Airborne quantification of lightning-induced NO_x production in deep convective storms over the continental United States

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1. Introduction

Objective:

- Determine a measurement-based constrained range for NO_x produced per lightning flash for storms sampled during the 2012 Deep Convection Clouds and Chemistry (DC3) experiment
- Compare results for storms sampled over the continental U.S. during DC3 with reported global average range

Advantages of DC3 data set:

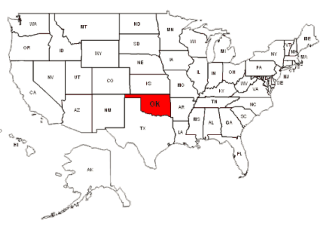
- Storms sampled by two instrumented aircraft (NASA DC-8 *and* NSF/NCAR GV)
- NO and NO_2 measurements; Radar and lightning mapping data products

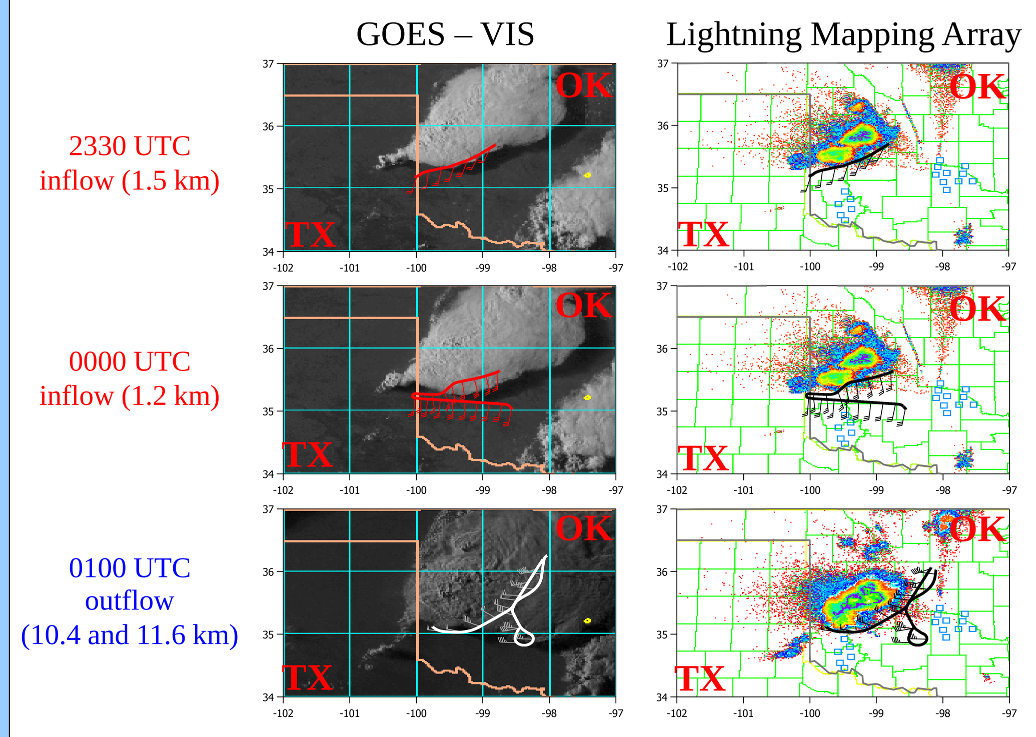
Approach:

- Calculate NO_x production per flash using two different analysis methods reported in the literature (demonstrated here using one example storm)
- Compare methods using results for all storms sampled over Oklahoma

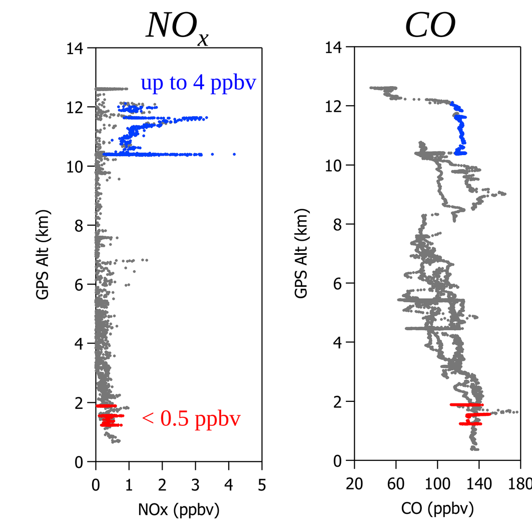
2. Example Storm: 19 May

Images show isolated storm with presence of lightning over OK:





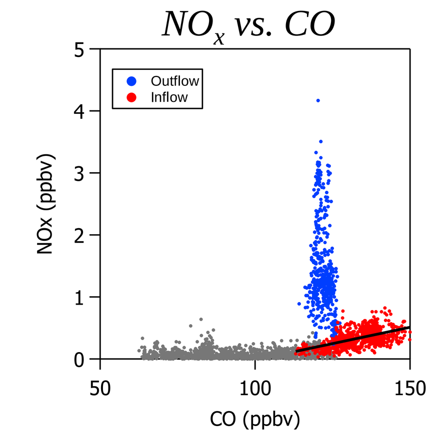
Chemical tracers illustrate LNO_x enhancements and transport:



Convective updraft ingests from 0.5 – 2 km; consistent with *Skamarock et al. (2000)*

DC-8 data

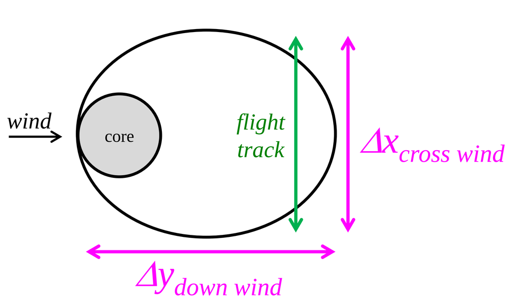
Calculate NO_x transported up from LLS fit of NO_x/CO and average CO in outflow



3. NOx production using Volume method

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

Top View



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

$P(NO_x)$ in units of molecules

Divide by #flashes to get molecules flash^{-1}

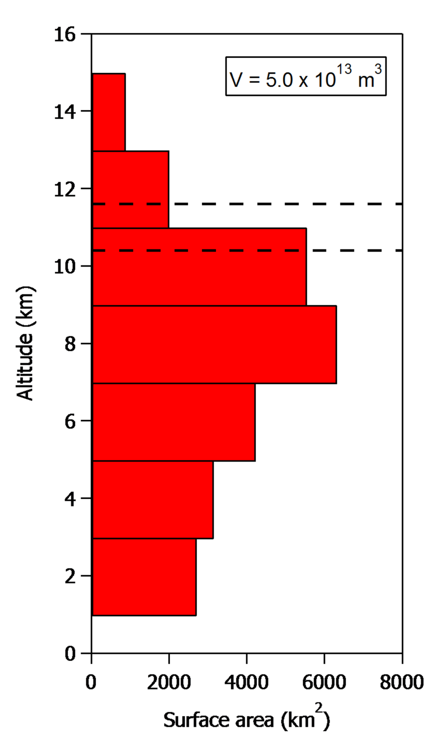
	z (km)	Mean $NO_x^{outflow}$ (ppbv)	Mean NO_x^{trans} (ppbv)	Mean $LNO_x^{enh}(z_i)$ (ppbv)	NO_x (molecules m^{-3})
Pass 1	10.4	1.24	0.22	1.02	8.5×10^{15}
Pass 2	11.6	1.64	0.21	1.43	10.3×10^{15}

Average NO_x = 9.4×10^{15} molecules m^{-3}

1097 cloud-to-ground (CG) lightning flashes estimated from NLDN → *Flashes counted from storm start to sampling end (Δt = 4 hrs) in LAT/LON region of storm*

$$P(NO_x) = \frac{(9.4 \times 10^{15}\ \text{molecules m}^{-3}) * (5.0 \times 10^{13}\ \text{m}^3)}{(1097\ \text{CG flashes})} = \mathbf{42 \times 10^{25}\ molecules\ CG\ flash^{-1}}$$

Estimated storm volume from composite radar images

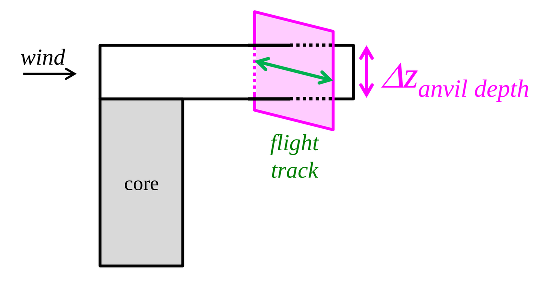


- Use CAPPI (constant altitude plan position indicator) images - 2 km vertical resolution
- Images selected during outflow sampling and when storm is most developed
- Image surface area calculated from pixels > 20 dZB; Total volume = 2 km*∑(surface areas)

4. NOx production using Flux method

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

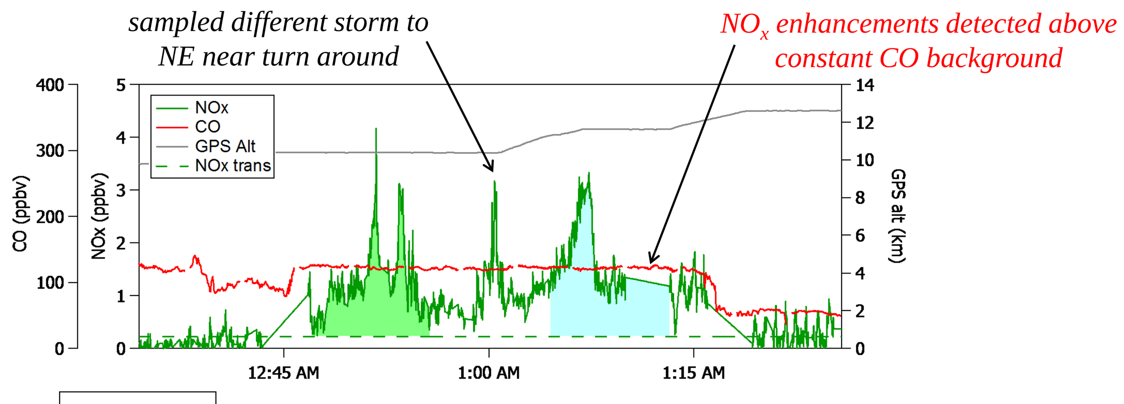
Vertical Cross Section



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

$P(NO_x)$ in units of molecules s^{-1}

Divide by #flashes s^{-1} to get molecules flash^{-1}



DC-8 data

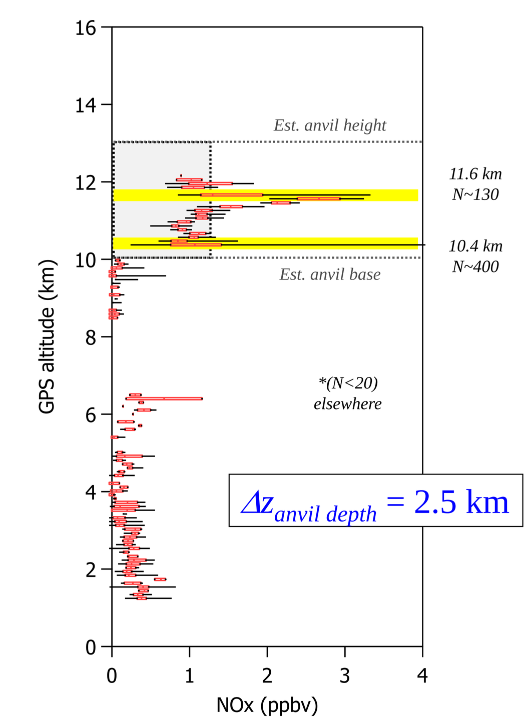
pass 1	pass 2
2.3×10^{25} molecules s^{-1}	3.5×10^{25} molecules s^{-1}

Average = 2.9×10^{25} molecules s^{-1}

Average CG flash rate (0.08 flashes s^{-1})
→ assumes constant average distribution of 1097 flashes over Δt = 4 hrs

$$P(NO_x) = \frac{(2.9 \times 10^{25}\ \text{molecules s}^{-1})}{(0.08\ \text{CG flashes s}^{-1})} = \mathbf{38 \times 10^{25}\ molecules\ CG\ flash^{-1}}$$

Estimated anvil depth from NO_x vertical distribution



- Minimal samplings, but similar medians
- Assumes constant average NO_x distribution

5. Summary of Results

Oklahoma Storms	# CG flashes (hrs)	Volume Method: $\times 10^{15}$ molecules m^{-3}	Volume Method: Volume $\times 10^{13}$ m^3	Volume Method: $P(NO_x)$ $\times 10^{25}$ molecules flash^{-1}	Flux Method: $\times 10^{25}$ molecules s^{-1}	Flux Method: Flash rate flashes s^{-1}	Flux Method: $P(NO_x)$ $\times 10^{25}$ molecules flash^{-1}	Volume/Flux Ratio
19 May[a]	1097 (4)	9.4	5.0	42	2.9	0.08	38	1.1
25 May[a]	2009 (3)	8.3	4.3	18	1.5	0.19	8	2
29 May[b,c]	2963 (3)	3.8	17.3	22	1.9	0.27	7	3
16 June[b]	--	10.1	22.4	--	9.9	--	--	--
DC3 Mean				27			18	Results for CG flashes only
DC3 Mean				9			6	Results for total (IC+CG) flashes estimated using IC:CG ratio ~ 2:1 from *Boccippio et al. (2000)**
DC3 Range				6 – 14			2 – 13	
Global Mean							15	Compiled from lab, field, and modeling studies since mid-1970s by *Schumann and Huntrieser (2007)*
Global Range							2 – 40	
Continental U.S. Mean							22	Compiled from field studies over the continental U.S. since mid-1970s by *Schumann and Huntrieser (2007)*
Continental U.S. Range							2 – 40	

[a]DC-8 data
[b]DC-8 and GV data
[c]Most outflow samplings

**Better estimates of total flashes pending available data from lightning mapping arrays*

- Volume method overestimates $P(NO_x)$ by about a factor of 2 compared to the flux method
- Volume-based results depend on estimated storm volume; Flux-based results depend on estimated anvil depth
- Range for storms sampled over the continental U.S. during DC3 is within the reported average range of 2 – 40 x 10^{25} molecules per total flash
- Improvement in individual storm estimates will be possible as additional DC3 data products become available