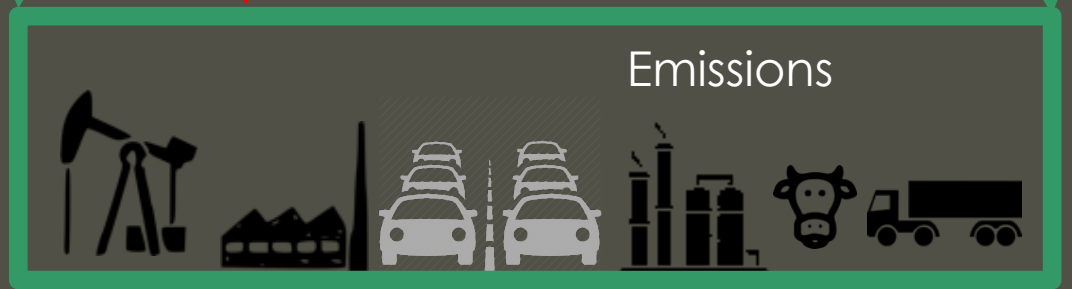


Lab-based process investigations

compare

Evaluate using flight and mobile lab data

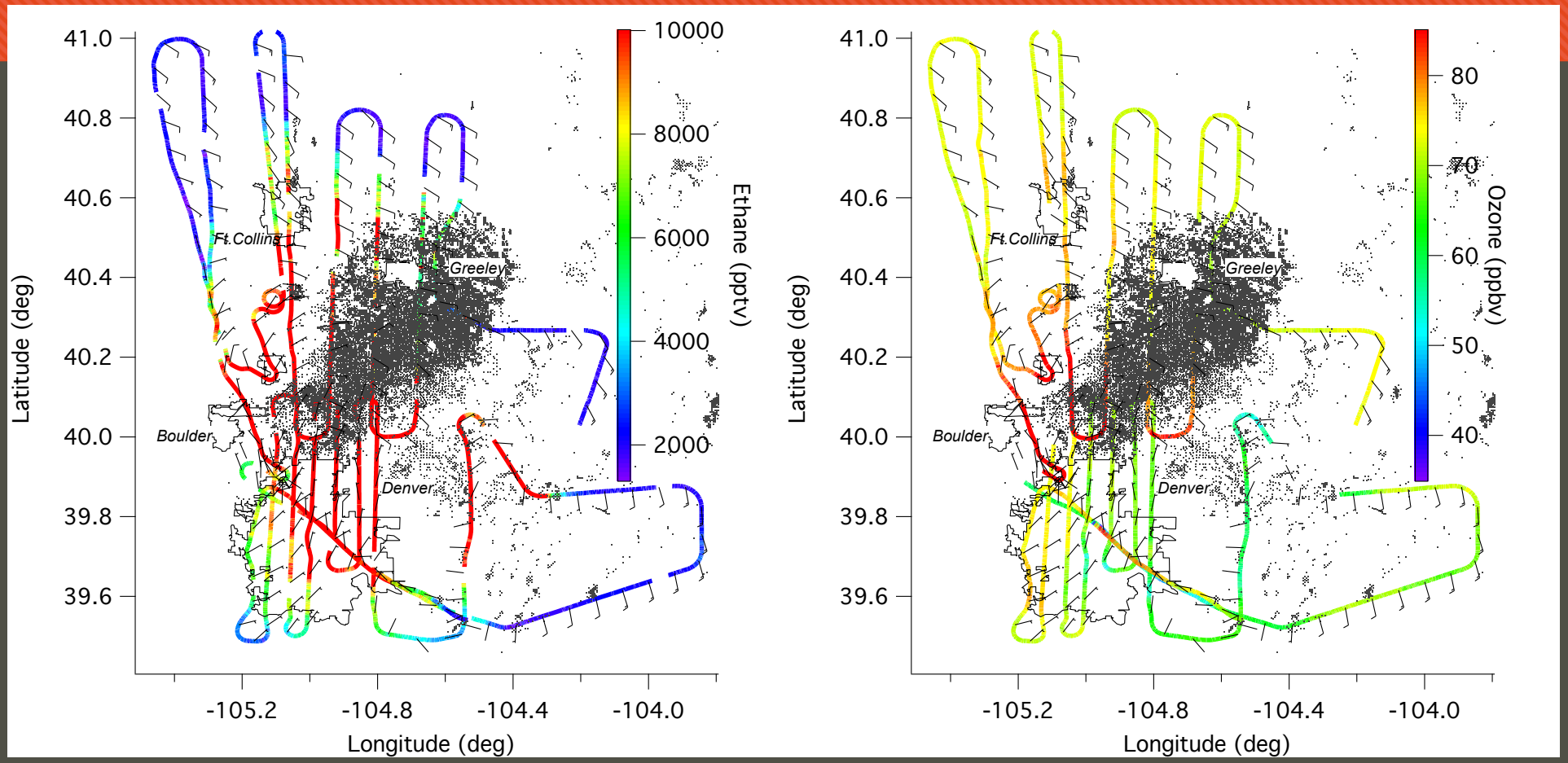
Refine using flight data and high-resolution models



AQ research is a combination of high precision measurements and high resolution models

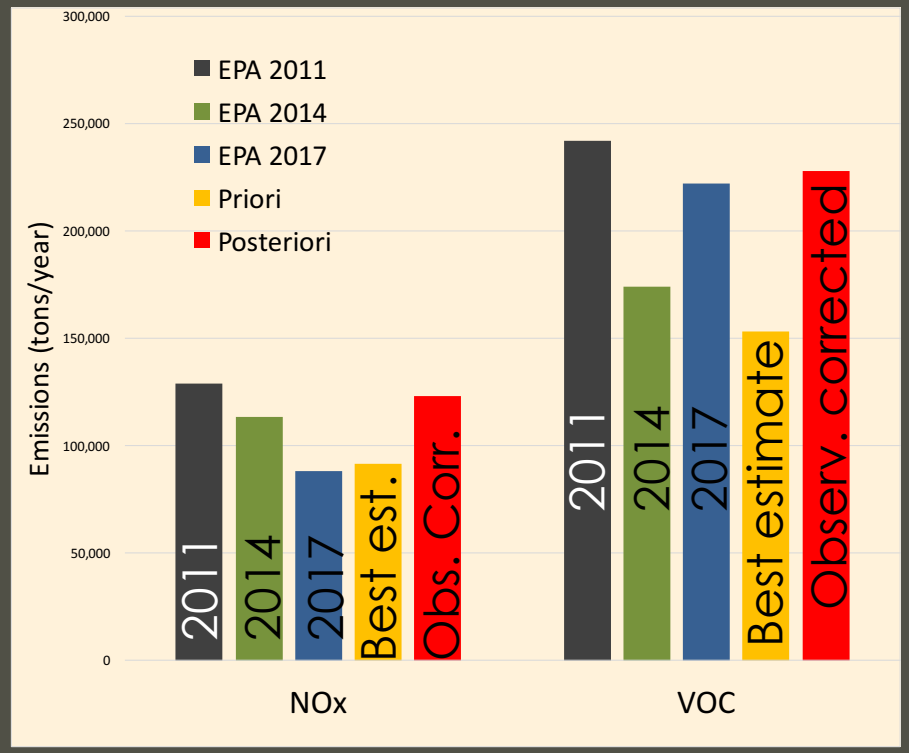
- Perform measurements in as many places as possible, from aircraft, mobile ground equipment, towers, and fixed ground stations
  - Primary and secondary species
  - Meteorological parameters
- Combine these measurements with satellite and ground based remote sensing data
- Attempt to simulate the measurements with high resolution models
  - Dispersion validated with meteorological observations
  - Chemistry validated with explicit chemical "box" models and laboratory measurements
- Adjust emission inventories to match all primary and secondary species as well as possible

"Emission flights" were raster patterns flown over the area during stable meteorological conditions

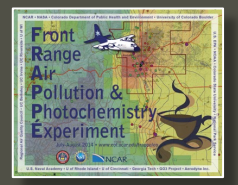


On July 28, highest ozone was measured where Denver's urban/industrial and Weld County's oil and natural gas emissions mix

Emission inventories were generally too low, slightly less so for mobile emissions but quite strongly for oil and natural gas emissions

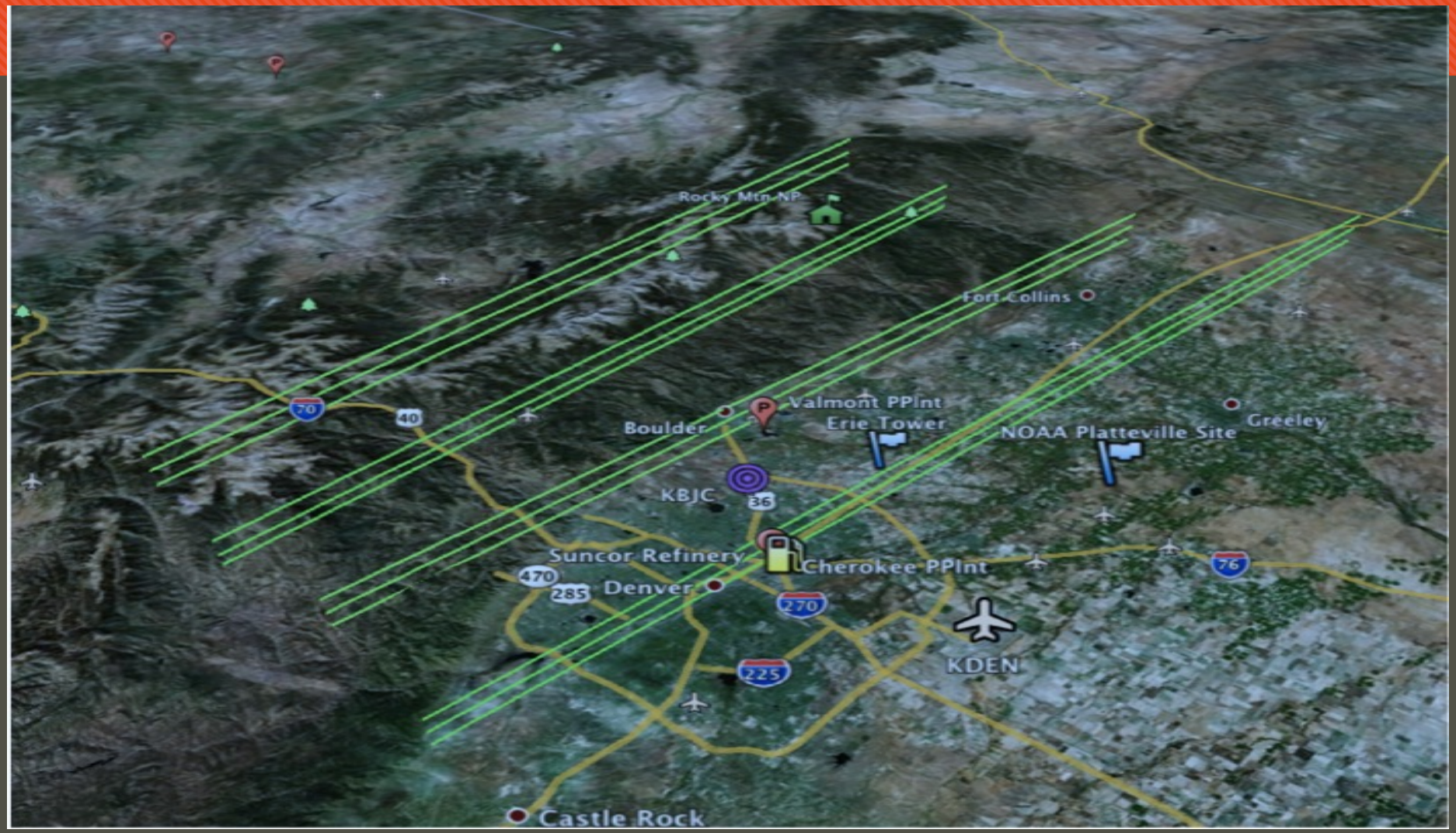


- Yellow bars are the a priori best estimate based on EPA and CDPHE data
- We had to **increase NOx** emissions from transportation **outside of the Denver Urban area by a factor of 2**
- We had **to double all oil and natural gas emissions** (VOC and NOx, except Ethane, conservative approach – some indicators for 4x VOC)
- Red bars are observation corrected total emissions used for chemistry/transport modeling with WRF-CMAQ[1]

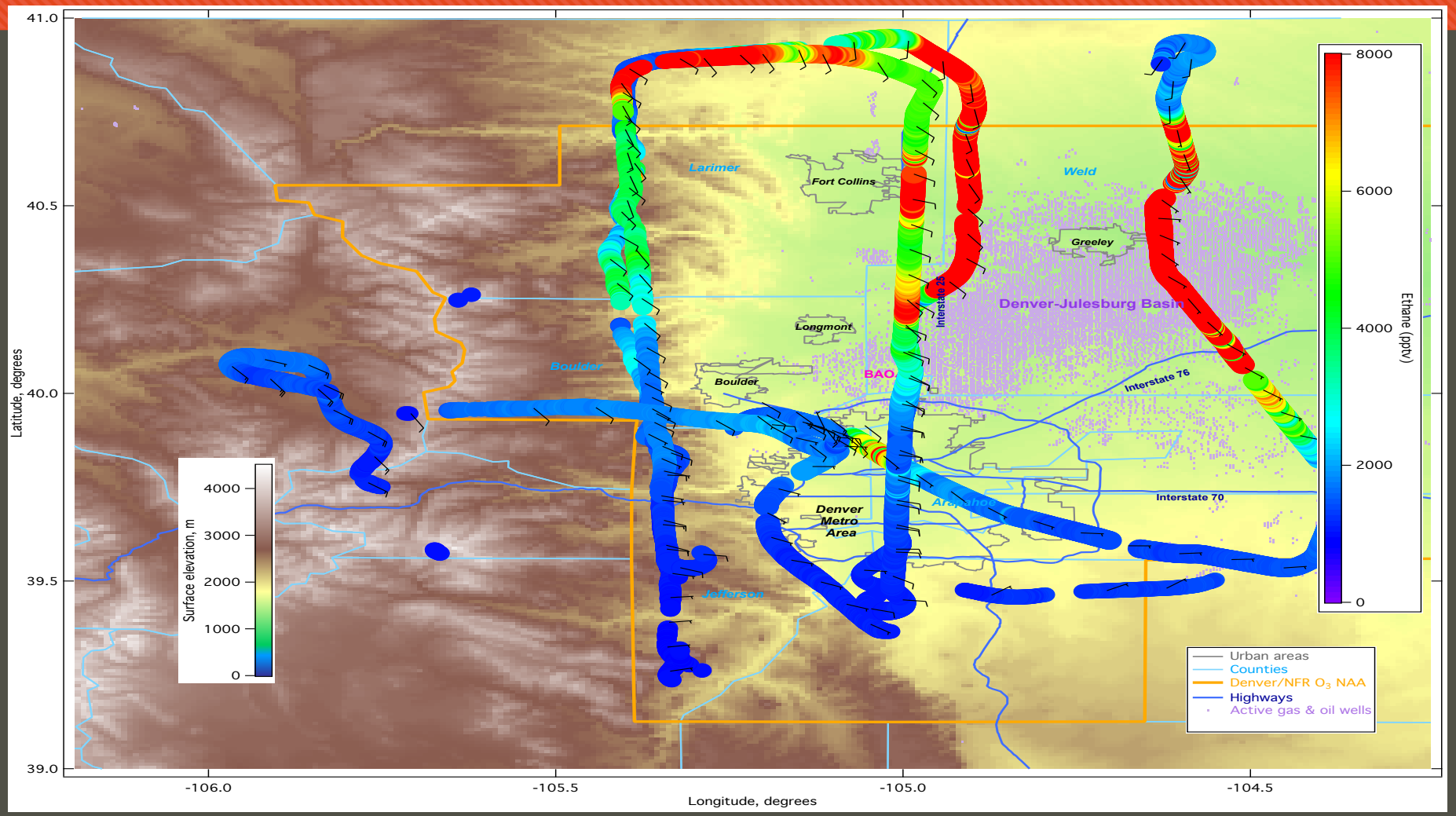


[1]Weather Research and Forecast Model / Community Multiscale AQ Model

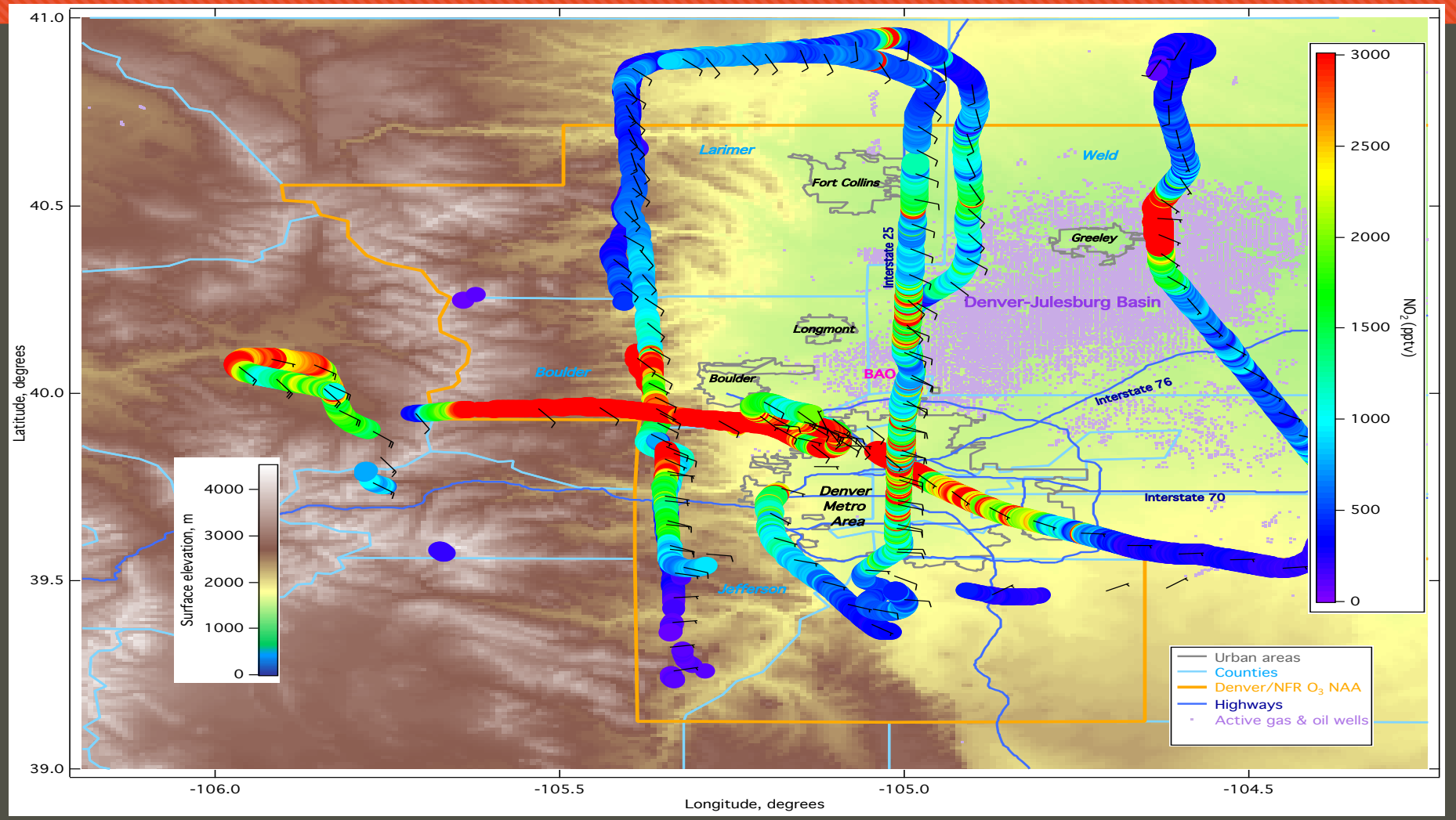
"Upslope" flights followed the air masses into the mountains and observed ozone production and chemistry along the way

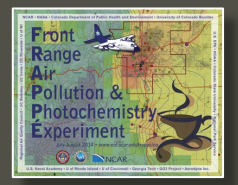


Ethane, an O&nG tracer, is concentrated over and downwind of the DJB

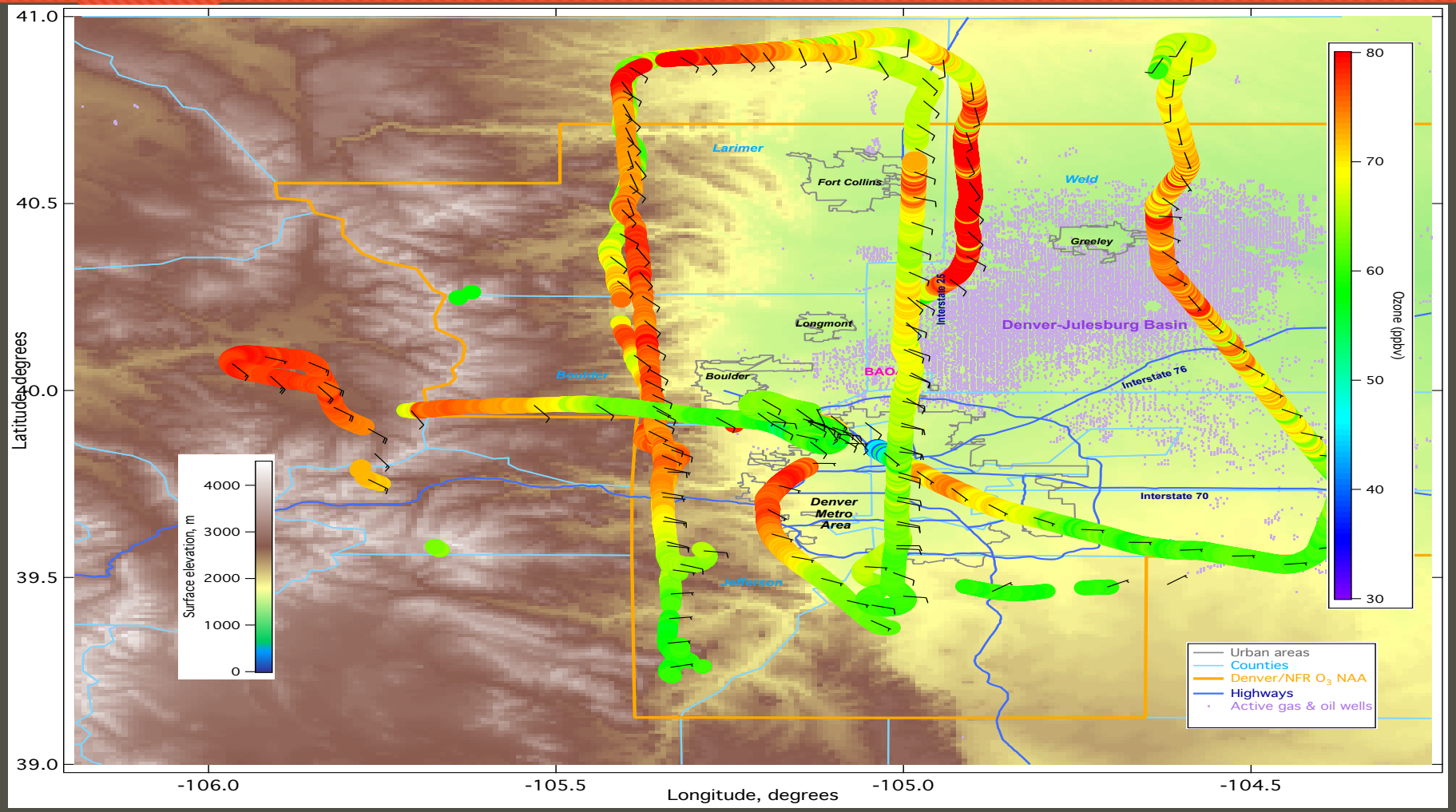


NOx, a transportation and combustion tracer, is concentrated over the urban areas and downwind of some Weld County O&nG facilities

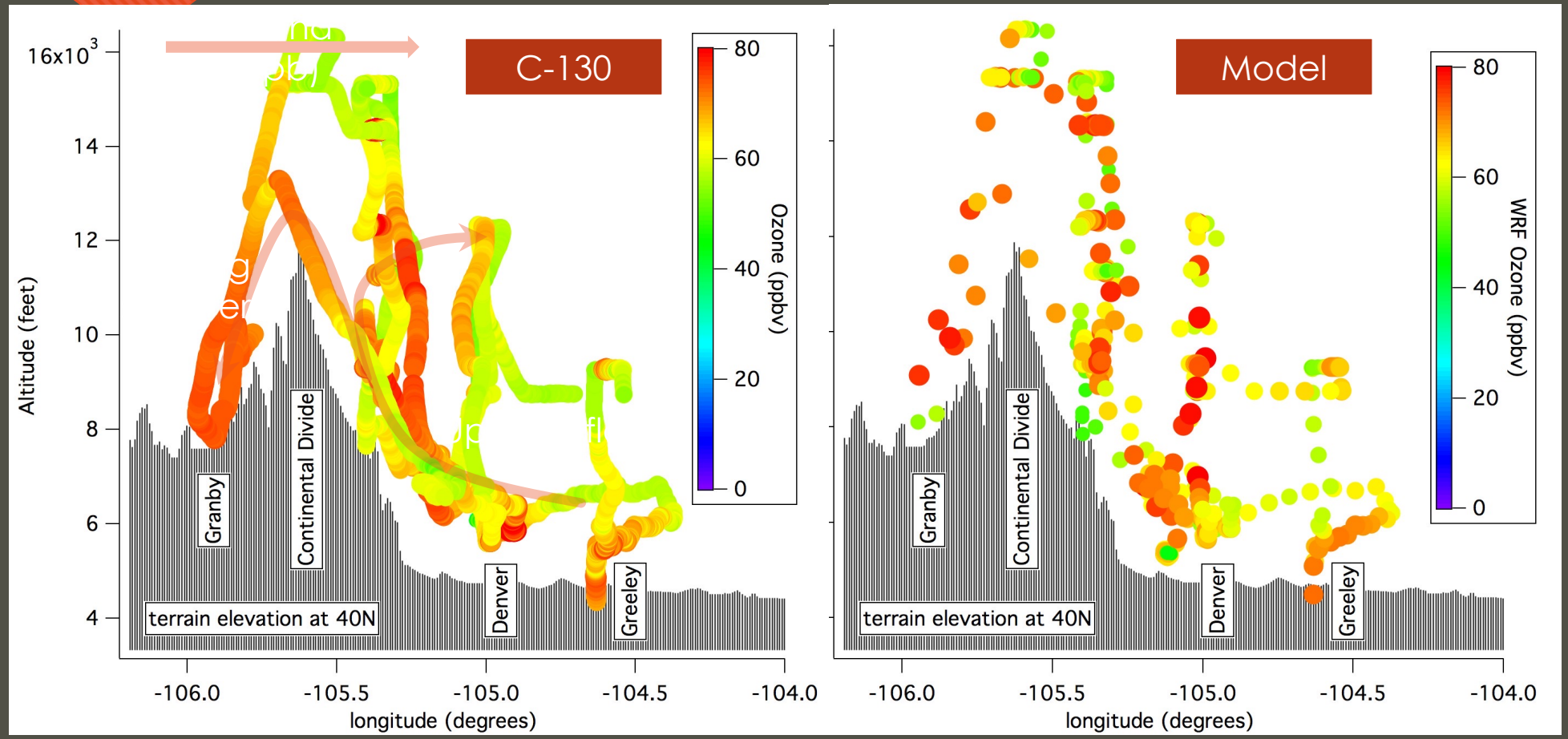




Ozone is produced efficiently downwind of both the O&nG dominated and the urban areas, and upslope flow spills over the Continental Divide into Grand County



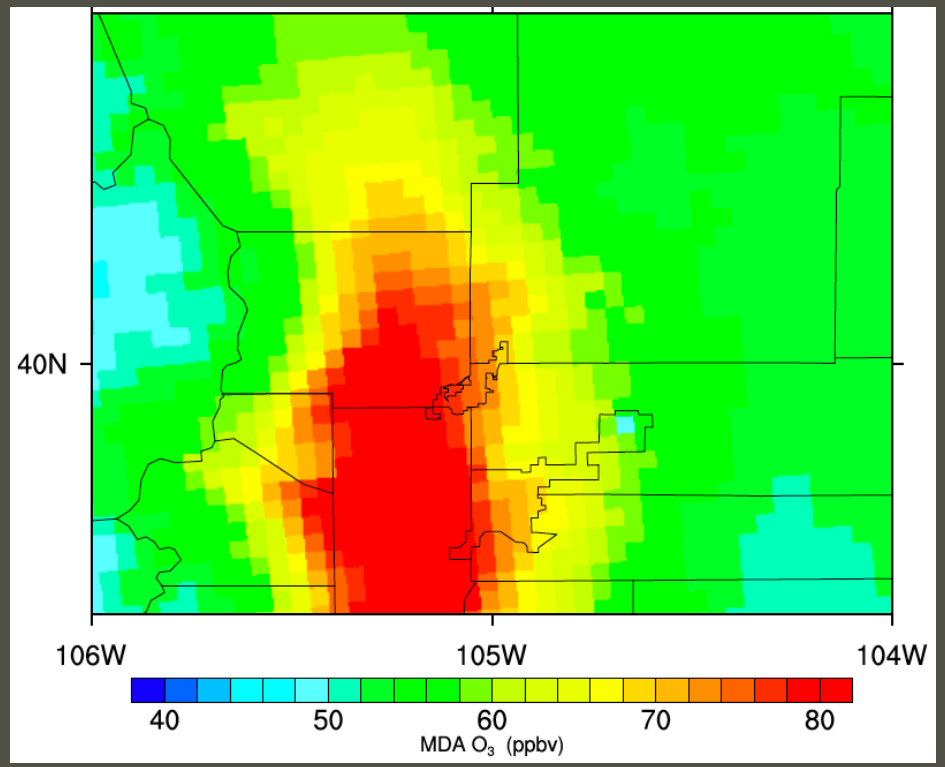
WRF-Chem modeling reproduces the transport and the ozone formation quite well.



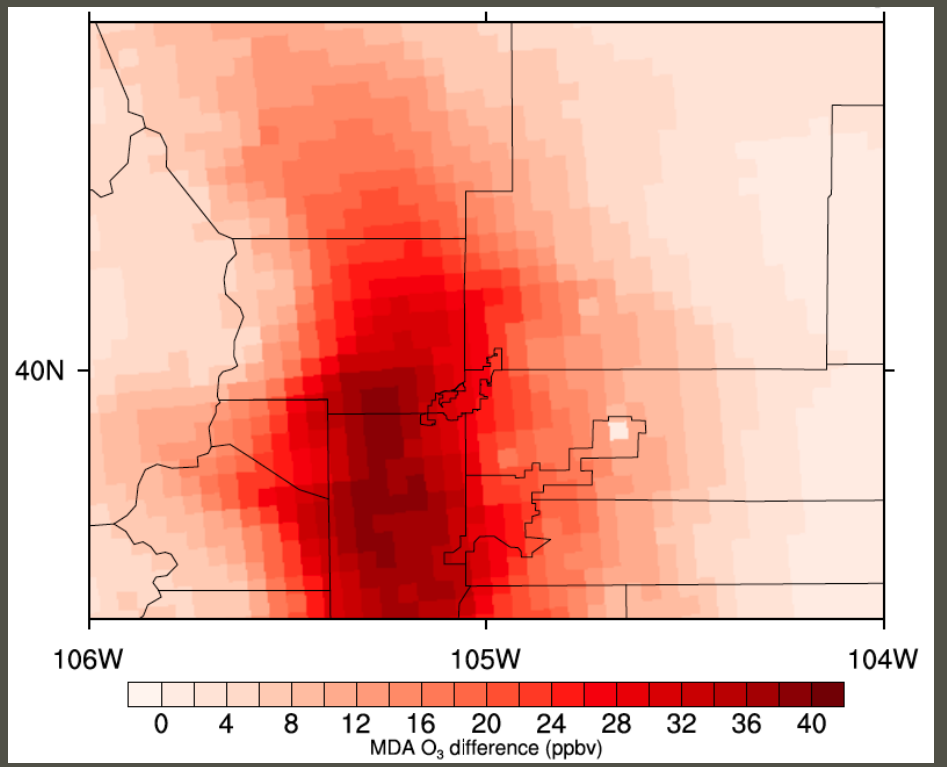
12 August 2014

On high-ozone days, locally produced excess ozone can reach more than 40 ppb, easily exceeding the NAAQS

Posteriori Ozone MDA8
28 July 2014



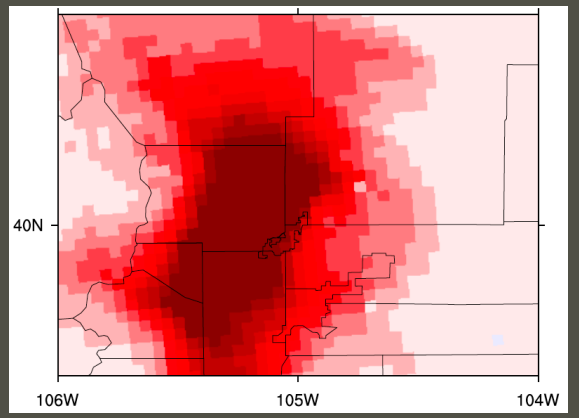
NFRMA Anthropogenic Emission *Contribution*
28 July 2014



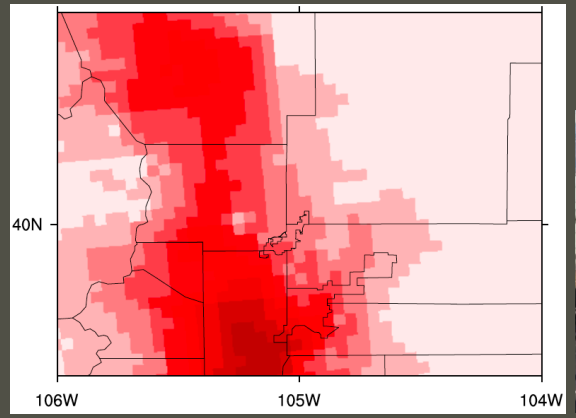
MDA-8 = Median Daily 8-hour Average

Zeroing out individual emission sectors shows that transportation and oil and gas are the main contributors to ozone formation in the NFRMA

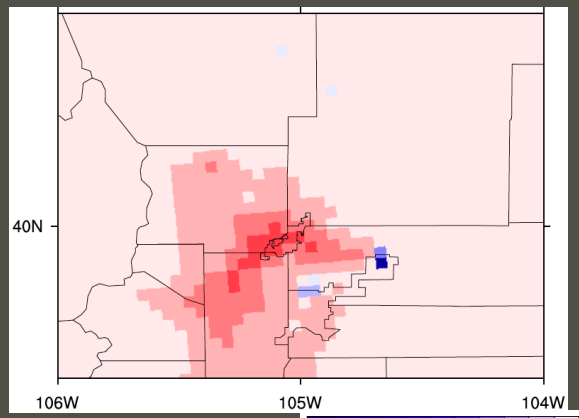
O&G Contribution



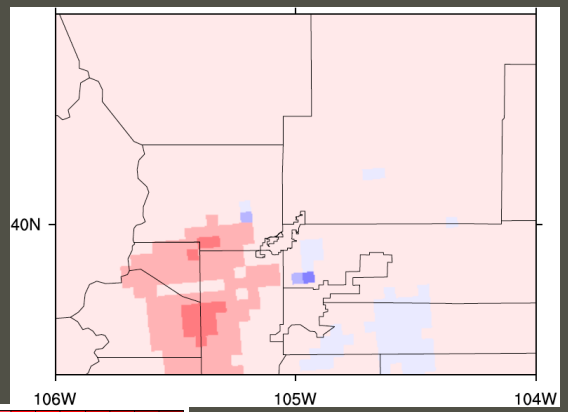
Mobile Contribution

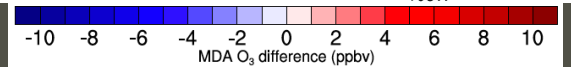


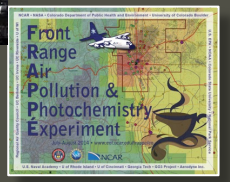
Industrial Contribution



CEM Contribution







28 July 2014

FRAPPÉ provided useful and actionable data to the CDPHE and the public

- Brought together a very large team to address a timely problem
- Raised public awareness through numerous outreach events
- Published a campaign overview paper summarizing all results
- Produced a report to CDPHE, 20+ publications
- Defined steps necessary to address AQ in the NFRMA and the impact on the adjacent mountains, including RMNP
- Elevated image of NCAR / ACOM capabilities and expertise in public and regulatory stakeholder community

FRAPPÉ open house, NCAR RAF

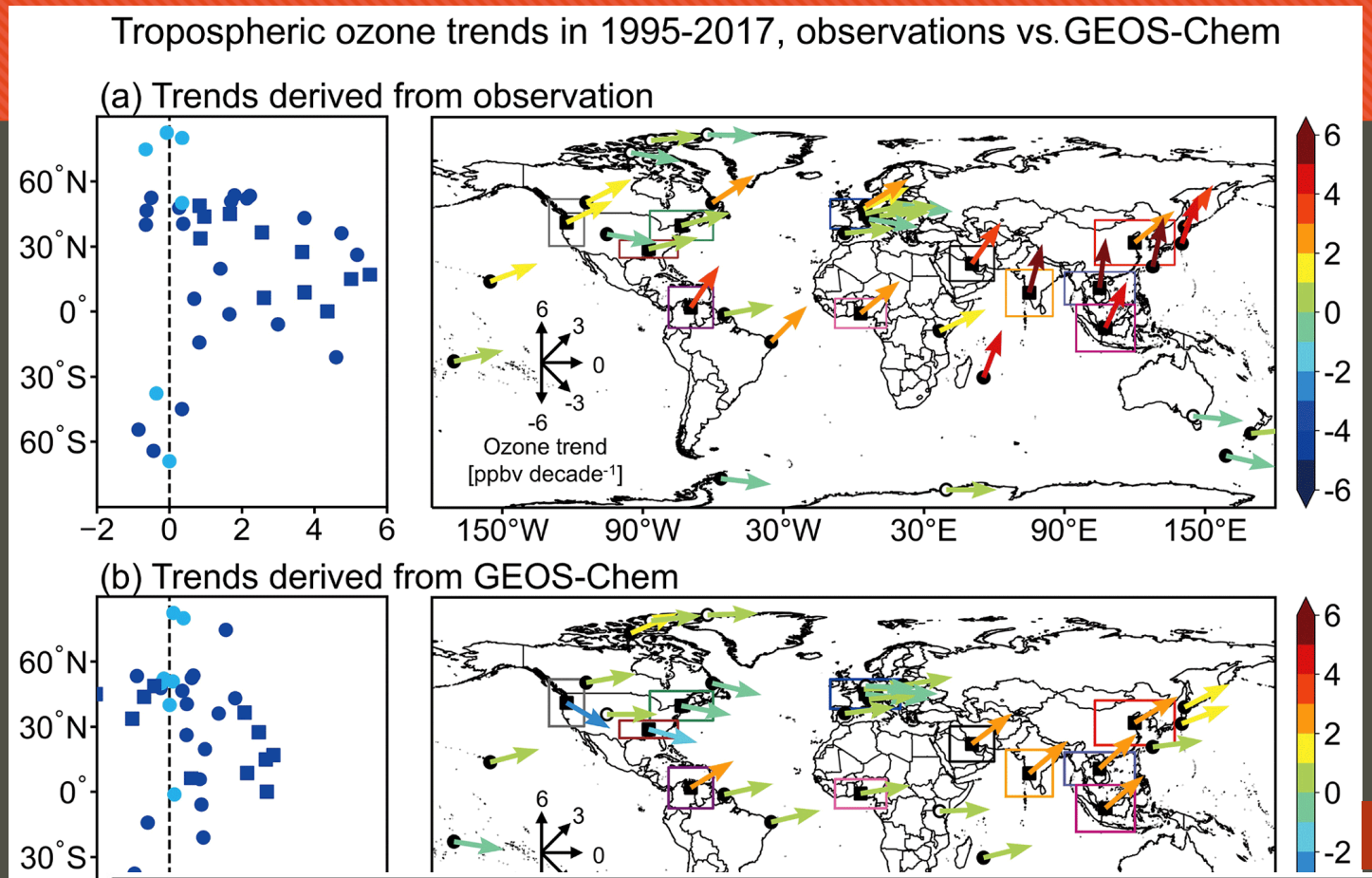
Pfister and Flocke, 2017, Flocke et al., 2020

What has changed in the last decade?

- Continued growth and increases in traffic
- Post pandemic culture changes (deliveries)
- Increased truck traffic
- Emission reductions from O&nG industry (but yet to be evaluated)
  - Have emission regulations helped?
  - Increasing production
- Some older vehicles aged out of the fleet – general trend towards cleaner light duty vehicles
- Increased construction activities and emissions
- Commuter traffic reduced during pandemic and post-pandemic, but seems to have recovered to pre pandemic levels
- Rising housing costs near employment centers increases commuting
- Efforts to shifting commuter behavior overall not very successful

"Background" ozone

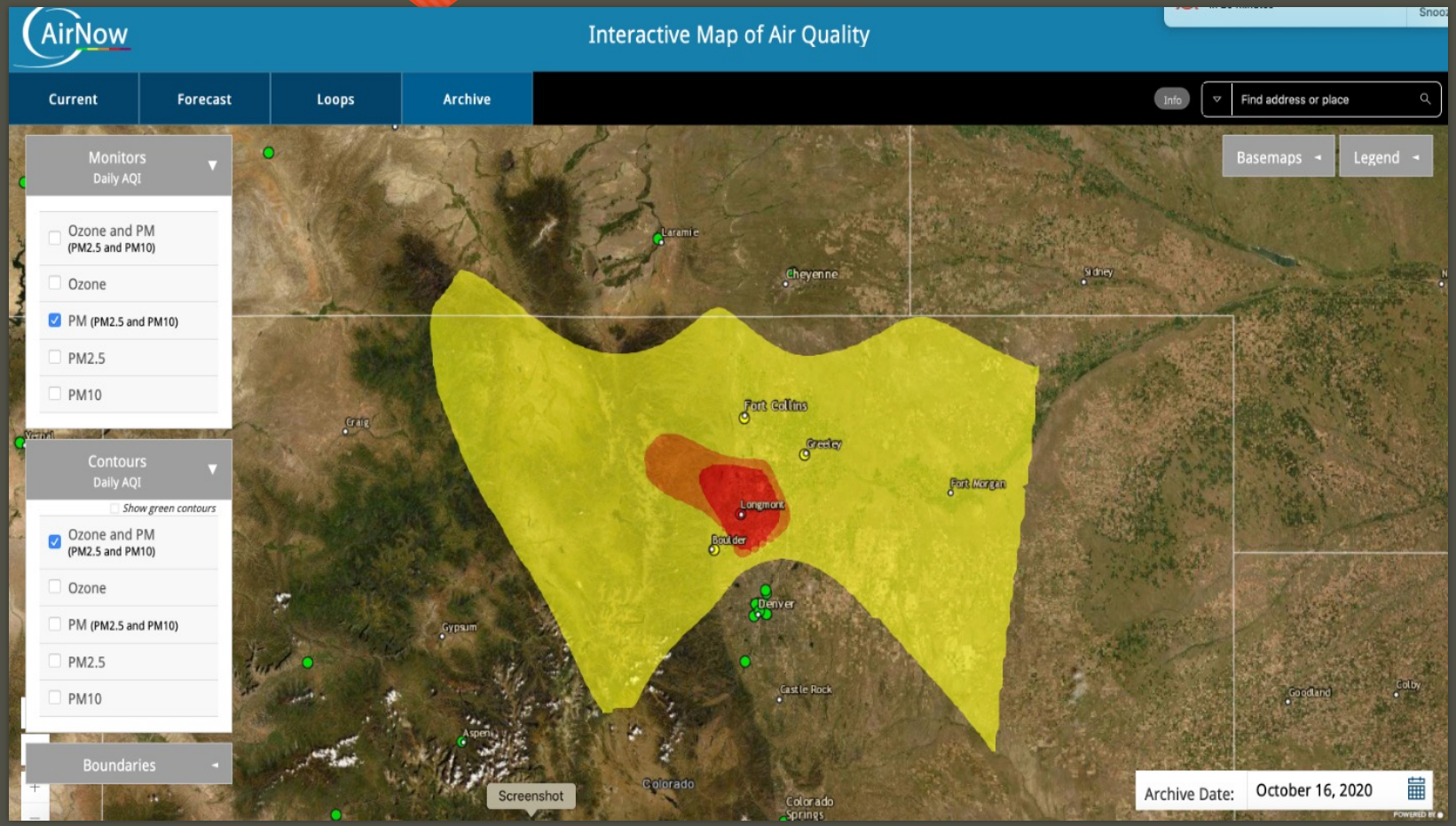
Wang et al ,2022



- Ozone trends for NA continent have been mostly flat for the last decade
- FRAPPÉ flights show a regional ozone background of ~45 ppb in the free troposphere (measured by the C-130 in synoptic westerly winds above the continental divide)
- FRAPPÉ showed that the excess ozone pushing the Front Range into non compliance is locally produced.

			Ozone sondes		GEOS-Chem model	
United States	Ozonesonde	Boulder ESRL HQ (CO)	-0.64 ± 0.34	< 0.01	0.009 ± 0.35	0.96
	IAGOS	Eastern North America	0.96 ± 0.13	< 0.01	-0.70 ± 0.12	< 0.01
	IAGOS	Southeast US	0.86 ± 0.22	< 0.01	-1.02 ± 0.16	< 0.01
	IAGOS	Western North America	1.67 ± 0.32	< 0.01	-2.03 ± 0.37	< 0.01

Wildfires



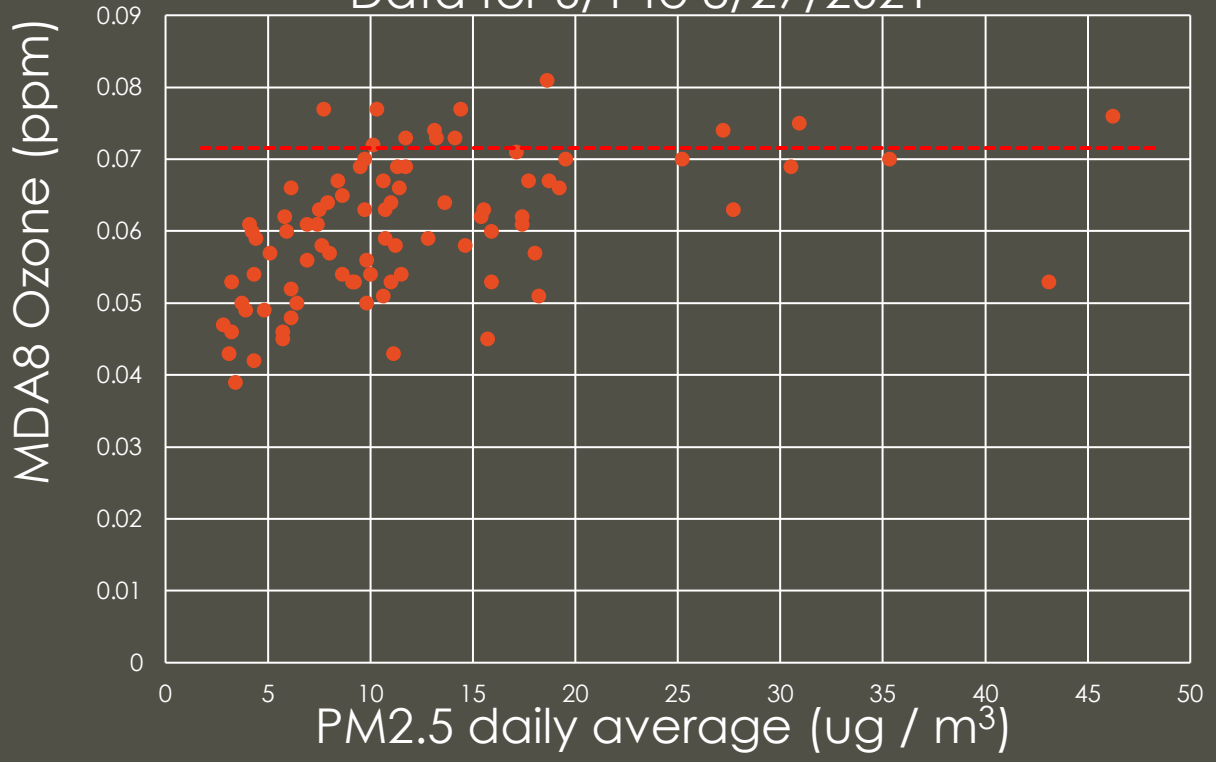
- Main AQ impact is PM
- Wildfires also emit large amounts of VOC, NOx more variable
- Potential for ozone formation, but…
- PM block UV light, slows local ozone production

Longmont area impacted by smoke from Cameron Peak / East Troublesome fires on 10/16/2020

Ozone contribution from wildfires appears small

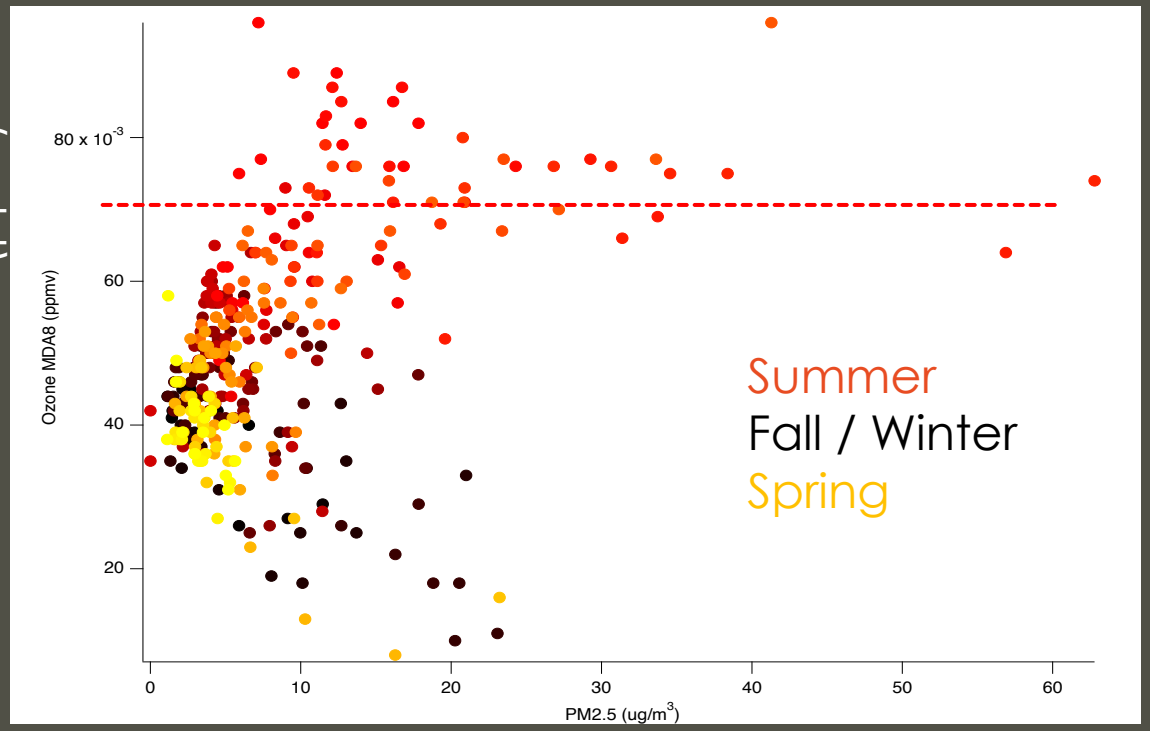
CAMP Site 18th+Broadway Denver

Data for 6/1 to 8/27/2021



Chatfield Reservoir monitoring site

2021 Average daily data



Red line is O3 NAAQS

Ozone contribution from wildfires appears small

- High PM episodes this summer coincide with high ozone in all locations
  - The same meteorological conditions that bring western WF smoke to the NFRMA (e.g., high pressure over the great basin) are also the most conducive conditions for high ozone due to subsidence conditions without strong meteorological forcing.
- However, high ozone in Front Range is also observed when PM was not significantly elevated. At Chatfield (which is a receptor site for urban photochemical smog from Denver) higher ozone was observed during lower PM episodes
- This is a Q&D analysis of a small data set and it compared 8-hour ozone to 24-hour PM, which would need to be averaged over the MDA8 period to be accurate. However, the fire smoke PM episodes we had this summer often extended over several days so this likely is not a large source of uncertainty.
- This preliminary analysis shows
  - The NFRMA doesn't require wildfire influence to exceed ozone standards
  - Ozone enhancements from wildfires in the NFRMA appear small small
- Similar conclusions resulted from a preliminary data analysis for Broomfield monitoring program

Monitoring / SIP planning

- State relies largely on a relatively small number of ground observations
- Mostly PM and ozone, very few continuous NOx and VOC observations
- Rigid, prescribed modeling systems without thorough verification through observations
- Emission inventory evaluations needed on a regular basis
- Huge task that requires adequate funding and help from the scientific community
- Scientists and facilities in the Front Range are among the top in the country for air quality research
- Putting together a project like FRAPPÉ requires several years of planning
- AQE is a great start to involve scientific community
  - Data portal is an excellent cause
  - Funding for measurements and AQ model evaluation

Monitoring Recommendations

- Establish measurement program for emission inventory verification
  - Will require aircraft measurements (could be supplemented by UAS)
  - Some can be done via remote sensing
  - Emphasis on O&nG extraction, trucking, variable emissions from large industrial operations
- Establish mechanism to make use of geostationary satellite data (TEMPO)
  - Data assimilation
  - Emission verification
  - Help with identification of super emitters

Acknowledgments

Gabi Pfister

FRAPPÉ and DISCOVER – AQ science teams

Participating and funding organizations