Aerosols and Meteorology

1) Background

2) Aerosol and precipitation

3) Aerosol effects on lightning

4) Smoke and severe storms

Lecture 4: Smoke and Severe Storms

- Aerosol-Radiation Interactions Affecting Storm Environments, specifically a tornado outbreak
  - Saide et al. (2015)
- Aerosol-Cloud Interactions in the context of wildfire smoke plume ingested into a storm

Aerosol Effects on Clouds and Precipitation
(from lecture 1)

- Do increased aerosol number concentrations increase or decrease precipitation in storms?
- In convective clouds?
- Severe convection?   hurricanes, tornadoes

➢ Combining cloud physics and storm dynamics

Tuscaloosa, Alabama, on Wednesday, April 27, 2011
http://www.theatlantic.com/photo/2011/04/storms-tornadoes-devastate-the-south/100055/

Aerosols and Radiation
(lecture 1)

- Aerosols scatter solar radiation cooling the atmosphere (sulfate, nitrate, sea salt)
- Aerosols absorb solar radiation heating regions of the atmosphere (BC, dust, BrC)

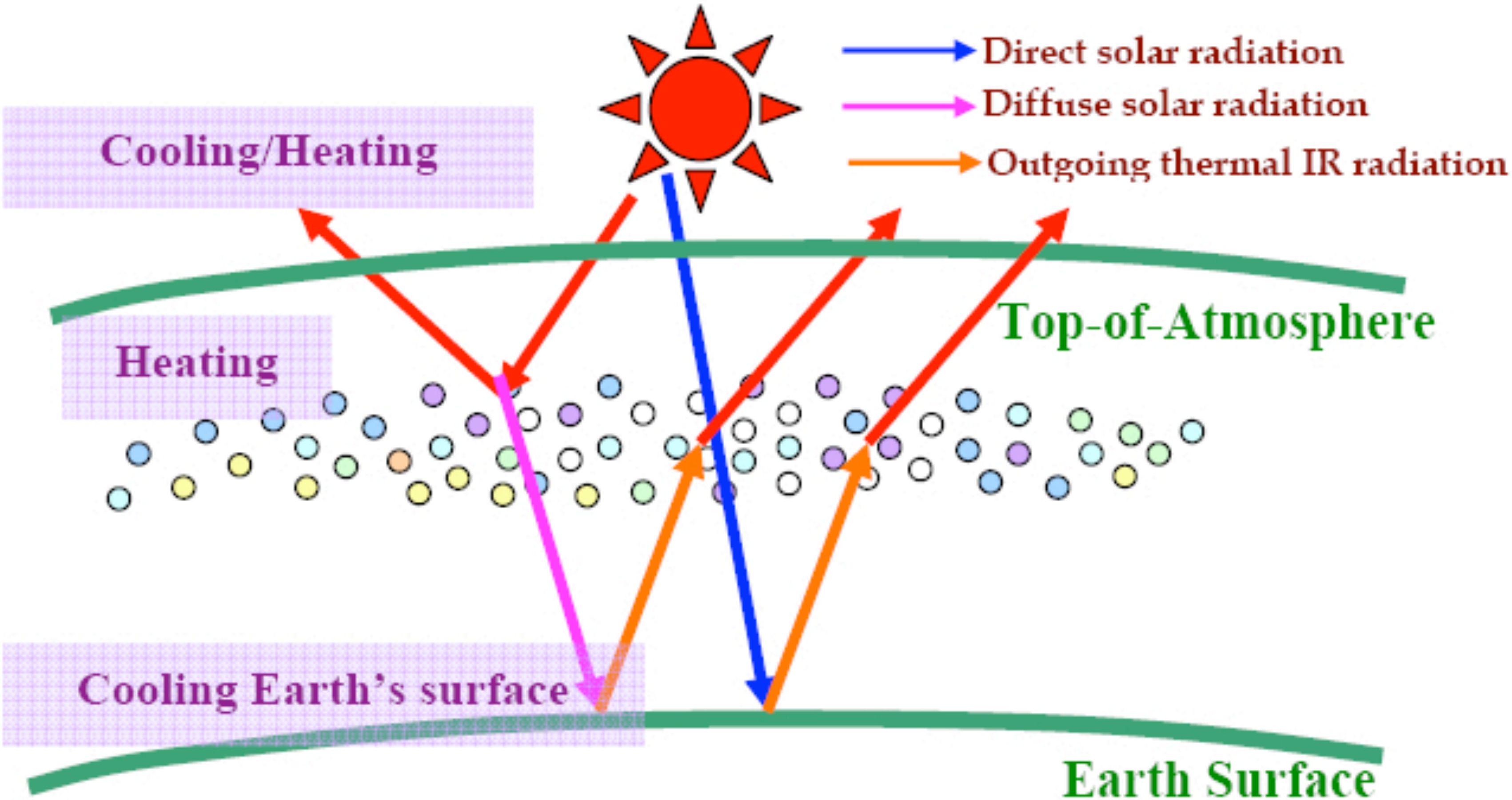
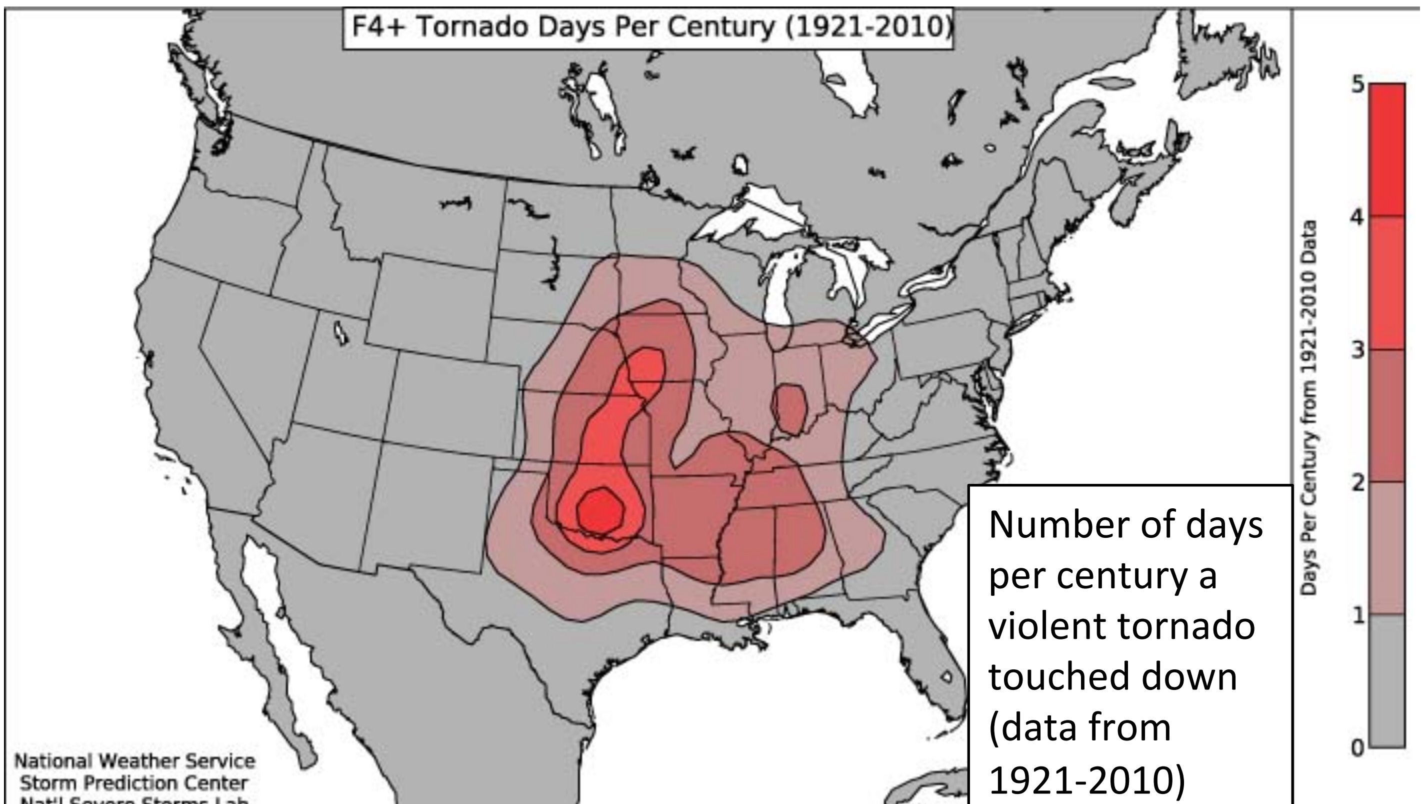


Image from S. Tripathy, IIT-Kanpur

Smoke Effects on Tornado Severity

- Severe storms and tornadoes occur most frequently during April-May in the southern and central U.S.
- Biomass burning in Central America also occurs during this time
- Periodically smoke from Central America is transported to the U.S.



Number of days per century a violent tornado touched down (data from 1921-2010)

Doswell et al. 2012 *Weather*

Smoke Effects on Tornado Severity

Saide et al. (2015) Geophys. Res. Lett.

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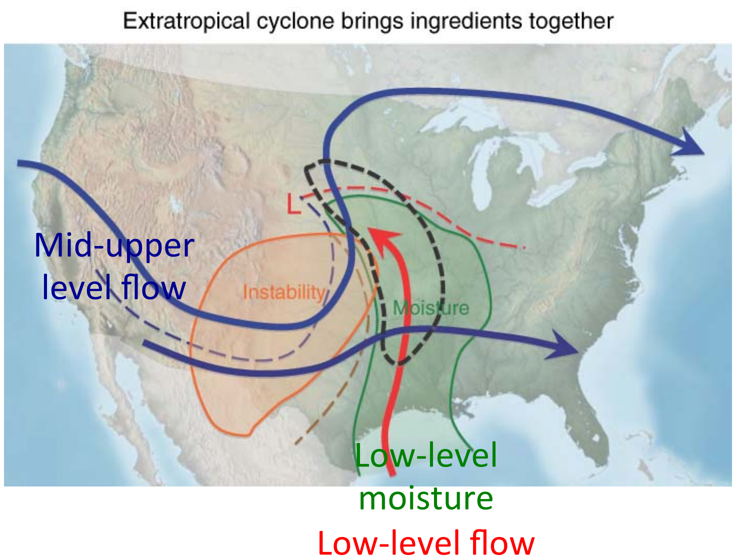
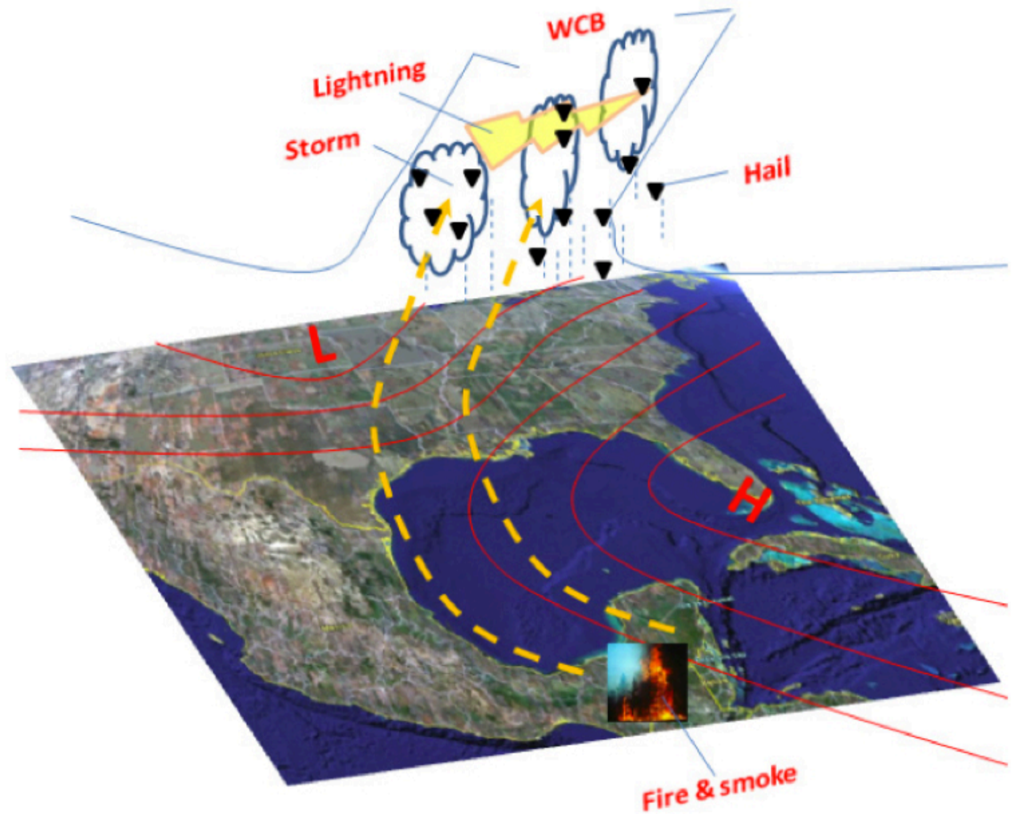


Doswell et al. 2012 *Weather*



Wang et al. 2009 *Monthly Weather Review*

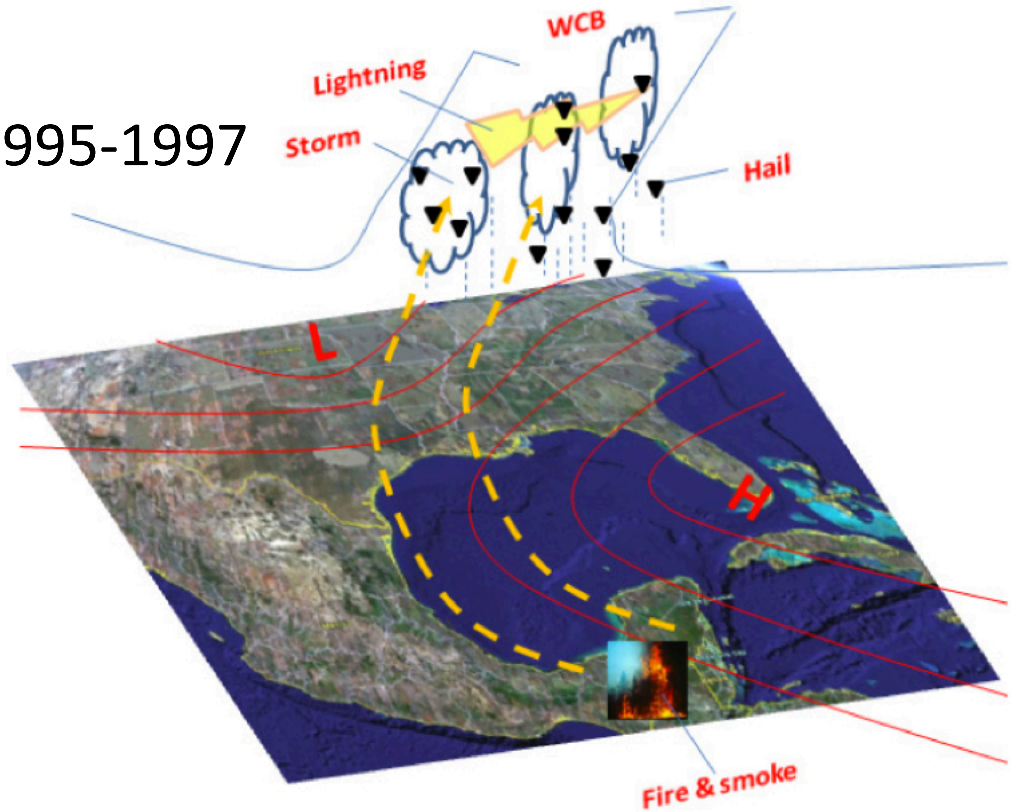
Effect of Pollution from Central American Fires on CG Lightning in May 1998 (Lecture 3)

Spring 1998

- El Nino: 1997-1998
- Central American Fires

Compared May 1998 to May 1995-1997 and 1999

- Percentage positive flashes
- Peak currents
- Number of strokes per flash

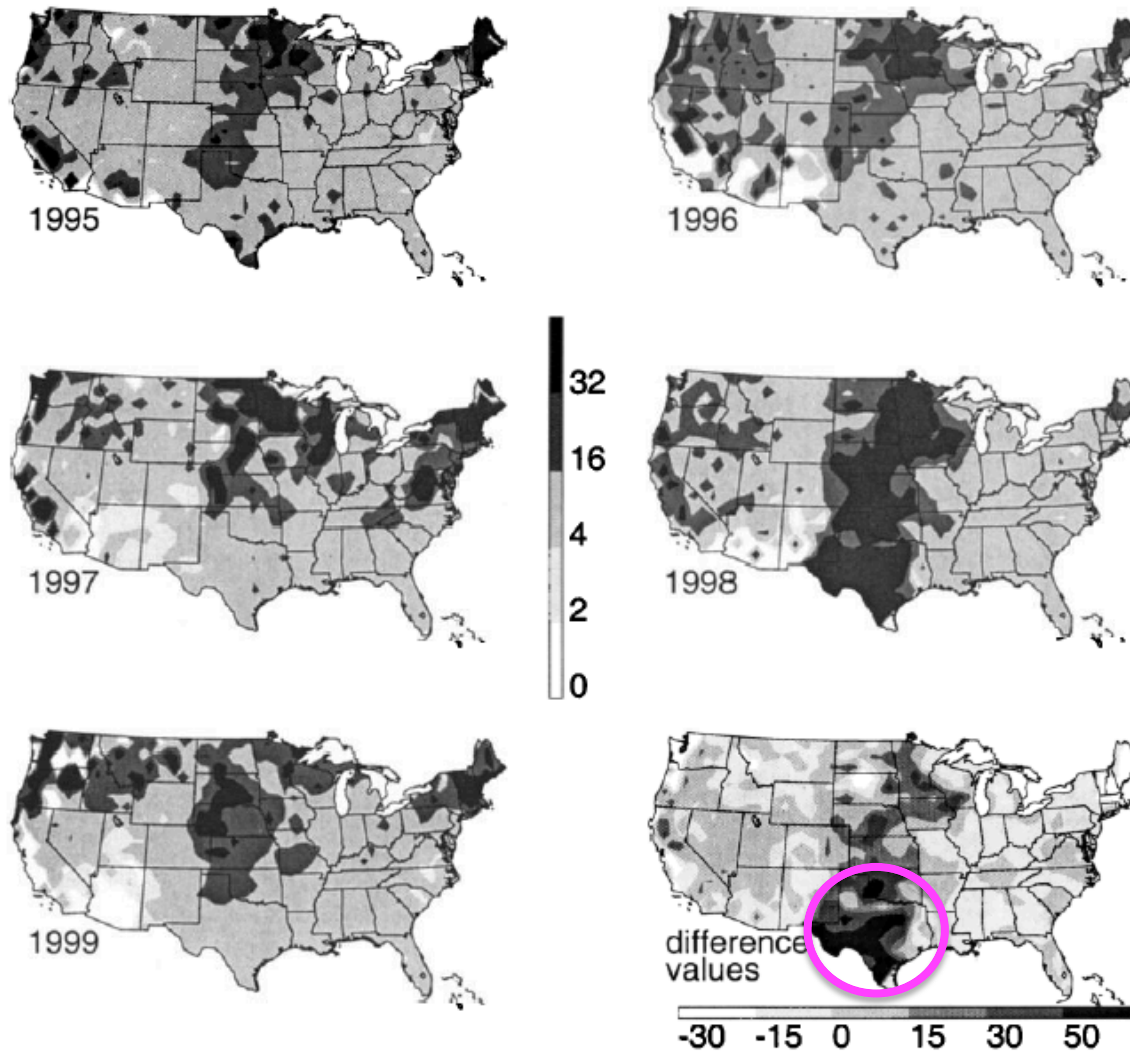


Murray et al. (2000) *Geophys. Res. Lett.*

Effect of Pollution from Central American Fires on CG Lightning in May 1998 (Lecture 3)

- Percentage positive flashes by year ↑
- Peak currents
  - Negative flash ↓ by 12 kA
  - Positive flash ↑ by 20 kA
- Number of strokes per negative flash ↓

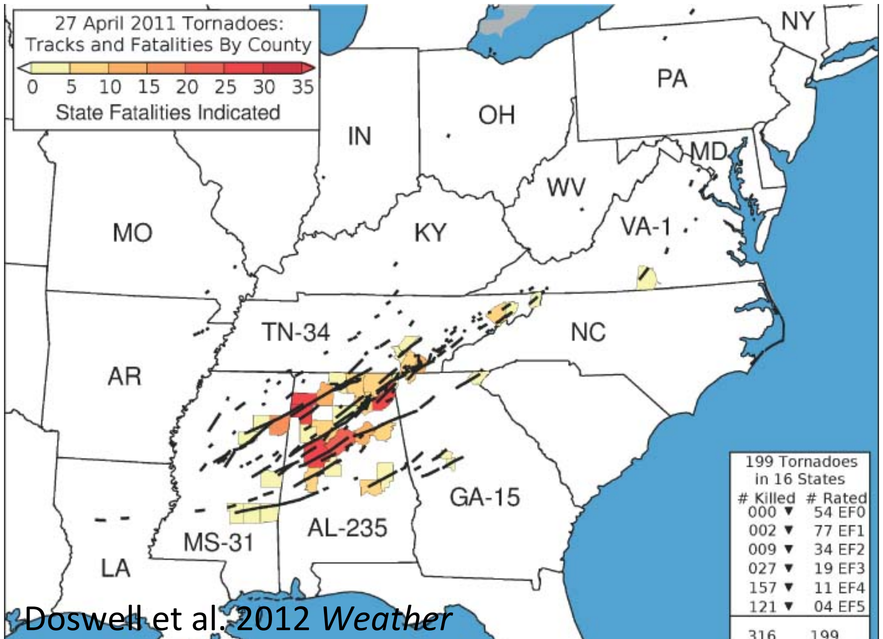
→ Suggest aerosols from fires may be affecting lightning characteristics



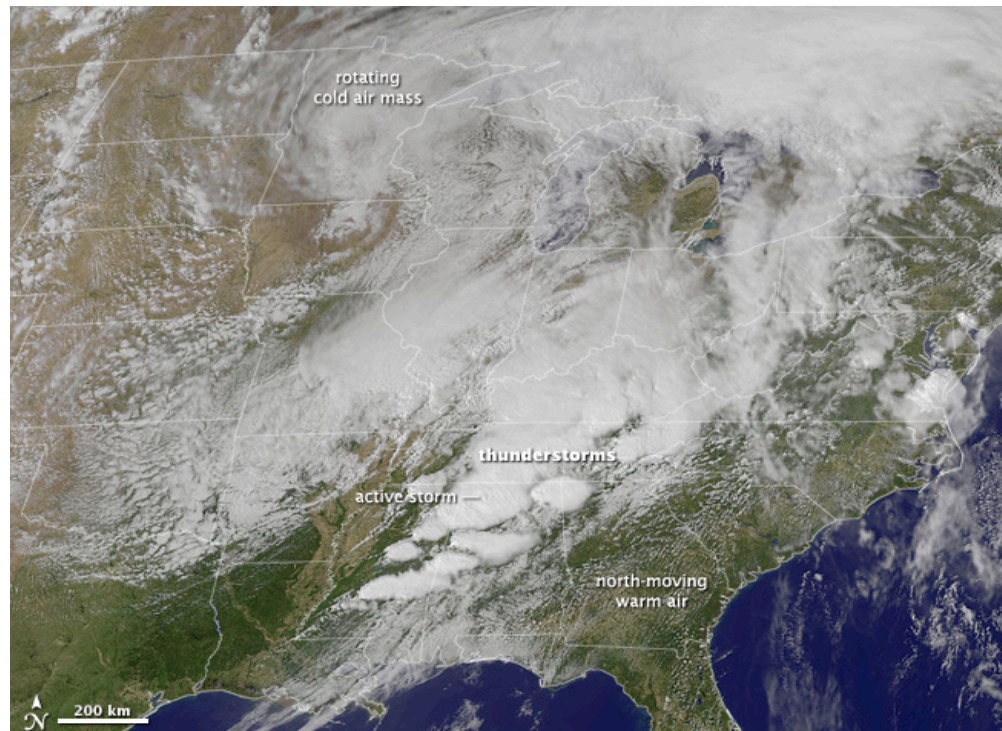
Murray et al. (2000) *Geophys. Res. Lett.*

27 April 2011 Tornado Tracks

122 tornadoes resulting in 313 deaths; 15 tornadoes were violent (EF4 or EF5)



Doswell et al. 2012 *Weather*

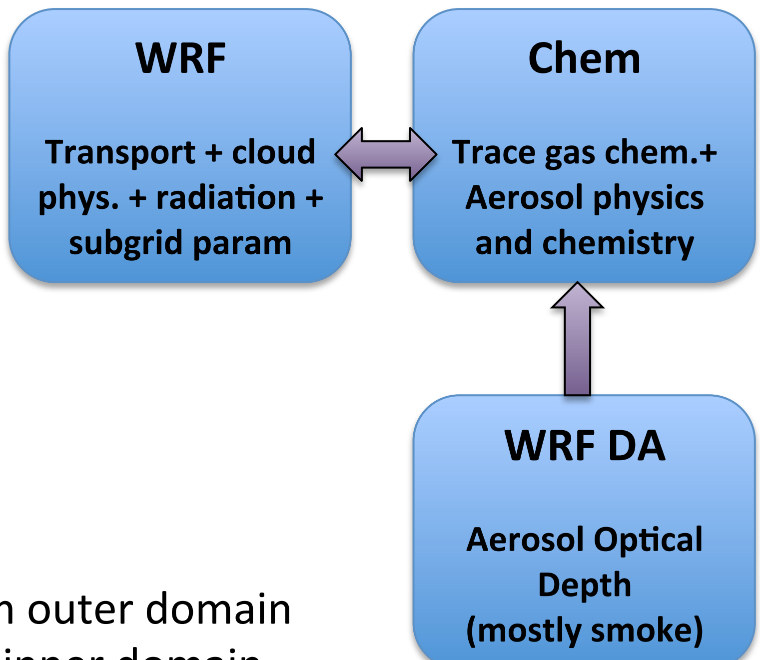


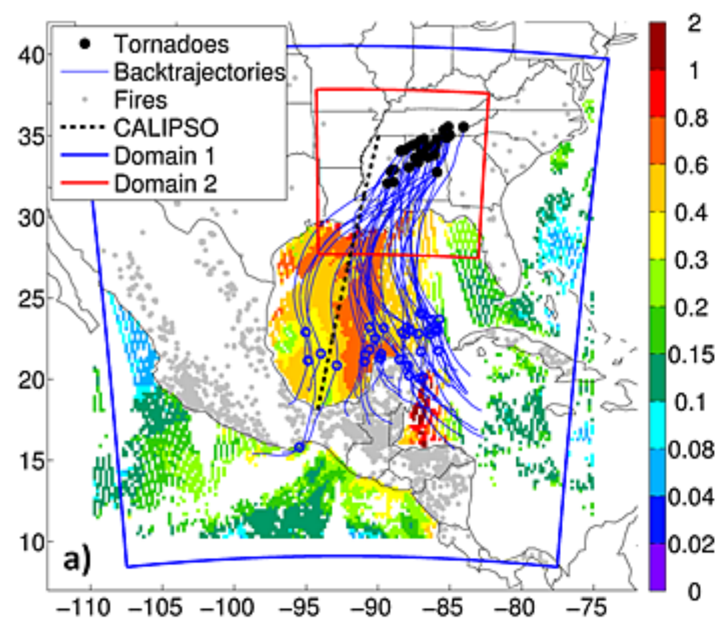
http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=50347

Smoke from biomass burning in Central America affecting April 2011 tornado outbreak in Alabama

Saide et al. (2015) *Geophys. Res. Lett.*

- Use WRF-Chem with data assimilation and observations
  - ➢ How smoke affects parameters used to predict severe weather outbreaks
  - ➢ Investigate mechanisms

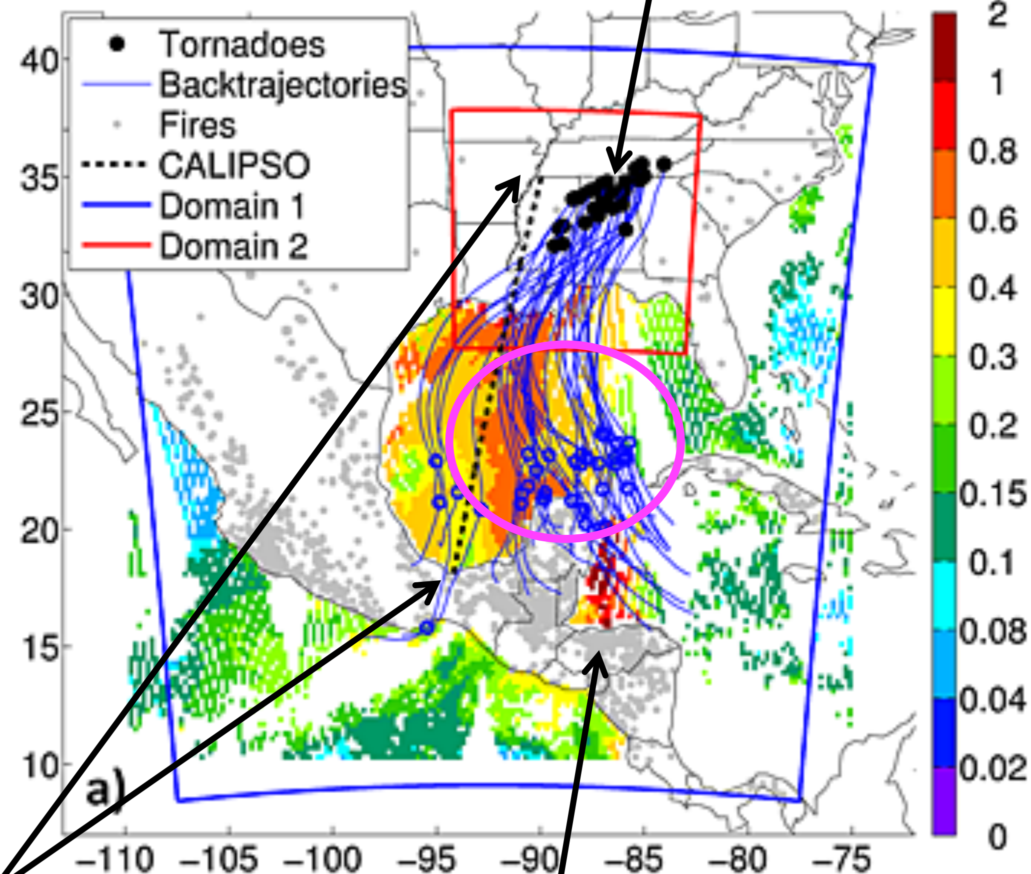




Δx = 12 km outer domain
Δx = 4 km inner domain

Smoke from central America present in region

Tornadoes



Aerosol Optical Depth from satellite data (only for ocean regions)

Warm, moist air

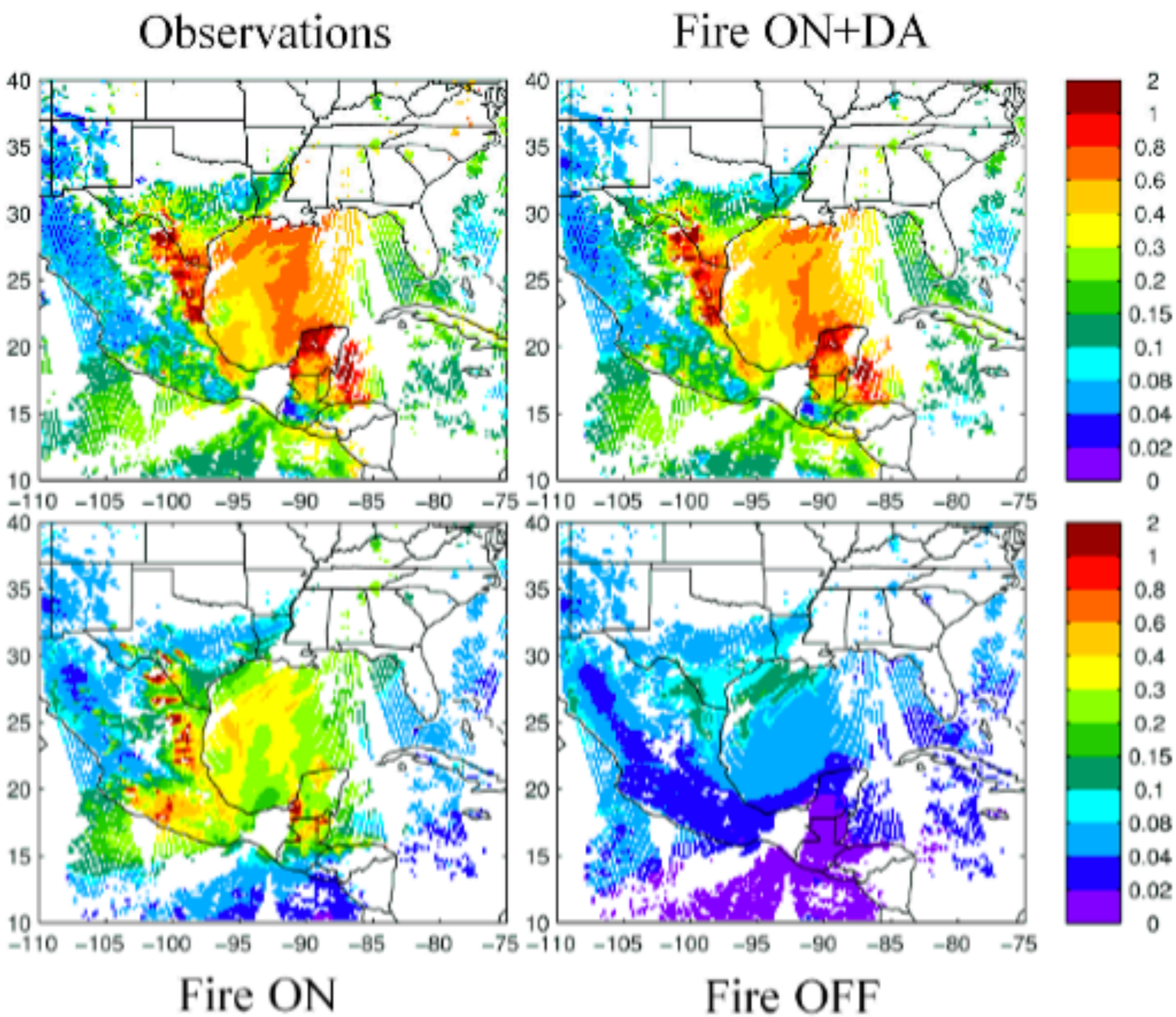
And smoke

CALIPSO track

Fires
(gray dots)

Saide et al. 2012 *Geophys. Res. Lett.*

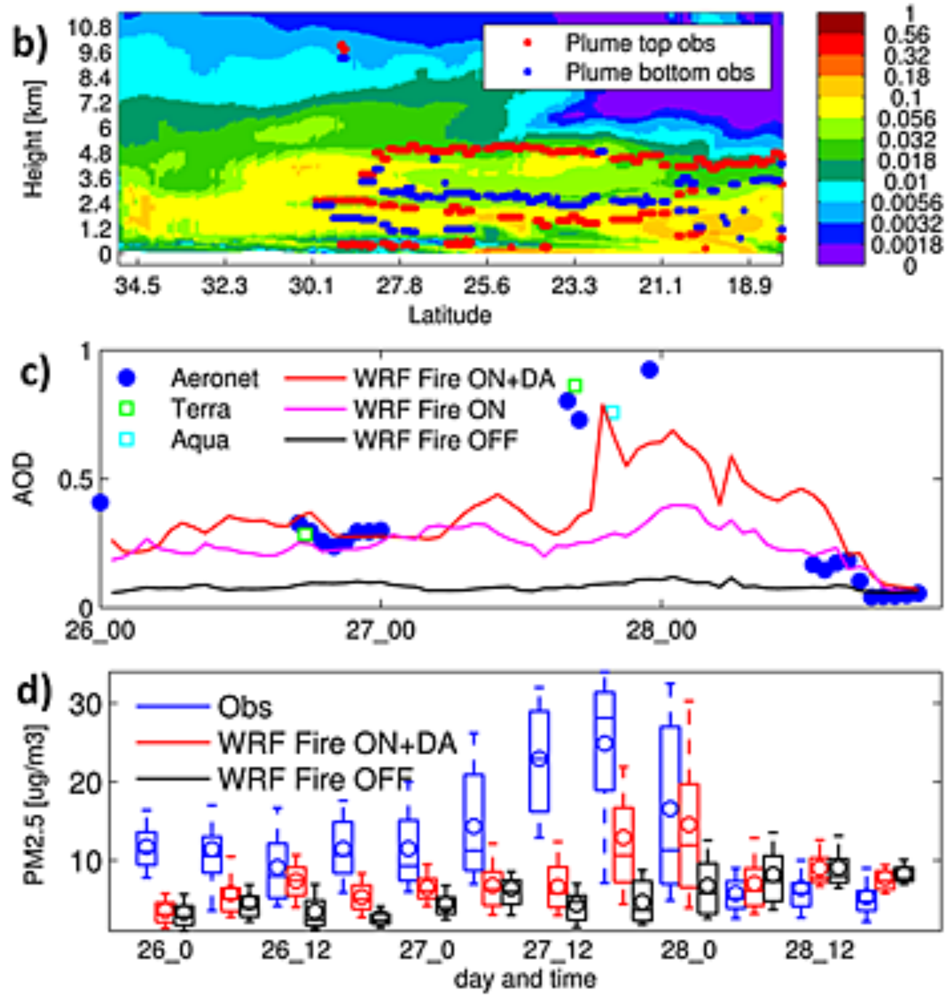
WRF-Chem represents smoke well with biomass burning emissions on and data assimilation of AOD



Saide et al. 2012 *Geophys. Res. Lett.*

WRF-Chem represents smoke well with biomass burning emissions on and data assimilation of AOD

Vertical location of smoke plume represented well when compared to CALIPSO lidar data



BB emissions and DA needed to match AOD

Particulate Matter concentrations underestimated at surface

Saide et al. 2012 *Geophys. Res. Lett.*

Significant Tornado Parameter (STP) used to forecast tornado occurrence and severity

$$\mathrm{STP} = \left(\frac{\mathrm{CAPE}[\mathrm{J/kg}]}{1000[\mathrm{J/kg}]}\right)\left(\frac{0-6\ \mathrm{km\ shear}[\mathrm{m/s}]}{20[\mathrm{m/s}]}\right)\left(\frac{\mathrm{SRH}[\mathrm{m^2/s^2}]}{100[\mathrm{m^2/s^2}]}\right)\left(\frac{2000[\mathrm{m}]-\mathrm{LCL}[\mathrm{m}]}{1500[\mathrm{m}]}\right)$$

CAPE = convective available potential energy

Low level wind shear

SRH = storm relative helicity

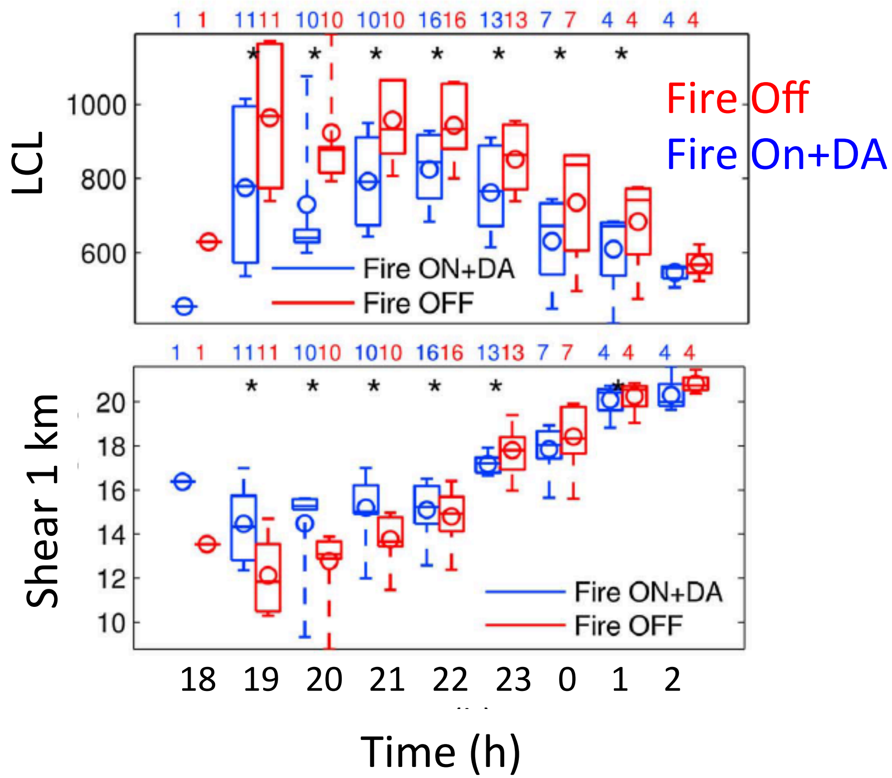
LCL = lifting condensation level

Saide et al. examine effects of smoke on these parameters

Saide et al. 2012 *Geophys. Res. Lett.*

Significant Tornado Parameter (STP) used to forecast tornado occurrence and severity

Time Series of Tornado Parameters

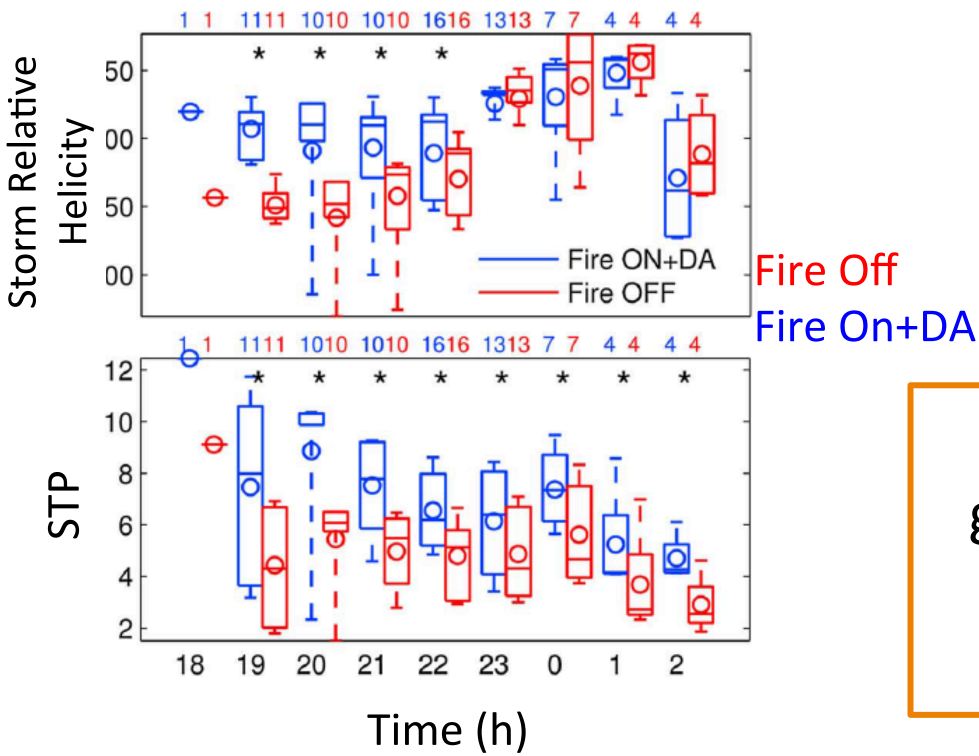


LCL is lower when smoke aerosols are included

Low level wind shear is greater during afternoon hours with smoke aerosols

Saide et al. 2012 *Geophys. Res. Lett.*

Significant Tornado Parameter (STP) used to forecast tornado occurrence and severity



SRH (helicity) is higher during afternoon when smoke aerosols are included

Significant Tornado Parameter is greater when smoke aerosols are included because of LCL and SRH changes

$$STP = \left(\frac{CAPE[J/kg]}{1000[J/kg]}\right)\left(\frac{0-6\ km\ shear[m/s]}{20[m/s]}\right)\left(\frac{SRH[m^2/s^2]}{100[m^2/s^2]}\right)\left(\frac{2000[m]-LCL[m]}{1500[m]}\right)$$

Saide et al. 2012 *Geophys. Res. Lett.*

Components of Significant Tornado Parameter (STP) increase due to smoke aerosols

$$\mathrm{STP} = \left(\frac{\mathrm{CAPE}[\mathrm{J/kg}]}{1000[\mathrm{J/kg}]}\right)\left(\frac{0-6\ \mathrm{km\ shear}[\mathrm{m/s}]}{20[\mathrm{m/s}]}\right)\left(\frac{\mathrm{SRH}[\mathrm{m^2/s^2}]}{100[\mathrm{m^2/s^2}]}\right)\left(\frac{2000[\mathrm{m}]-\mathrm{LCL}[\mathrm{m}]}{1500[\mathrm{m}]}\right)$$

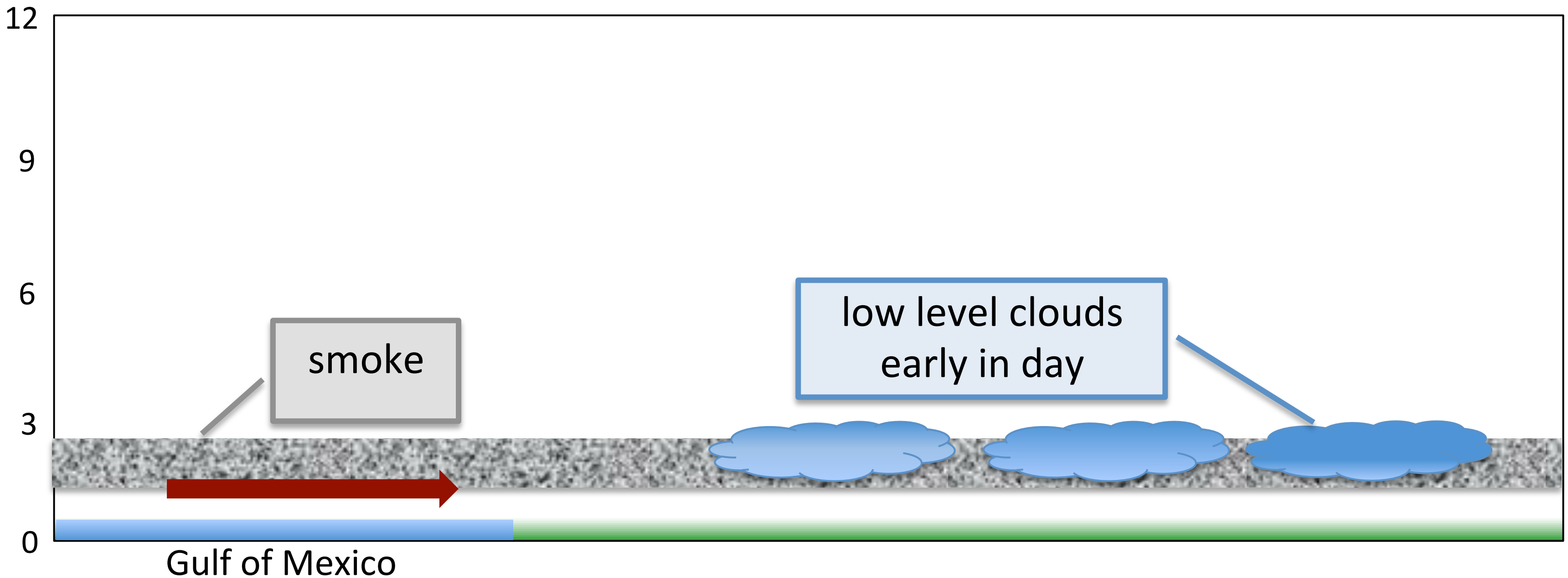
Why does LCL decrease?

Why does low-level shear increase?

Why does storm relative helicity increase?

Saide et al. 2012 *Geophys. Res. Lett.*

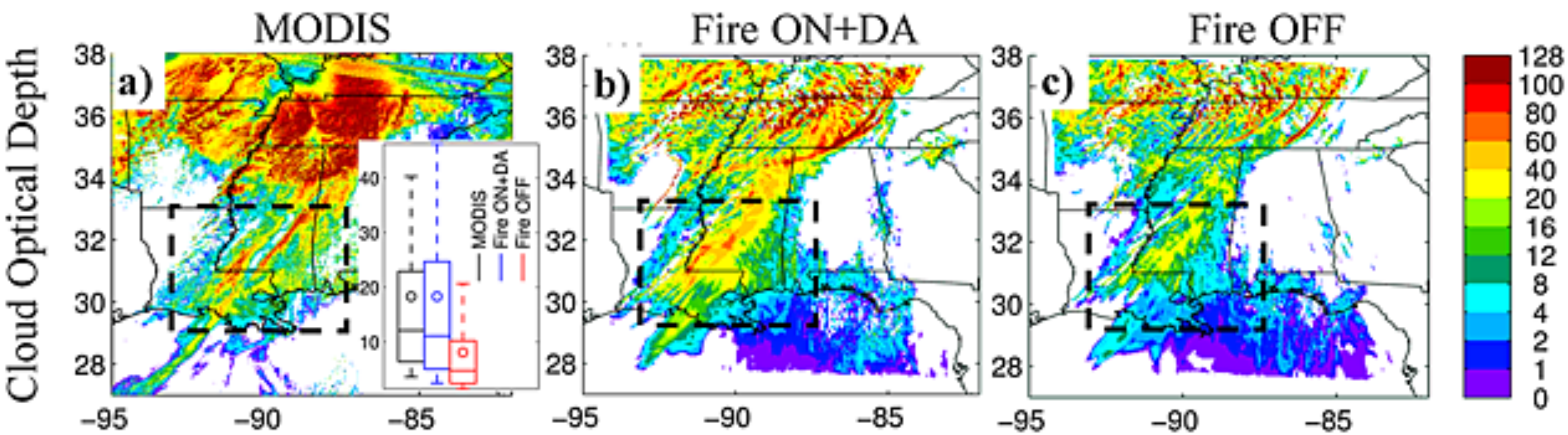
Aerosol – Cloud Interactions Modify Pre-storm Environment



More CCN → More cloud droplets
→ Decreased drizzle rates
→ Increased LWC
→ Increased cloud optical depth

Saide et al. 2012 *Geophys. Res. Lett.*

Cloud Optical Depth



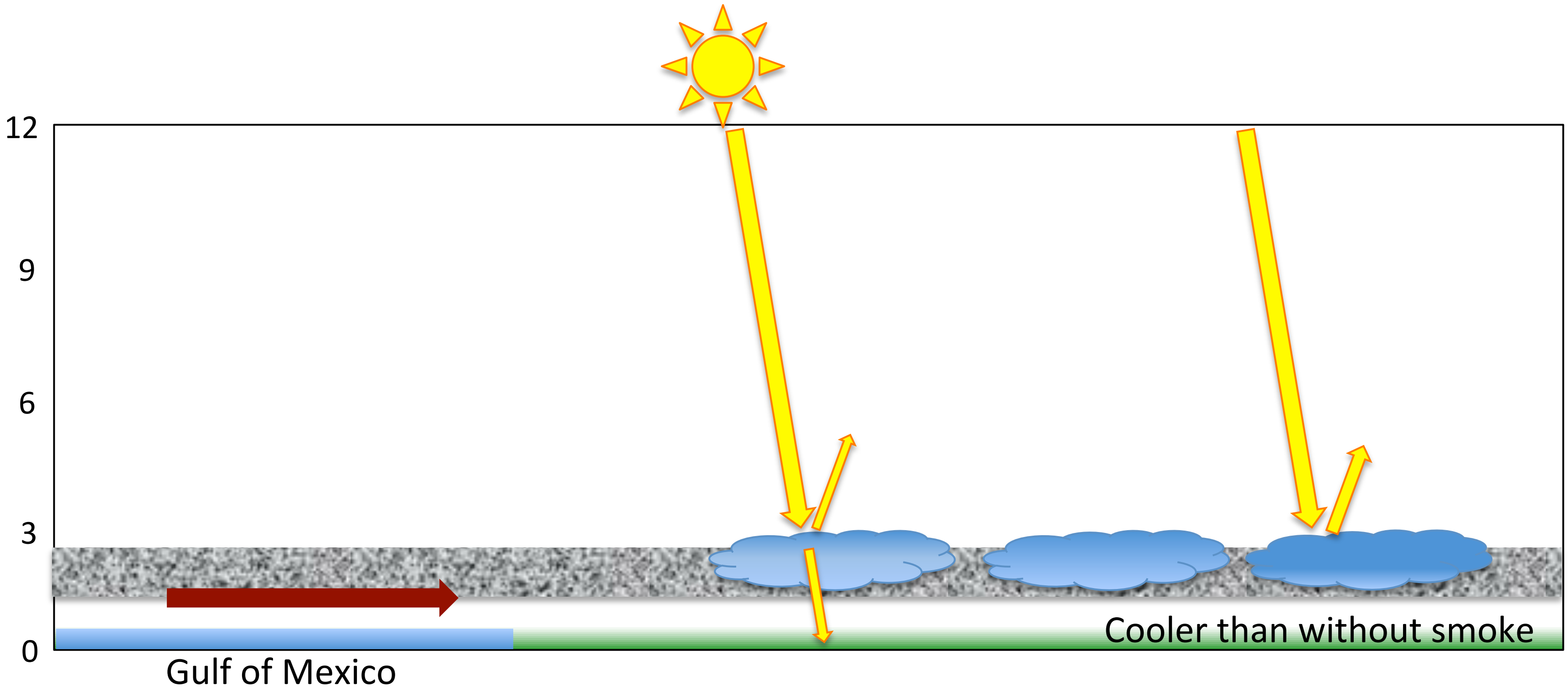
More CCN → More cloud droplets
→ Decreased drizzle rates
→ Increased LWC
→ Increased cloud optical depth

Biomass burning emissions and DA produced greater cloud optical depth

Matches observations better than simulation without smoke aerosols

Saide et al. 2012 *Geophys. Res. Lett.*

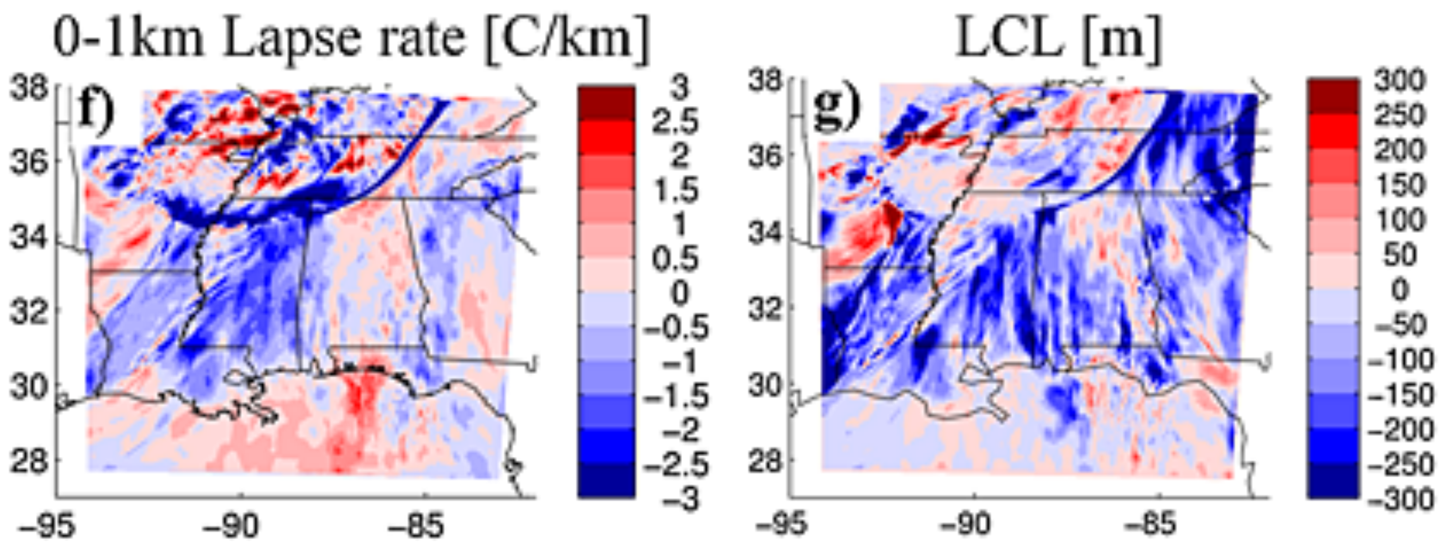
Aerosol – Cloud Interactions Modify Pre-storm Environment



More CCN → More cloud droplets → Decreased drizzle rates → Increased LWC
→ Increased cloud optical depth
→ Reduced solar radiation reaching ground
→ Reduced surface heat fluxes
→ Lower surface temperatures
→ More stable boundary layer

Saide et al. 2012 *Geophys. Res. Lett.*

Low-level Lapse Rate and Lifting Condensation Level



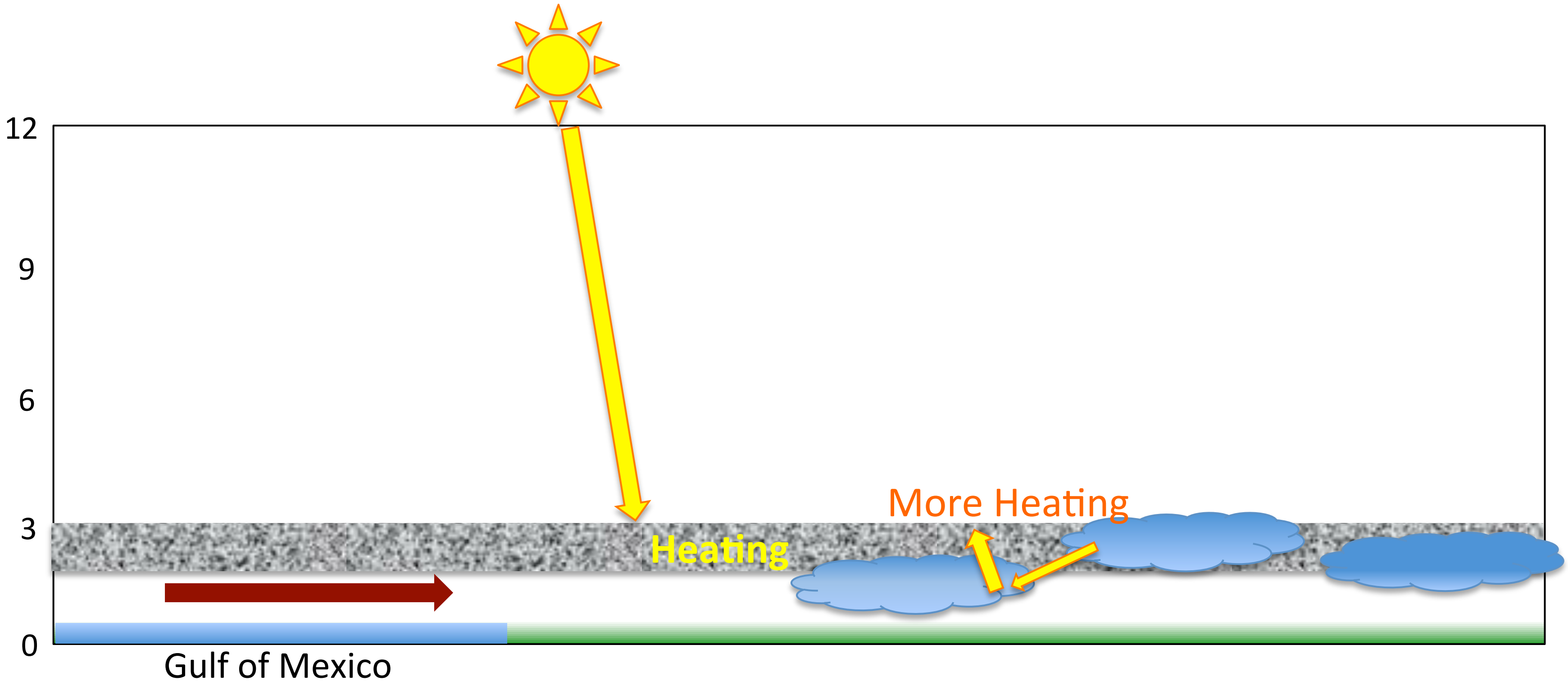
More CCN → More cloud droplets
→ Decreased drizzle rates
→ Increased LWC
→ Increased cloud optical depth
→ Reduced solar radiation reaching ground
→ Reduced surface heat fluxes
→ Lower surface temperatures
→ More stable boundary layer

→ Reduces mixing in BL and lowers cloud base

→ Resulting increased vertical gradients increase low-level wind shear
→ Which affects SRH

Saide et al. 2012 *Geophys. Res. Lett.*

Soot Absorption



Black carbon (soot) was 1-4% of smoke mass

Black carbon contributed to changes in LCL, low-level shear, and SRH for the afternoon tornadoes (as tested by simulation without BC absorption)

Heating by smoke aerosol can also stabilize the atmosphere below the plume

→ Increases capping inversion → reduces entrainment of dry air above BL → moister BL and enhanced cloud cover

Multiple cloud layers reflected light back to smoke plume causing more absorption and heating

Saide et al. 2012 *Geophys. Res. Lett.*

Soot Absorption

WRF-Chem simulations suggest that biomass burning smoke plumes from central America ***may*** contribute to tornado modulation for this April 2011 case

→Aerosol interactions with radiation can affect storm development

Does it happen in other cases? Saide et al (2016) *submitted* examines this question. Stay tuned!

Saide et al. 2012 *Geophys. Res. Lett.*

Wildfire Smoke Plume and Thunderstorm
22 June 2012 DC3 Case

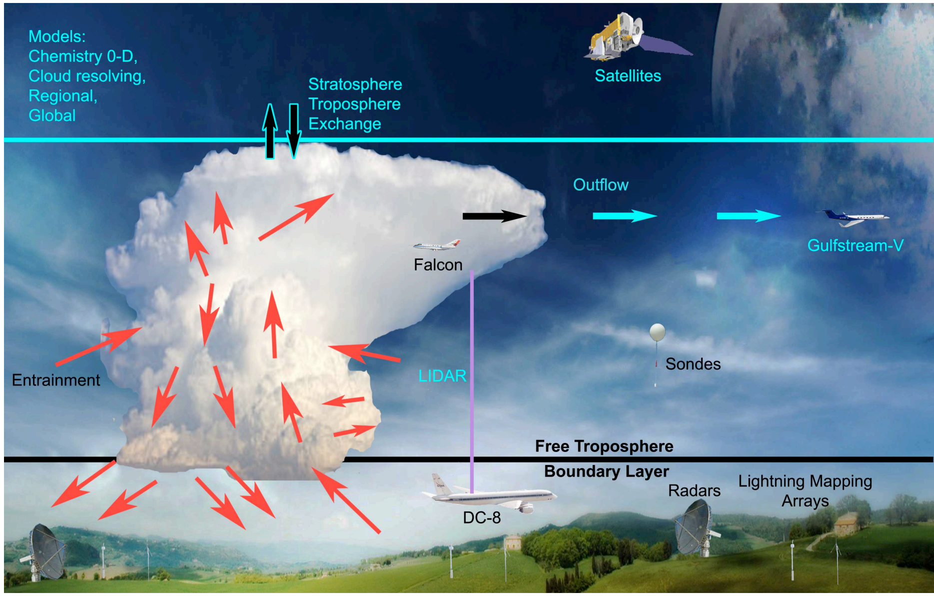
Mary Barth (NCAR), Steven Saleeby, Sue van den Heever (Colorado State Univ.)

Deep Convective Clouds and Chemistry (DC3) Field Campaign

When: May – June 2012

Where: Based Salina, Kansas

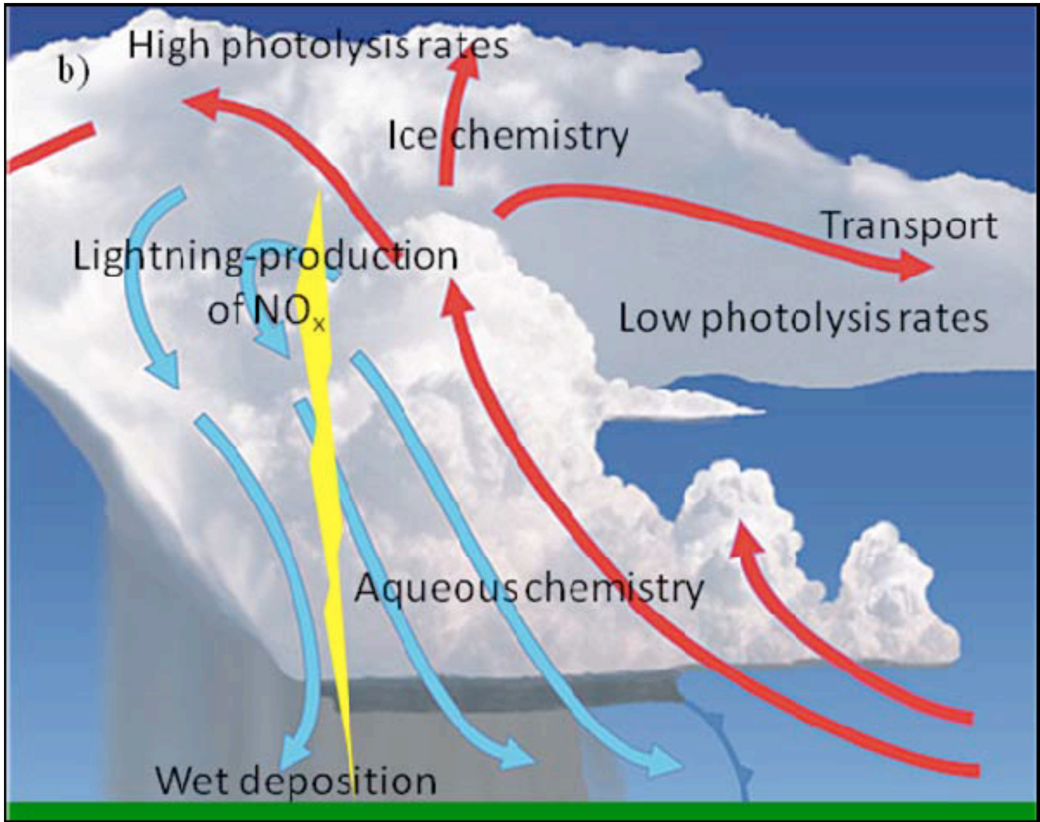
Sampled storms in NE Colorado, W Texas to central Oklahoma, and N Alabama



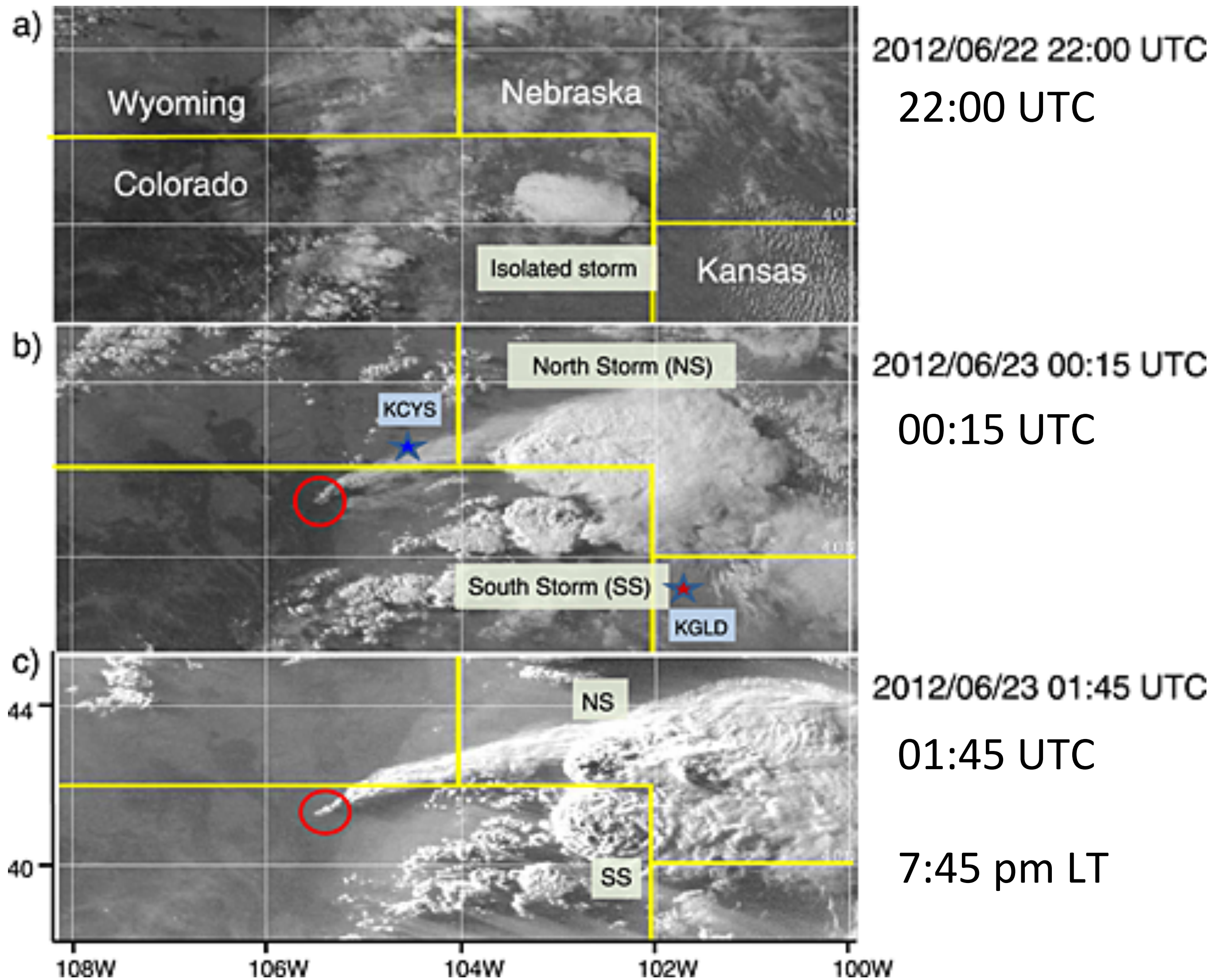
Goals of the Deep Convective Clouds and Chemistry (DC3) Field Campaign

1. ***To characterize thunderstorms and how they process chemical compounds that are ingested into the storm*** (transport, scavenging, lightning, production of NOx from lightning, chemistry)

2. ***To learn how the air that exits the storm in the upper troposphere (UT) changes chemically during the next day*** (chemical aging)



22 June 2012 DC3 Case



22:00 UTC

00:15 UTC

01:45 UTC

7:45 pm LT

From Apel et al. (2015) JGR

22 June 2012 DC3 Case

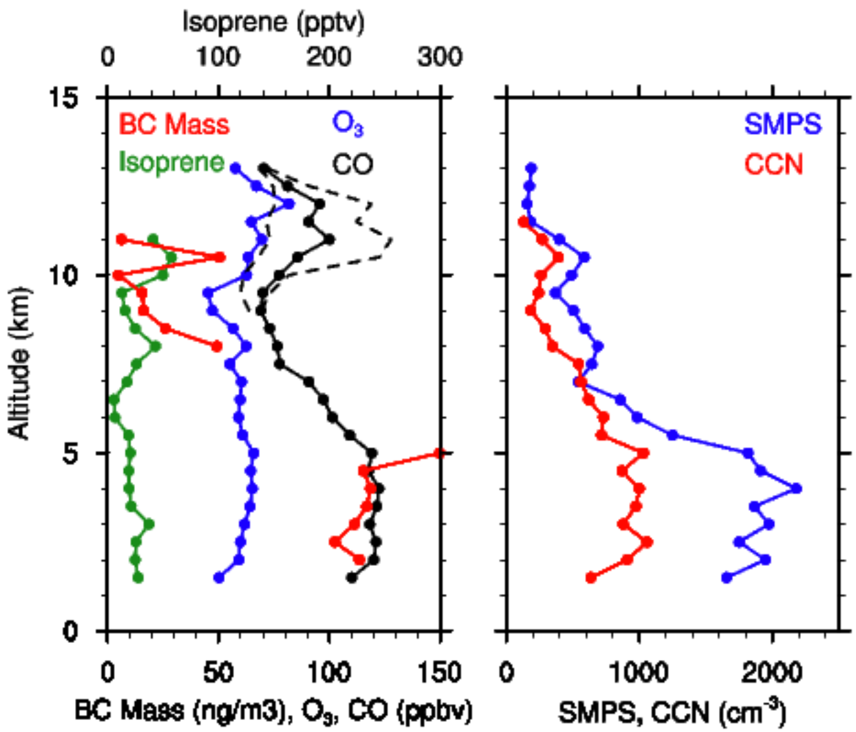
To see movie of radar reflectivity of this case along with flight tracks of NASA DC-8 and NCAR GV aircraft, go to the following link:
http://catalog.eol.ucar.edu/dc3_2012/research/nexrad/20120622/research.NEXRAD.2012062200.flight_track_movie.mov

DC3 data can be found from the following webpage:
https://www.eol.ucar.edu/field_projects/dc3

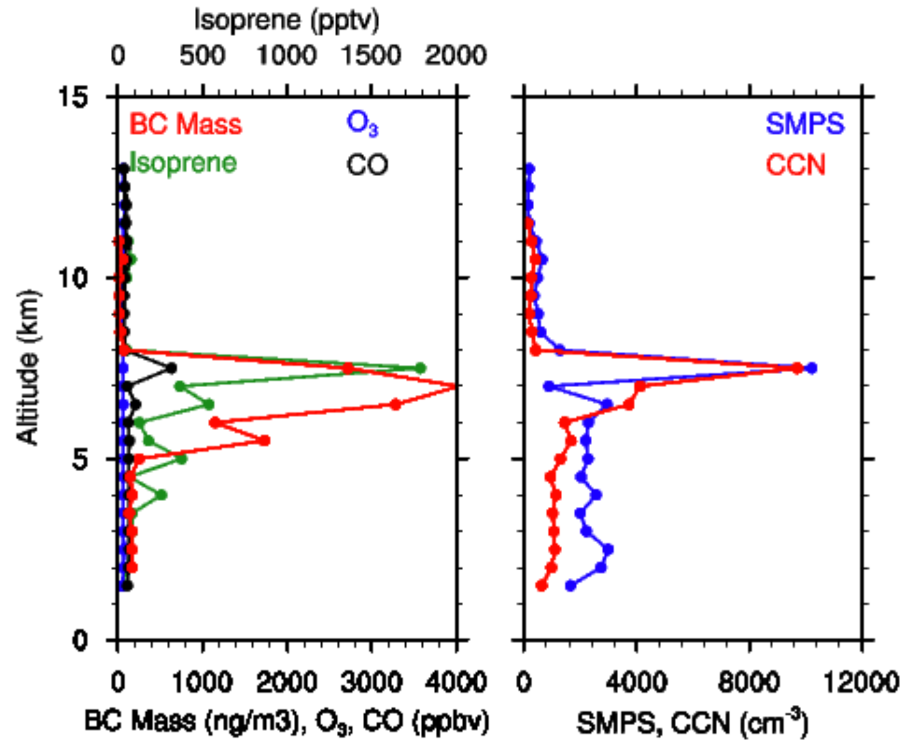
Science highlights can be found here:
https://www2.acom.ucar.edu/dc3

22 June 2012 DC3 Case

Smoke Plumes Removed from Data



Including Smoke Plumes

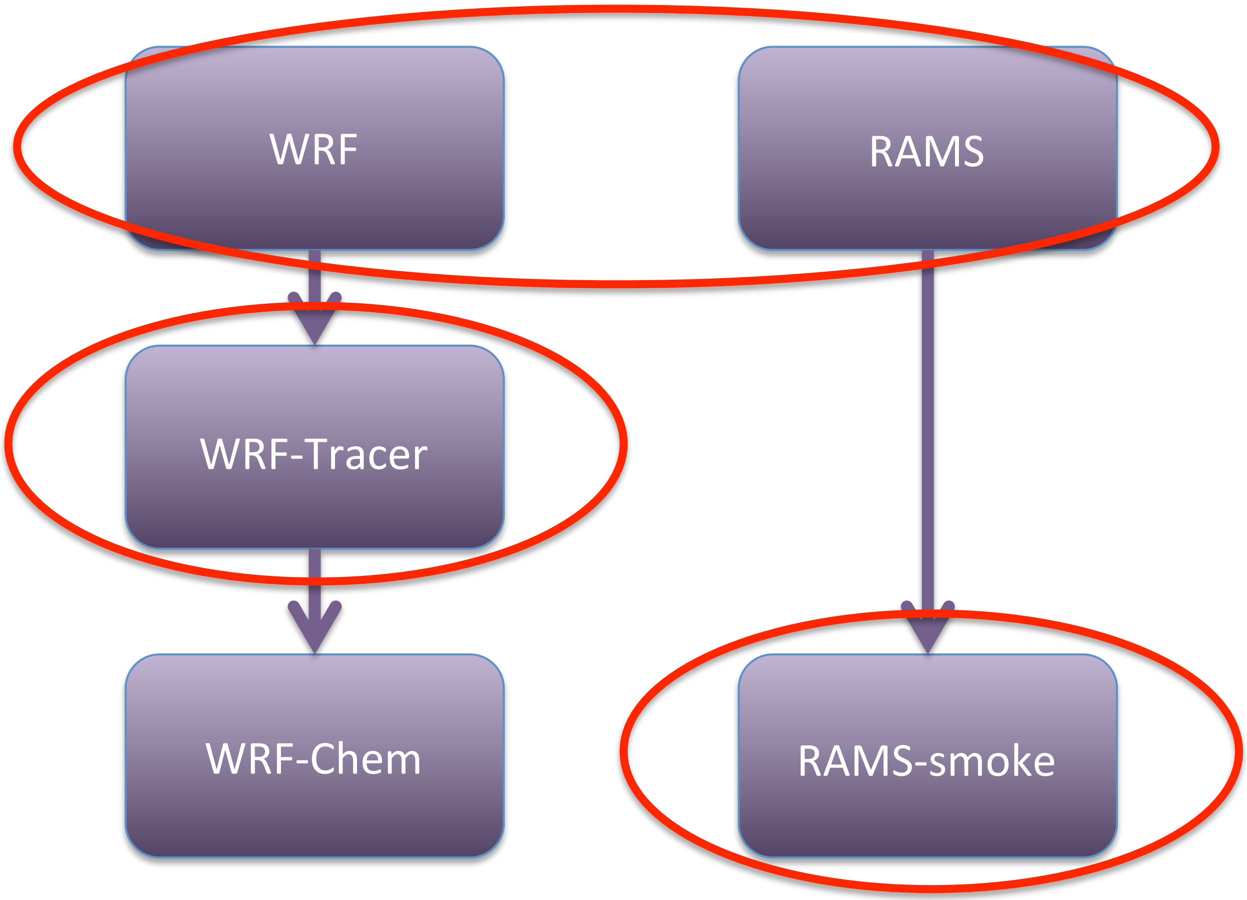


SMPS measures aerosol concentration in the 10-340 nm size range.
Maximum concentrations ~ 10,000/cm^3 at ~7 km MSL.

→ This case provides a unique opportunity to examine the effect of aerosols ingested into a storm at an elevated altitude

Modeling the 22 June 2012 DC3 Case

Objectives of Study



Does model represent storm well?

Does smoky air get into storm? Where does the outflow air come from?

Do aerosols affect storm properties?

One of first times aerosol-cloud interactions will be examined with 2 models addressing the same case

Modeling the 22 June 2012 DC3 Case

WRF, WRF-tracer, WRF-Chem

3-grids: Δx = 15, 3, 1 km
Δz = 50 m stretched to 250 m

Initialization: 12 km NAM at 1200 UTC

Cloud physics: Morrison double moment

Cu parameterization: Grell-Freitas in outer domain only

Nesting: 2-way for WRF and WRF-tracer
1-way for WRF-Chem run

RAMS (S. Saleeby)

3-grids: Δx = 25, 5, 1 km
Δz = 75 m stretched to 500 m

Initialization: 12 km NAM at 1800 UTC

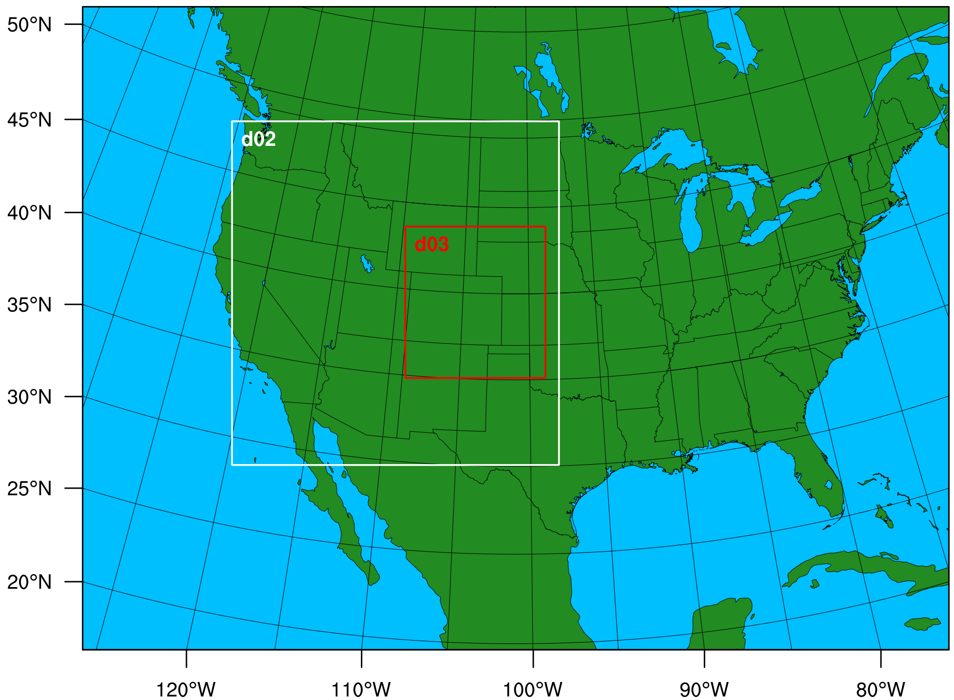
Cloud physics: 2-moment, binned riming (Saleeby and Cotton 2004; Saleeby and van den Heever 2013)

Cu parameterization: Kain-Fritsch in outer domain only

Nesting: 2-way

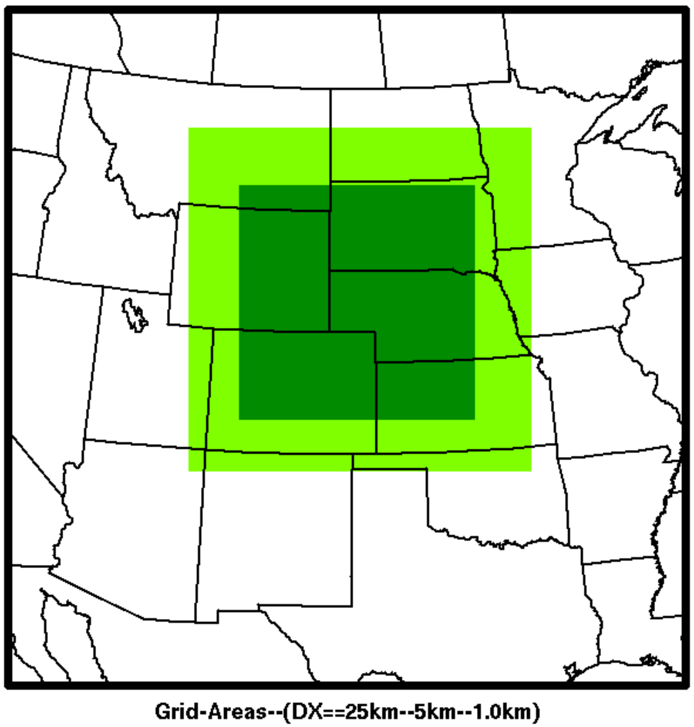
Modeling the 22 June 2012 DC3 Case

<u>WRF, WRF-tracer, WRF-Chem</u>



Δx: 15 km, 3 km, 1 km

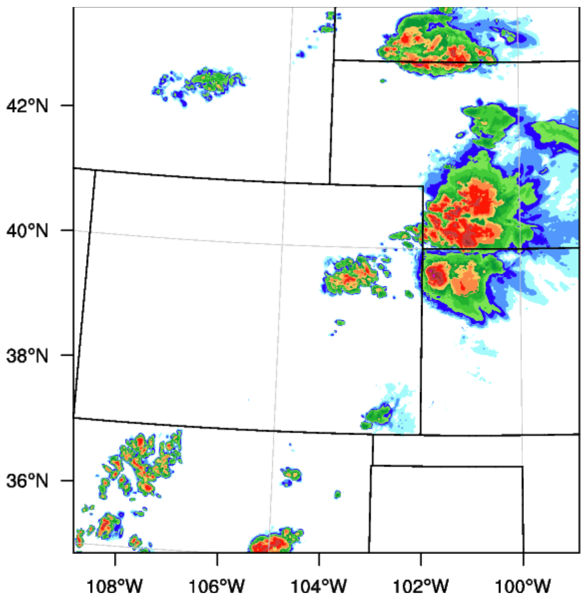
<u>RAMS (S. Saleeby)</u>



Δx: 25 km, 5 km, 1 km

Do WRF and RAMS represent storms well?

WRF Max. Reflectivity

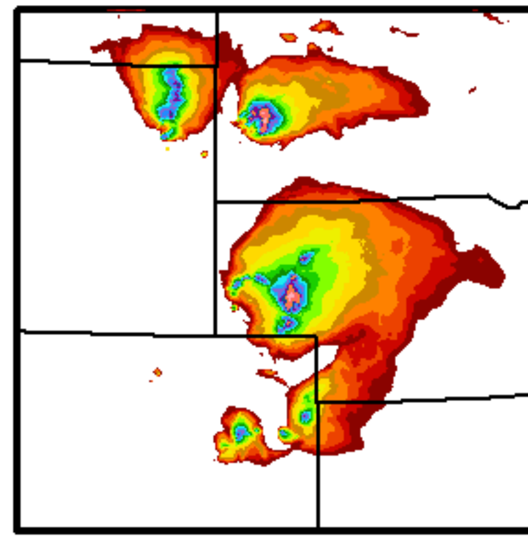


At 0200 UTC

- WRF simulation east of obs, with more convection
- RAMS simulation a little north of obs

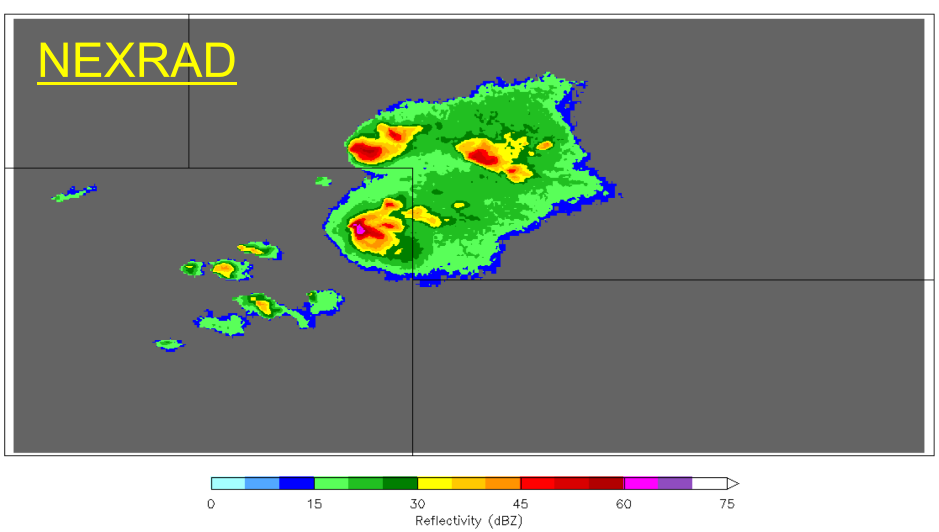
→ About as good as we can get

RAMS Total Condensate Path

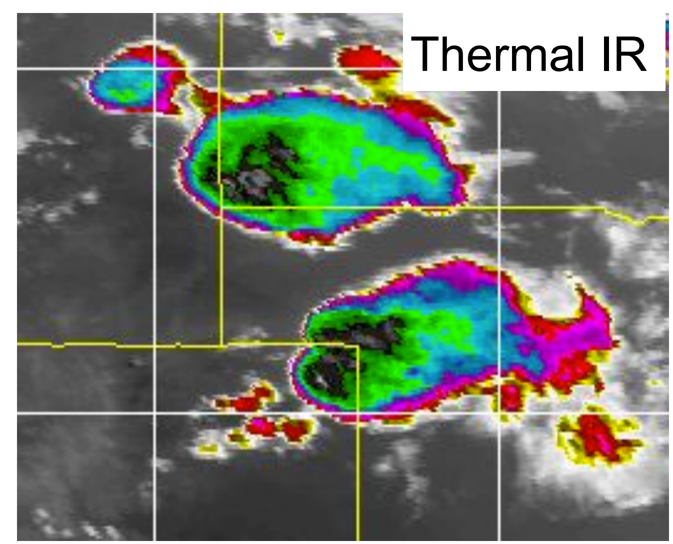


NAM 1.0km 18Z 2-mom small

NEXRAD Composite Reflectivity valid 20120623T0200Z

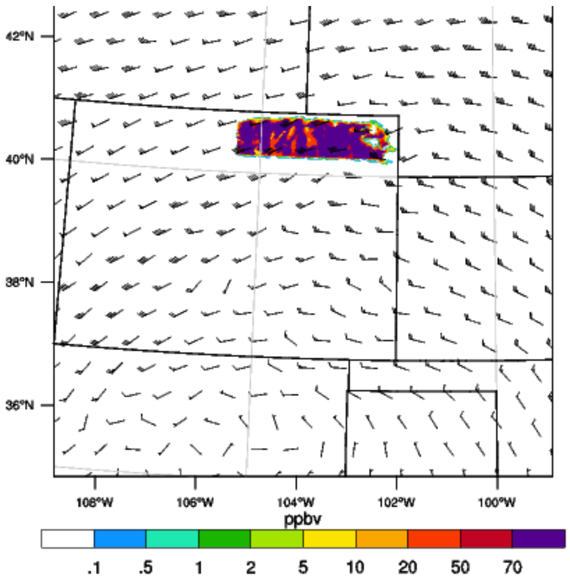


Cameron R. Homeyer, NCAR (chomeyer@ucar.edu)

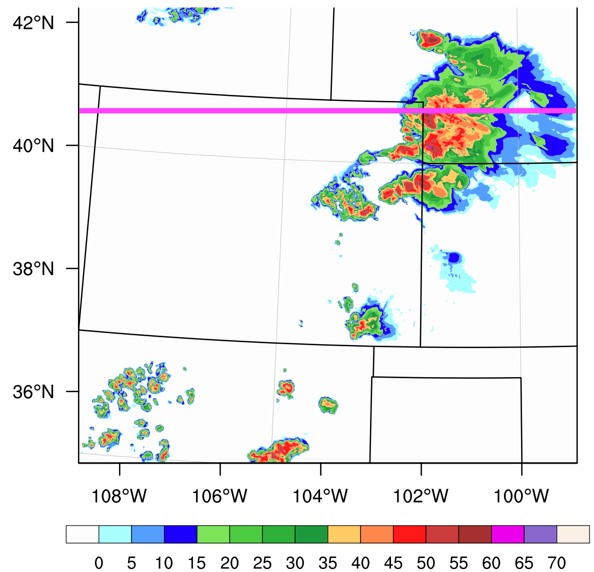


Does smoky air at 7 km get into storm?

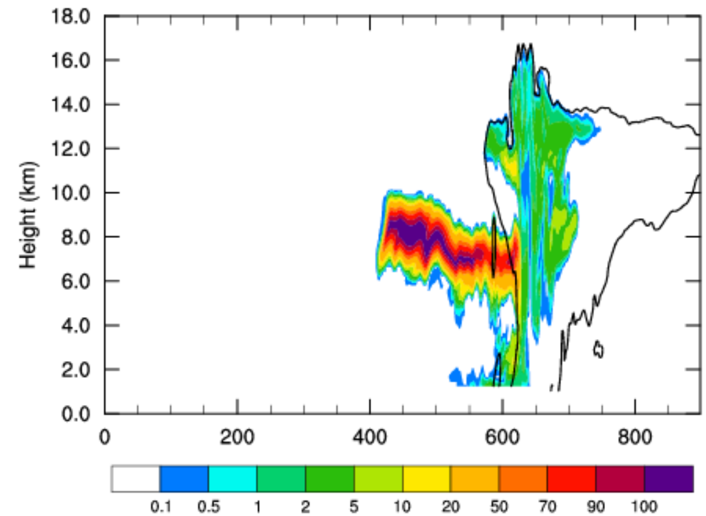
00 UTC 23 June
“smoke tracer” at z = 7 km



01 UTC 23 June
Maximum reflectivity



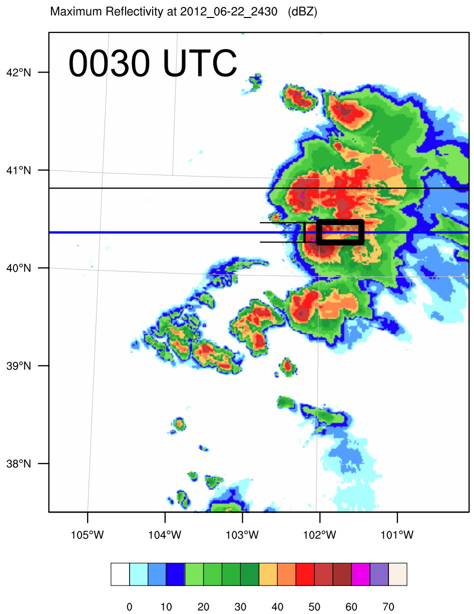
01 UTC 23 June
“smoke tracer”
Total condensate (black contour)

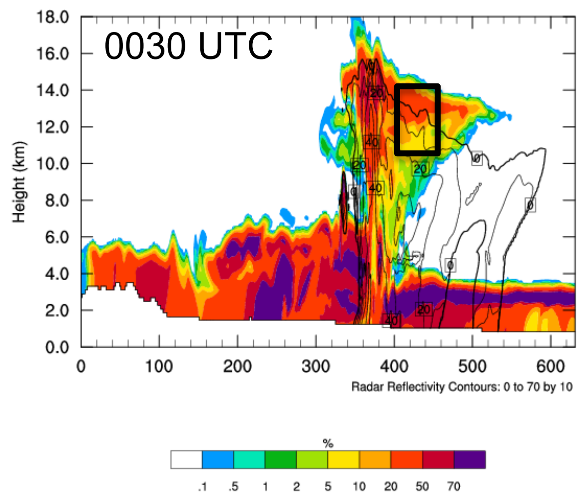


Smoke plume tracer initialized from 2340-2400 UTC
→ Results shown at 0100 UTC
→ Smoke plume tracer ingested into and transported to top and bottom of storm

Where does the outflow air come from?

Passive tracers each 1-km altitude

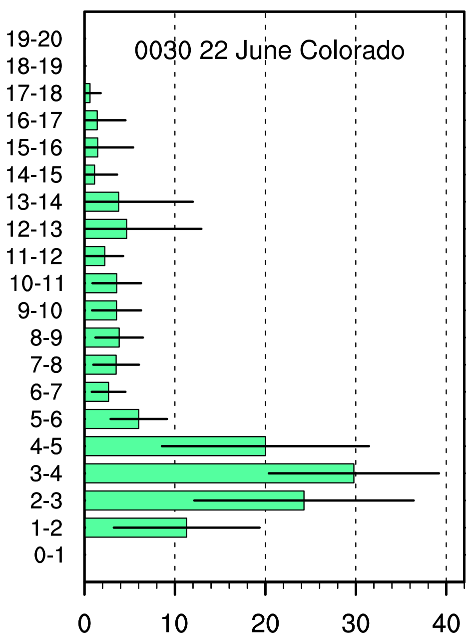


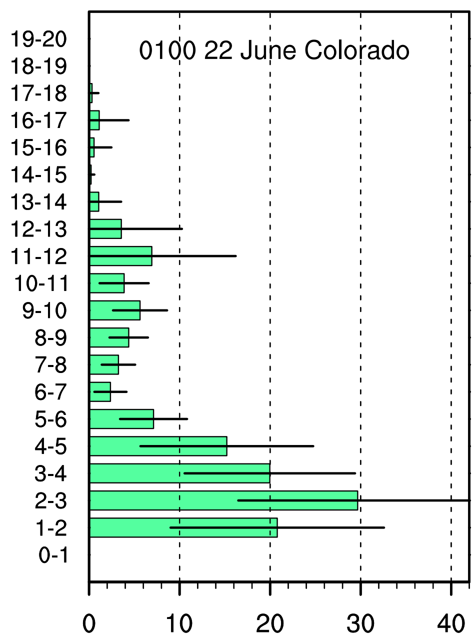


"Layer" tracers initialized from 2245-2300 UTC

Results shown at 0030 UTC

Analyze white box region to find how much of each 1-km altitude contributed to outflow region





→ Most air entrained from below 5 km altitude

→ 0100 UTC shows a little more entrainment from upper troposphere

Simulations with Aerosols
(WRF-Chem and RAMS)

WRF-Chem

MOZART gas chemistry mechanism
MOSAIC aerosol model with 4 bins
 EPA anthropogenic emissions
 MEGAN biogenic emissions
 FINN fire emissions with plumerise

Chemistry is initialized with results from the global chemistry transport model, MOZART

→ Number of aerosols predicted is a result of emissions and atmospheric processes

Only cloud drop activation affected by aerosols

There are no IN in this configuration

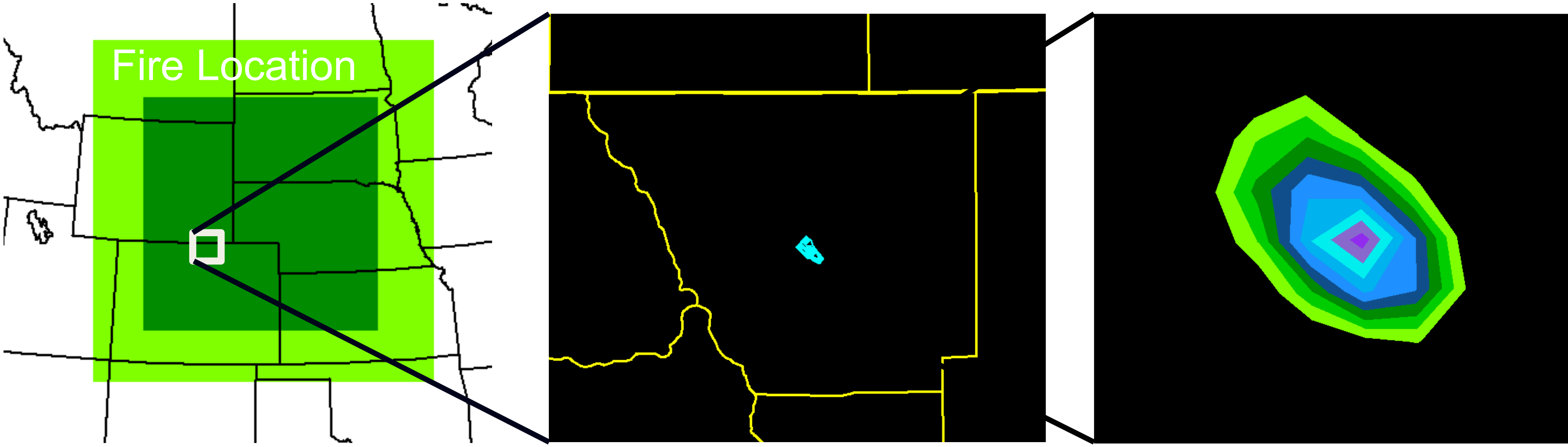
RAMS (S. Saleeby)

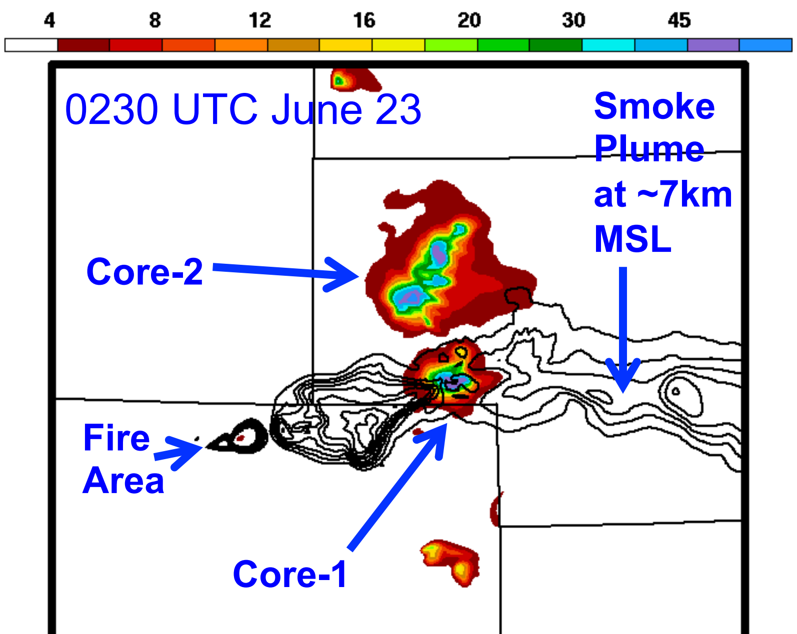
Initial CCN = 600 cm^{-3} decreasing exponentially with height
IN = 1 mg^{-1} decreasing exponentially with height

Fire aerosols added with an ad-hoc emissions method

Results shown are only from RAMS

Simulations with Aerosols
(RAMS)





Smoke Aerosols (/cm3, black, every 500)
Total Water Path (mm, shaded) 120623/0230

<u>Addition of Wildfire</u>

Surface heat flux ~8 kW/m2

2D varying smoke aerosol flux: 30,000-80,000 #/m2/sec

→ Aerosol plume at 7 km ingested by southern storm

Simulations with Aerosols
(RAMS)

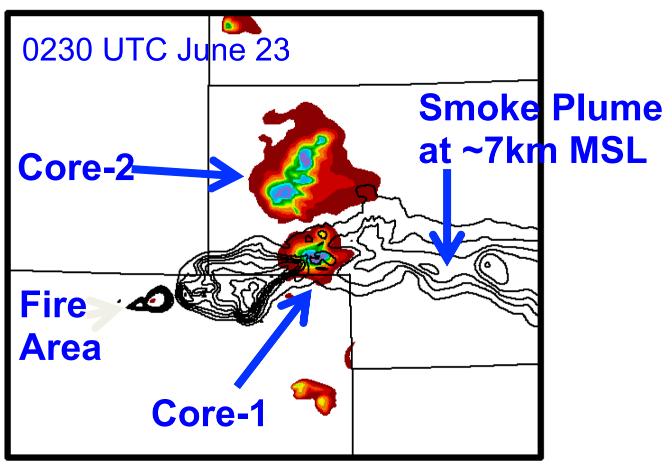
Two Simulations

1. “Fire” with fire heat flux and with smoke aerosol emissions
2. “NoFire” with fire heat flux and without smoke aerosol emissions

Two Convective Regions Analyzed

1. “Core-1”: southern storm, impacted by smoke
2. “Core-2”: northern storm, less impacted by smoke

Cores identified by total water condensate path > 10 mm

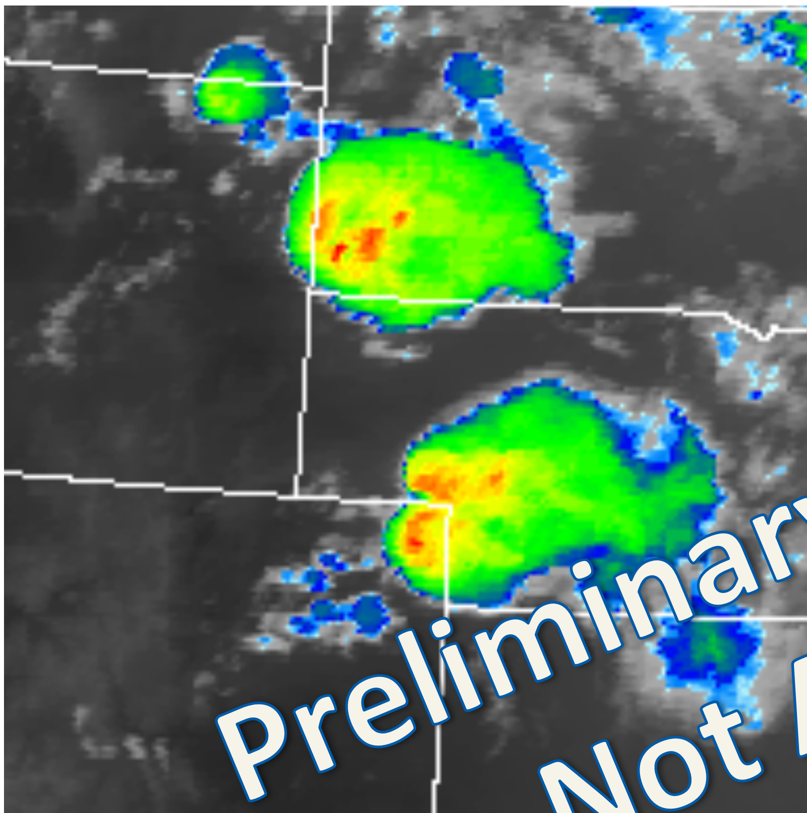


Smoke Aerosols (/cm3, black, every 500)
Total Water Path (mm, shaded) 120623/0230

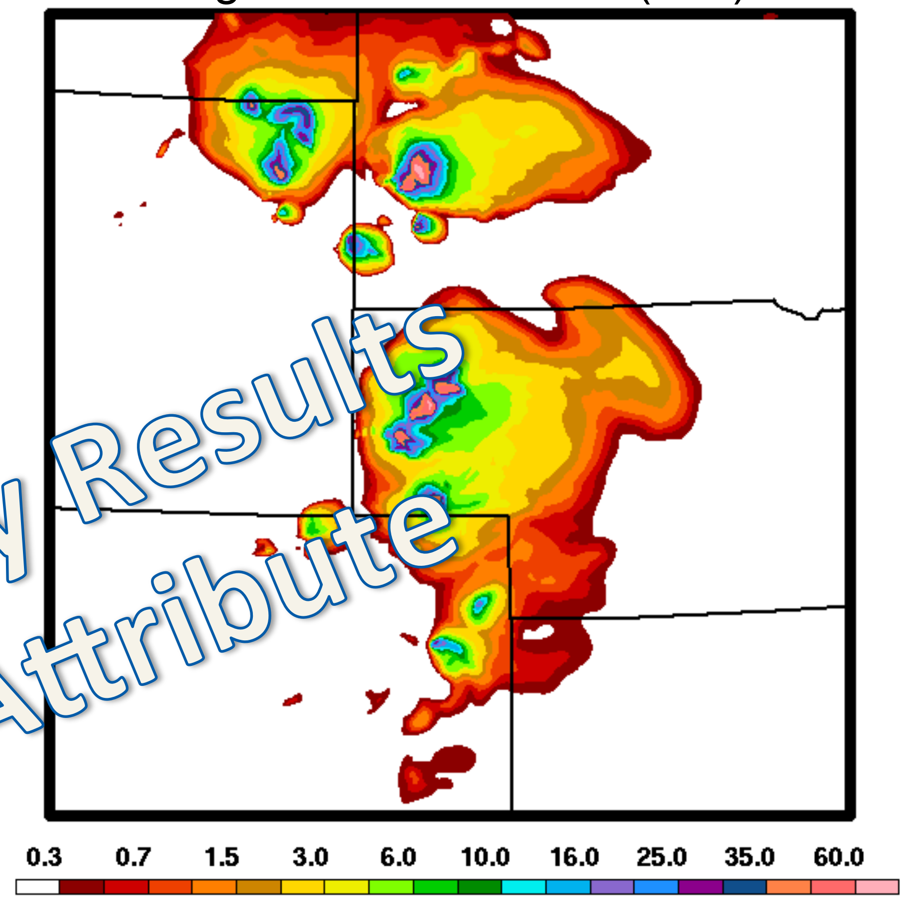
Meteorology agrees well with observations

0200 UTC June 23

GOES – Enhanced IR

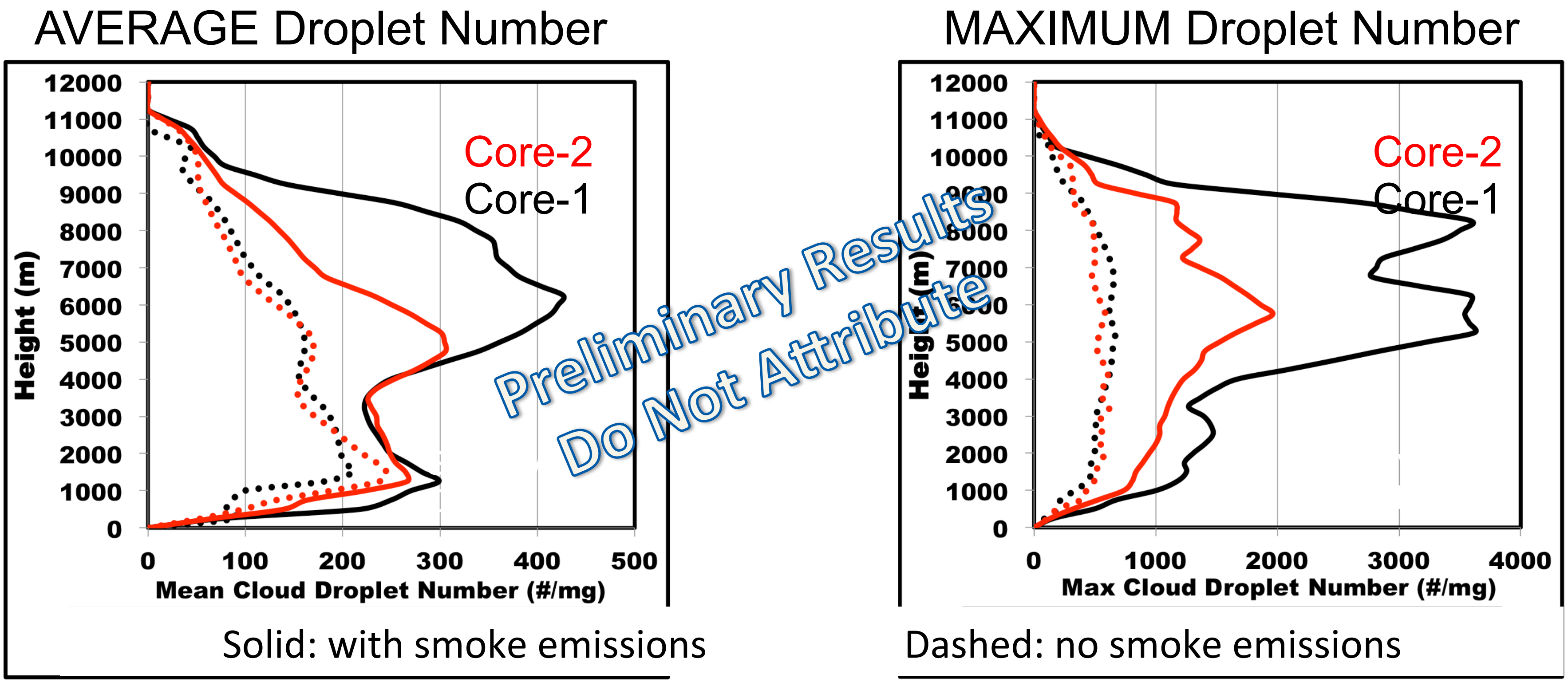


RAMS - 12km NAM – 1.0km
Integrated Condensate (mm)



Impact on Cloud Droplet Number

Vertical profiles are averaged temporally over each convective core

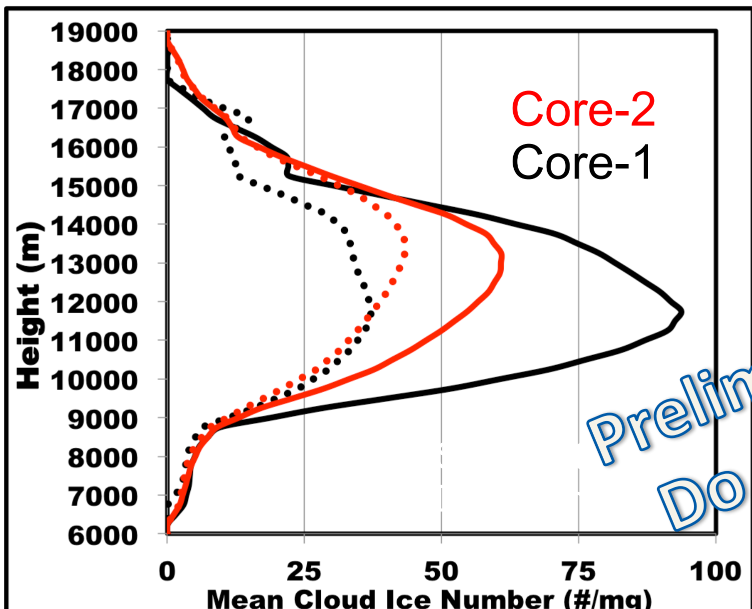


1. Both convective cores impacted by smoke aerosols, but the direct impact on Core-1 is significantly greater.
2. Cloud droplet number concentrations are much greater with smoke plume influence, with maximum impact at mid- to upper-levels where smoke plume is most concentrated.

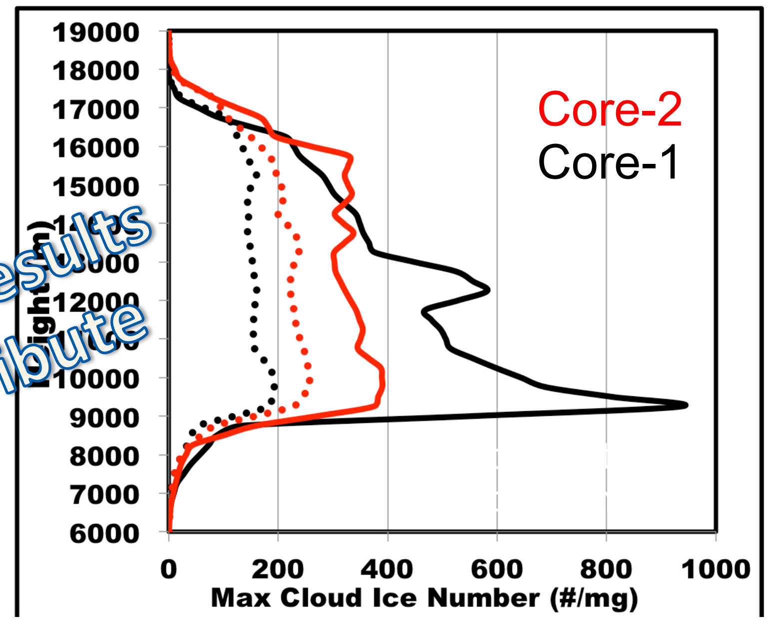
Impact on Cloud Ice Number

Vertical profiles are averaged temporally over each convective core

AVERAGE Cloud Ice Number



MAXIMUM Cloud Ice Number



Solid: with smoke emissions

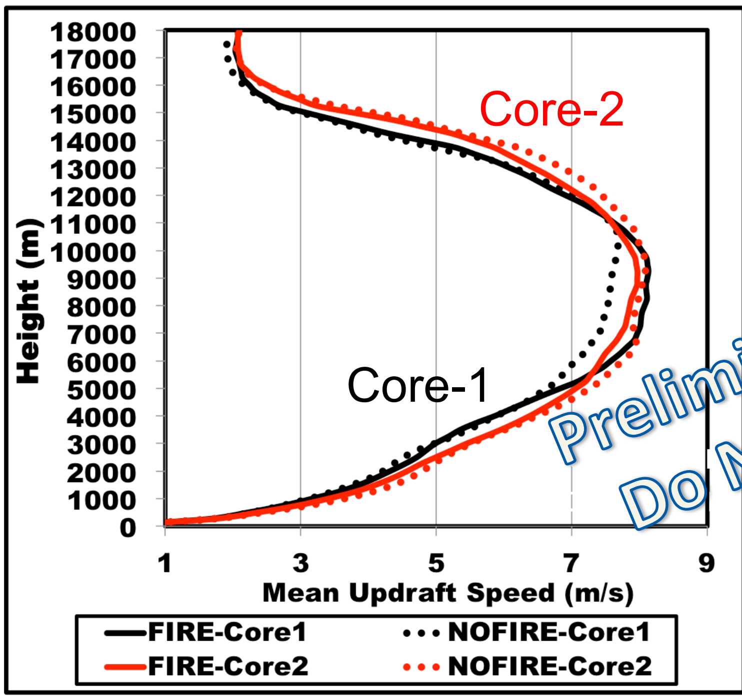
Dashed: no smoke emissions

1. Both convective cores impacted by smoke aerosols, but the direct impact on Core-1 is significantly greater.
2. Cloud ice number concentrations are much greater with smoke plume influence.

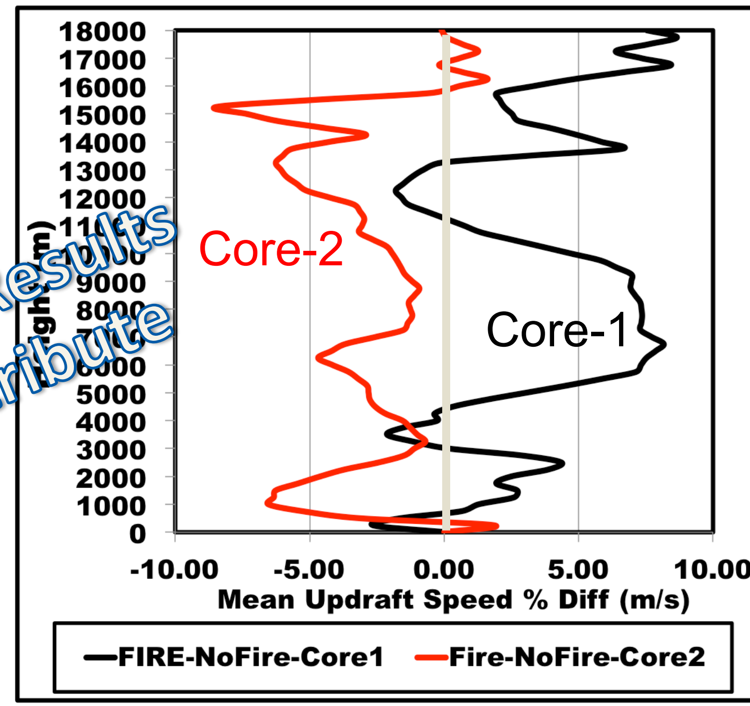
Convective Updrafts

Vertical profiles are averaged temporally over each convective core

AVERAGE Updraft Speed



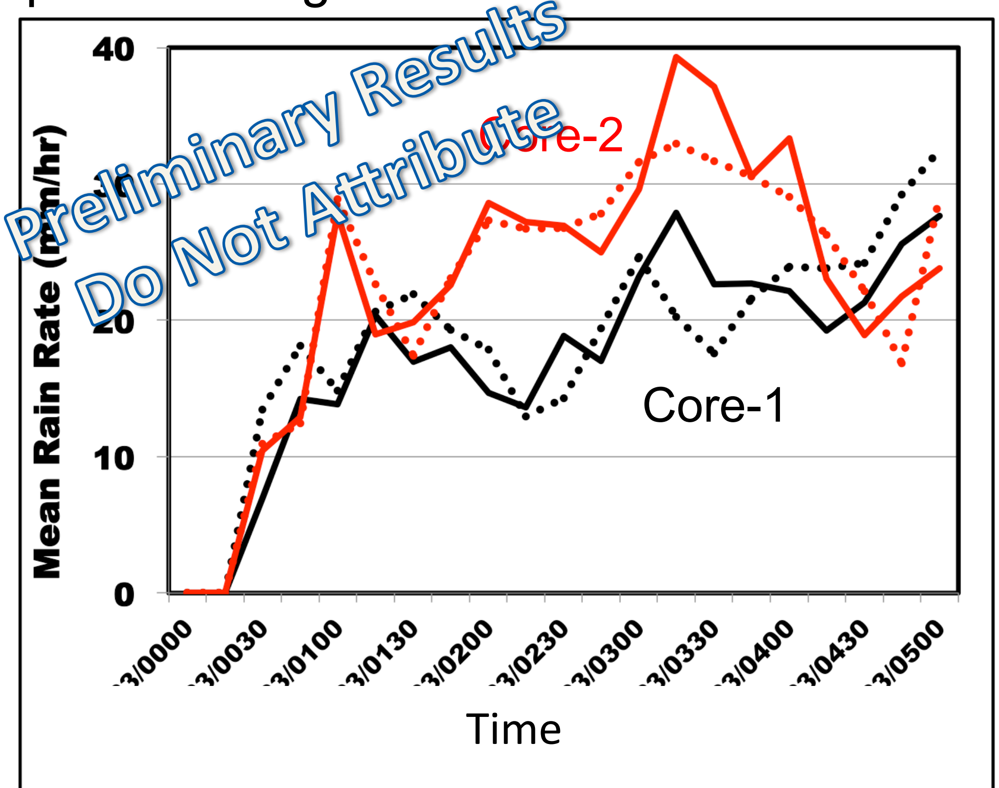
% Difference (Fire – NoFire)



1. Stronger updrafts throughout the column in Core-1 (direct smoke core)
2. Weaker updrafts throughout the column in Core-2 (non-smoke core)

Precipitation Rate

Spatial average over each convective core



Solid: with smoke emissions

Dashed: no smoke emissions

- No clear trend in fire aerosol impacts on precipitation rate.
- I suspect that the increased cloud drop number did not grow large enough drops to be affect the riming process, and therefore precipitation (similar to shallow warm cloud depth)

Summary of DC3 Case Study

- WRF-Chem and RAMS model runs of the 22 June 2012 DC3 case where a thunderstorm ingested a smoke plume at ~7 km altitude

- Meteorology-only simulations reasonably represent convection

- WRF-tracer simulation shows
  - "smoke tracer" at 7 km is transported into storm
  - Most of air in outflow from altitudes at and below 5 km

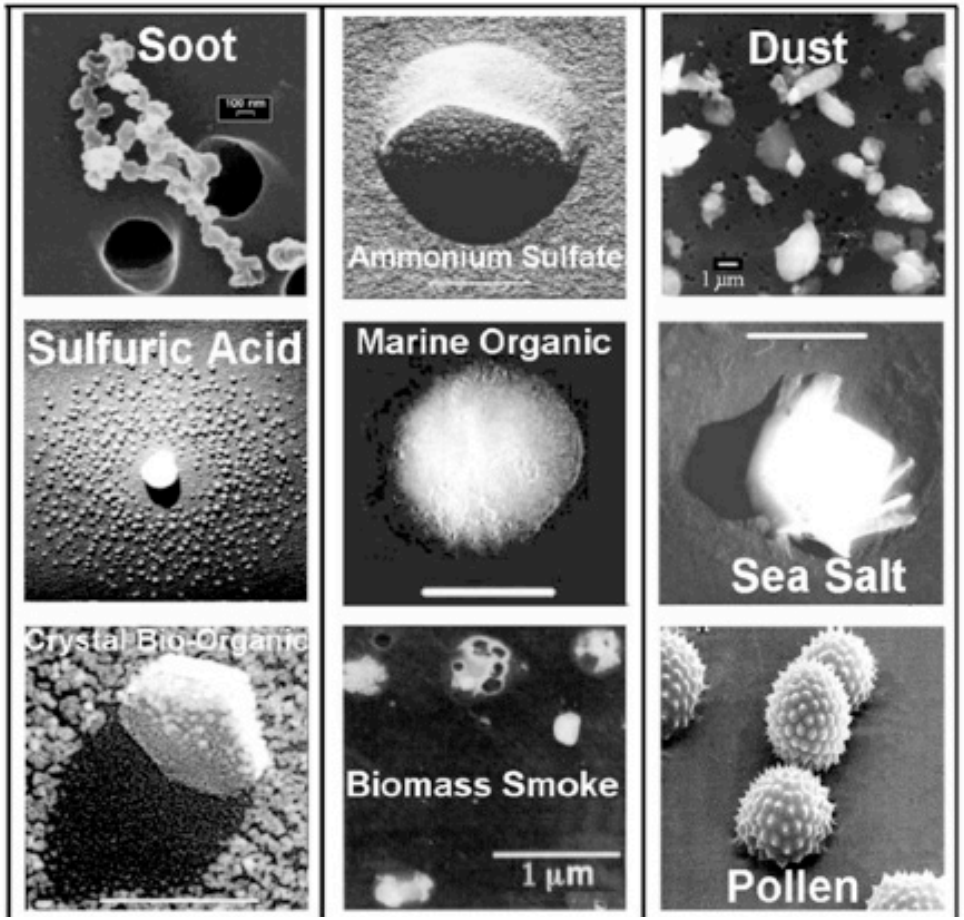
- RAMS simulations show interaction between smoke and thunderstorm
- Storm ingesting smoke plume produced
  - ➢ more cloud drops, more cloud ice, stronger updrafts, but similar precipitation rate

  compared to simulation without smoke aerosols

What was learned about Aerosols and Meteorology?

1. What is an aerosol?
   A colloidal system of solid or liquid particles in a gas. An aerosol includes both the particles and the suspending gas, which is usually air.

2. Give some examples of aerosols.
   Soot, Dust, Sulfuric Acid,
   Ammonium Sulfate, Sea Salt,
   Black Carbon (soot), Pollen,
   Organic Carbon



What was learned about Aerosols and Meteorology?

3. What 2 ways do aerosols affect meteorology and climate?
    1. Aerosols scatter and absorb radiation
    2. Aerosols affect cloud properties

4. Do aerosols increase or decrease precipitation from convective storms?
    1. Both. It depends on the timing, cloud type, etc. See next question.

5. What are explanations for aerosols changing amount of precipitation?
    1. Cloud physics: more CCN produce more but smaller cloud drops, narrowing the drop size distribution and suppressing rain
    2. Latent heat – dynamics: small cloud drops lofted to above freezing level; Freezing of drops releases latent heat, enhancing updrafts
    3. Cool Pool Effect: stronger evaporative cooling from more, but smaller, raindrops enhances strength of cold pool; interactions with wind shear can invigorate updrafts and convection
    4. Cloud type, relative humidity, wind shear, depth from cloud base to freezing level

What was learned about Aerosols and Meteorology?

6. Do aerosols affect lightning flash rate?
   The few studies performed all show an increase in flash rate when more aerosols are present. But too many CCN can decrease flash rate.

7. How can black carbon affect convective precipitation (e.g. in India)?
   Absorption of solar radiation increases temperature in PBL, affecting CAPE. Aerosols also affect cloud physics invigorating storm.

8. How can black carbon affect tornadogenesis?
   Black carbon absorbs solar radiation heating atmosphere, stabilizing PBL, lowering lifting condensation level and increasing low-level wind shear and storm relative helicity. All factors increase the severe tornado potential.

9. Any outstanding questions to pursue? Any questions on the topic?