Elevated O_3 in Fresh and Aged Lightning-NOx Plumes Interacting with Biomass Burning Plumes over the Central U.S. during DC3*

*(*Deep Convective Clouds and Chemistry Experiment)*

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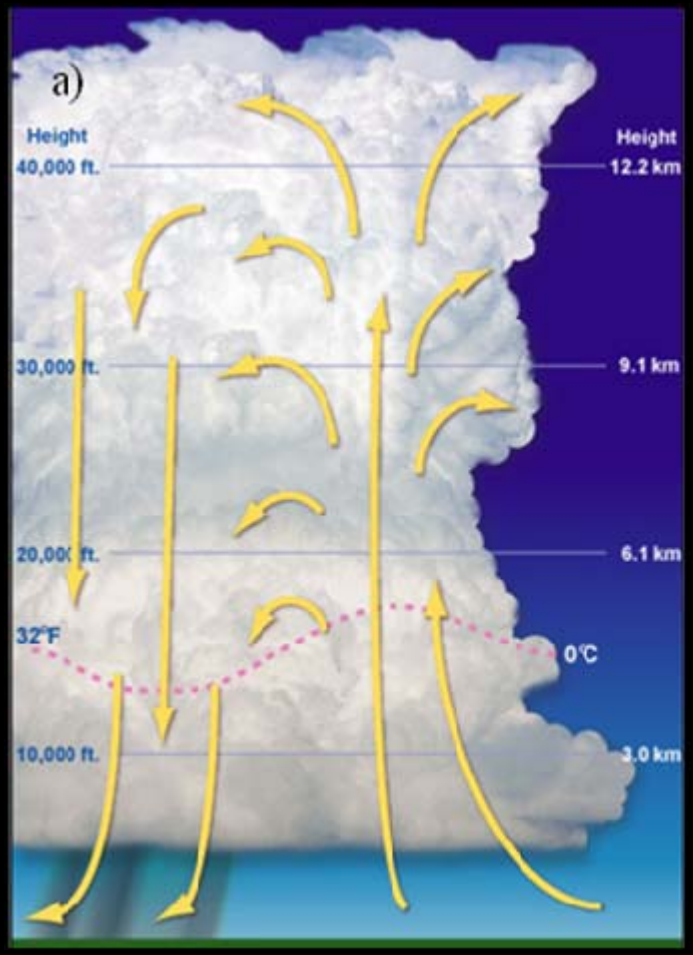
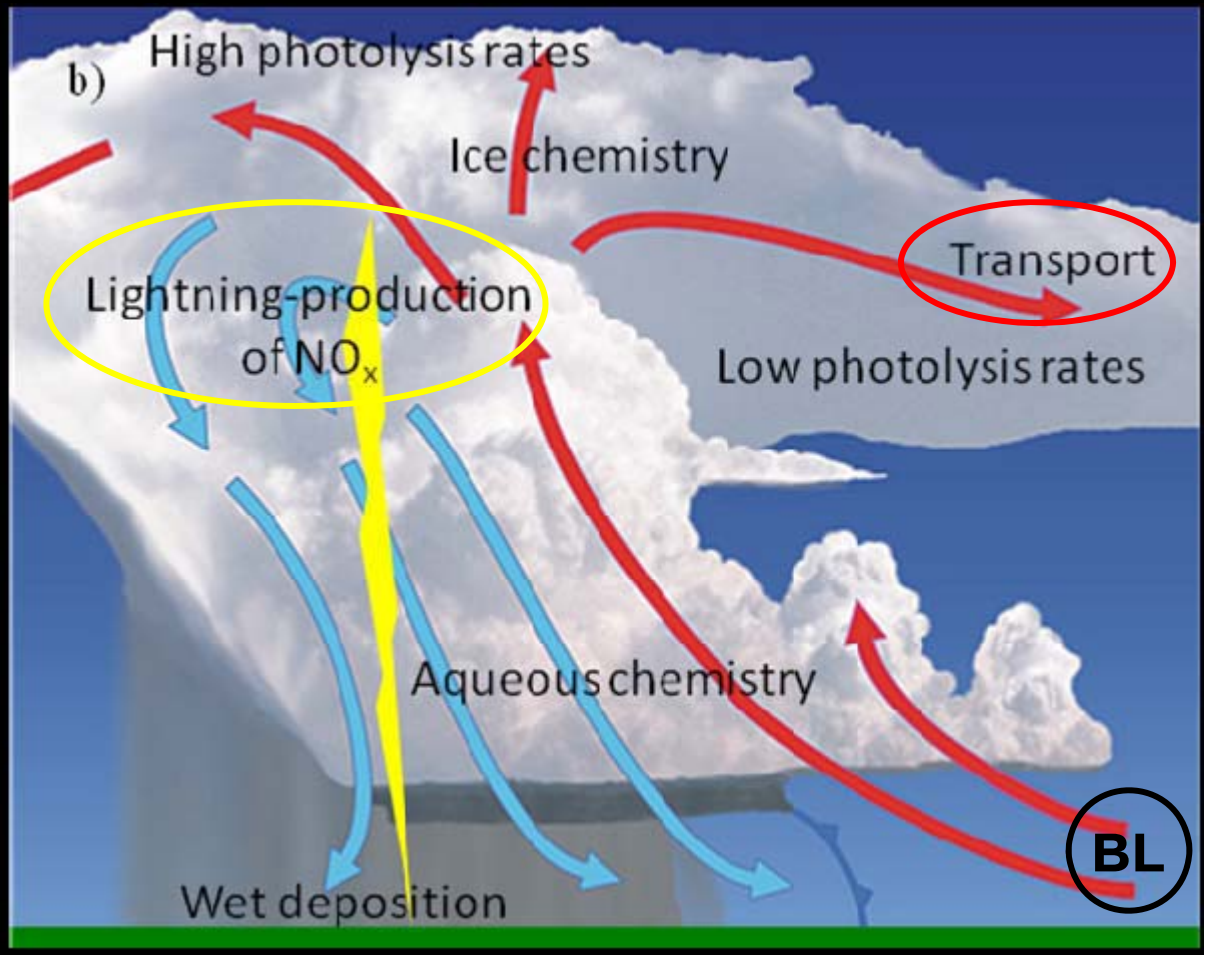
DLR

German Aerospace Center

[1]Deutsches Zentrum für Luft- und Raumfahrt

http://www.eol.ucar.edu/projects/dc3





Schematic of a) a mature airmass thunderstorm and b) a squall line vertical cross section. Superimposed on panel b are processes affecting chemical species that are ingested into storms.

http://www.srh.weather.gov/srh/jetstream/index.htm

Motivation of the German DLR Falcon team to participate in DC3 – *Deep Convective Clouds and Chemistry Experiment*

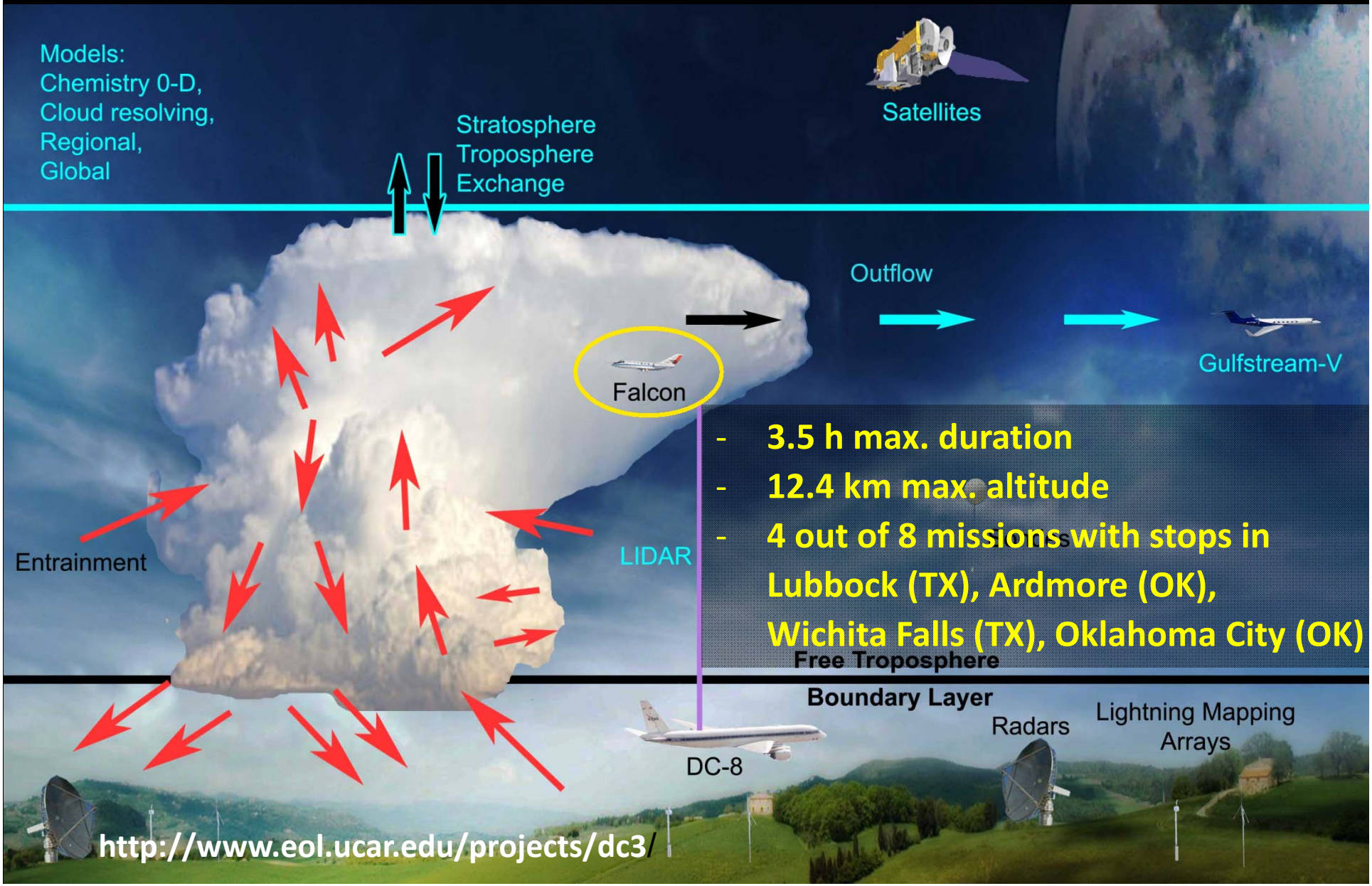
- Quantification of lightning-produced NO_x (**LNOx**) (fresh and aged) including tracer transport and **O_3 production**

- Aerosol characterization (fresh and aged) in thunderstorm inflow/outflow and in **biomass burning** (BB) plumes

DLR

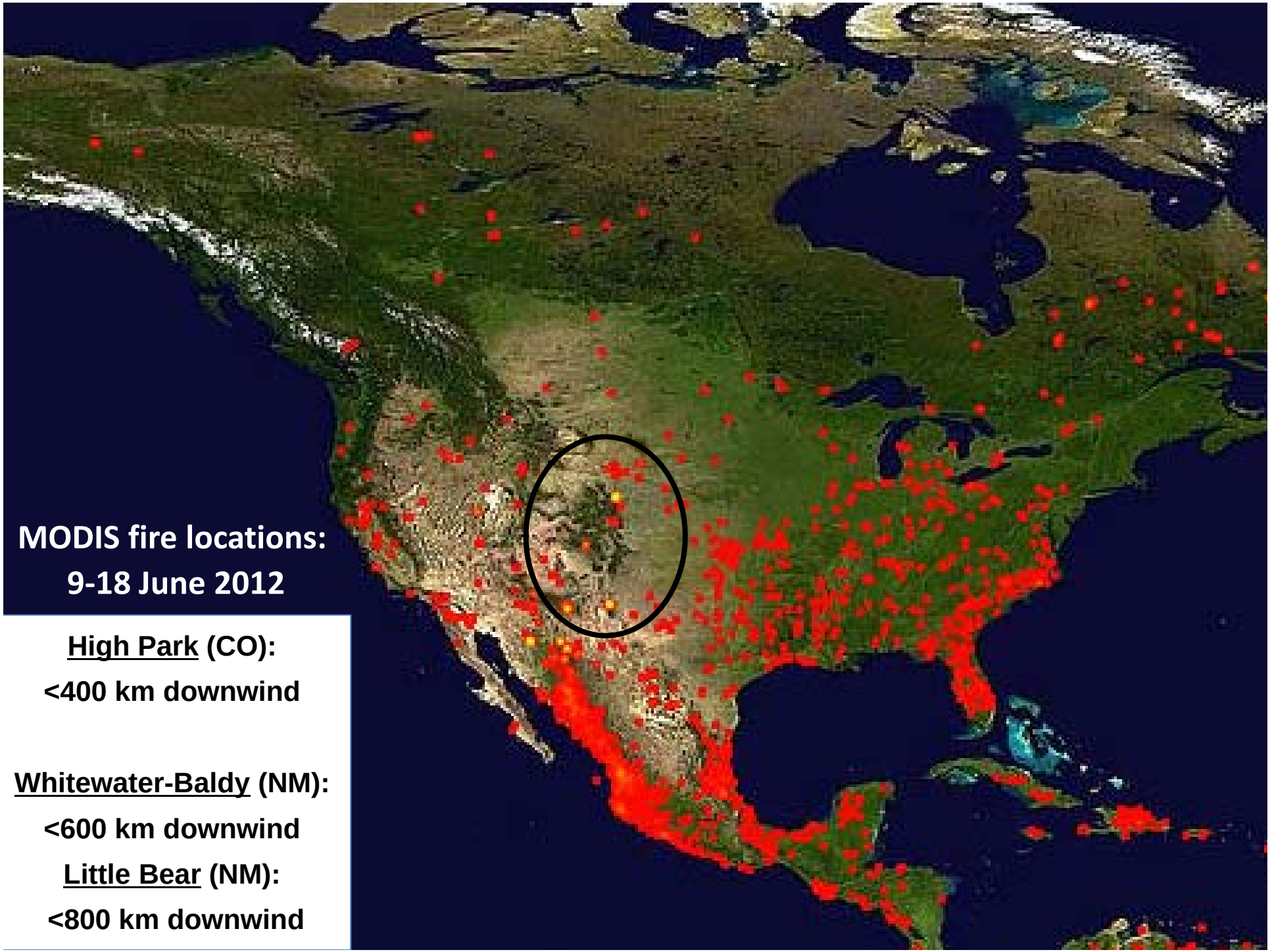
1. DC3 Field experiment design:
   - role of the German DLR Falcon
   - Falcon instrumentation
   - Falcon flight tracks
2. Falcon mission flights in summer 2012 (KS):
   - general overview
   - selected flights: 12 June "fresh LNOx" (CO/KS) + BB
     30 May "fresh LNOx" (OK/TX) + BB
     8 June "aged LNOx" (CO/KS) + BB
3. Summary

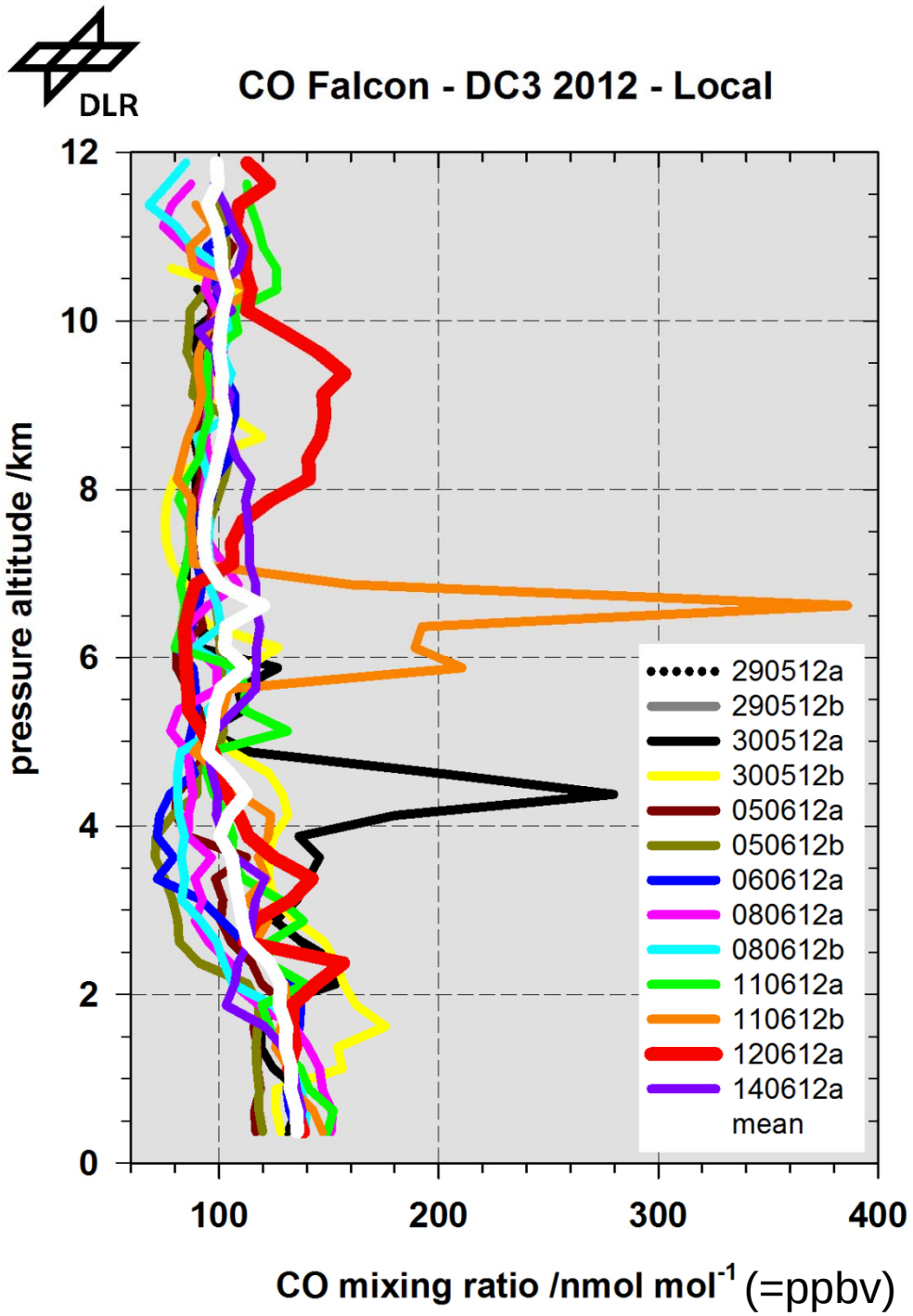
DC3 field experiment design



Instrumentation on the German DLR Falcon during DC3
Aircraft base in Salina (KS)

- **13** DLR Falcon DC3 missions from 29 May – 14 June 2012
  ~40 local flight hours


MODIS fire locations:
9-18 June 2012
High Park (CO):
<400 km downwind
Whitewater-Baldy (NM):
<600 km downwind
Little Bear (NM):
<800 km downwind



Intense BB plumes intercepted on:

- 29 May (b) however no CO data*

- 30 May (a+ b)*

- 11 June (b)**

- 12 June (a)***

→ between BL and 10 km

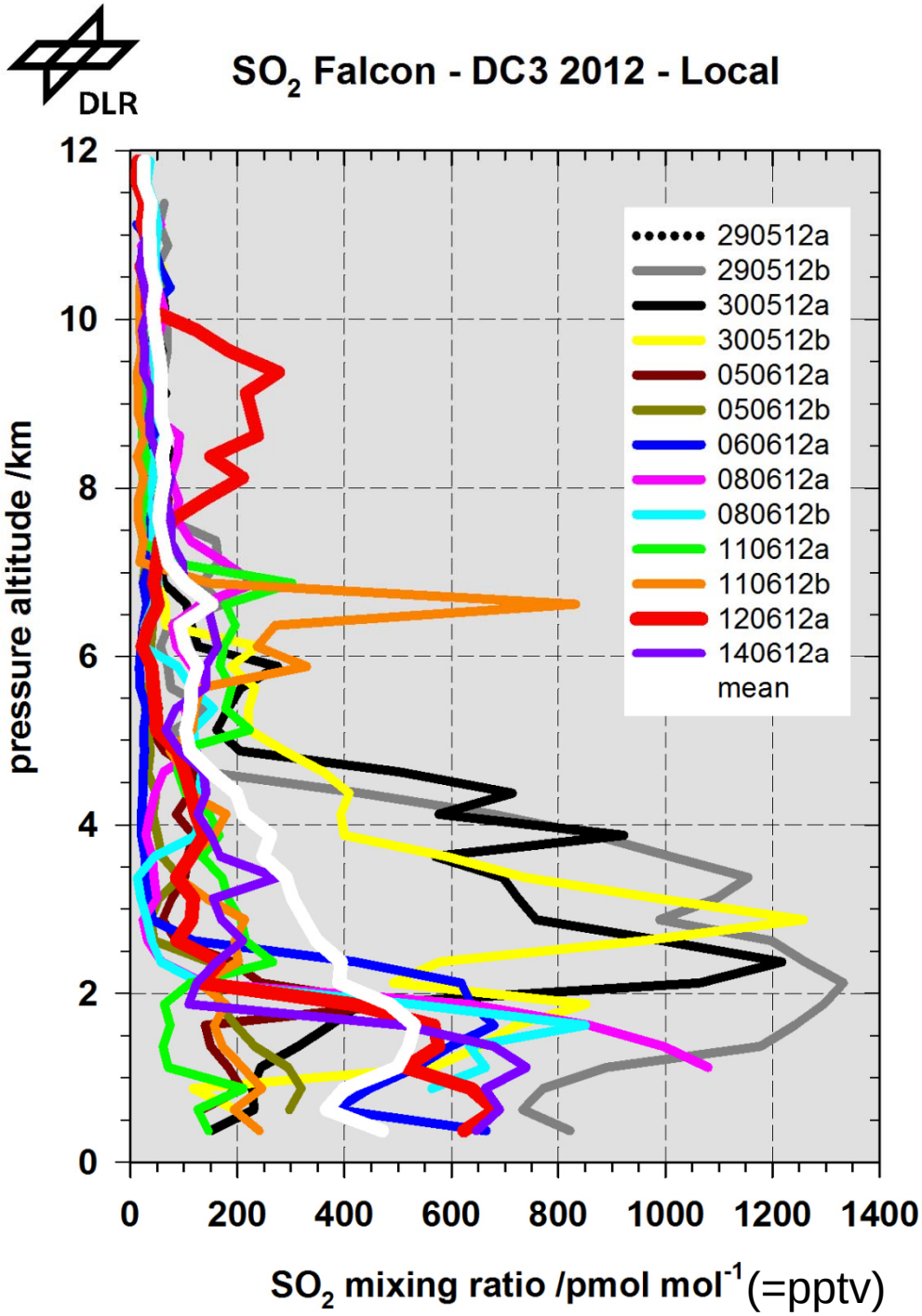
→ BB plumes probed outside of TS however also mixed into TS!

***Whitewater-Baldy (NM):**
<600 km downwind

****Little Bear (NM):**
<800 km downwind
(CO peak ~700 nmol mol^{-1})

*****High Park (CO):**
<400 km downwind

Vertical profiles: 250 m mean values

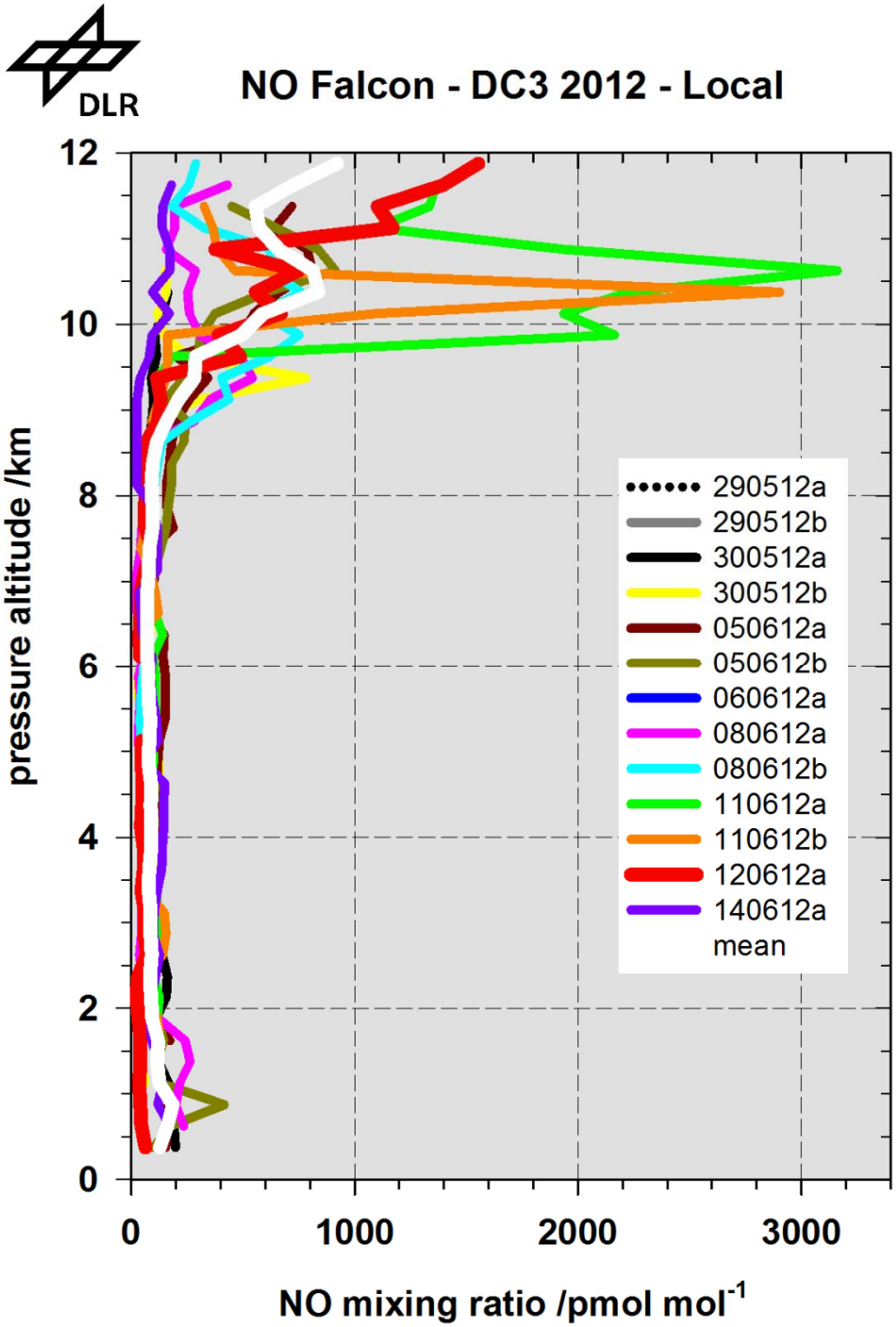


Intense BB plumes intercepted on:

- 29 May (b)
- 30 May (a+ b)
- 11 June (b)
- 12 June (a)

SO_2 strongly elevated in BB plumes!

Vertical profiles: 250 m mean values



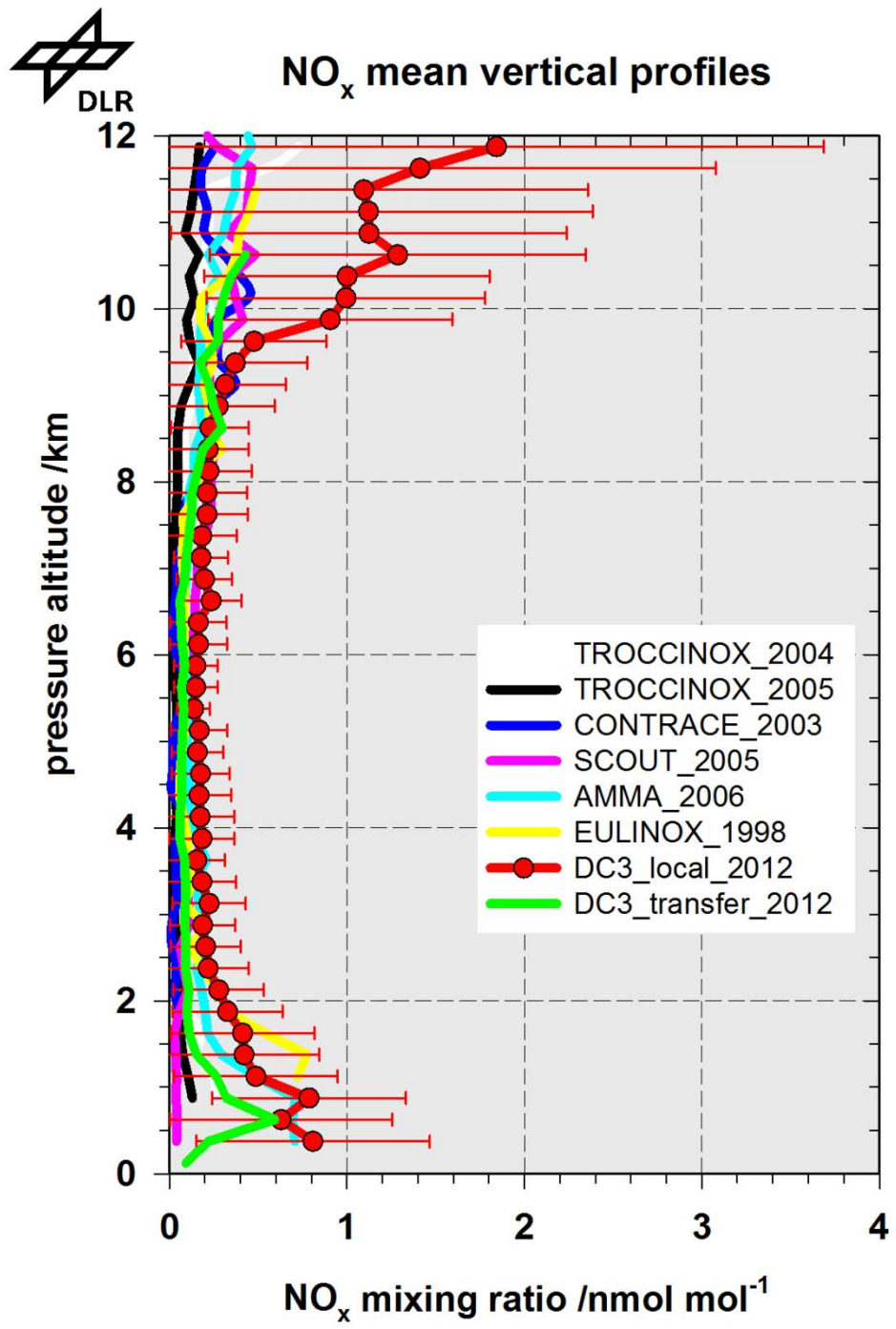
***Intense* (*in bold*) <u>fresh</u> LNOx plumes intercepted on:**

- *29 May (b)* *however no NO data*
- **30 May (b)** supercell
- 5 June (a+b)
- *6 June (a)* *however no NO data*
- **11 June (a+b)** MCS
- **12 June (a)** squall line

<u>Aged</u> LNOx plumes (12-24 h) intercepted on:

- 8 June (a+b) squall line

Vertical profiles: 250 m mean values



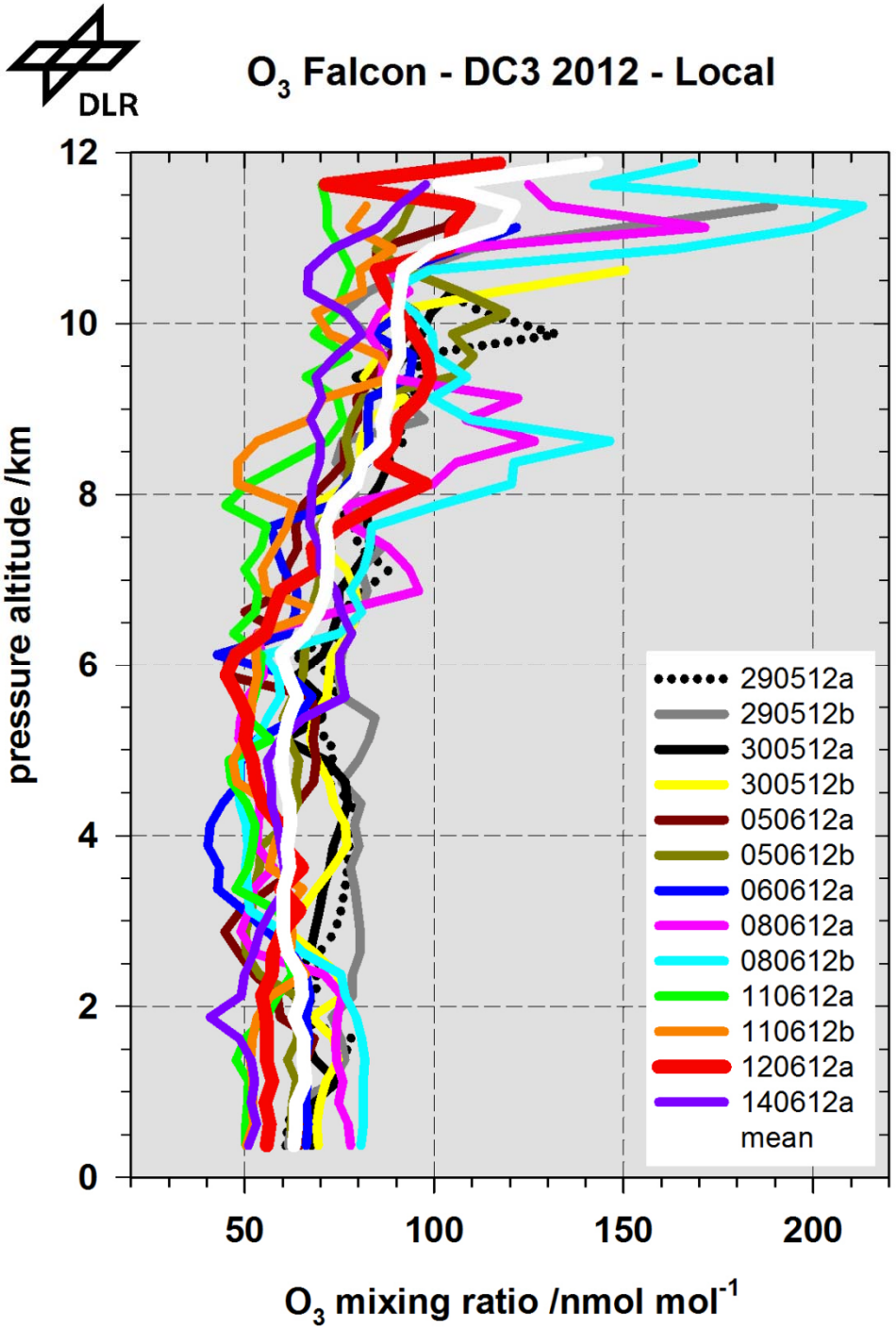
DC3:

On average very high NOx mixing ratios in the UT (mainly LNOx) compared to other Falcon thunderstorm 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

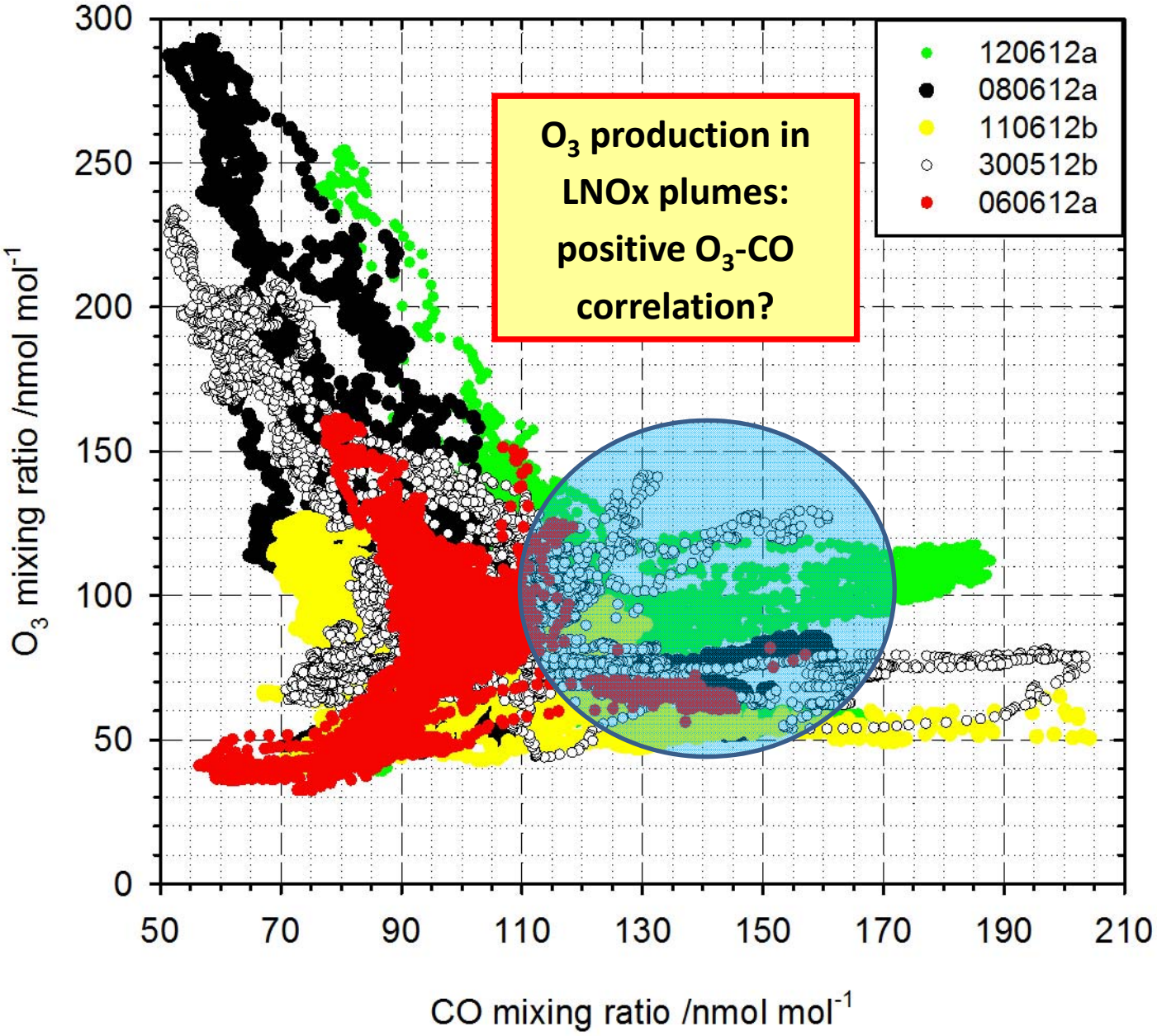


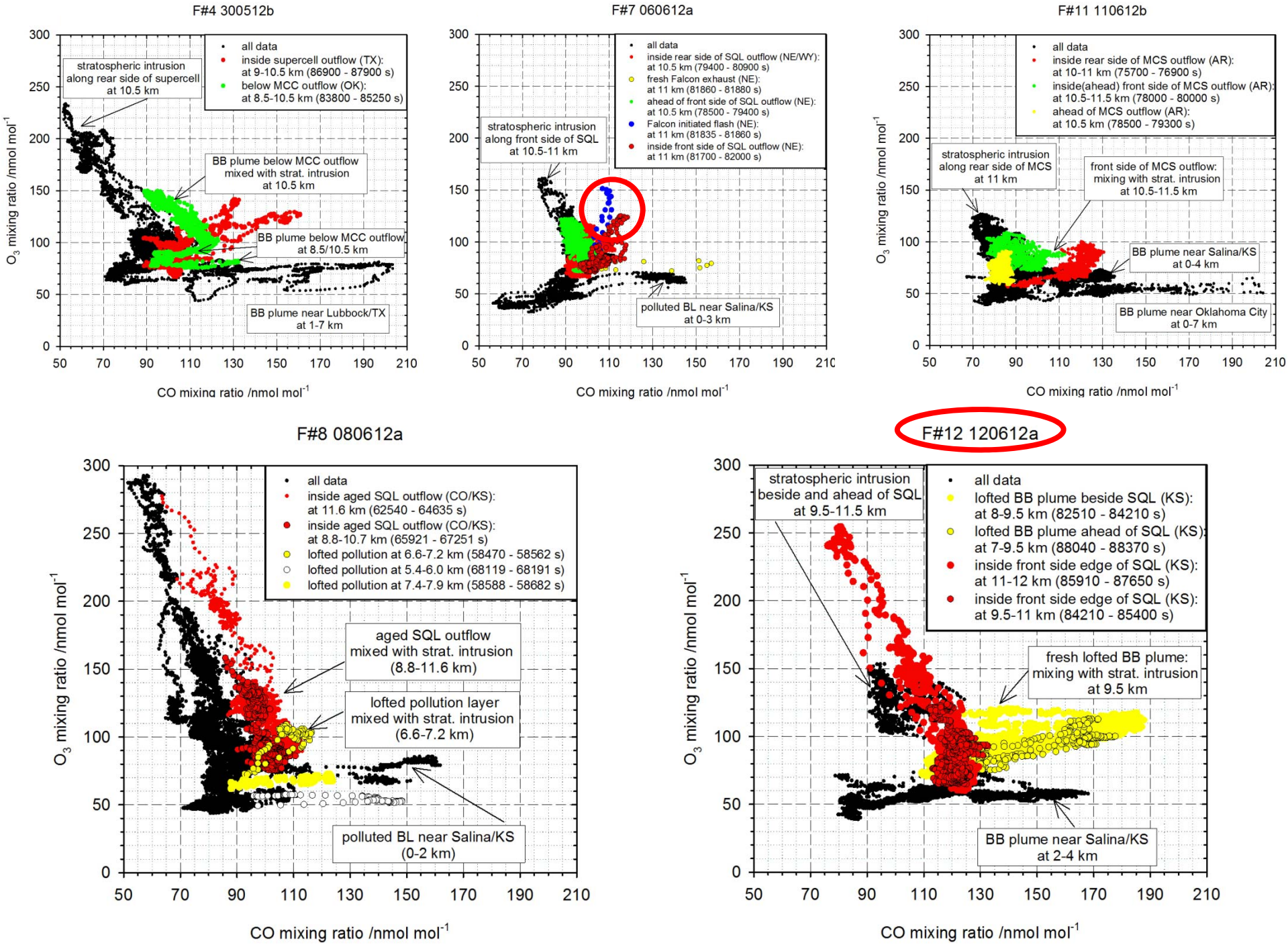
Highest O_3 in UTLS and at the ground on 8 June during probing of aged LNOx outflow.

Major source of elevated O_3 in the aged anvil outflow: photochemical production (due to elevated LNOx) or downward transport from the stratosphere?

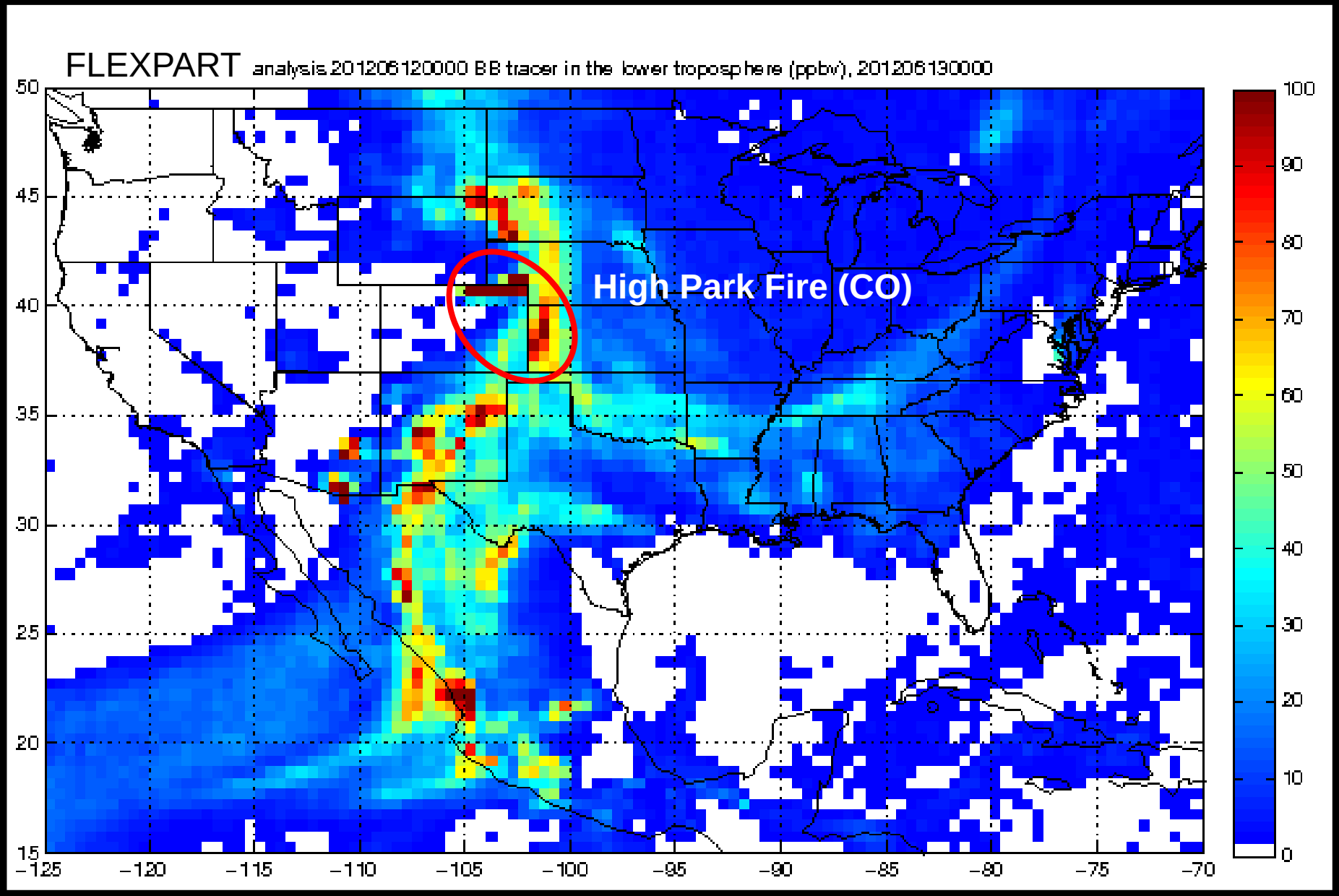
Vertical profiles: 250 m mean values

Main DC3 objective: quantify O_3 production in UT from LNOx



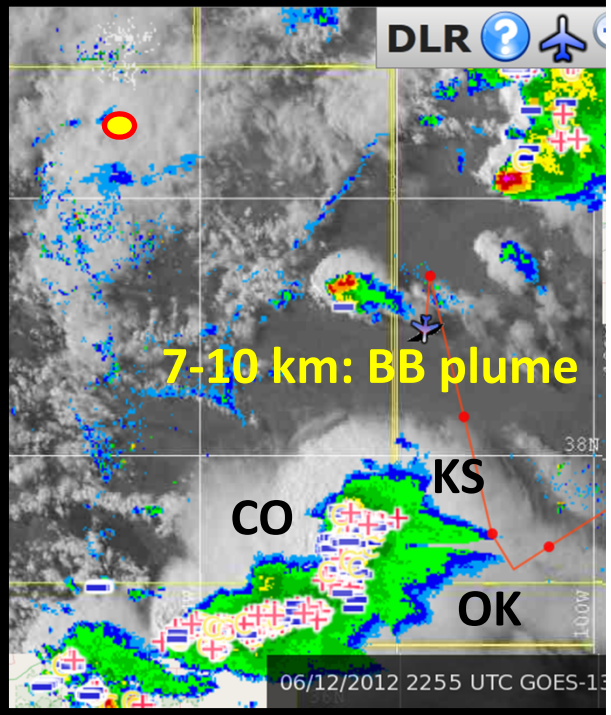

F#4 300512b
all data
inside supercell outflow (TX):
at 9-10.5 km (86900 - 87900 s)
below MCC outflow (OK):
at 8.5-10.5 km (83800 - 85250 s)
stratospheric intrusion
along rear side of supercell
at 10.5 km
BB plume below MCC outflow
mixed with strat. intrusion
at 10.5 km
BB plume below MCC outflow
at 8.5/10.5 km
BB plume near Lubbock/TX
at 1-7 km
F#7 060612a
all data
inside rear side of SQL outflow (NE/WY):
at 10.5 km (79400 - 80900 s)
fresh Falcon exhaust (NE):
at 11 km (81860 - 81880 s)
ahead of front side of SQL outflow (NE):
at 10.5 km (78500 - 79400 s)
Falcon initiated flash (NE):
at 11 km (81835 - 81860 s)
inside front side of SQL outflow (NE):
at 11 km (81700 - 82000 s)
stratospheric intrusion
along front side of SQL
at 10.5-11 km
polluted BL near Salina/KS
at 0-3 km
F#11 110612b
all data
inside rear side of MCS outflow (AR):
at 10-11 km (75700 - 76900 s)
inside(ahead) front side of MCS outflow (AR):
at 10.5-11.5 km (78000 - 80000 s)
ahead of MCS outflow (AR):
at 10.5 km (78500 - 79300 s)
stratospheric intrusion
along rear side of MCS
at 11 km
front side of MCS outflow:
mixing with strat. intrusion
at 10.5-11.5 km
BB plume near Salina/KS
at 0-4 km
BB plume near Oklahoma City
at 0-7 km
F#8 080612a
all data
inside aged SQL outflow (CO/KS):
at 11.6 km (62540 - 64635 s)
inside aged SQL outflow (CO/KS):
at 8.8-10.7 km (65921 - 67251 s)
lofted pollution at 6.6-7.2 km (58470 - 58562 s)
lofted pollution at 5.4-6.0 km (68119 - 68191 s)
lofted pollution at 7.4-7.9 km (58588 - 58682 s)
aged SQL outflow
mixed with strat. intrusion
(8.8-11.6 km)
lofted pollution layer
mixed with strat. intrusion
(6.6-7.2 km)
polluted BL near Salina/KS
(0-2 km)
F#12 120612a
stratospheric intrusion
beside and ahead of SQL
at 9.5-11.5 km
all data
lofted BB plume beside SQL (KS):
at 8-9.5 km (82510 - 84210 s)
lofted BB plume ahead of SQL (KS):
at 7-9.5 km (88040 - 88370 s)
inside front side edge of SQL (KS):
at 11-12 km (85910 - 87650 s)
inside front side edge of SQL (KS):
at 9.5-11 km (84210 - 85400 s)
fresh lofted BB plume:
mixing with strat. intrusion
at 9.5 km
BB plume near Salina/KS
at 2-4 km
O3 mixing ratio /nmol mol-1
CO mixing ratio /nmol mol-1

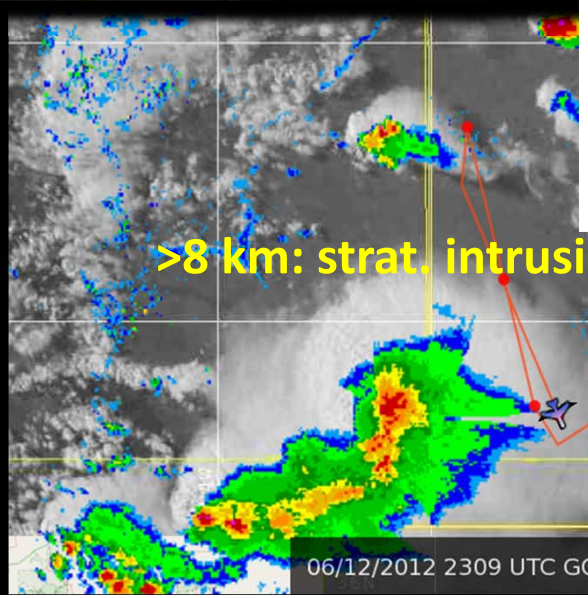
Falcon flight on 12 June 2012: Squall line (border CO/KS)

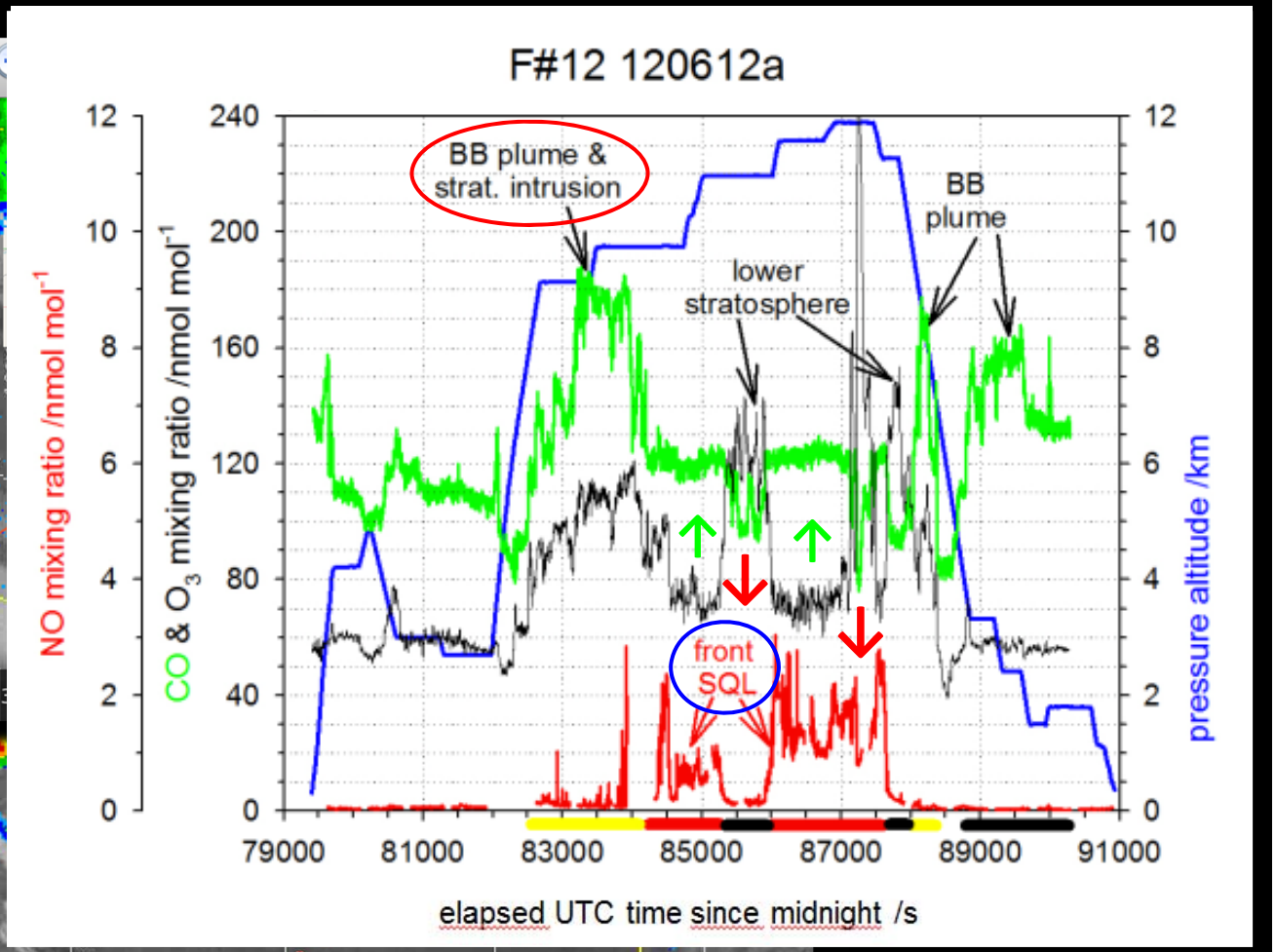


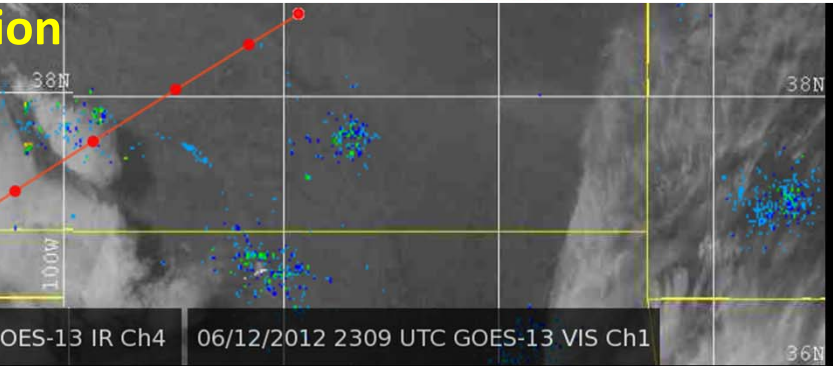
Owen Cooper et al. (NOAA)

Falcon flight on 12 June 2012: Squall line (border CO/KS)



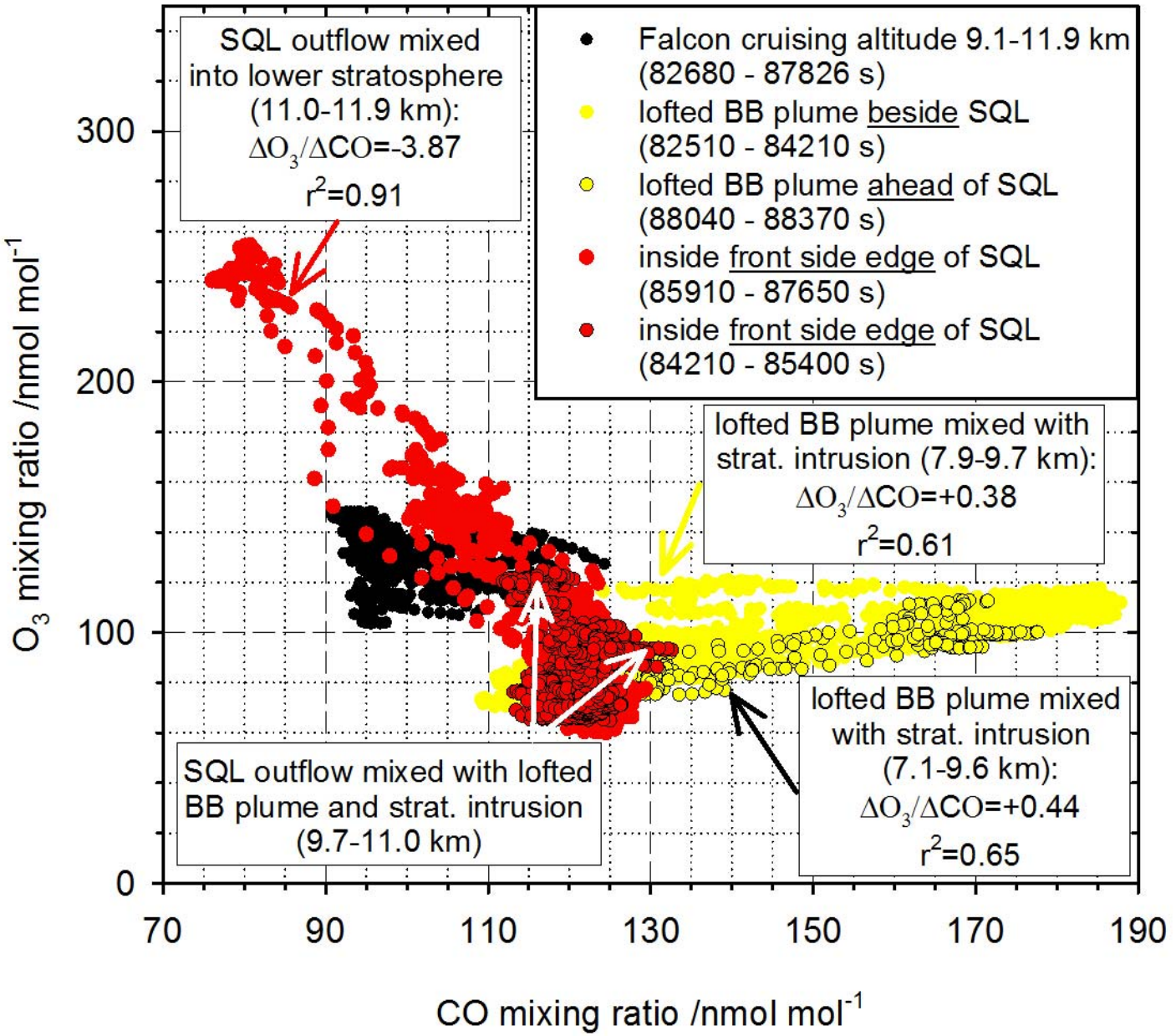






Higher O_3 and partly CO outside compared to inside SQL!

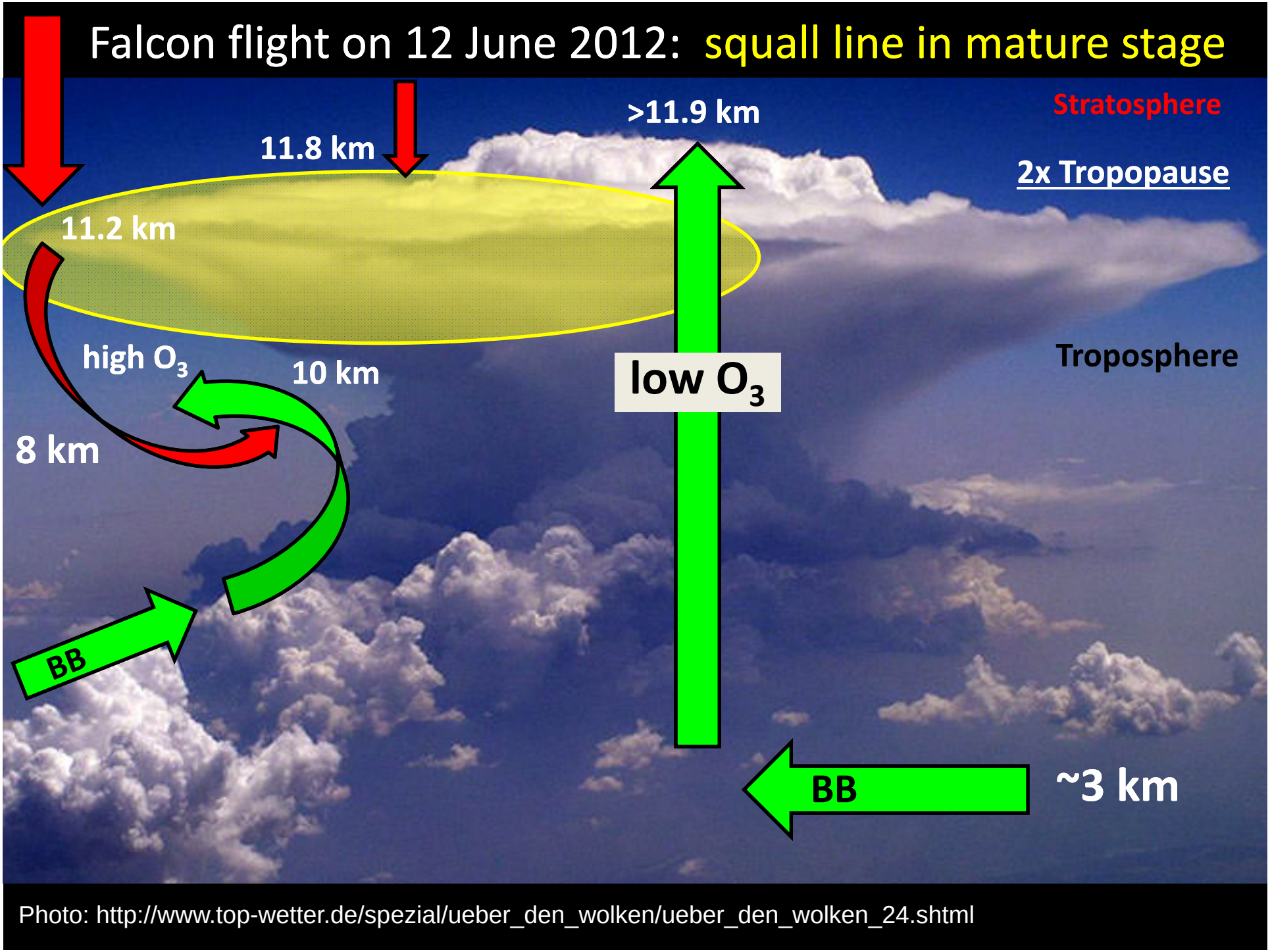
F#12 120612a



Fresh SQL outflow:

Mainly negative but also partly positive O_3-CO correlation, however not due to O_3 production!

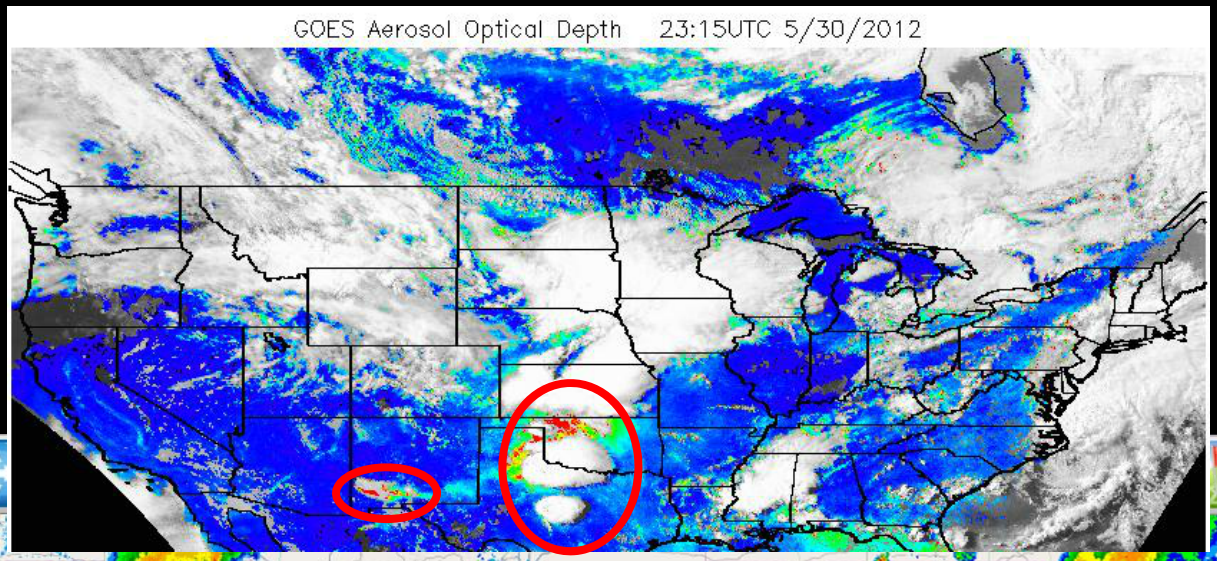
→in-mixing of SQL outflow into O_3-rich lower stratosphere and mix with CO-rich lofted BB plume (~3 and 10 km)


Falcon flight on 12 June 2012: squall line in mature stage
11.8 km
>11.9 km
Stratosphere
2x Tropopause
11.2 km
high O_3
10 km
Troposphere
low O_3
8 km
BB
BB
~3 km
Photo: http://www.top-wetter.de/spezial/ueber_den_wolken/ueber_den_wolken_24.shtml

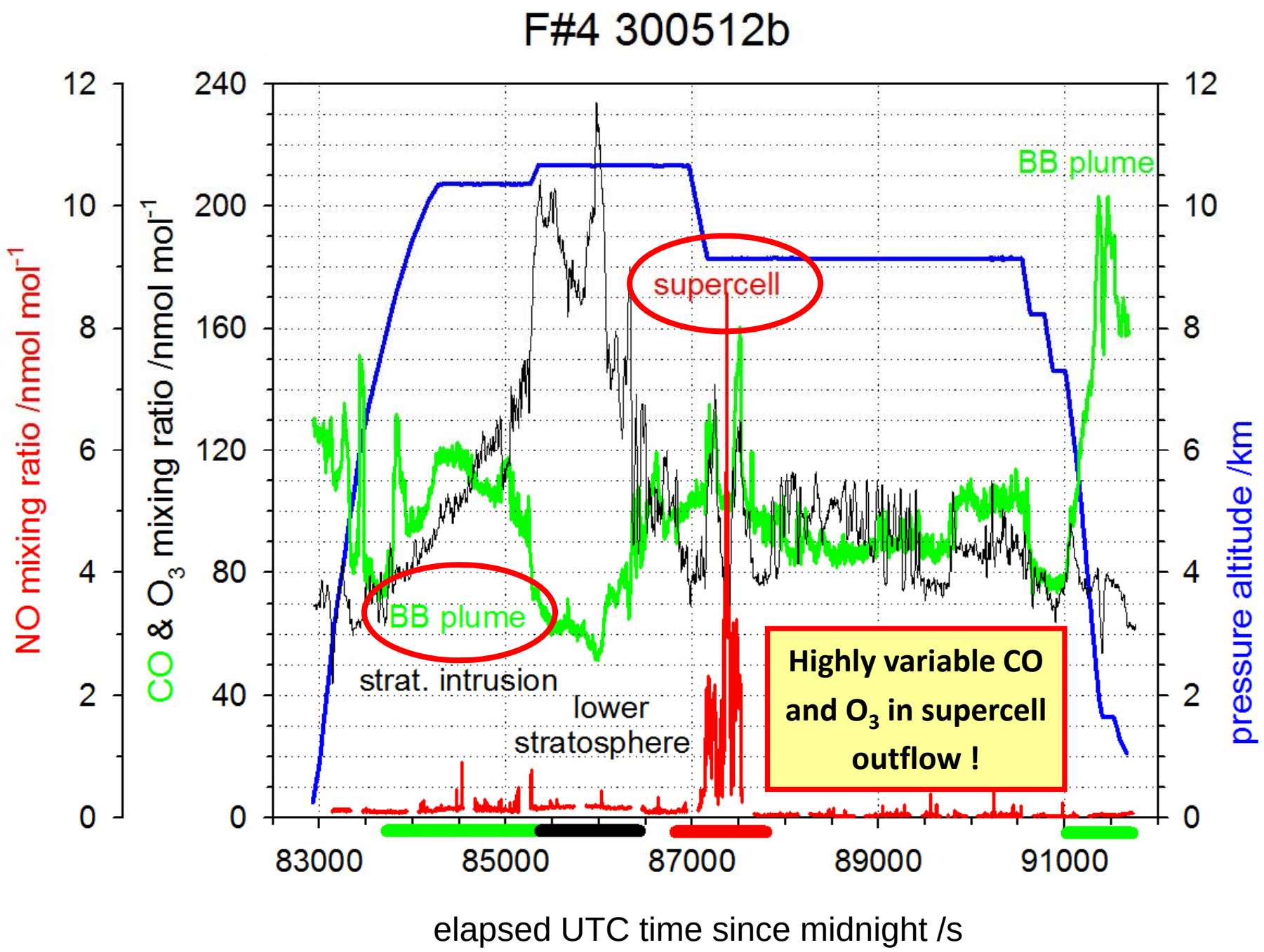
DC3 Flight Number, Date, Flight a or b, anvil time	Pressure Altitude, km	CO Mixing Ratio, nmol mol^{-1}	O_3 Mixing Ratio, nmol mol^{-1}	NO Mixing Ratio, nmol mol^{-1}	Ethane, pmol mol^{-1}	Propane, pmol mol^{-1}
F#12 120612a 84536-85260 s *upward (inside)*	10.3	120±3 (113/126)	73±4 (65/85)	0.6±0.2 (0.2/1.1)	-	-
Netto Impact 84210-85400 s	***10.4***	↑***121±3***	↓***82±14***	↑***0.7±0.5***	-	-
Background 87939-87965 s	**10.3**	**106±1**	**120±1**	-	-	-
F#12 120612a 85996-86999 s *upward (inside)*	11.6	123±2 (117/129)	72±4 (60/80)	1.5±0.4 (0.8/3.1)	↑ 821/1073 (BB)	↑656/615 (BB)
Netto Impact *85910-87650 s*	***11.6***	**+20%**	**-30%! mature SQL→ *outflow penetrates into LS***	**x8**	↑***821/1073 (BB)***	↑***656/615 (BB)***
Background 87659-87832 s	**11.3**				-	-
BB plume (BL ~2km)					976	454

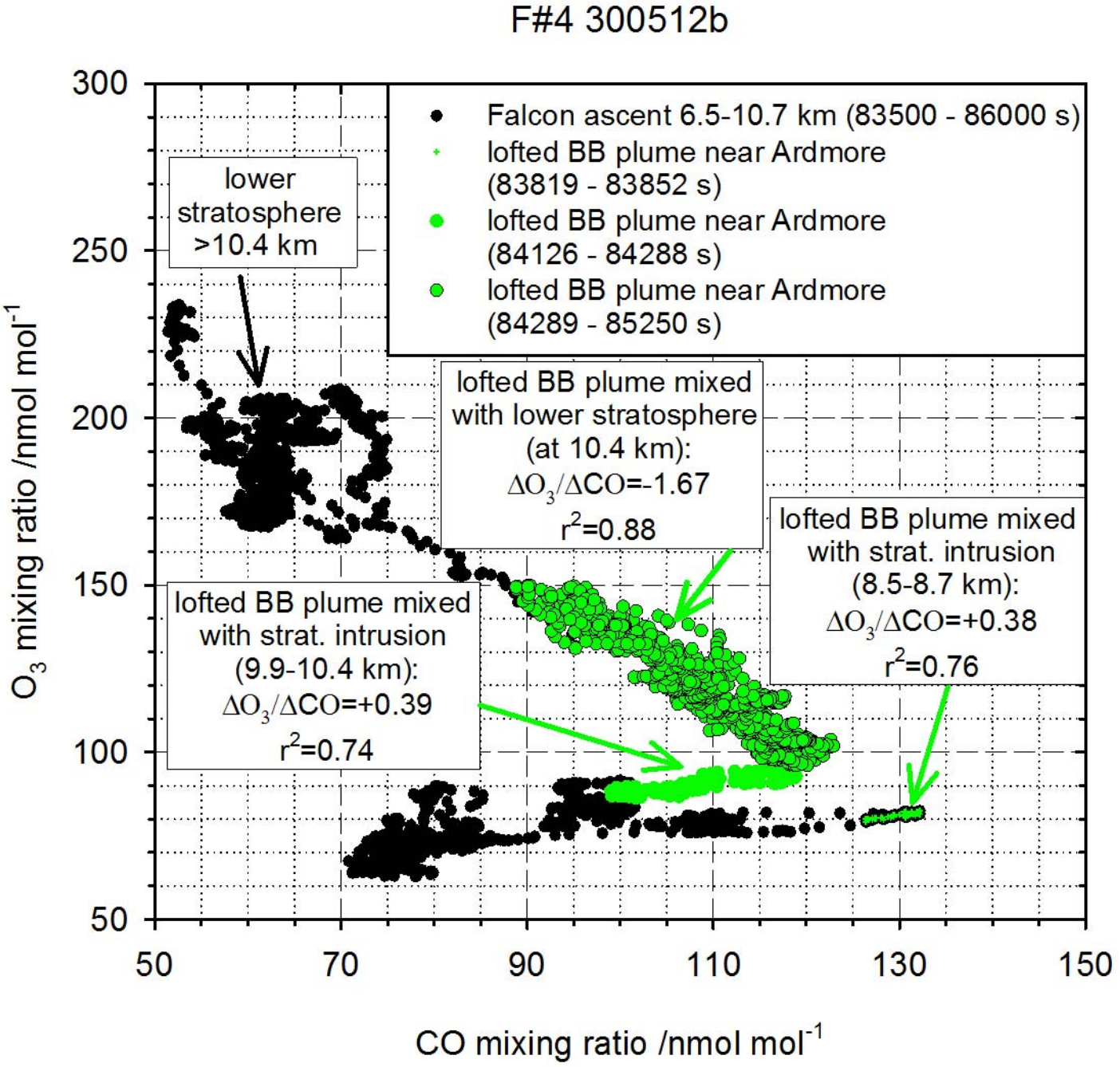
Falcon flight on 30 May 2012: Supercell (border TX/OK)

Whitewater-Baldy Fire (NM)



8 UTC GOES-13 IR Ch4 | 05/30/2012 2325 UTC GOES-/2012 1538 UTC GOES-13 IR Ch4 | 05/31/2012 0008 UTC GOES-13 VIS Ch1

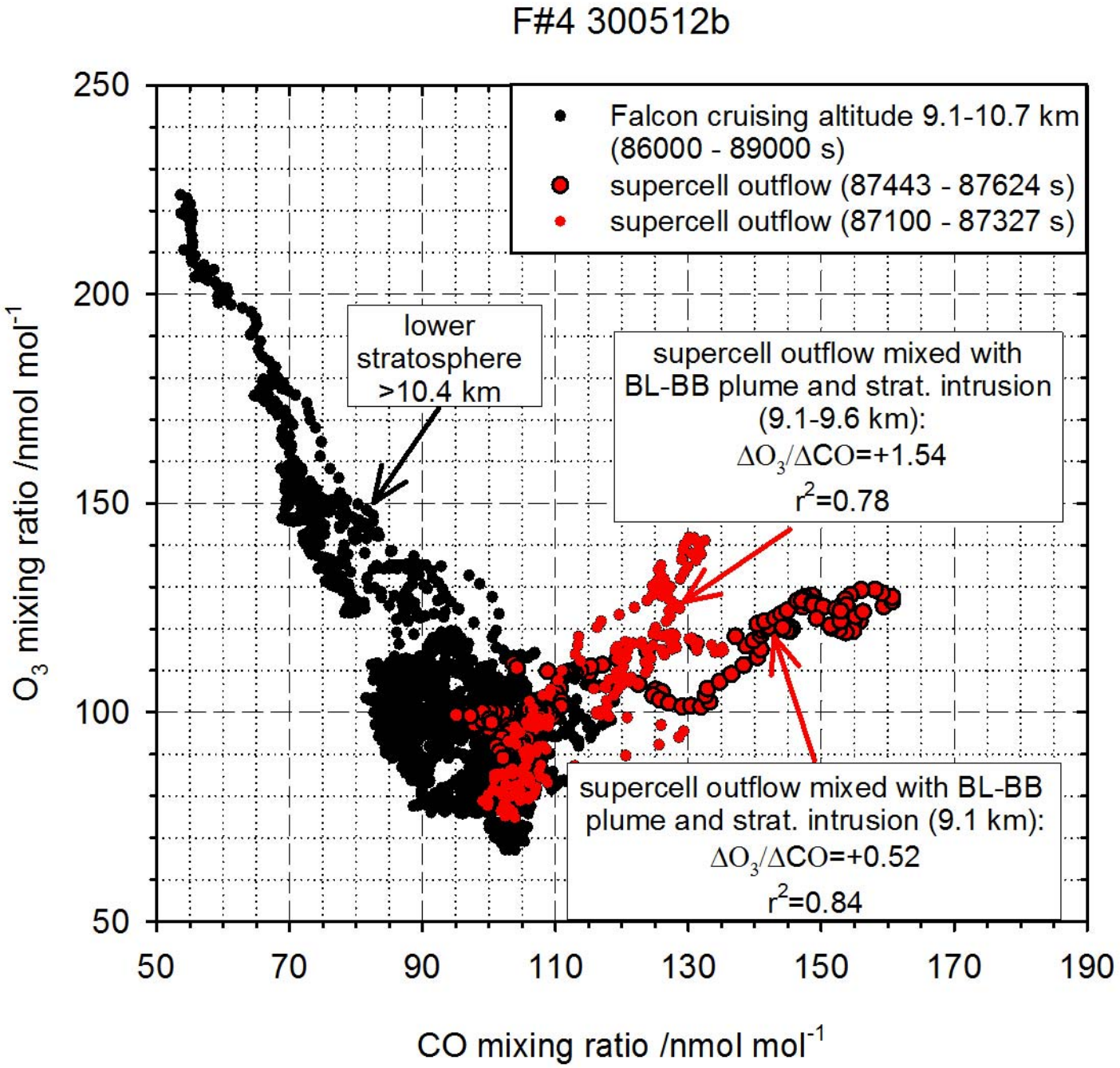

F#4 300512b
NO mixing ratio /nmol mol-1
CO & O3 mixing ratio /nmol mol-1
pressure altitude /km
elapsed UTC time since midnight /s
supercell
BB plume
BB plume
strat. intrusion
lower stratosphere
Highly variable CO and O3 in supercell outflow !
0
2
4
6
8
10
12
0
40
80
120
160
200
240
83000
85000
87000
89000
91000



Lofted BB plume:

First positive and then negative O_3-CO correlation caused by mixing!

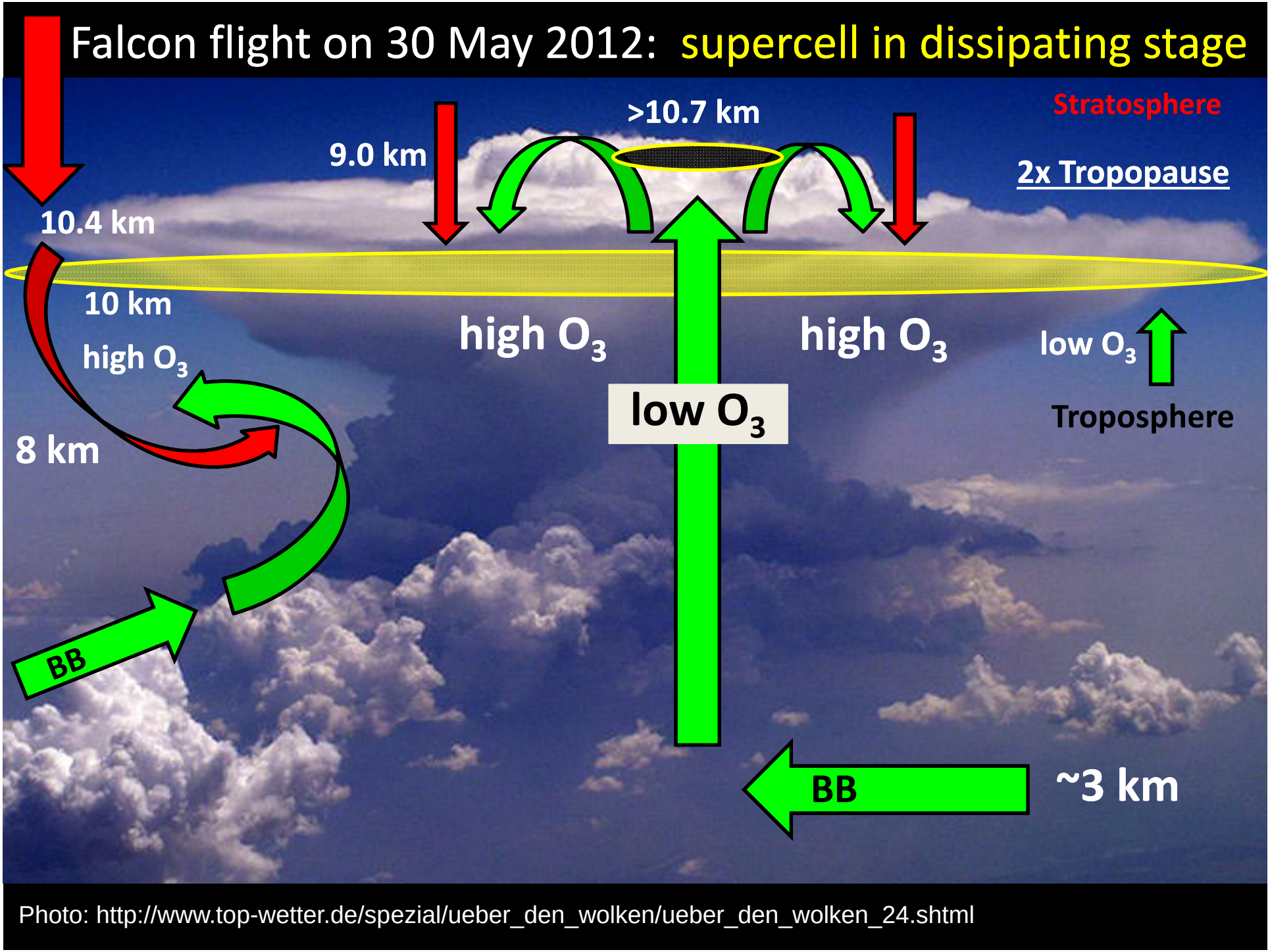
→in-mixing of O_3-rich air from the lower stratosphere



Fresh supercell outflow:

Positive O_3-CO correlation however caused by mixing and not due to O_3 production!

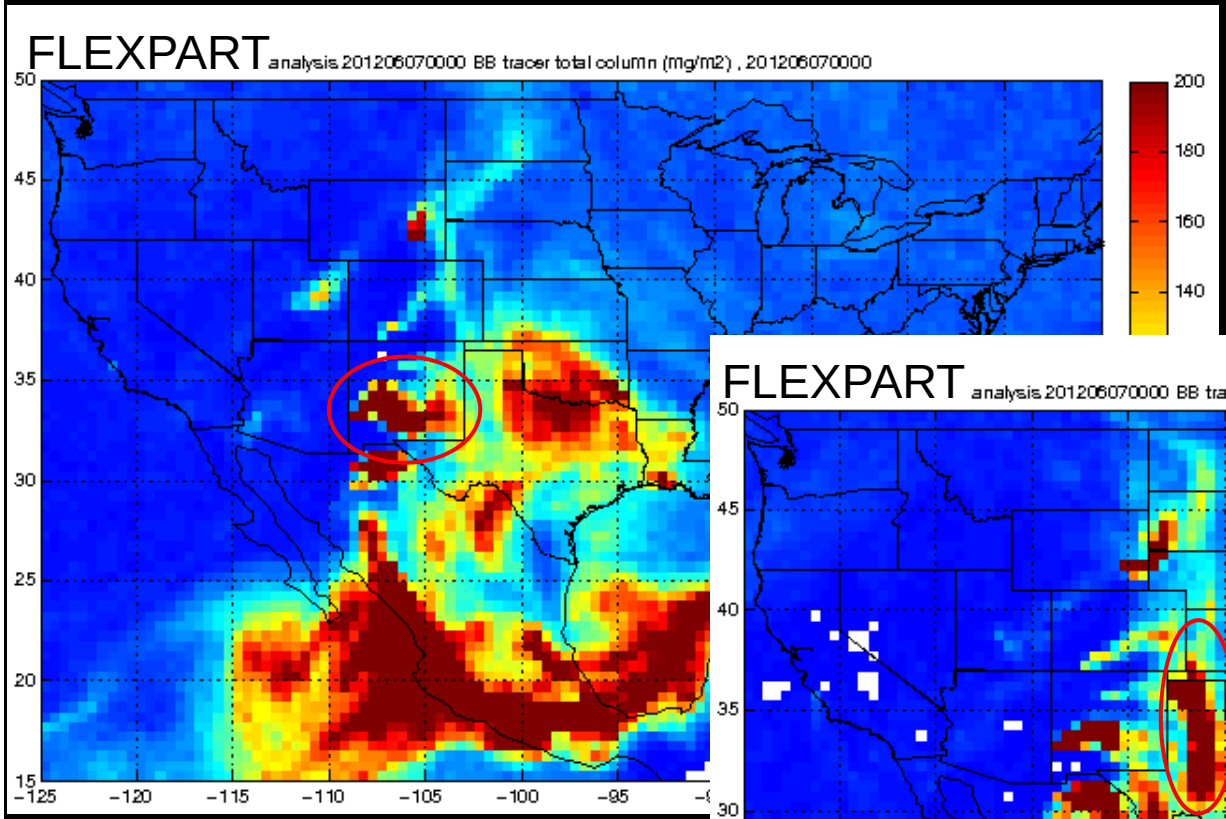
→in-mixing of O_3-rich air from the lower stratosphere (>10.4 km) and CO-rich air from the BL-BB plume (~3 km)

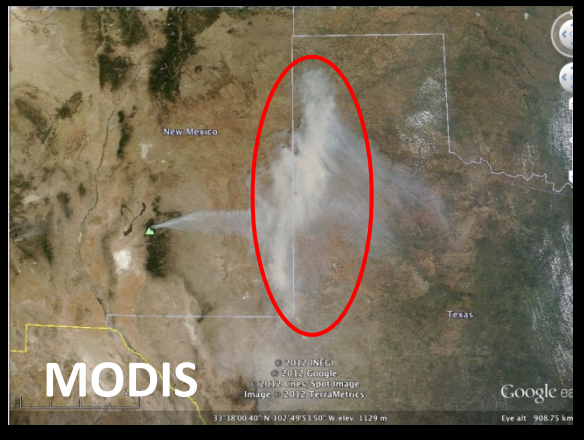

Falcon flight on 30 May 2012: supercell in dissipating stage
Stratosphere
2x Tropopause
>10.7 km
9.0 km
10.4 km
10 km
high O3
high O3
high O3
low O3
Troposphere
low O3
8 km
BB
BB
~3 km
Photo: http://www.top-wetter.de/spezial/ueber_den_wolken/ueber_den_wolken_24.shtml

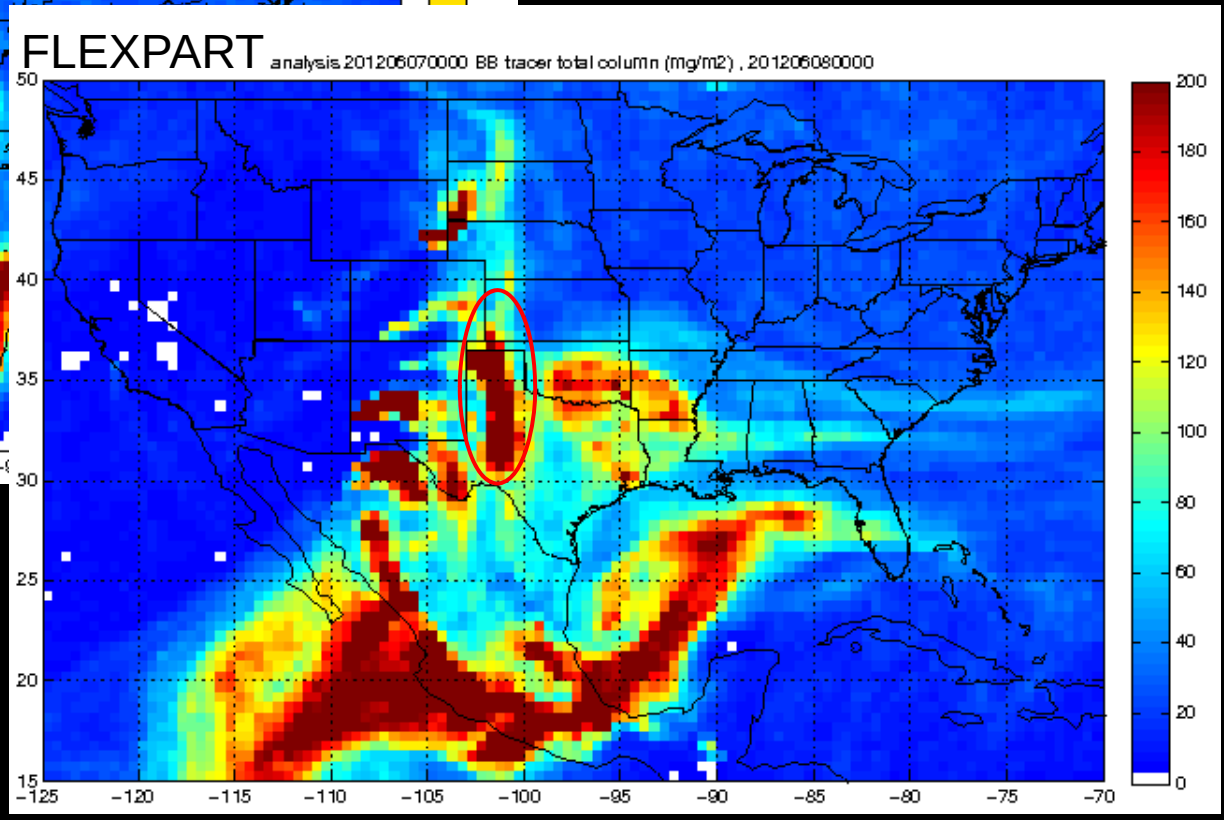
DC3 Flight Number, Date, Flight a or b, anvil time	Pressure Altitude, km	CO Mixing Ratio, nmol mol^{-1}	O_3 Mixing Ratio, nmol mol^{-1}	NO Mixing Ratio, nmol mol^{-1}	Ethane, pmol mol^{-1}	Propane, pmol mol^{-1}
F#4 300512b 86852-87133 s *upward (outside)*	10.3	103±3 (97/110)	82±5 (69/92)	0.2±0.1 (0.1/0.5)	-	-
87134-87323 s *downward (inside)*	9.2	**↑117±16 +20%**	**↑102±20 +20%! dissipating supercell → *strat. O_3 mixes into troposphere***	**↑1.8±1.3 x36**	-	-
87324-87440 s *upward (inside)*	9.1				-	-
87441-87577 s *downward (inside)*	9.1				-	-
87578-87838 s *upward (outside)*	9.1	98±6 (89/120)		0.05±0.01 (0.03/0.08)	-	-
Netto Impact 86852-87838 s	***9.5***	***↑108±14***		***↑1.0±1.3***	-	-
Background 83988-84040 s	**9.5**	**97±2**	**86±4**	**0.05±0.03**	-	-

Falcon flight on 8 June 2012:
Flight over Kansas in aged outflow (12-24 h) from squall line over Colorado

BB plumes from New Mexico advected to Kansas

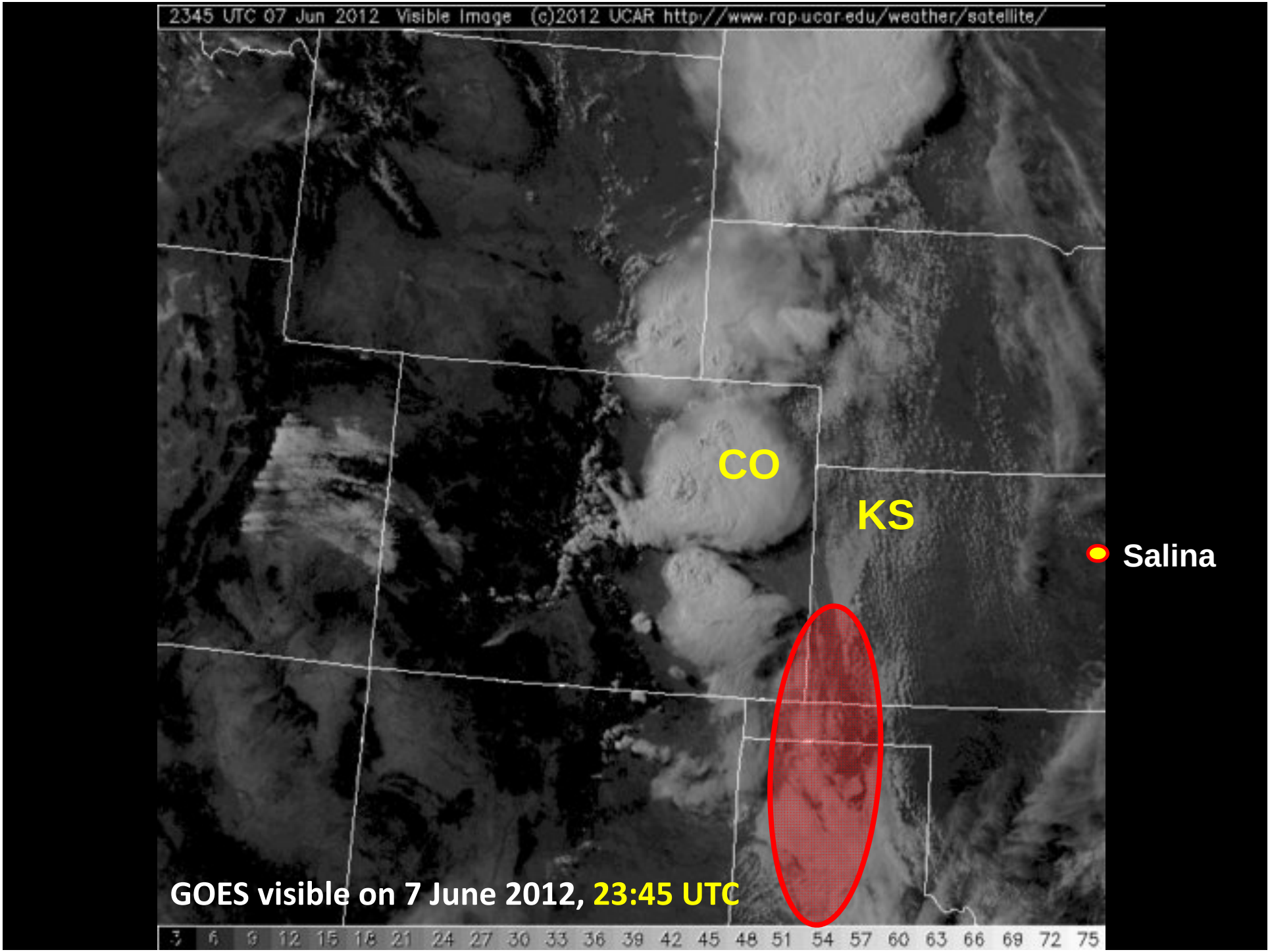






Whitewater-Baldy &
Little Bear Fires (NM)

Owen Cooper et al. (NOAA)

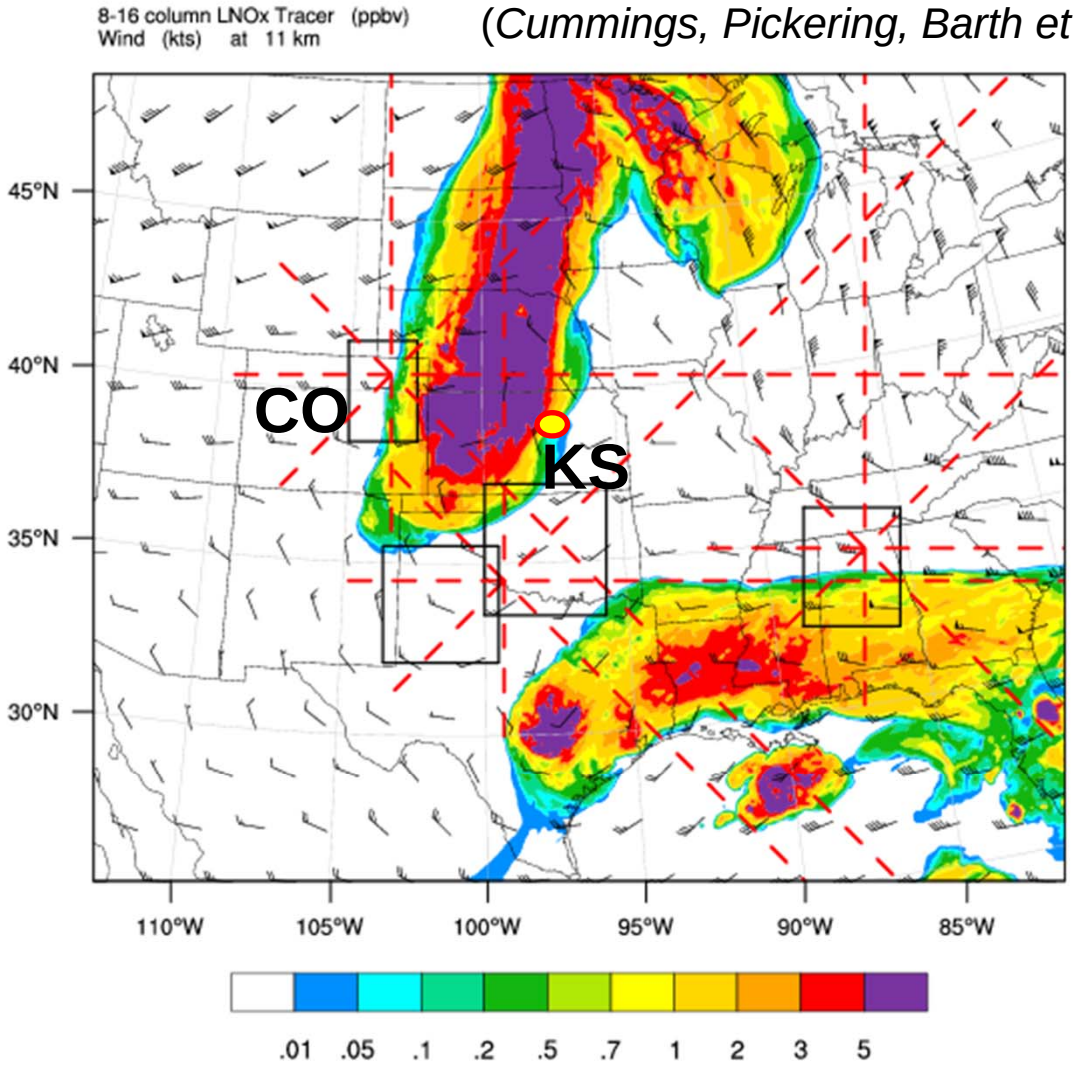

2345 UTC 07 Jun 2012 Visible Image (c)2012 UCAR http://www.rap.ucar.edu/weather/satellite/
CO
KS
Salina
GOES visible on 7 June 2012, 23:45 UTC
3 6 9 12 15 18 21 24 27 30 33 36 39 42 45 48 51 54 57 60 63 66 69 72 75

2012-06-08
11:00 UTC

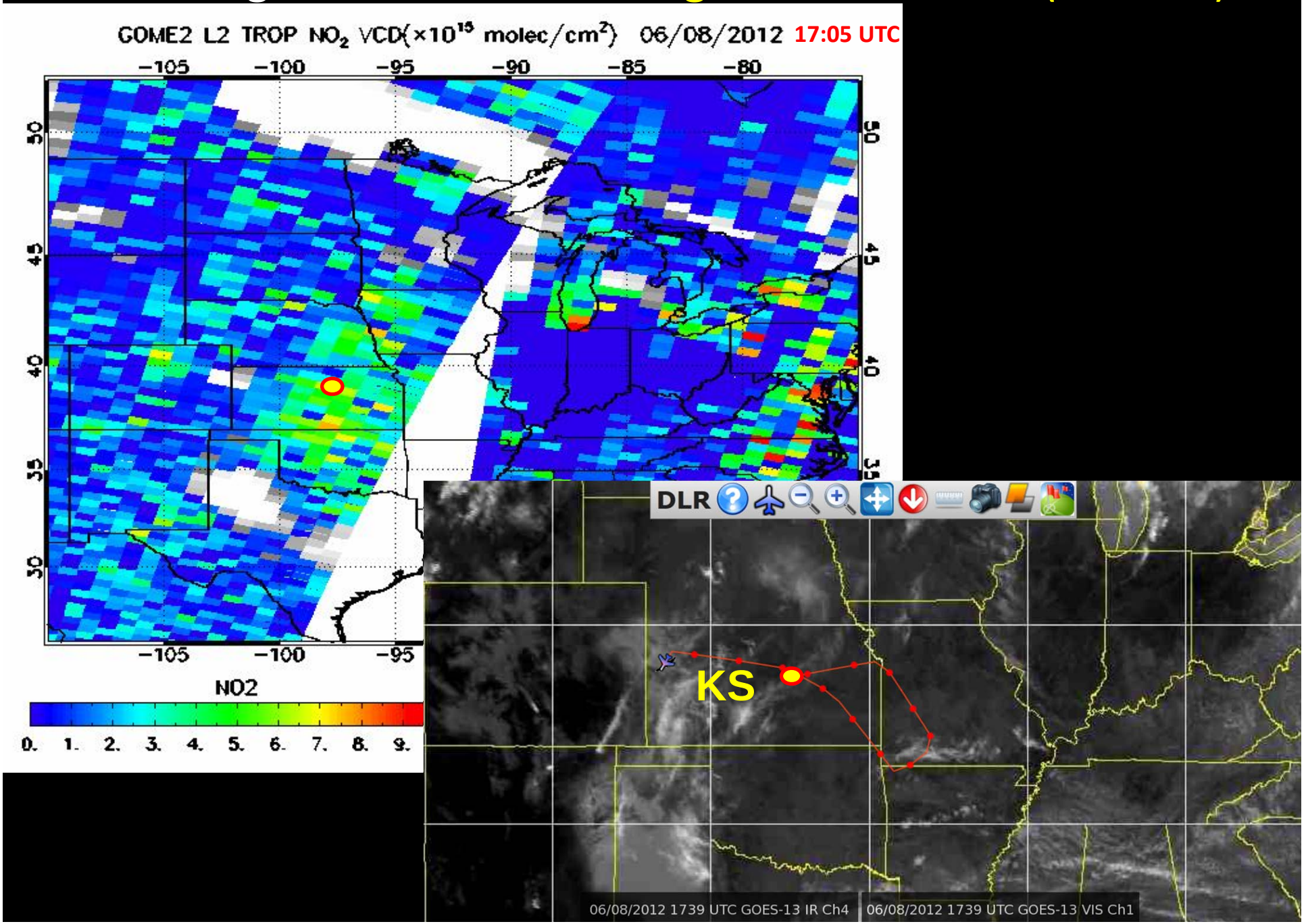
NCAR WRF ARW Forecast (Δx=3 km)

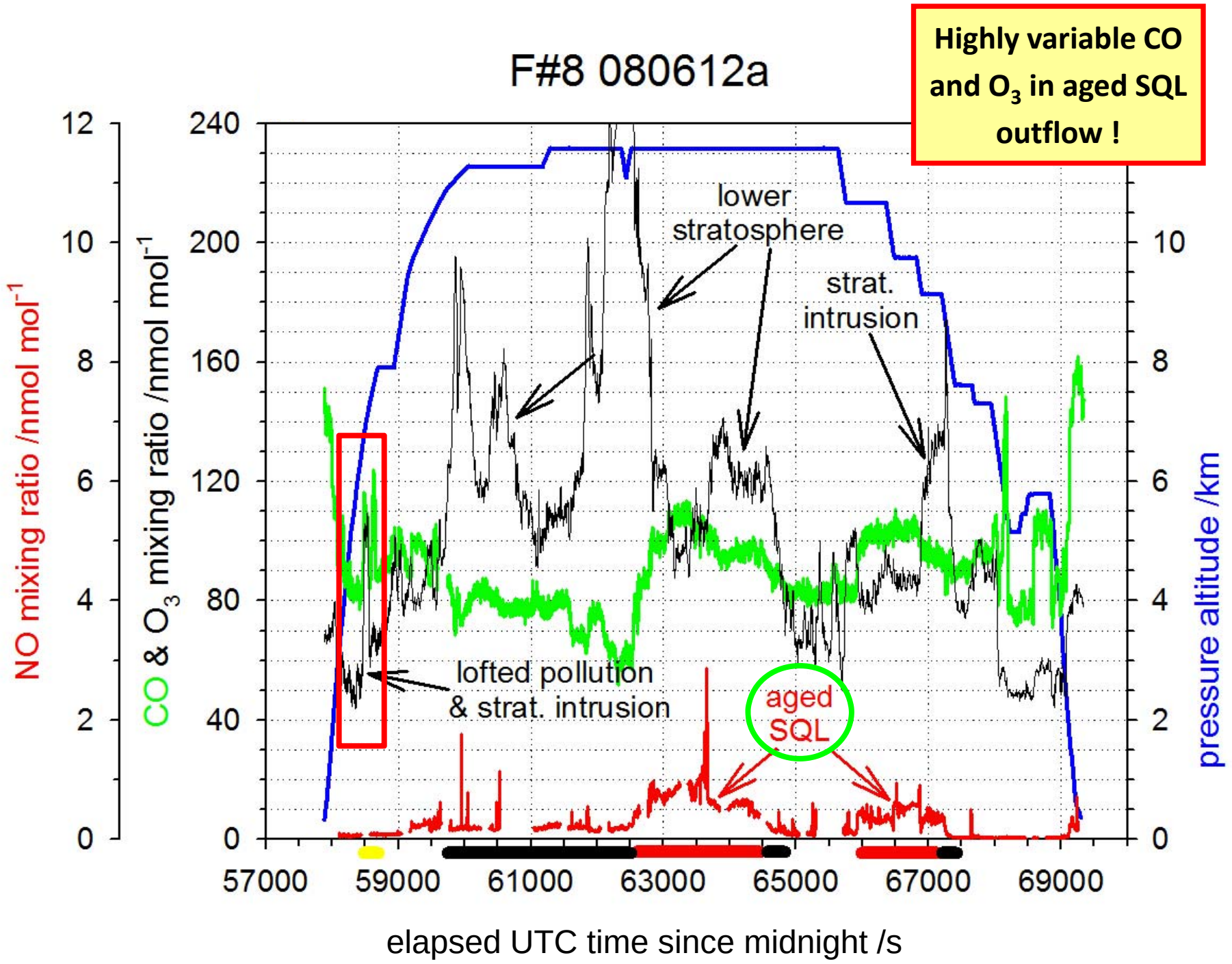
8-16 km column LNOx Tracer (ppbv)

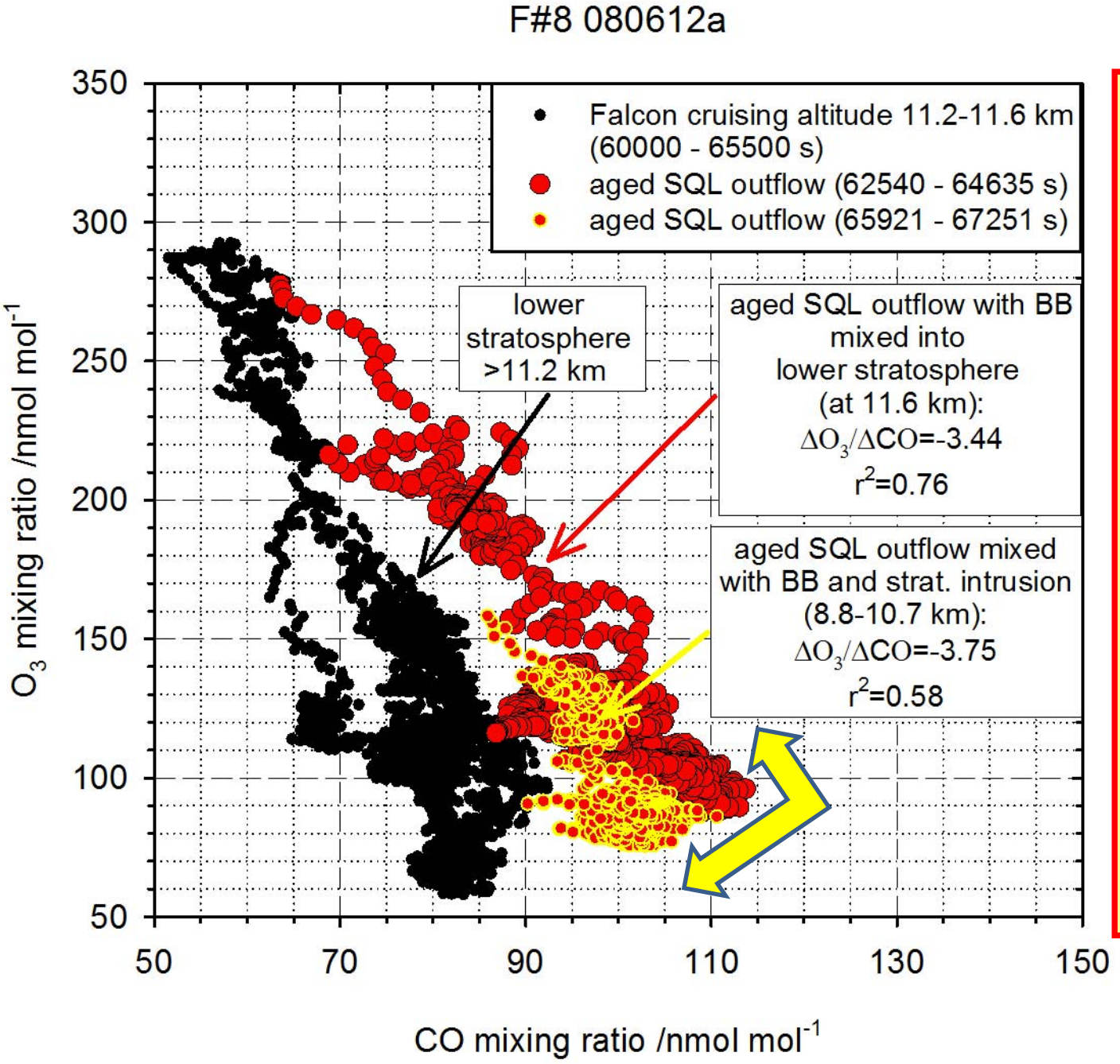
(*Cummings, Pickering, Barth et al.*)



Falcon flight on 8 June 2012: aged SQL outflow (12-24 h)

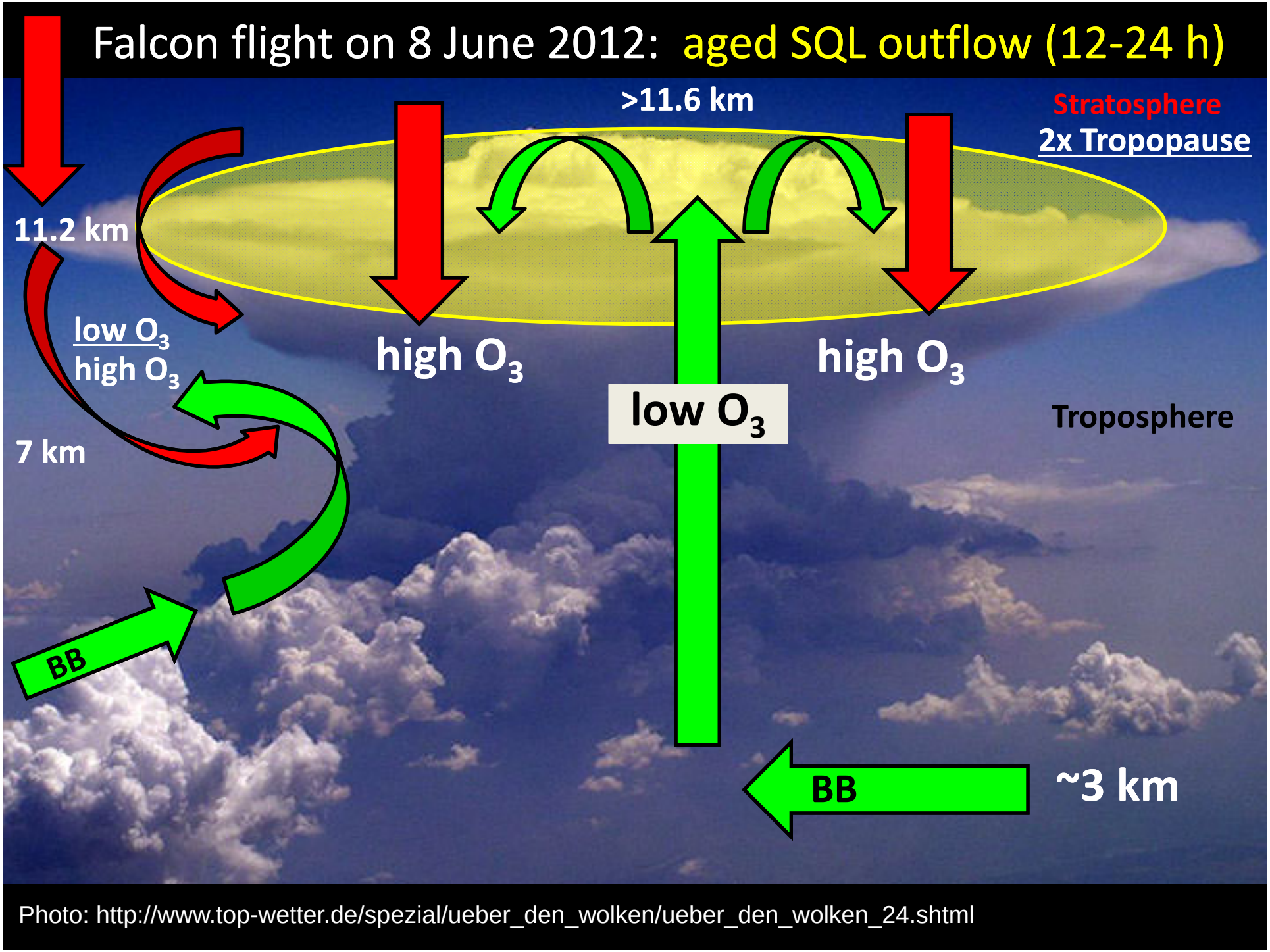



F#8 080612a
Highly variable CO and O_3 in aged SQL outflow !
lower stratosphere
strat. intrusion
lofted pollution & strat. intrusion
aged SQL
NO mixing ratio /nmol mol^{-1}
CO & O_3 mixing ratio /nmol mol^{-1}
pressure altitude /km
elapsed UTC time since midnight /s
0
2
4
6
8
10
12
40
80
120
160
200
240
57000
59000
61000
63000
65000
67000
69000



One day after active convection almost the complete aged anvil outflow mixed with lower stratospheric air

→ Elevated O_3 and CO in aged LNOx plumes, however negative O_3/CO ratio (mix with LS and no obvious O_3 production)


Falcon flight on 8 June 2012: aged SQL outflow (12-24 h)
>11.6 km
Stratosphere
2x Tropopause
11.2 km
low O3
high O3
high O3
high O3
low O3
Troposphere
7 km
BB
BB
~3 km
Photo: http://www.top-wetter.de/spezial/ueber_den_wolken/ueber_den_wolken_24.shtml

DC3 Flight Number, Date, Flight a or b, anvil time	Pressure Altitude, km	CO Mixing Ratio, nmol mol^{-1}	O_3 Mixing Ratio, nmol mol^{-1}	NO Mixing Ratio, nmol mol^{-1}	Ethane, pmol mol^{-1}	Propane, pmol mol^{-1}
F#8 080612a *(62540-64635 s) aged outflow*	*11.6*	**up to +40%**	**+60% or -20%**	**up to x7**	↑*1930 (BB)*	↑*1357 (BB)*
Background (64636-65638 s) (61260-62539 s)	**11.6 rear** **11.6 front**				**478** -	**124** -
F#8 080612a *(65921-67251 s) aged outflow*	*9.9*	**no change**	**+20%! aged outflow→** ***strat. intr. mixes into lower part of anvil outflow***	**x2**	↑*1737 (BB)*	↑*1243 (BB)*
Background (59286-59366 s)	**9.8-10.0**				-	-

Summary of the DC3 Falcon measurements

Fresh and *aged* LNOx successfully measured:

- on 30 May, *8 June*, 11 June, and 12 June 2012
- in MCS, squall lines and isolated supercells
- repeated penetrations and long flight duration times in selected anvil outflows covering lower outflow boundaries up to 12 km
- highest NOx mixing ratios (mean 2-3 ppbv) in supercell and MCS outflow (comparable to Hector in Australia)
- LNOx mixed into the lower stratosphere (LS) and LNOx mixed with BB plumes

O_3 in fresh and *aged* LNOx plumes:

- in general O_3 decrease compared to background observed (upward transport)
- frequently stratospheric intrusions at the anvil outflow edges enhance O_3
- frequently direct downward transport from UT/LS into the anvil enhances O_3
- *downward transport of O_3-rich air dominates in aged LNOx outflow*[NEW]
- photochemical O_3 production is not a prominent feature

→ **Strong UT/LS exchange caused by DC3 thunderstorms (2x tropopause & strat. intr.):**
Role of thunderstorm intensification by ingested BB plumes?

[NEW]**Outside thunderstorms ("=obstacles"): lofted BB plumes mix with strat. intrusion**