The Effects of Deep Convection on Atmospheric Chemistry

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Effects of Deep Convection

Convection over "Polluted Regions"

- Venting of boundary layer pollution
- Transport of NO_x, NMHCs, CO, and HO_x precursors to the upper troposphere (UT) and sometimes to the lower stratosphere (LS), where chemical lifetimes are longer and wind speeds greater
- Downward transport of cleaner air to PBL
- Transported pollutants allow efficient ozone production in UT, resulting in enhanced UT ozone over broad regions

$$NO + HO_2 \rightarrow NO_2 + OH$$

$$NO_2 + h\upsilon \rightarrow NO + O^*$$

$$O_2 + O^* + M \rightarrow O_3 + M$$

- Increased potential for intercontinental transport
- Enhanced radiative forcing by ozone

Effects of Deep Convection

Convection over "Clean" Regions

- In remote regions low values of PBL O_3 and NO_x are transported to the upper troposphere
- Potential for decreased ozone production in UT
- Larger values of these species tranported downward to PBL where they can more readily be destroyed

Convection over all Regions

- Lightning production of NO (much more over land)
- Perturbation of photolysis rates
- Effective wet scavenging of soluble species
- Nucleation of particles in convective outflow

Observations and Models

- **Combination of observations and model simulations is a powerful tool to better understand physical and chemical processes in thunderstorms**

- **Convection/chemistry field experiments (the last 25 years):**
  PRESTORM – OK, KS 1985
  ABLE-2A – Brazil 1985
  ABLE-2B – Brazil 1987
  STEP – Australia 1987
  NDTE – North Dakota 1989
  TRACE-A – Brazil 1992
  STERAO – Colorado 1996
  EULINOX – Germany 1998
  CRYSTAL-FACE – Florida 2002
  TROCCINOX – Brazil 2005
  SCOUT-O3/ACTIVE – Australia 2005
  AMMA – West Africa 2006
  TC4 – Costa Rica 2007

Observations and Models

- <u>Cloud-resolved chemistry models</u>:
  - Storm simulation with Goddard Cumulus Ensemble (GCE) Model or cloud-resolved MM5 drives offline transport and chemistry model with lightning NO production.
  - Cloud-resolved WRF-Chem (online transport/chemistry) now being used.

- <u>Regional chemistry models</u>:
  - Driven by WRF with parameterized convection (examples: offline CMAQ; on-line WRF-Chem). Lightning schemes being developed.

- <u>Global chemical transport models</u>:
  - Offline global chemistry and transport in UMD-CTM and NASA/GMI CTM driven by GEOS-DAS from Goddard GMAO. Lightning parameterized with model convective mass fluxes and constrained with satellite observations.

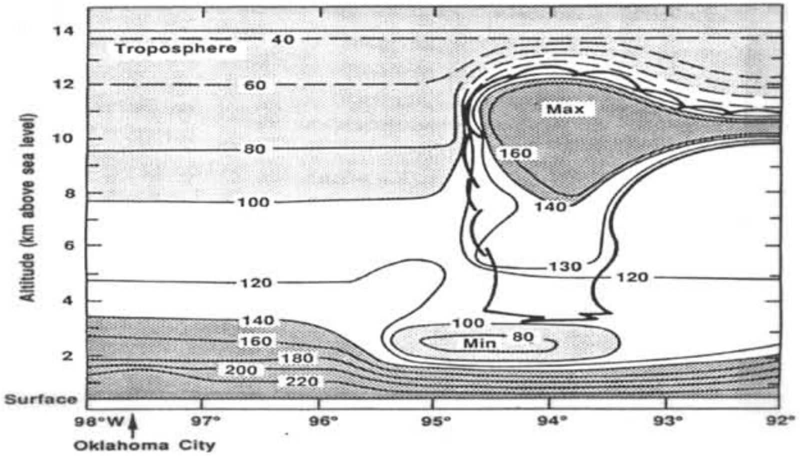
  - Online chemistry and transport in GEOS-5 Chemistry and Climate Model, allowing chemistry to feedback to meteorology through perturbations to radiative fluxes. Physically-based lightning scheme under development.

Midlatitude Convection

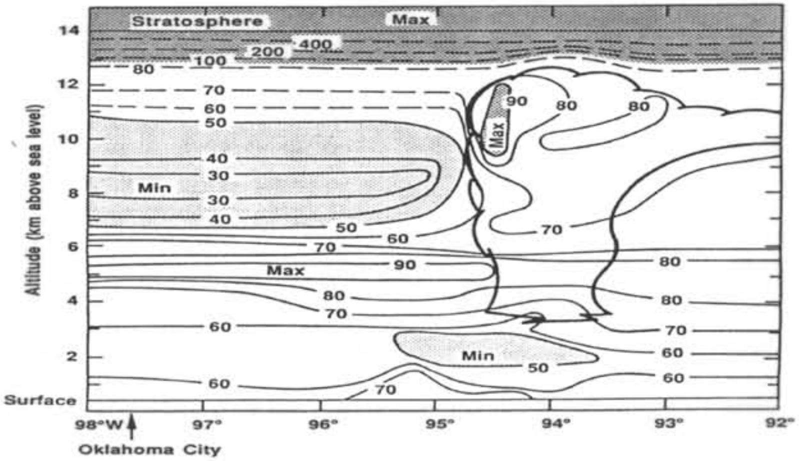
Examples from field experiments and models

Aircraft Measurements of Trace Gas Redistribution in Oklahoma PRESTORM June 15, 1985 MCC

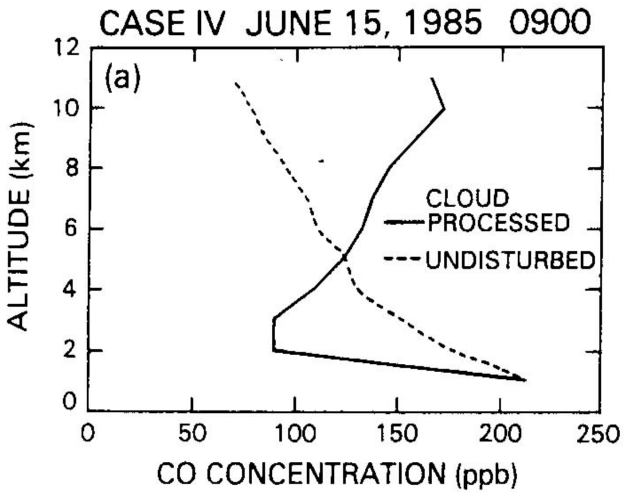
CO

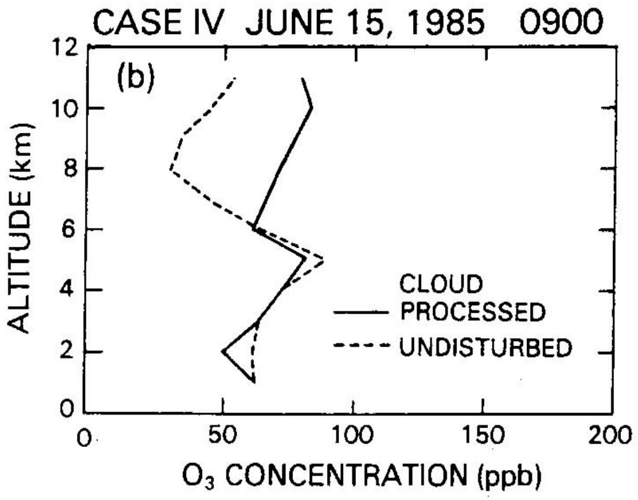


O_3

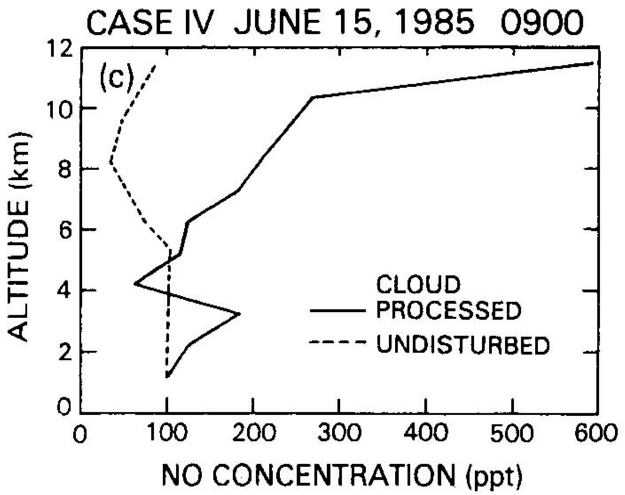


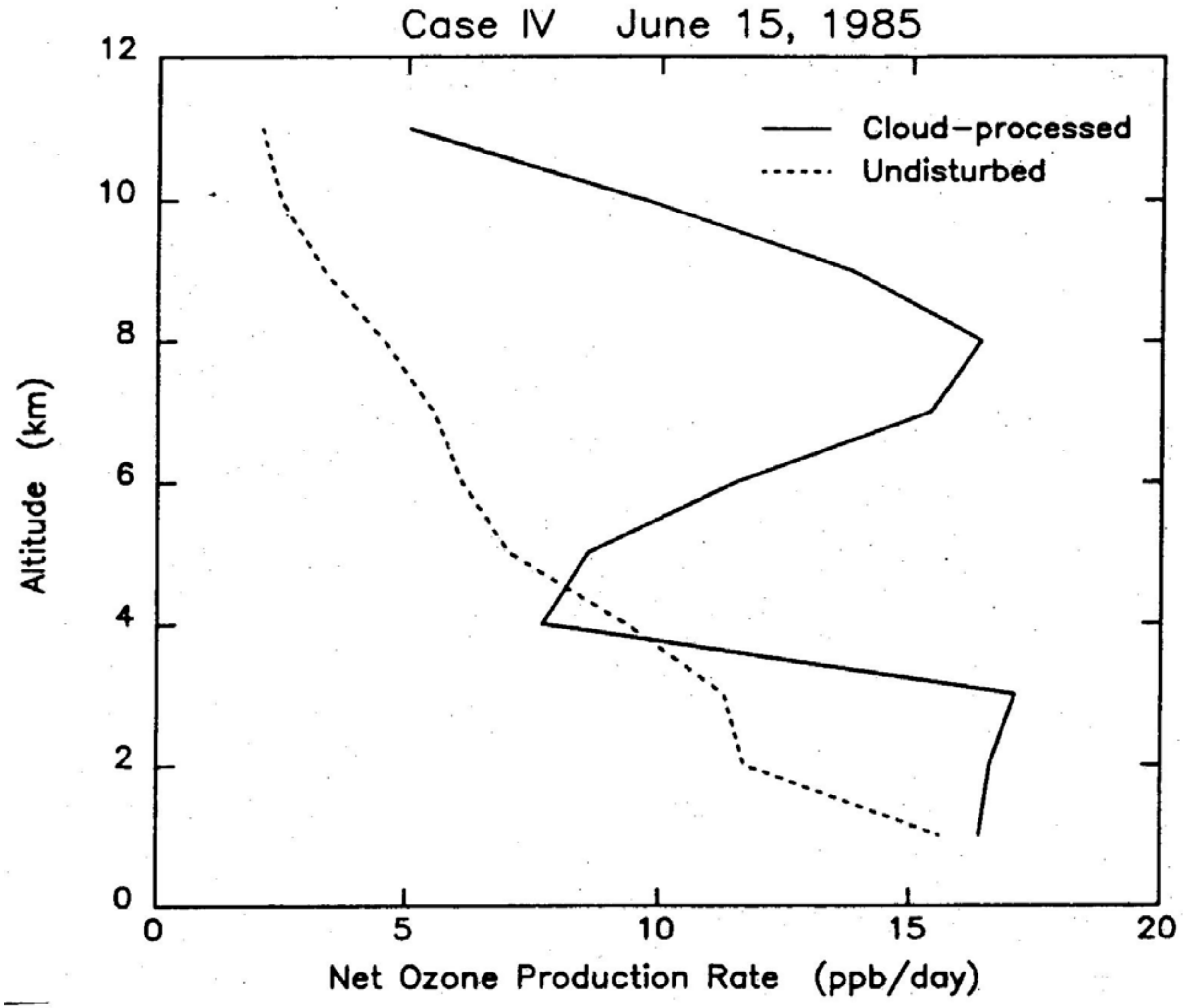
Dickerson et al., 1987, Science





Pickering et al., 1990

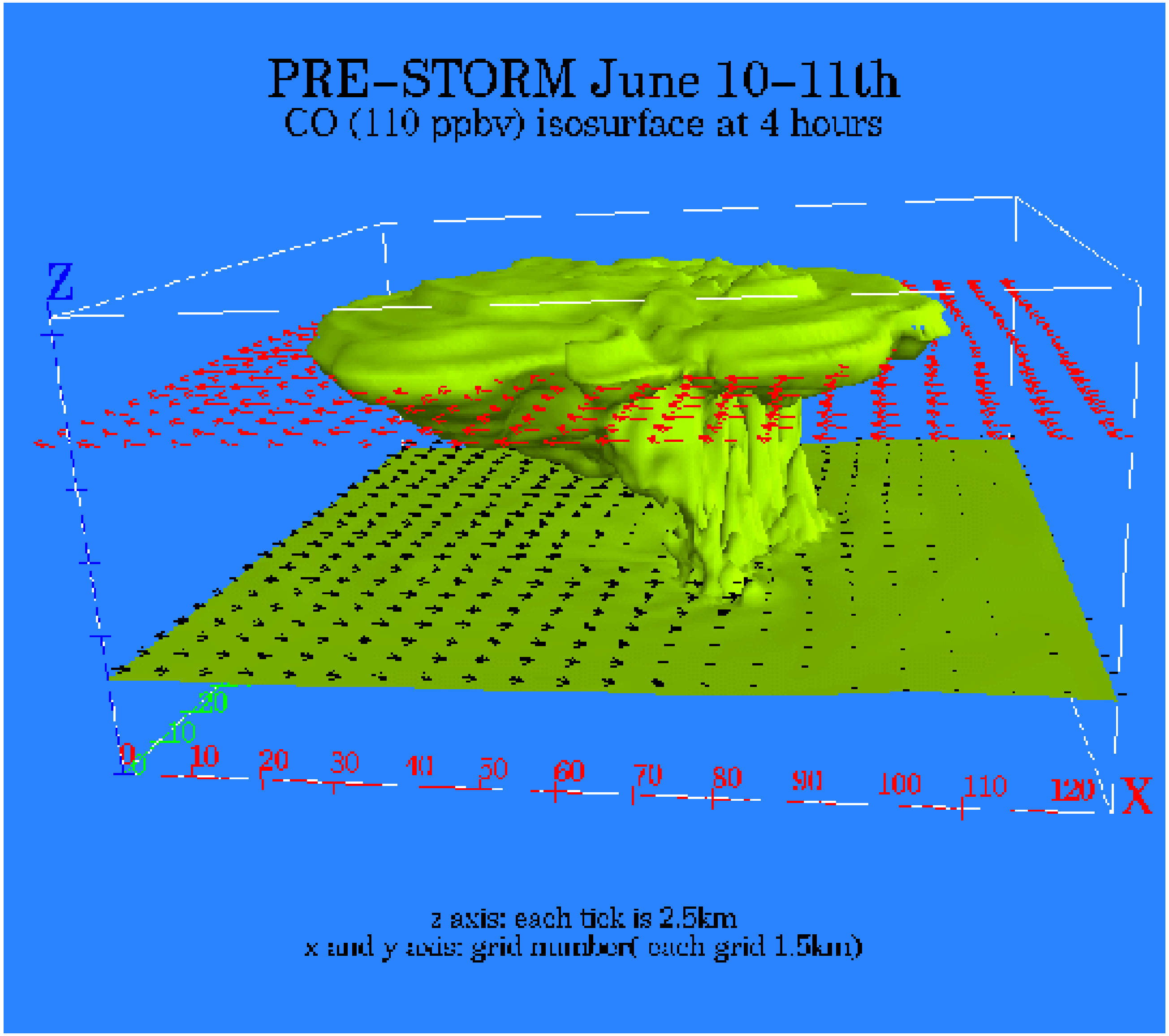




Mid – upper trop. ozone production enhanced by factor of 4

Pickering et al., 1990

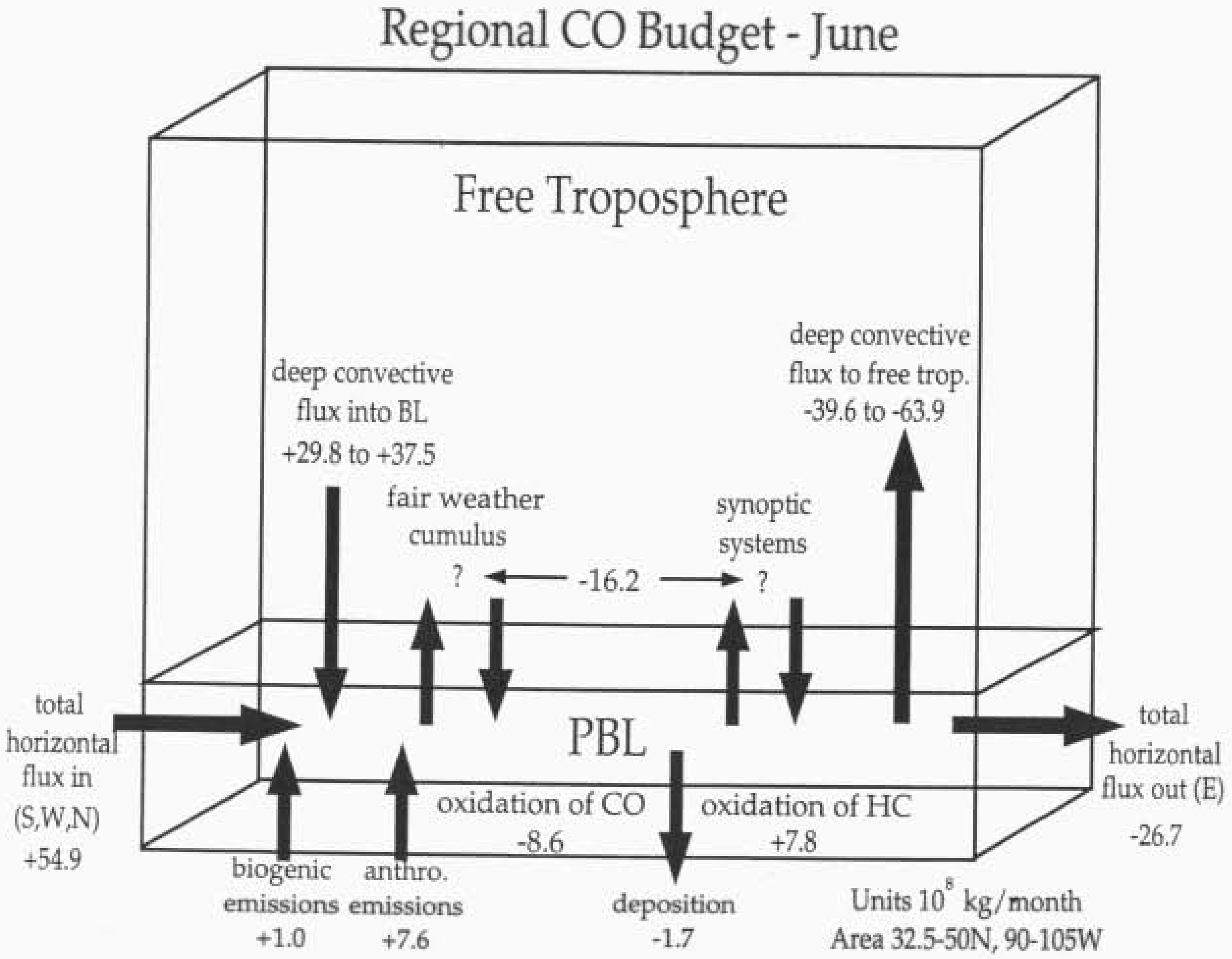
Kansas-Oklahoma Squall Line Cell



Pickering et al., 1992

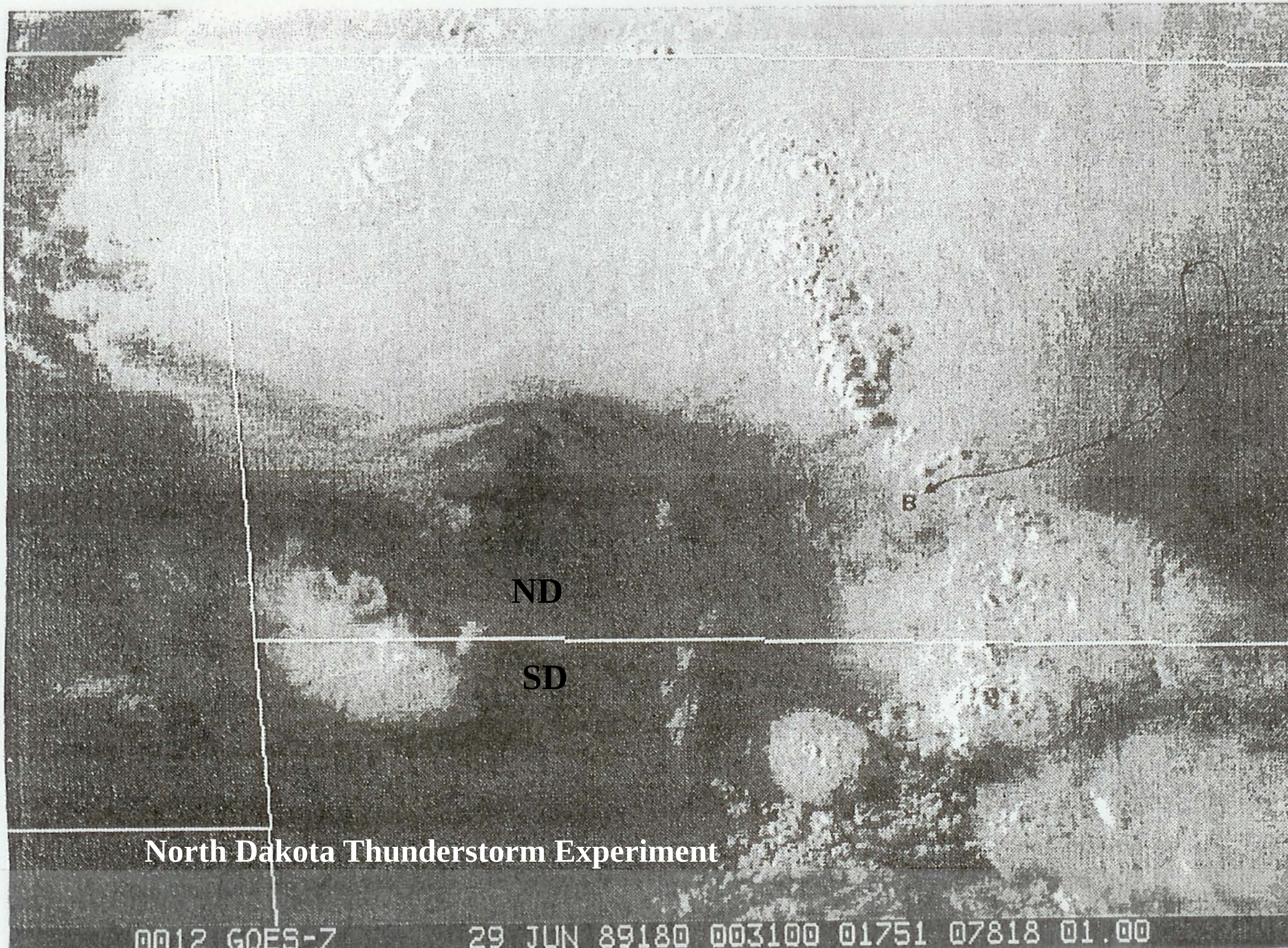
3-D GCE model simulation of one squall line cell

Central United States



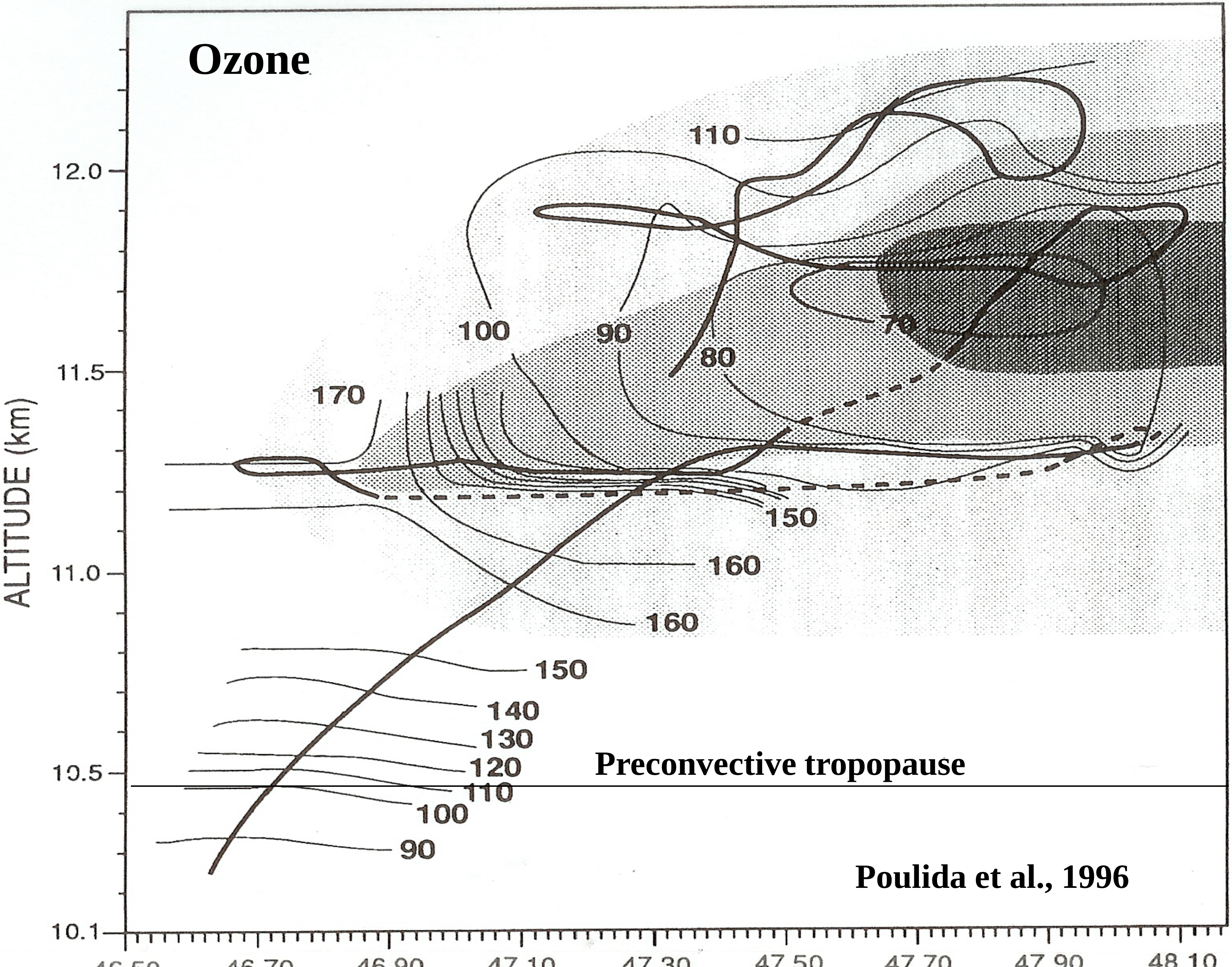
Thompson et al., 1994

Uses cloud-resolved model transport statistics and ISCCP convective cloud climatology



North Dakota Thunderstorm Experiment

North Dakota Thunderstorm Experiment – July 28, 1989

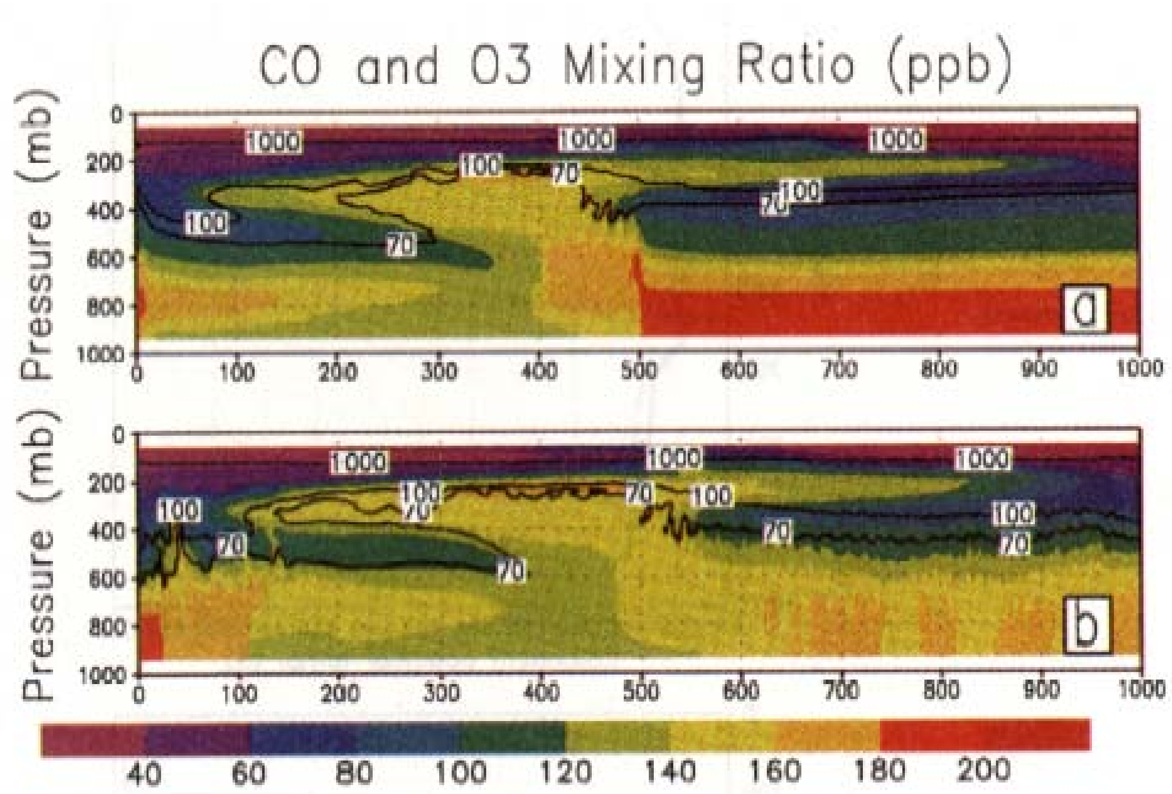


Ozone

Preconvective tropopause

Poulida et al., 1996

CO and O_3 Tracer Simulation for June 28, 1989 NDTP storm



CO – color scale; O_3 – isolines
(a) base simulation; (b) moist boundary condition simulation

Note downward ozone transport near rear anvil

Stenchikov et al. (1996)

CO and O_3 Tracers Along Anvil Passes for July 10, 1996 STERAO storm

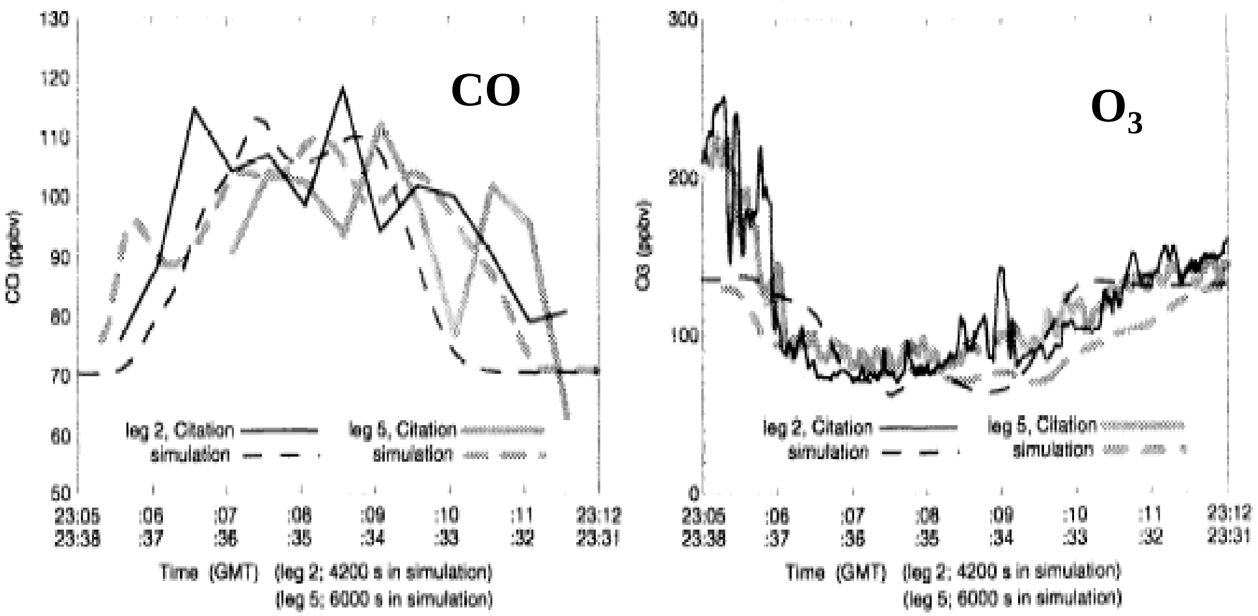


Figure 11. Citation CO and O_3 measurements for anvil passes close to the southeasternmost convective cell (leg 2, 10 km downwind, 11.6 km msl) and downwind (leg 5, 50 km downwind, 11.2 km msl), along with analogous tracks taken through the simulation. The plot tracks are from the southwest (left) to the northeast (right).

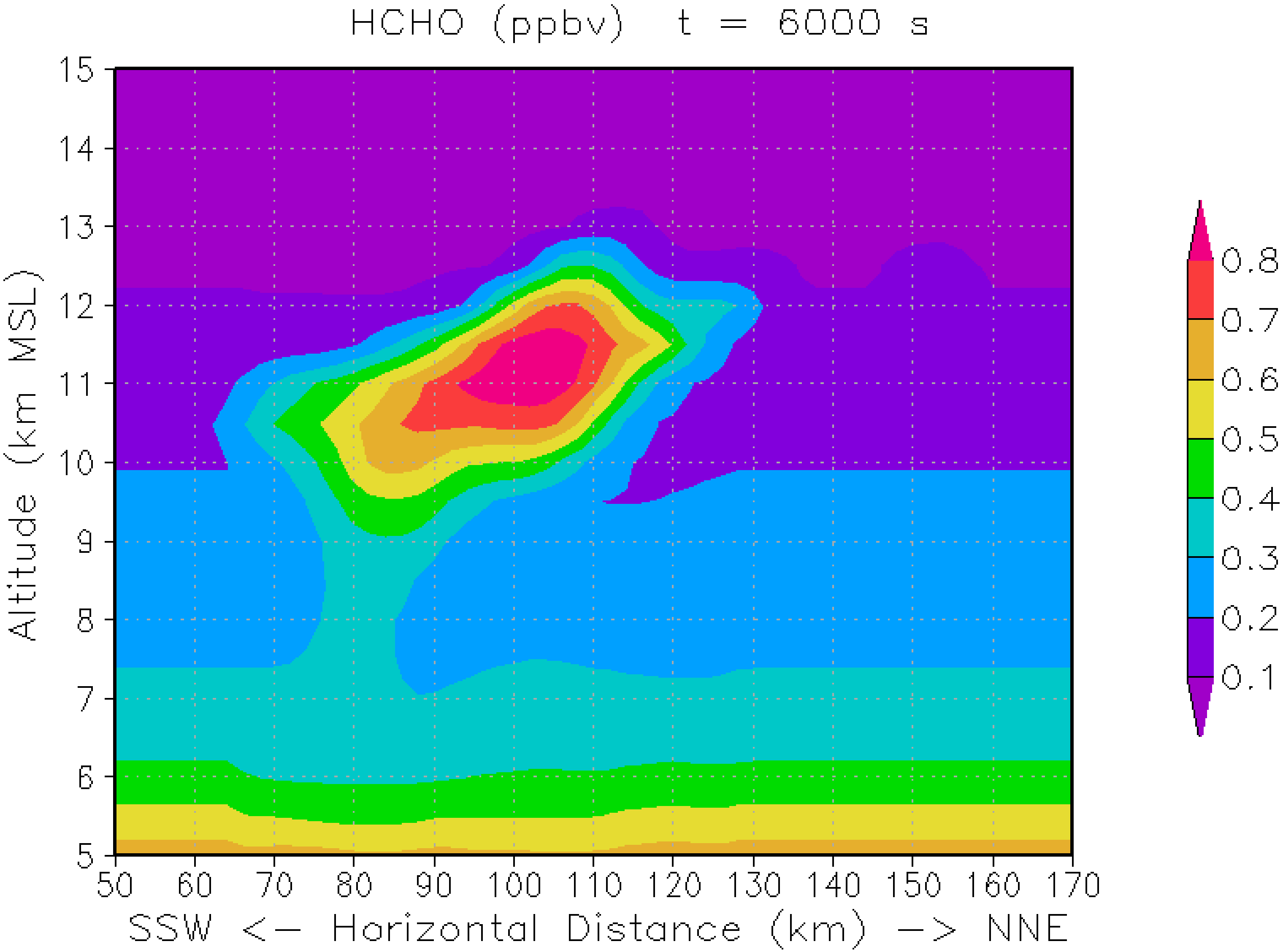
Note enhanced ozone at southwest (upwind) edge of anvil

Skamarock et al. (2000)

Enhanced UT HO_x Production

- Jaeglé et al. (1997) and Prather and Jacob (1997) noted that deep convection is effective in transporting HO_x precursors to the upper troposphere.
- Water vapor, acetone, methylhydroperoxide, and formaldehyde shown to be important as HO_x precursors.
- Enhanced HO_x leads to enhanced O_3 production

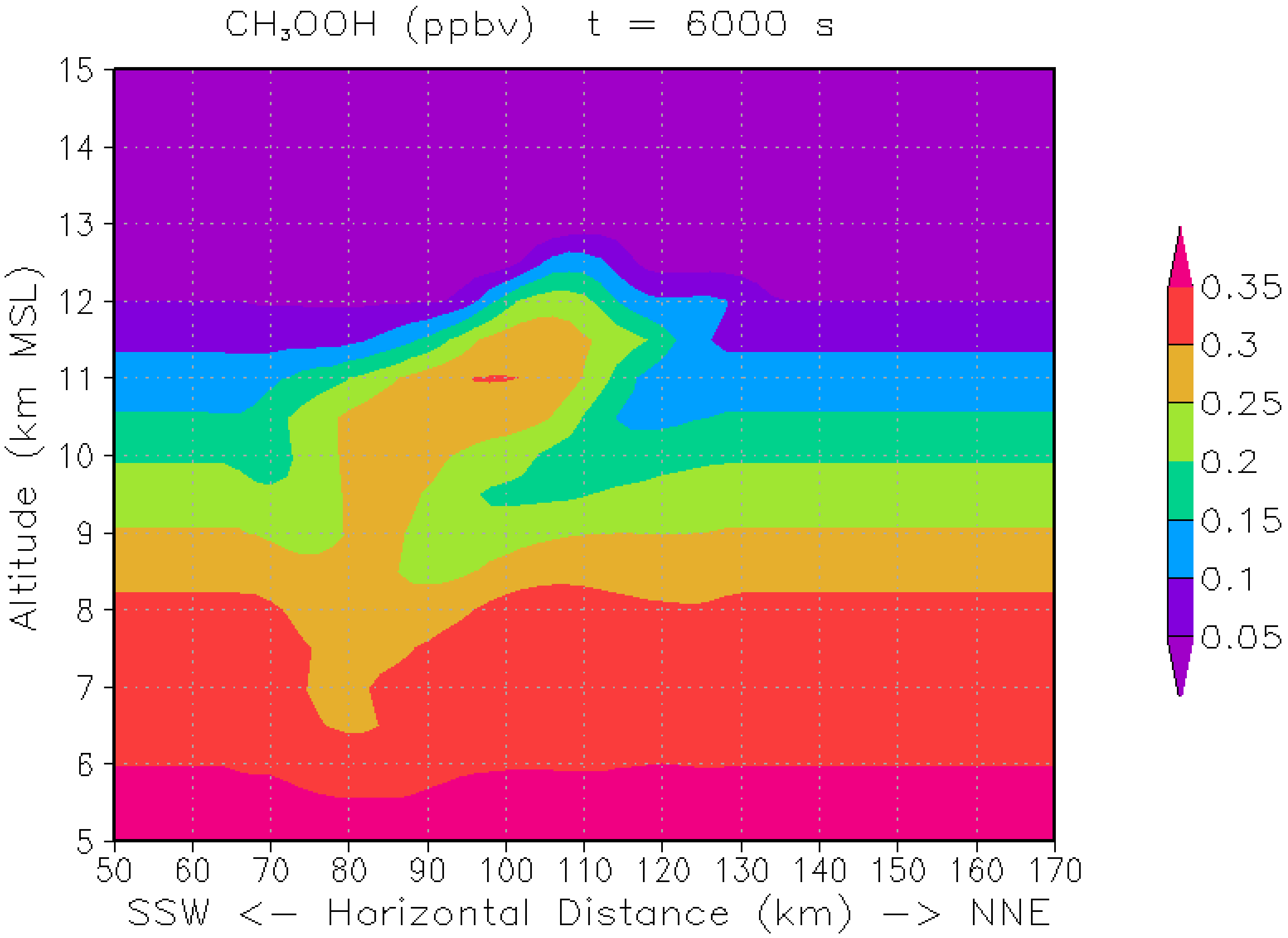
STERAO-A July 10, 1996



Fried et al.(2008) INTEX-A obs showed 46% of samples had HCHO enhanced above background, and 30% of these samples resulted from direct convective injection to the UT

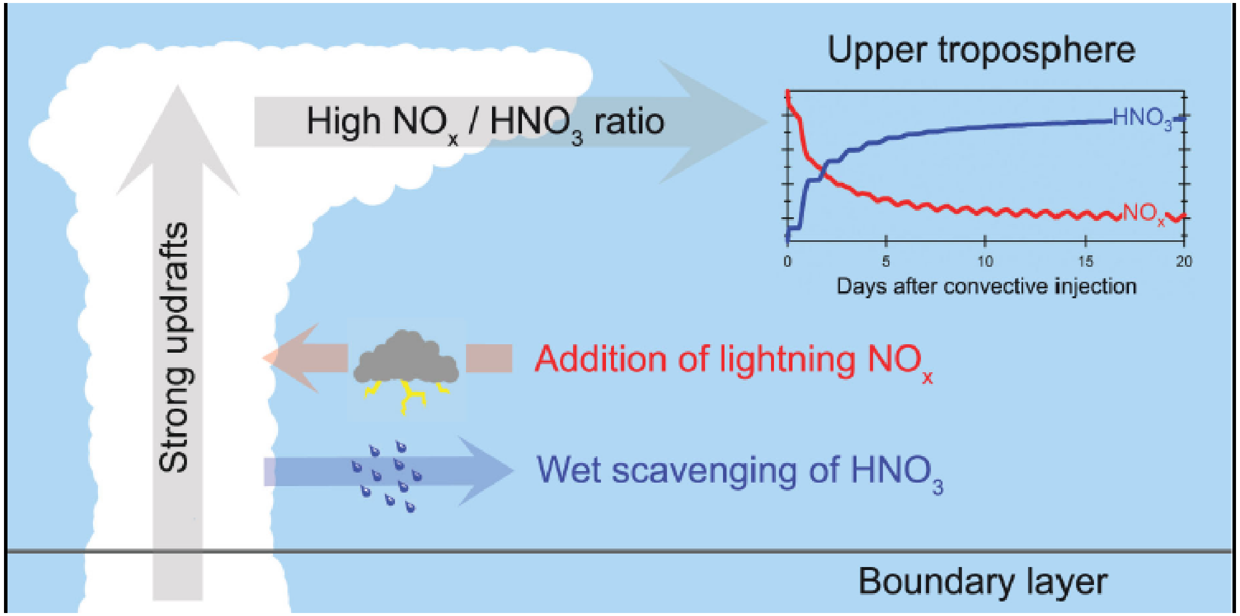
Ott et al. (2006)

STERAO-A July 10, 1996

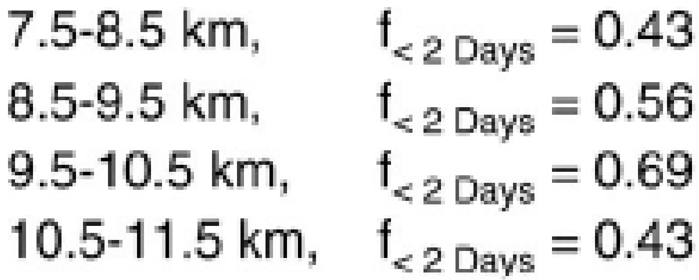


Ott et al. (2006)

NASA INTEX-A Observations over US – Summer 2004



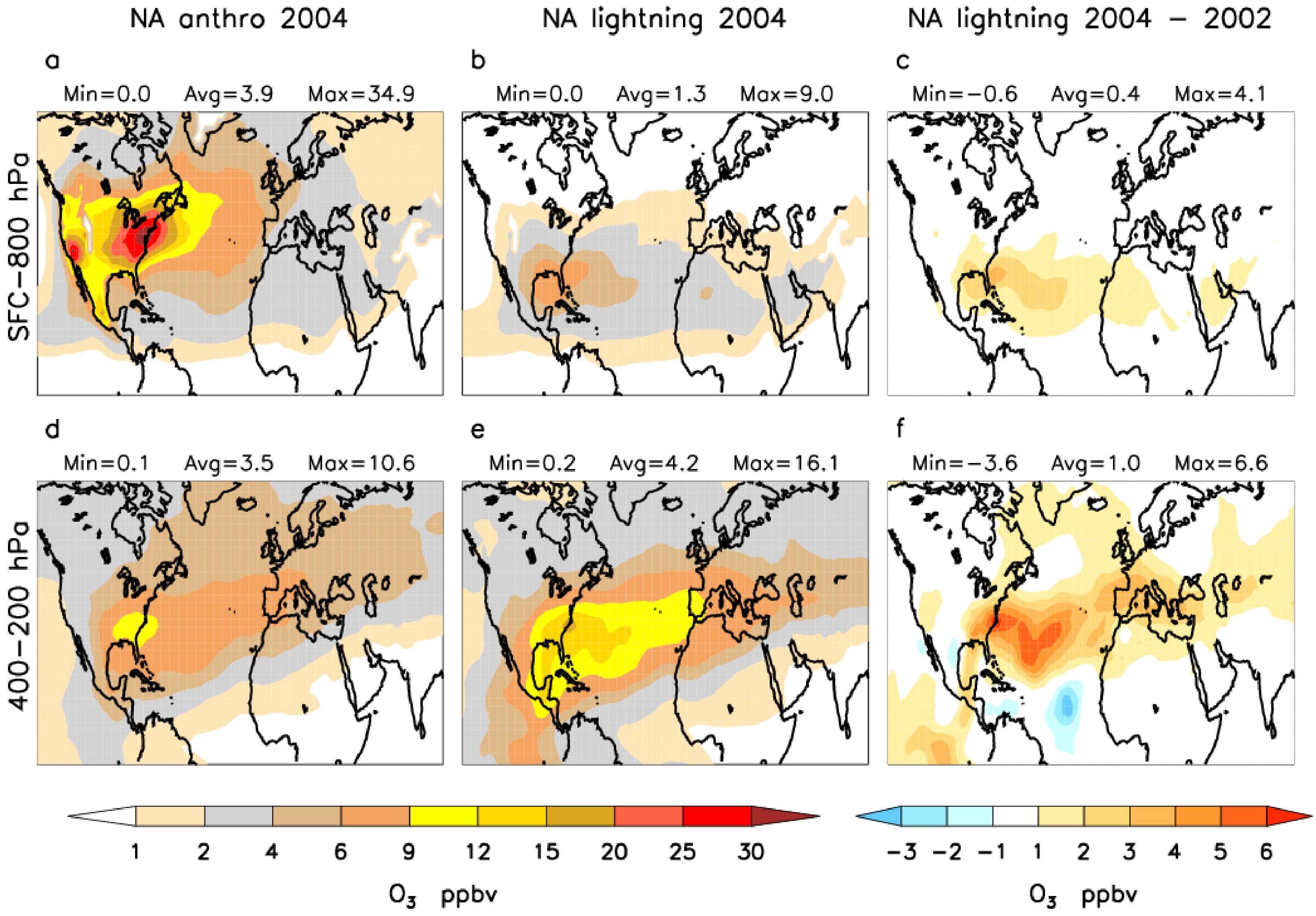
NO_x/HNO_3 ratio used as a chemical clock to determine time since air was influenced by convection



Altitude	Frequency
7.5-8.5 km,	$f_{< 2\ \mathrm{Days}} = 0.43$
8.5-9.5 km,	$f_{< 2\ \mathrm{Days}} = 0.56$
9.5-10.5 km,	$f_{< 2\ \mathrm{Days}} = 0.69$
10.5-11.5 km,	$f_{< 2\ \mathrm{Days}} = 0.43$
Mean	**0.54**

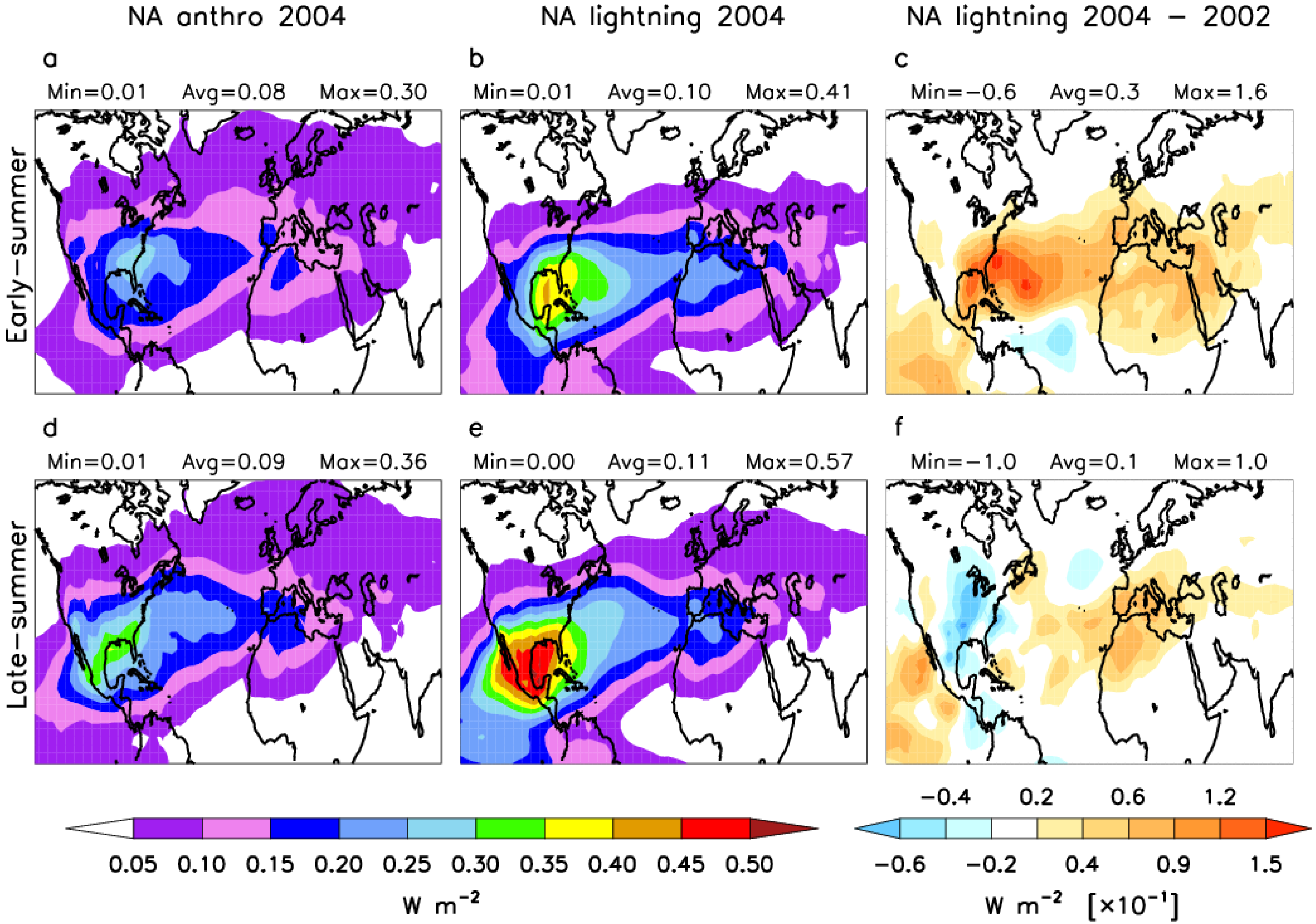
Bertram et al., 2007

Ozone Export from North America – Early Summer



Martini et al., 2010

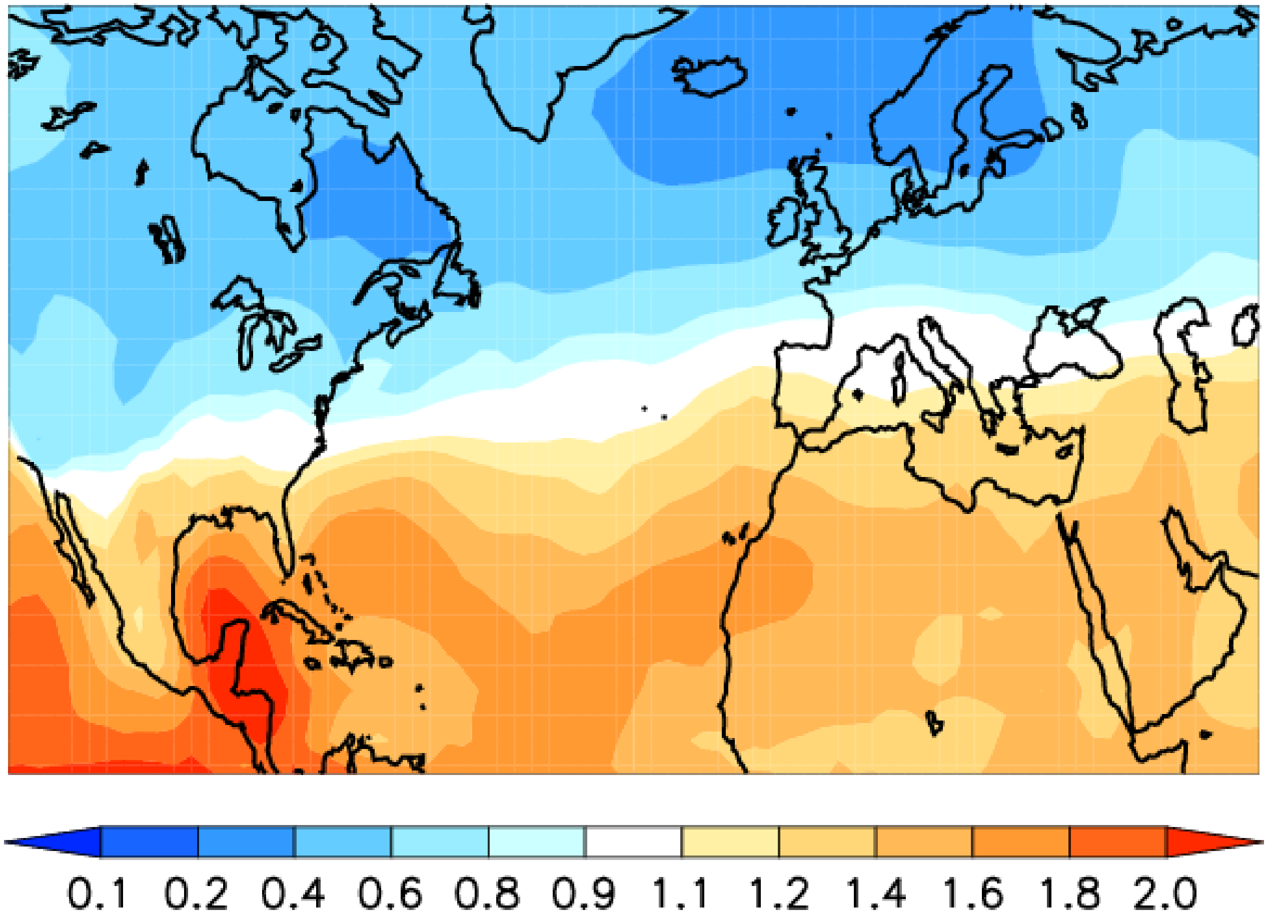
Net Downward LW Radiative Flux Perturbations at the Tropopause Due to Tropospheric Ozone



Martini et al., 2010

Relative Importance of Anthropogenic and Lightning Emissions on Radiative Forcing by Ozone

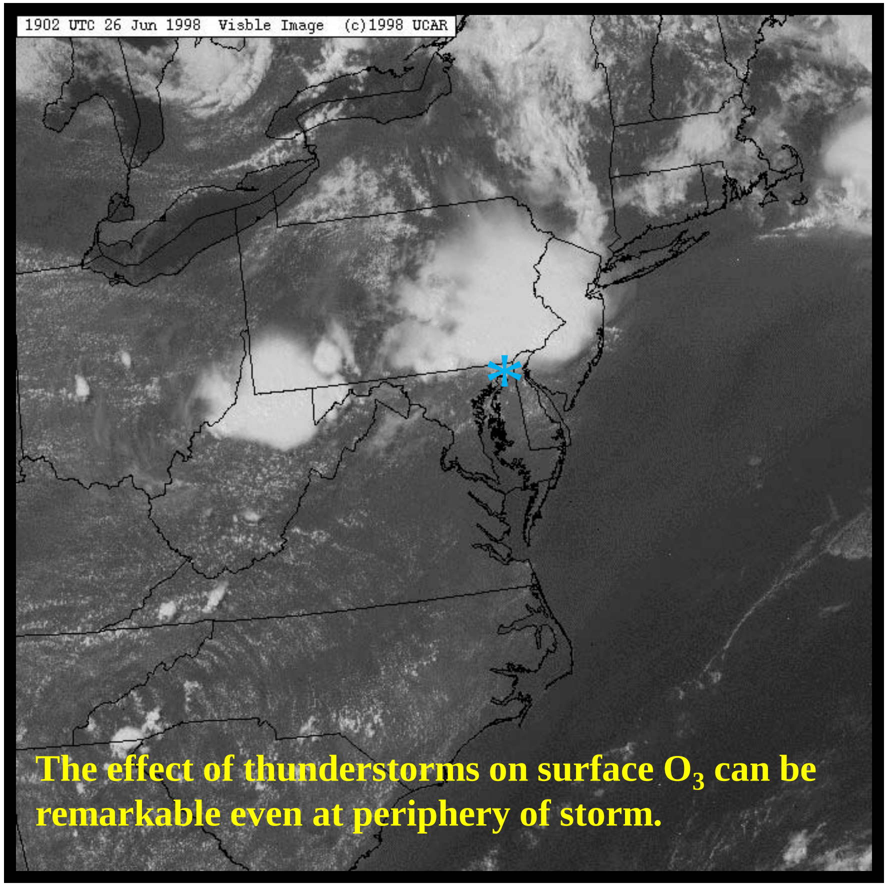
Early Summer 2004



RF_{LNOx}/RF_{ANTHRO}

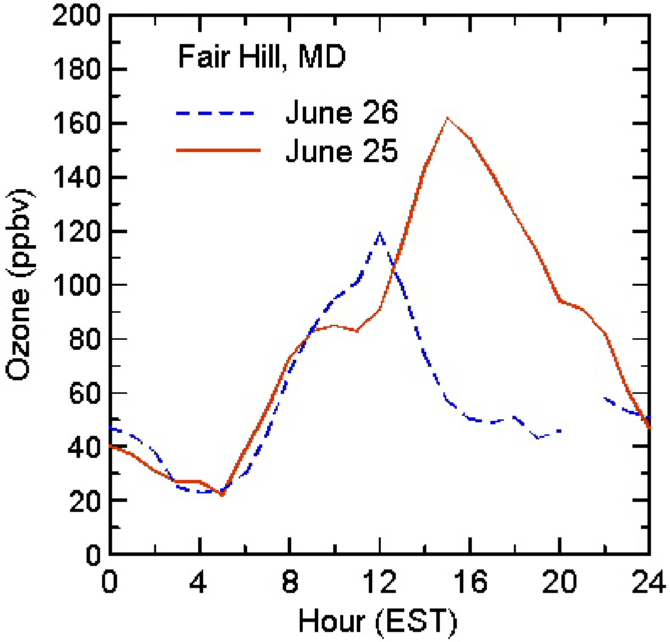
Martini et al., 2010

Surface air quality effects of deep convection



The effect of thunderstorms on surface O_3 can be remarkable even at periphery of storm.

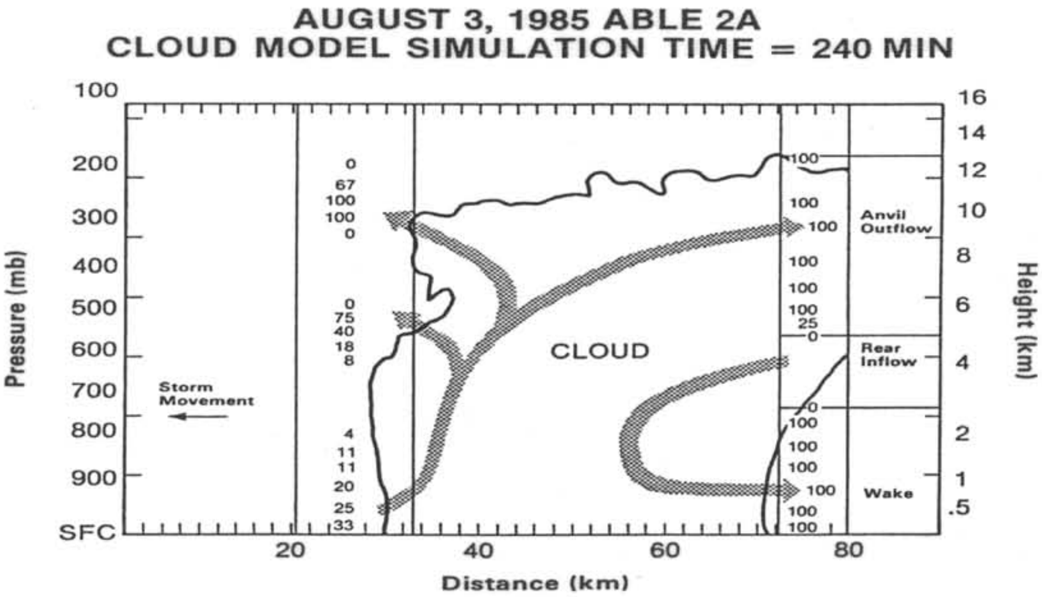
On the third day of a high O_3 episode (June 24-26 1998), a line of thunderstorms passed just north of the Fair Hill, MD monitoring station.



C. Piety

Tropical Convection

Tropical squall line over Amazon Basin

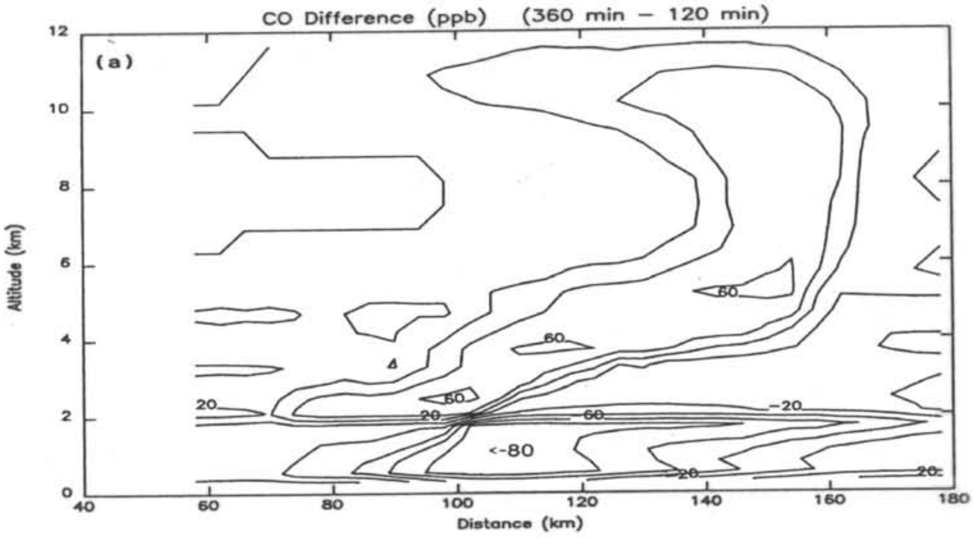


Arrows indicate major transport paths

Columns of numbers indicate percentage of air at these locations that is cloud outflow based on trajectory analysis

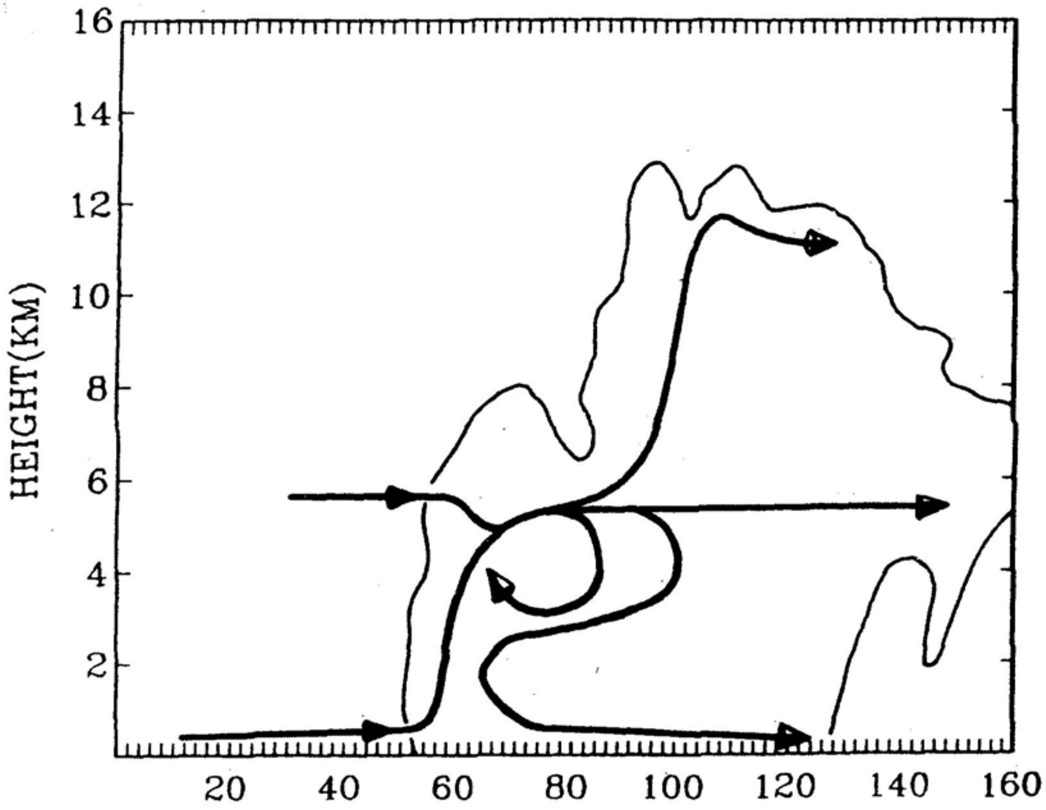
Dry Season

Pickering et al, 1991



CO redistribution from biomass burning plume

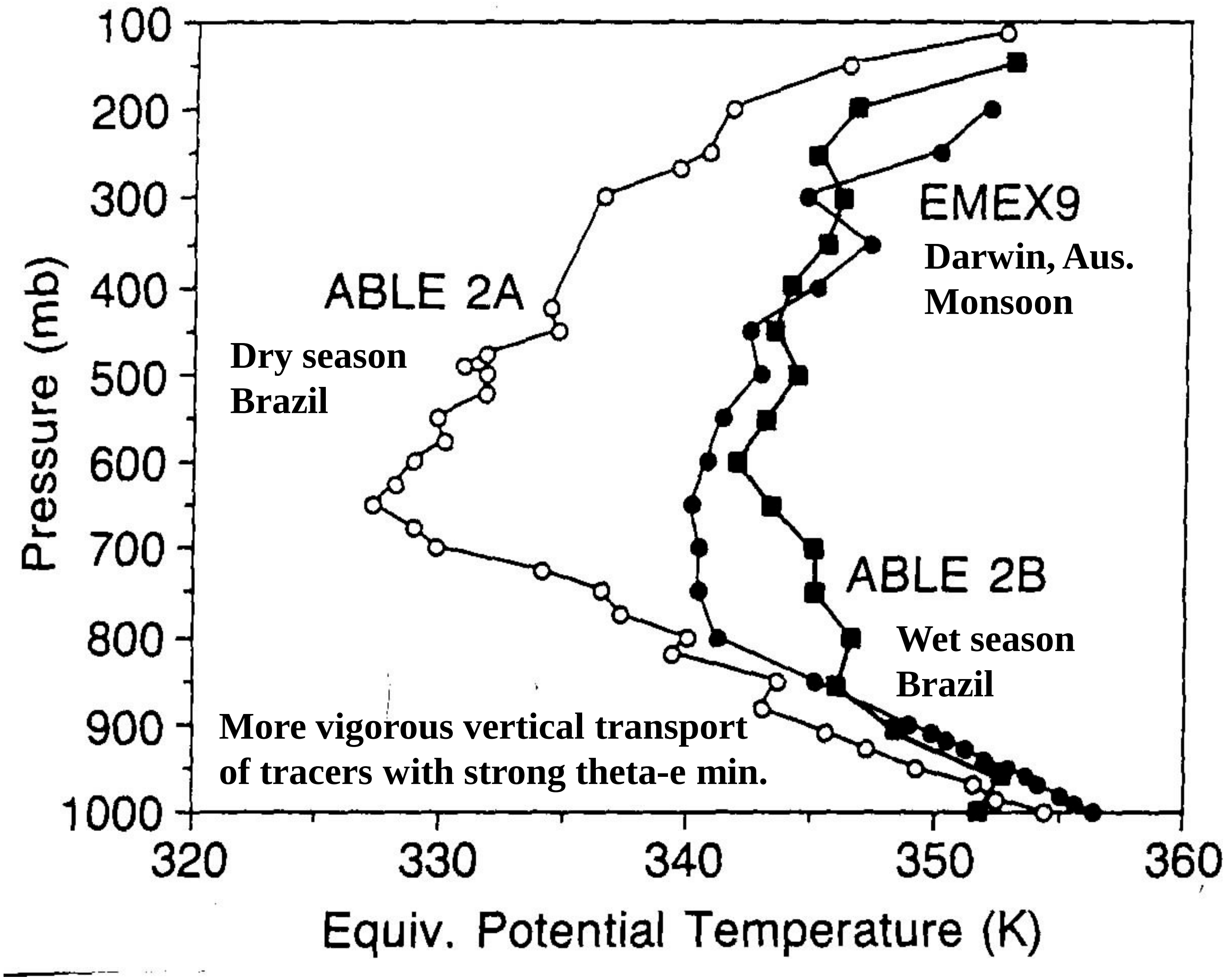
ABLE-2B April 26, 1987 Brazil Squall Line



Arrows indicate major transport pathways

Wet Season

Scala et al., 1990



Darwin, Aus.
Monsoon

Dry season
Brazil

Wet season
Brazil

More vigorous vertical transport
of tracers with strong theta-e min.

Pickering et al., 1993

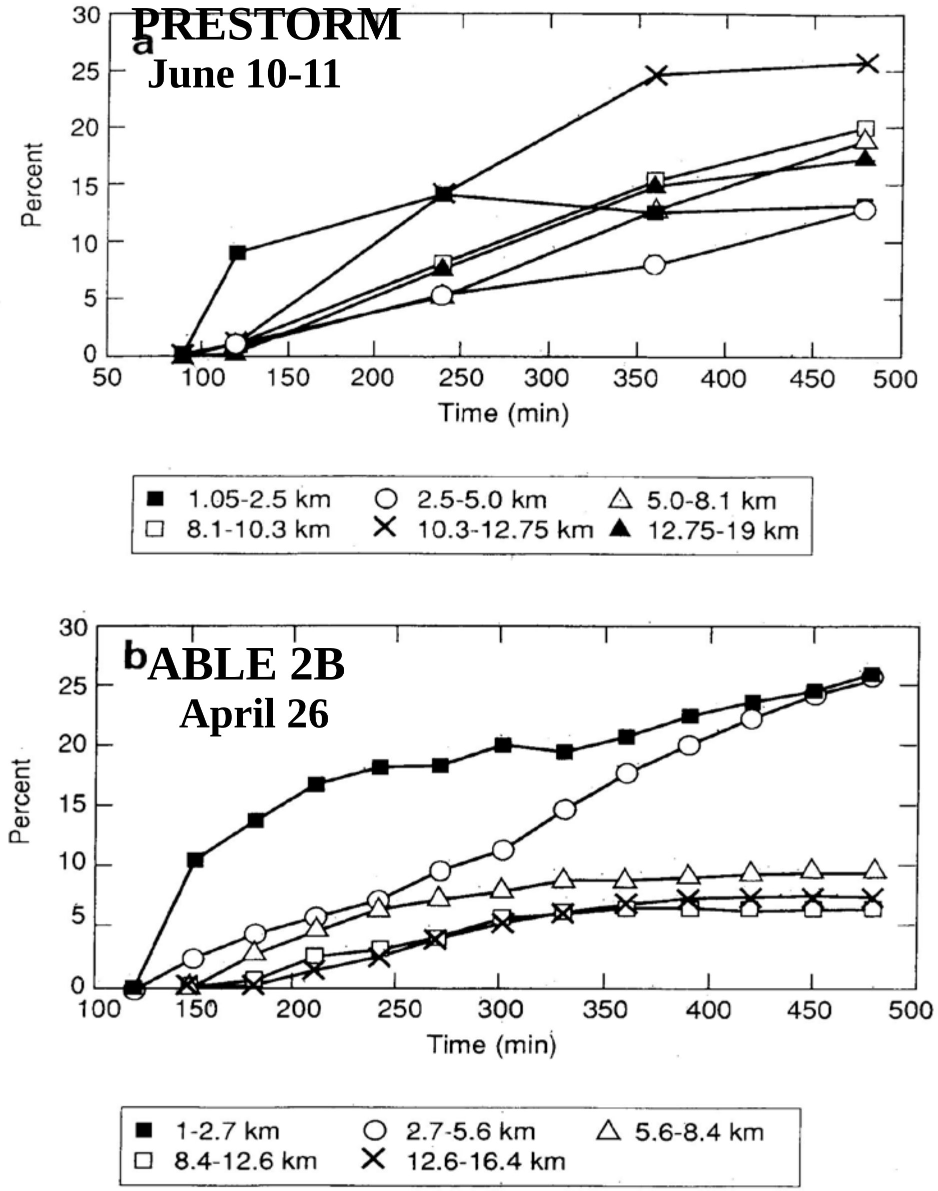


Fig. 6. Fractional redistribution of tracer mass initially in lowest kilometer to other indicated layers for (*a*) Kansas-Oklahoma PRESTORM event (June 10–11, 1985) and (*b*) April 26, 1987, Amazonian ABLE 2B event.

26% of BL tracer reaches 10-12 km

Weak vertical transport to upper troposphere due to midlevel overturning

7% of BL tracer reaches 12-16 km; 6% reaches 8-12 km

Pickering et al., 1992

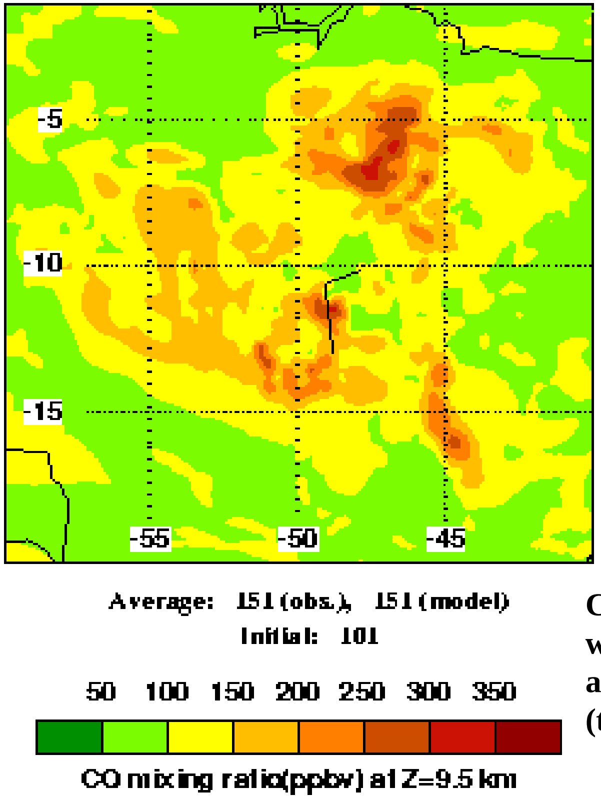
Convective Transport of Biomass Burning Emissions over Brazil

Kain-Fritsch Convective Parameterization

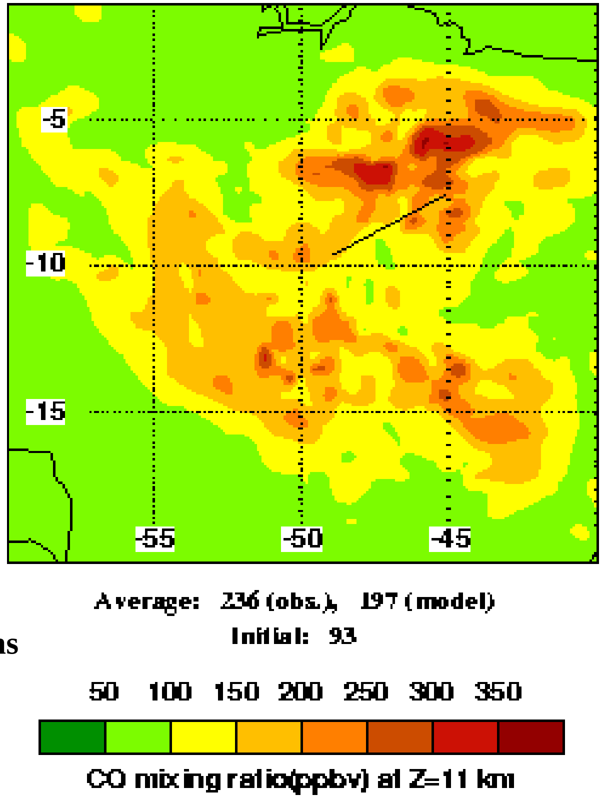
MM5 Simulation of System Sampled on GTE/TRACE-A

Positive definite scheme, grid+subgrid transport

9.5 km



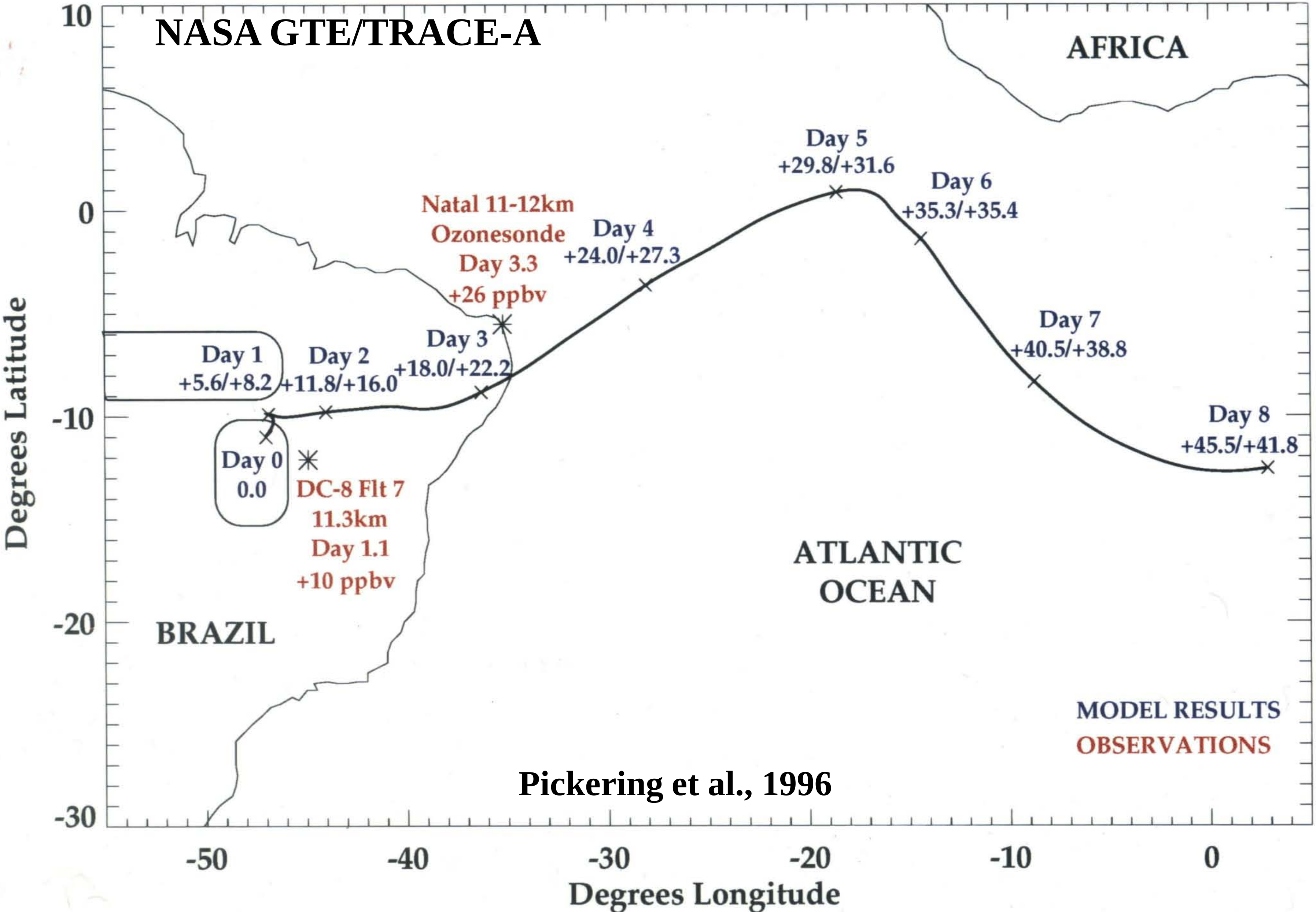
11 km



Comparison of model with DC-8 observations along sampling tracks (thin lines)

Pickering et al., 1996

Ozone Production Downstream of 26-27 Sept 92 Convection
Box Model Calculations vs. Observations (9.5-12km)



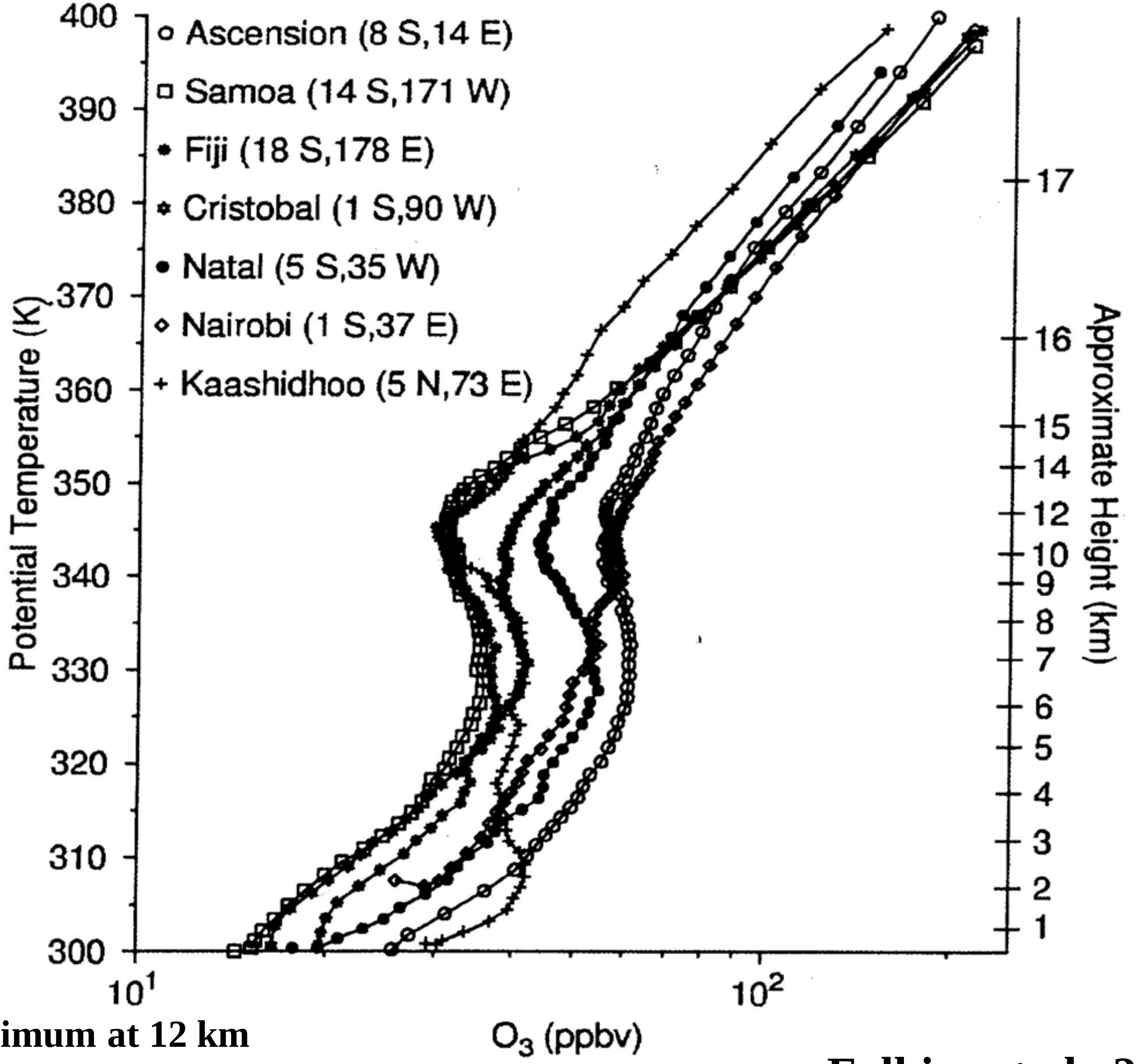
NASA GTE/TRACE-A

Pickering et al., 1996

Convection over Remote Oceans

- Pickering et al. (1993) noted O_3 and NO_y minima in UT convective outflow in STEP (near Darwin, Australia) and computed a decrease in $P(O_3)$ due to convection.

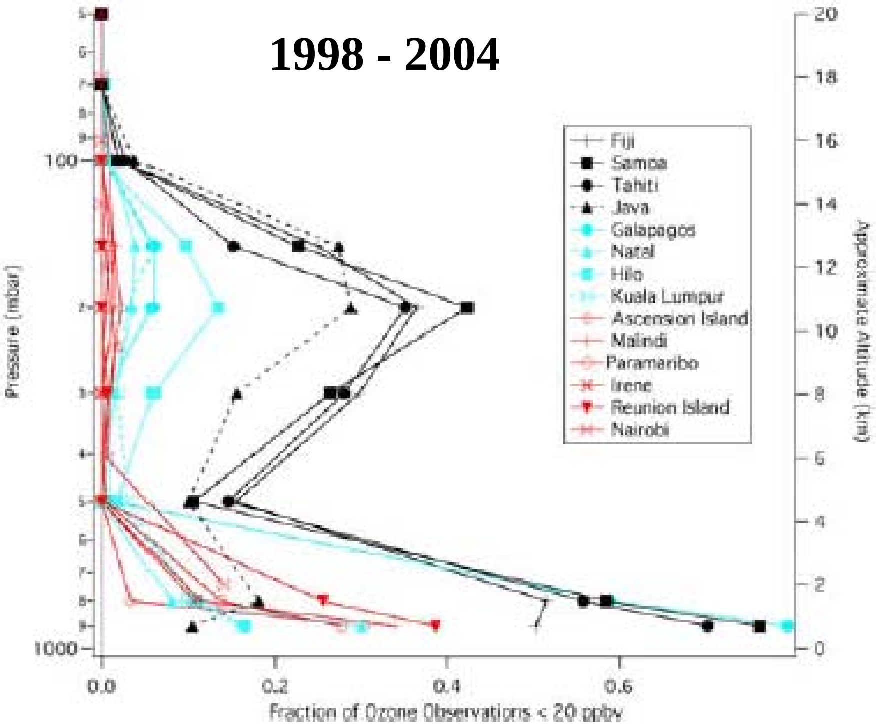
- Kley et al. (1996) reported very low ozone measurements near tropopause over the Central Pacific. Resulted from convective transport of very clean marine boundary layer air.



Note ozone minimum at 12 km resulting from convective outflow

Folkins et al., 2002

Low Ozone Events in UT Indicative of Convective Frequency



1998 - 2004

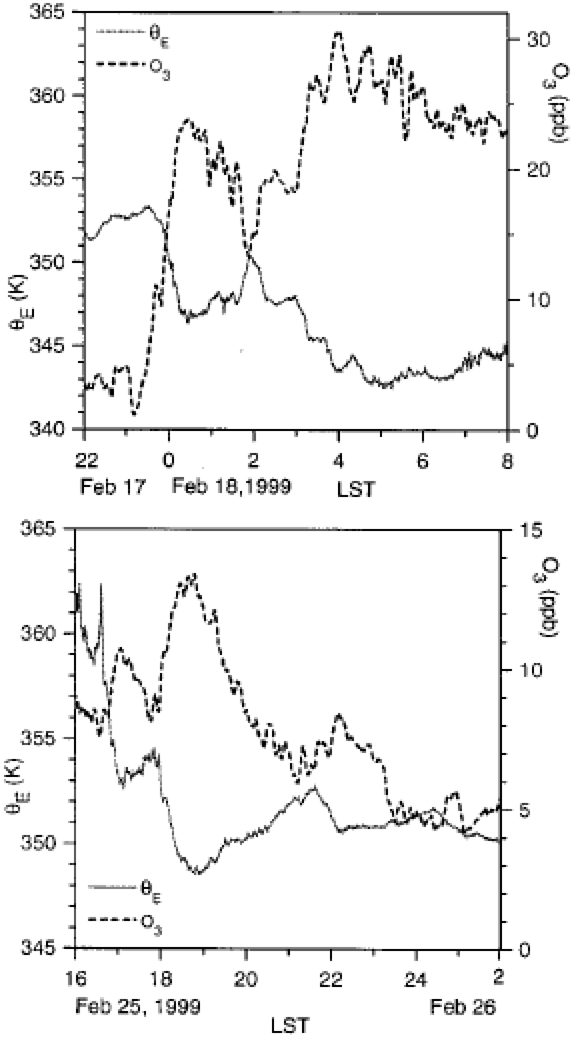
Table 1. Changes in Reduced Ozone in the Upper Troposphere From the Late 1970s to Present

Period	Number of Sondings	Percent of Reduced Ozone Events at 200 mbar
	Samoa	
1986–1990	115	10 (<20 ppbv)
1995–1996	96	18
1997–1999	82	47
2000–2002	104	42
2003–mid 2005	73	32
	Hawaii	
1982–1985	84	7 (<20 ppbv)
1986–1990	221	4
1991–1995	184	15
1996–1999	159	16
2000–2004	189	14
	Natal	
1979–1982	32	3 (<30 ppbv)
1990–1992	65	2
1997–2000	123	18
2001–2002	117	14
2003–mid 2005	103	5

Increases in frequency of low ozone events in the UT in the mid to late 1990s suggest increased convection

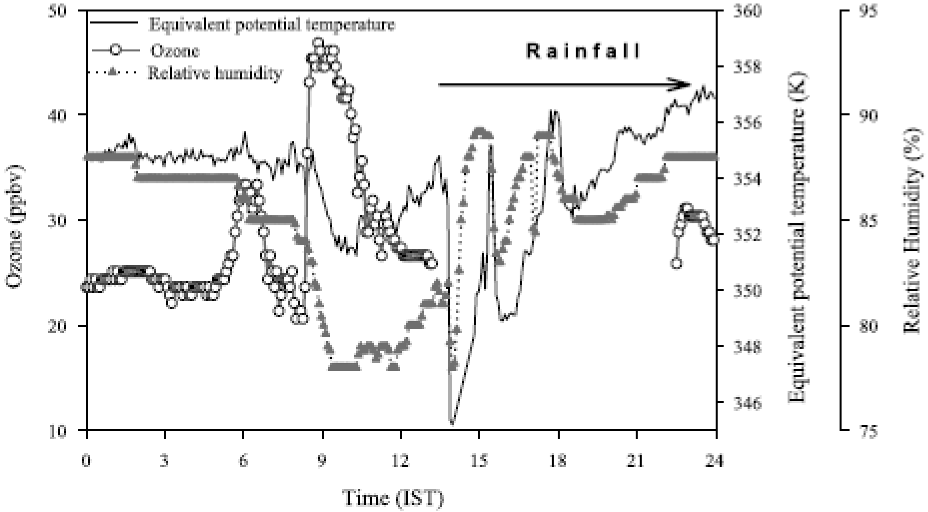
Solomon et al., 2005

Convective Downdrafts Transport Ozone Downward into PBL

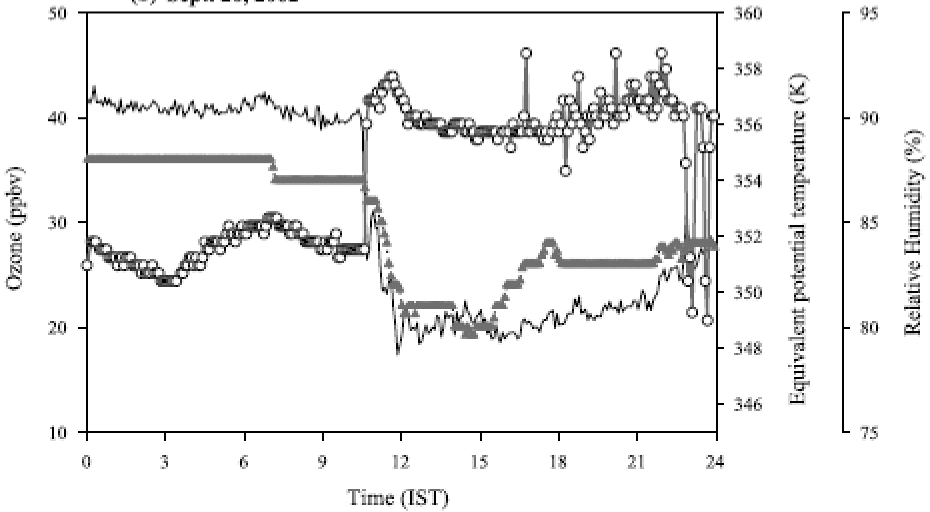


Betts et al., 2002
Rondonia, Brazil

(a) Sept. 25, 2002



(b) Sept. 26, 2002



Sahu and Lal, 2006
Bay of Bengal

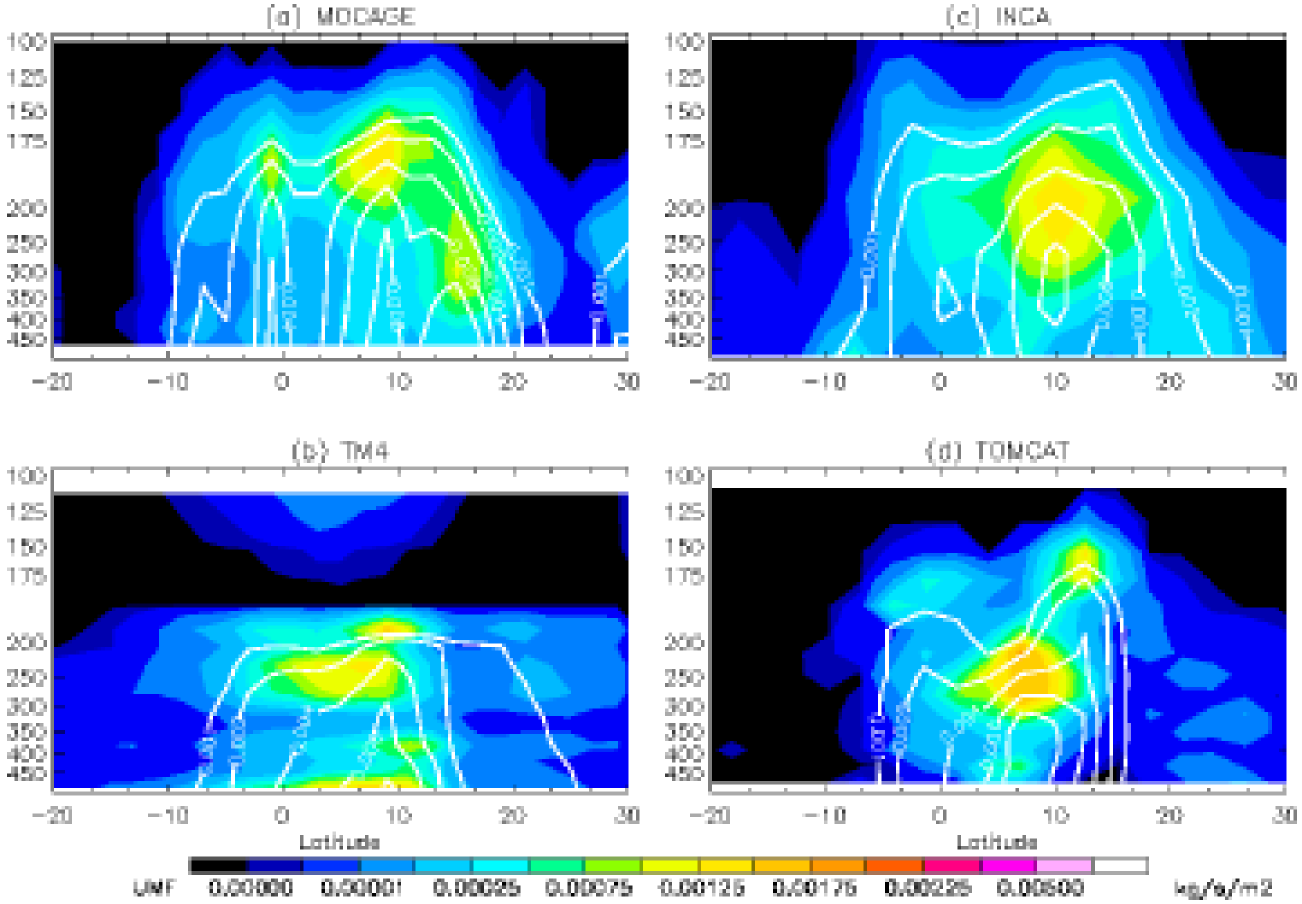
NET EFFECT OF CONVECTION ON TROPOSPHERIC OZONE

- **Lelieveld and Crutzen (1994) model calculations indicate that dominant effect of convection is to enhance ozone destruction**

- **Lawrence et al. (2003) with better treatment of convection and hydrocarbons found that convection caused an overall net increase of tropospheric ozone**

- **Doherty et al. (2005) found that convective overturning of ozone dominates over changes in ozone chemistry. Obtained a decrease in global tropospheric ozone burden with convection. Differences in convective and chemical schemes yield results in contrast to Lawrence et al. (2003)**

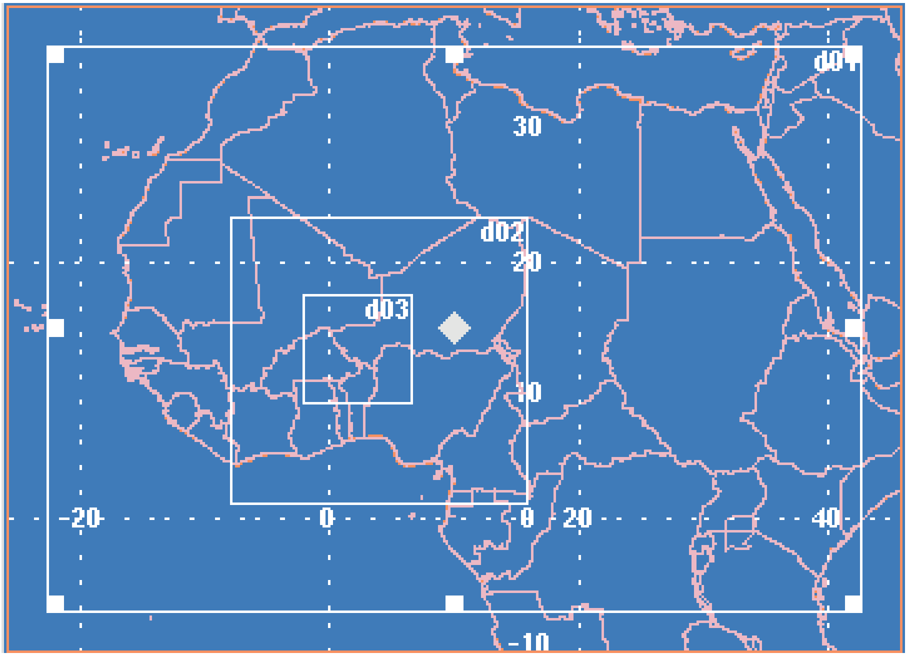
Convective Mass Flux and Detrainment During AMMA as Computed by Four Models



Averaged over 0 -30 deg. E
Colors – detrainment
White contours – upward convective mass flux

Barret et al., 2010

AMMA WRF Simulations



Resolutions: 18, 6 and 2 km

Grid size: 391x271, 424x412, 466x466, and 61 vertical layers

Δt = 18 seconds

Starting time: 00Z 08/06/2006

Initial and Boundary Conditions:

NCEP/GFS, no data assimilation

Physics:

- **Cu parameterization:**

  Kain-Fritsch scheme (for the outer grid only)

- **Cloud microphysics:**

  Goddard microphysics 3ice-Graupel

- **Radiation:**

  New Goddard radiation scheme for both longwave and shortwave

- **PBL parameterization:**

  Mellor-Yamada-Janjic TKE scheme

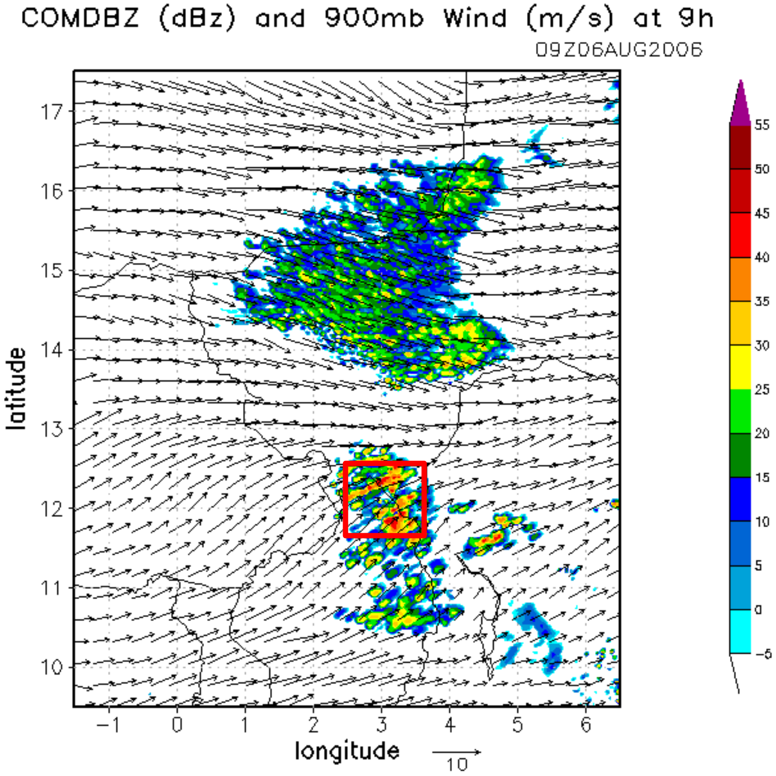
- **Surface Layer:**

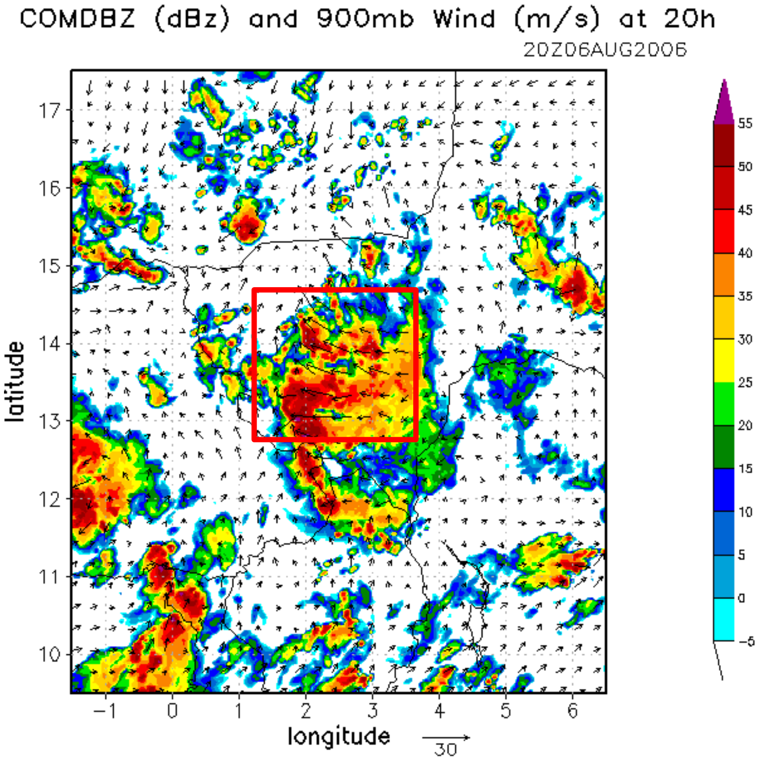
  Monin-Obukhov (Janjic)

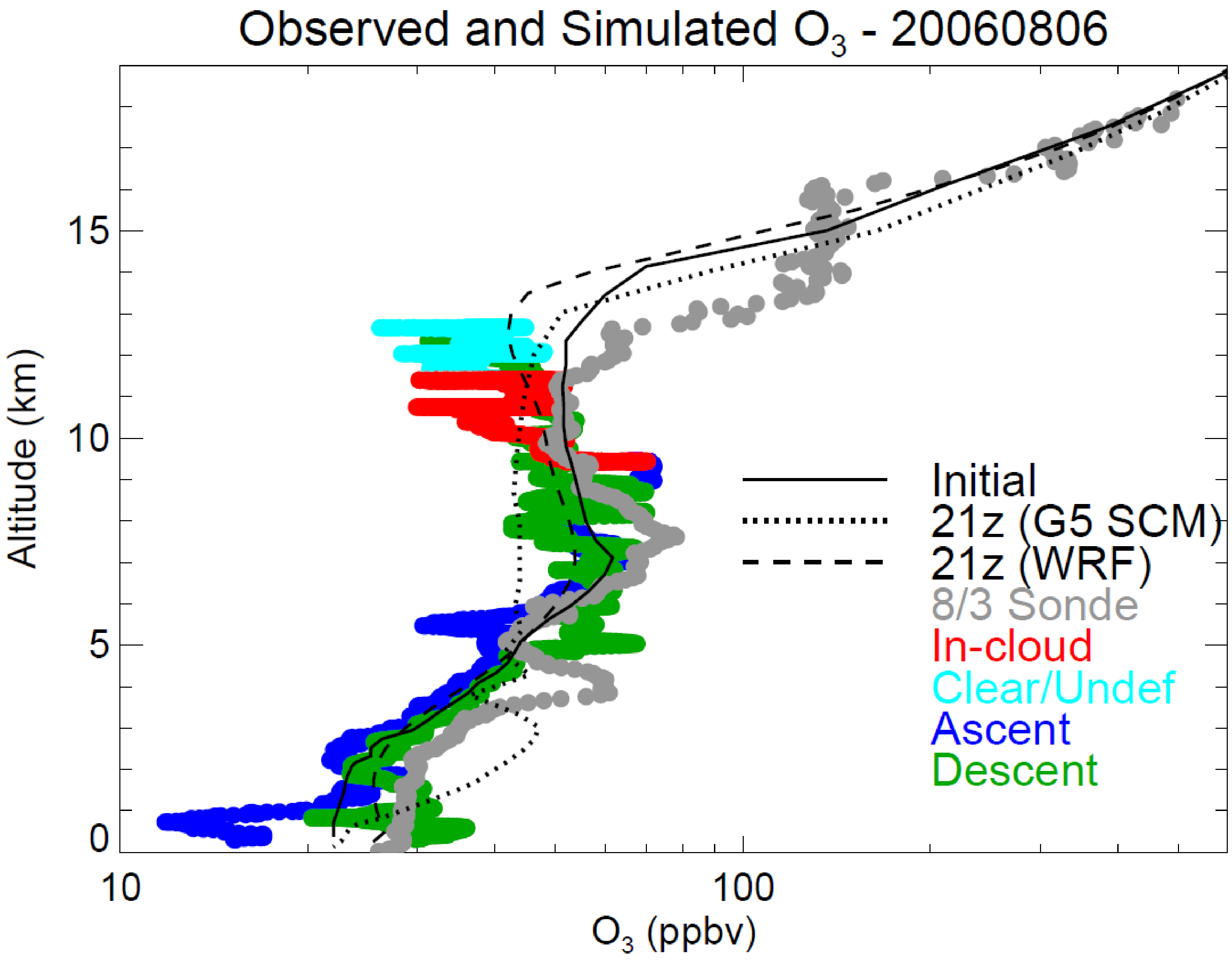
- **Land Surface Model:**

  Noah land-surface

WRF-Calculated Radar Reflectivity

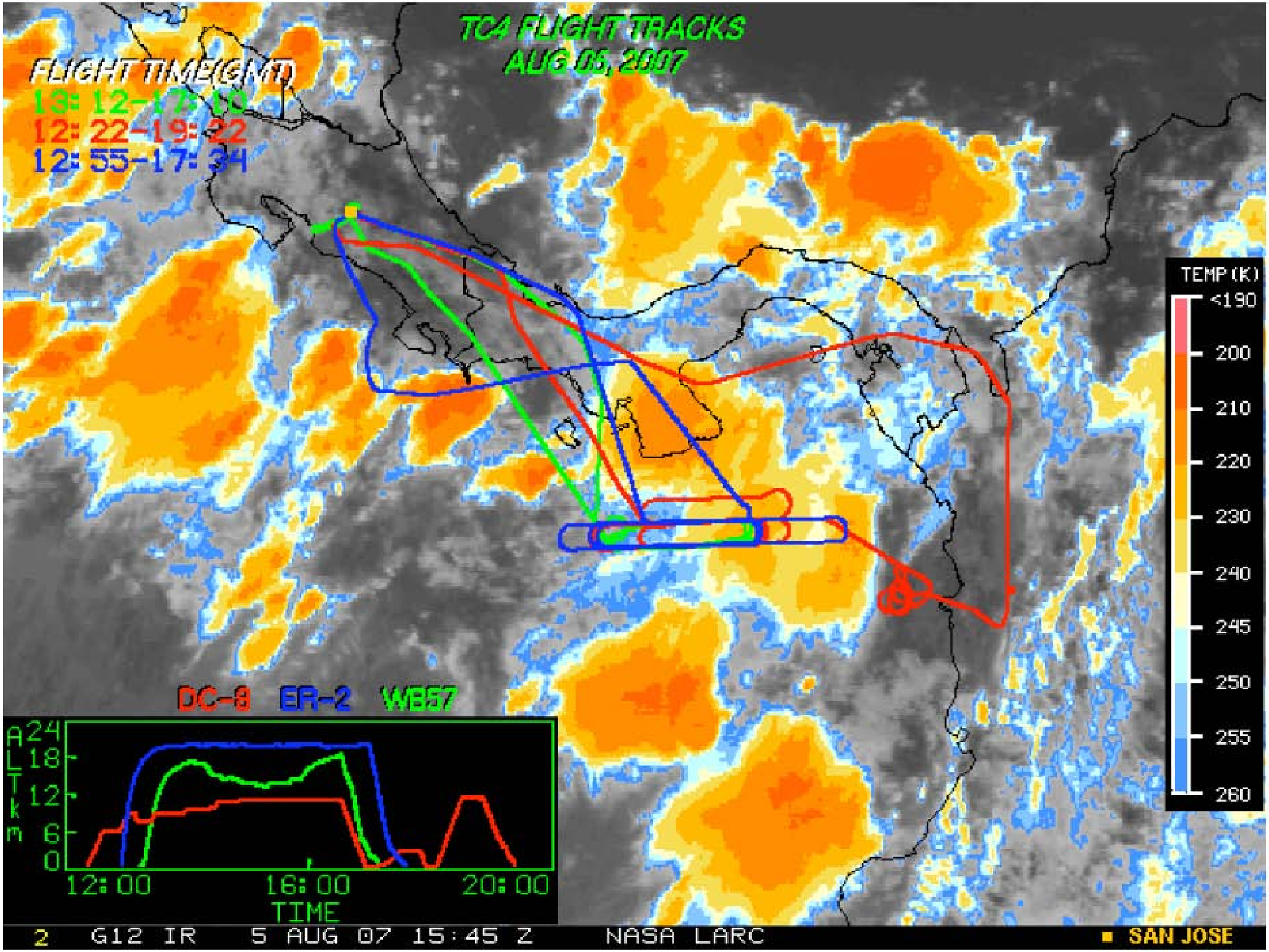




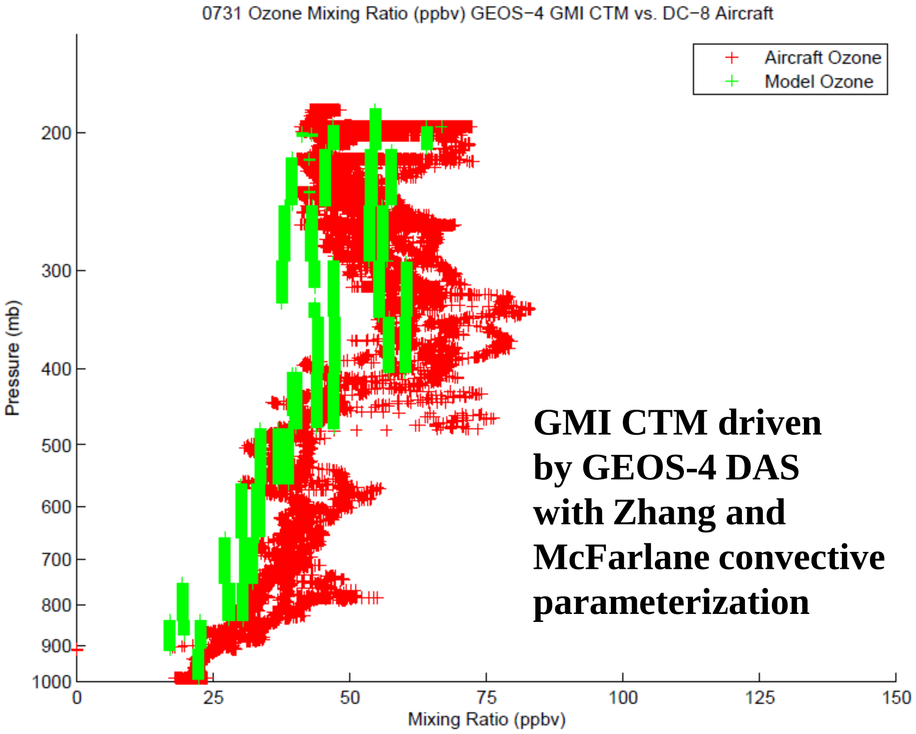


Observed and Simulated O_3 - 20060806

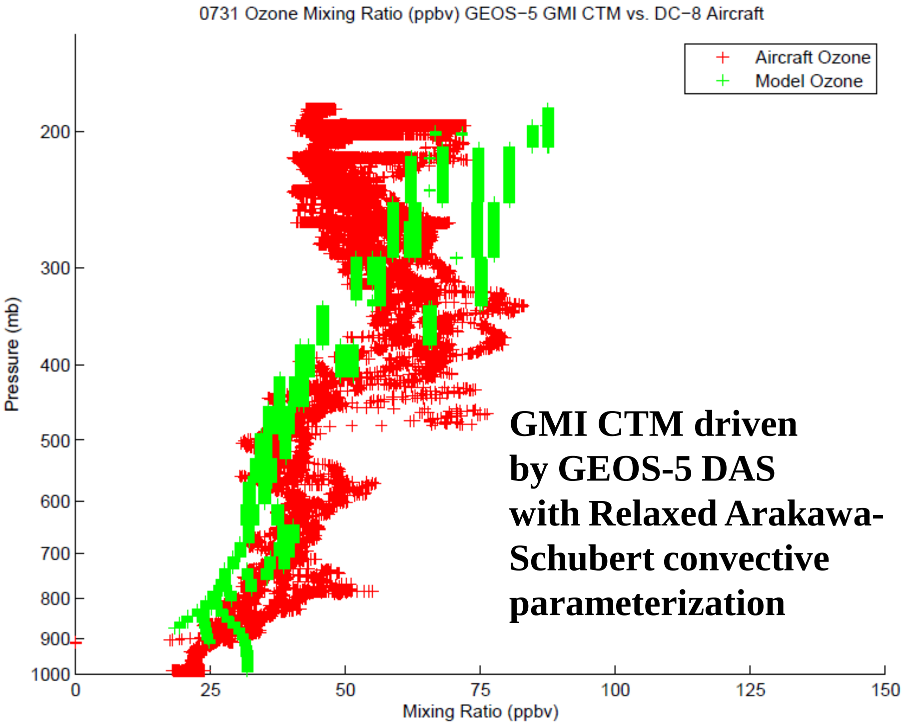
Tropical Composition, Cloud and Climate Coupling (TC4) – July/August 2007



Evaluation of Parameterized Convective Transport in the Offline NASA Global Modeling Initiative (GMI) Chemistry and Transport Model



GMI CTM driven by GEOS-4 DAS with Zhang and McFarlane convective parameterization



GMI CTM driven by GEOS-5 DAS with Relaxed Arakawa-Schubert convective parameterization

NASA DC-8 data from TC4 flight matched in time and with nearest grid cell in GMI model with deep convection

T. Lyons

Wet Scavenging

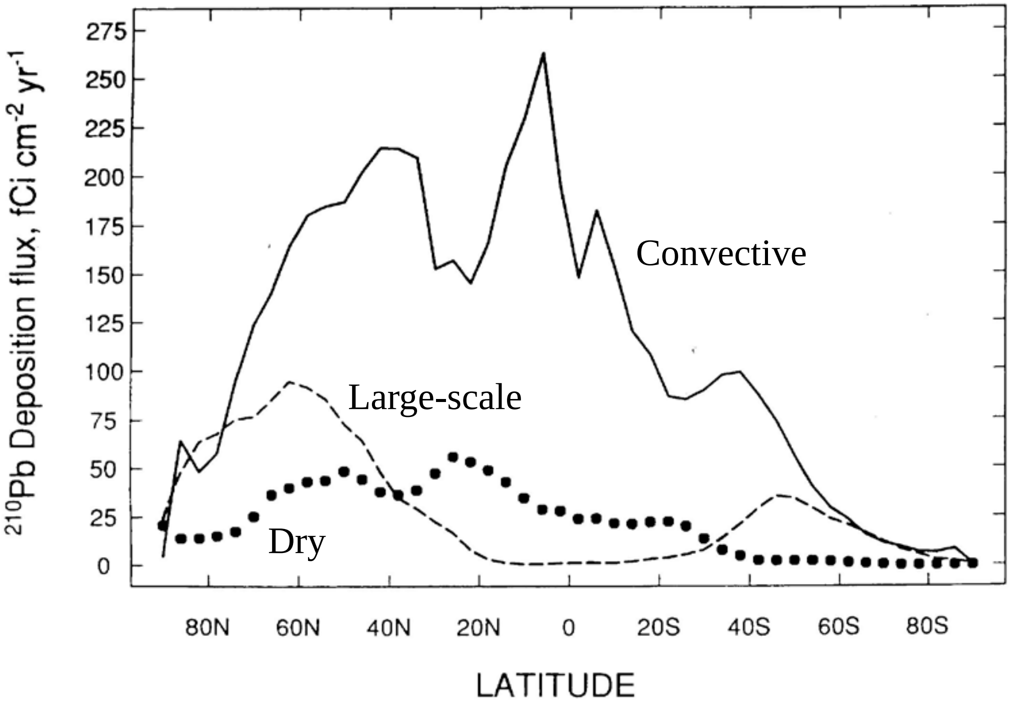
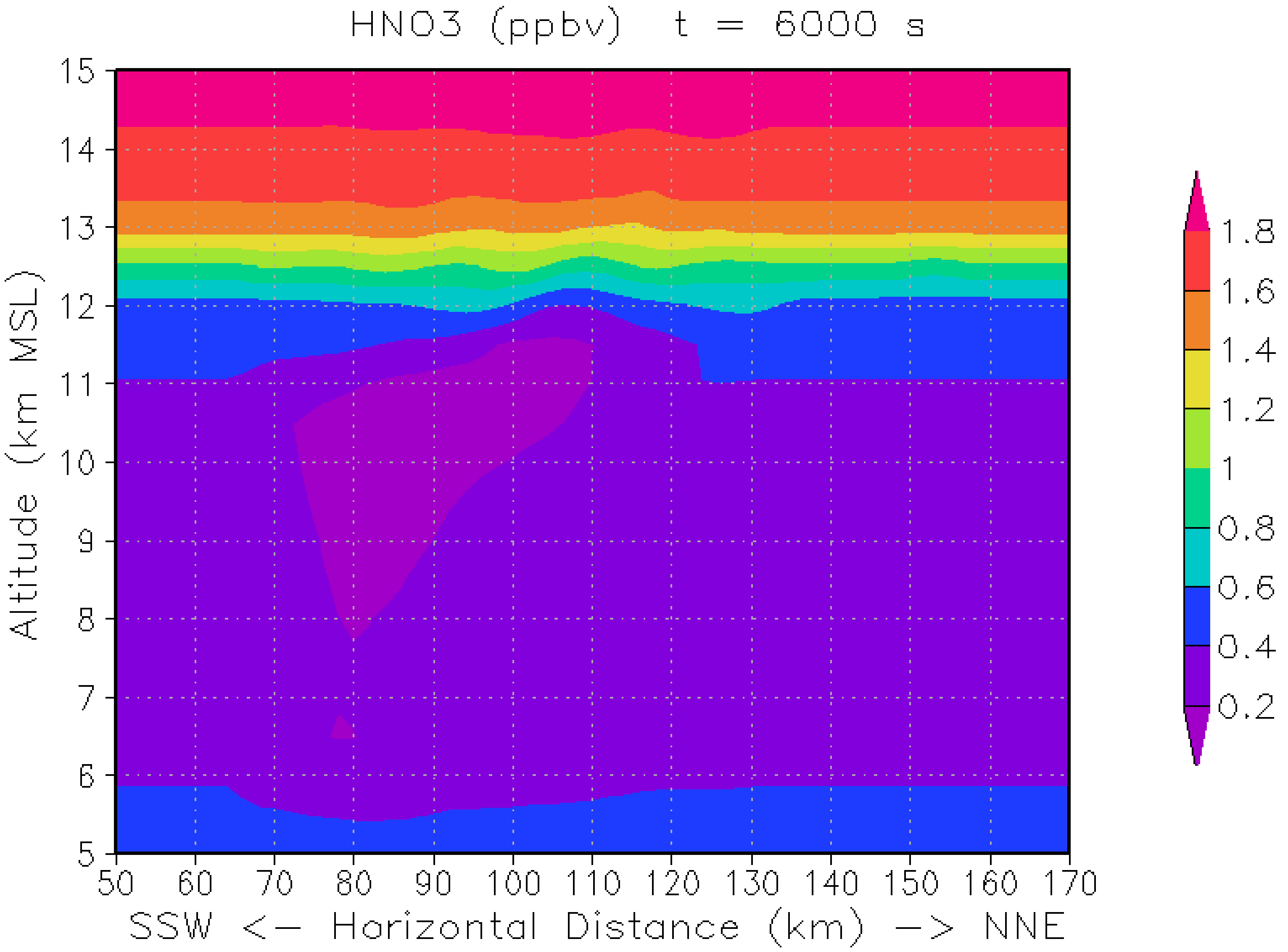


Fig. 2. Zonal mean deposition fluxes of ^{210}Pb in the model contributed by convective precipitation (solid line), large-scale precipitation (dashed line), and dry processes (dotted line). Values are yearly averages.

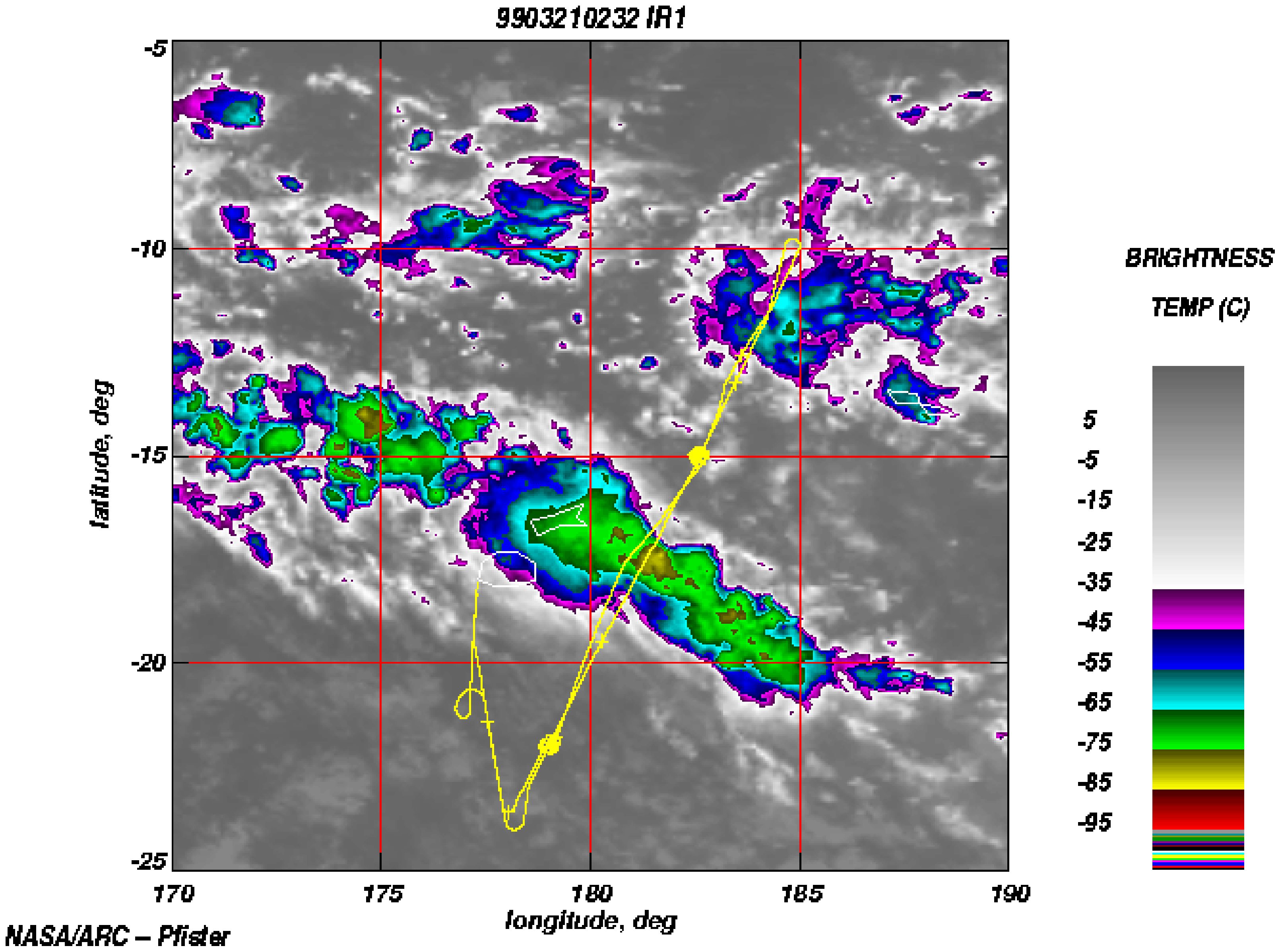
Balkanski et al. (1993)

July 10, 1996 STERAO storm



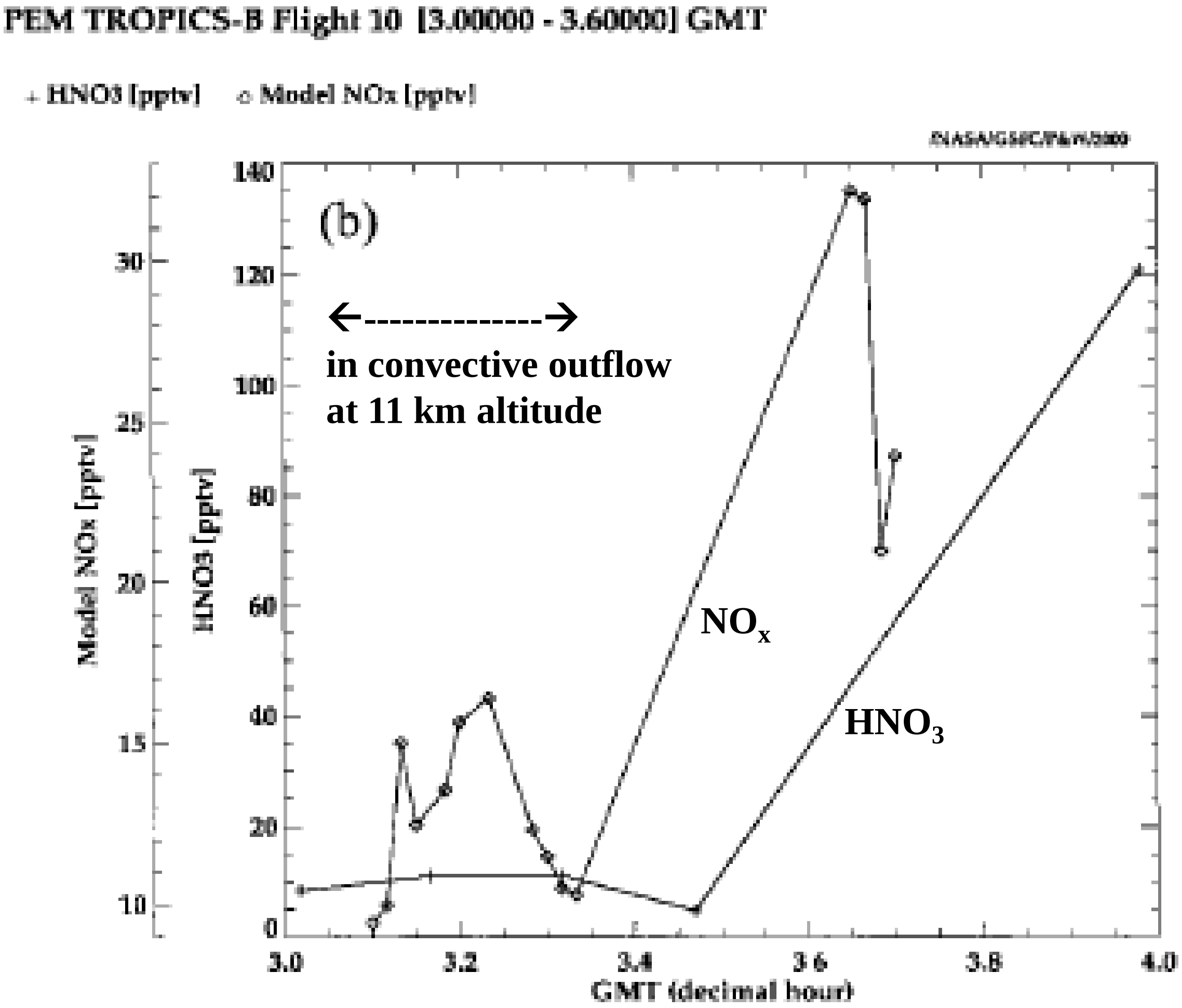
Ott et al., 2006

South Pacific Convergence Zone Convection Near Fiji



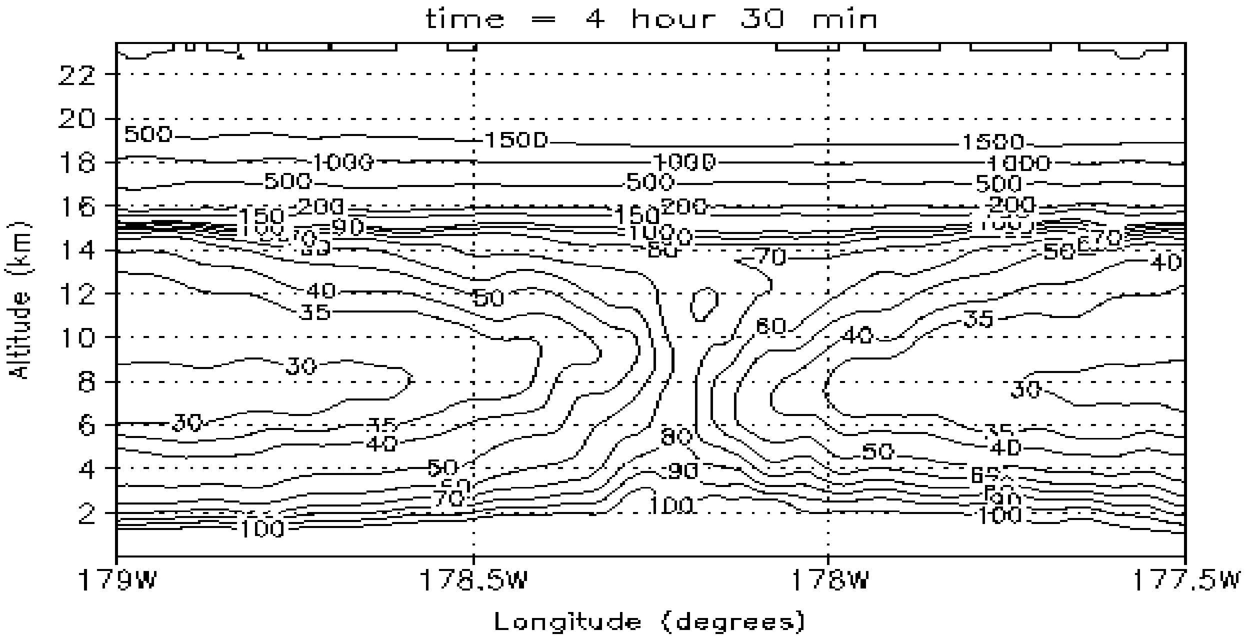
Pickering et al. (2001)

DC-8 Aircraft Measurements in SPCZ System



←-------------→
in convective outflow
at 11 km altitude

Pickering et al., 2001



HNO3 simulation for SPCZ convection

without wet scavenging (~80 pptv at 11 km)

Comparison with observations (~5-10 pptv) at 11 km

within storm suggest ~90-95% removal

Pickering et al., 2001

Lightning NO Production

- How much NO is produced per cloud-to-ground (CG) flash and per intracloud (IC) flash? Or per meter of flash length?

  Varies over two orders of magnitude

- How are lightning channels distributed throughout a storm?

  Some indication of bimodal distribution in the vertical

- How is the NO distributed in the vertical at the end of the storm?

  Mostly in middle and upper troposphere

How many flashes occur globally?

Satellite observations indicate ~44 flashes/s

How are the flashes distributed geographically?

At least 75% occur over continents

What is the IC/CG flash number ratio, and how does it vary from storm to storm?

Over continental U.S. annual mean varies from ~1.5 to ~10, with mean ~3

What is the global annual production ?

Literature estimates range from 2-20 Tg/yr

in the most recent decade, but 2-8 Tg/yr appears most likely

Motivation for Lightning NO Studies

- Production of NO by lightning is an important part of the tropospheric NO_x budget (tropical UT: >50-60%), but it is also the most uncertain component.
- In most of the free troposphere O_3 production rates are highly sensitive to NO_x mixing ratios.
- The maximum effectiveness of ozone as a greenhouse gas is in the UT/LS. Ozone is the third most important greenhouse gas.
- Global annual lightning NO production has been estimated to be 2-20 Tg N/yr, but recent observations and modeling have reduced the range to 2-8 Tg N/yr (Schumann and Huntrieser, 2007)
- Lightning observations from surface networks and satellites are being used in conjunction with cloud-resolving and global models in attempts to further reduce this uncertainty.

Requirements for Specifying Lightning NO Production in Global/Regional Chemical Transport and Climate Models

1) NO production per flash (DeCaria et al., 2000; 2005; Ott et al. (2006; 2007; 2010)

2) A method of specifying the effective vertical distribution of lightning NO_x at the end of a storm (e.g., Pickering et al., 1998; Ott et al., 2010).

3) Flash rates need to be estimated for the times and locations for which parameterized convection is active in the model (e.g., Allen and Pickering, 2002).

Methods of Estimating NO Production Per Flash

- **Theoretical estimates (e.g., Price et al., 1997)**
  - **6.7×10^{26} molecules/CG flash ~ 1100 moles/flash**
  - **6.7×10^{25} molecules/IC flash ~ 110 moles/flash**
- **Laboratory experiments (e.g., Wang et al., 1998)**
  - **6.2×10^{25} molecules/flash ~ 103 moles/flash**
- **Field experiments – anvil measurements by aircraft of NO from individual flashes and integrated effects (e.g., STERAO-A, EULINOX, CRYSTAL-FACE)**
- **Cloud-resolved models, lightning parameterizations, anvil measurements (e.g., Pickering et al., 1998; DeCaria et al., 2000; 2005; Ott et al., 2006; 2007; 2010)**
- **Cloud-resolved models with explicit electrophysics**
- **Satellite-based NO_2 observations and flash counts (Bucsela et al., 2010)**

Cloud-Resolved Model Lightning Placement Parameterization

NO production by lightning injected into the model based on either observed flash rates or flash lengths.

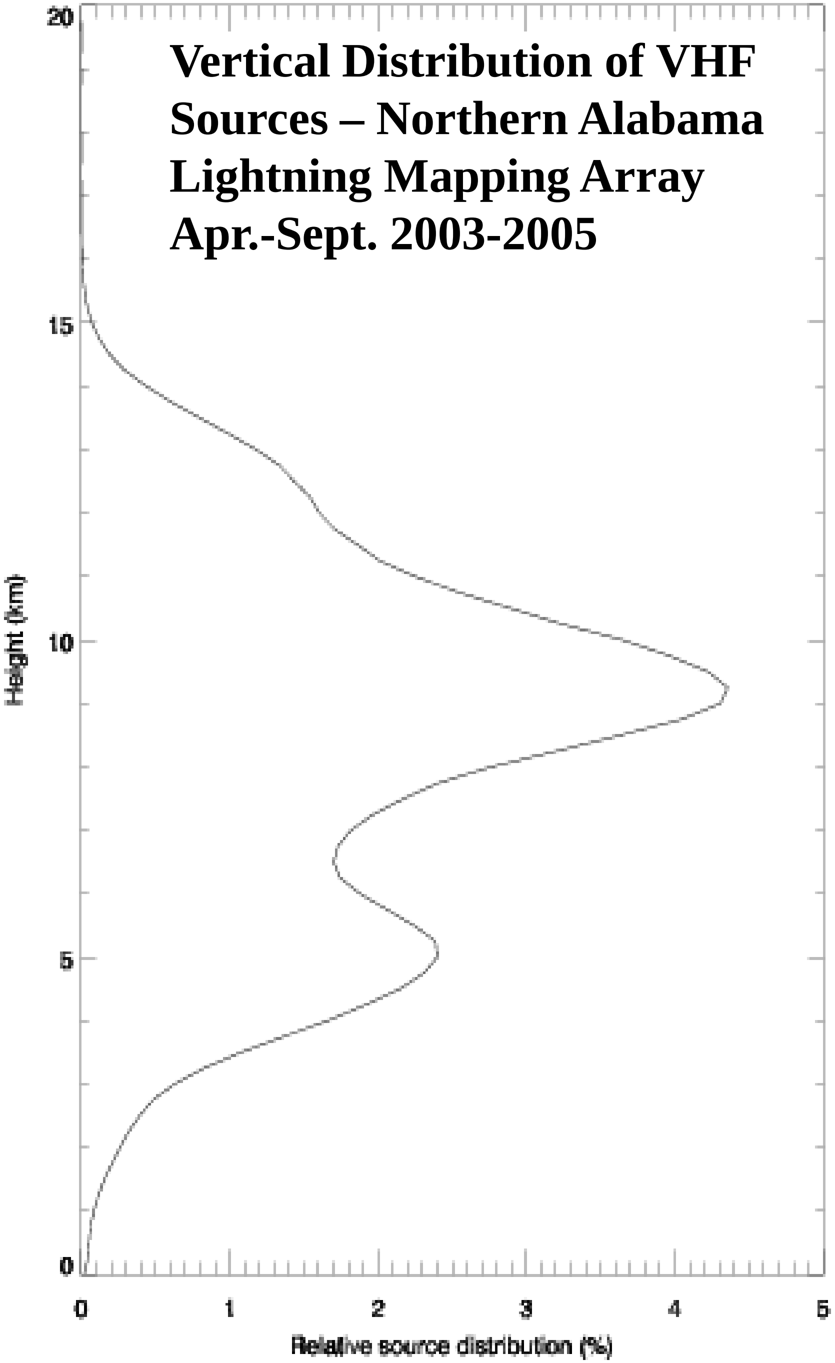
Flash Rate Scheme

- Lightning NO production is calculated using observed CG and IC flash rates over 3-minute periods and specified production of NO per CG and per IC flash.

- NO production is assumed to be proportional to pressure and to the vertical distribution of lightning channel segments which is assumed to be bimodal.

- In each model layer, lightning NO production is distributed uniformly within the 20 dBZ contour.

Vertical Distribution of VHF Sources – Northern Alabama Lightning Mapping Array Apr.-Sept. 2003-2005



Similar shape factors used in cloud/chemistry model along with assumption of NO production being proportional to pressure

D. Buechler, NASA/MSFC

NO Production Parameterization

Make initial estimate of P_{CG} using Price et al. (1997) equation: $P_{CG} = E_{CG}\,P$

where $E_{CG} = 1.823 \times 10^5\, I_o$ Joules

$P = 1 \times 10^{17}$ molecules NO/Joule

I_o = peak current from observations

Let $P_{IC} = \alpha\, P_{CG}$ and test production scenarios with various values of α. Compare simulation results with anvil NO_x observations in terms of :

1) mean anvil profile (peak value, shape)

2) probability distributions at specific altitudes

3) anvil column mass

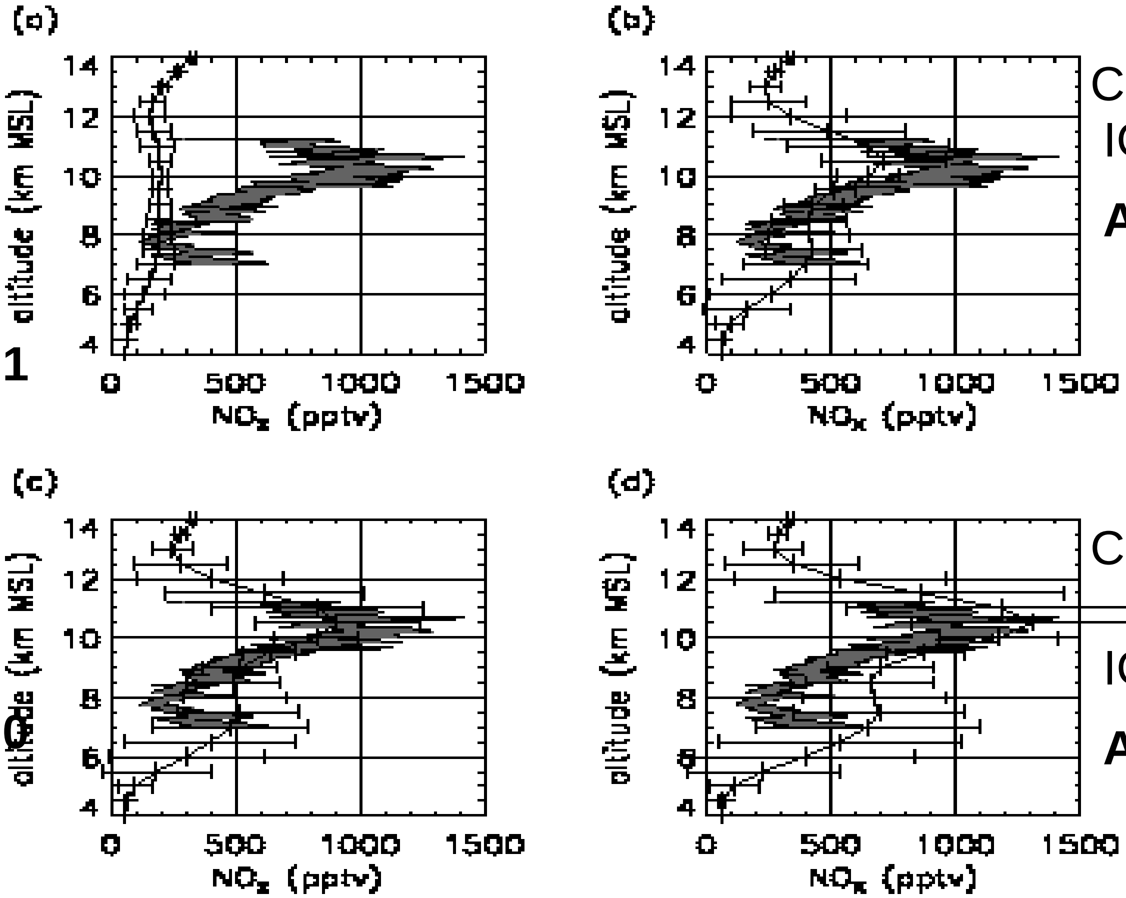
Simulated Storms

Storm	Location	References
STERAO - 7/12/96	NE Colorado	DeCaria et al.(2000, JGR; 2005, JGR)
STERAO – 7/10/96	NE Colorado	Ott et al. (2010, JGR)
EULINOX – 7/21/98	Bavaria	Ott et al. (2007, JGR)
		Fehr et al. (2004, JGR)
CRYSTAL-FACE		
7/29/02*	S. Florida	Ott et al. (2006;
7/16/02**	S. Florida	2010, JGR)

* Run using MM5

** Run using ARPS

July 12, 1996 STERAO-A Storm – NE Colorado



CG: 460
IC:46
Moles NO
Per Flash

Alpha = 0.1

CG: 460
IC: 345

Alpha = 0.75

CG: 460

IC: 460

Alpha = 1.0

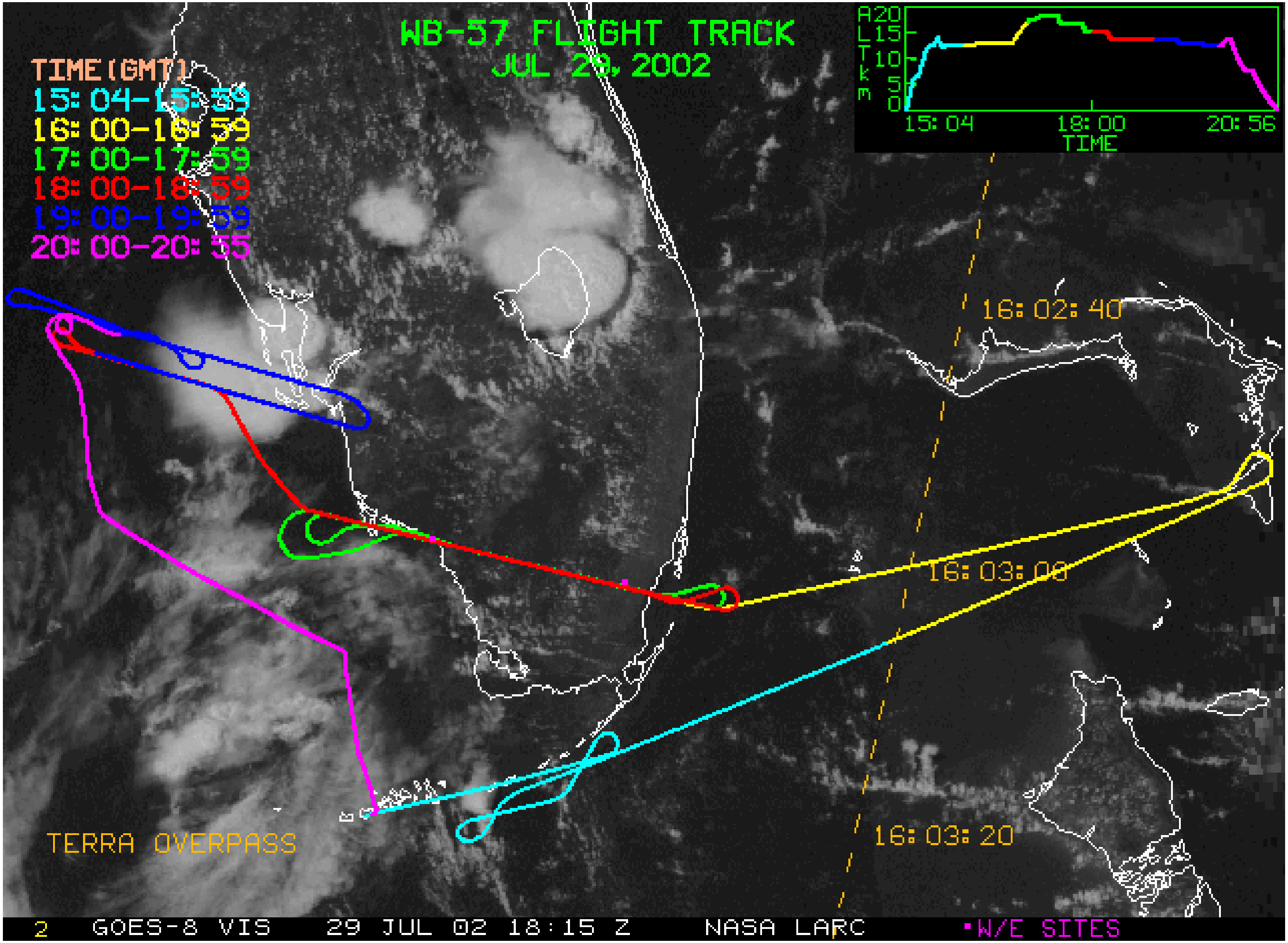
CG: 460

IC: 690

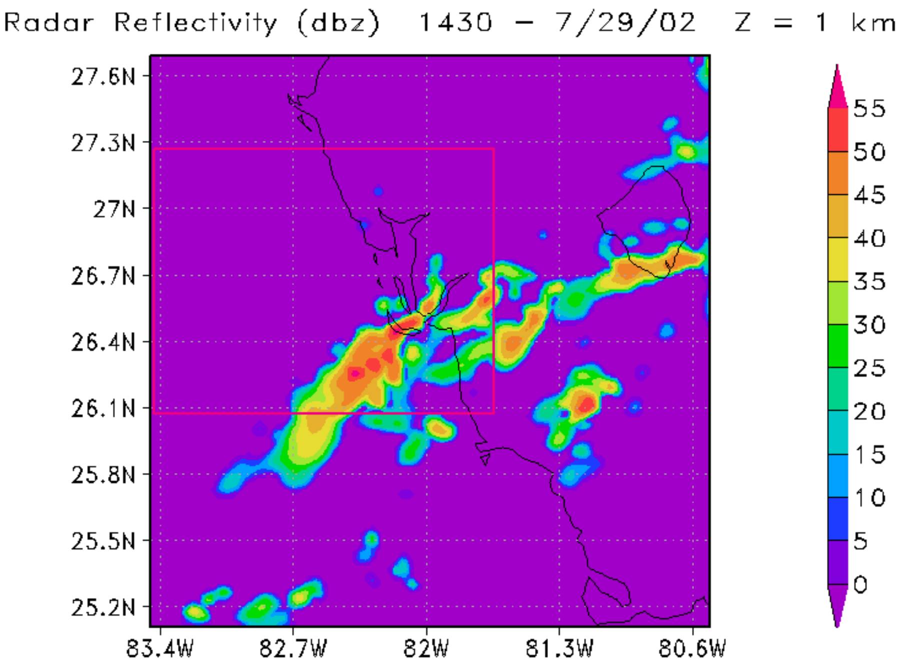
Alpha = 1.5

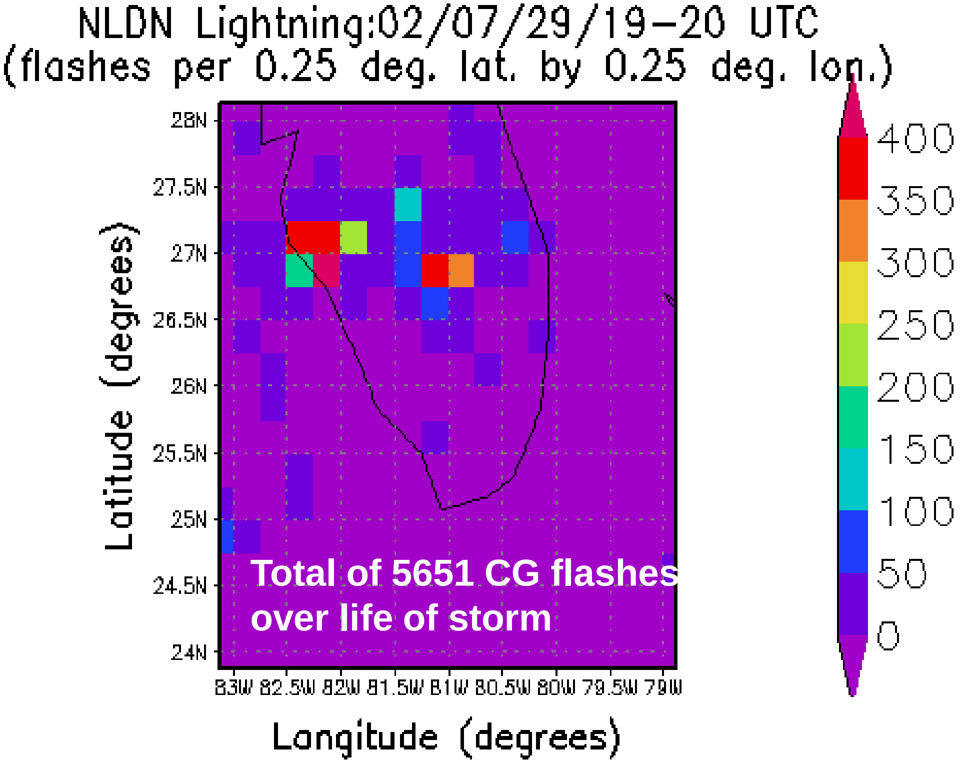
Model-simulated vs. Measured NOx Profiles
For Four Lightning NO Production Scenarios
DeCaria et al. (2005)

NASA CRYSTAL-FACE



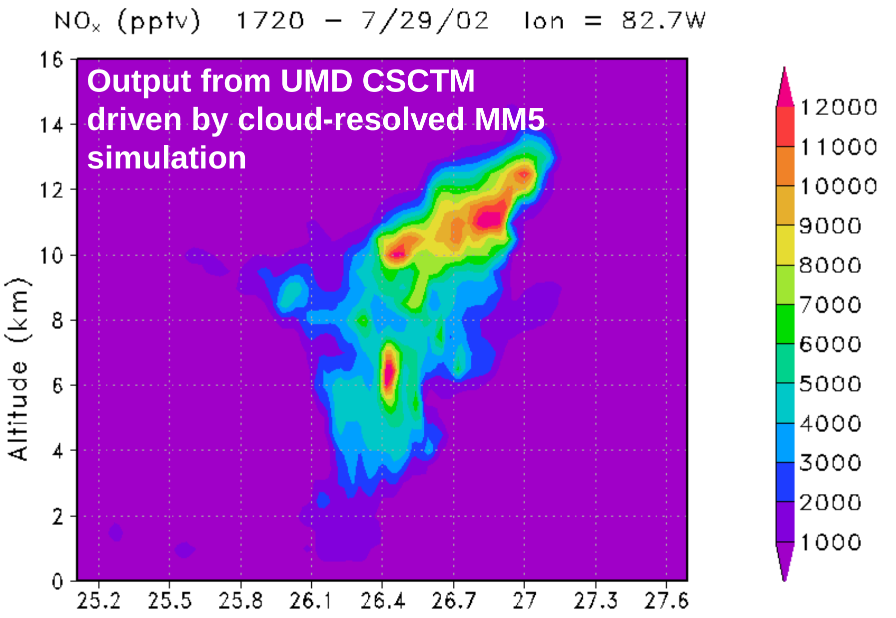
From MM5 simulation run at 2-km horiz. res.



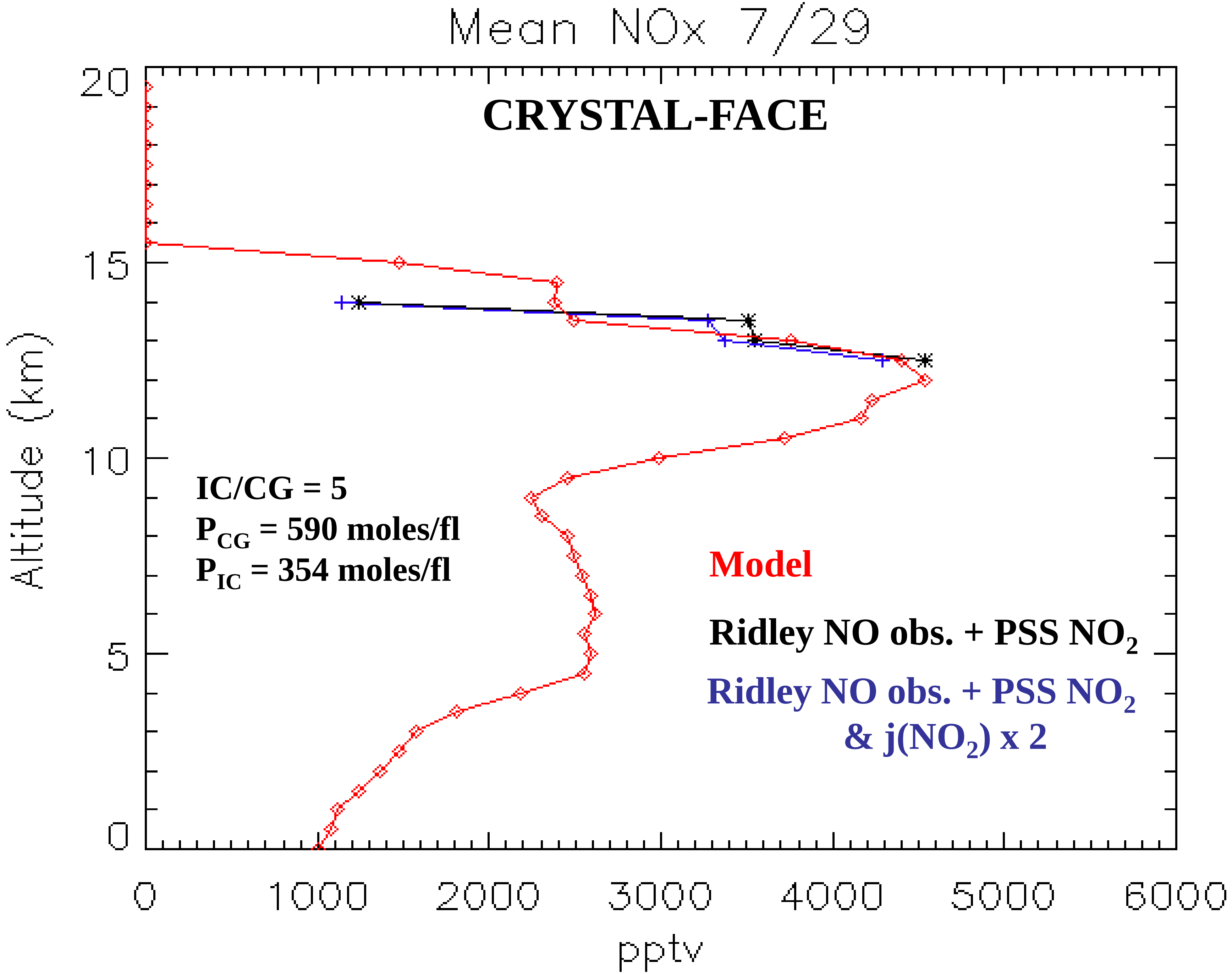


Total of 5651 CG flashes over life of storm

CRYSTAL-FACE
South Florida
July 29, 2002



Output from UMD CSCTM driven by cloud-resolved MM5 simulation



CRYSTAL-FACE

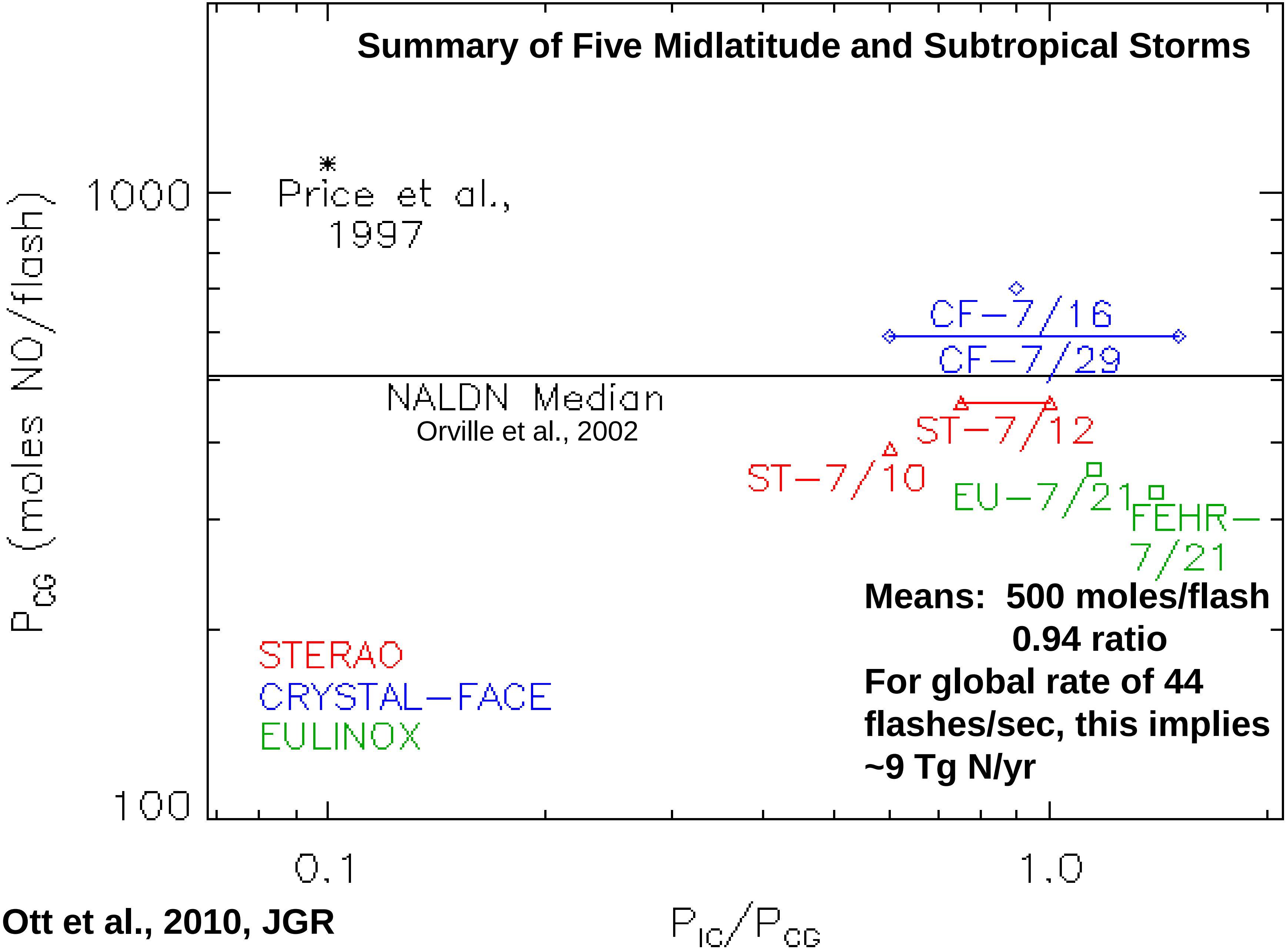
IC/CG = 5
P_{CG} = 590 moles/fl
P_{IC} = 354 moles/fl

Model

Ridley NO obs. + PSS NO_2

Ridley NO obs. + PSS NO_2
& $j(NO_2)$ x 2

Lightning NO Production Scenarios



Summary of Five Midlatitude and Subtropical Storms

Means: 500 moles/flash
0.94 ratio
For global rate of 44 flashes/sec, this implies ~9 Tg N/yr

Ott et al., 2010, JGR

Vertical Distribution of Lightning NO_x

- Analysis performed by Pickering et al. (1998, JGR) using 2-D cloud/transport model with simple lightning parameterization. These profiles have been used in many regional/global CTMs.

- New calculations of vertical profiles using output from 3-D CSCTM containing a more realistic lightning parameterization have been performed for five midlatitude and subtropical events (Ott et al., 2010). Now used in NASA GMI CTM.

NO Production in Midlatitude, Subtropical, and Tropical Flashes

- Cloud-resolved modeling of observed midlatitude and subtropical storms yields an average of ~500 moles NO per flash (both CG and IC).
- This result is supported for North America by GEOS-Chem model simulations by Hudman et al. (2007, *JGR*) for the ICARTT period of 2004 evaluated with NASA DC-8 data and by Jourdain et al. (2008, *ACPD*) evaluated with TES O_3 data.
- Huntrieser et al. (2008, *ACP*) has hypothesized that on average a tropical flash may produce less NO than a flash in a midlatitude or subtropical storm. This may be due to lesser vertical wind shear in the tropics, leading to shorter flash channel lengths.
- Recent tropical experiments will aid in obtaining improved estimates of LNO_x production per flash

TROCCINOX	São Paulo State, Brazil	Feb. 2005
SCOUT-O3/ACTIVE	Darwin, Australia	Nov 2005 – Jan 2006
AMMA	West Africa	Aug. 2006
TC^4	Costa Rica, Panama	July – Aug. 2007

TC^4 = Tropical Composition, Cloud and Climate Coupling

Hector Simulations

- **Cloud-resolved chemistry simulation of “Hector” storm observed over Tiwi Islands near Darwin, Australia during the SCOUT-O3 and ACTIVE field experiments. Goal: Estimate LNOx production per flash.**

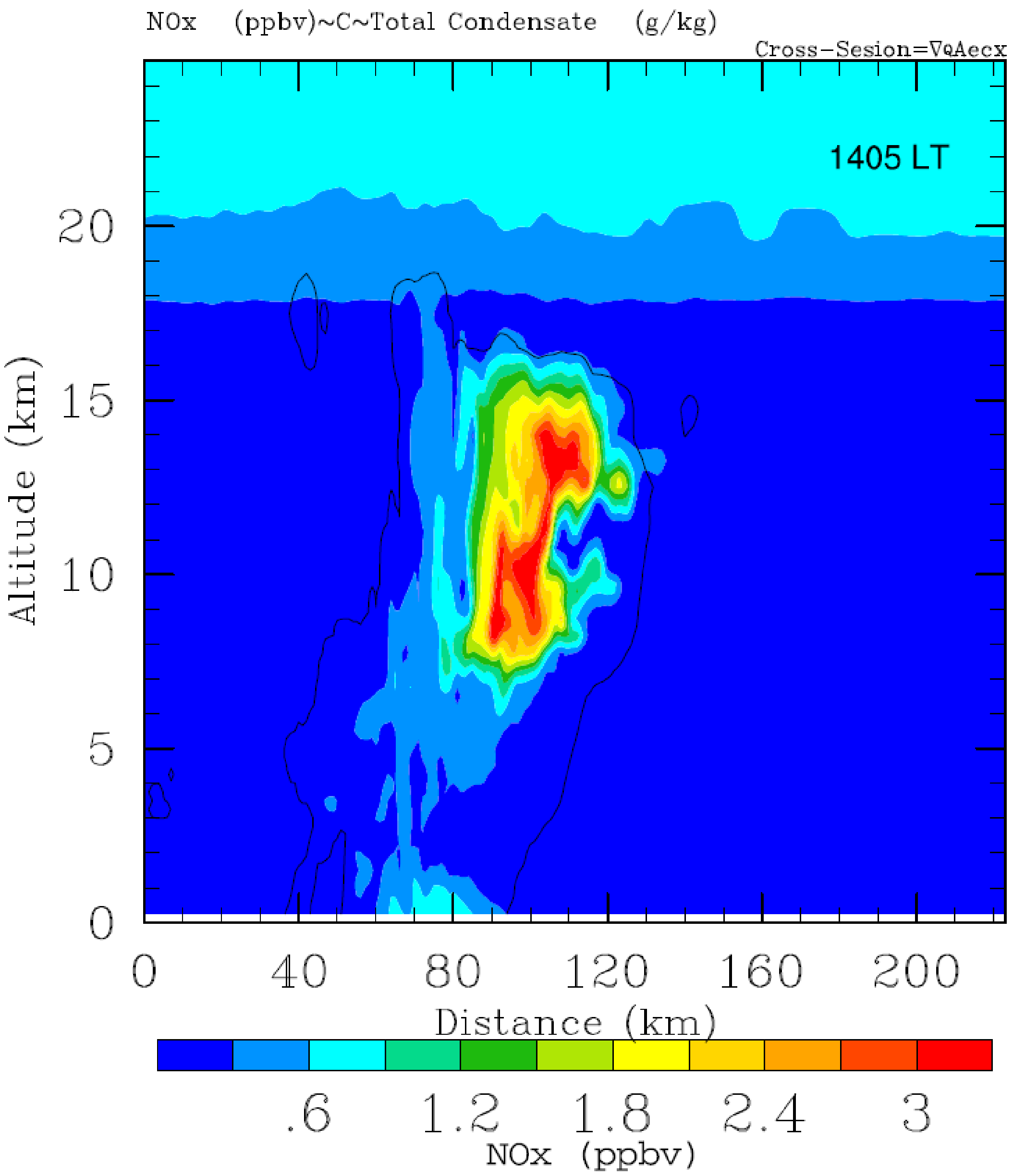
- **“Hector” thunderstorm is simulated with the WRF-AqChem cloud-resolving model (Barth et al., 2007) at 1-km horizontal resolution, and cloud simulation is evaluated with radar, satellite, and aircraft data**

- **Trace gases are transported and chemical reactions are computed on-line in the cloud simulation. Same lightning scheme as in GCE/CSCTM.**

- **How does NO prod. per flash in Hector storm compare with that in higher latitude storms? Run simulation with assumption of 500 moles/flash.**

- **Work in progress!**

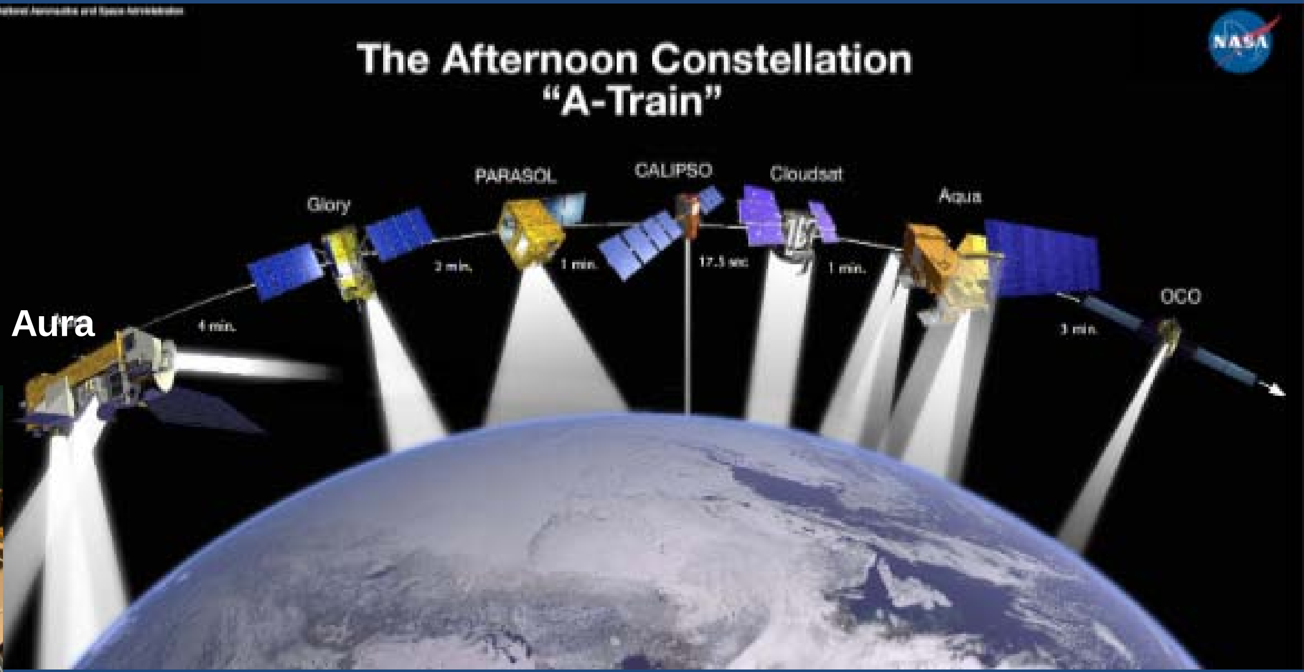
Hector WRF-AqChem simulation with Lightning NOx

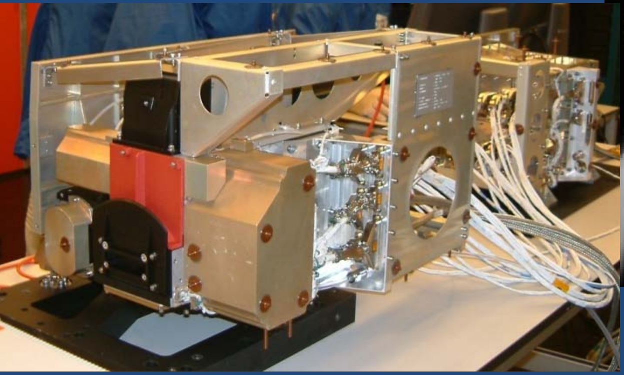


K. Cummings

Aura/OMI

Ozone Monitoring Instrument





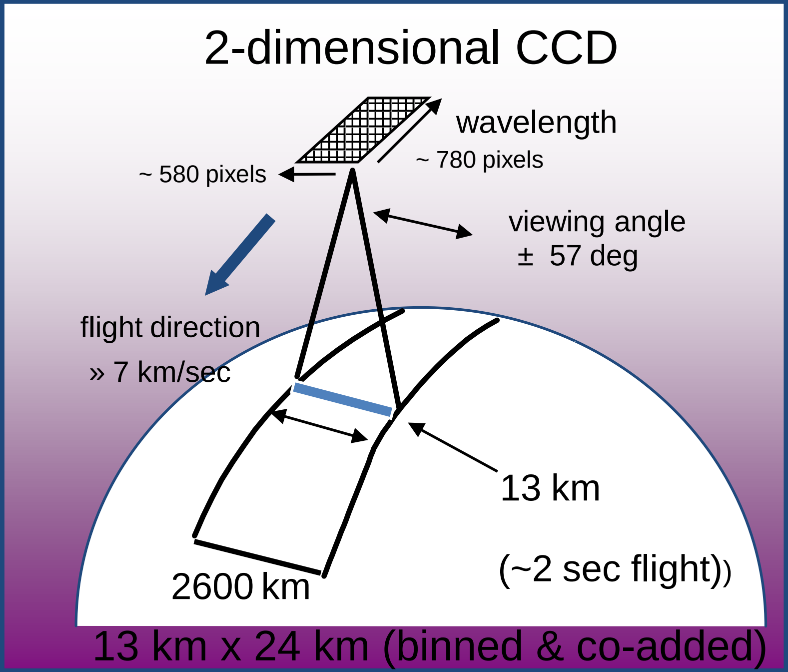
Wavelength range: 270 – 500 nm

Sun-synchronous polar orbit;
Equator crossing at 1:30 PM LT

2600-km wide swath; horiz. res.
13 x 24 km at nadir

Global coverage every day

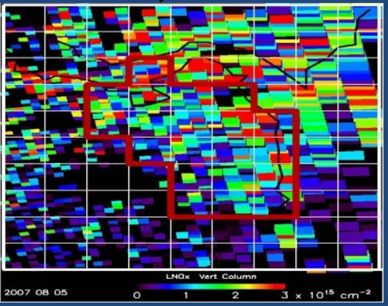
O_3, NO_2, SO_2, HCHO, aerosol,
BrO, OClO



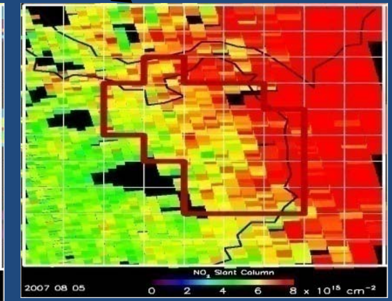
Analysis of LNO_x from OMI

The vertical column of NO_x due to lightning is:

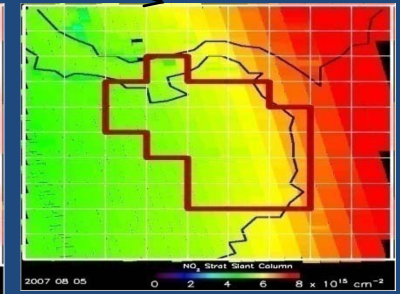
$$V_{LNOx} = [\, S - \underline{(V_S - V_{tCorr}) \cdot A_S} - \underline{V_{tBG} \cdot A_{tBG}} \,] \;/\; A_{tL}$$



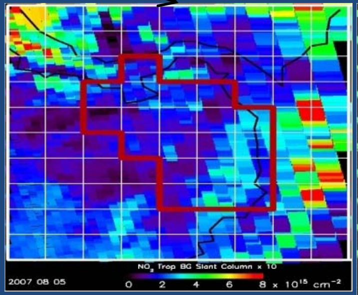
LNOx
vertical column



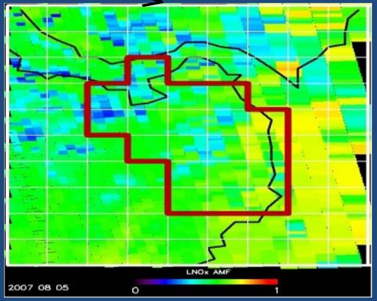
NO_2 total
slant column



NO_2 stratospheric
slant column (corrected)



10 x NO_2 tropospheric
background slant column



LNOx air mass factor

V_S = OMI-derived stratospheric NO2 vertical column ("clean" region data with wave-2 pattern imposed)

V_{tCorr} = GMI model correction (about ~10%) of V_S for tropospheric contamination

V_{tBG} = GMI model tropospheric background in region of lightning measurement

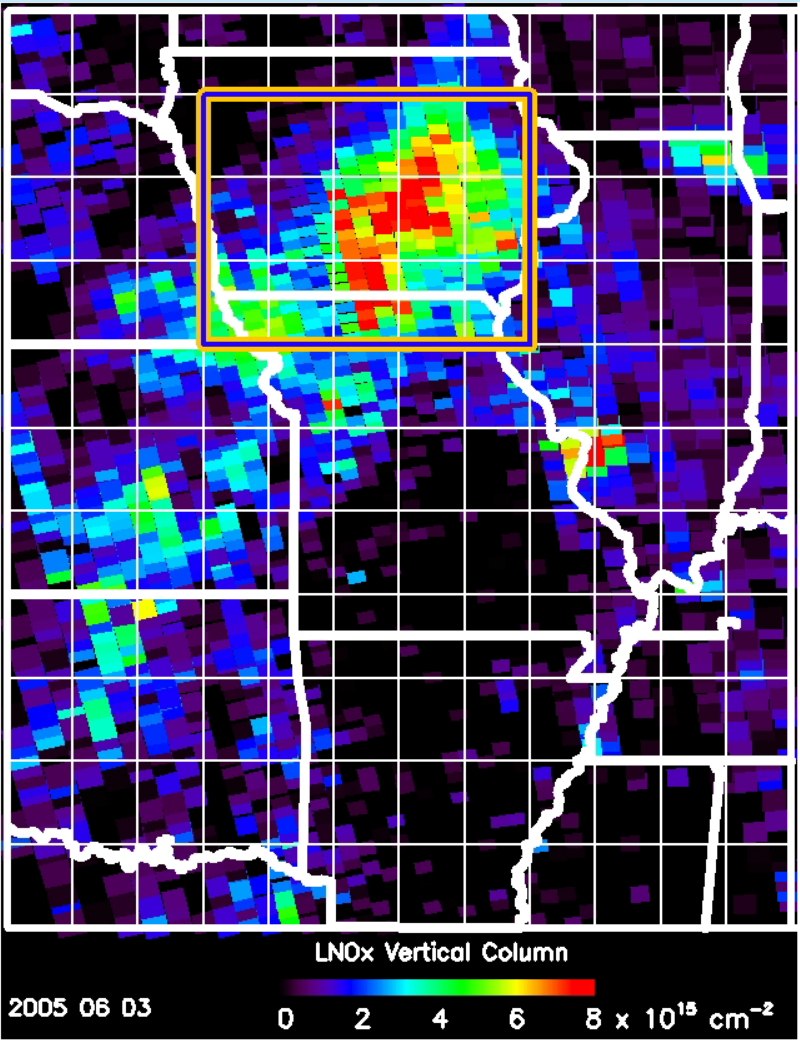
Analysis of Results from TC4 cases

Day	LNO_x (moles/flash)	300 hPa NCEP wind (m/s)
7/31	246 ± 287	8
8/5	227 ± 223	14
7/17	87 ± 252	4
7/21	135 ± 114	2

Smaller LNO_x production per flash is associated with weaker upper tropospheric wind speeds in these example cases.

Perhaps lesser flash length associated with weaker anvil-level winds?

Case 1: Production Per Flash



Summing LNOx over the box and adjusting for 2 – 4 day chemical lifetime (7.2% decay in this case) we obtain:

8452 ± 4858 kmoles

Dividing by vertically mass-weighted flash count of 15,829 flashes yields:

534 ± 351 moles LNOx per flash

Vertical Distribution of Lightning NO_x

- **Analysis performed by Pickering et al. (1998, JGR) using 2-D cloud/transport model with simple lightning parameterization. These profiles have been used in many regional/global CTMs.**

- **New calculations of vertical profiles using output from 3-D CSCTM containing a more realistic lightning parameterization have been performed for five midlatitude and subtropical events (Ott et al., 2010). Now used in NASA GMI CTM.**

- **Direct use of vertical profiles derived from 3-D Lightning Mapping Array data being used in CMAQ and WRF-Chem regional models.**

Summary

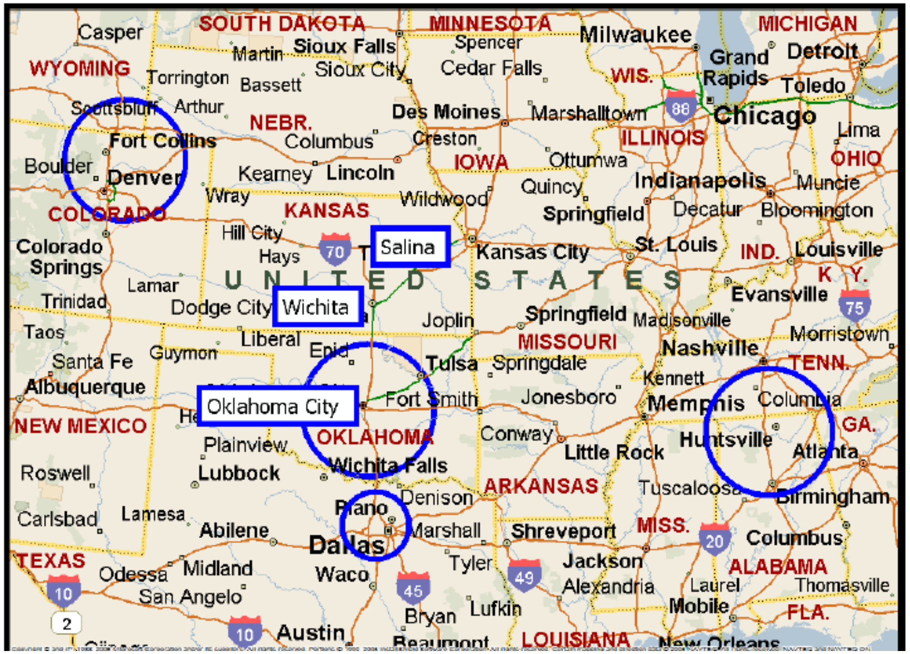
- Convection is an effective mechanism for transporting pollution from the boundary layer to the upper troposphere where it can more readily contribute to intercontinental transport.
- As a result, ozone production is enhanced, contributing to enhanced radiative forcing.
- Ozone destroyed as a result of remote marine convection.
- Net effect of convection on tropospheric O_3 remains uncertain.
- Lightning is a major contributor to the upper tropospheric NO_x budget and to ozone production.
- On a per flash basis, IC flashes are nearly as productive of NO as CG flashes. For five simulated storms, estimates of mean NO production per flash vary by a factor of two.
- Approximately 500 moles NO produced per flash on average over the five midlatitude and subtropical storms → ~9 Tg N/yr. Simulations of tropical events in progress.

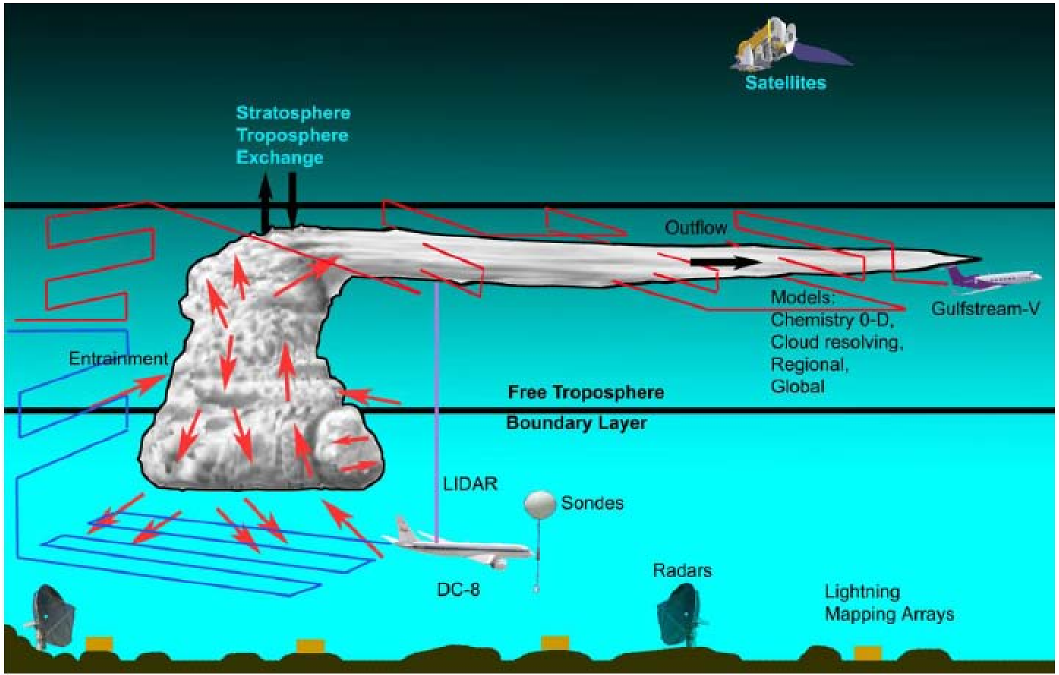
Future Research

- Lightning NO - need more field projects with comprehensive data collection (radar, 3-D lightning flash mapping, chemistry)
- Ozone measurements downstream of convection to evaluate model estimates of ozone production
- Wet scavenging - better 3-D precipitation fields needed for use in CTMs; measurements of soluble species in cloud-scale field experiments
- Aerosol effects on convective strength and lightning
- Studies of new particle production in convective outflows
- Evaluation and improvement of convective parameterizations in regional and global models

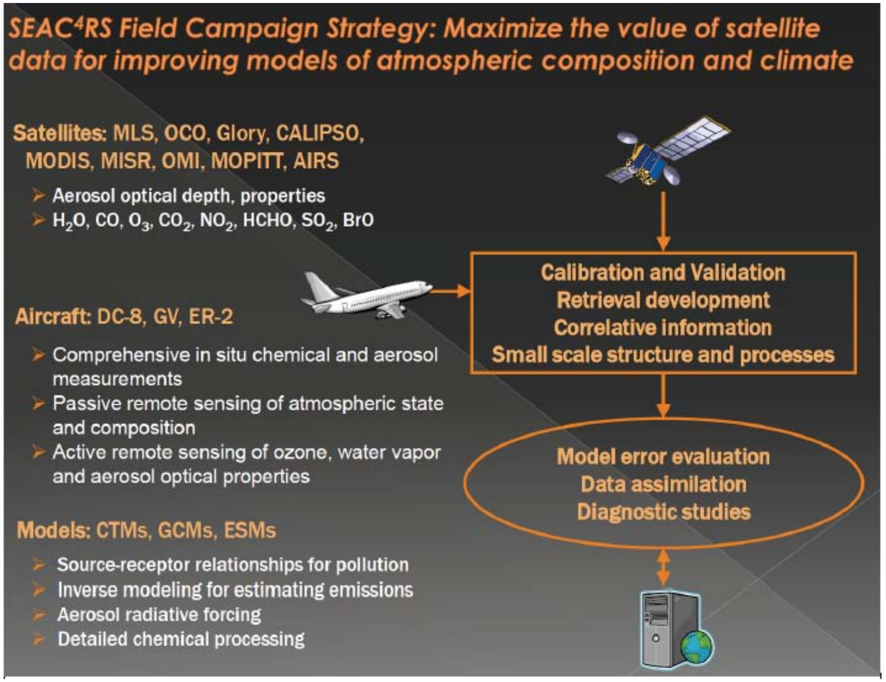
Deep Convective Clouds and Chemistry – DC3

May/June 2012





Southeast Asia Composition, Cloud, Climate Coupling Regional Study (SEAC4RS)



SEAC^{4}RS Field Campaign Strategy: Maximize the value of satellite data for improving models of atmospheric composition and climate

Satellites: MLS, OCO, Glory, CALIPSO, MODIS, MISR, OMI, MOPITT, AIRS

- Aerosol optical depth, properties
- H_2O, CO, O_3, CO_2, NO_2, HCHO, SO_2, BrO

Aircraft: DC-8, GV, ER-2

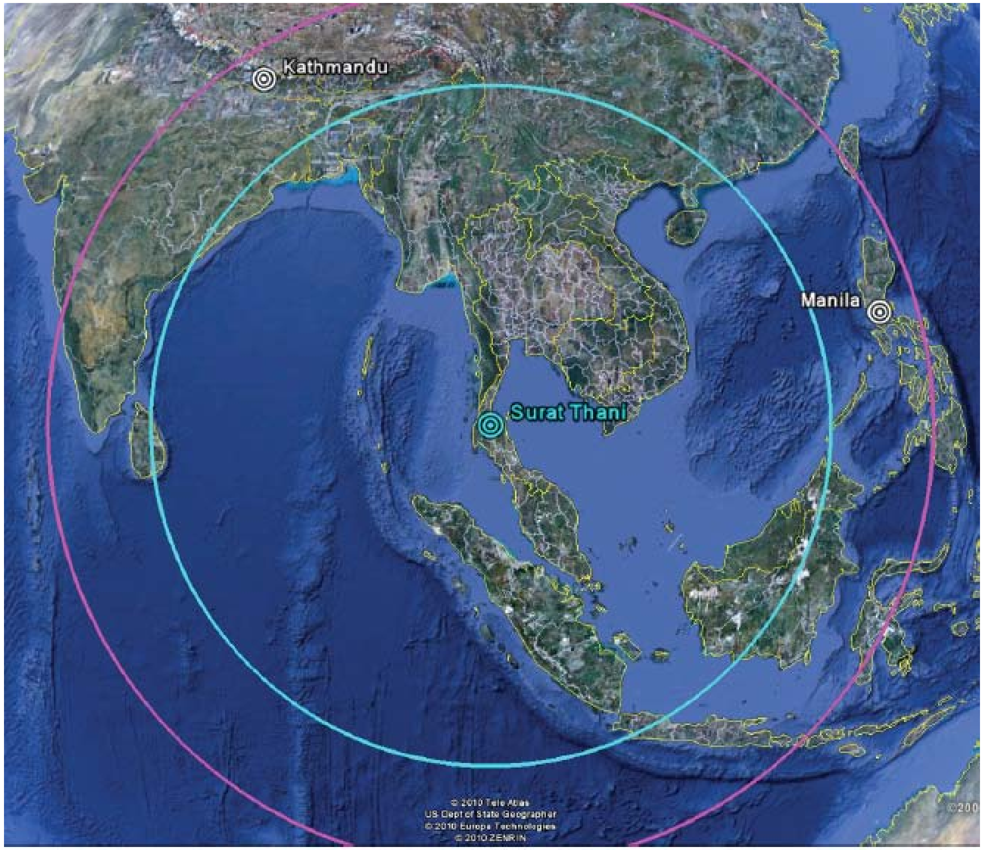
- Comprehensive in situ chemical and aerosol measurements
- Passive remote sensing of atmospheric state and composition
- Active remote sensing of ozone, water vapor and aerosol optical properties

Models: CTMs, GCMs, ESMs

- Source-receptor relationships for pollution
- Inverse modeling for estimating emissions
- Aerosol radiative forcing
- Detailed chemical processing

Calibration and Validation
Retrieval development
Correlative information
Small scale structure and processes

Model error evaluation
Data assimilation
Diagnostic studies



Measurement Objectives:

1) Characterize the chemical gradients associated with the dynamical background of the Asian Monsoon Anticyclone.

2) Characterize the chemical composition of convective outflow and microphysical properties of anvil cirrus.

3) Characterize the chemical and meteorological impact of biomass burning plumes.

August/September 2012

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