An Overview of Lightning NO_x Production Research Associated with the Deep Convective Clouds and Chemistry (DC3) Experiment

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8 DLR, Germany
9 New Mexico Tech
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11 NASA Marshall Space Flight Center
12 University of Alabama - Huntsville

Lightning NO_x

- **Lightning is responsible for approximately 10-15% of NO_x emissions globally. This is roughly 2 – 8 Tg N yr-1 [Schumann and Huntrieser, 2007]. <u>Much of uncertainty stems from little knowledge of NO_x production per flash or per unit flash length.</u>**

- **Most of lightning-produced NO_x (LNO_x) is injected into middle and upper troposphere. Lifetime is long (a few days) relative to lower troposphere. NO_x in this region plays a key role in the chemistry of ozone, the importance of which as a greenhouse gas maximizes in the UT.**

- **Methods used to estimate LNO_x/flash include theoretical estimates, laboratory experiments, analysis of aircraft NO_x observations and flash rates, cloud-resolved chemistry modeling constrained by aircraft obs., and analysis of satellite NO_2 data.**

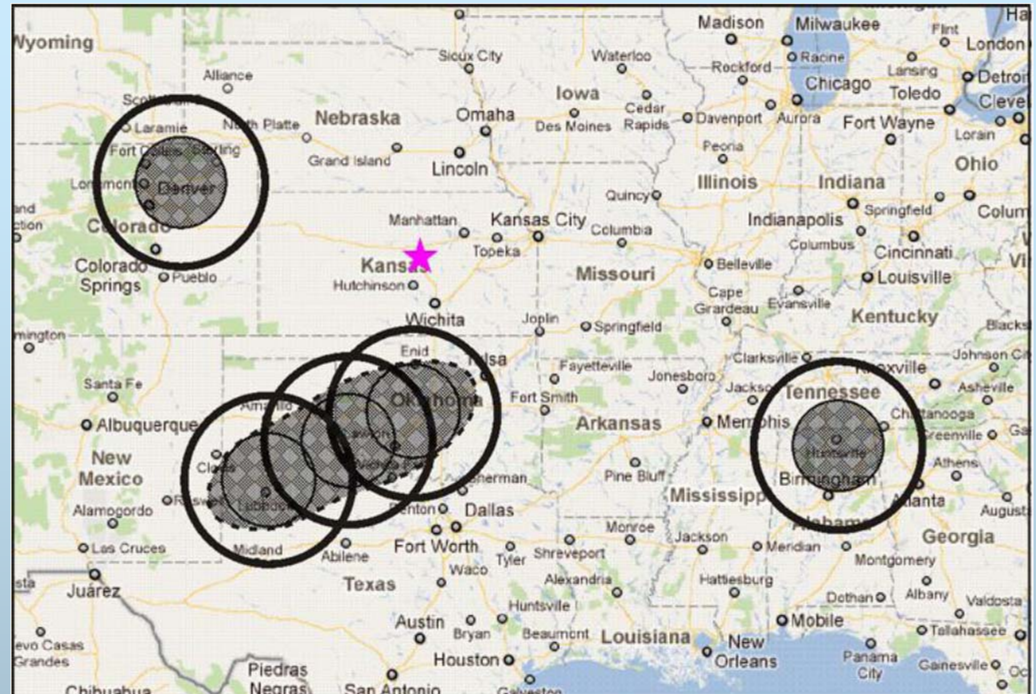
Previous investigations of lightning NO_x production for individual storms

Method	Moles NO/flash (Notes)	Reference
Theoretical	1100 (CG), 110 (IC)	Price et al., 1997
Laboratory	~103	Wang et al., 1998
Aircraft data, cloud model	345-460 (STERAO-A)	DeCaria, et al., 2005
Aircraft data, cloud model	360 (STERAO-A, EULINOX)	Ott et al., 2007; 2010
Aircraft data, cloud model	590-700 (CRYSTAL-FACE)	Ott et al., 2010
	500 (Mean midlat. from model)	Ott et al., 2010
Satellite (OMI)	440 (Central US, Gulf)	Pickering et al. (in prep)
LMA/Theoretical	484 (CG), 34 (IC)	Koshak et al., 2013
Aircraft data	70-210 (TROCCINOX)	Huntrieser et al., 2008
Aircraft data	121-385 (SCOUT-O3 Darwin)	Huntrieser et al., 2009
Aircraft data	70-179 (AMMA)	Huntrieser et al., 2011
Aircraft data, cloud model	500 (Hector)	Cummings et al., 2013
Satellite (GOME)	32-240 (Sub-Tropical)	Beirle et al., 2006
Satellite (OMI)	87-246 (TC4 – tropical marine)	Bucsela et al., 2010
	174 (TC4 mean from OMI)	Bucsela et al., 2010
Satellite (SCIAMACHY)	33-50 max. (global analysis)	Beirle et al., 2010

Recent aircraft/cloud model studies suggest intracloud (IC) flashes at least as productive as cloud-to-ground (CG) flashes

Mid-latitude storms possibly more productive per flash than tropical storms (Huntrieser et al., 2008)

Deep Convective Clouds and Chemistry (DC3)



May 15 – June 30, 2012

1) *quantify and characterize the convective transport of fresh emissions and water to the upper troposphere within the first few hours of active convection, investigating storm dynamics and physics, lightning and its production of nitrogen oxides, cloud hydrometeors effects on scavenging of species, surface emission variability, and chemistry in the anvil.*
2) *quantify the changes in chemistry and composition in the upper troposphere after active convection, focusing on 12-48 hours after convection and the seasonal transition of the chemical composition of the UT.*

DC3 Facilities

- **Aircraft**

NCAR G-V

NASA DC-8

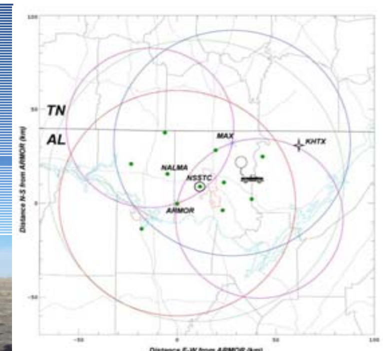
DLR Falcon

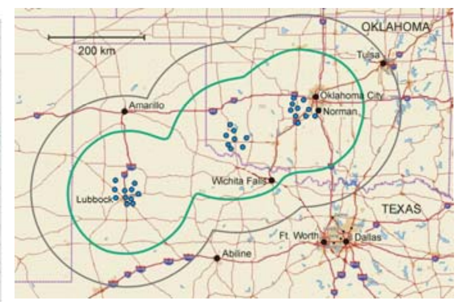
- **Lightning Mapping Arrays**

Northeast Colorado

Oklahoma – West Texas

Northern Alabama



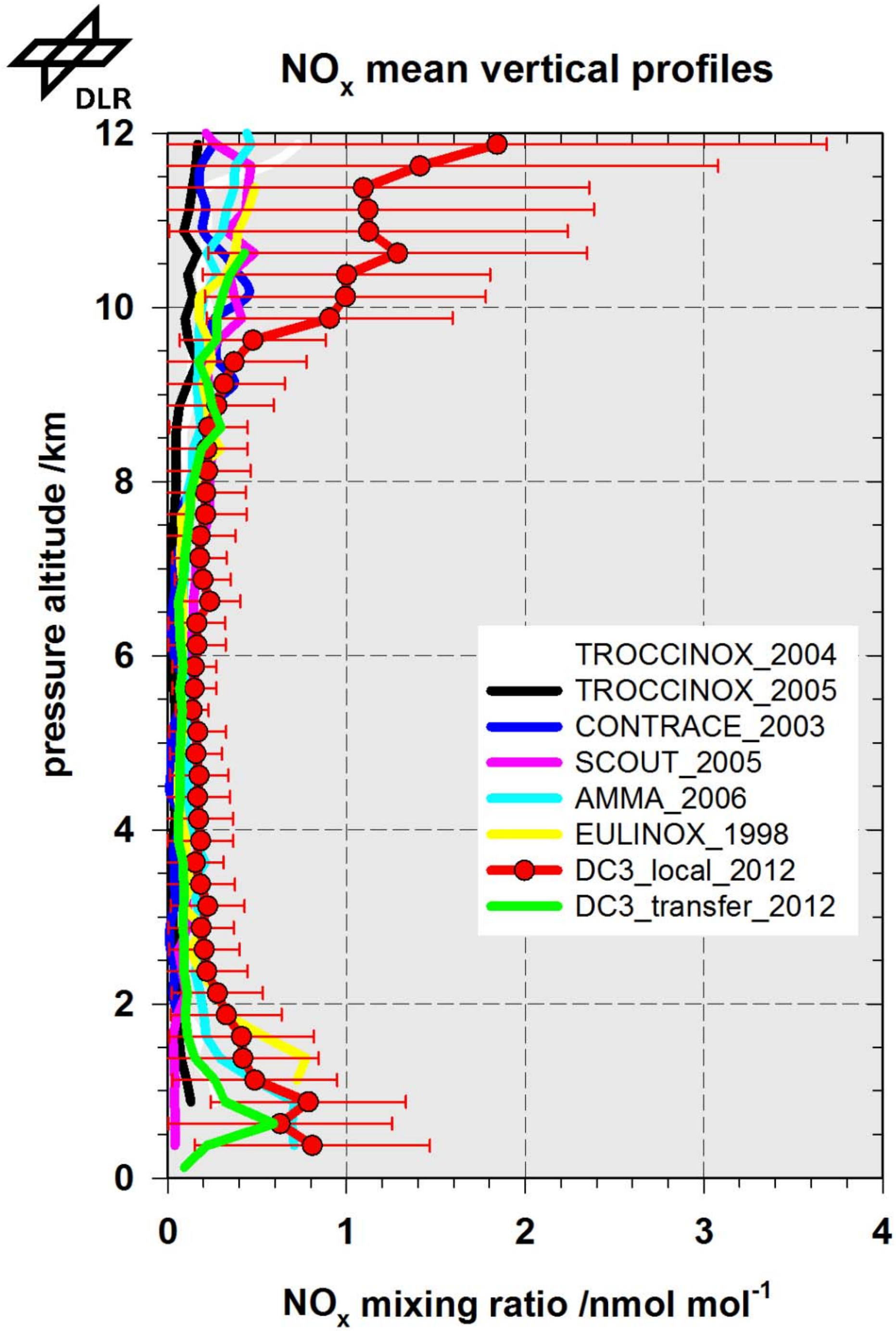


- **Radar**

Colorado: CHILL-PAWNEE

Oklahoma: SR2, NOXP

Alabama: ARMOR, MAX



<u>DLR-Falcon during DC3:</u>

On average very high NOx mixing ratios in the UT (mainly LNOx) compared to other Falcon campaigns in Europe, South America, Africa and Australia.

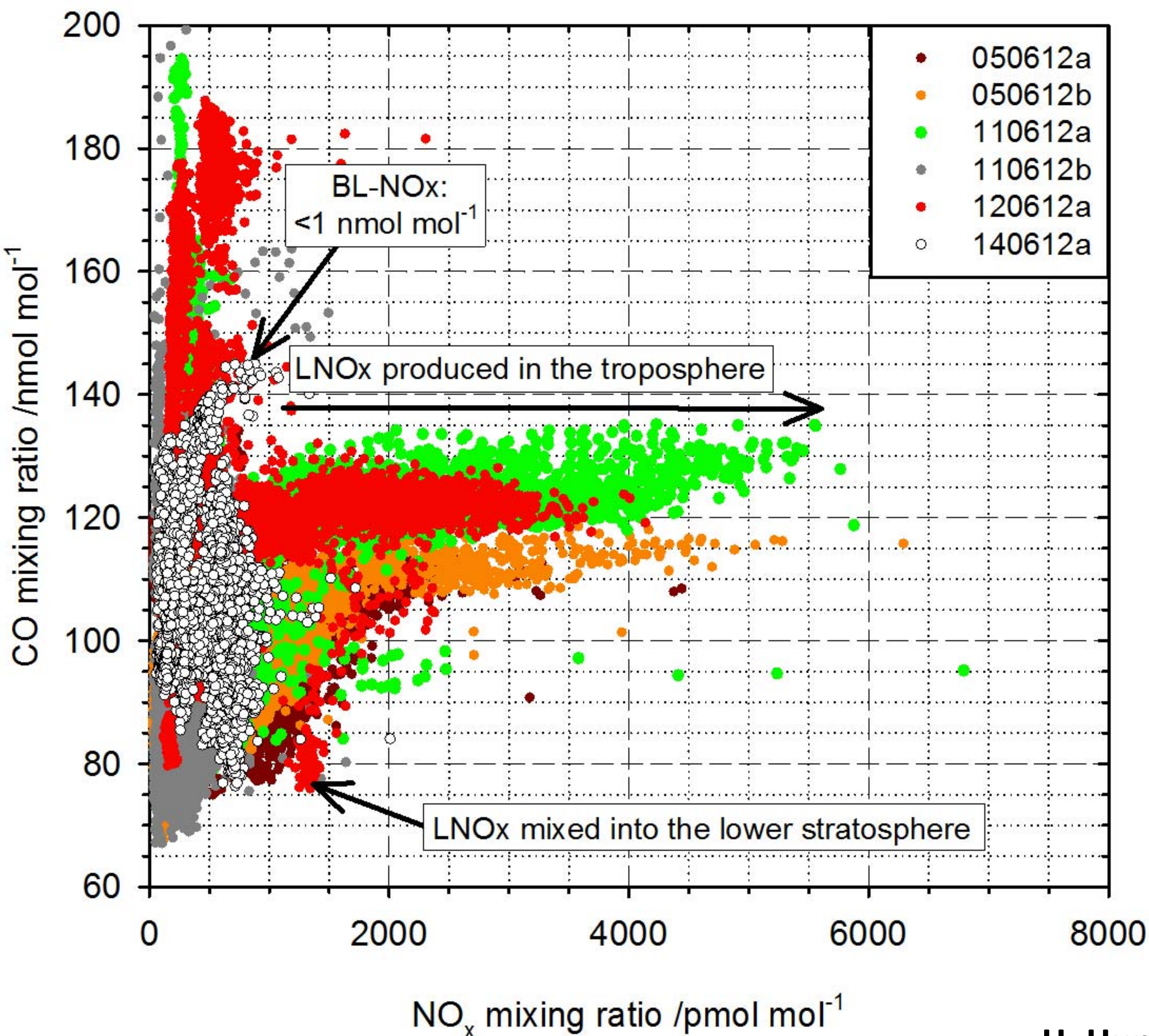
In a DC3 supercell and MCS similar average NOx mixing ratios (~2-3 nmol mol^{-1}) as in Hector!

BL-NOx similar as over Africa and Europe.

Vertical profiles: 250 m mean values

H. Huntrieser et al.

DLR-Falcon: LNOx mixed into lower stratospheric air mass



DLR

H. Huntrieser et al.

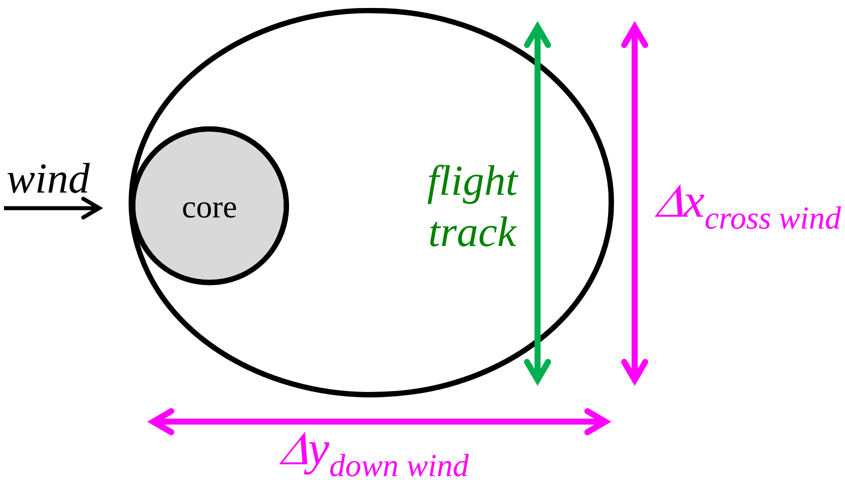
Two methods for calculating NO_x production per flash

Molecules NO_x estimated from **volume**
Ridley et al. (1996, 2004),
Koike et al. (2007)

NO_x **flux** out of anvil
Chameides et al. (1987),
Huntrieser et al. (1998, 2002)

Top View

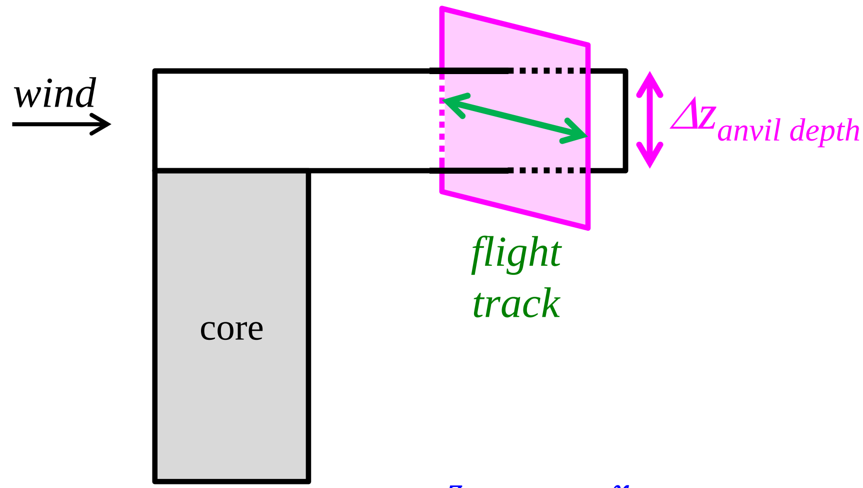
**Horizontal anvil area from GOES, core area from NLDN*



$$P(NO_x) \propto LNO_x^{enh} * Volume$$

P(NO$_x$) in units of molecules
Divide by #flashes to get molecules flash^{-1}

Vertical Cross Section



$$P(NO_x) \propto v_{wind} * \int^{z} n_{air} * \int^{x} LNO_x$$

P(NO$_x$) in units of molecules s^{-1}
Divide by #flashes s^{-1} to get molecules flash^{-1}

Averaged over 3 Oklahoma storms (19, 25, 29 May):

9 x 10^{25} molec/flash → ~150 moles/flash

6 x 10^{25} molec/flash → ~100 moles/flash

Literature: 30 - 650 moles/flash

I. Pollack et al.

Six flash rate parameterizations to test using CHILL radar and Colorado LMA

1. Maximum Vertical Velocity: $f = (5.7 \times 10^{-6}) \times w_{max}^{4.5}$

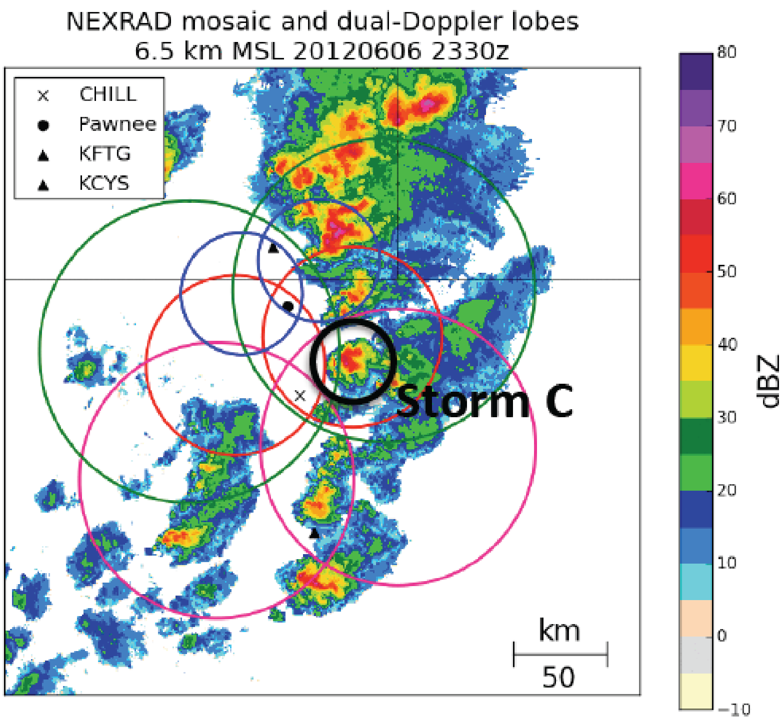
2. Updraft volume > 5 m/s: $f = (6.75 \times 10^{-11}) \times UV5 - 13.9$

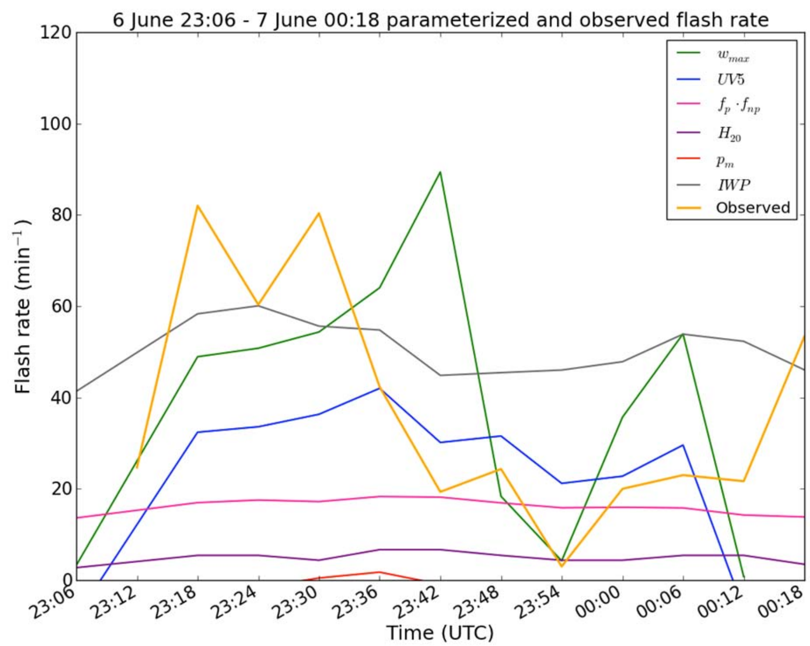
3. Maximum height of 20 dBZ echo: $f = (3.44 \times 10^{-5}) \times H_{20}^{4.9}$

4. Precipitation ice mass: $f = (3.4 \times 10^{-8}) \times p_m - 18.1$

5. Ice mass flux product: $f = (9.0 \times 10^{-15}) \times (f_p \cdot f_{np}) + 13.4$

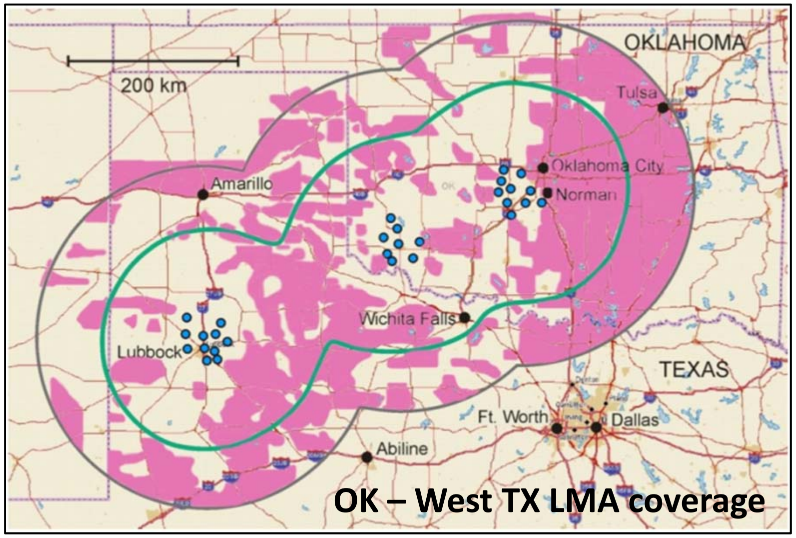
6. Ice water path: $f = 33.33 \times IWP - 0.17$

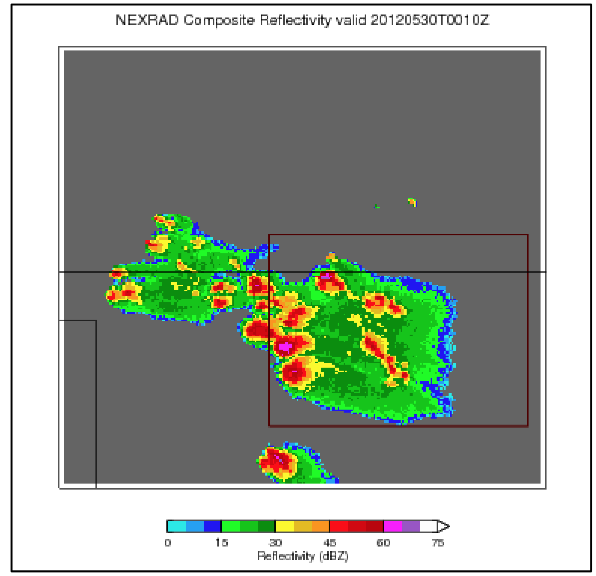


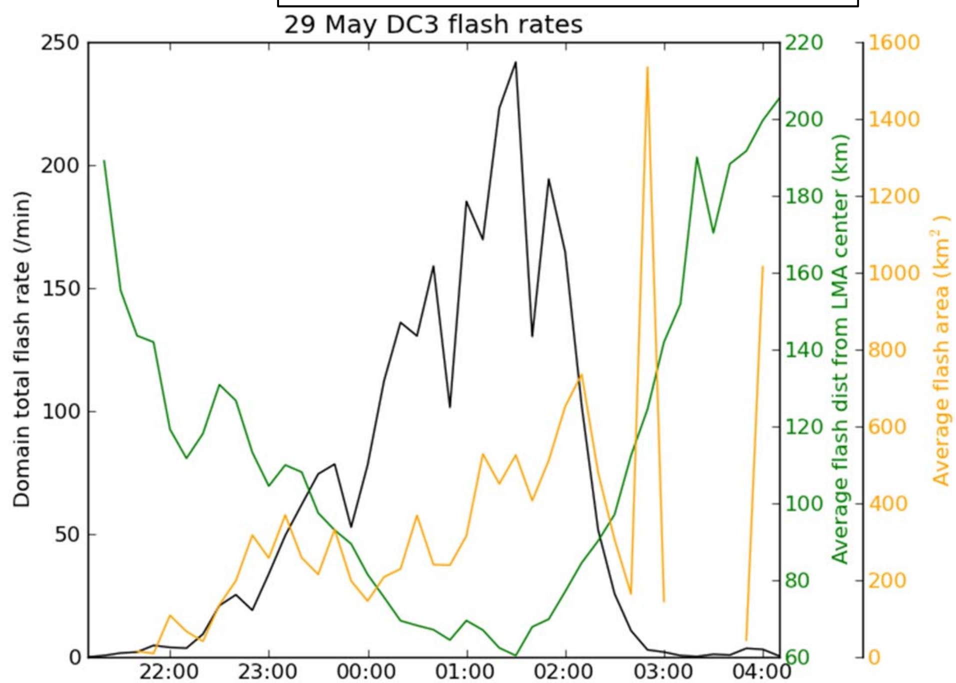


Brett Basarab - Poster AE33B – 0341 this afternoon

LMA Flash Analysis for 29-30 May DC3 storm in Oklahoma







Storm tracked for five hours as it traversed the LMA domain.

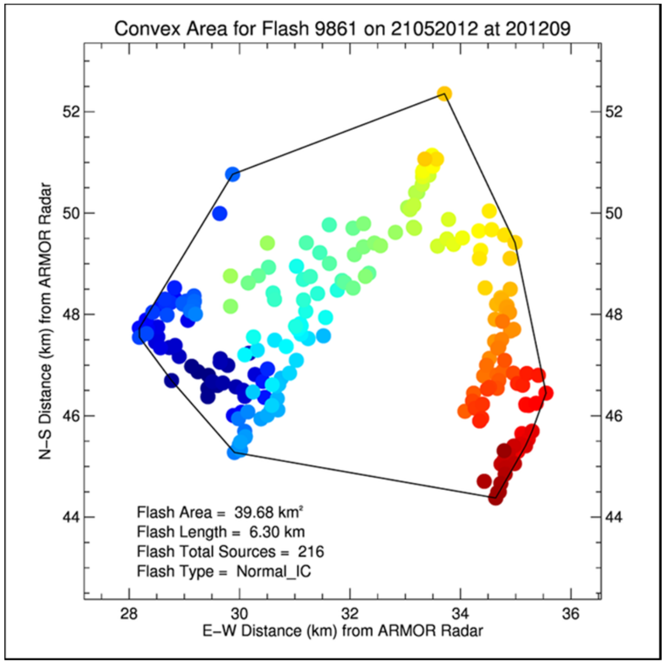
Some flashes in far northern part of storm may have been undetected.

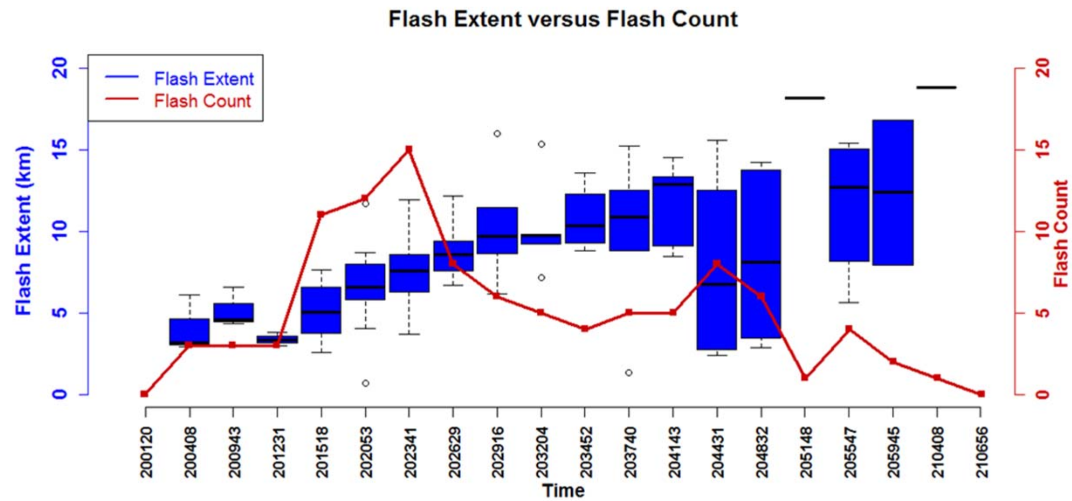
Flash area may be useful for correlating with LNOx production

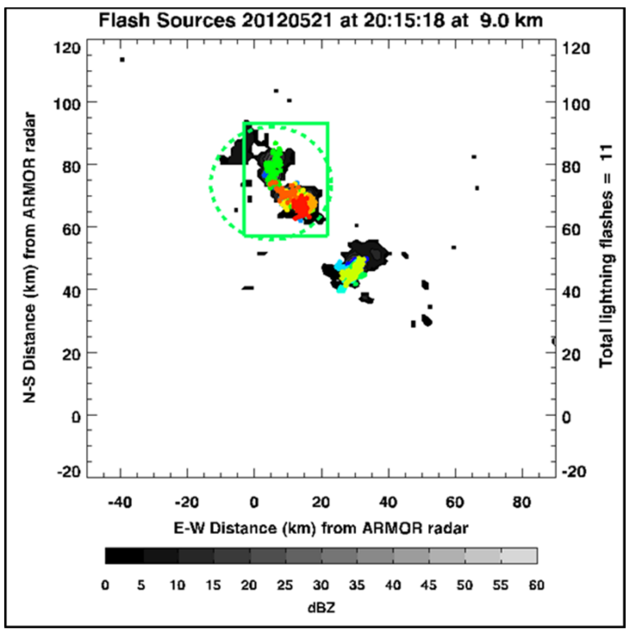
Brody Fuchs - CSU

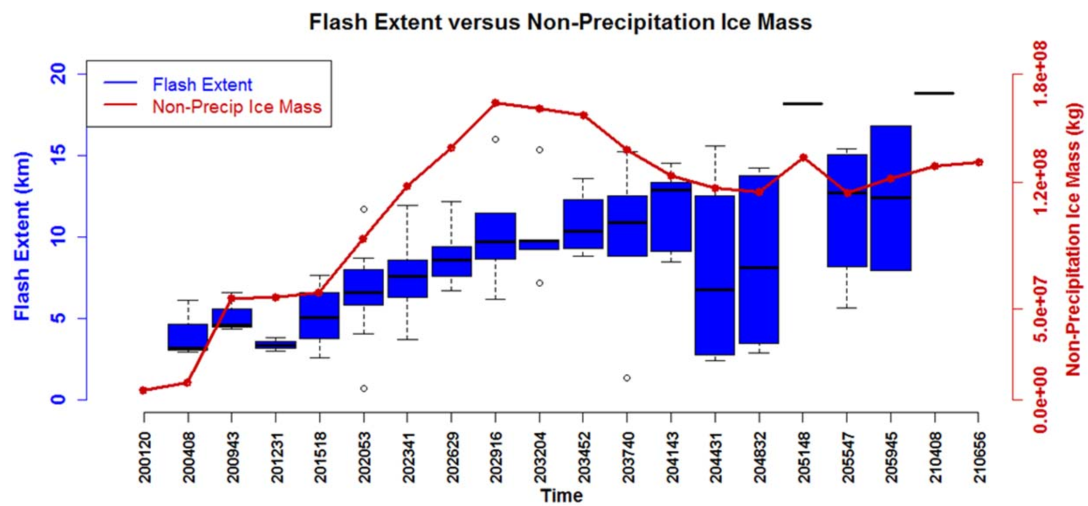
Storm Physics and Lightning Properties over Northern Alabama during DC3 (on 21 May 2012)

R. Matthee Poster: AE33B-0342 (Wednesday 1:40 PM)



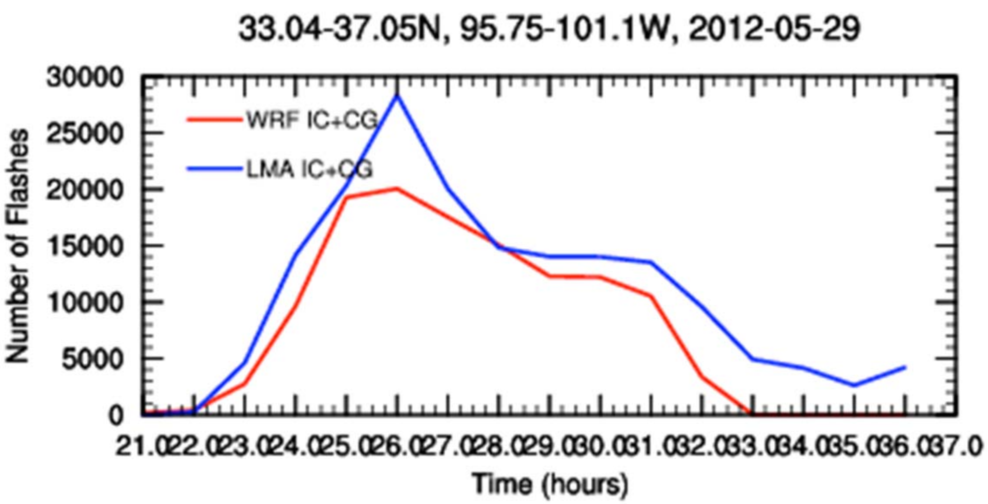






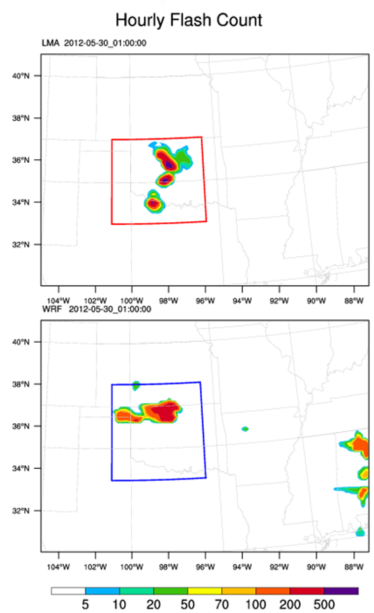
L. Carey talk AE31A-03 8:30 AM

Comparison of lightning flash rate for storm lifetime in Oklahoma LMA region is reasonably predicted by WRF at 15 km resolution



FR = 5 × (3.44x10^{-5} z$_{top}$$^{4.9}$)

LMA data summed to 15km grid and then interpolated to WRF grid



WRF predicted flash rates

z$_{top}$ = level neutral buoyancy from Grell 3D convective parameterization scheme

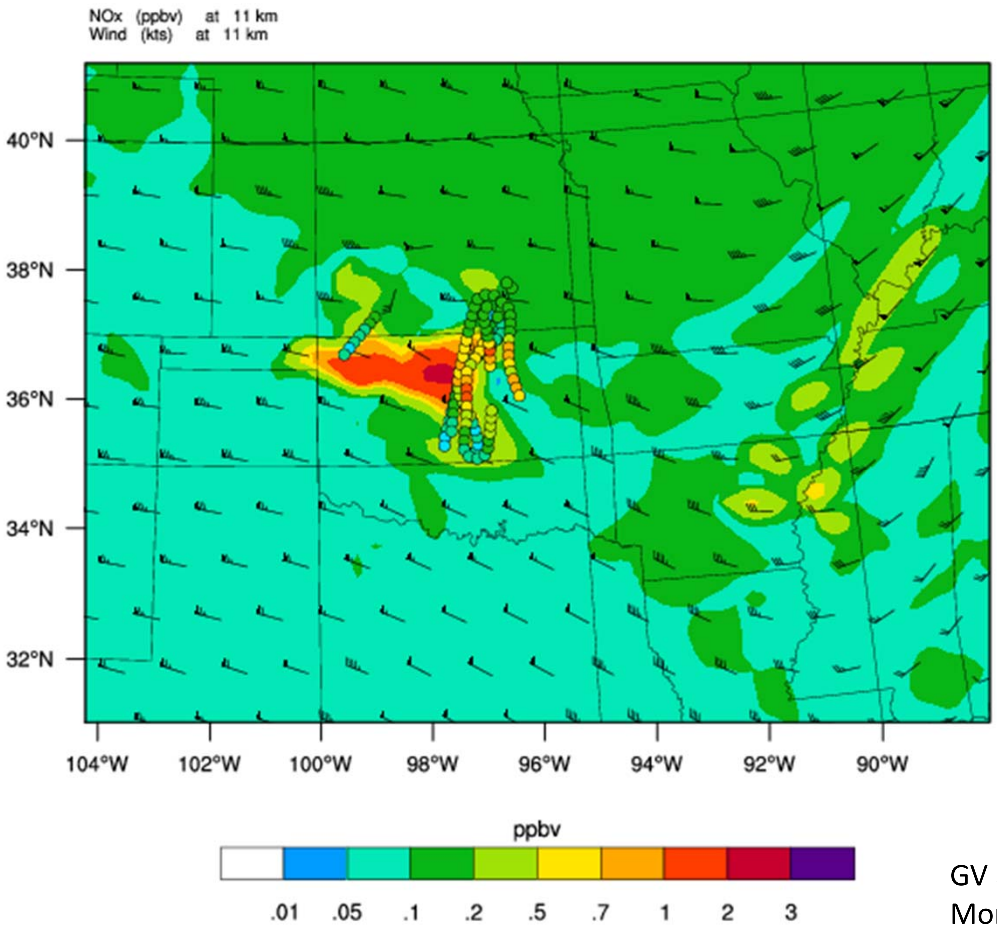
FR limited to columns where qtot > 0.5 g/kg

500 moles NO/flash placed vertically following Ott et al. (2010) curves

M. Barth et al.

Comparison of Upper Troposphere (z = 11 km) NO to Aircraft Observations (10 < z < 12 km)

WRF-Chem: 0000 UTC   Aircraft: 2145-0045 UTC



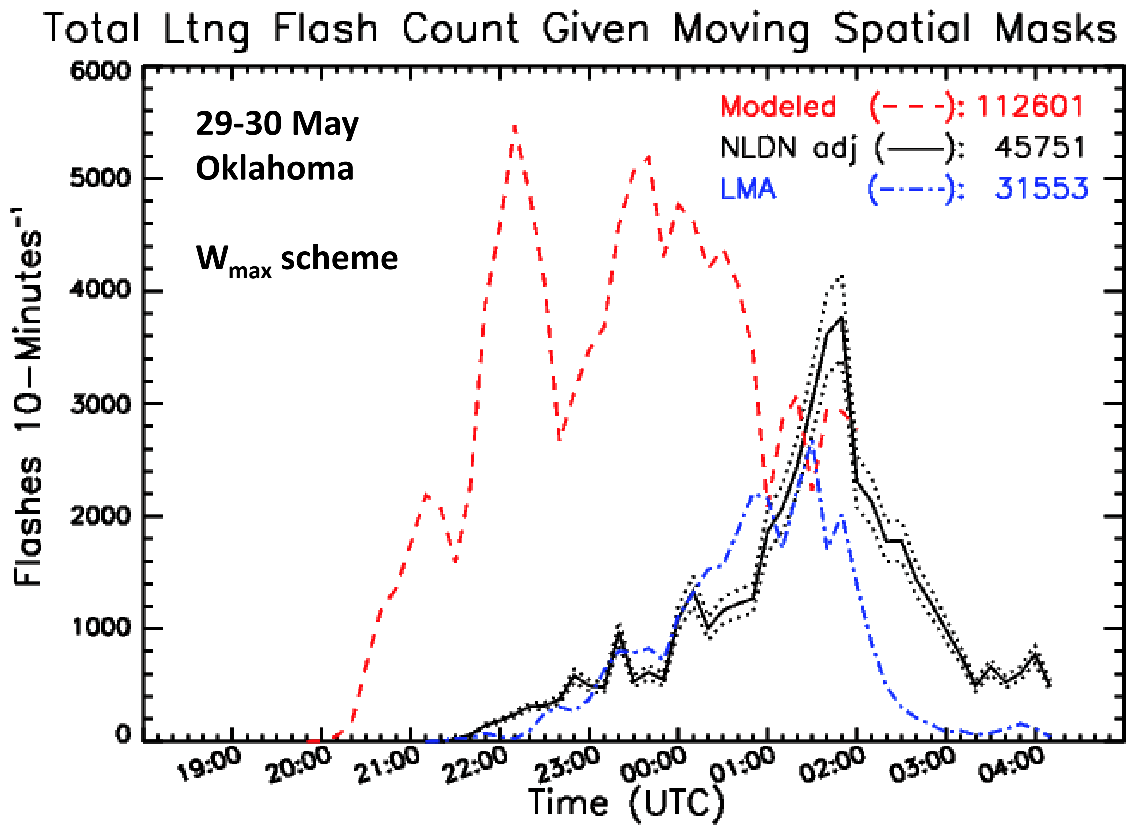
- UT background NO is well predicted, 50-200 pptv, higher values to north
- UT convective outflow
    - WRF: 1-3 ppbv
    - Obs: 0.5-2 ppbv
    - → Within 50%

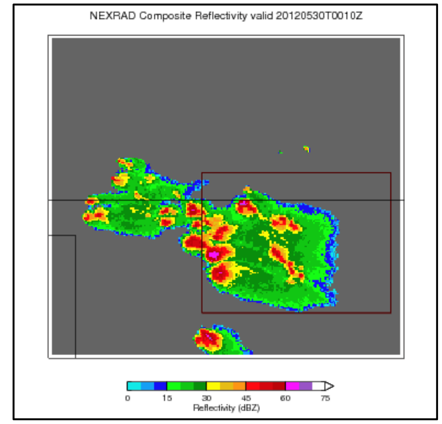
GV aircraft final data courtesy of Weinheimer, Knapp, Montzka, Flocke, Campos (NCAR)

DC-8 aircraft preliminary data courtesy of Ryerson, Pollack, Peischl (NOAA/ESRL)

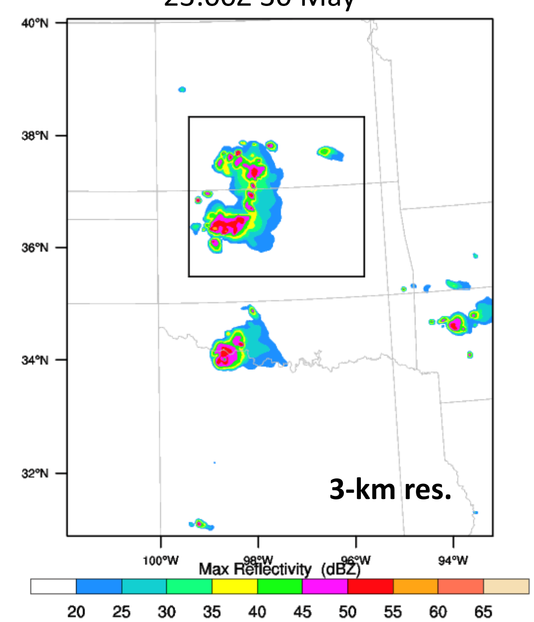
M. Barth et al.

Flash Rate Parameterization in Cloud-Resolved WRF-Chem





Model-simulated Composite Reflectivity
23:00Z 30 May



- **Model storm began 80 minutes too early**
- **Covers nearly twice the area of the observed storm, which accounts for much of the factor of 2.5 flash rate over-prediction compared with adjusted NLDN**
- **LMA flashes may be biased low due to storm location at northern edge of network**

Kristin Cummings, Ken Pickering – Poster AE33B – 0345 this afternoon

Treatment of LNO_x in Cloud-Resolved WRF-Chem

- **LNO_x parameterization scheme *(DeCaria et al., 2005)***
  - **Gaussian vertical distributions of IC (bimodal) and CG (single mode) NO production based on typical lightning flash channel distributions**
  - **Lightning channels set to maximize at -15°C (CG and IC) and -45°C (IC)**
  - **Average of 500 moles NO per IC and CG flash *(Ott et al., 2010)***
  - **Horizontal placement of NO based on reflectivity ≥ 20 dBZ**
  - **Sum of IC and CG LNOx produced at each model time step injected into grid cells as designated above.**

Compare model and aircraft-observed NO_x mixing ratios at various altitudes within the cloud to determine if the assumed mean LNO_x moles NO $flash^{-1}$ for IC and CG flashes in the model is over or underestimated. Test additional values as necessary.

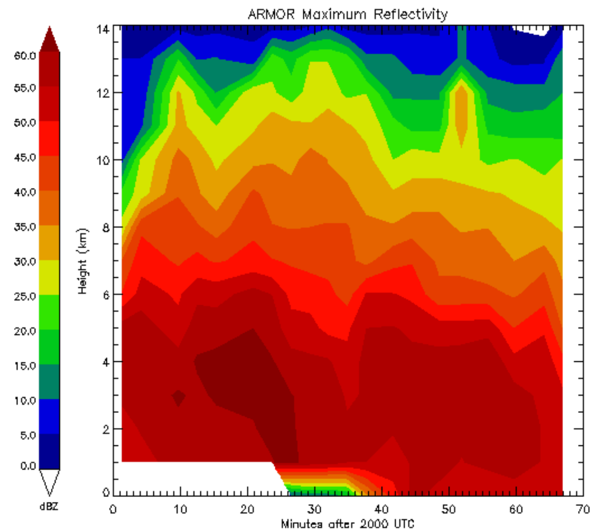
Potential Improvements to the LNO_x Scheme in WRF-Chem Suggested by LMA Analysis

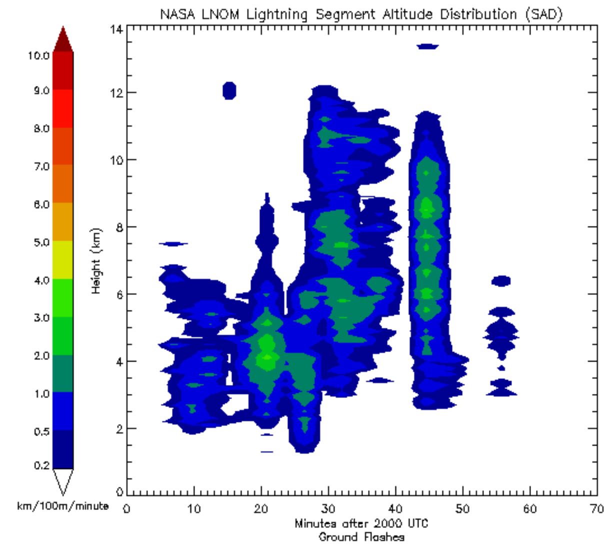
- Evaluate model flash rates based on LMA flash counts; compare LMA rates with adjusted NLDN data
- Test new flash rate parameterization schemes to determine which scheme performs best for specific DC3 regions and storm types
- Use LMA data to:
  - Improve vertical distribution of LNO_x production based on LMA data (vertical distribution of flash segments)
  - Modify region within storm where LNO_x is placed (flash extent information) in relation to reflectivity
  - Use IC/CG ratio from LMA data
  - Modify model to use <u>flash area or length</u> data rather than flash counts to drive LNOx production

An Investigation of the Kinematic and Microphysical Control of Lightning Rate, Extent and NO_X Production using DC3 Observations and the NASA Lightning Nitrogen Oxides Model (LNOM)

UAH ARMOR Maximum Reflectivity

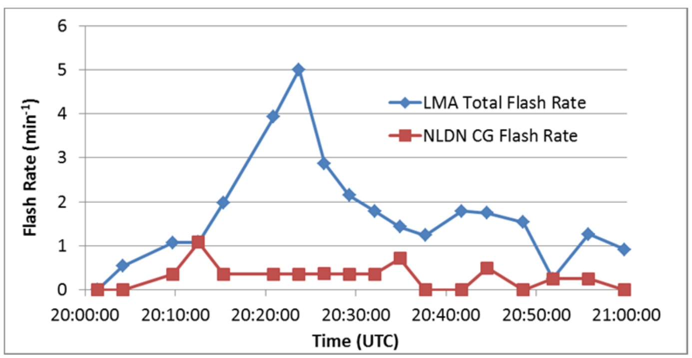
21 May 2012



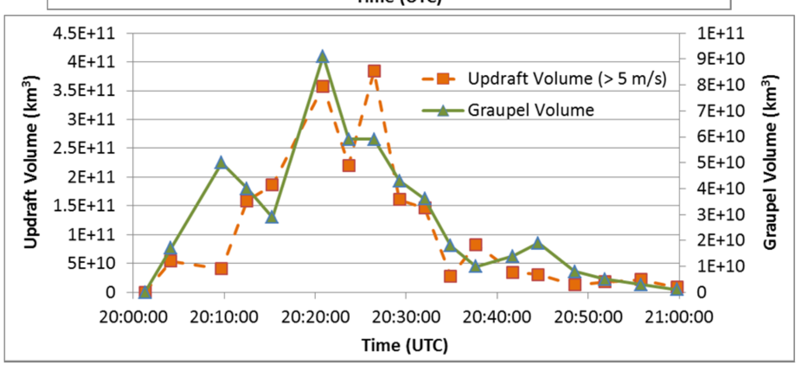


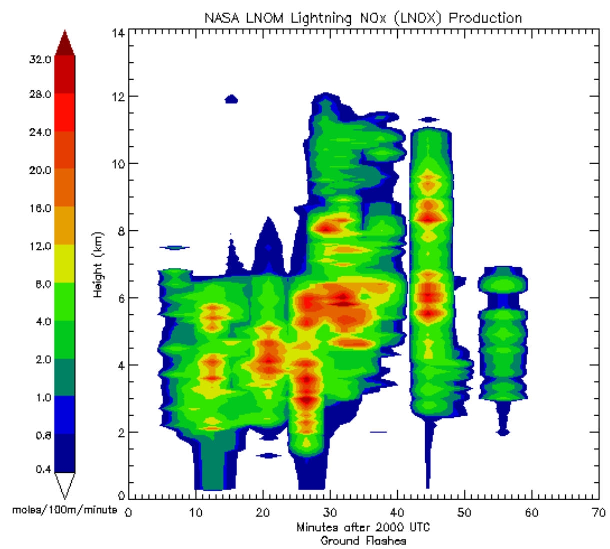
NASA LNOM Lightning Segment Altitude Distribution (SAD)

LMA Flash vs. ARMOR-KHTX dual-Doppler and polarimetric radar



Ground Flashes





NASA LNOM Lightning NO_x Production

L. Carey talk AE31A–03 8:30 AM

Summary

Data Analysis

- NOx production (in terms of mixing ratio) was larger in DC3 than in campaigns conducted in other parts of the world (Europe, Brazil, W. Africa, Australia).
- Preliminary analysis (volume and flux methods) of aircraft NOx observations in relation to observed flash rates yields NOx production of 100 – 150 moles/flash averaged over three Oklahoma storms
- Flash rates parameterized using radar-observed storm parameters compared with LMA flashes. W_{max} scheme performed best for Colorado storm.
- LMA flash rates useful for evaluating model-parameterized flash rates.
- LMA-derived flash area will be tested as indicator of LNOx production.

Modeling

- WRF-Chem (15-km) with parameterized convection overestimated UT NOx by ~50% with 500 moles/flash for OK storm.
- Cloud-resolved WRF (3-km) using W_{max} overestimated observed flashes by factor of 2.5 for OK storm. Size of model storm is the main issue. LNOx in WRF-Chem to be tested next.
- Estimates of LNOx production as a function of altitude and time in Alabama storms simulated with LNOM using LMA data as input