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

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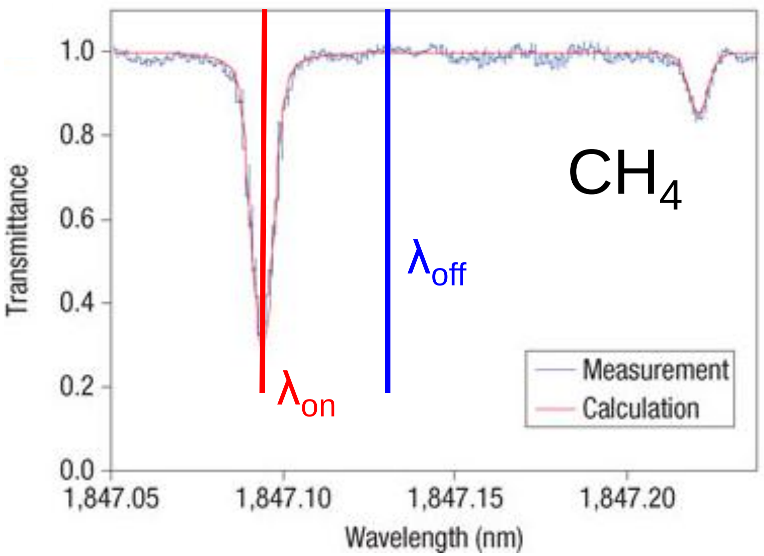
Outline

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

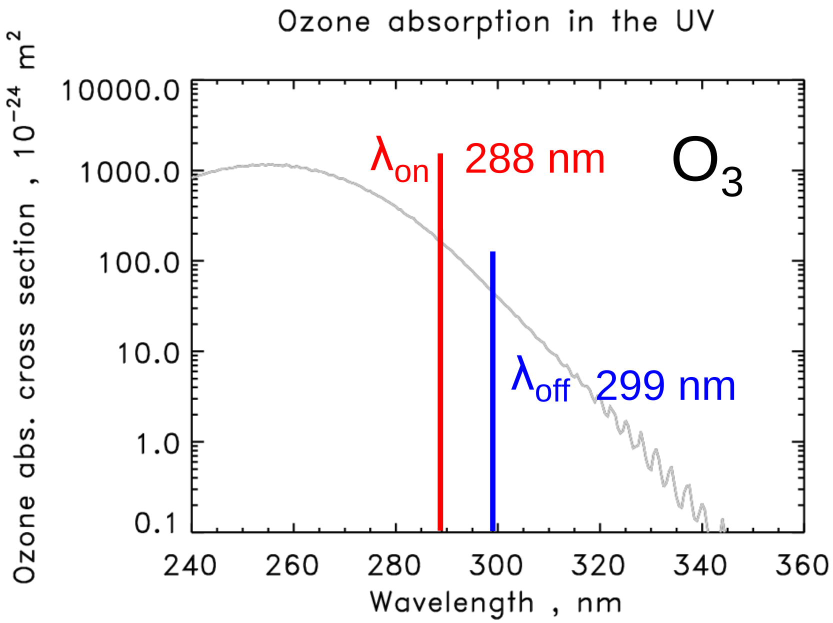
DIAL system components: Transmitter (1)

Narrow absorption line



- $\Delta\lambda \approx 50$ 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



- $\Delta\lambda = 10$ 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)

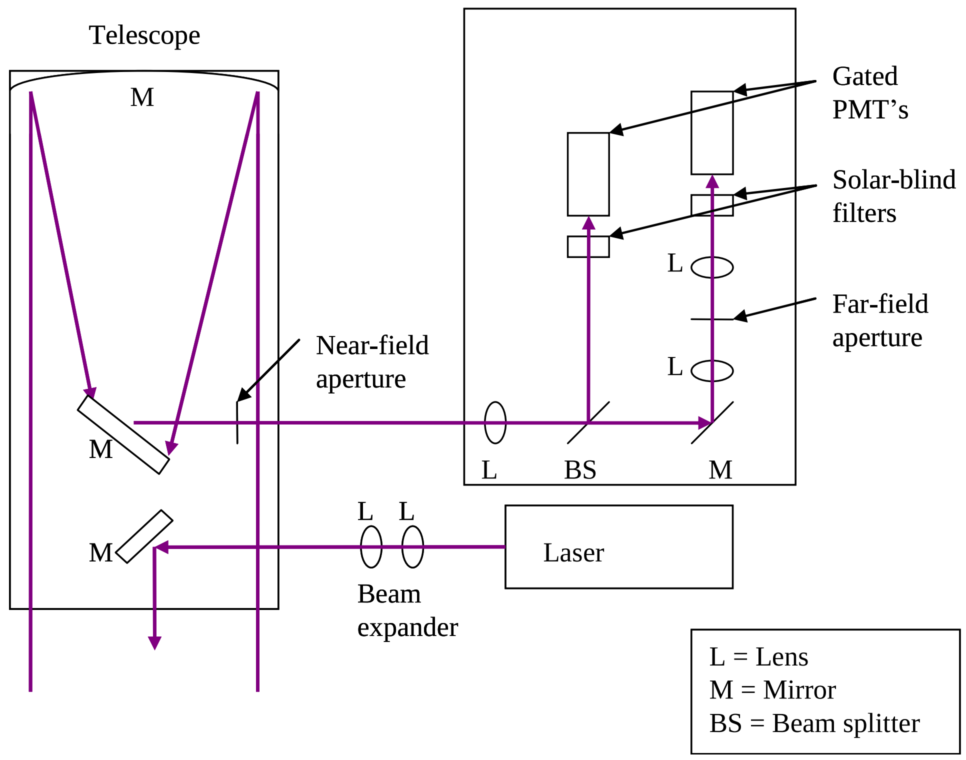
- High laser power (high pulse energy or lower pulse energy & high rep rate)
- Tunable laser or appropriate fixed frequencies

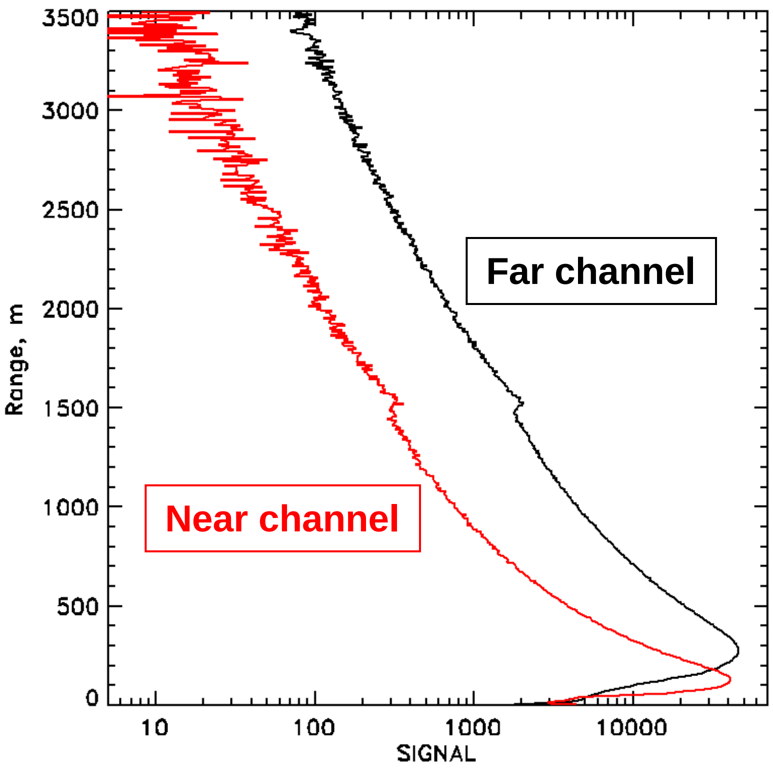
Species	Laser transmitter	Wavelengths
O_3	4x Nd:YAG / Excimer + Raman shift OPO, CeLiCAF, 3x Ti:Sapphire	Fixed: 266 – 359 nm Tunable: 280 – 320 nm
H_2O	Ti:Sapphire, Alexandrite, OPO, Fiber laser	720 – 940 nm, 1.5 μm
CH_4	OPO	1.67 μm, 3.3 μm
CO_2	Fiber laser, OPO, Tm:Ho:YLF	1.57 μm, 2.05 μm
VOCS	Dye lasers	Mid-IR @ several μm
NH_3	Dye laser, CO_2 laser	208 nm, 9 – 10 μm

OPO = Optical Parametric Oscillator

DIAL system components: Receiver

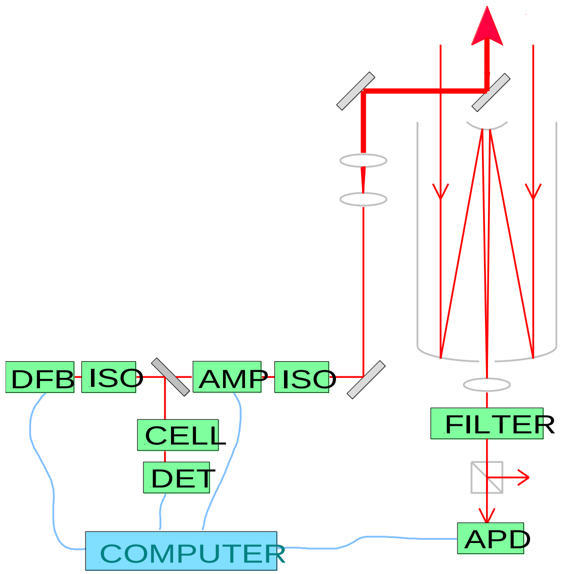
- Large telescope
- Narrow field of view to suppress background light
- Combination of near and far channels to compress large dynamic range



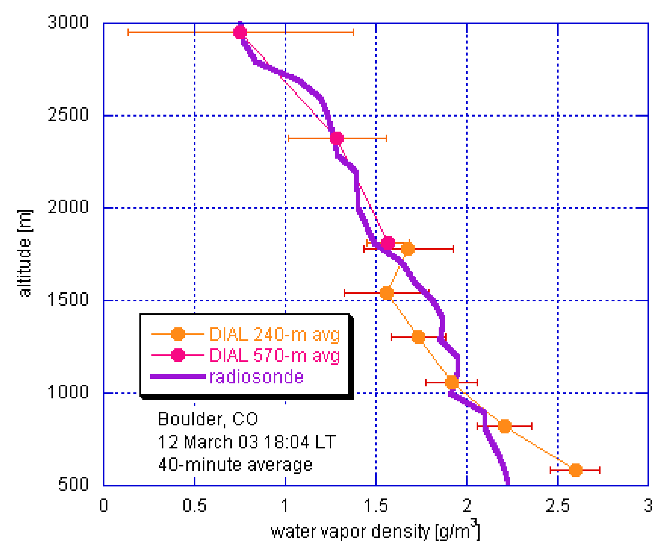


DIALs at NOAA/ESRL/CSD: Water Vapor

CODI = COmpact DIAL (prototype of small, autonomous H_2O DIAL system)



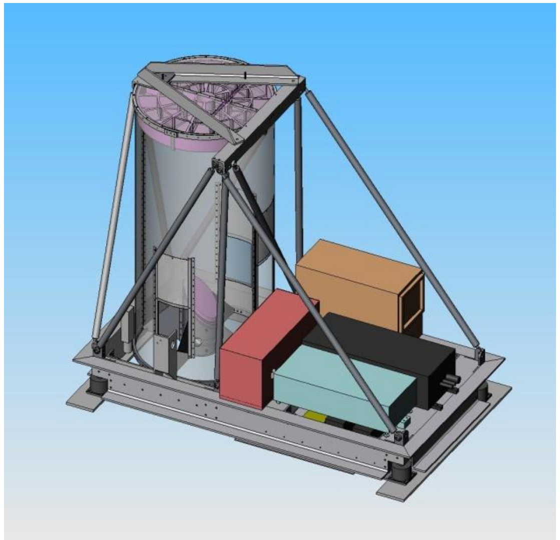
wavelength	823 nm
output pulse energy	~0.15 µJ
pulse duration	600 ns
pulse repetition freq.	8 – 10 kHz
telescope diameter	34 cm
field-of-view	180 µRad



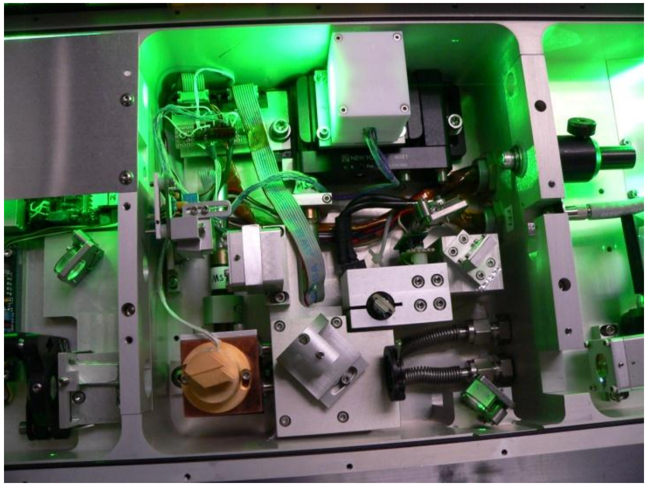
DIALs at NOAA/ESRL/CSD: Ozone

TOPAZ = Tunable Optical Profiler of Aerosol and oZone

- Tunable, all-solid state, compact O_3 DIAL
- Replaced previous fixed-wavelength O_3 lidar in 2006
- Size & weight were reduced significantly

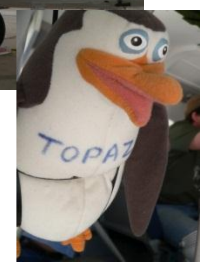


TOPAZ Specifications	
Wavelengths	3
Wavelength tuning range	285-310 nm
Pulse energy	0.2-0.8 mJ/pulse
Pulse rate	1 kHz with pulse-to-pulse tuning capability
Minimum/maximum range	0.3 km / 5 km
Eye-safe range	~150 m
System weight	~800 lbs (including chiller and control electronics)
Output	Ozone and aerosol backscatter profiles
Vertical/horizontal resolution (O_3)	90 m / 600 m
Precision (O_3)	3 - 15 ppbv



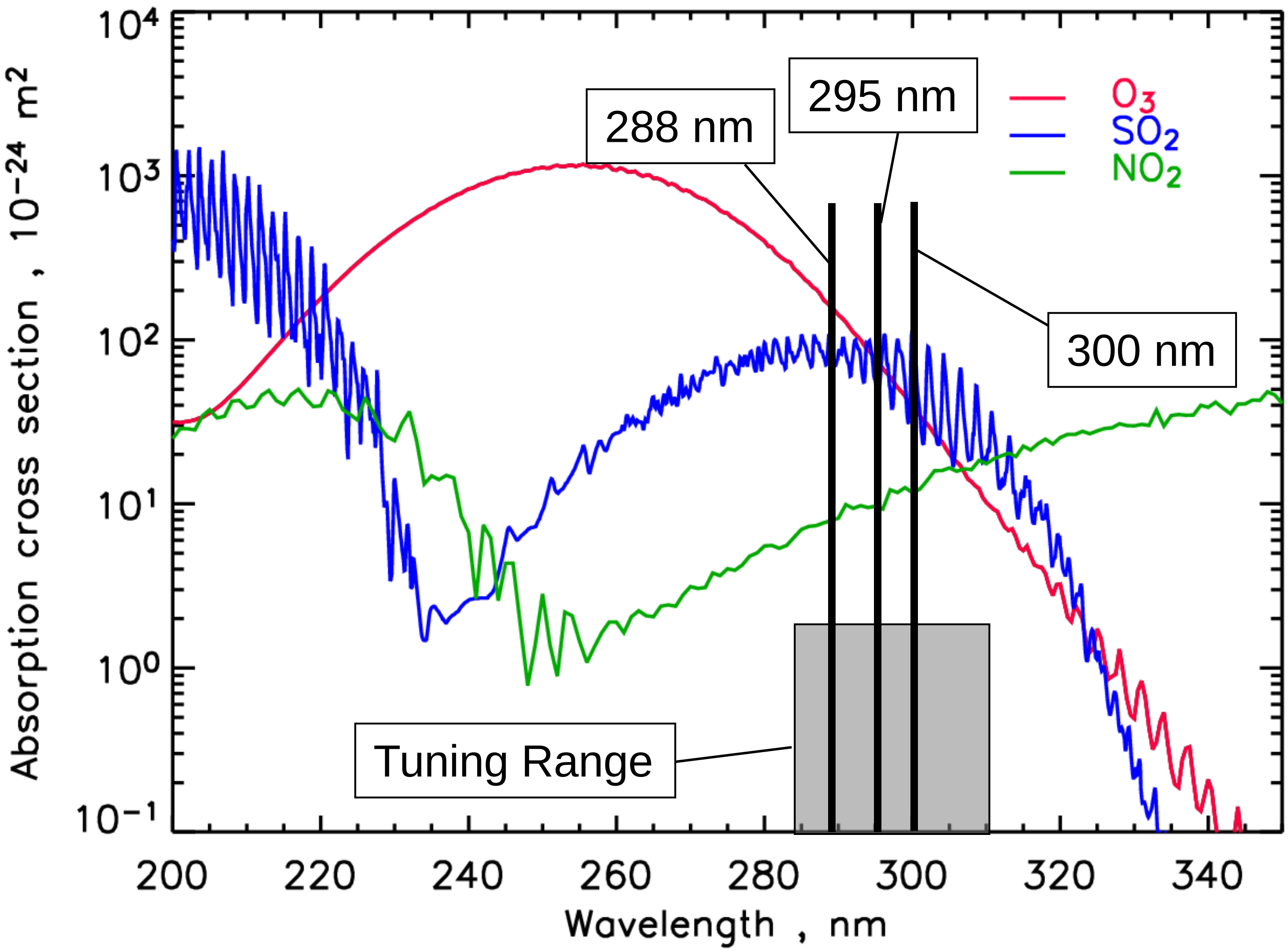
TOPAZ Ozone Lidar

2006 – 2011: Airborne deployments on NOAA Twin Otter



2012: Conversion to truck-based, scanning instrument

TOPAZ wavelengths & tuning range



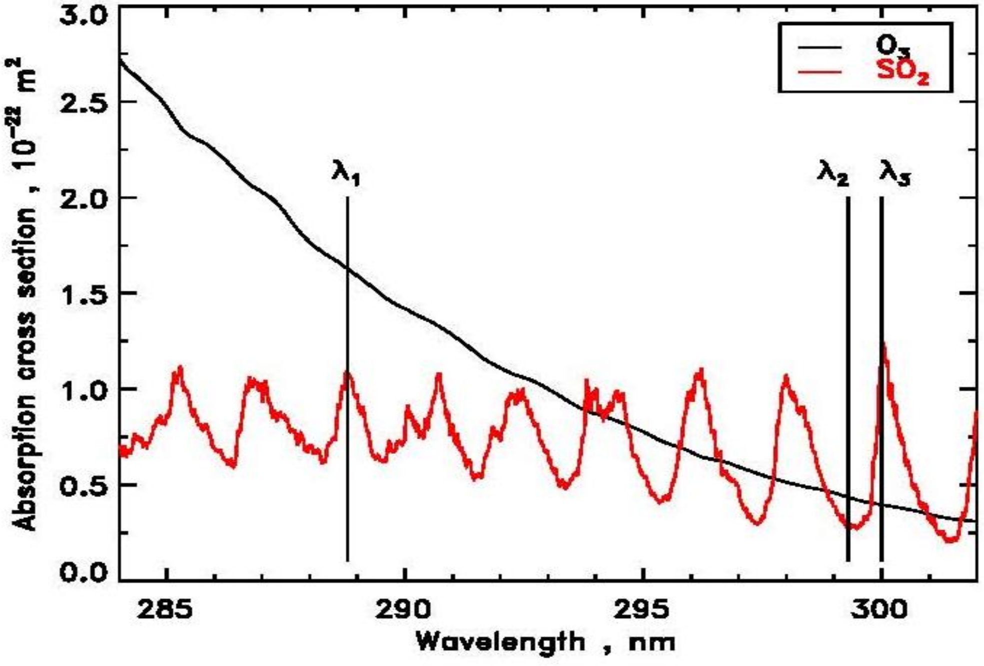
TOPAZ is a tunable, multi-wavelength DIAL system

Advantages of tunability:

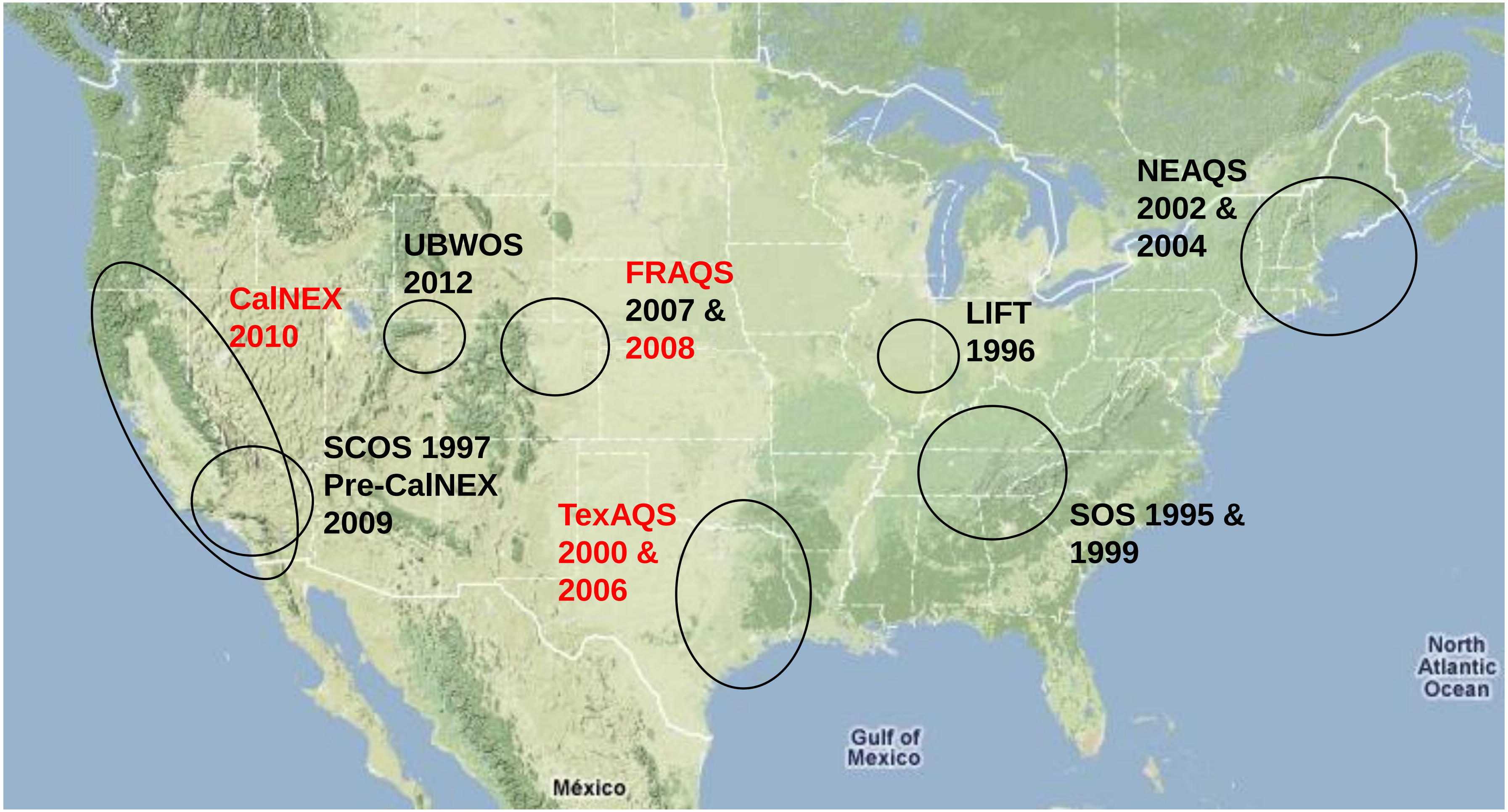
- Wavelengths can be optimized for given atmospheric ozone loading
- Minimize interference from other trace gases, e.g. SO_2

Advantages of multi-wavelength capability:

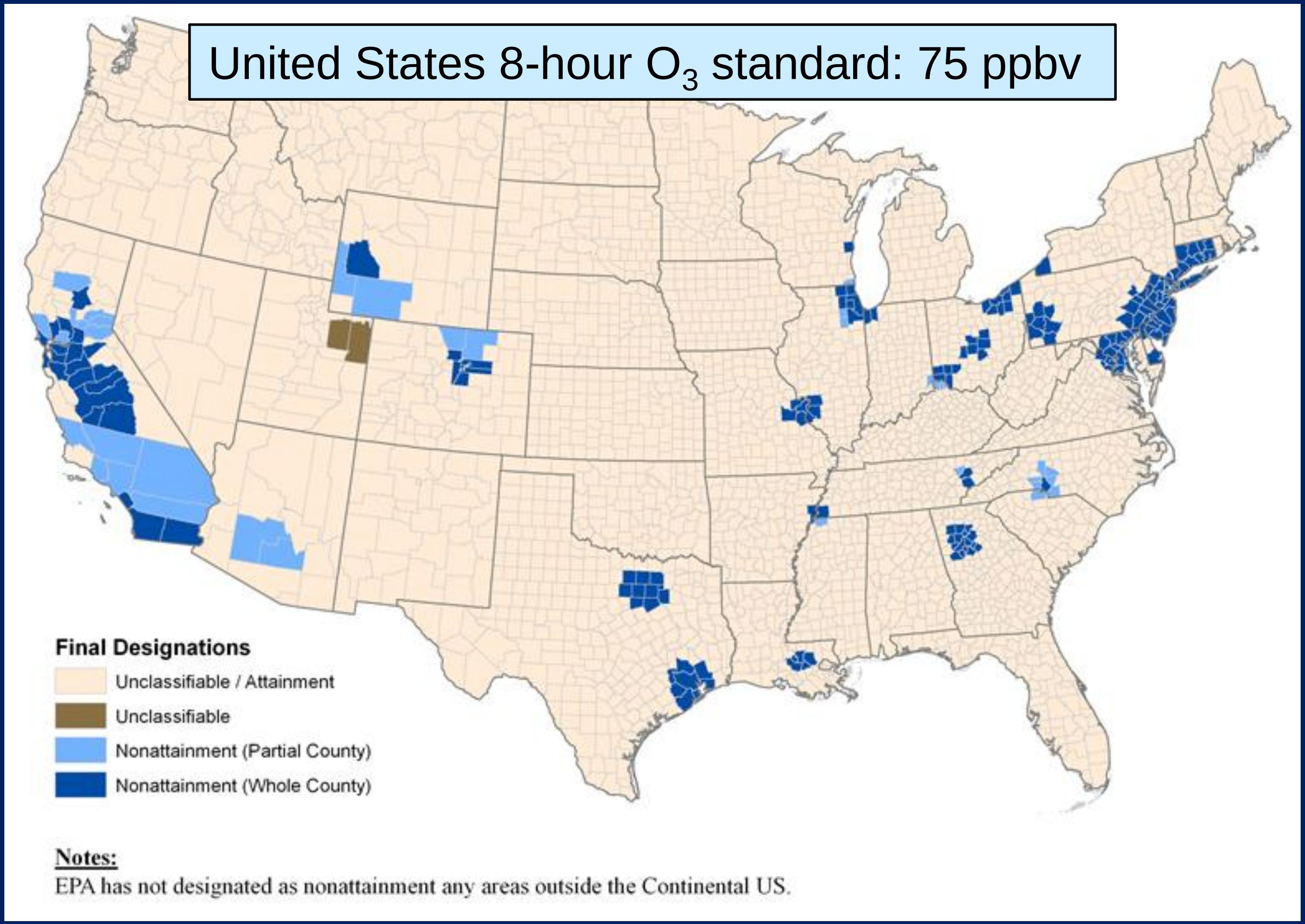
- Allows simultaneous measurement of 2 species (O_3 & SO_2)
- Dual-DIAL application to minimize uncertainties due to aerosol backscatter and extinction corrections



Ozone DIAL Application: Regional Air Quality



Ozone non-attainment areas in the US

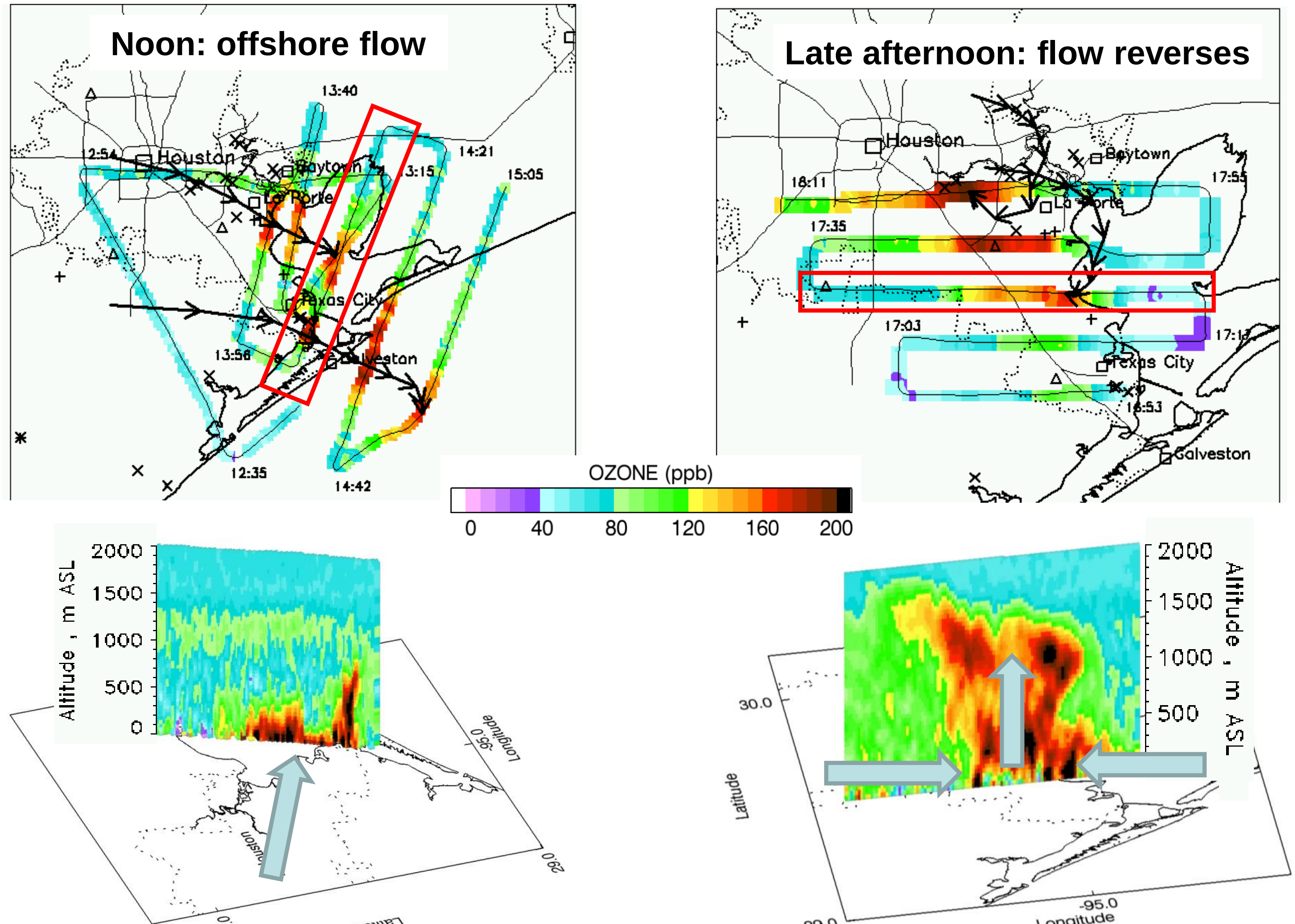


Area is in non-attainment if 3-year average of the annual 4th highest daily maximum 8-hr ozone concentration exceeds 75 ppbv.

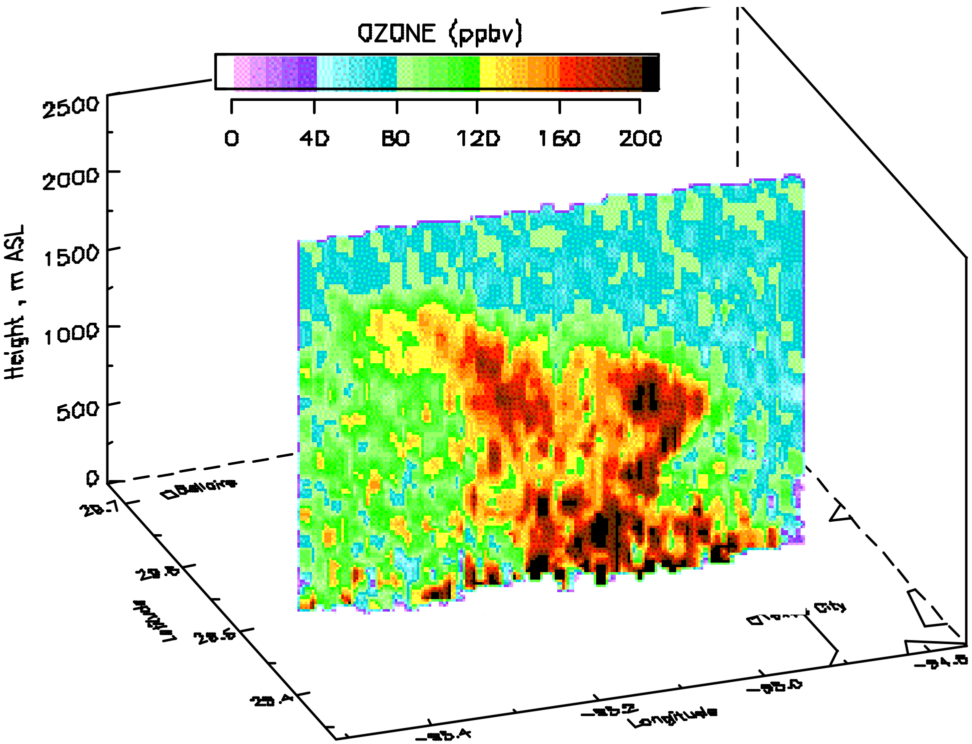
Ozone lidar science objectives

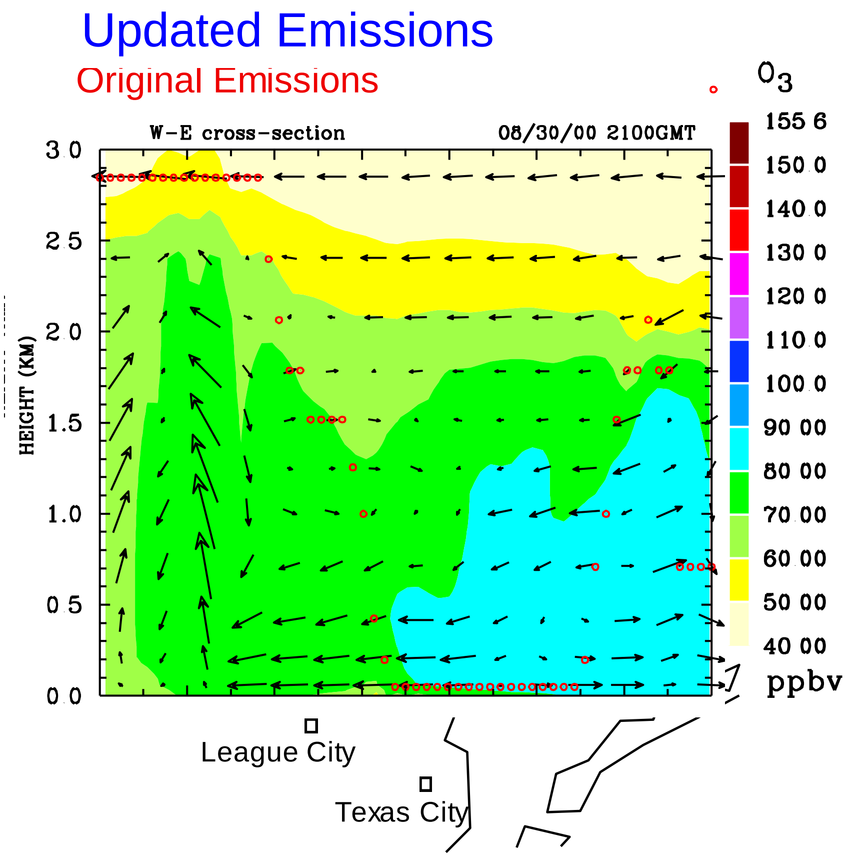
- 3-d distribution of ozone
- Horizontal and vertical transport of ozone on local and regional scales
- Validation of air quality forecasting models

TexAQS 2000 - Local Transport:
Sea-breeze re-circulation of pollutants near Houston, TX



Air Quality forecast model comparison with O_3 DIAL

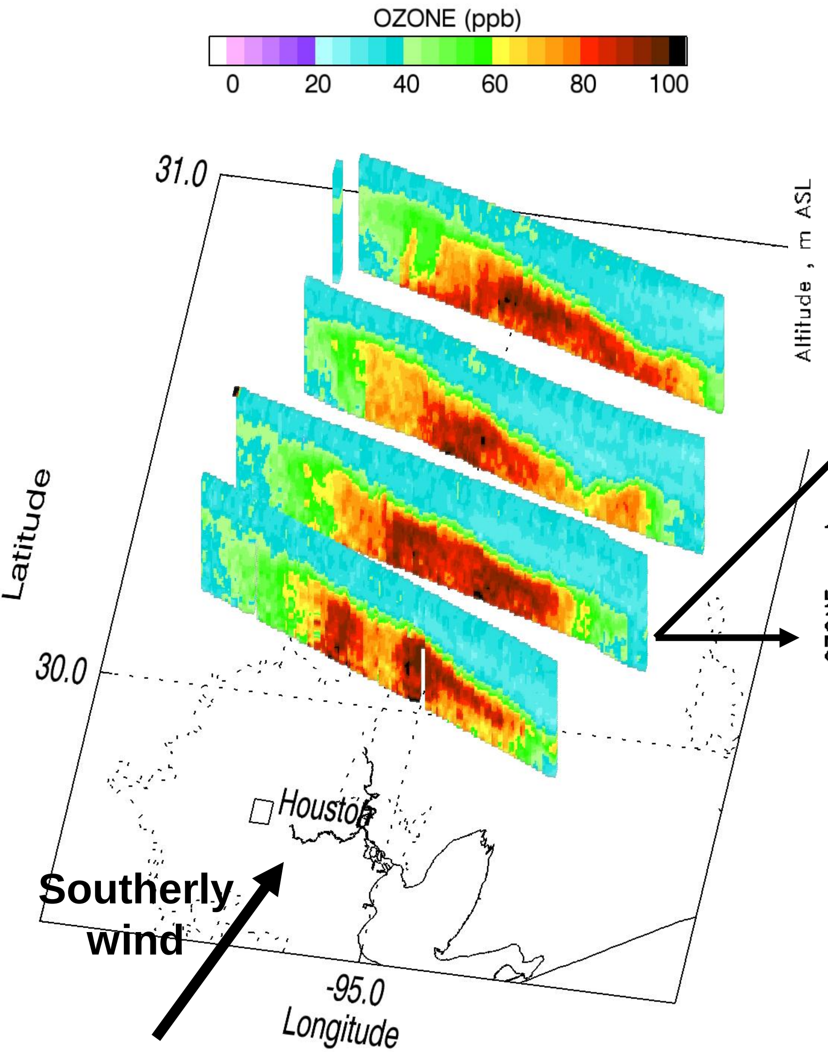


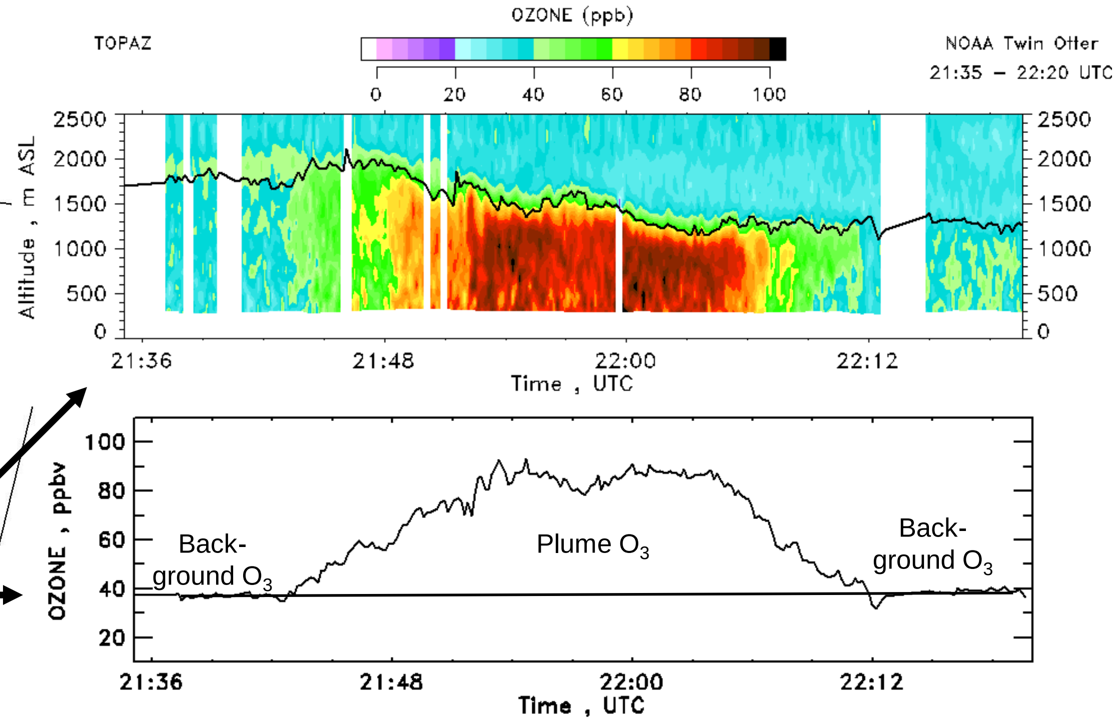


O_3 DIAL measurement

AQ model prediction

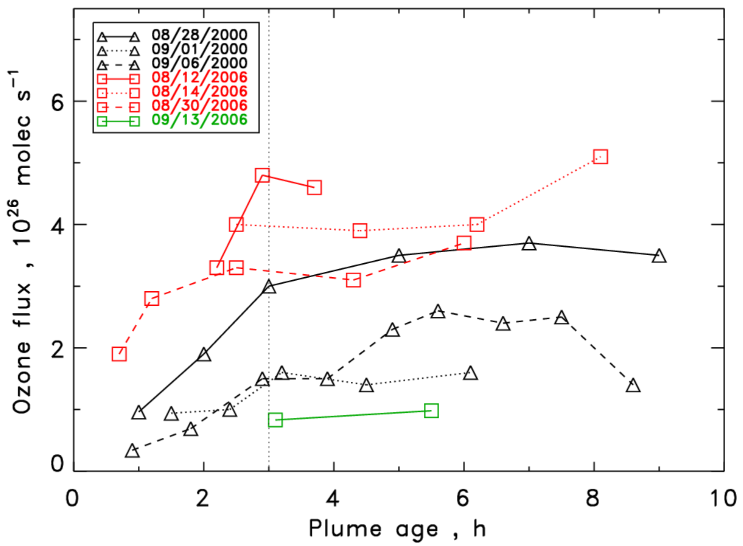
TexAQS 2000 & 2006 - Regional Transport: Estimating ozone exported from Houston

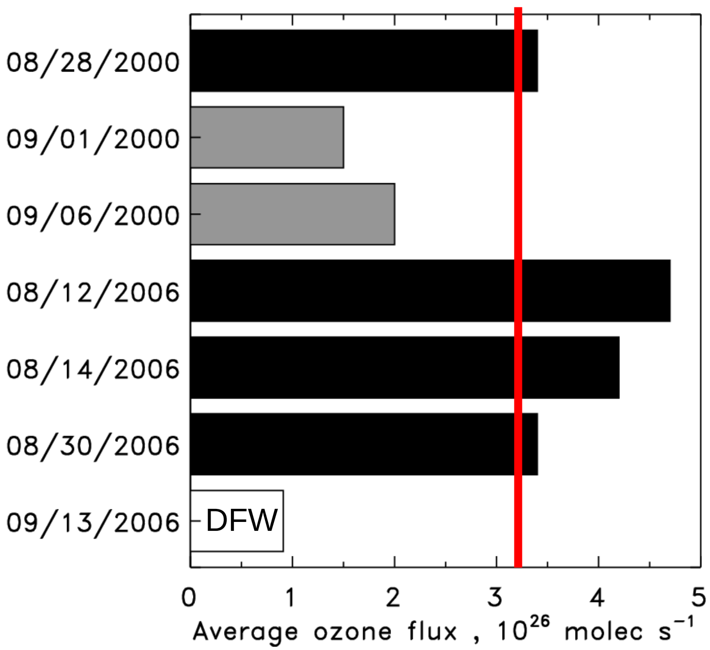


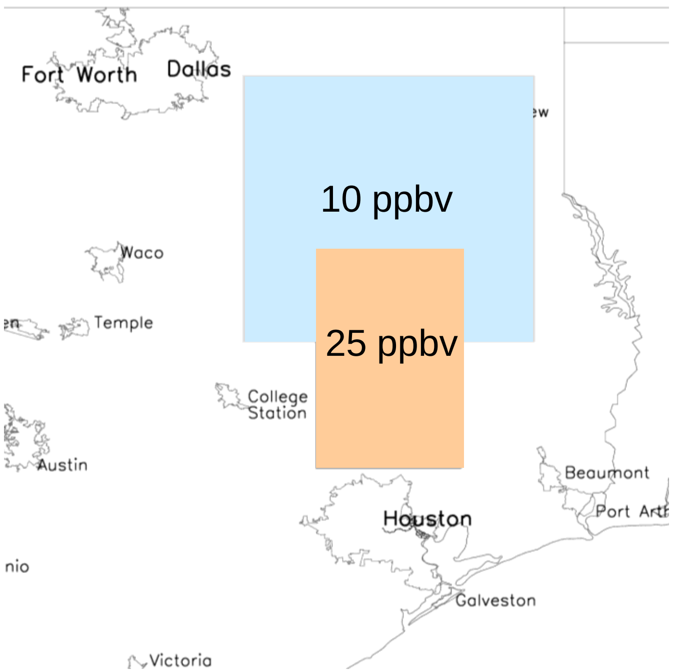


- Integrate excess ozone in plume (plume O_3 – background O_3).
- Multiply with horizontal wind speed (from wind profiler network) to yield ozone flux for each transect.

Horizontal ozone flux and impact on regional air quality

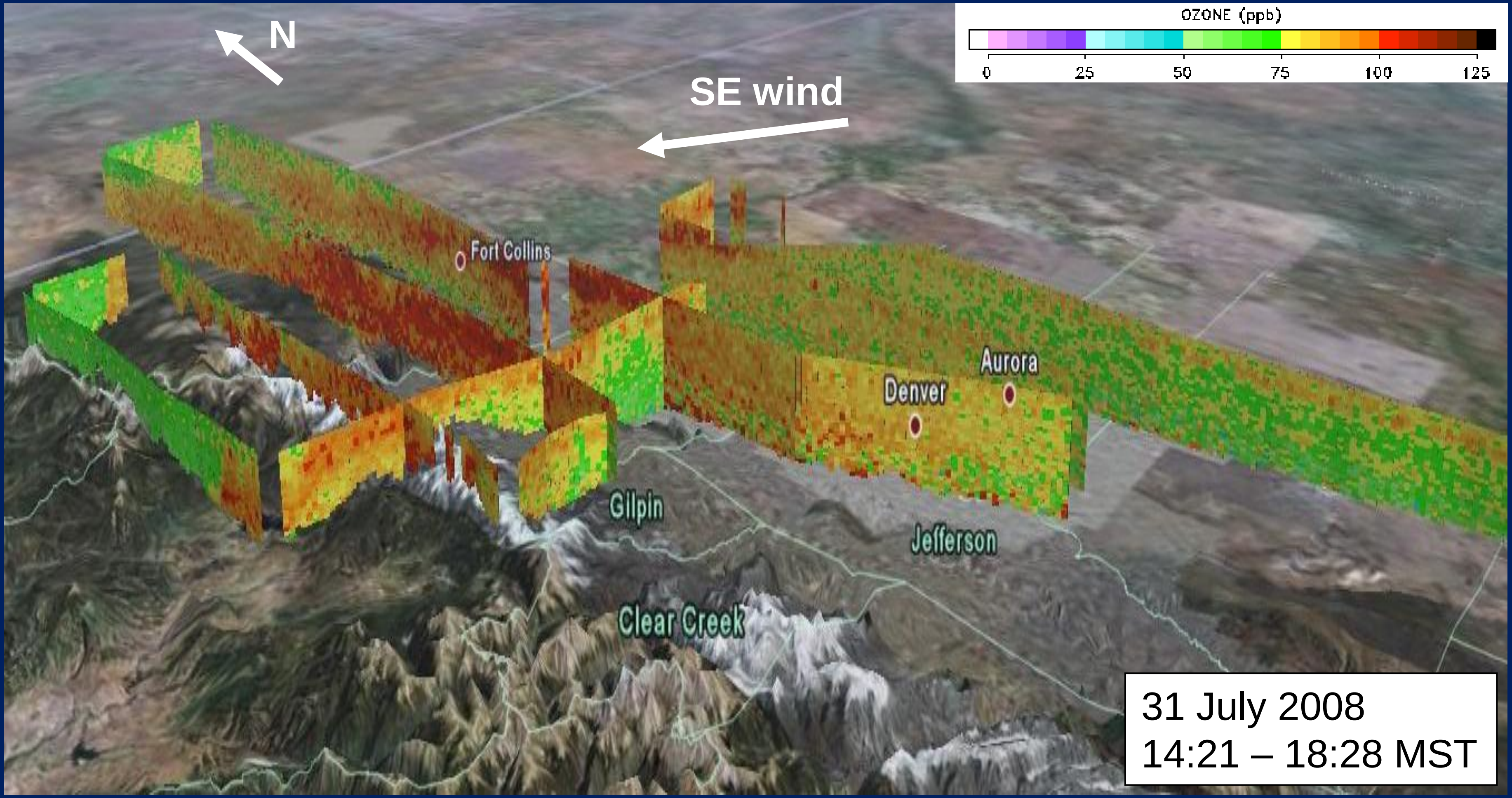






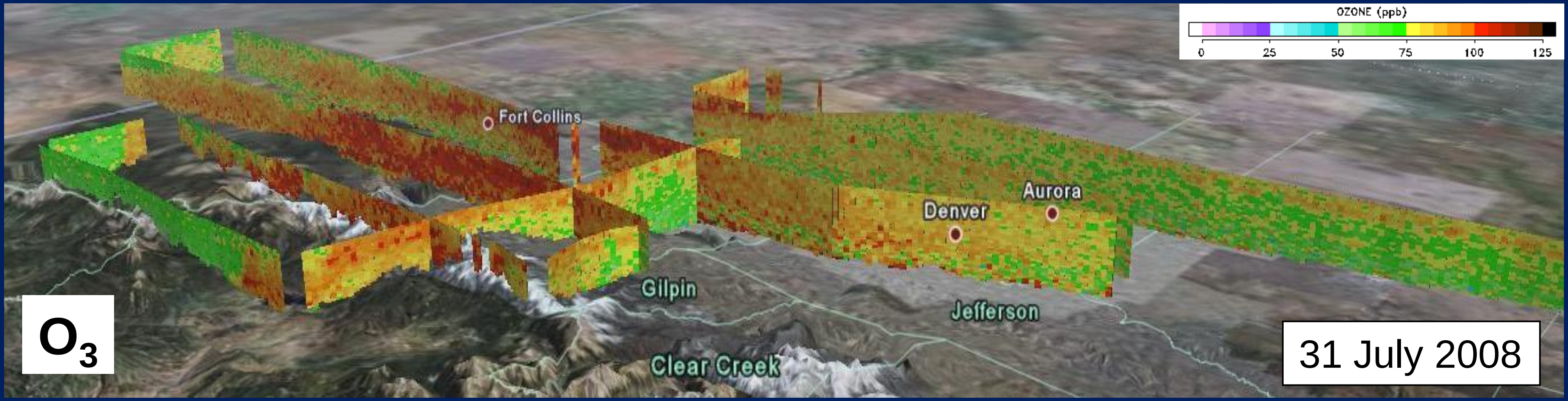
An ozone flux of $3.2 \cdot 10^{26}$ molec s^{-1} emitted over 12 hours is equivalent to a 10 ppbv increase in ozone over a ~ 40,000 km^2 area, assuming a 1.5-km deep mixed layer.

Front Range Air Quality Study 2008: Transport of O_3 into and over the mountains

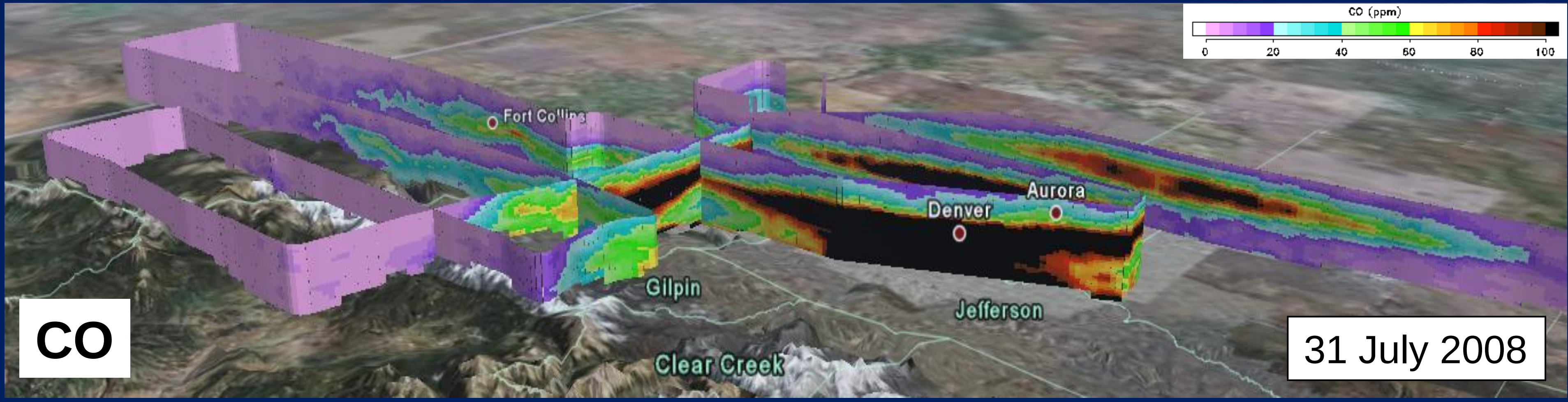


3-d distribution of O_3 from TOPAZ lidar

Front Range Air Quality Study 2008: Comparison of O_3 DIAL measurements with air quality model predictions



TOPAZ lidar measurement

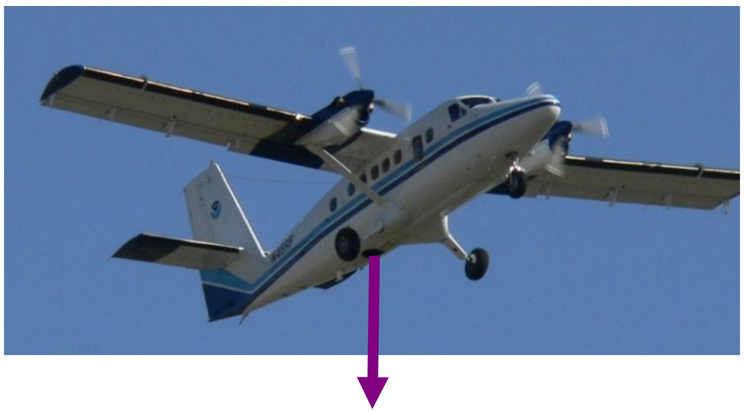


WRF-FLEXPART model results

CalNex 2010:
Export of O_3 from the Los Angeles Basin

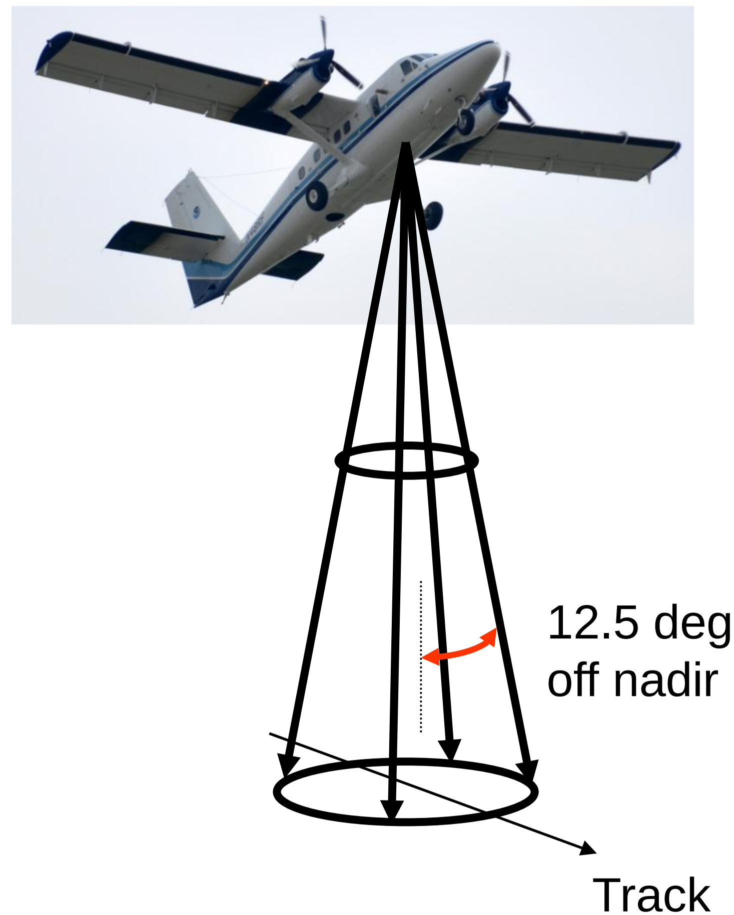
<u>TOPAZ lidar:</u>

Ozone profiles

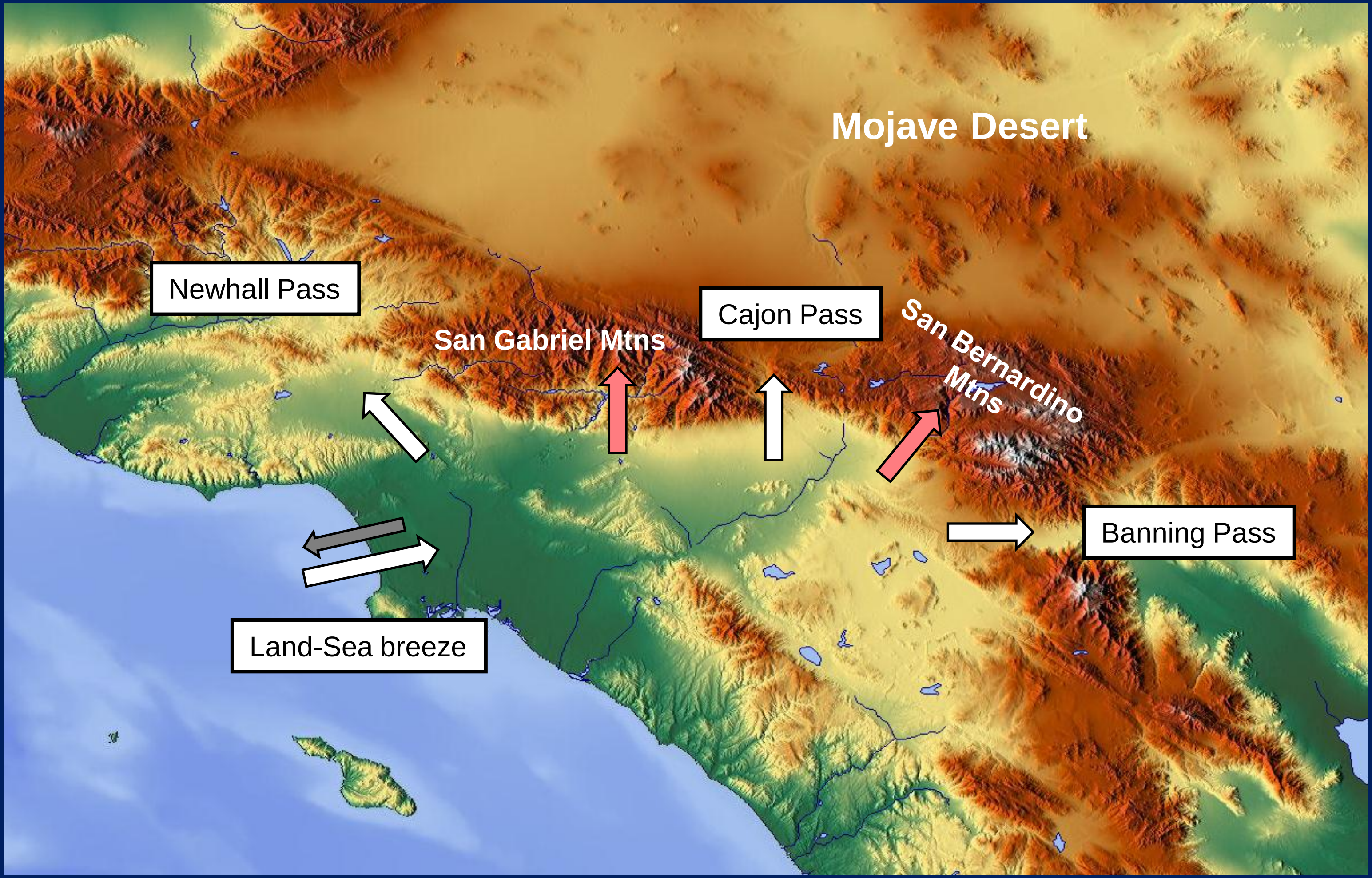


<u>U of Leeds Doppler lidar:</u>

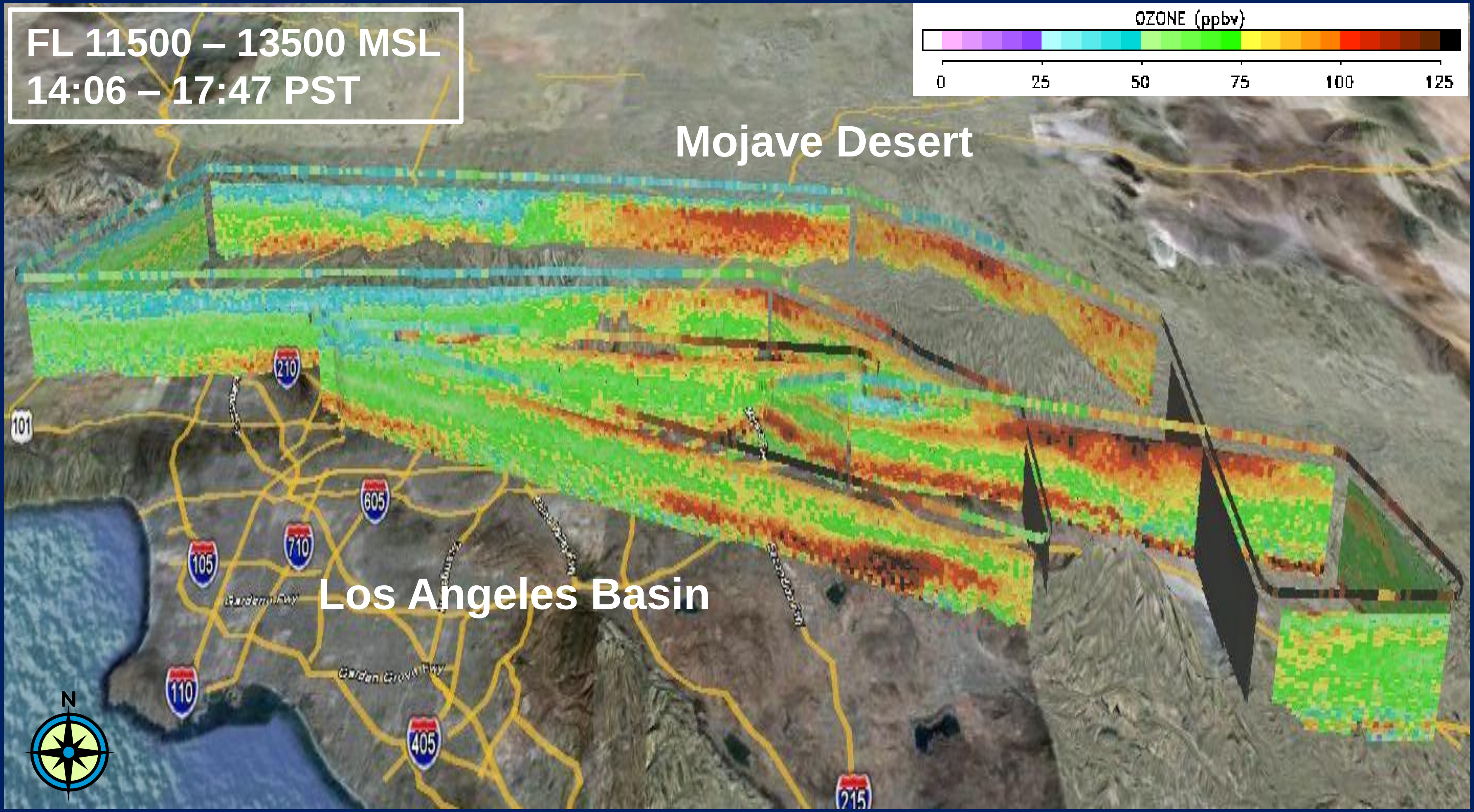
Wind speed & direction profiles



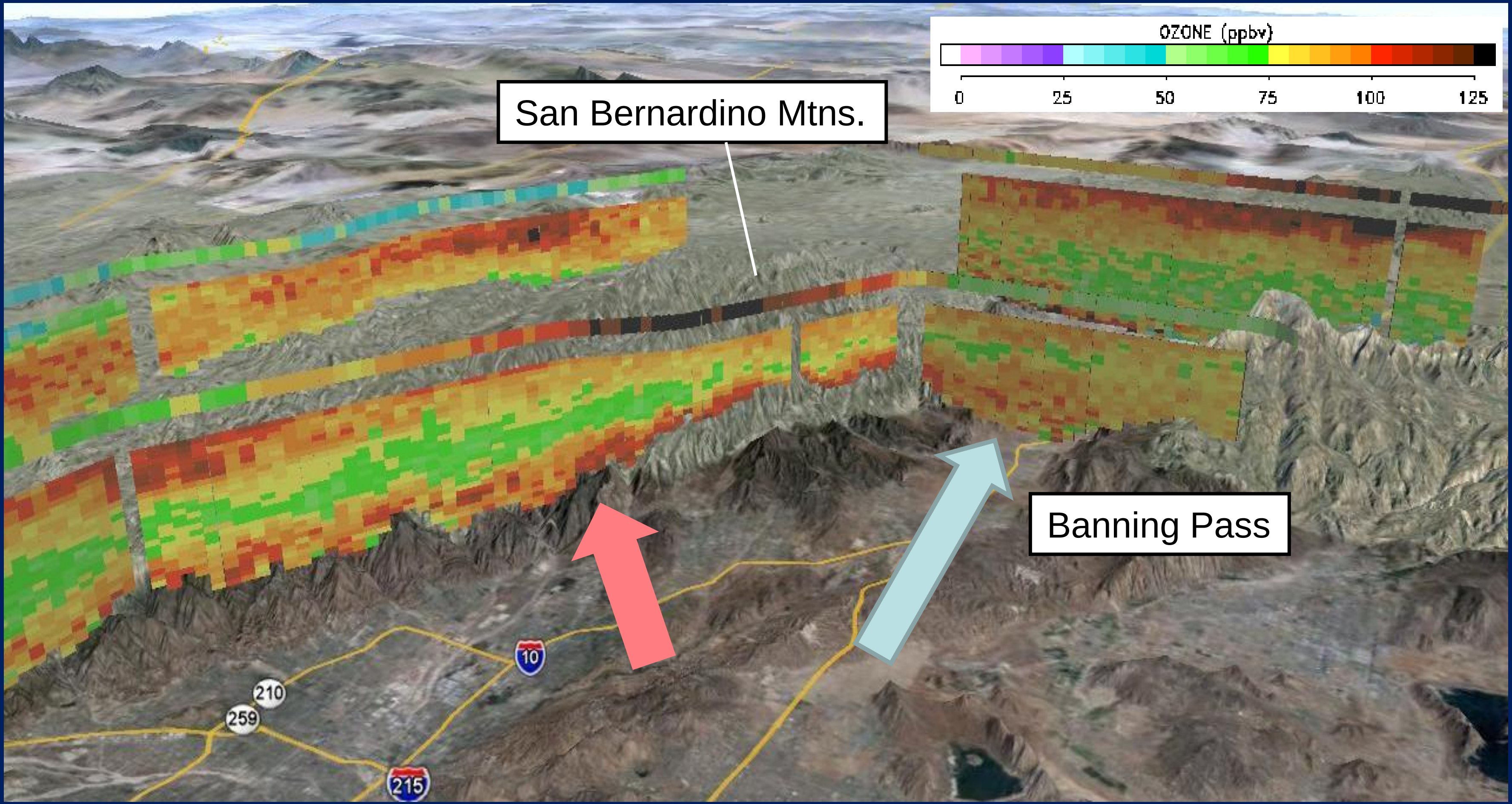
Pollution export pathways from the L A Basin



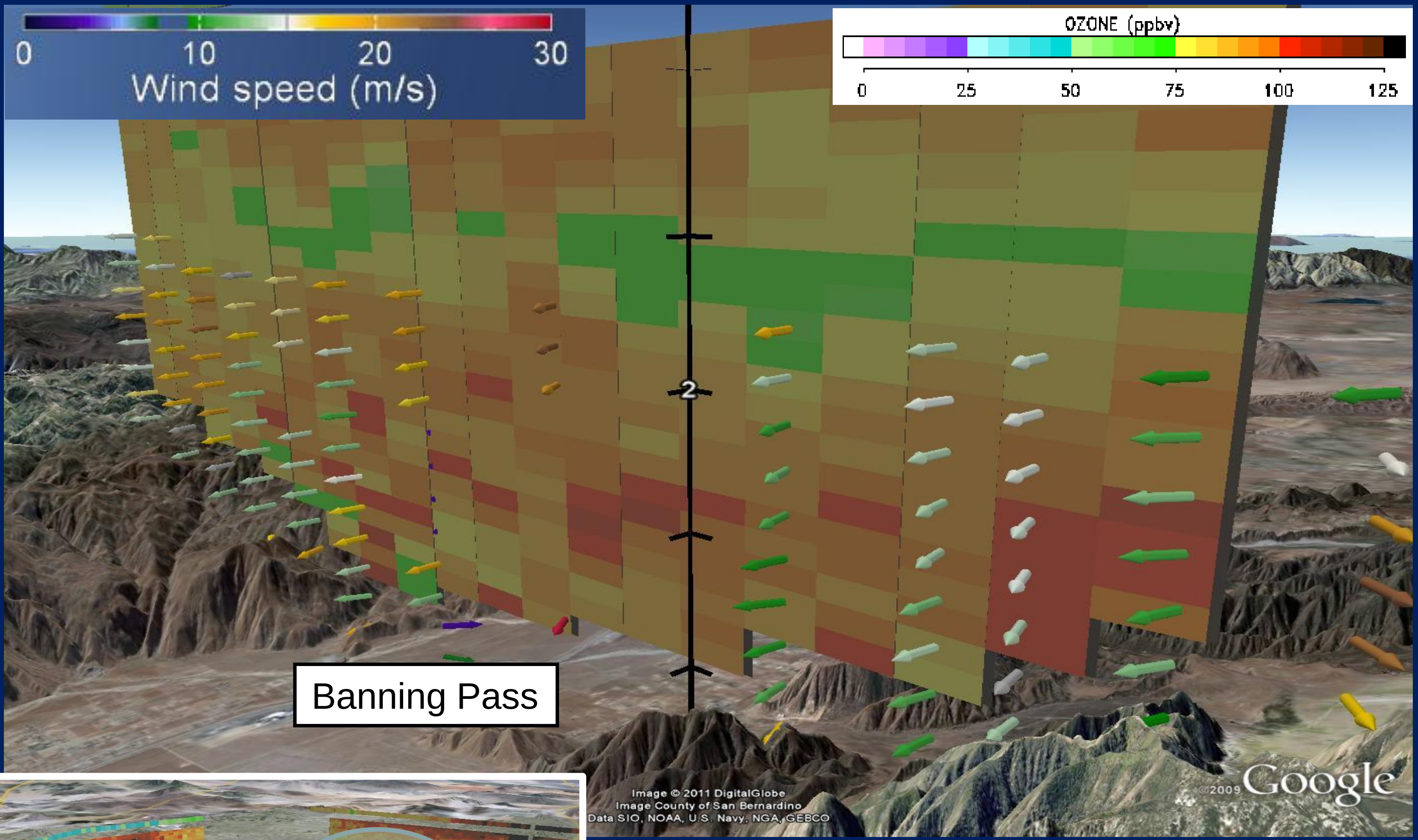
2 July 2010
O_3 distribution over L A Basin and Mojave Desert

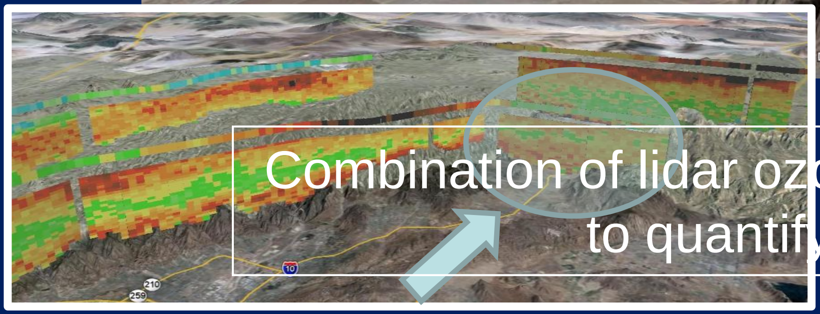


2 July 2010: Transport thru Banning Pass and along/over San Bernardino Mtns



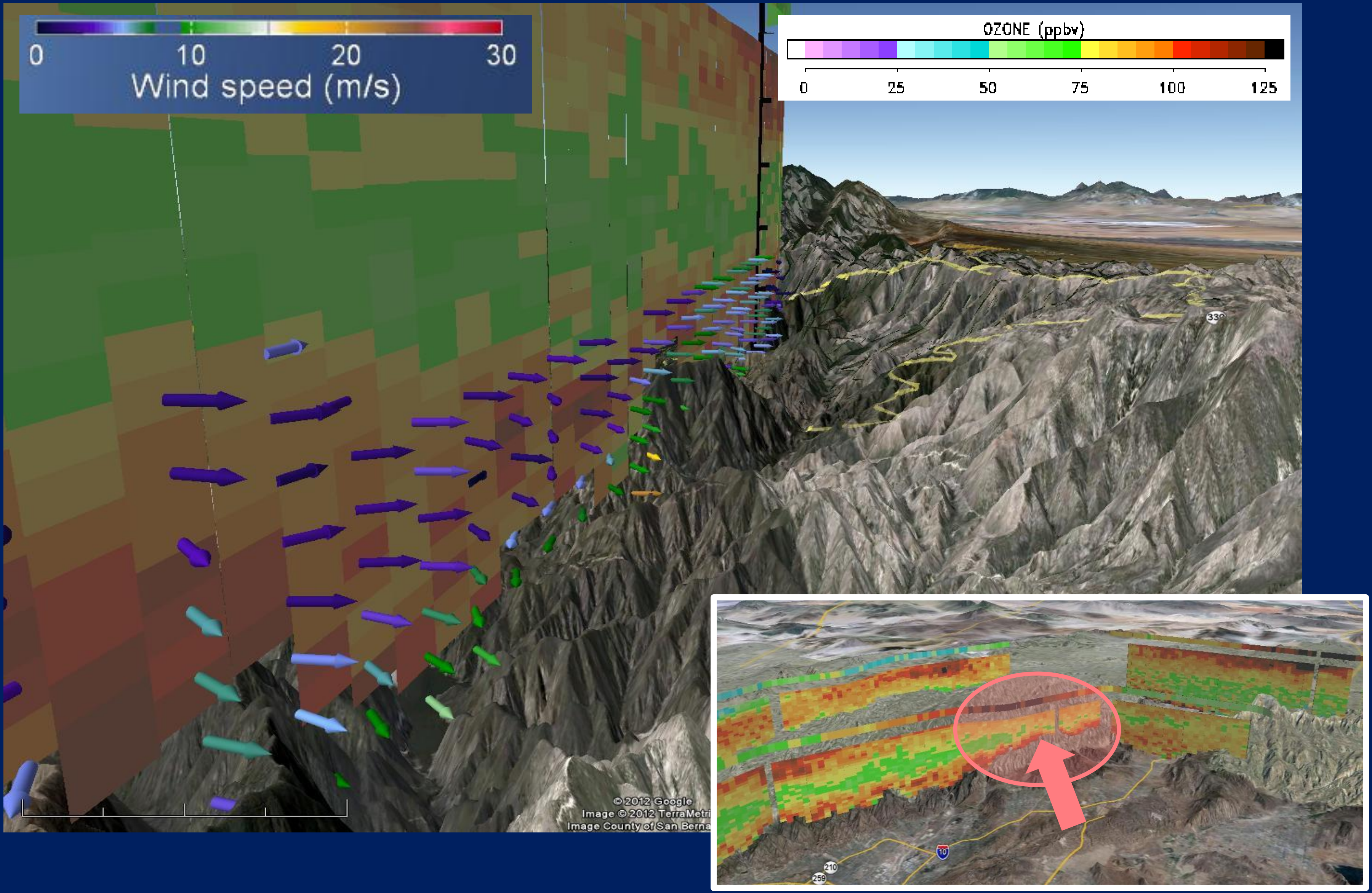
2 July 2010: Transport thru Banning Pass





Combination of lidar ozone and wind measurements allows to quantify horizontal ozone flux

2 July 2010: Transport along/over San Bernardino Mtns



Selected References (1)

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.
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NOAA/ESRL/CSD DIAL systems (slides 6 - 10)

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., C. J. Senff, A. O. Langford, A. M. Weickmann, D. C. Law, J. L. Machol, D. A. Merritt, R. D. Marchbanks, S. P. Sandberg, W. A. Brewer, R. M. Hardesty, R. M. Banta, 2011: Development and application of a compact, tunable, solid-state airborne ozone lidar system for boundary layer profiling, *J. Atmos. Oceanic Technol.*, doi: 10.1175/JTECH-D-10-05044.1.

Selected References (2)

Ozone DIAL applications (slides 11- 25)

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.

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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.