A WRF-Chem Flash Rate Parameterization Scheme & LNO_x Analysis of the 29-30 May 2012 Convective Event in Oklahoma during DC3

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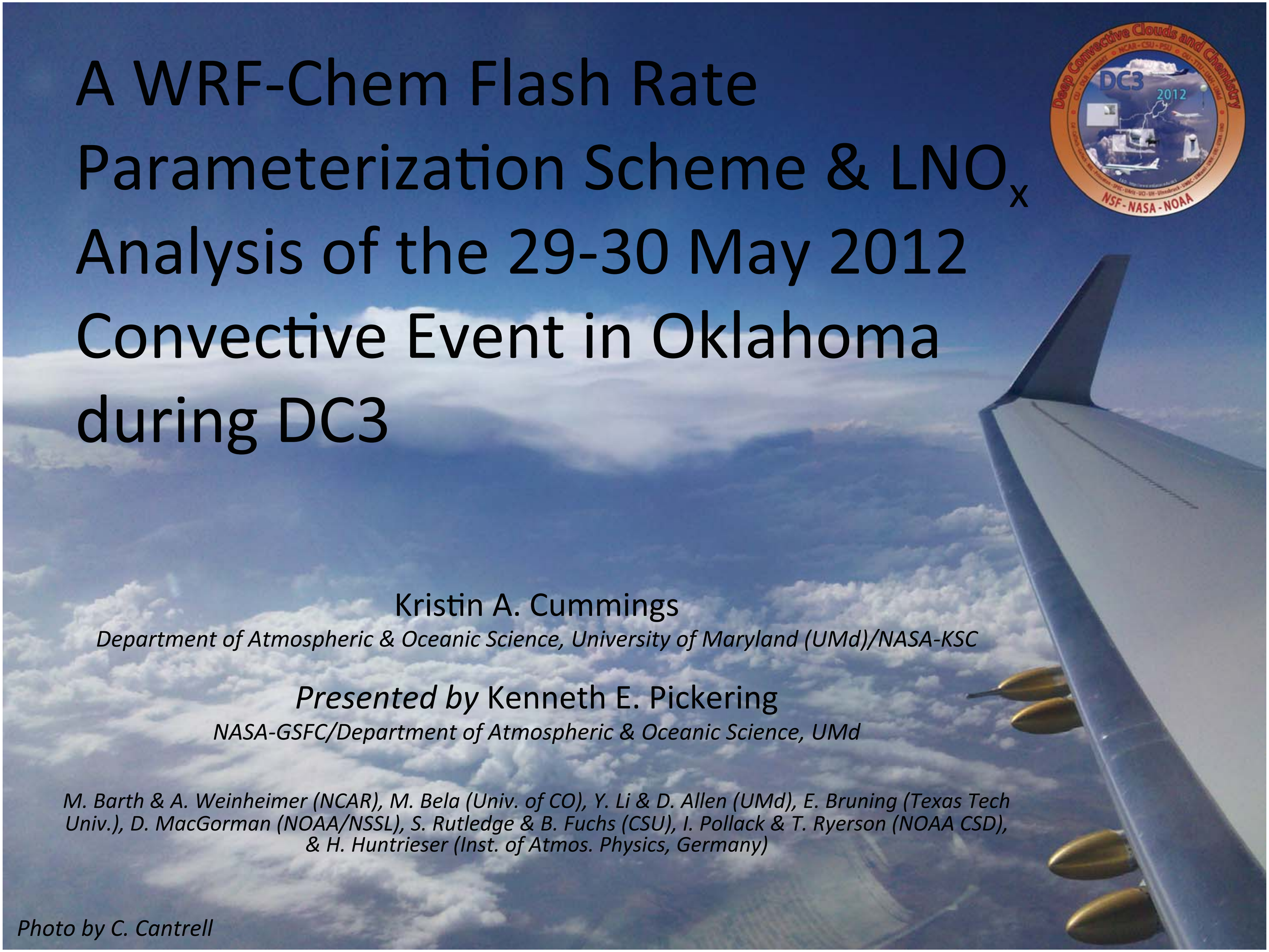


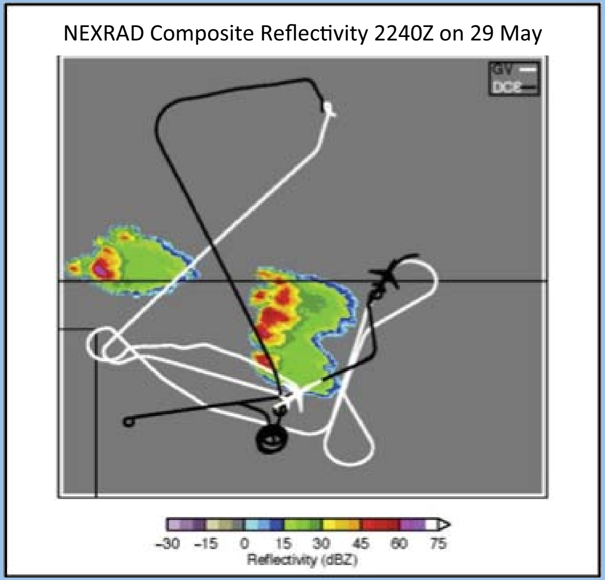
Photo by C. Cantrell

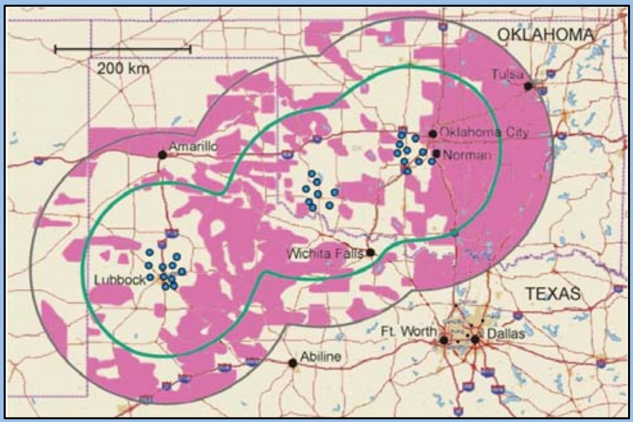
Key Objectives

- To study the 29-30 May 2012 deep convective storm observed during the Deep Convective Clouds and Chemistry (DC3) experiment over Oklahoma, including its:
  - Convective transport of trace gases
  - Associated lightning occurrence and nitrogen oxide (NO_x) production
- Simulate the observed storm using WRF-Chem
- Compare the physical features of the simulated storm against aircraft and ground-based observations
- Add flash rate parameterization schemes (FRPSs) to the model and identify the best match to observations
- Determine NO production scenario for IC and CG flashes following a lightning-generated NO_x (LNO_x) scheme

Background

- Storm system developed ~21Z May 29 along KS/OK border and continued until 04Z May 30
- Aircraft sampled storm and its environment from 20Z May 29 to 01Z May 30
  - DC-8 focused on storm inflow and outflow
  - GV and Falcon concentrated on outflow
- Ground-based instrumentation included:
  - Dual-Doppler radar (NEXRAD level II regional; *Data courtesy of C. Homeyer*)
  - National Lightning Detection Network (NLDN) cloud-to-ground flash data
  - Oklahoma Lightning Mapping Array (LMA) flash initiation density data

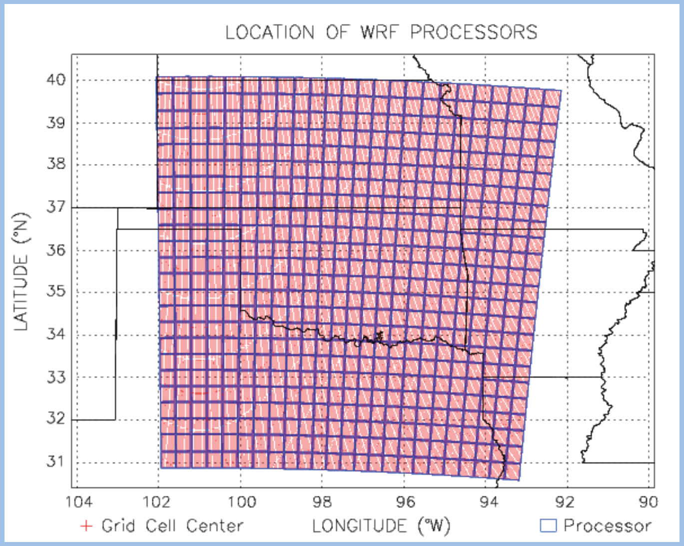




Blue circles: LMA stations
Green outline: Extent of 3-D lightning mapping capability
Gray outline: Extent of 2-D lightning detection

WRF-Chem Model V3.5

- Nested domains: 15-km and 3-km
- Initialized with DART and GFS for boundary conditions
- Used coarsely prescribed IC:CG ratios (*Boccippio et al., 2001*)



Type of Scheme	Selection for Simulation
Microphysics	Morrison
Planetary boundary layer	Yonsei University (YSU)
Radiation	Rapid radiative transfer model for GCMs (RRTMG)
Flash rate	Maximum vertical velocity (W_{max})
Lightning-generated NO_x (LNO_x)	DeCaria et al. (2000, 2005)

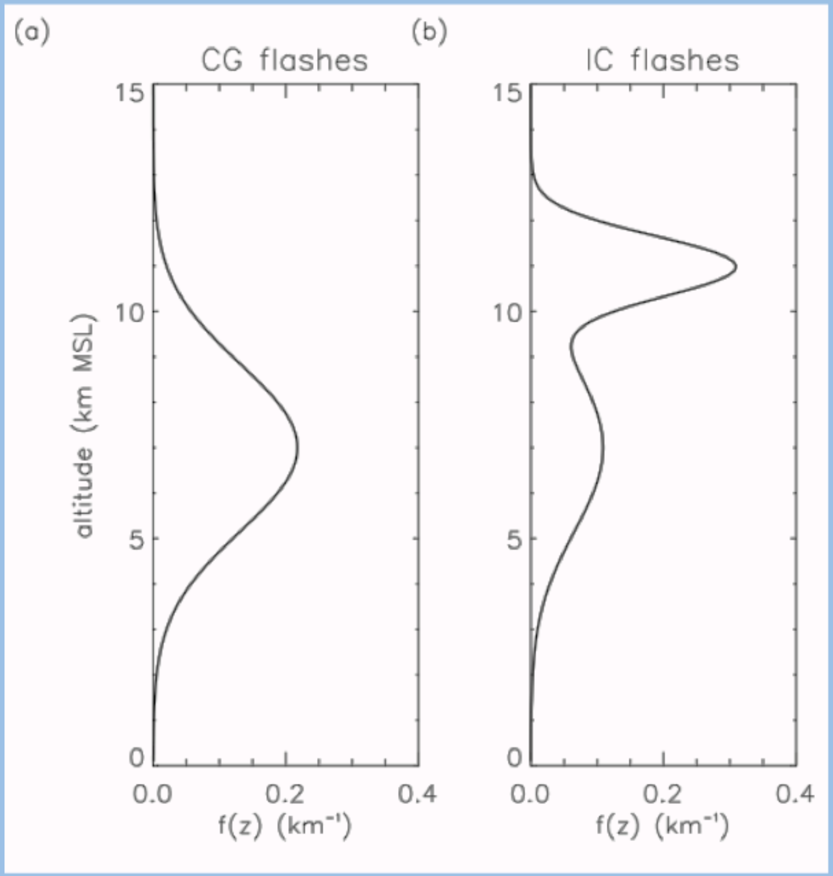
Flash Rate Parameterization Schemes

- Based on simulated thunderstorm's physical features
- Six types have previously been used in cloud-resolving models:

Type of FRPS	Equation (flashes min^{-1})	References
Maximum vertical velocity	$5.7 \times 10^{-6} \times W_{max}^{4.5}$	Price & Rind, 1992
Cloud top height	$3.44 \times 10^{-5} \times H^{4.9}$	Price & Rind, 1992
Updraft volume	$6.75 \times 10^{-11} \times w_5 - 13.9$	Deierling & Petersen, 2008
Ice water path	$33.33 \times IWP - 0.17$	Petersen et al., 2005
Ice mass flux product	$9.0 \times 10^{-15} \times (f_p \times f_{np}) + 13.4$	Deierling, 2006; Deierling et al., 2008
Precipitation ice mass	$3.4 \times 10^{-8} \times p_m - 18.1$	Deierling et al., 2008

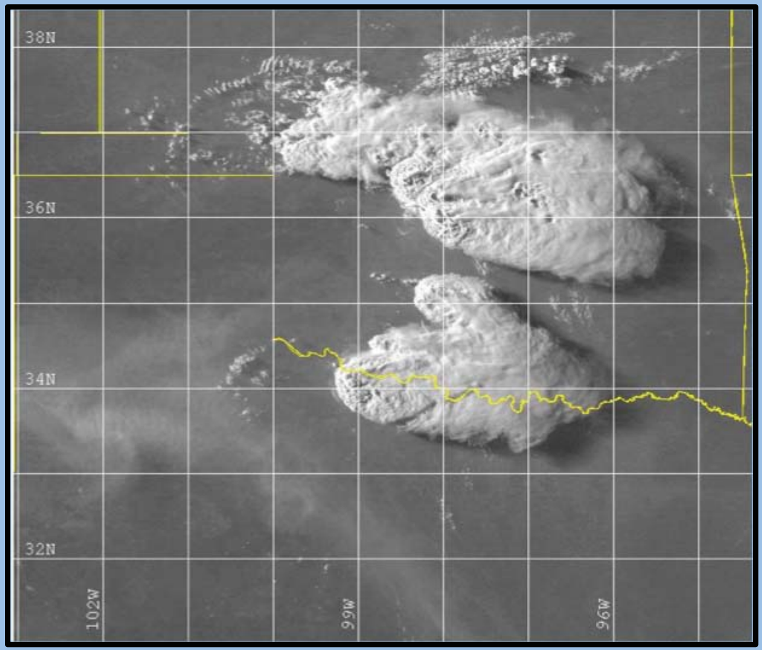
LNO_x Parameterization Scheme (DeCaria et al., 2005)

- Gaussian vertical distribution 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)
- 500 moles NO per IC and CG flash (*Ott et al., 2010*)
- Horizontal placement of NO based on reflectivity ≥ 20 dBZ in each grid cell



Methodology

- Created moving spatial masks at 10-min intervals for comparison of observed and model-simulated storms
- Used offline calculations, with adjustment factors, to analyze the six FRPS trends
- Calculated NLDN total flashes given NLDN CG flashes and mean IC:CG ratio for the storm region (3.9 ± 0.49), which is based on Boccippio et al. (*2001*)



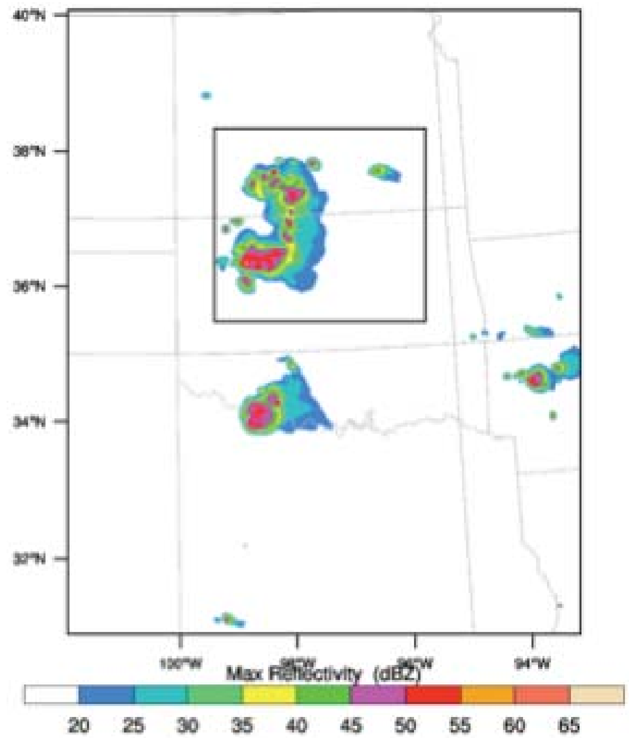
GOES-13 1-km Visible at 0008Z (NCAR/EOL)

Total flashes = CG flashes × [1/0.93] NLDN DE × [IC:CG ratio + 1]

- Compared flash rate trends over the observed and model-simulated storm's lifetime

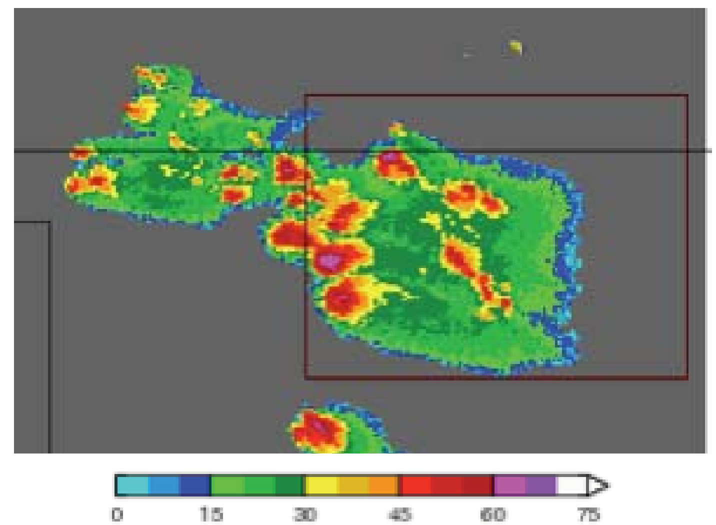
Initial Comparison of Storm Features

Model-Simulated Composite Reflectivity 2300 Z on 30 May



Black rectangle represents the spatial mask surrounding the model-simulated cell of interest at 2300Z May 30

NEXRAD Composite Reflectivity 0010Z on 30 May



Reflectivity (dBZ)

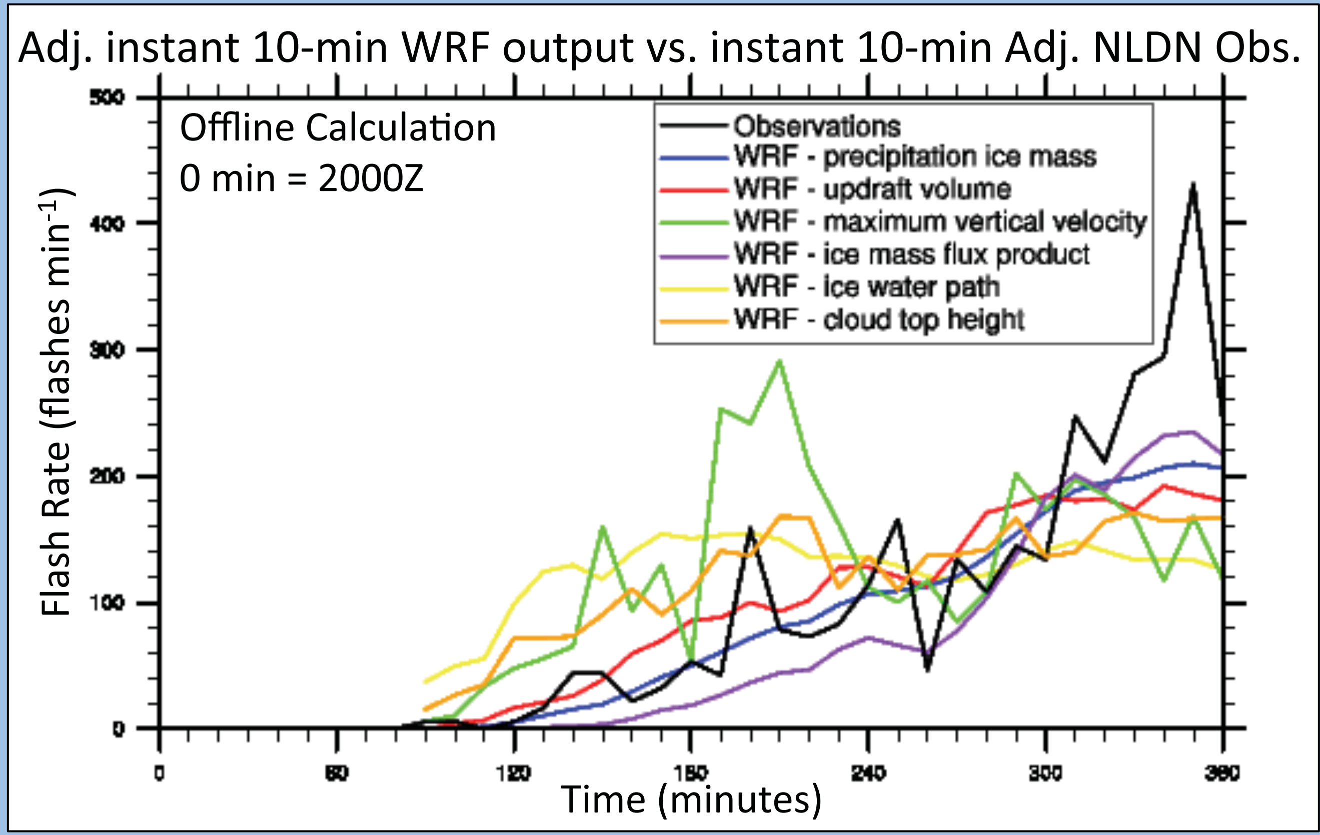
Red rectangle represents the spatial mask surrounding the cell of interest at 0010Z May 30

Model-simulated storm:

- Began ~1-1.5 hour before observed storm
- <u>*Exceeds*</u> area of observed storm by roughly a factor of two

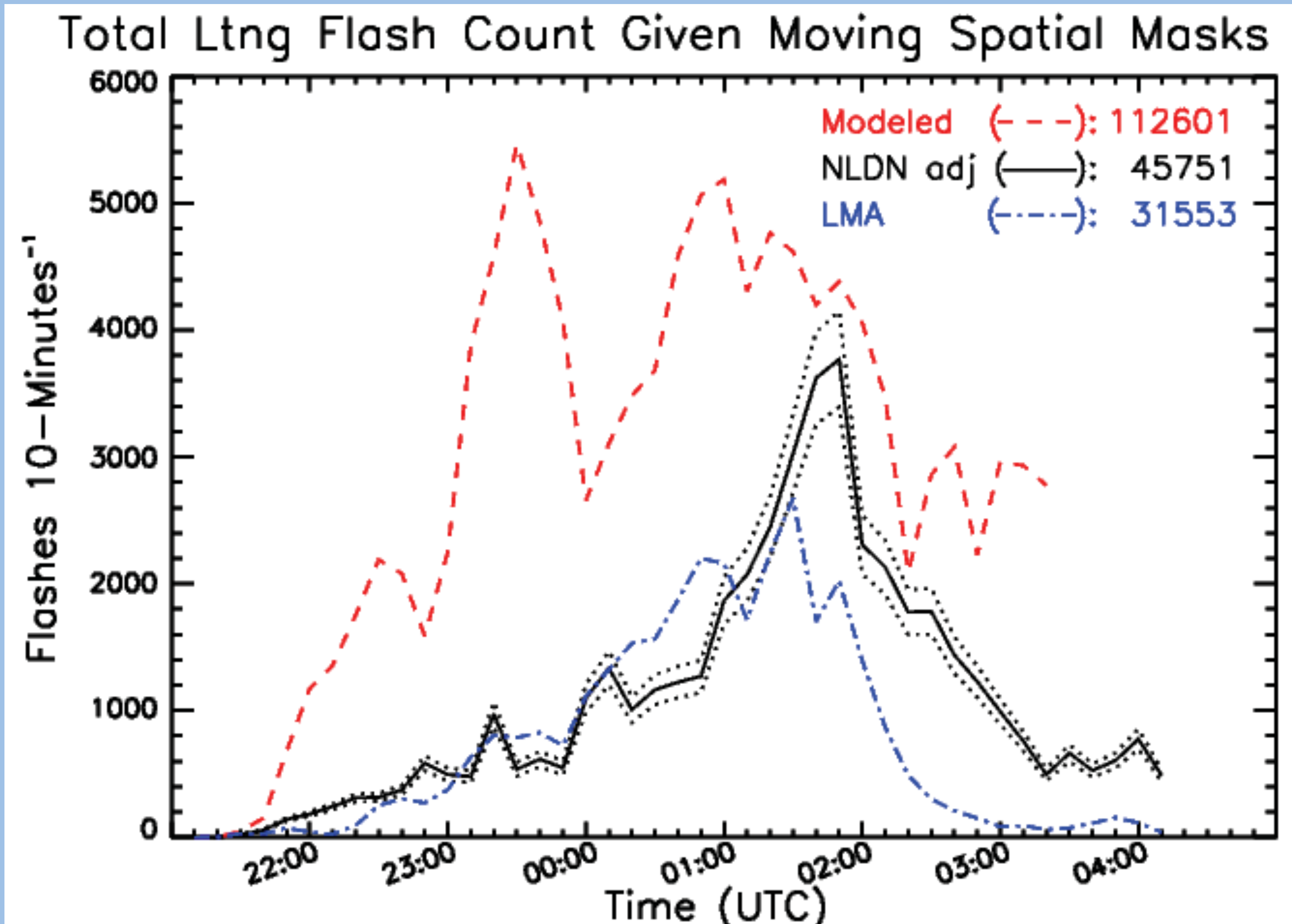
Compared instantaneous flash rates from WRF at 10-min intervals with corresponding 1-min periods from the observed NLDN flash rates

Model-simulated flash rate trends are adjusted 90 minutes later to coincide with observations

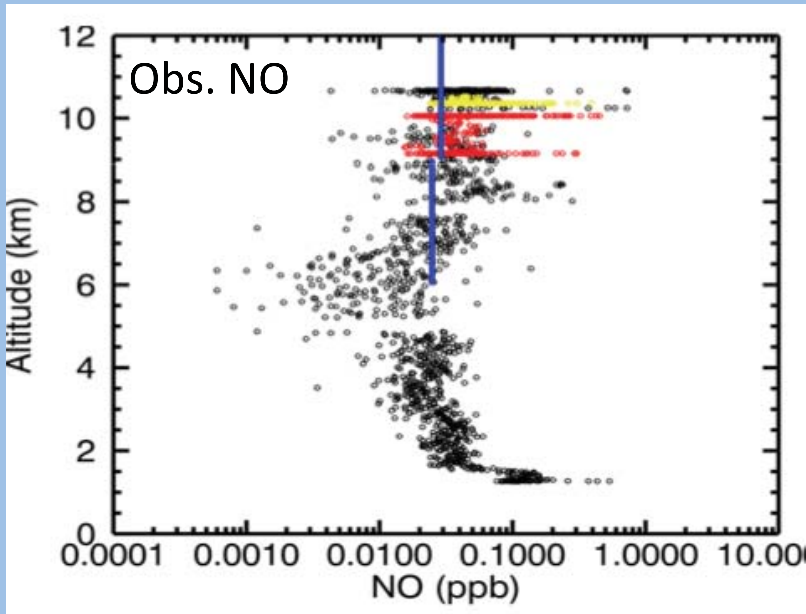


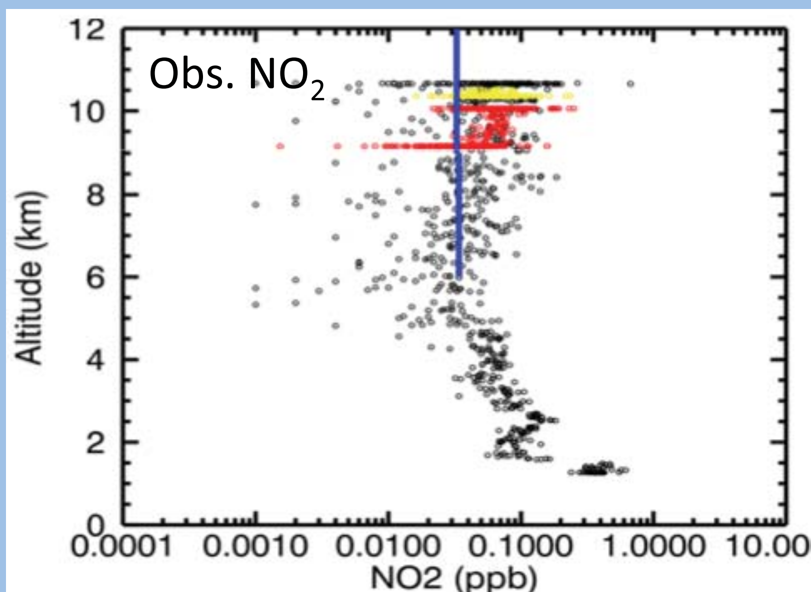
Flash Rate Parameterization Scheme	Total Flashes Prior to Scaling	Scaling Factor
Maximum vertical velocity	**3,951**	**1.1310**
Cloud top height	708	6.3138
Updraft volume	21,118	0.2116
Ice water path	**4,452**	**1.0035**
Ice mass flux product	36,745,336	0.0001
Precipitation ice mass	164,749	0.0271

- *Flux product*, *precipitation ice mass*, and *updraft volume* trends are similar to the increasing trend of observations
- Timing of W_{max} and *ice water path* peaks is similar to observations (140, 200, & 310 min)
- Magnitude of observed primary peak greater than those in FRPSs
- W_{max} and *ice water path* schemes need the least adjustment to match observed total flashes at each 10-min interval (4,468 flashes)



W_{max} FRPS <u>*overestimates*</u> the total flashes of both the NLDN (~2.5) and LMA (~3.5)





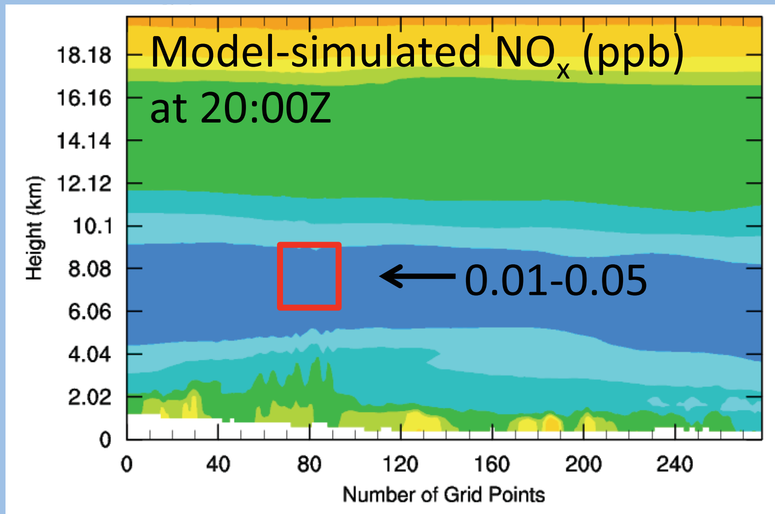
Observations taken in cloud-free air to the south of the storm system

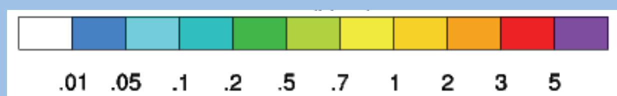
To define the real background air at 9-12 km, the 10th percentile is used to remove any influence from old convective outflow

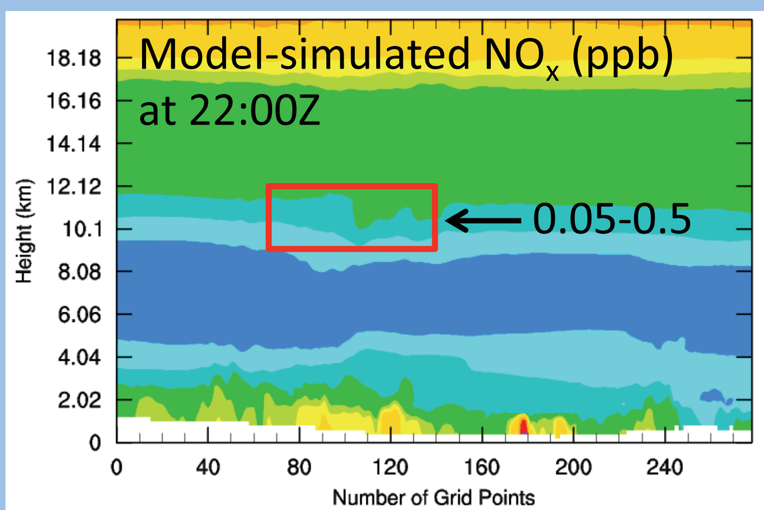
Aircraft	Time of UT Background Sampling (Z)
DC-8	20:40-21:10 (black)
GV	22:15-22:30 (red); 22:58-23:05 (yellow)

Obs. Species	6-9 km (*DC-8*)	9-12 km (*DC-8, GV*)
	Median (ppb)	10th percentile (ppb)
NO	0.025	0.029
NO_2	0.034	0.033
NO_x	0.059	0.062

**Plots courtesy of M. Bela*







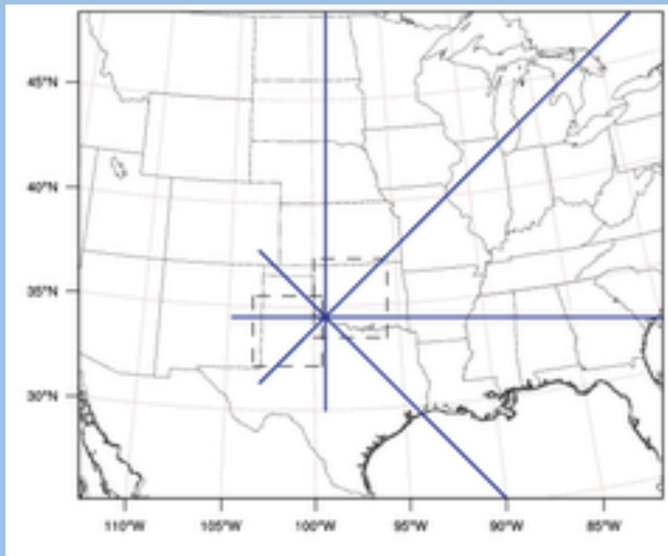
Model-simulated vertical cross-section taken in cloud-free air to the south of the storm system

Aircraft	Time of UT Background Sampling (Z)	Model Time (Z)
DC-8	20:40-21:10	20:00
GV	22:15-22:30; 22:58-23:05	21:00; 22:00

Altitude		NO (ppb)	NO_2 (ppb)	NO_x (ppb)
6-9 km (*Median*)	Obs.	0.025	0.034	0.059
	Model	0.020	0.017	*0.01-0.05*
9-12 km (*10^{th} percentile*)	Obs.	0.029	0.033	0.062
	Model	0.041	0.023	*0.05-0.5*

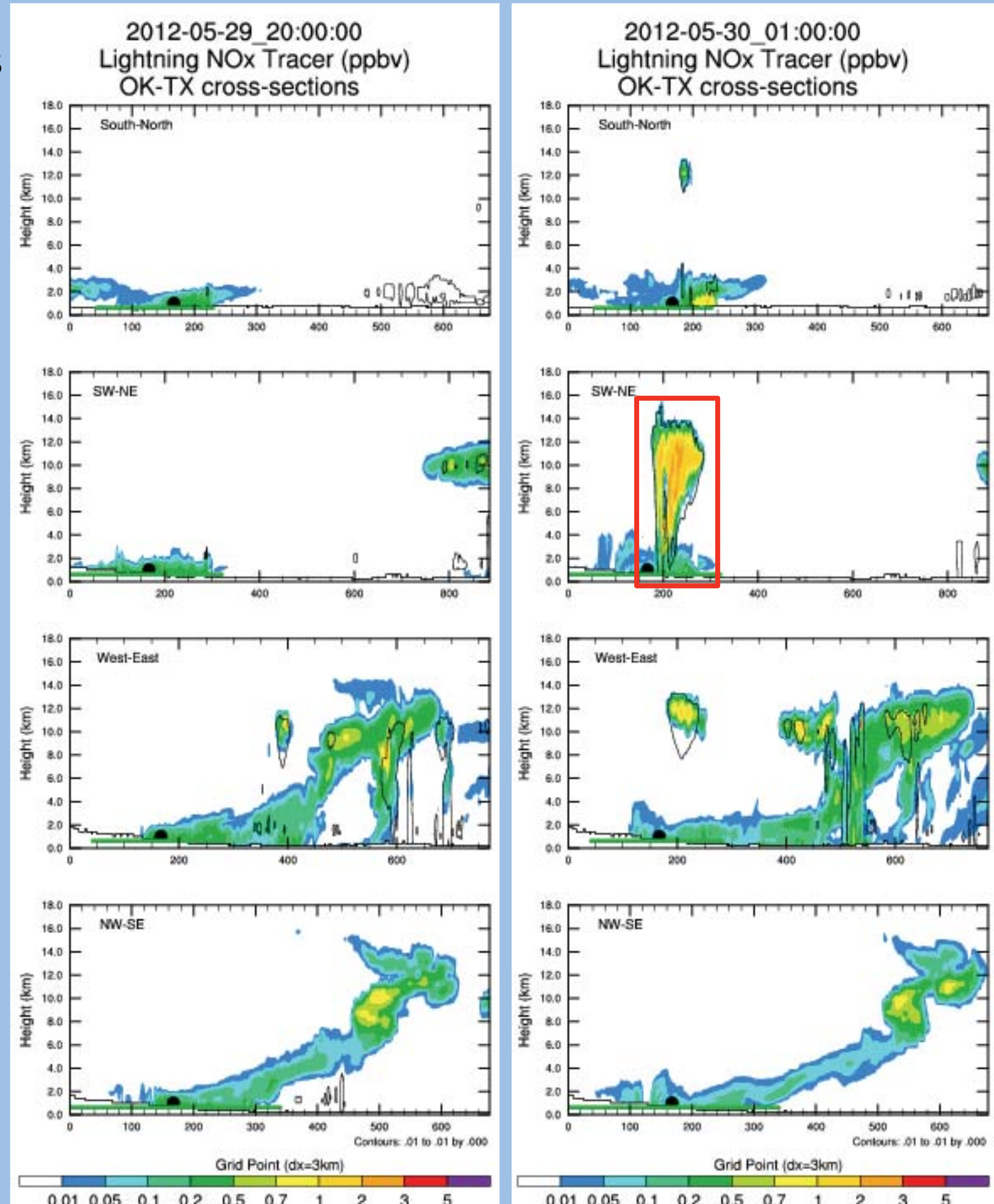
Model-simulated NO_x at 9-12 km is given as a range. Although the observed NO_x is found at the lower end of this range, it should be kept in mind that the observed value represents the 10^{th} percentile.

Location of vertical cross-sections



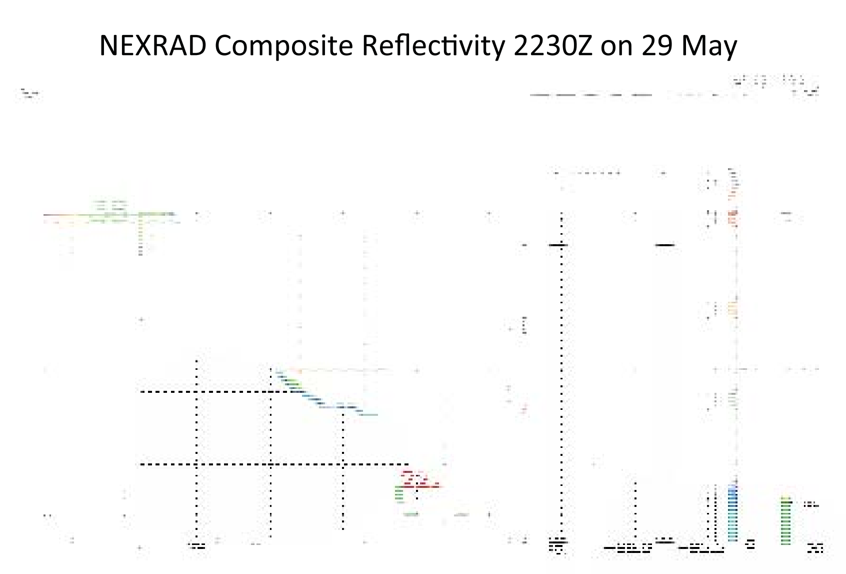
LNO$_x$ forecast for Oklahoma convection the morning of flight. Forecast based on WRF ARW 00Z May 29 model run.

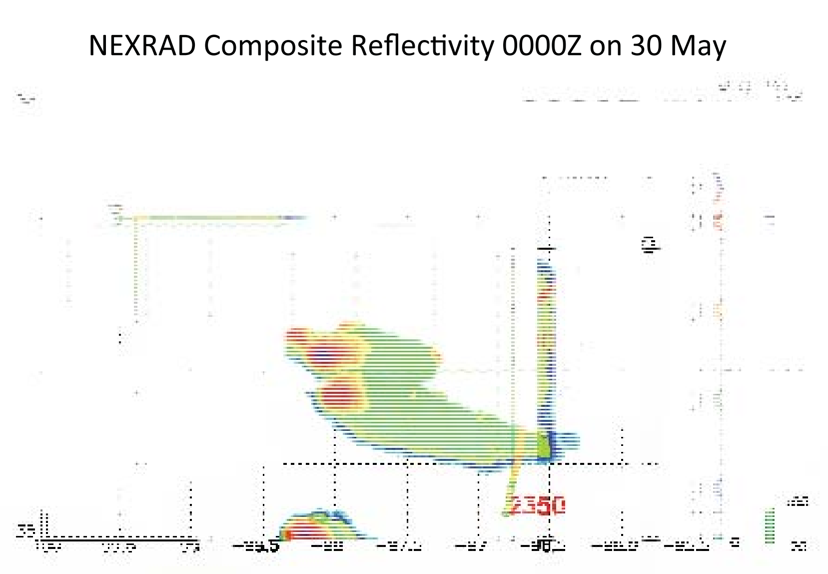
Will compare LNO$_x$ prediction of 2-3 ppbv in forecasted storm against observed aircraft measurements and WRF-Chem model-simulated NO$_x$

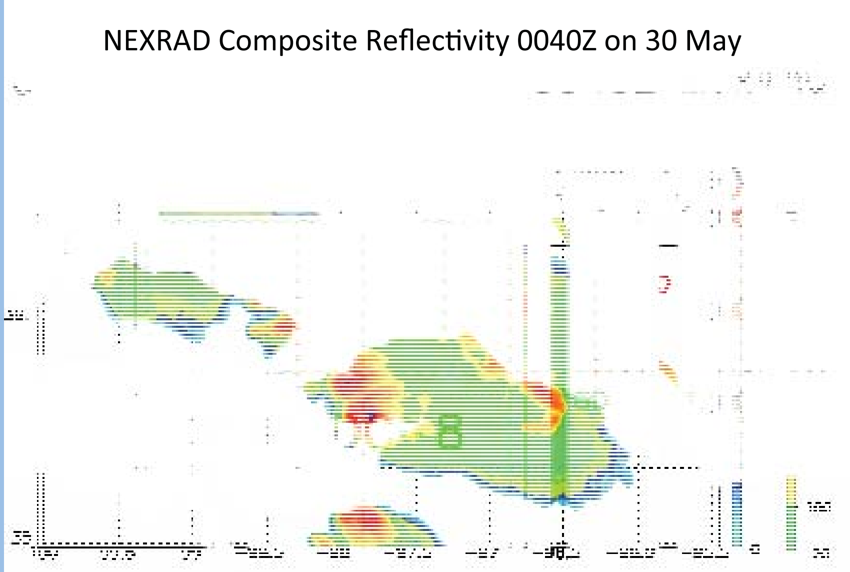


** Black dot along the x-axis represents intersection of the four cross-sections*

Initial LNO_x Analysis from Aircraft







Radar observations overlaid with 10-min intervals of aircraft NO_x measurements

NO_x measurements increase from sampling in cloud-free upper tropospheric air (0.02-0.1 ppbv) to making transects through anvil outflow (peaks to ~2 ppbv)

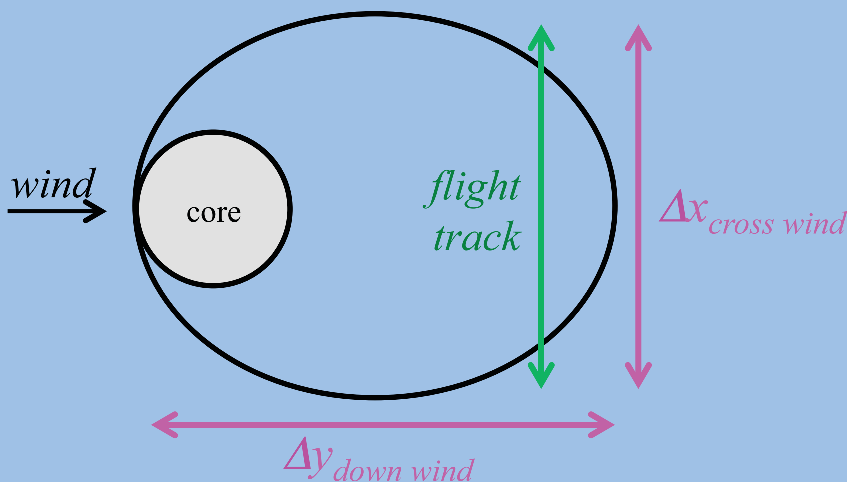
Two methods for calculating NO_x production per flash

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

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

Top View

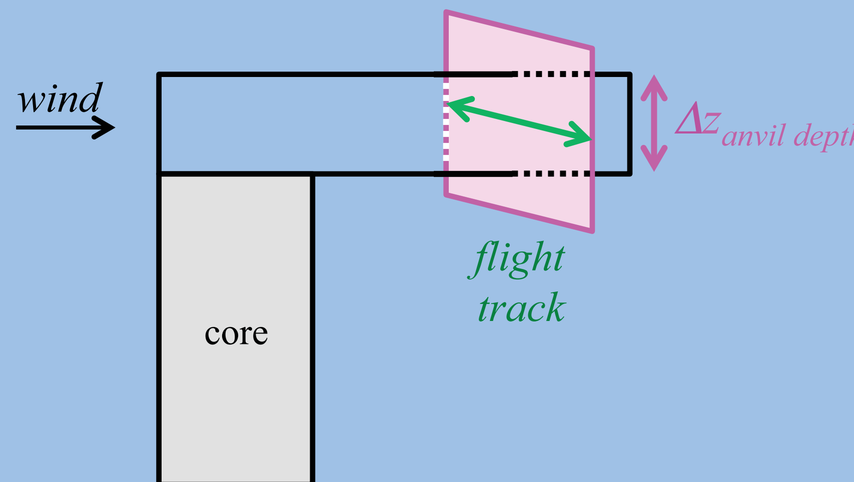
**Volume= sum of surface areas from NEXRAD CAPPI images (2 km resolution)*



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

$P(NO_x)$ 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}

**Slide courtesy of I. Pollack*

Total number of lightning flashes during the 29-30 May 2012 storm:

Storm start (UTC)	Storm end (UTC)	Duration (hrs)	CG flashes (NLDN)	Total flashes (NLDN)		Total flashes (LMA)
				IC:CG=2	IC:CG=10	
29 May 21:00	30 May 00:49	3.82	2,851	8,553	64,361	69,650

Using **volume method** to find $P(NO_x)$ in units of ($\times 10^{25}$ molecules flash^{-1}):

Mean LNOx ($\times 10^{15}$ molec m^{-3})	Storm volume ($\times 10^{13}$ m^3)			$P(NO_x)_{NLDN}$			$P(NO_x)_{LMA}$		
	30 dBZ	20 dBZ	10 dBZ	30 dBZ	20 dBZ	10 dBZ	30 dBZ	20 dBZ	10 dBZ
5.2 ± 0.1	6.0	16.2	40.6	3.7 61.4 (mol flash^{-1})	9.9	24.8	0.5 8.3 (mol flash^{-1})	1.2	3.0

Using **flux method** to find $P(NO_x)$ in units of ($\times 10^{25}$ molecules flash^{-1}):

Mean LNO_x ($\times 10^{25}$ molec s^{-1})	NLDN flash rate (flashes s^{-1})	$P(NO_x)_{NLDN}$	LMA flash rate (flashes s^{-1})	$P(NO_x)_{LMA}$
2.7 ± 0.1	0.64	4.2 69.7 (mol flash^{-1})	5.20	0.5 8.3 (mol flash^{-1})

**Slide courtesy of I. Pollack*

Conclusions

- Based on offline calculations, W_{max} FRPS was selected for use in model:
  - Needs little adjustment to match the observed total flashes
  - Coincides with several of the observed flash rate peaks
- Scale up model-simulated flash rates in offline calculations and scale down online:
  - May partly be due to how offline calculations are computed
- Model overestimate of observed flashes may be due to:
  - Area of model-simulated storm ~2x larger than observed
  - Observed storm passes over northern edge of LMA
- Initial look at NO_x chemistry in UT air undisturbed by storm:
  - At 6-9 km, NO values similar between aircraft and model, and model-simulated NO2 underestimates observations by ~0.02 ppbv
  - At 9-12 km, the 10th percentile NO_x values are similar (~0.06 ppbv) between the aircraft and model
- Generate similar P(NO_x) when using volume (> 30 dBZ) and flux methods
  - Estimated P(NO_x) is much smaller than 500 moles flash^{-1} used in WRF-Chem
- WRF-Chem model estimates of P(NO_x) in works

Future Work

- Perform a trace gas simulation and analysis of NO_x, CO, and O_3 using WRF-Chem
- Compare model-simulated LNO_x against aircraft measured NO_x
- Determine NO production scenario per IC and CG flash that best matches aircraft observed NO_x mixing ratios
- Investigate O_3 changes downwind of flight

Photo by C. Cantrell