

# Optical Remote Sensing with DIfferential Absorption Lidar (DIAL)

## Part 2: System Design and Applications

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<http://www.esrl.noaa.gov/csd/groups/csd3/>

Guest lecture for ASEN-6519 Lidar Remote Sensing  
CU Boulder

March 4, 2011

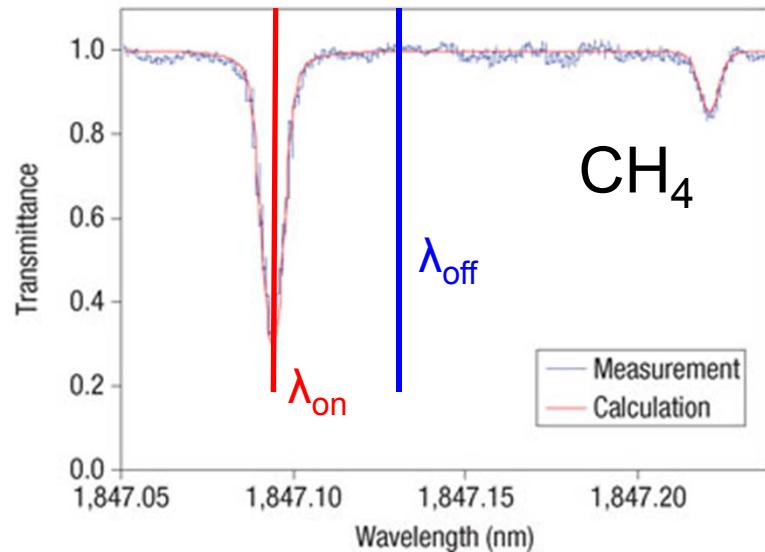
# Outline

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- DIAL system components
- DIAL instruments at NOAA/ESRL
- Applications of airborne ozone DIAL

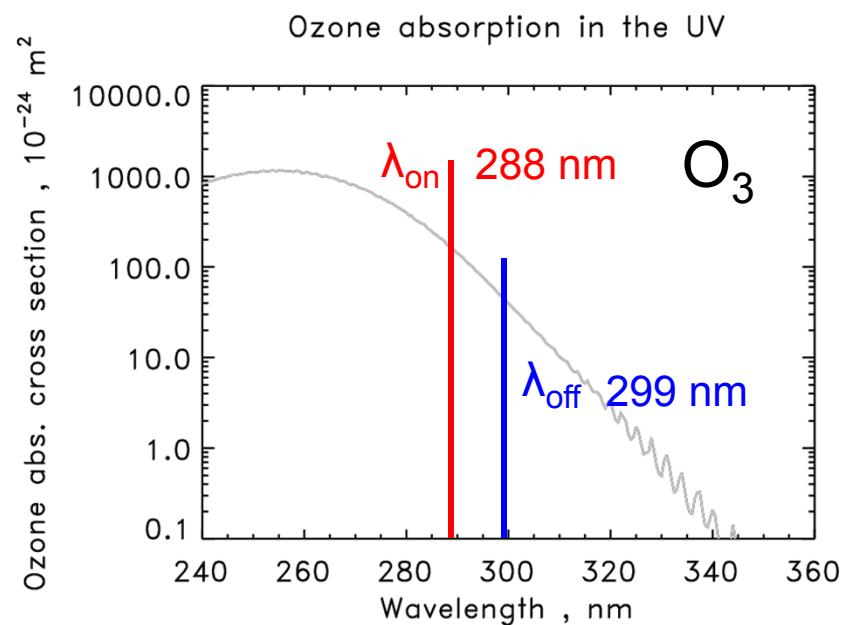
# DIAL system components: Transmitter (1)

## Narrow absorption line



- $\Delta\lambda \approx 50 \text{ pm}$
- No correction for differential backscatter or extinction needed
- Transmit laser needs to be tunable
- High frequency stability, narrow bandwidth, high spectral purity

## Broad absorption feature



- $\Delta\lambda = 10 \text{ nm}$
- Correction for differential backscatter or extinction necessary
- Fixed wavelength lasers OK
- High frequency stability, narrow bandwidth, high spectral purity not needed

## DIAL system components: Transmitter (2)

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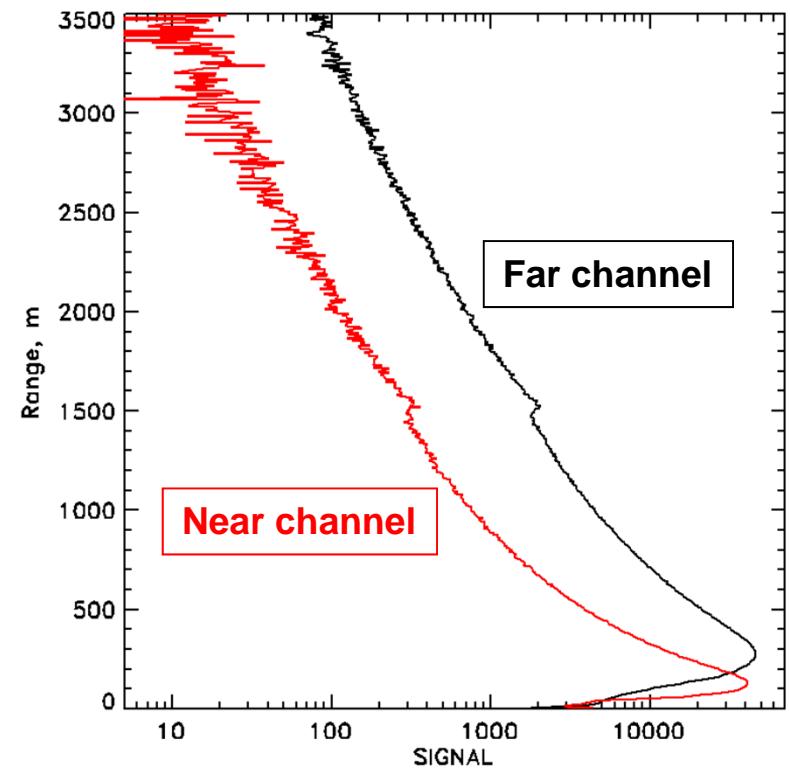
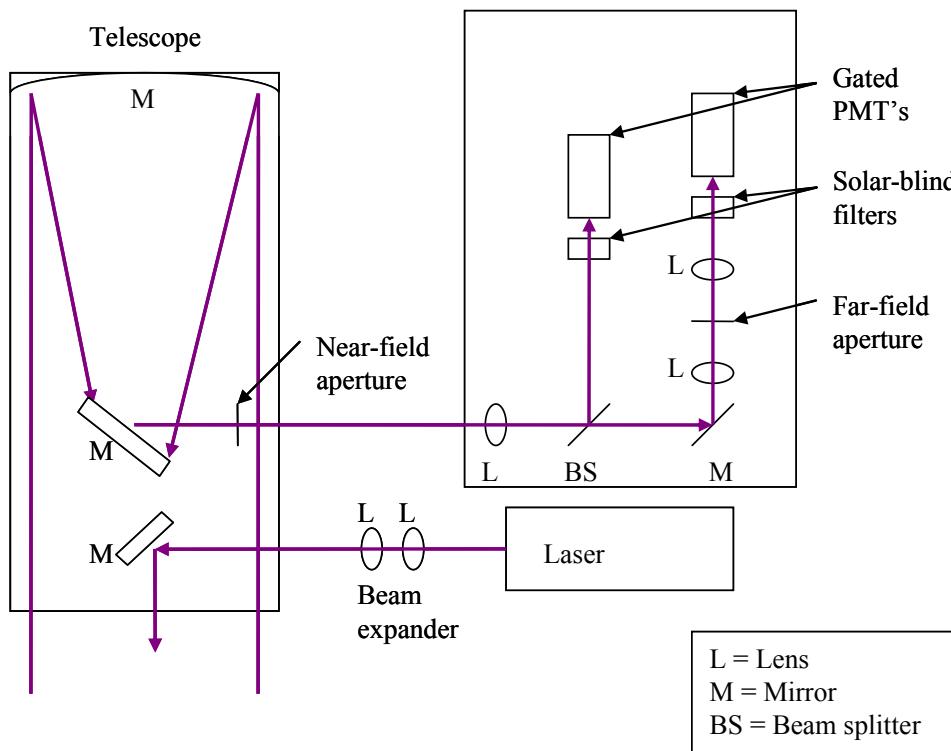
- High laser power (high pulse energy or lower pulse energy & high rep rate)
- Tunable laser or appropriate fixed frequencies

Species	Laser transmitter	Wavelengths
O <sub>3</sub>	4x Nd:YAG / Excimer + Raman shift OPO, CeLiCAF, 3x Ti:Sapphire	Fixed: 266 – 359 nm Tunable: 280 – 320 nm
H <sub>2</sub> O	Ti:Sapphire, Alexandrite, OPO, Fiber laser	720 – 940 nm, 1.5 μm
CH <sub>4</sub>	OPO	1.67 μm, 3.3 μm
CO <sub>2</sub>	Fiber laser, OPO, Tm:Ho:YLF	1.57 μm, 2.05 μm
VOCS	Dye lasers	Mid-IR @ several μm
NH <sub>3</sub>	Dye laser, CO <sub>2</sub> laser	208 nm, 9 – 10 μm

OPO = Optical Parametric Oscillator

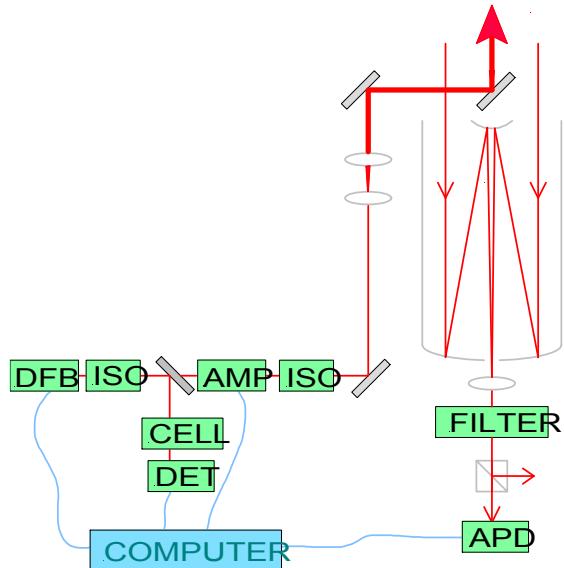
# DIAL system components: Receiver

- ❑ Large telescope
- ❑ Narrow field of view to suppress background light
- ❑ Combination of near and far channels to compress large dynamic range

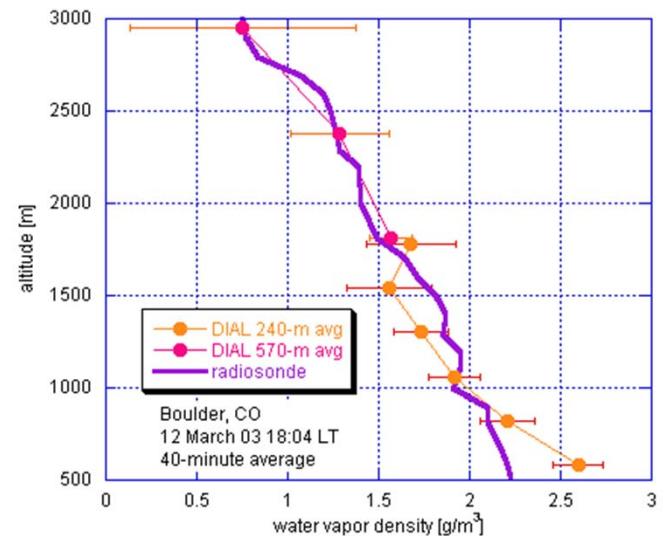


# DIALs at NOAA/ESRL/CSD – Ground-based

CODI = COmpact DIAL (prototype of small, autonomous DIAL system)



wavelength	823 nm
output pulse energy	$\sim 0.15 \mu\text{J}$
pulse duration	600 ns
pulse repetition freq.	8 – 10 kHz
telescope diameter	34 cm
field-of-view	180 $\mu\text{Rad}$



## DIALs at NOAA/ESRL/CSD - Shipborne

OPAL = Ozone Profiling Atmospheric Lidar (recently retired)

- Wavelengths: 266, 289, 299 nm
- 4x Nd:YAG + Raman-shifting in H<sub>2</sub> and D<sub>2</sub>
- Motion-compensated elevation angle scanner from 0 – 90 deg
- Ship deployments on NOAA R/V Ron Brown in 2002 - 2006

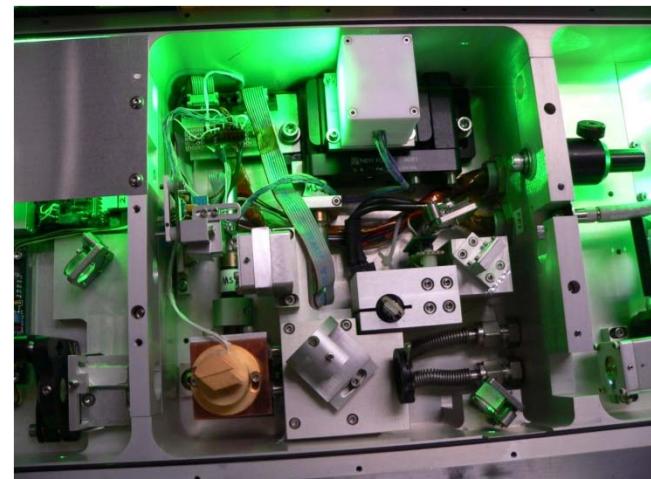
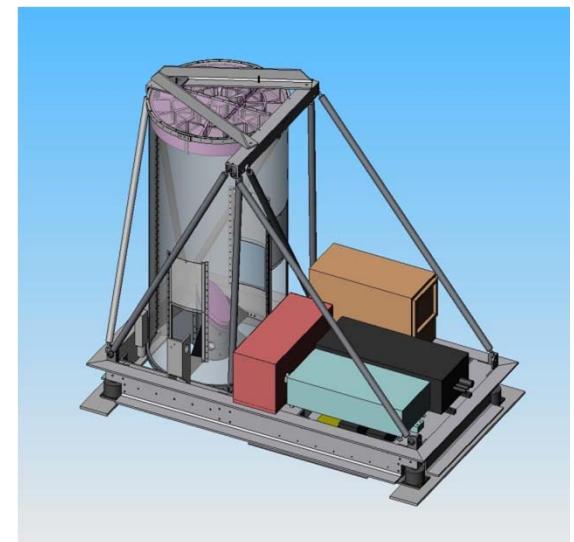


## DIALs at NOAA/ESRL/CSD - Airborne

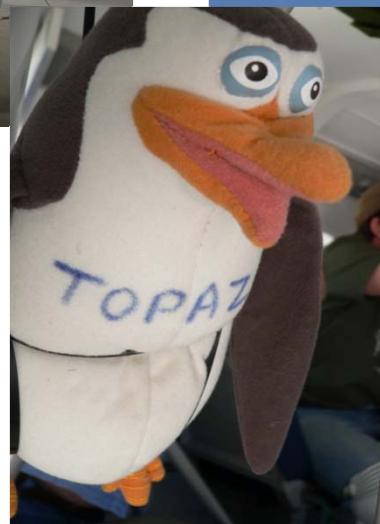
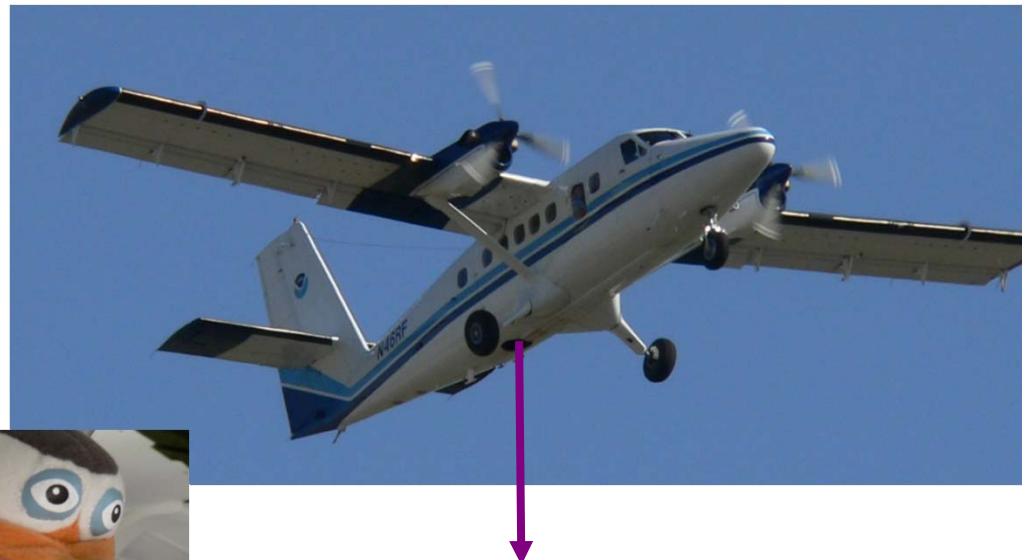
TOPAZ = Tunable Optical Profiler of Aerosol and oZone

- Tunable, all-solid state, compact airborne O<sub>3</sub> DIAL
- Replaced previous fixed-wavelength O<sub>3</sub> lidar in 2006
- Size & weight were reduced significantly

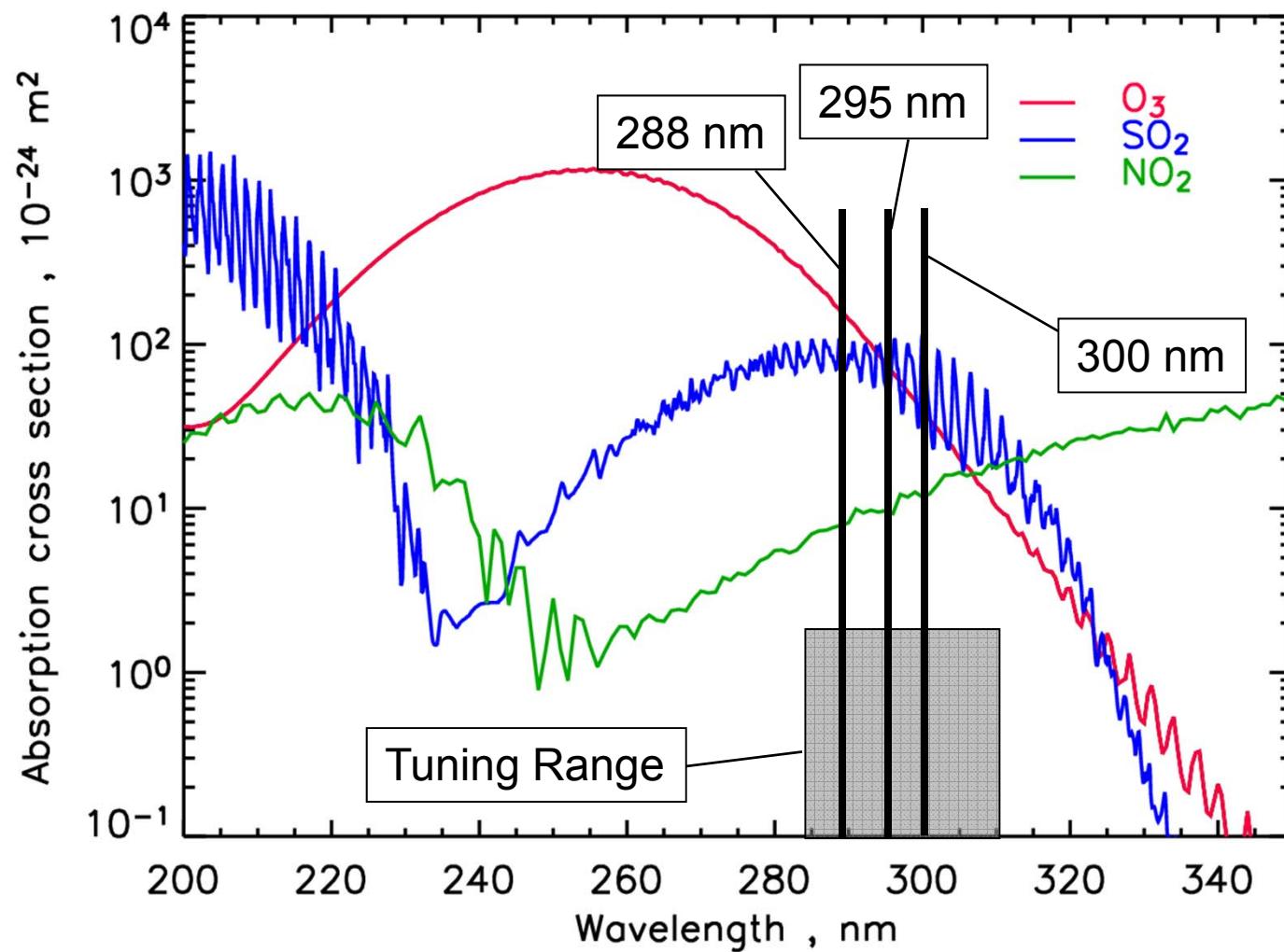
TOPAZ Specifications	
Wavelengths	3
Wavelength tuning range	285-310 nm
Pulse energy	0.2-0.8 mJ/pulse
Pulse rate	1 kHz with pulse-to-pulse tuning capability
Minimum/maximum range	0.3 km / 5 km
Eye-safe range	~150 m
System weight	~800 lbs (including chiller and control electronics)
Output	Ozone and aerosol backscatter profiles
Vertical/horizontal resolution (O <sub>3</sub> )	90 m / 600 m
Precision (O <sub>3</sub> )	3 - 15 ppbv



# TOPAZ lidar on NOAA Twin Otter



## TOPAZ wavelengths & tuning range



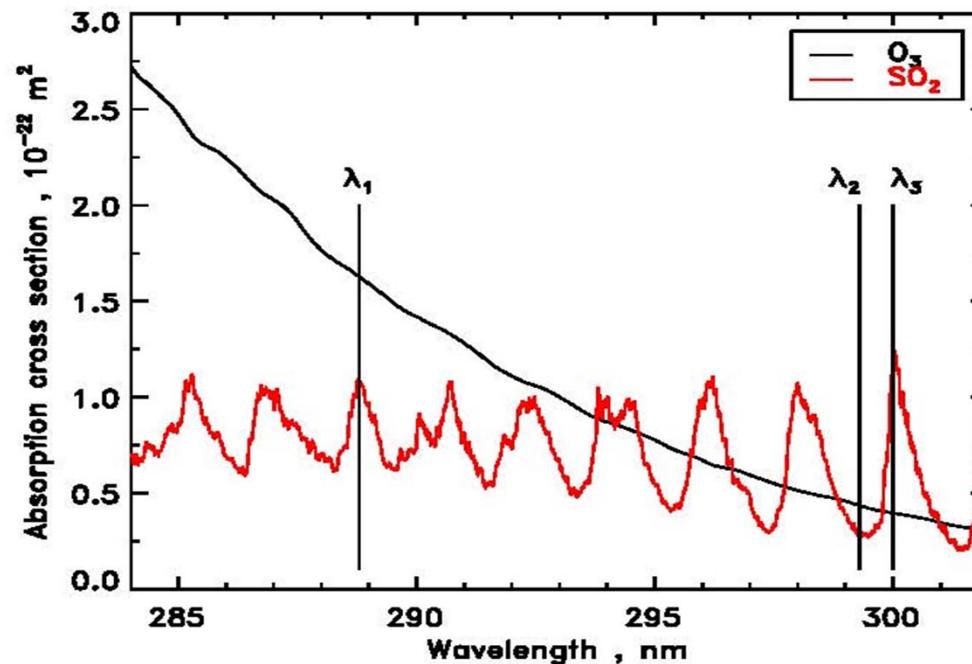
# TOPAZ is a tunable, multi-wavelength DIAL system

## Advantages of tunability:

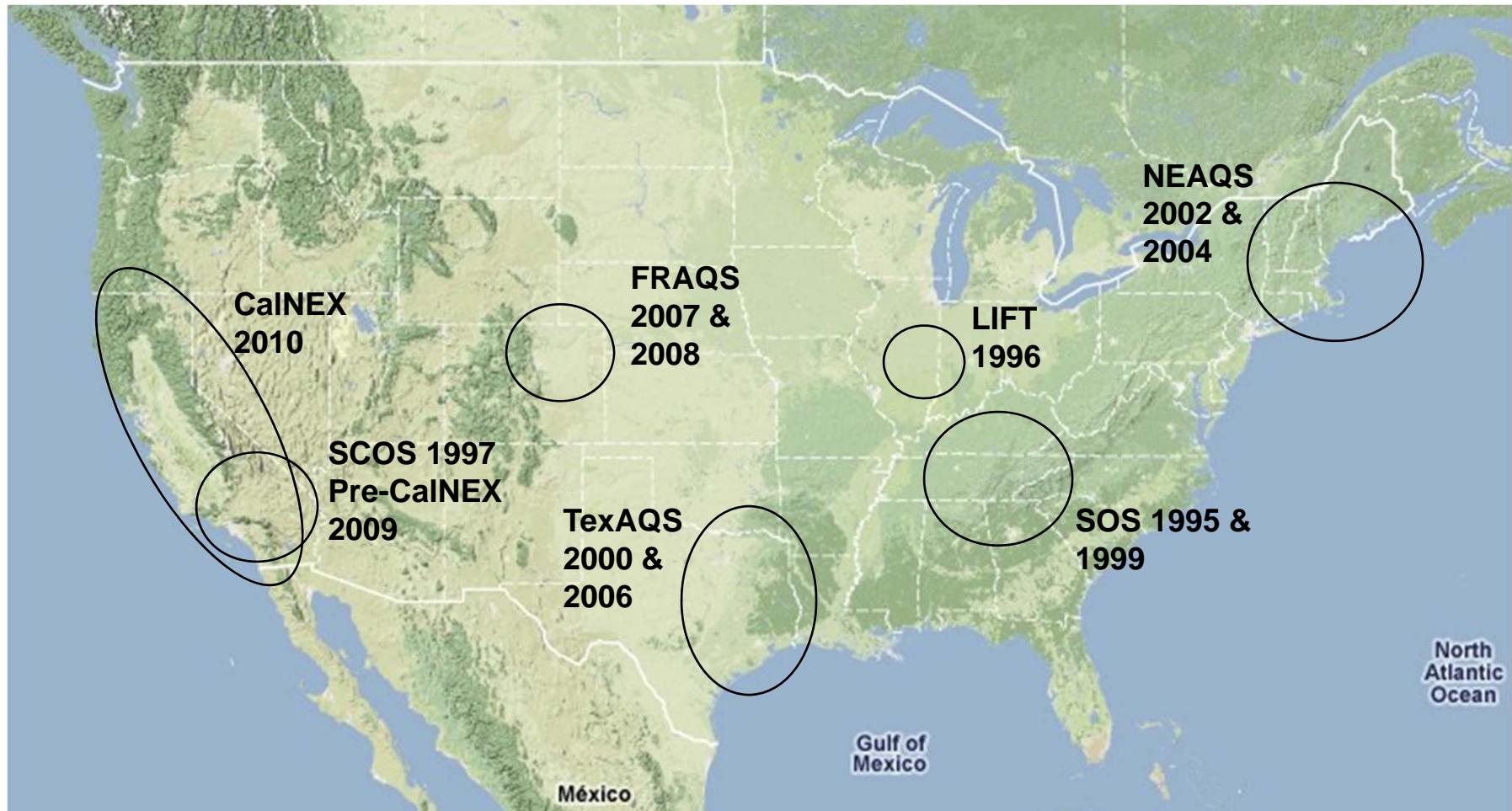
- Wavelengths can be optimized for given atmospheric ozone loading
- Minimize interference from other trace gases, e.g. SO<sub>2</sub>

## Advantages of multi-wavelength capability:

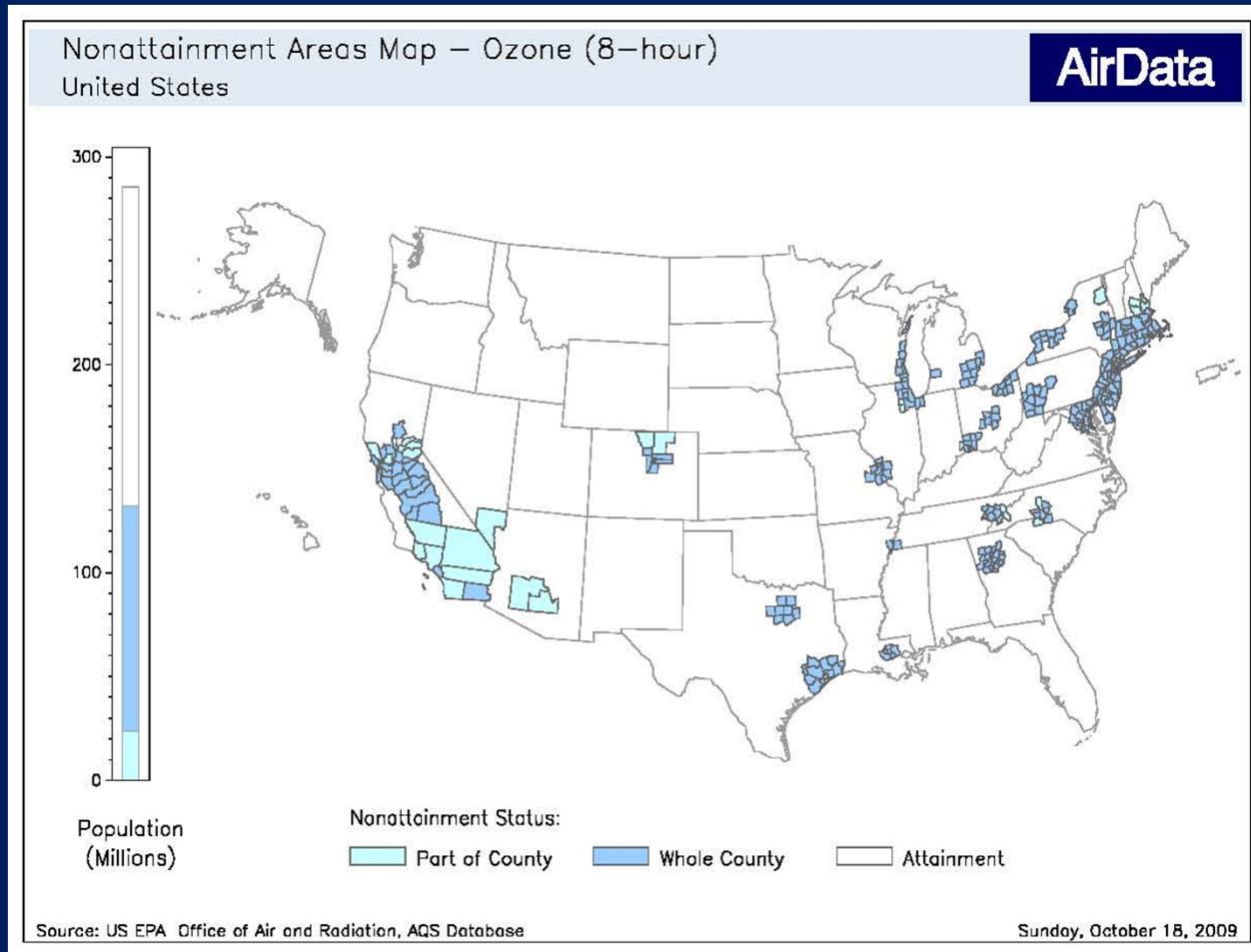
- Allows simultaneous measurement of 2 species (O<sub>3</sub> & SO<sub>2</sub>)
- Dual-DIAL application to minimize uncertainties due to aerosol backscatter and extinction corrections



# Ozone DIAL Application: Regional Air Quality



# Ozone non-attainment areas in the US



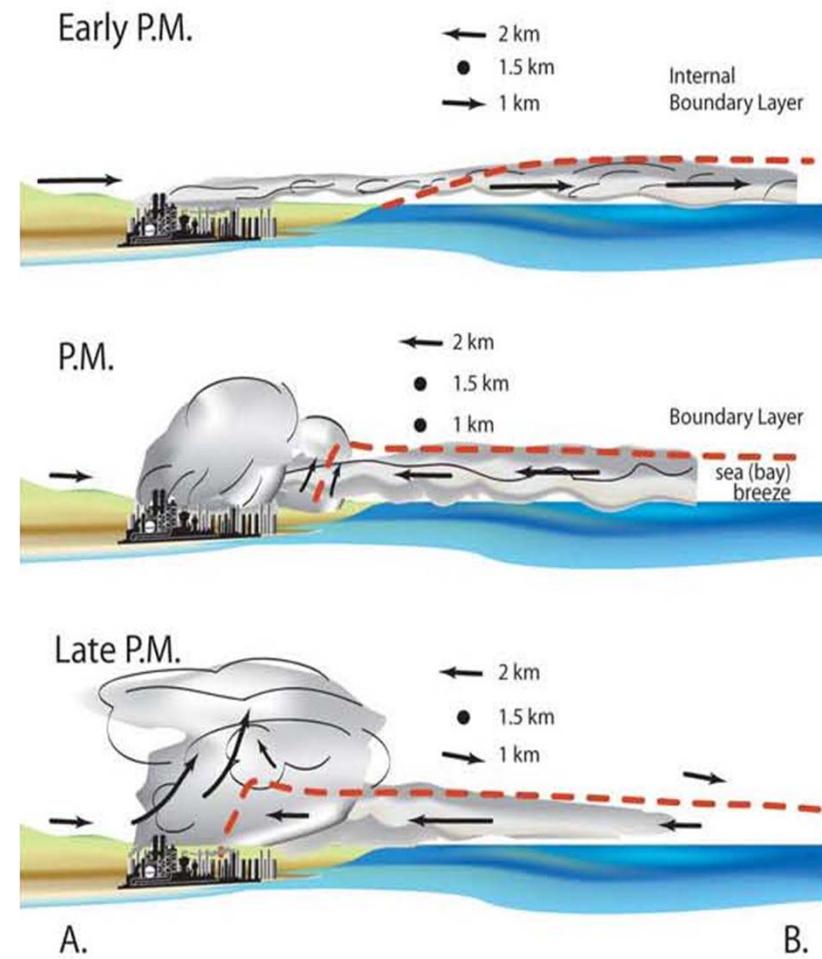
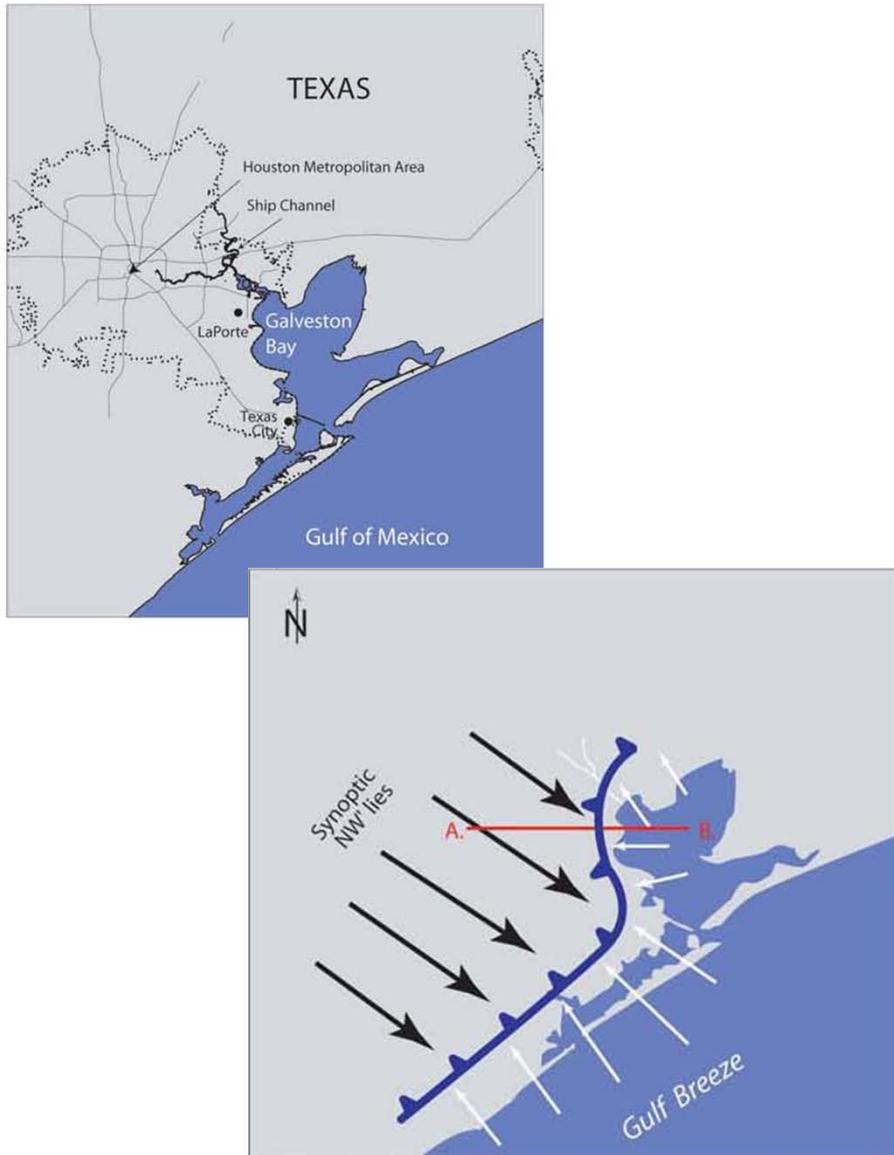
- U. S. 8-hour  $O_3$  standard: 75 ppbv (since May 2008, before: 84 ppbv)
- Greater Denver area violated the 8-hour  $O_3$  standard in 2005 -2007

# Airborne ozone lidar science objectives

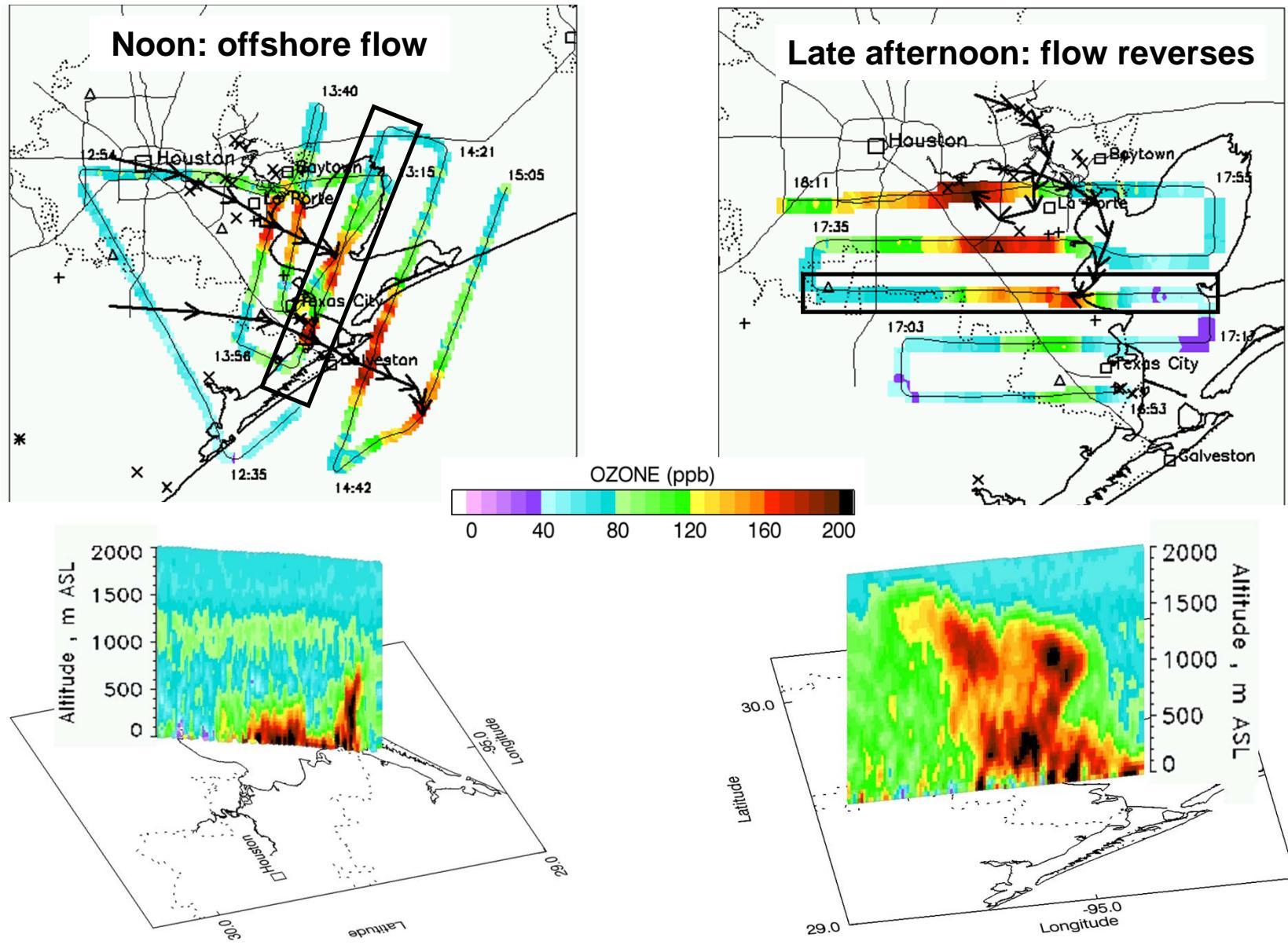
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- 3-d distribution of ozone and aerosols
- Horizontal and vertical transport of ozone on local and regional scales
- Validation of air quality forecasting models

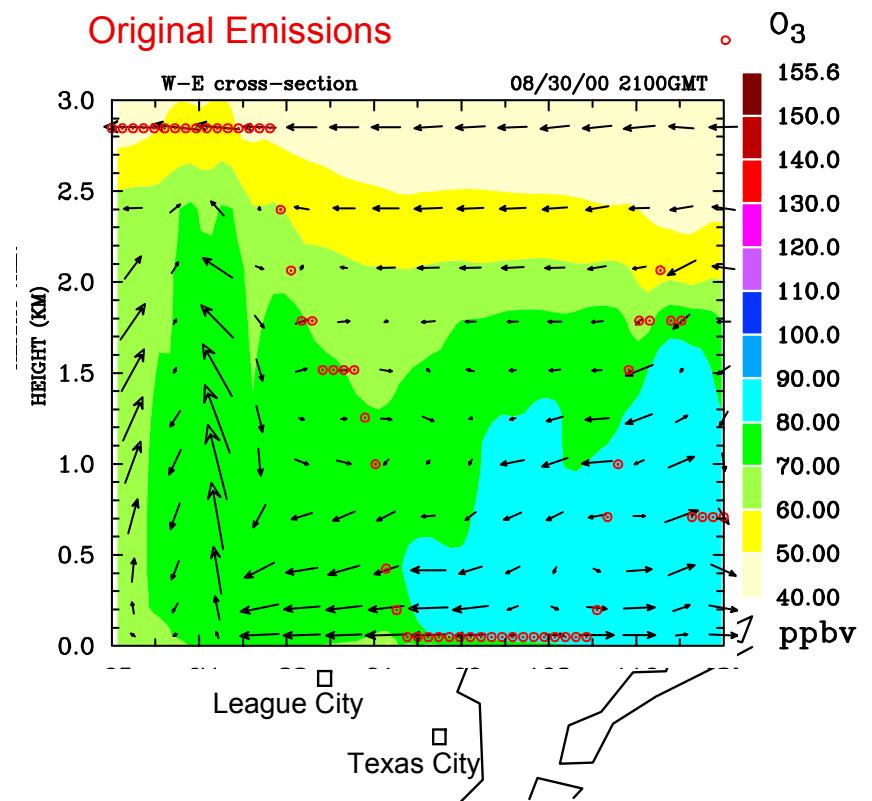
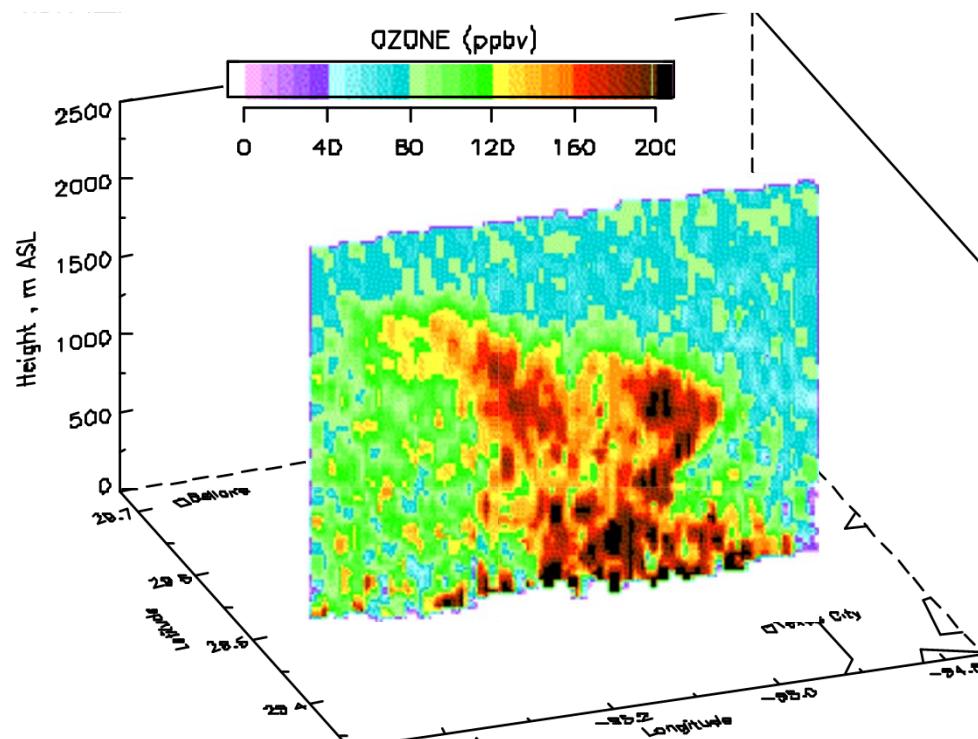
# TexAQS 2000: High ozone event due to sea-breeze re-circulation of pollutants near Houston, TX



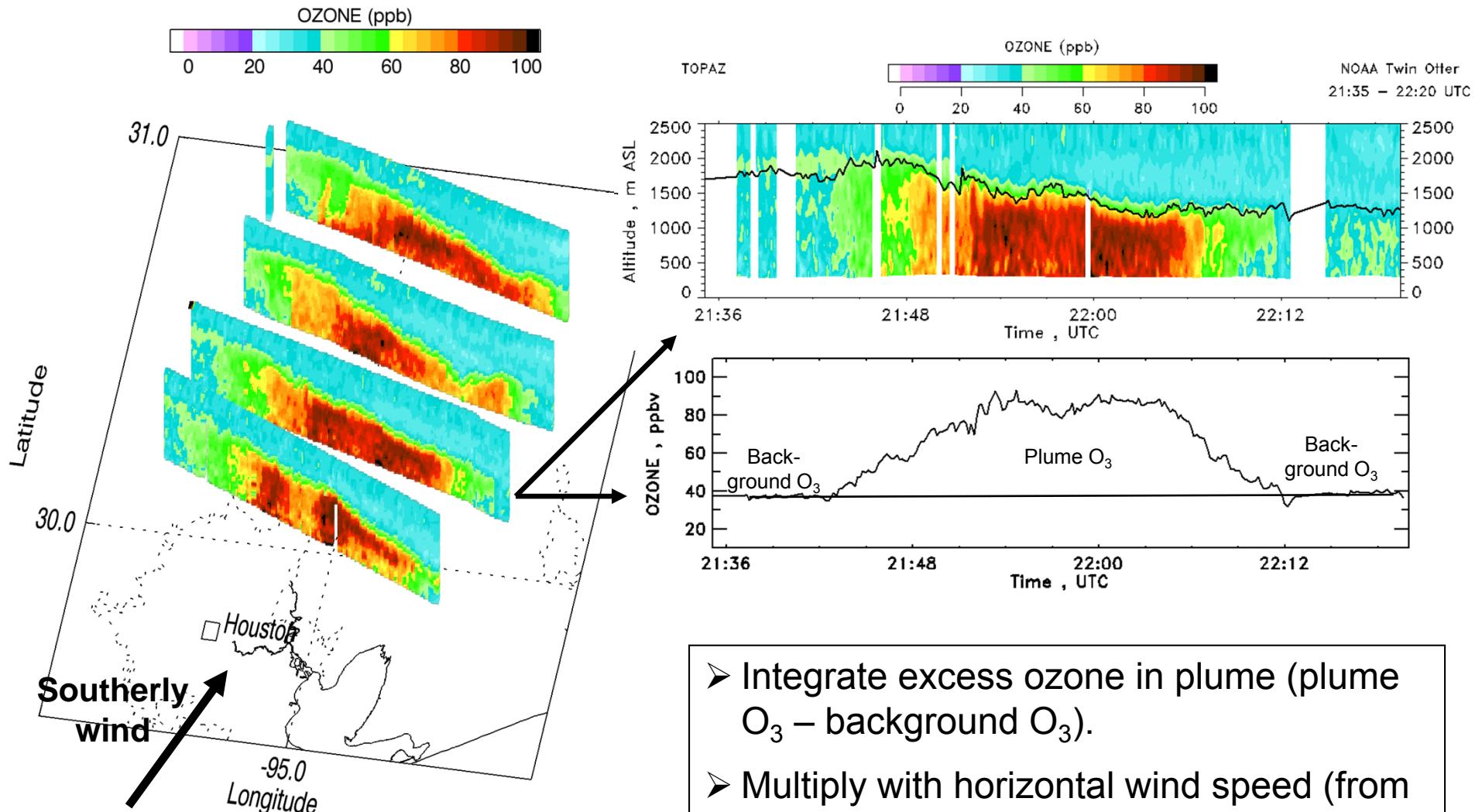
# Local Transport: Houston land-sea breeze recirculation



# AQ forecast model comparison with O<sub>3</sub> DIAL

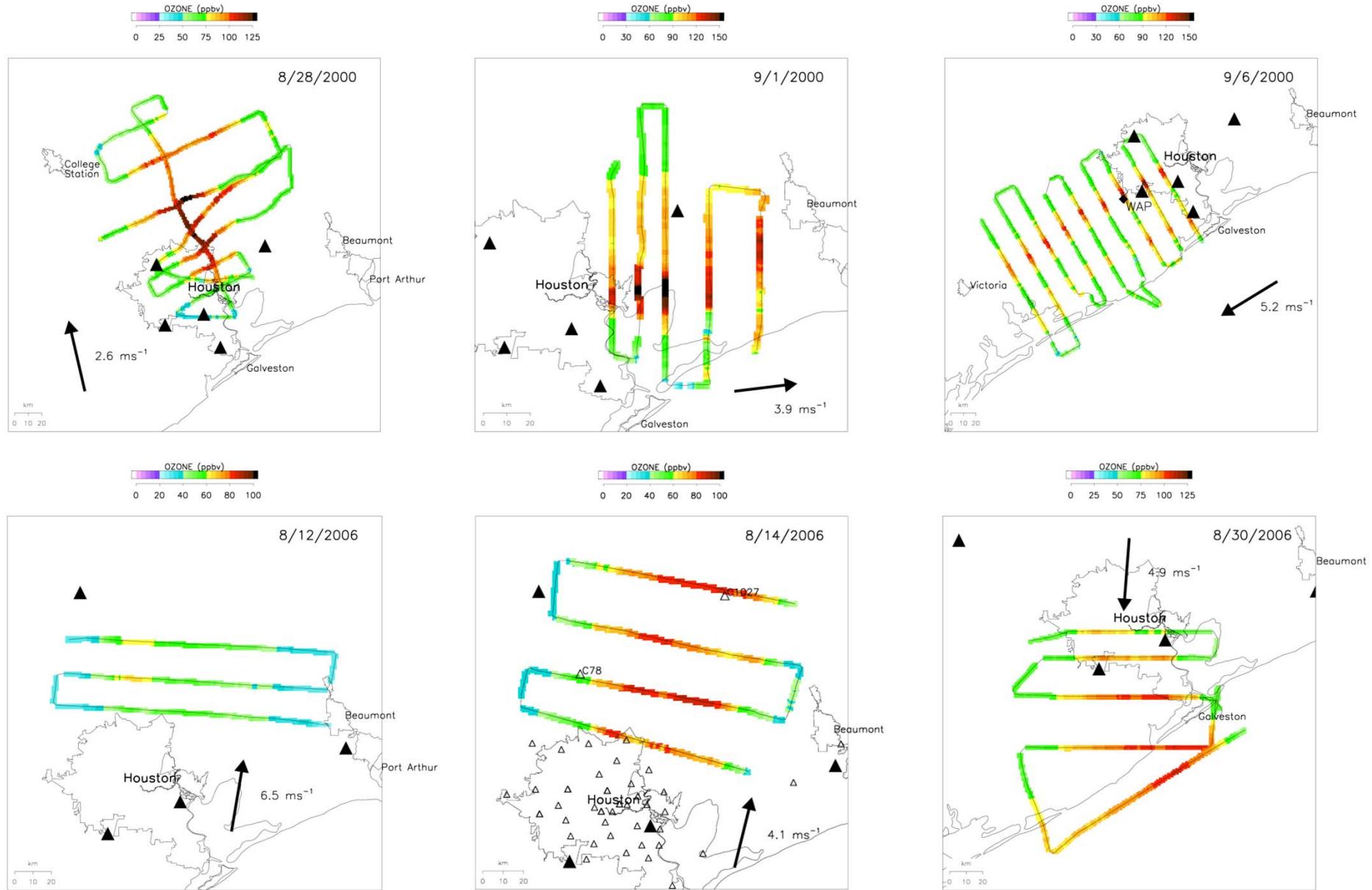


# TexAQS 2000 & 2006 - Regional Transport: Estimating ozone exported from Houston

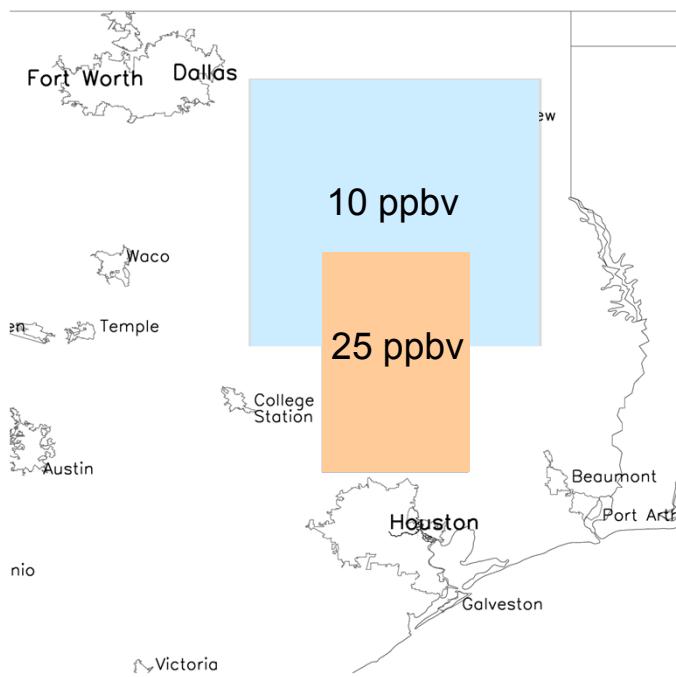
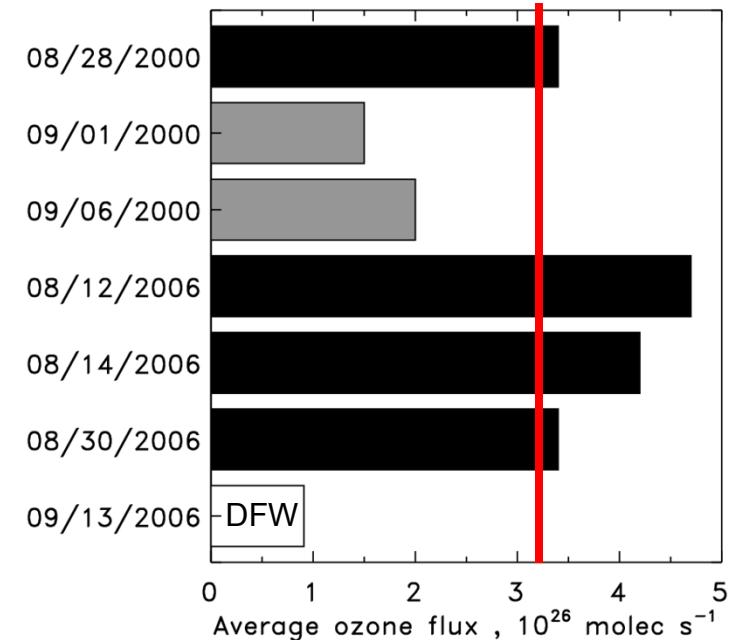
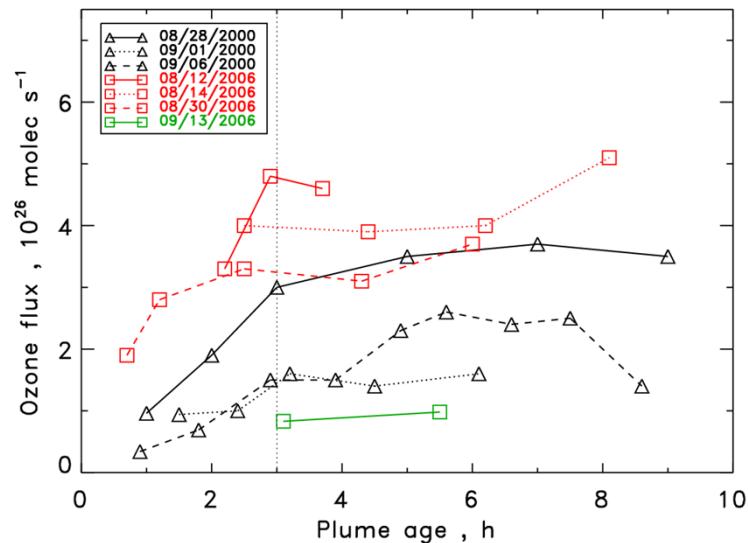


- Integrate excess ozone in plume ( $\text{plume O}_3 - \text{background O}_3$ ).
- Multiply with horizontal wind speed (from wind profiler network) to yield ozone flux for each transect.

# Six Houston ozone export cases

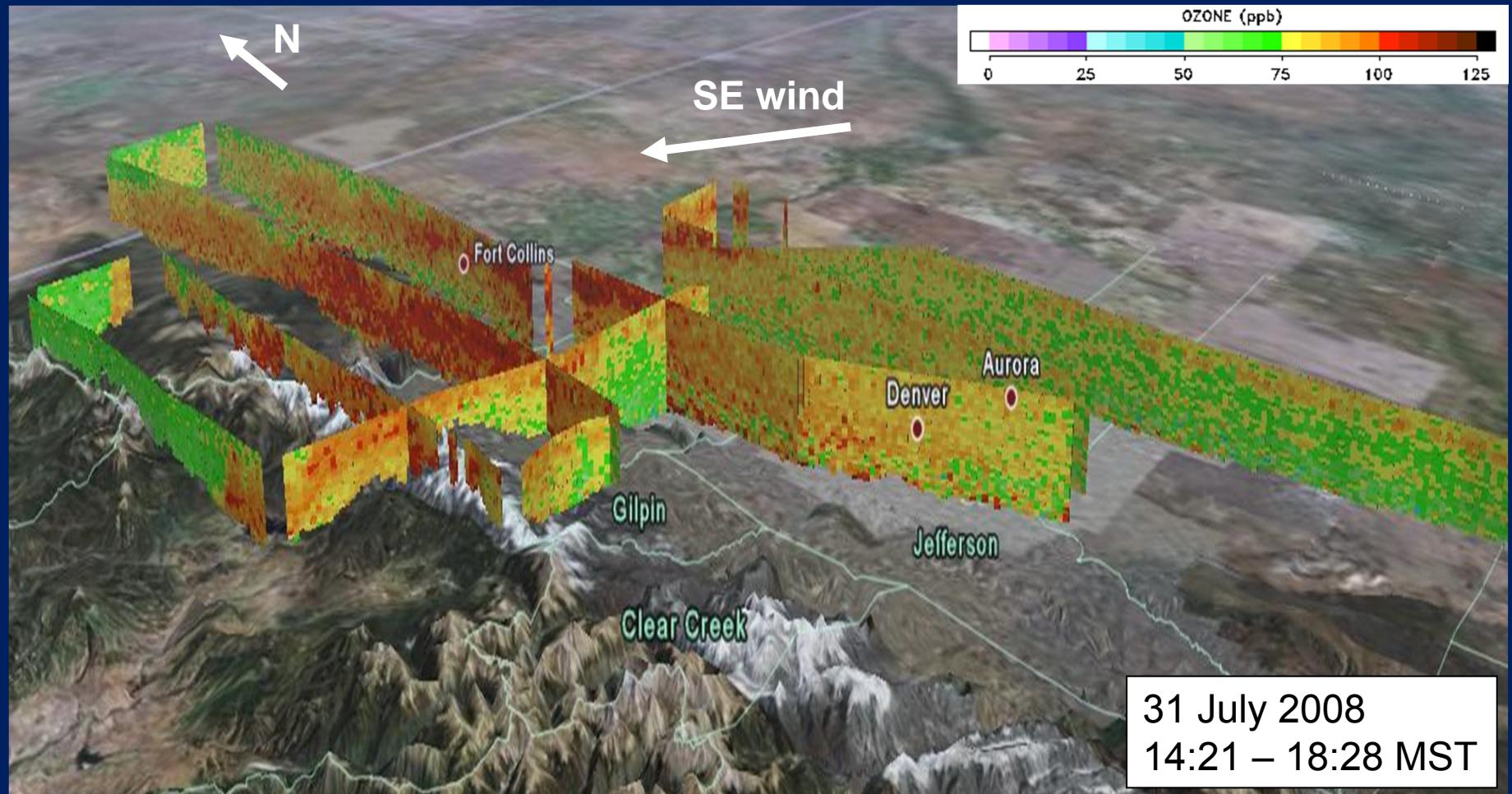


# Horizontal ozone flux and impact on regional air quality



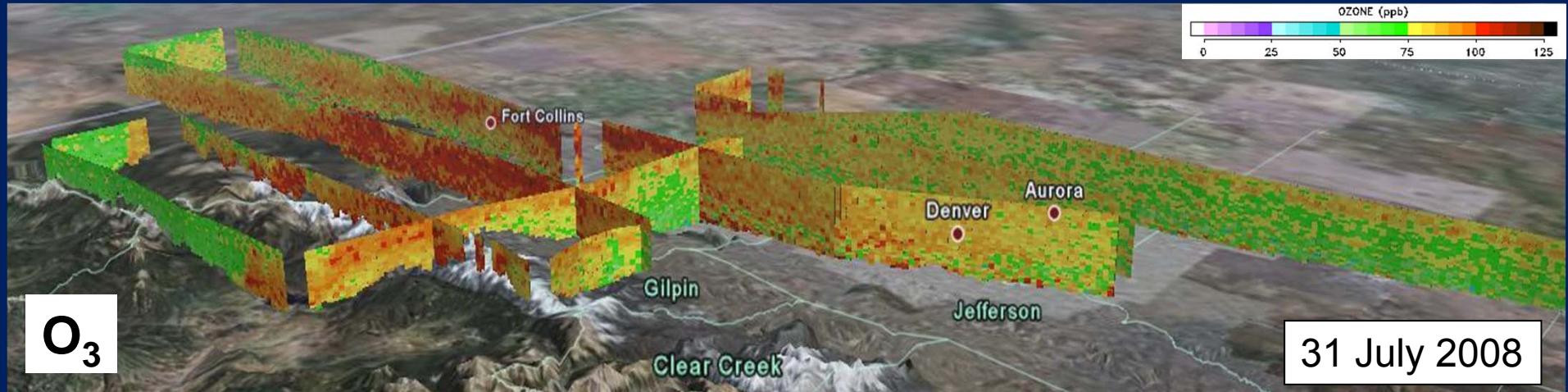
An ozone flux of  $3.2 \cdot 10^{26}$  molec  $s^{-1}$  emitted over 12 hours is equivalent to a 10 ppbv increase in ozone over a  $\sim 40,000$  km $^2$  area, assuming a 1.5-km deep mixed layer.

# Front Range Air Quality Study 2008: Transport of O<sub>3</sub> into and over the mountains

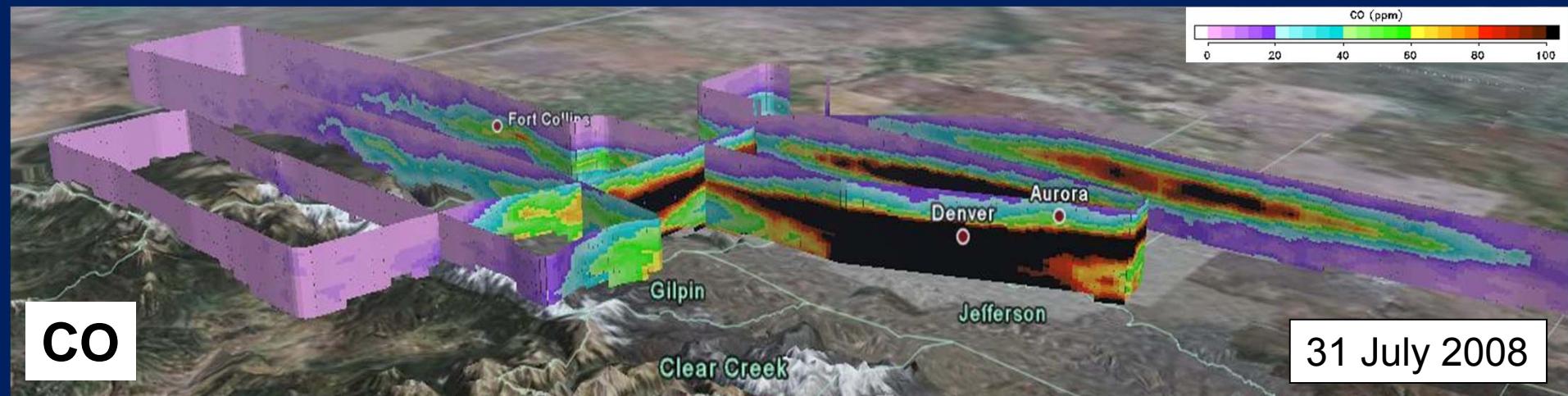


3-d distribution of O<sub>3</sub> from TOPAZ lidar

# Front Range Air Quality Study 2008: Comparison of O<sub>3</sub> DIAL measurements with air quality model predictions



TOPAZ lidar measurement



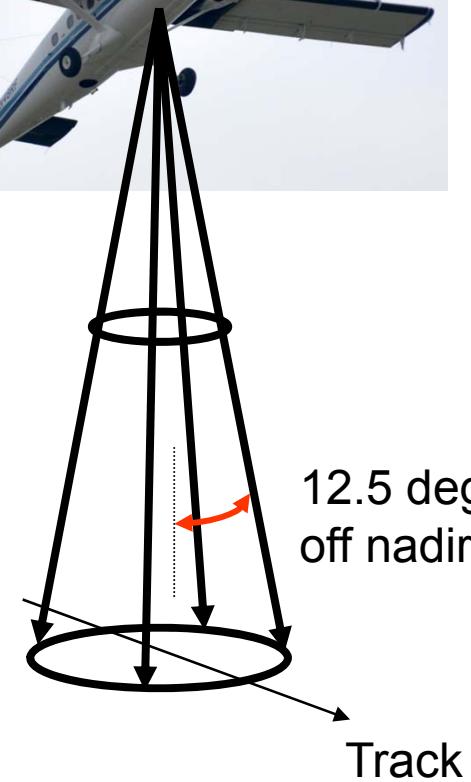
WRF-FLEXPART model results

# CaINEX 2010



TOPAZ lidar:

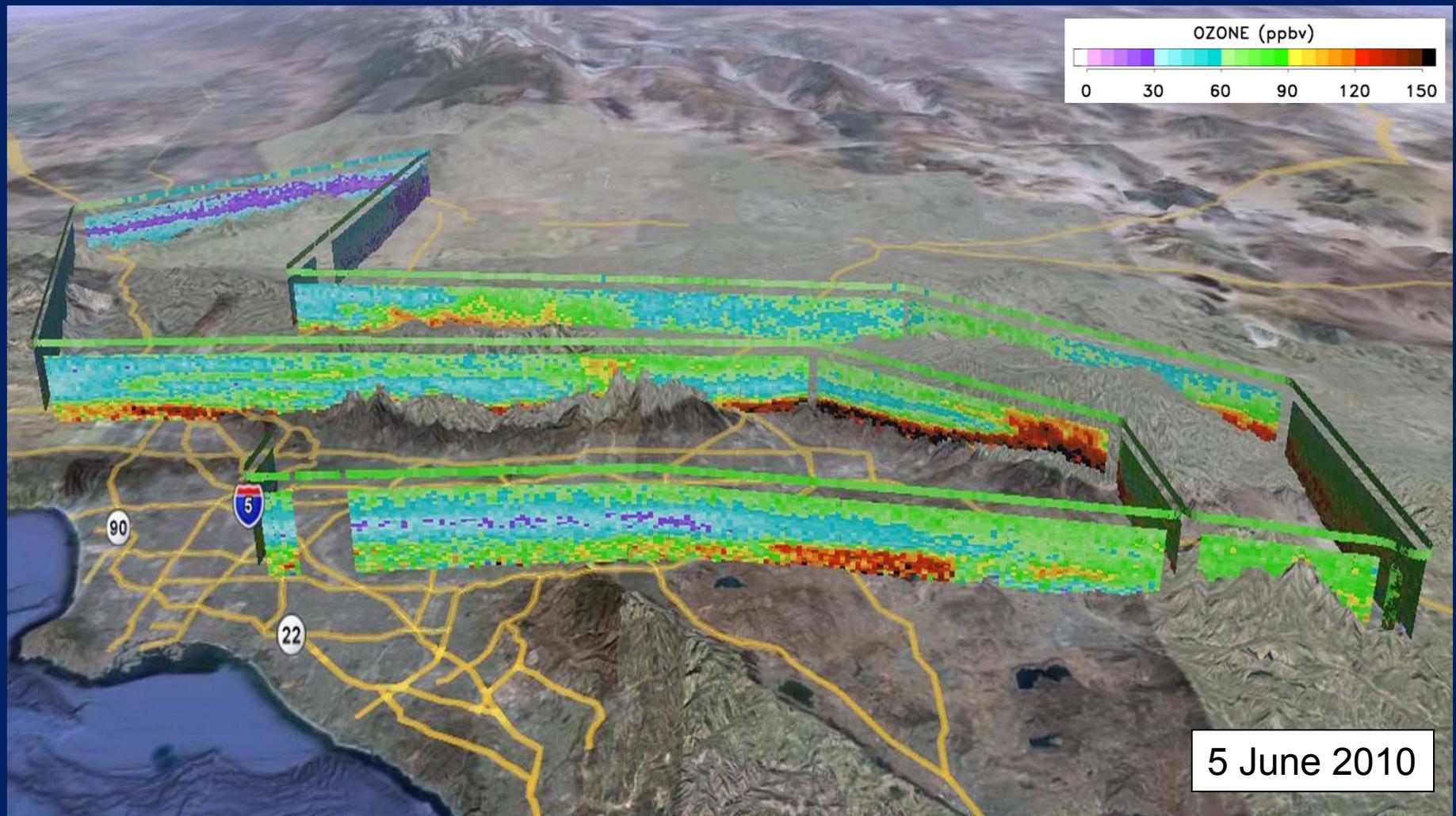
Ozone & aerosol backscatter  
profiles



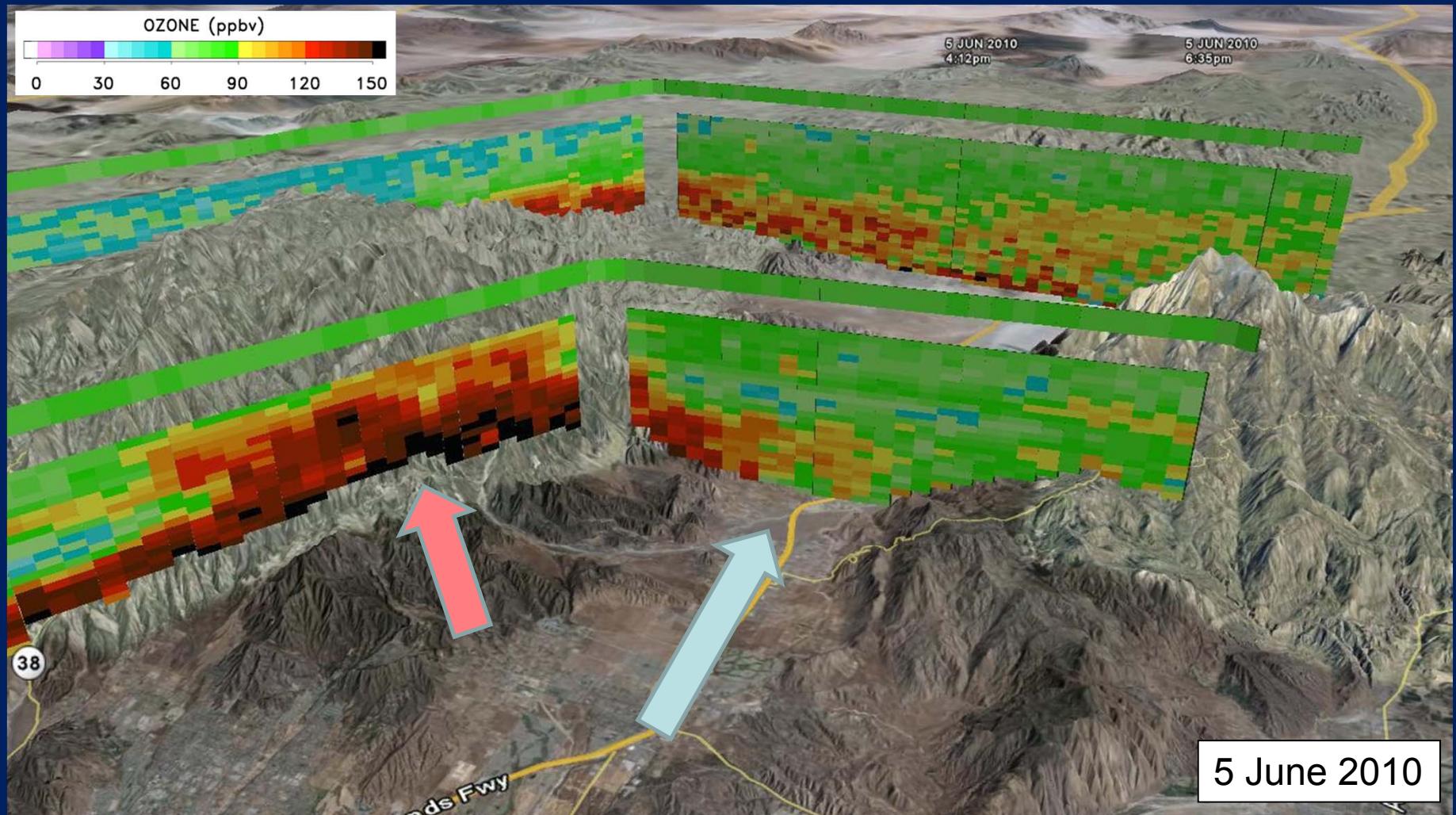
U of Leeds Doppler lidar:

Wind speed & direction profiles

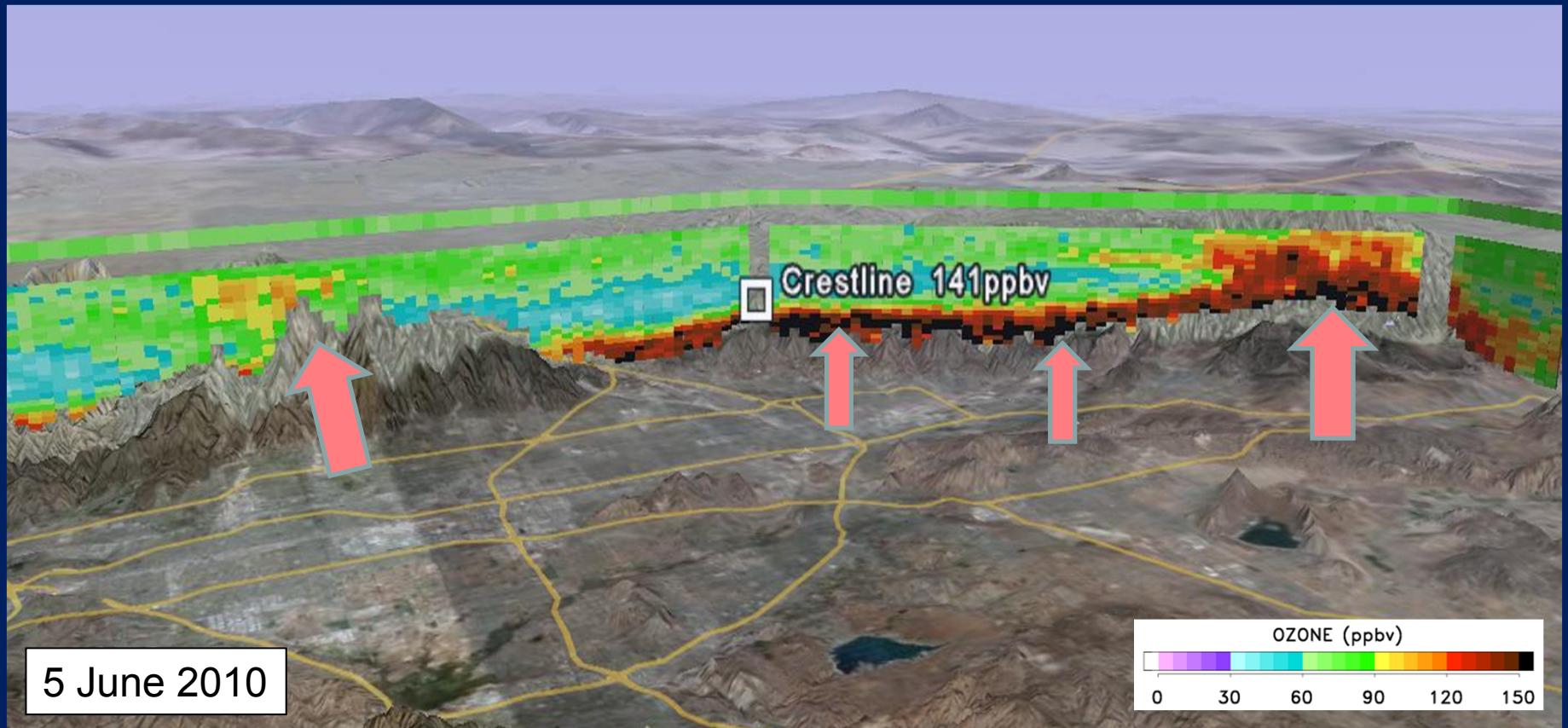
# CalNEX 2010: O<sub>3</sub> distribution over L A Basin and Mojave Desert



# CalNEX 2010: Transport thru Banning Pass



# CalNEX 2010: Upslope transport along the San Gabriel and San Bernardino Mountains



# Selected References (1)

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## DIAL transmitters (slide 4)

Fix, A., M. Wirth, A. Meister, G. Ehret, M. Pesch, and D. Weidauer, 2002: Tunable Ultraviolet Optical Parametric Oscillator for Differential Absorption Lidar Measurements of Tropospheric Ozone, *Appl. Phys. B*, **75**, 153 – 163.

Poberaj, G., A. Fix, A. Assion, M. Wirth, C. Kiemle, G. Ehret, 2002: Airborne All-solid-state DIAL for Water Vapour Measurements in the Tropopause Region: System Description and Assessment of Accuracy, *Appl. Phys. B*, **75**, 165 – 172.

Gibert, F. P. H. Flamant, D. Bruneau, and C. Loth, 2006: Two-micrometer Heterodyne Differential Absorption Lidar Measurements of the Atmospheric CO<sub>2</sub> Mixing Ratio in the Boundary Layer, *Appl. Opt.*, **45**, 4448-4458.

## NOAA/ESRL/CSD DIAL systems (slides 6- 11)

Machol, J. L., T. Ayers, K. T. Schwenz, K. W. Koenig, R. M. Hardesty, C. J. Senff, M. A. Krainak, J. B. Abshire, H. E. Bravo, and S. P. Sandberg, 2004: Preliminary Measurements with an Automated Compact Differential Absorption Lidar for Profiling Water Vapor. *Appl. Opt.*, **43**, 3110-3121.

Alvarez II, R. J., W. A. Brewer, D. C. Law, J. L. Machol, R. D. Marchbanks, S. P. Sandberg, C. J. Senff, A. M. Weickmann, 2008: Development and Application of the TOPAZ Airborne Lidar System by the NOAA Earth System Research Laboratory, Proceedings of *24th International Laser Radar Conference*, Boulder, Colorado, USA, 23-27 June, 2008, 68-71.

## Selected References (2)

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### Ozone DIAL applications (slides 12- 27)

Senff, C. J., R. J. Alvarez, II, R. M. Hardesty, R. M. Banta, and A. O. Langford (2010), Airborne lidar measurements of ozone flux downwind of Houston and Dallas, *J. Geophys. Res.*, 115, D20307, doi:10.1029/2009JD013689.

Langford, A. O., C. J. Senff, R. J. Alvarez II, R. M. Banta, and R. M. Hardesty, 2010: Long-range transport of ozone from the Los Angeles Basin: A case study, *Geophys. Res. Lett.*, 37, L06807, doi:10.1029/2010GL042507.

Banta, R. M., C. J. Senff, J. Nielsen-Gammon, L. S. Darby, T. B. Ryerson, R. J. Alvarez, S. P. Sandberg, E. J. Williams, and M. Trainer, 2005, A Bad Air Day in Houston, *Bull. Amer. Meteo. Soc.*, 657-669.