

TOLNet

Tropospheric Ozone LIDAR Network

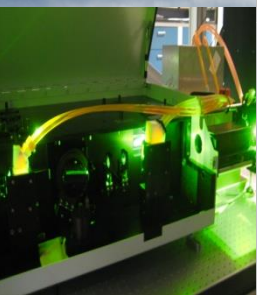


TOLNet Ozone and Aerosol Observations during Past Major Campaigns

Mike Newchurch, Raul Alvarez, Sunil Baidar, Tim Berkoff, Gao Chen, Guillaume Gronoff, Matthew Johnson, Fernando Keil, Shi Kuang, Andy Langford, Thierry Leblanc, Liqiao Lei, Brandi McCarty, M. Patrick McCormick, Tom McGee, Fred Moshary, Christoph Sneff, Michael Shook, Jia Su, John Sullivan, Kevin Strawbridge, Bo Wang, Michael Zucker

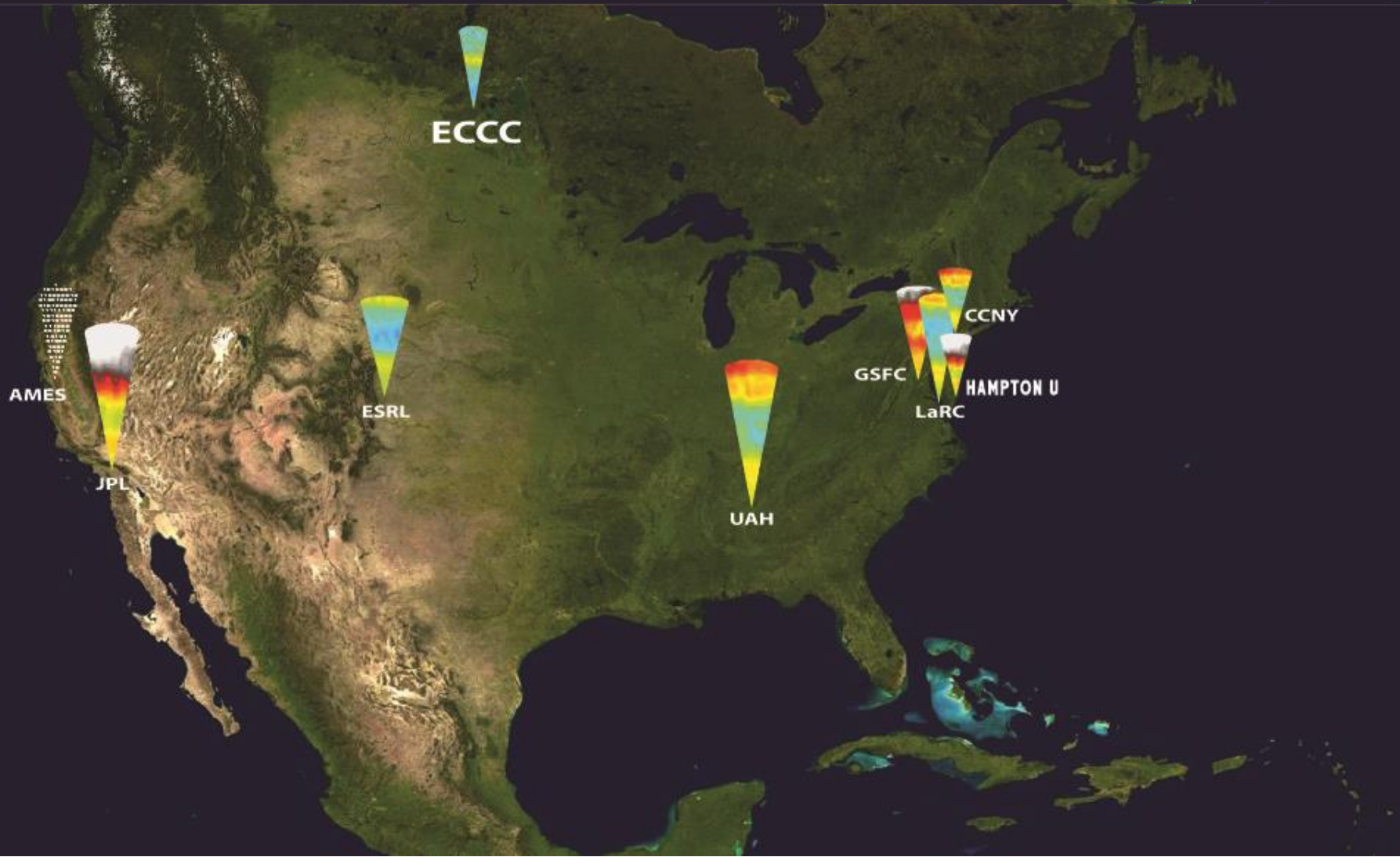
AMS Meeting
12-17 January 2020
Boston, MA

<https://www-air.larc.nasa.gov/missions/TOLNet/>



TOLNet

Tropospheric Ozone LIDAR Network



- **Tropospheric Emissions: Monitoring of Pollution (TEMPO) mission is planned for launch in 2022**

- **TEMPO will be the first geostationary air quality satellite for North America to provide hourly measurements throughout the U.S. for key trace gases**

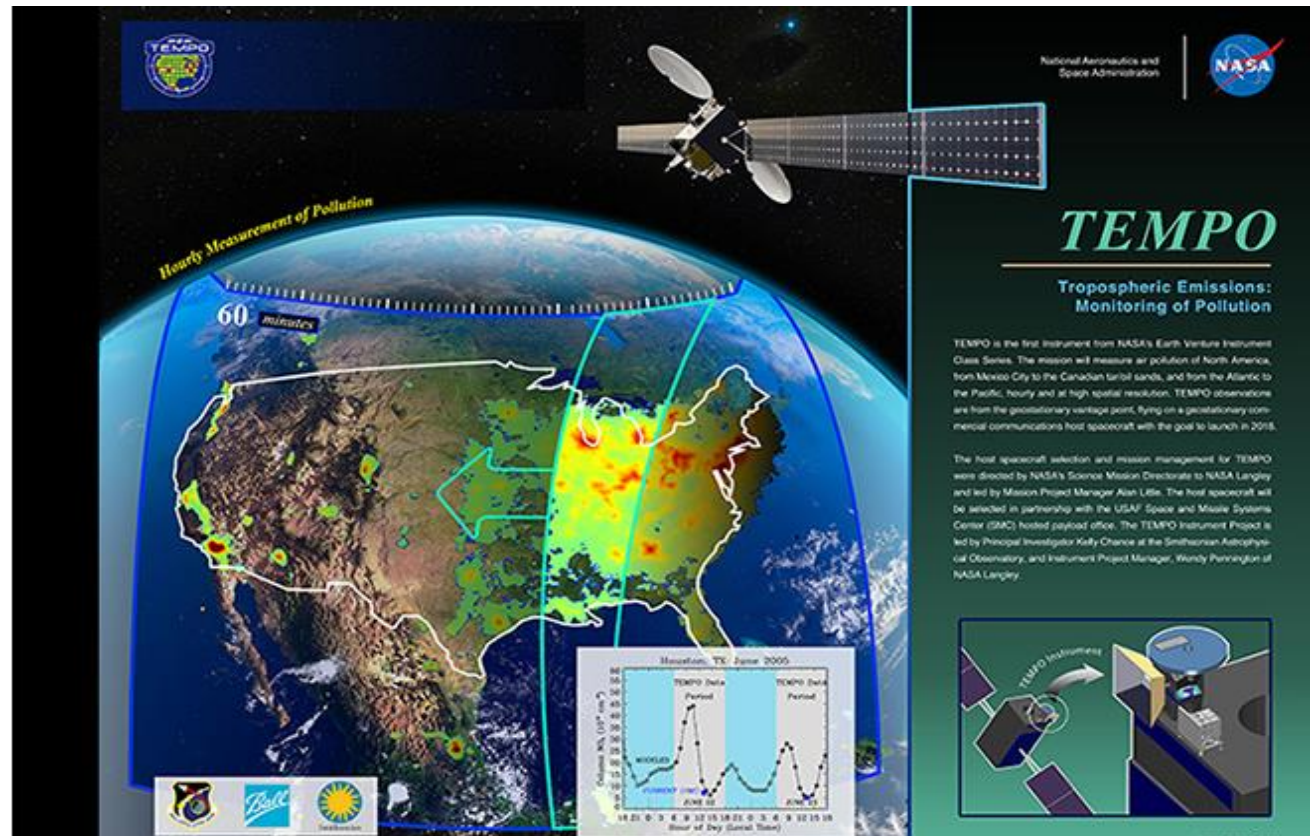
- **TEMPO data products planned to be generated include ozone 0–2 km O_3 , free tropospheric O_3 , and the stratospheric O_3 column**

- **Observations of ozone and other constituents in complex coastal regions are critical for TEMPO validation and improvement in its data product retrievals**

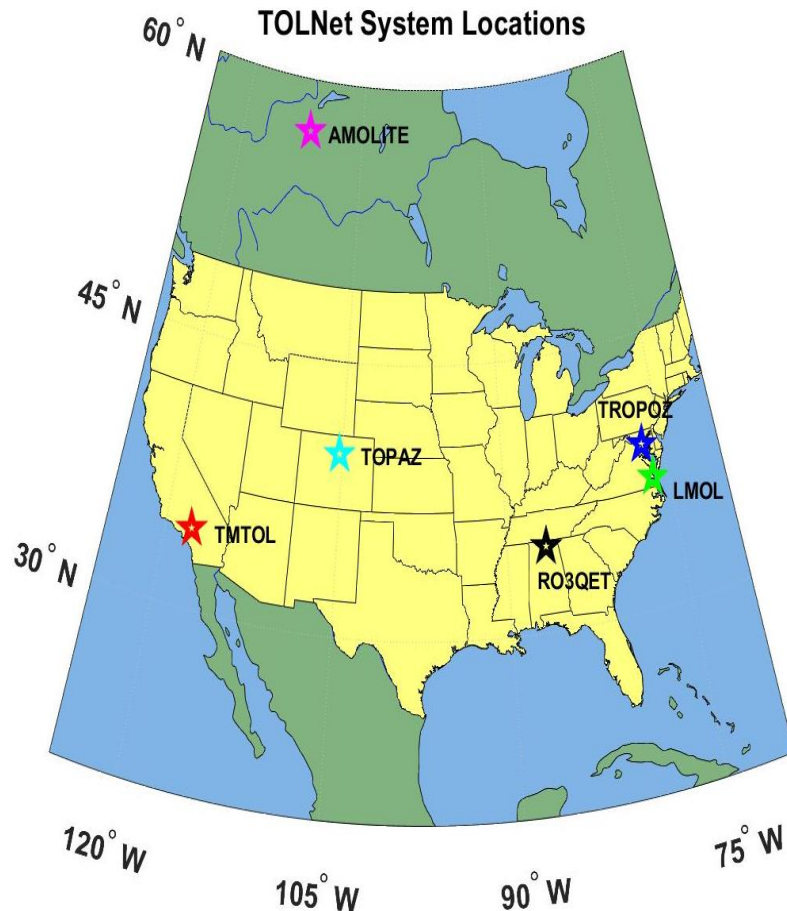
- **Key OWLETS motivation was to examine AQ in a transition zone where spatial variability can be large over small distances**

OWLETS Motivation: Satellite evaluation

Tim Berkoff/NASA/LaRC

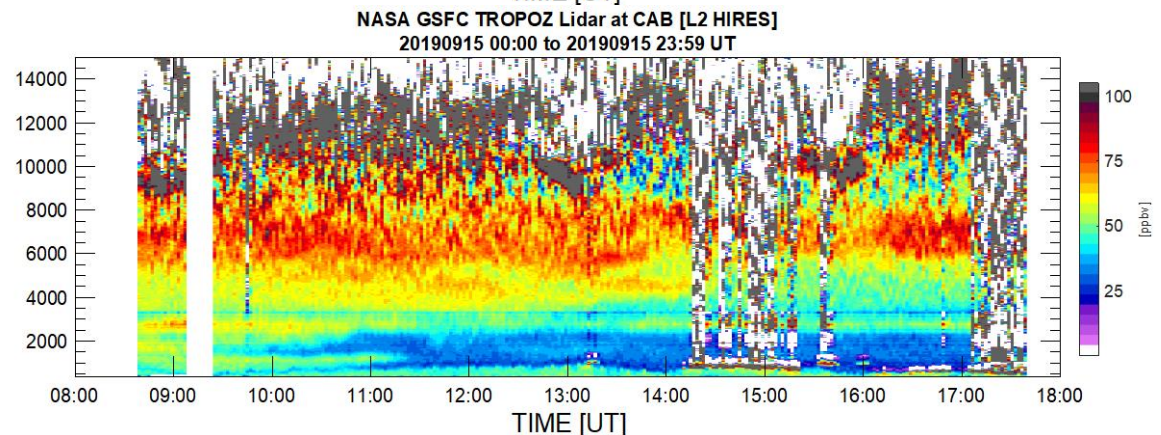
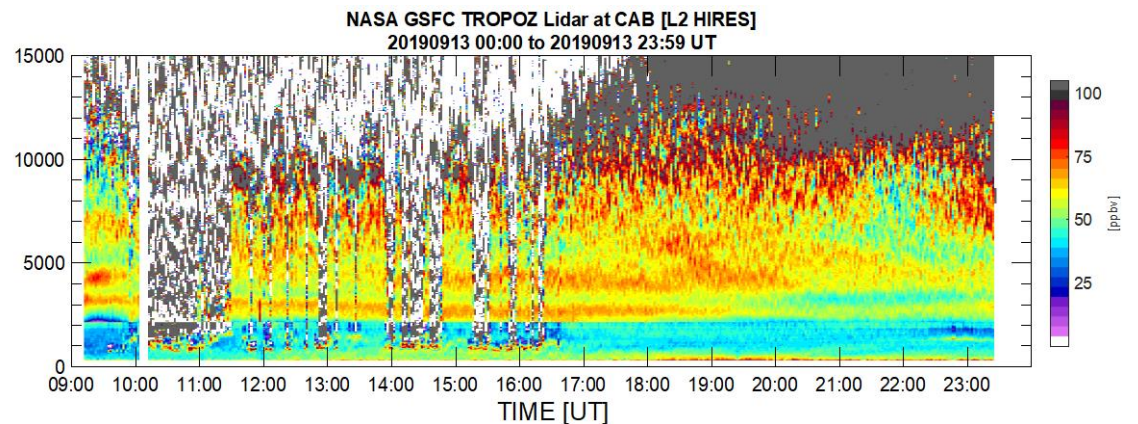
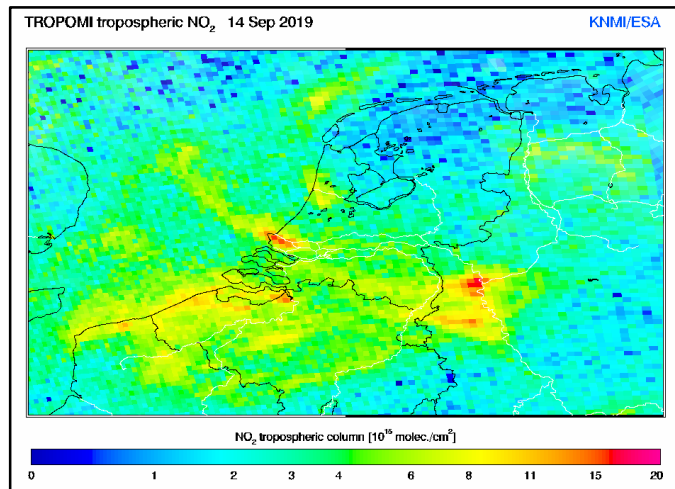


Network-wide TOLNet Validation of TROPOMI Ozone



- Proposal “Validation of TROPOMI ozone profile retrievals using observations from the Tropospheric Ozone Lidar Network (TOLNet)” selected for the Sentinel-5 Precursor Validation Team (S5PVT).
- TOLNet measurements are a desirable validation dataset as the observations have:
 1. higher vertical resolution compared to satellite retrievals in the troposphere
 2. high accuracy
 3. minimal dependence on a priori information
- 100’s of hours of correlative observations made during S5P overpass times (+/- 30 min.) from the six TOLNet systems.
- Provide novel information about the accuracy/precision of the O₃ profiles at all vertical layers of the troposphere (e.g., planetary boundary layer (PBL), free troposphere (FT), and the upper troposphere (UT)).
- Geophysical validation (i.e., characterize accuracy (systematic and random bias) and precision) of the Level 2 (L2) ozone profile products ('full' and 'tropospheric') from S5P TROPOMI retrievals.

The 2019 TROPOMI vaLidation eXperiment (TROLIX): A Sentinel-5p/TROPOMI validation campaign at the Cabauw Experimental Site for Atmospheric (CESAR)



*Above) TROPOMI NO₂ tropospheric columns for Sep 14.
Right) 2-min high-resolution lidar curtains showing upper tropospheric active region*

Courtesy John Sullivan
John.t.Sullivan@nasa.gov;



Using TOLNet to assess the impact of a priori ozone profiles on TEMPO tropospheric ozone retrievals

Matthew S. Johnson, X. Liu, P. Zoogman, J. Sullivan, M. J. Newchurch, S. Kuang, T. Leblanc, and T. McGee
Atmos. Meas. Tech., 11, 3457-3477, <https://doi.org/10.5194/amt-11-3457-2018>, 2018

Background:

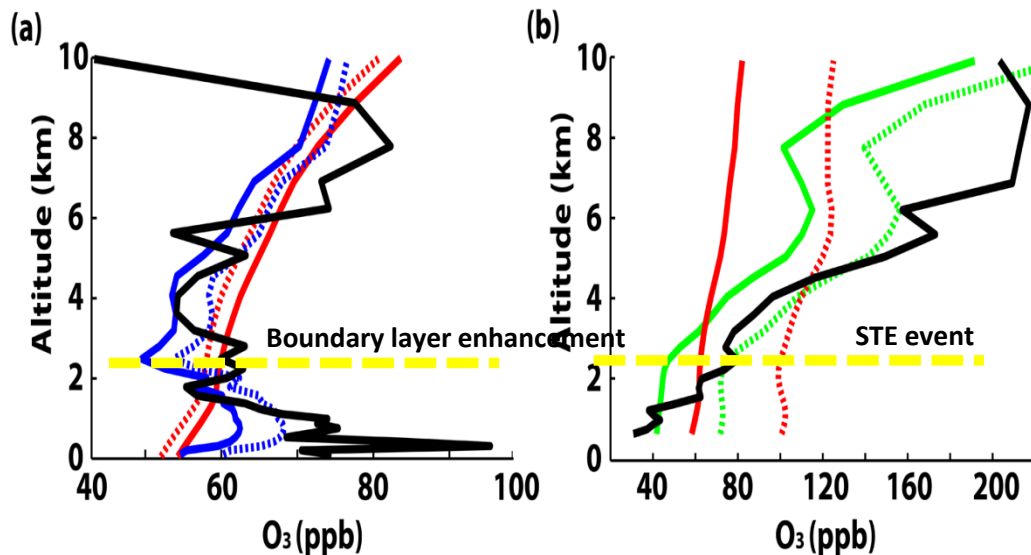
- NASA's Tropospheric Emissions: Monitoring Pollution (TEMPO) sensor will provide high spatiotemporal resolution air quality data. A major goal of TOLNet is to provide data to validate/evaluate TEMPO.
- More accurate a priori ozone (O_3) profiles result in higher accuracy remote-sensing O_3 retrievals.

Analysis:

- This study was designed to:
 1. evaluate the representativeness of O_3 profiles from an ozonesonde climatology (TB-Clim) and modeled products (GEOS-Chem and NASA GMAO GEOS-5 FP and MERRA2) using TOLNet observations.
 2. assess the impact of the various O_3 profile products, when applied as a priori, on the accuracy of tropospheric O_3 retrievals from TEMPO.

Findings:

- Modeled O_3 profiles, in particular those from a CTM, compare best to TOLNet observations, and when applied as the a priori, resulted in the most accurate TEMPO retrievals of near-surface (0-2 km column) O_3 .
- Using TOLNet to determine the most accurate source of a priori O_3 profiles resulted in the decision to use a CTM-derived a priori data set in future TEMPO O_3 retrievals.



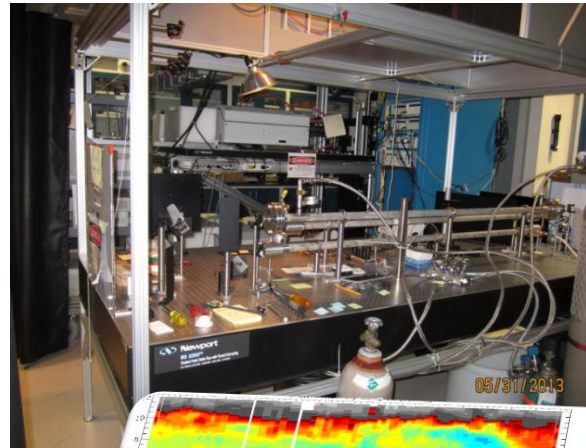
Vertical O_3 profiles from the TB-Clim ozonesonde climatology, initial product suggested to be used as a priori in TEMPO retrievals, do not capture the dynamic vertical O_3 profiles measured by TOLNet, however, model data demonstrate skill in reproducing an observed (a) lowermost tropospheric (LMT, 0-2 km) O_3 enhancement (GEOS-Chem) and a (b) STE event (GEOS-5 FP). This study/figure emphasizes that a priori profile shape (solid lines) will impact the ability of TEMPO (dashed lines) to accurately retrieve near-surface O_3 .

Significance:

- ✓ TOLNet provides a valuable data source to evaluate the ability of a priori products and high spatial resolution satellite (e.g., TEMPO and TROPOMI) retrievals to reproduce the dynamic vertical tropospheric O_3 profiles occurring in nature.

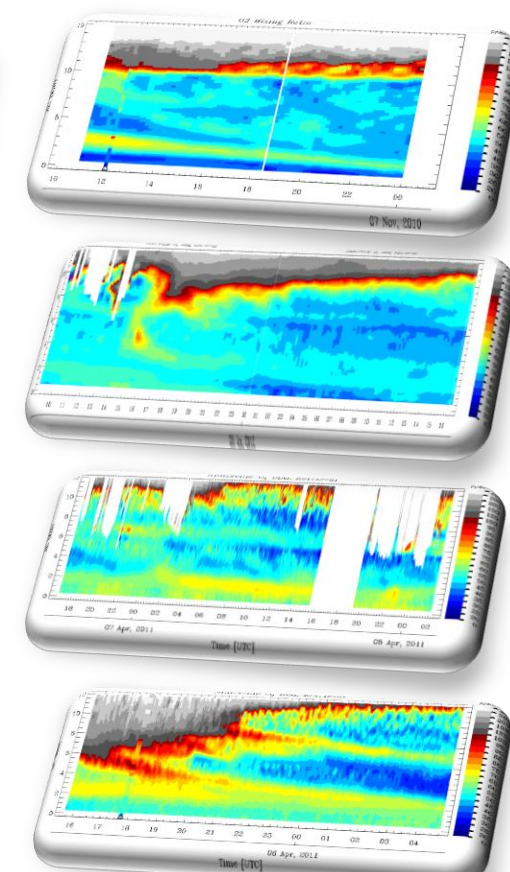
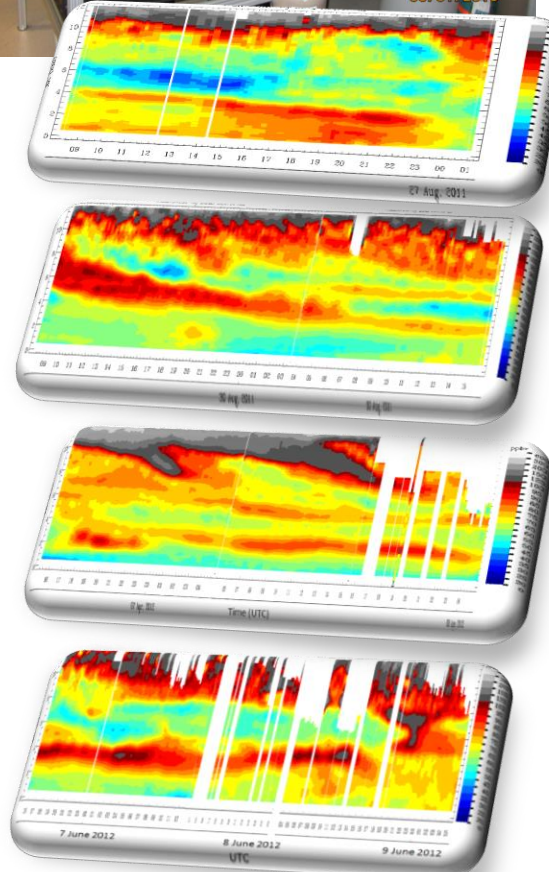
UAH Ground-based O3 lidar

Name	RO ₃ QET (Rocket-city O3 Quality Evaluation in the Troposphere) lidar
Affiliation	UAH
Host location	Huntsville, AL
Set-up	Fixed-location
Transmitter type	Quadruple Nd:YAG pumped Raman laser
Wavelength (nm)	289, 299
Receiver size (cm)	40, 10, 2.5
Measurable range (km AGL)	0.1-12
Reference	[Kuang et al., 2011, 2013]



Raman shifted 289/299

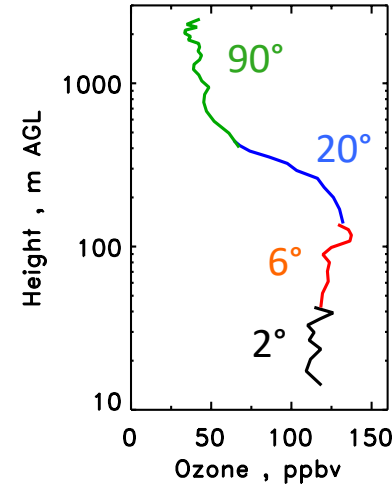
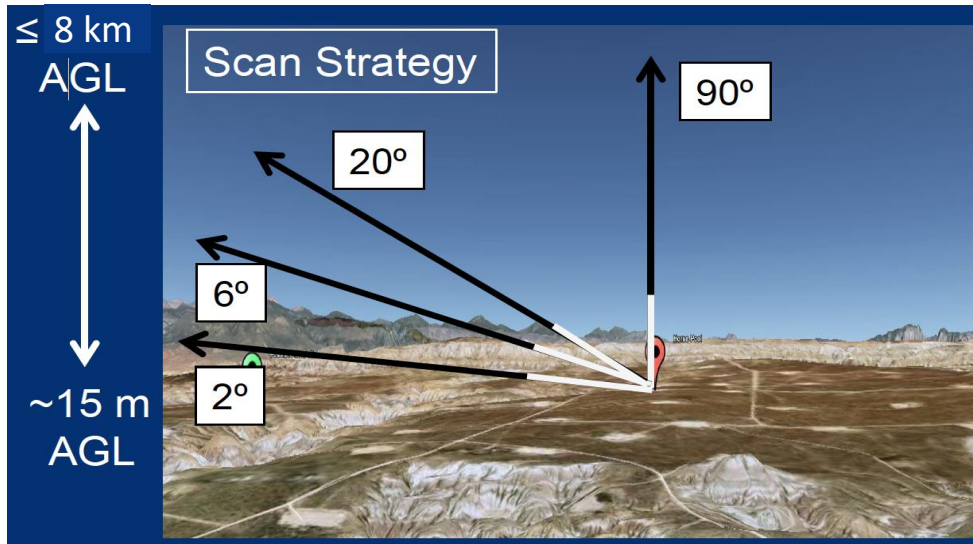
Examples



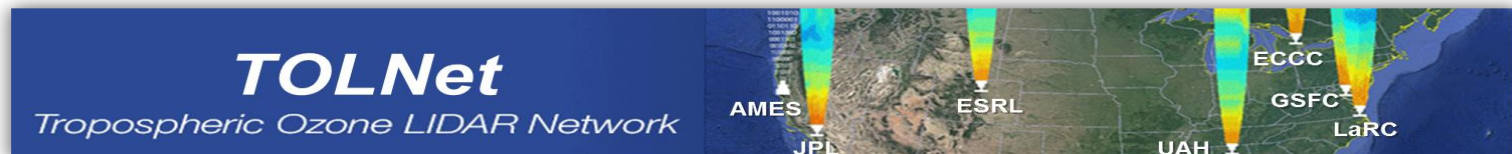
NOAA TOPAZ Ozone Lidar

(TOPAZ = **T**unable **O**ptical **P**rofiler for **A**erosol and **o**Zone)

- Tunable UV ozone DIAL
- Based on solid-state Ce:LiCAF laser
- Measures ozone and aerosol backscatter profiles



Composite vertical O₃ and aerosol profiles every 8 min



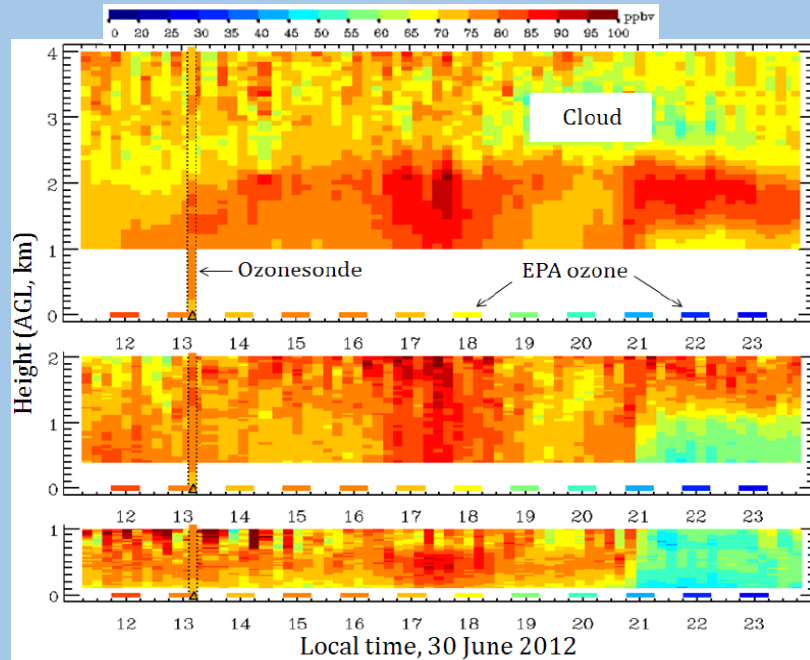


TOLNet lidars **Measuring Ozone Below 100 m**

TOLNet is an emerging ground-based network making the first ozone lidar profiles from < 100 m to the stratosphere.

Mike Newchurch¹, Raul Alvarez², Russell DeYoung⁴, Mike Hardesty², Shi Kuang¹, Andy Langford², Thierry Leblanc⁵, Stuart McDermid⁵, Tom McGee³, Christoph Senff², John Sullivan³

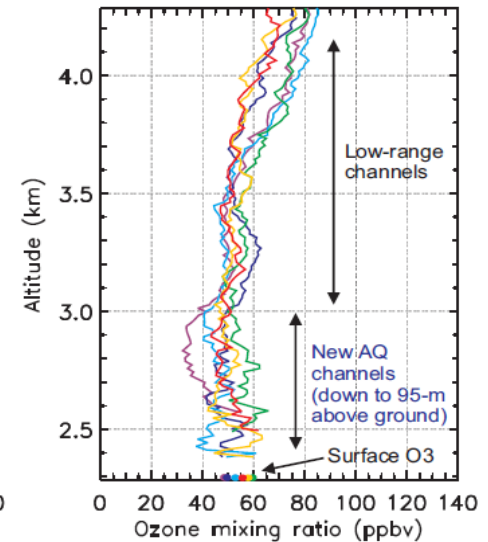
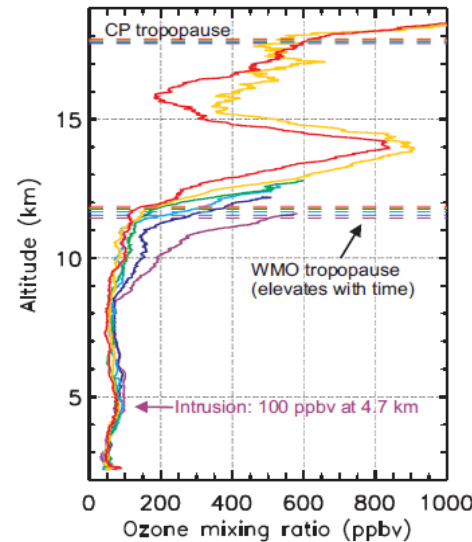
5 TOLNet Stations: ¹UAHuntsville, ²NOAA/ESRL, ³NASA/GSFC, ⁴NASA/LaRC, ⁵NASA/JPL



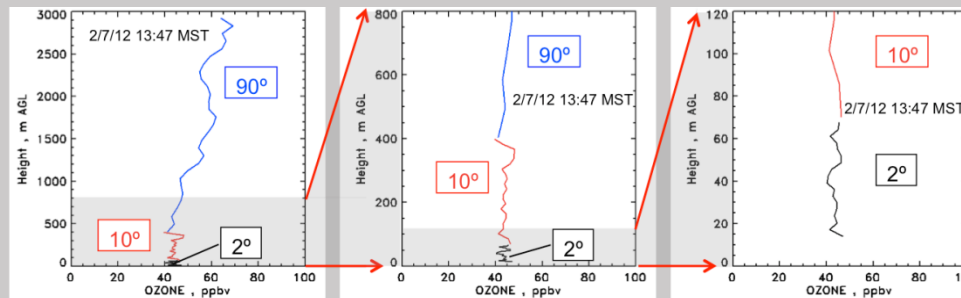
UAH Ozone lidar retrievals from the 3 lowest altitude channels compared with ozonesonde (marked by black triangle at 13:10 launch time) and EPA (~16 km away) hourly surface measurements. A 4th channel (not shown) measures the middle and upper troposphere.

JPL-Table Mountain tropospheric ozone lidar, April 9-10, 2013 (UT)
15-hour measurement streak (04/09 15:11 - 04/10 5:40) with experimental AQ channels

Purple: 15:11-17:15 UT Green: 22:54-00:58 UT
Blue: 17:15-19:20 UT Orange: 01:03-03:04 UT
Cyan: 19:52-22:19 UT Red: 03:37-05:40 UT



The NOAA/ESRL two-axis scanning lidar is installed in a truck. By using the scanner to direct the beam to low elevation angles, measurements are obtained to within **a few meters of the surface**. Azimuth scanning provides horizontal structure of ozone.



Lidar observations were made at elevation angles of 2°, 10°, 90° and pieced together to create a profile with higher vertical resolution near the surface.

TOLNET

Tropospheric Ozone LIDAR Network



Ozone lidar



Ozonesonde

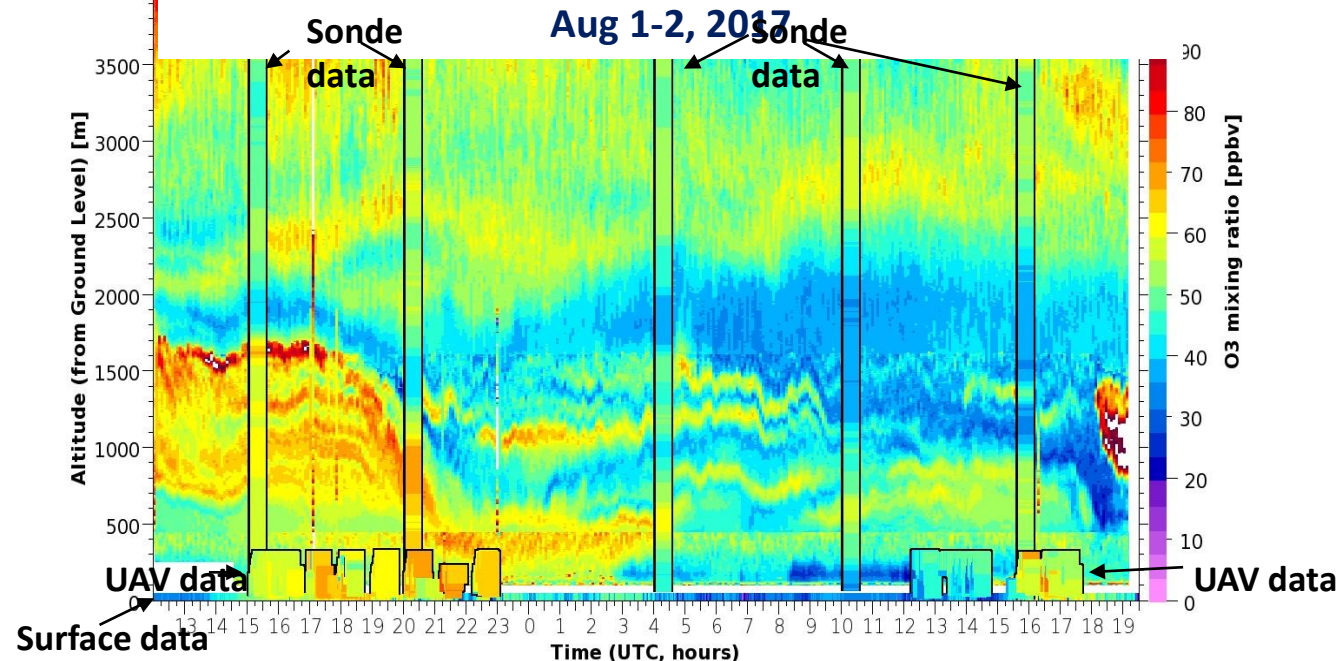


UAV

<http://www-air.larc.nasa.gov/missions/TOLNet/>

Tim Berkoff/NASA/LaRC

TOLNet Langley Mobile Ozone Lidar: Preliminary Data Ozone Data Obtained at the “over-water” CBBT site



During the Summer 2017 Ozone Water Land Environmental Transition Study (OWLETS) in the Tidewater region of Southern Virginia, ozone profile data were obtained at the third island of the Chesapeake Bay Bridge Tunnel, 7.5 miles off-shore. On Aug 1-2, the Langley Mobile Ozone Lidar (LMOL) ran for 30+ hours capturing diurnal cycle ozone dynamics resulting from the collapse of the Aug 1 daytime boundary layer and resultant residual layers leading into Aug 2. Also highlighted are the ozonesonde launches and data collected by a UAV/drone carrying an in-situ ozone sensor. The UAV/drone sensor provided the ability to investigate near-range variability, and helped to validate the capabilities of a new near-surface lidar channel on LMOL. This data when combined with other OWLETS measurements will help evaluate **ozone transition behavior from land to water in complex coastal scenes** where large gradients in ozone can occur.

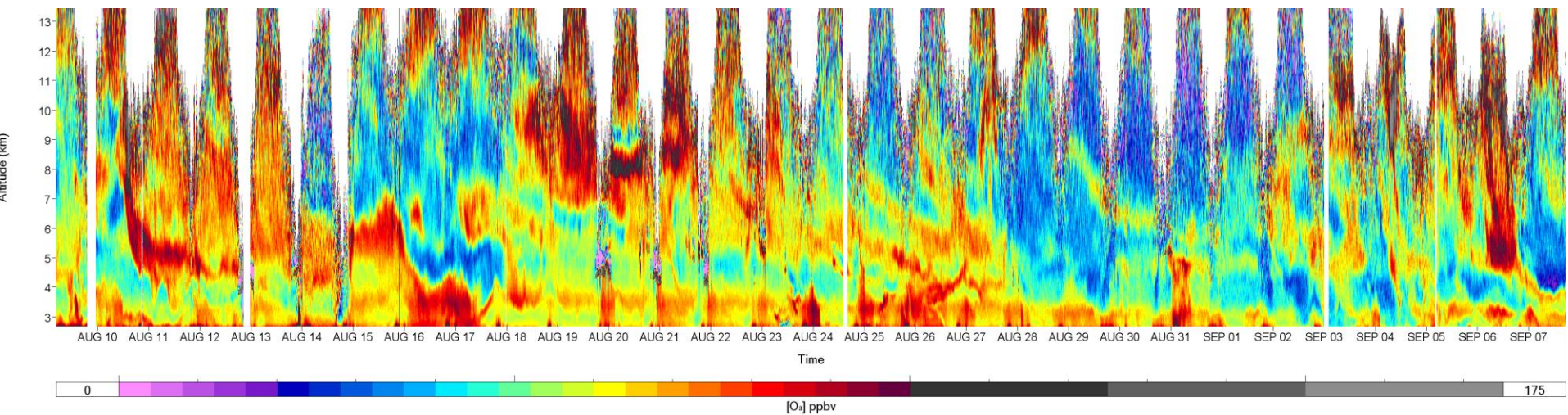
TOLNET

Tropospheric Ozone LIDAR Network



ECCC continuous, **autonomous** observations at SCOOP:
31 days including the BlueCut fire TMF evacuation

Courtesy of K. Strawbridge

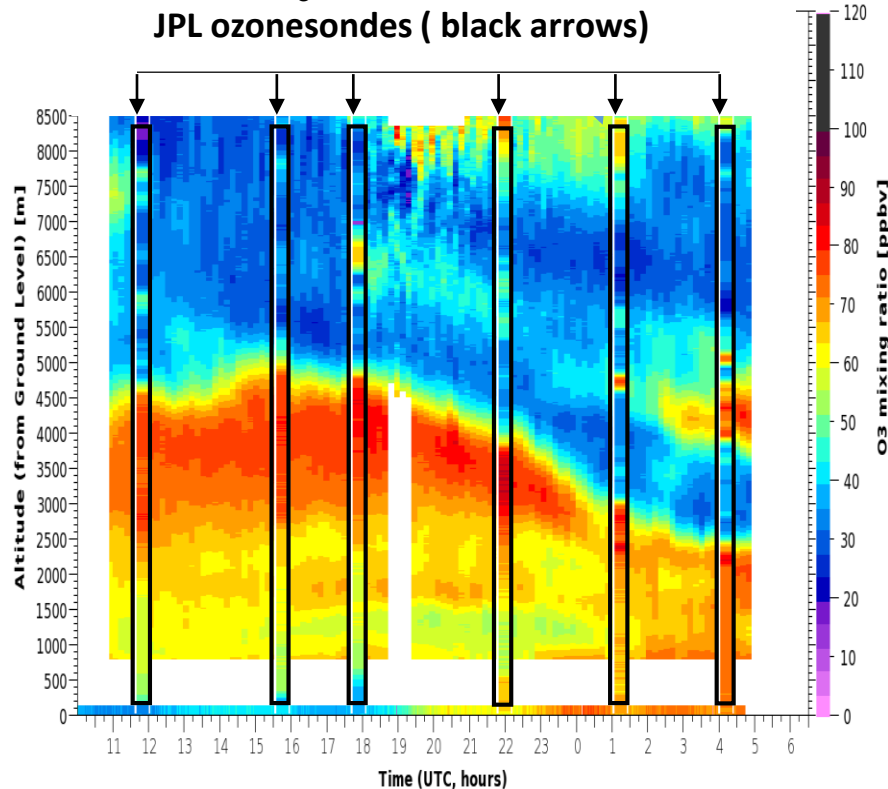


Tropospheric Ozone Lidar Network (TOLNet): Developing the maturity of O₃ lidar measurements

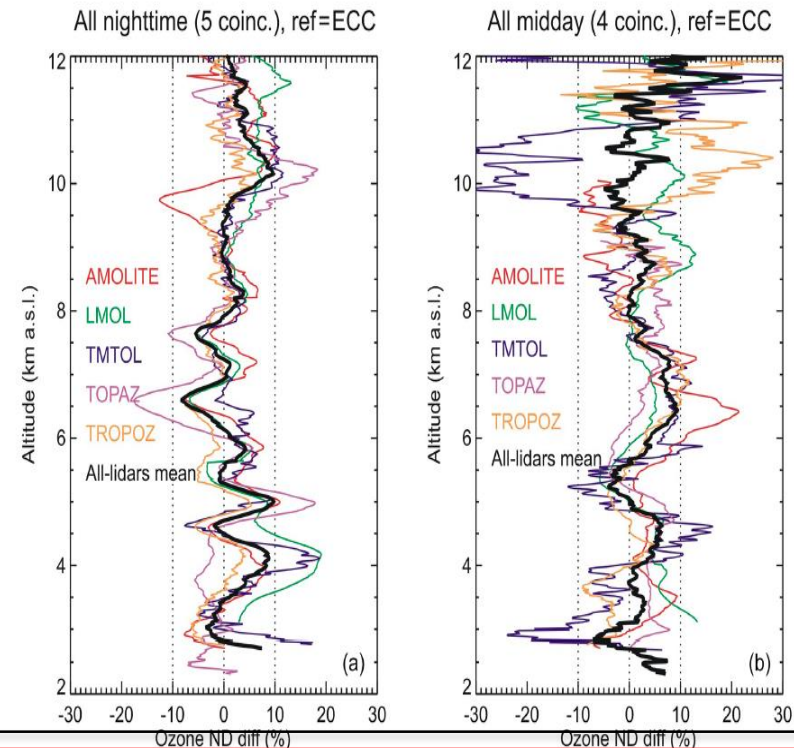


Southern California Ozone Observation Project (SCOOP campaign, 2016) See *Leblanc et al. AMT 2018*

Example LMOL O₃ curtain data overlapped with
JPL ozonesondes (black arrows)



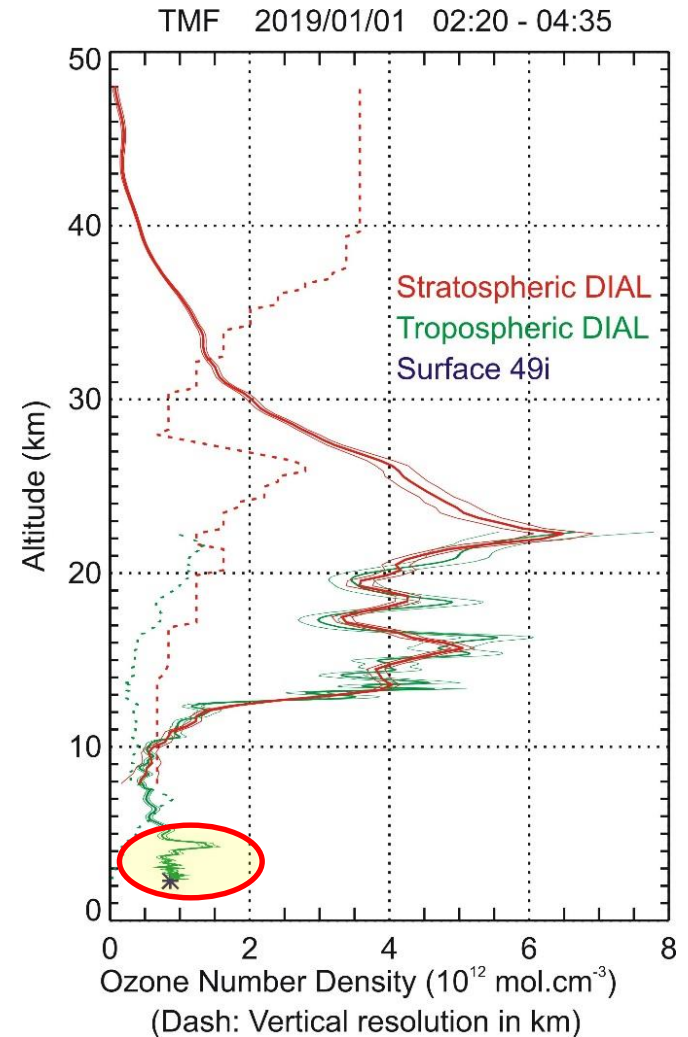
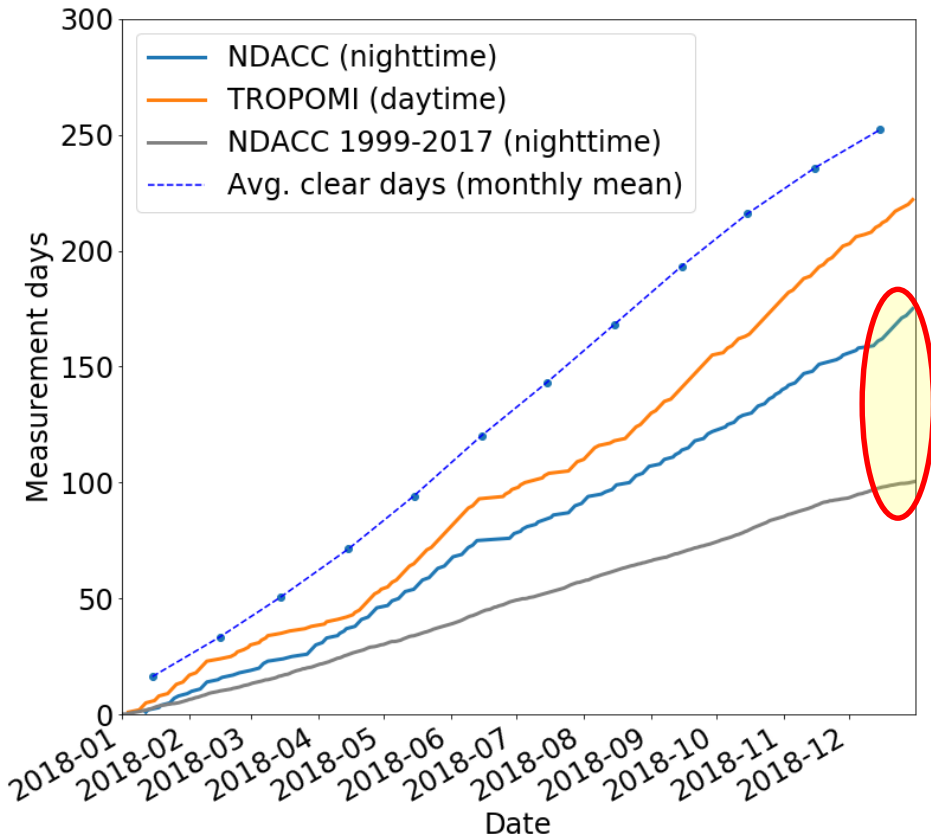
Five TOLNet O₃ lidars in one location!



1. TOLNet O₃ lidars utilize common approach for processing and error propagation, enabling rigorous lidar intercomparisons
2. SCOOP 2016 campaign: TOLNet O₃ lidars typically fall within +/-5% when compared to each other and to ozonesondes

Recent JPL-TMF Lidar Tech. developments

New automated measurement capabilities improved lidar temporal sampling, boosting satellite validation capability (TROPOMI, and soon TEMPO)



New very-near range receiver extended the measurement capabilities down to 100 m AGL, allowing unprecedented ozone profiling from ground to mesosphere (surface to 50 km without altitude gaps)

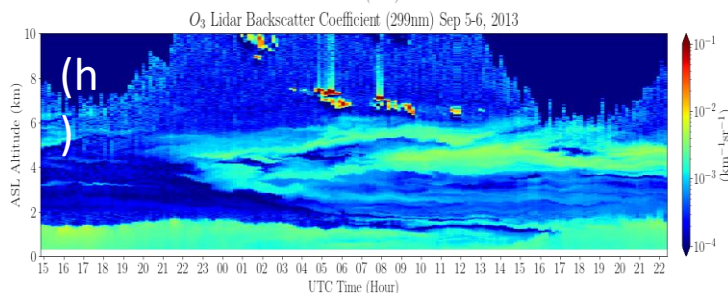
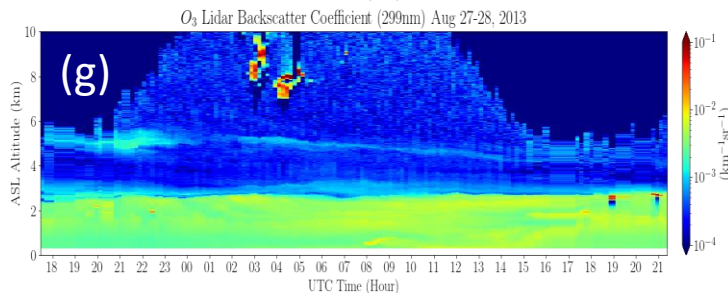
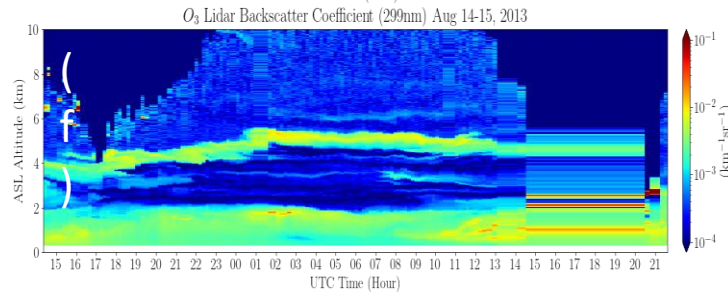
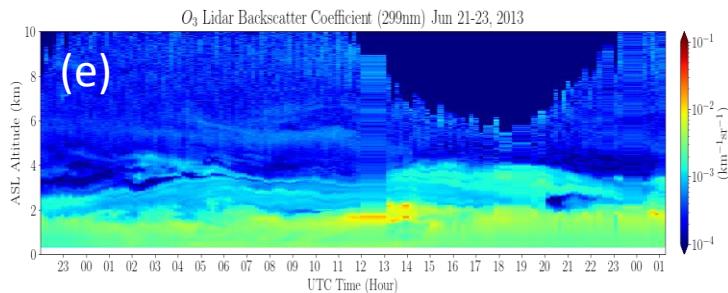
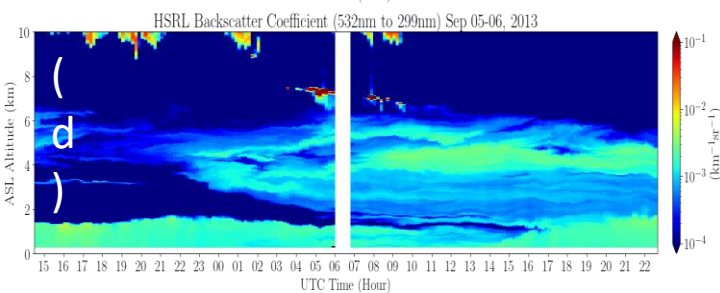
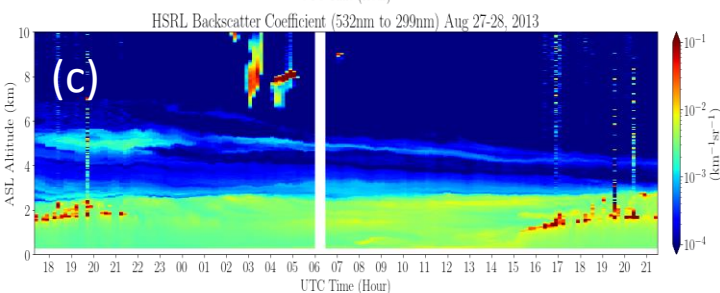
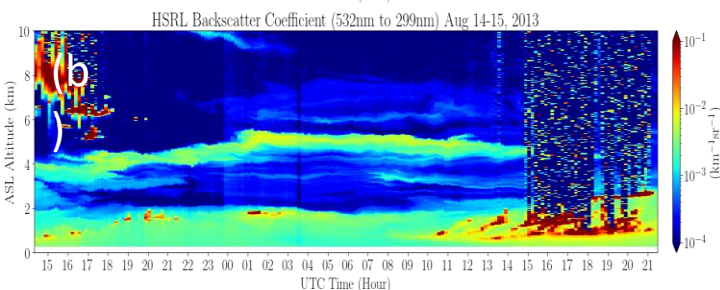
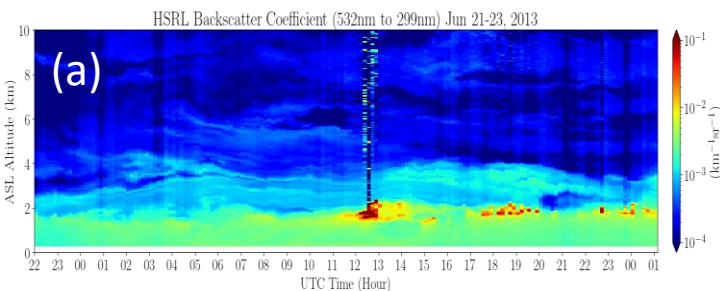


Aerosol Retrieval from the UAH RO₃QET DIAL compared to Wisconsin-HSRL

HSRL data credited to
Ed Eloranta group

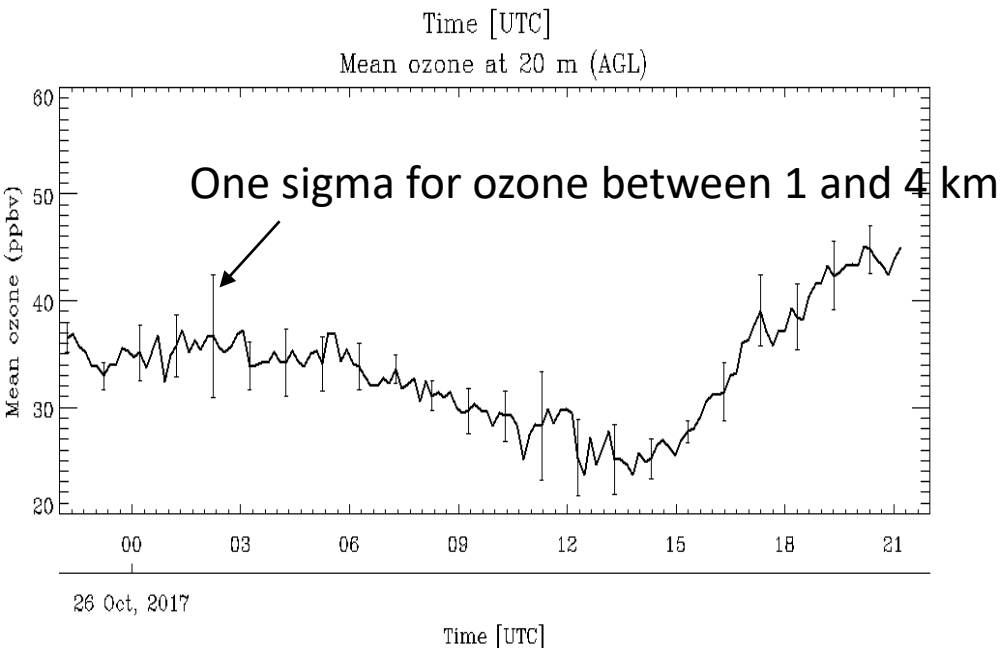
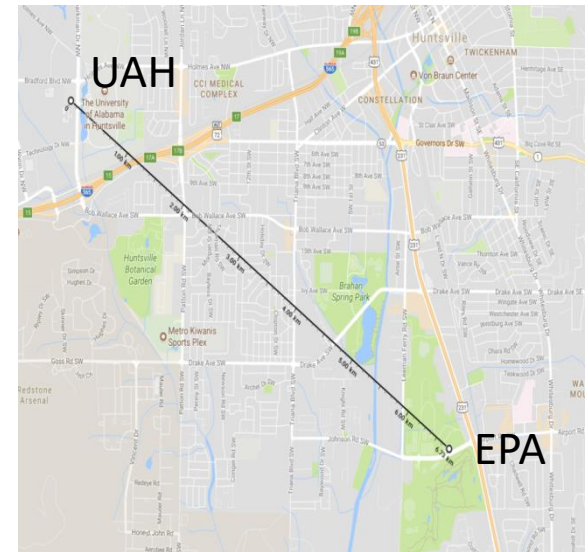
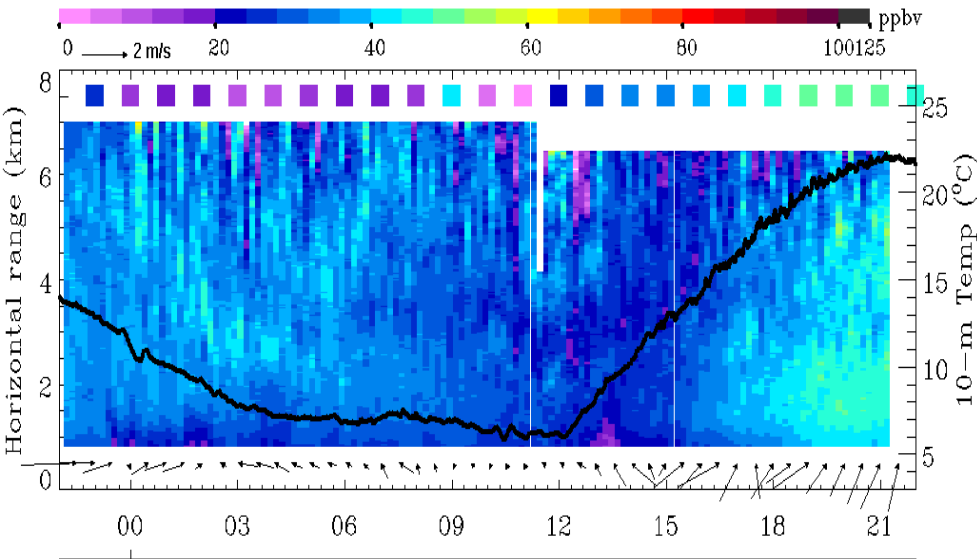
HSRL

O₃ DIAL



The aerosol
retrievals from
the RO₃QET DIAL
compare very
favorably to the
gold-standard
HSRL aerosol
measurements

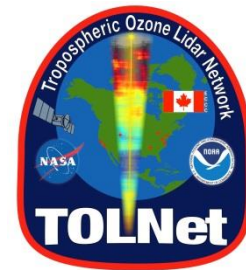
UAH RO₃QET Ozone Lidar Scanning Measurement, 10/26/2017, pointing SE



- **Nighttime ozone is higher than EPA because the lidar measured at a higher altitude (~20m AGL).**
- **The standard deviation of O₃ over range 1-4 km (where the lidar measurement uncertainties are small) is 2.7 ppbv.**
- **The spatio-temporal patterns of 20-m ozone indicates significant real, geophysical variations.**



Long-range transport of Siberian wildfire emissions to North America during FIREX-AQ



Matthew S. Johnson¹ and Kevin Strawbridge²

¹NASA Ames Research Center, ²Environment and Climate Change Canada



Background:

- The Fire Influence on Regional to Global Environments and Air Quality (FIREX-AQ) campaign investigated the impact of wildfires and agricultural fires on air quality and climate.
- During the campaign, unprecedented wildfires were burning in Siberia with expected impact on pollution levels and air quality in North America due to long-range transport.

Analysis:

- Applied NASA remote-sensing data (TOLNet lidar ozone (O_3) and aerosol backscatter, TROPOMI column carbon monoxide (XCO), etc.) and NASA GMAO GEOS-CF model simulations to investigate the trans-Pacific transport of Siberian wildfire emissions.

Findings:

- TOLNet lidar retrievals (AMOLITE) observed the transported Siberian wildfire plume over North America which was also simulated by GEOS-CF.
- Numerous satellite products (including multiple NASA sensors) and GEOS-CF simulations illustrate the emission source and trans-Pacific transport pathway of the smoke plume.

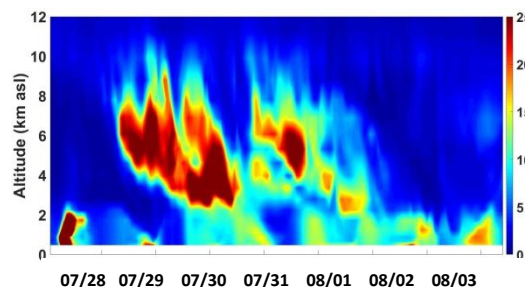
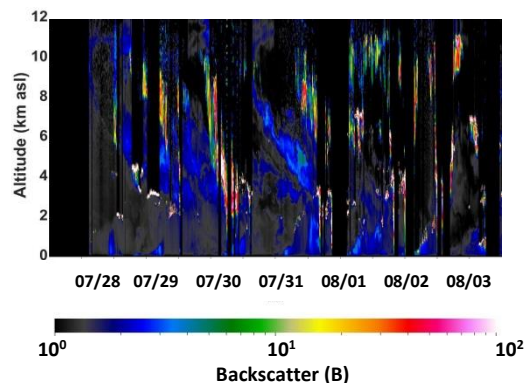


Figure 1. AMOLITE aerosol backscatter (top) and GEOS-CF $PM_{2.5}$ (bottom) demonstrating the large aerosol concentrations over North America.

Significance:

- ✓ NASA remote-sensing (e.g., TOLNet, CALIPSO, MODIS) and modeling systems (GMAO GEOS-CF) provide valuable data sources to evaluate complex global processes of dynamics and chemistry impacting tropospheric composition and air quality.

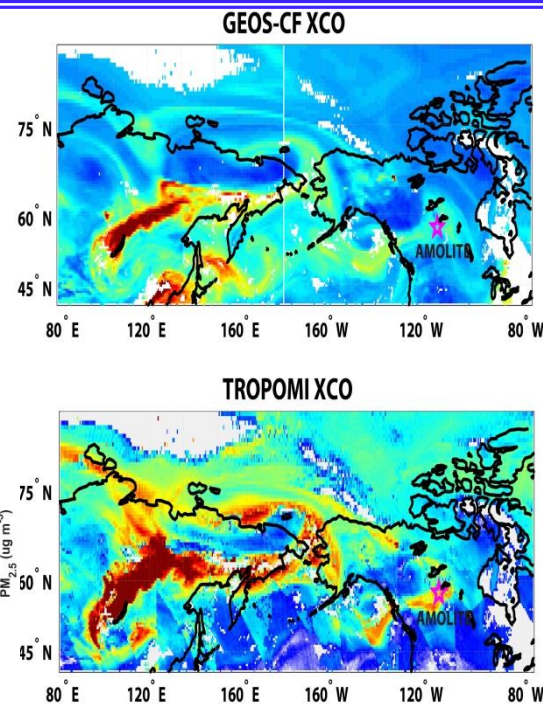
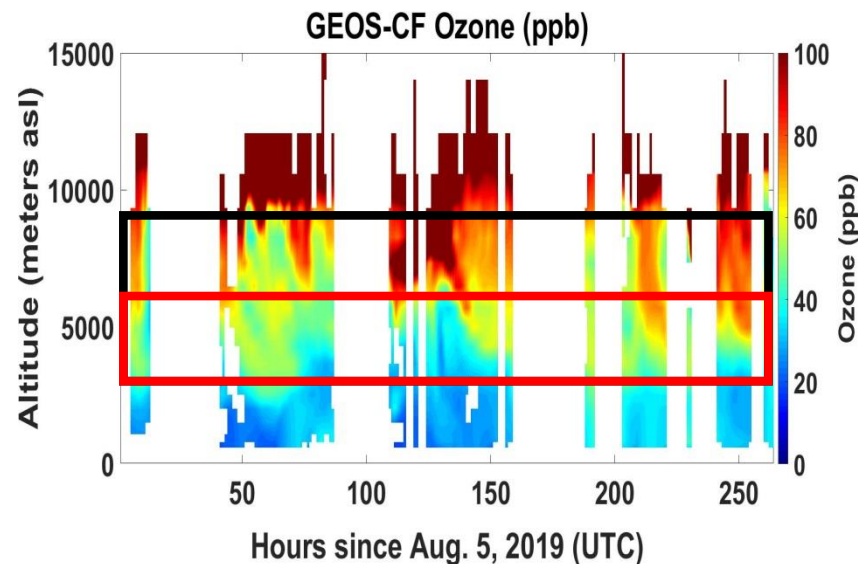
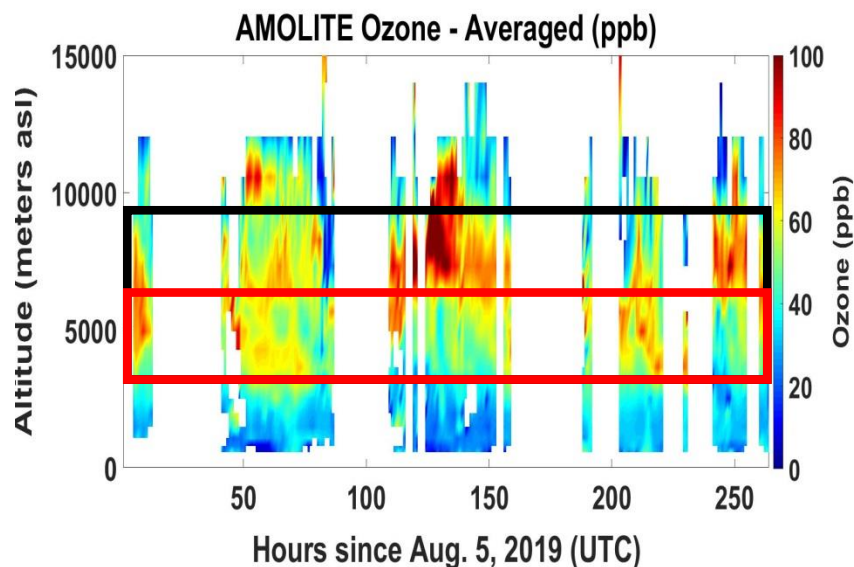


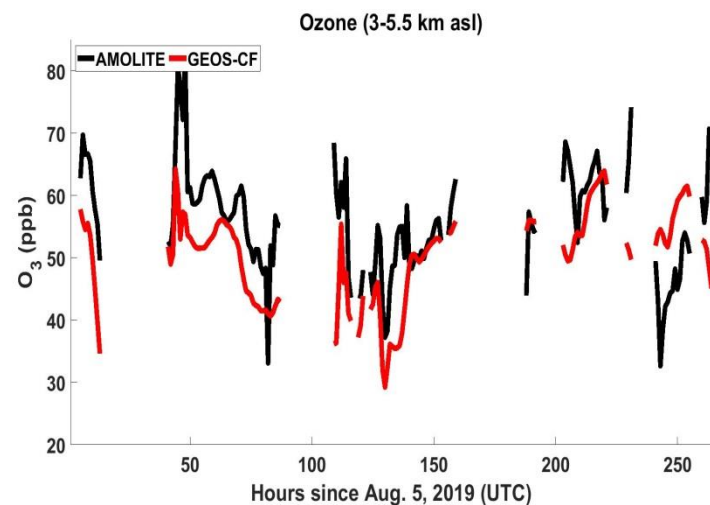
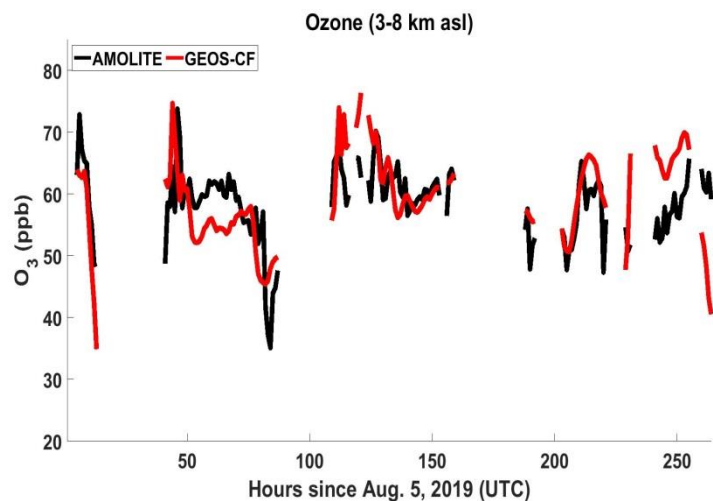
Figure 2. GEOS-CF (top) and TROPOMI (bottom) XCO on July 29, 2019 showing the Siberian wildfire plume over the location of AMOLITE.

GEOS-CF model O₃ evaluation using TOLNet during FIREX-AQ

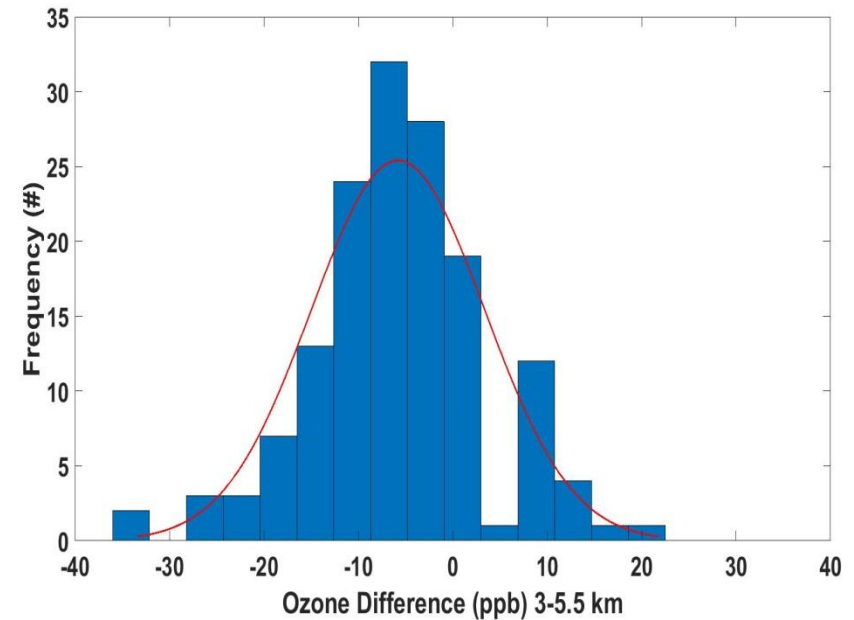
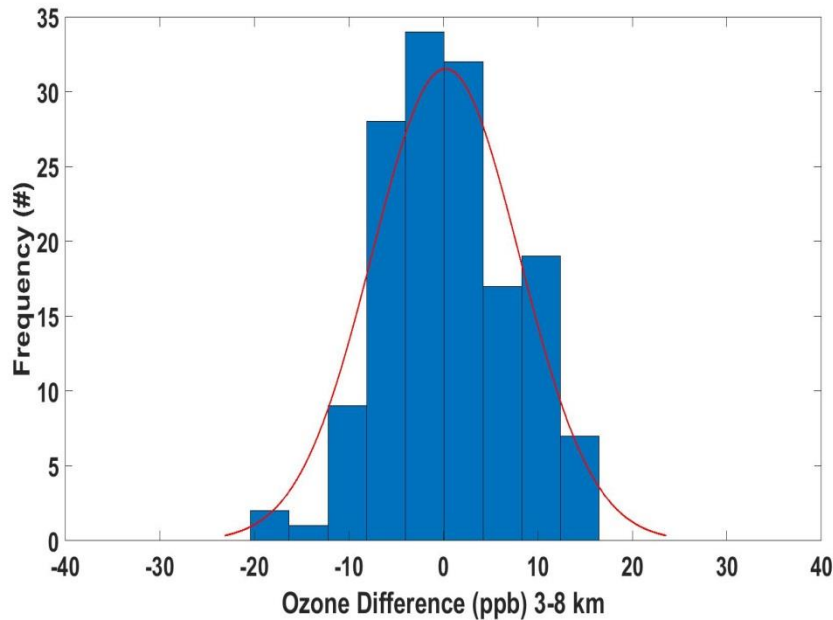
M. Johnson/NASA/ARC



AMOLITE lidar measurement of O₃ (averaged to the spatio-temporal resolution of the model) and GEOS-CF simulated O₃ (ppb) between August 5 – 15, 2019 at the lidar location during FIREX-AQ. The black and red box indicates the 3-8 km and 3-5.5 km vertical level where statistical evaluation occurs, respectively.



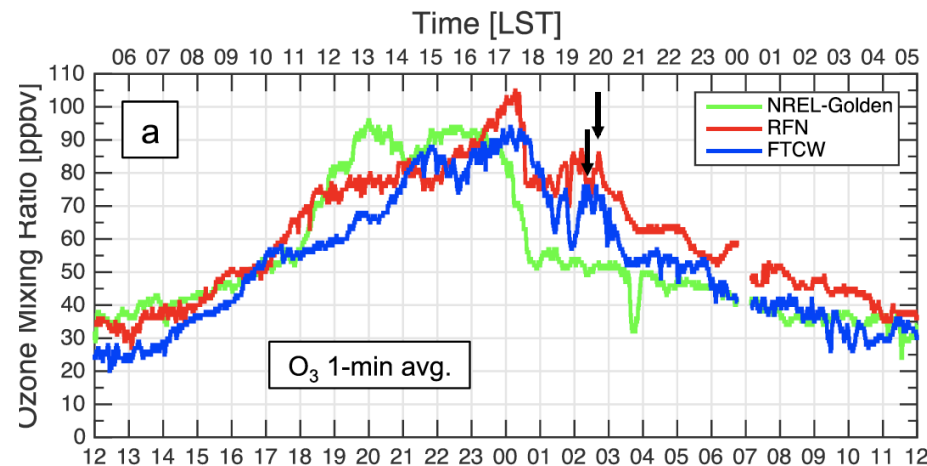
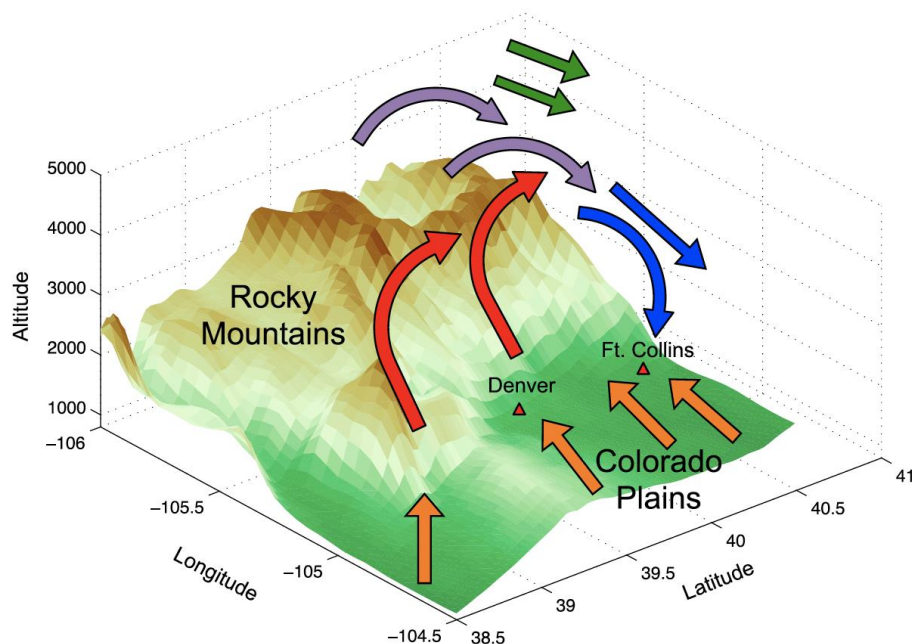
GEOS-CF model O₃ evaluation using TOLNet during FIREX-AQ



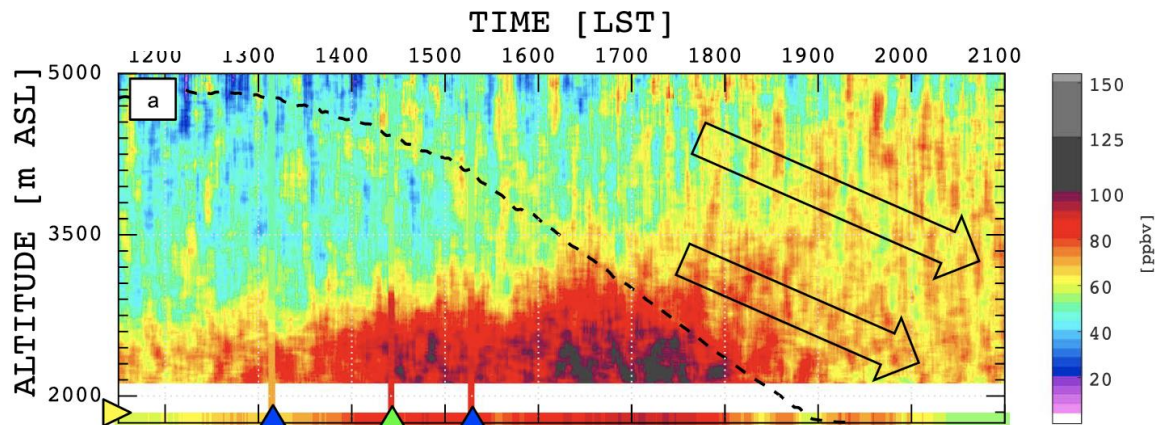
Histograms of the difference (ppb) between GEOS-CF and AMOLITE O₃ (model minus measurement) between August 5 – 15, 2019 at the lidar location during FIREX-AQ. The differences of the 3-8 km (left) and 3-5.5 km (right) are displayed.

- TOLNet allows for model evaluation of O₃ at all vertical levels of the troposphere.
- Model – measurement ozone correlation: 3-8 km (R=0.48); 3-5.5 km (R = 0.43); 5.5-8 km (R = 0.61).
- Model average bias: 3-8 km (0.2 ppb, 0.4%); 3-5.5 km (-5.8 ppb, -10.4%); 5.5-8 km (8.1 ppb, 13.0%).
- GEOS-CF ozone errors are normally distributed.
- GEOS-CF is able to capture the timing and magnitude of ozone laminar observed by AMOLITE.

Mountain–Plains Circulation Diagram (22 July 2014)



GSFC TROPOZ - Ft. Collins, CO
22-Jul-2014 1830 - 0400 UTC



Courtesy John Sullivan
John.t.Sullivan@nasa.gov



Fires, Asian, and Stratospheric Transport - Las Vegas Ozone Study (FAST-LVOS)



May 17 - June 30, 2017

Angel Peak

NOAA/ESRL/CSD

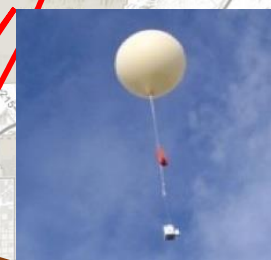
mobile lab

(O_3 , CO , CO_2 , CH_4 ,
 NO , NO_2 , NO_y , N_2O ,
 H_2O)



*Joe Neal

NOAA/ESRL/GMD
ozonesondes



Model study

NOAA/GFDL

AM4 model



NLVA

NOAA/ESRL/CSD

TOPAZ lidar

Doppler lidar

CCDAQ profiler

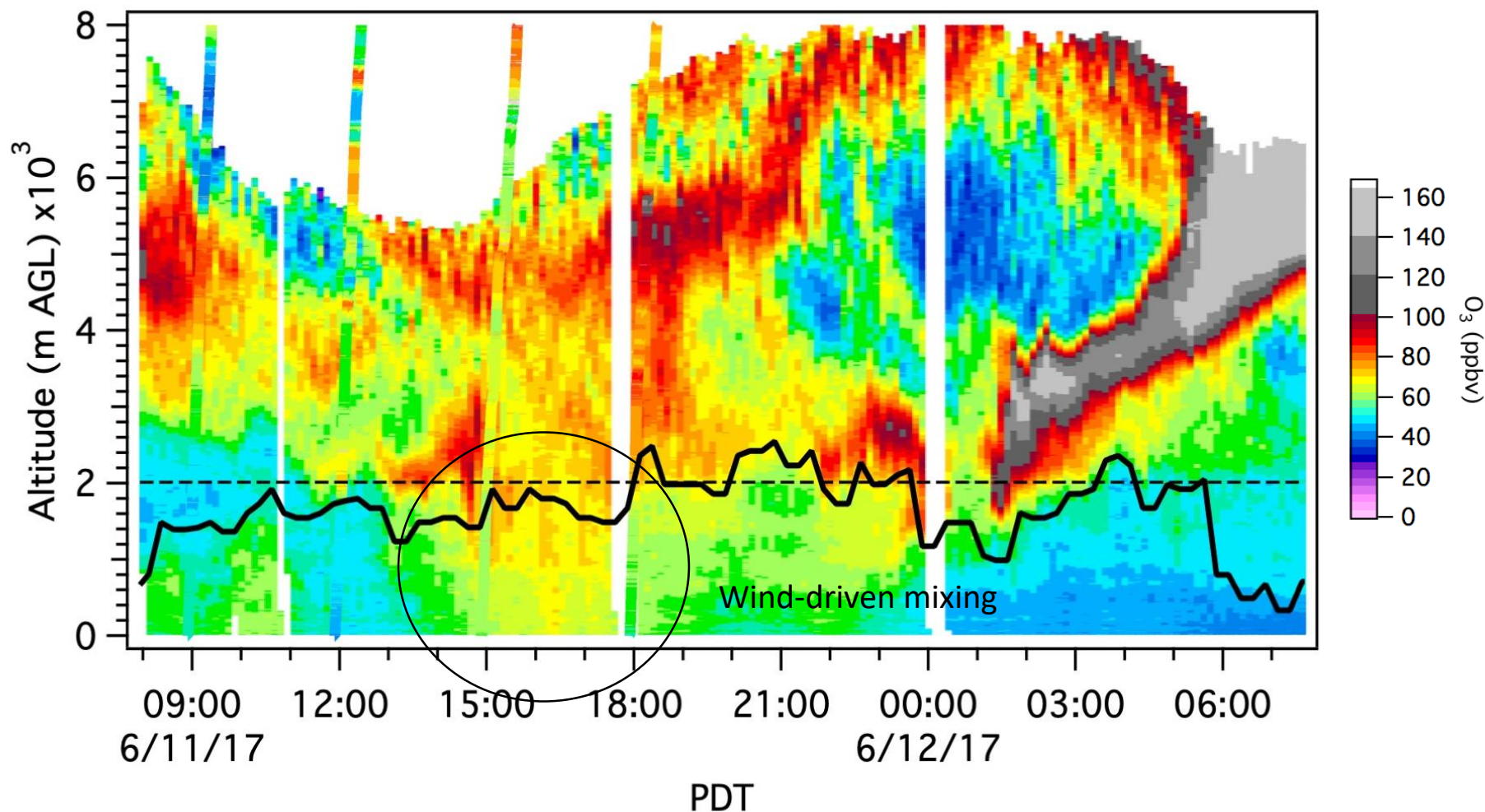


*NLVA-Big Bear Scientific Aviation Mooney (O_3 , NO_2 , CH_4 , C_2H_6 , H_2O)

*IOPs only

Entrainment of a deep stratospheric intrusion

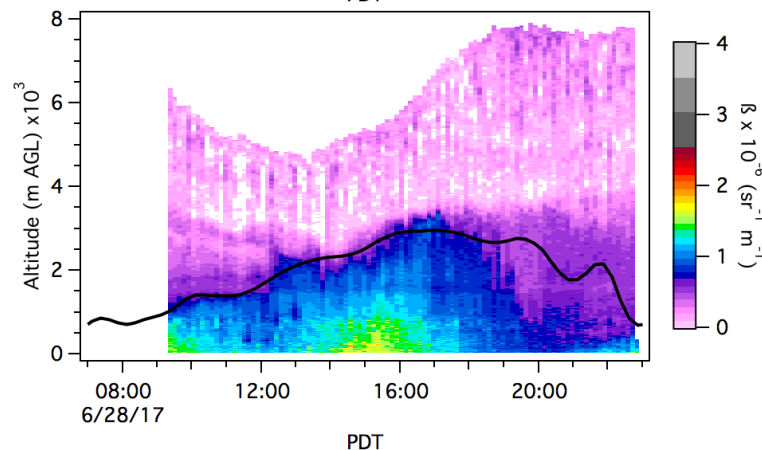
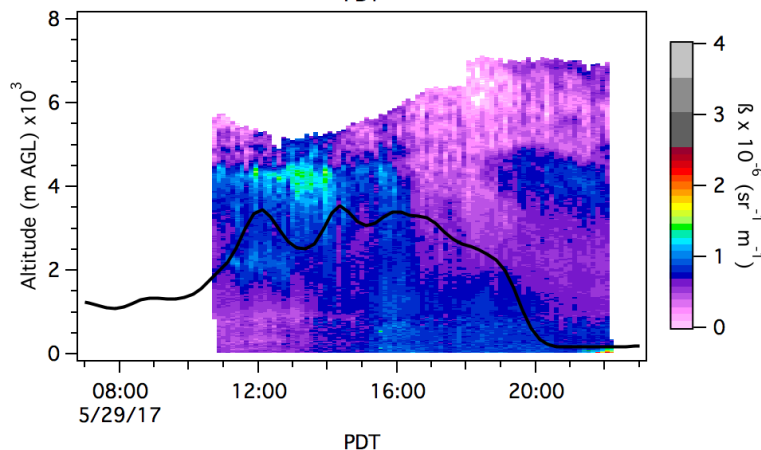
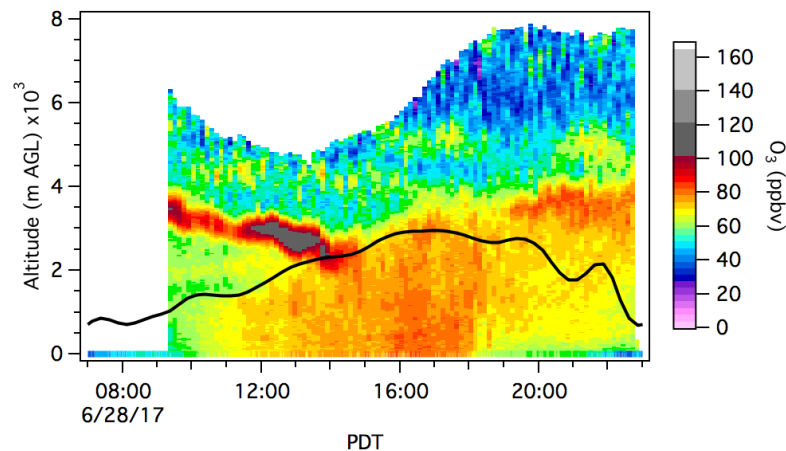
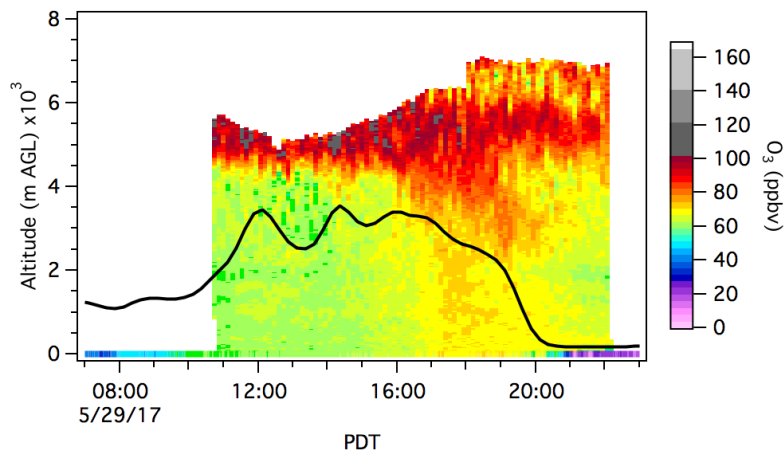
June 11-12, 2017



Entrainment of transported O_3 layers

May 29, 2017

June 28, 2017



During FAST-LVOS, boundary layer entrainment of elevated O_3 layers associated with stratospheric intrusions, Asian transport, or wildfires increased surface ozone by 5 – 10 ppbv in the Las Vegas Valley.

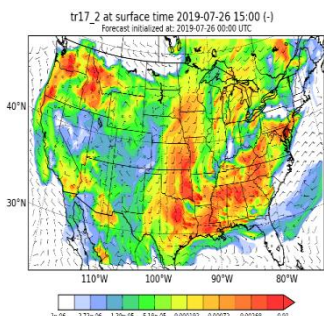


Evaluation of the Regional NCAR Air Quality Forecasting System using Ground-Based Ozone Lidar during FIREX-AQ

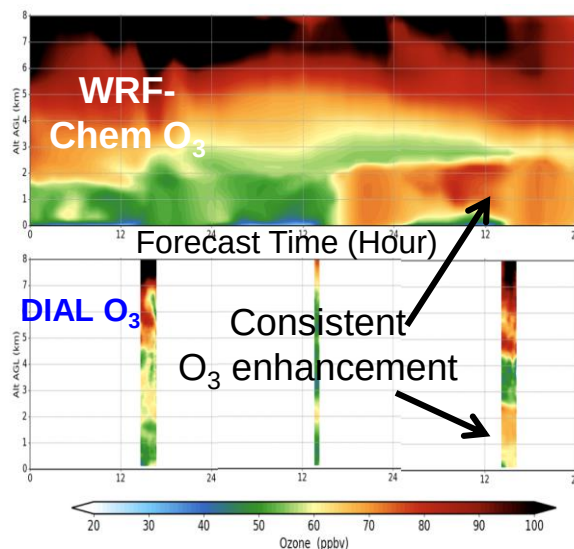
WRF-Chem products credited to NCAR/ACOM.
TOLNet RO₃QET lidar at Huntsville, AL

July 26, 2019

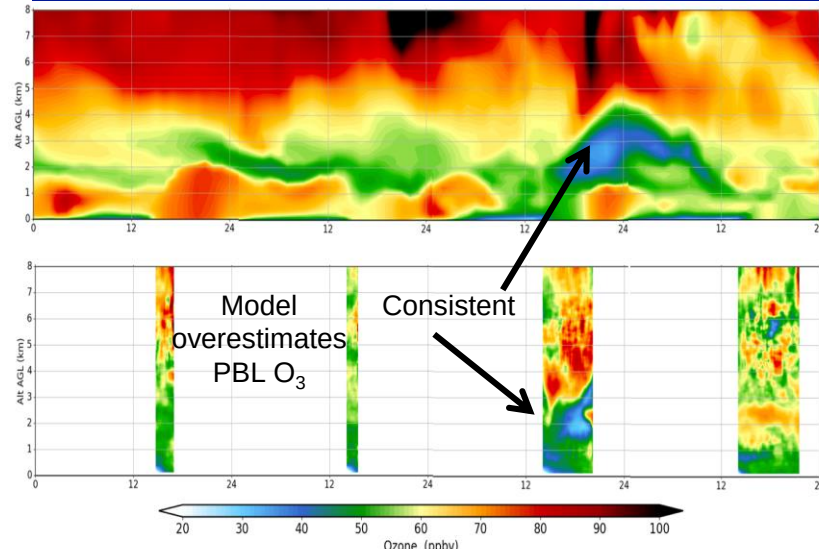
WRF-Chem Fire tracer at surface



SEUS Fires, Jul 24-26

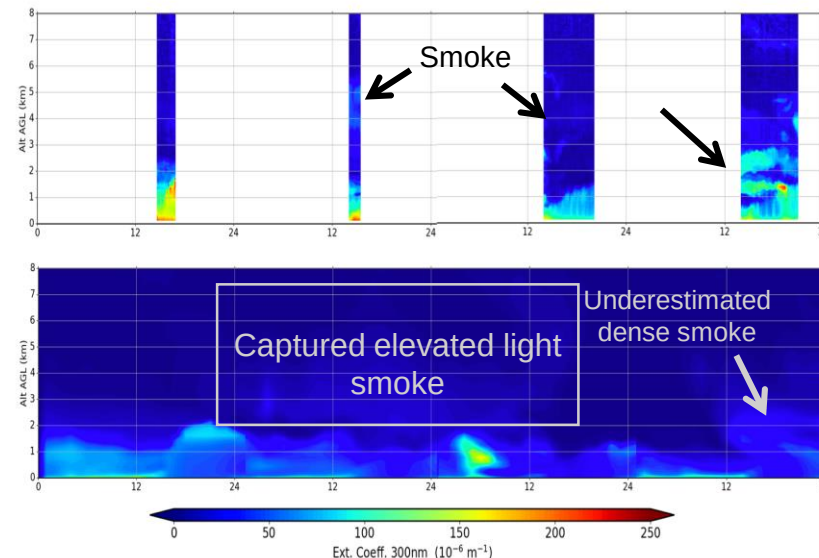
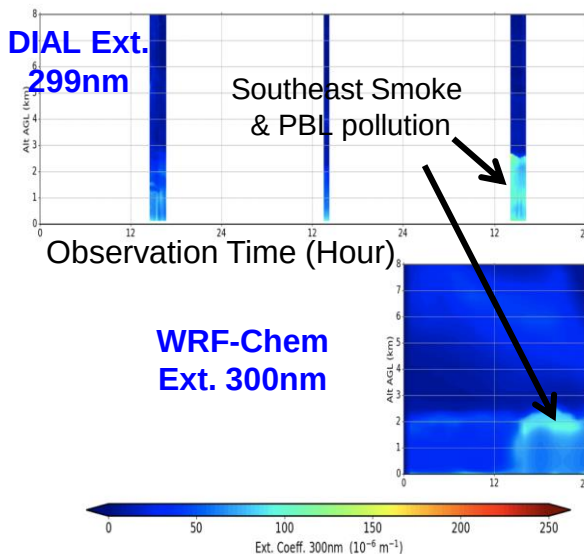
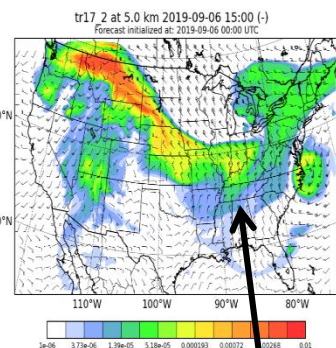


NWUS Fires, Sep 3-6



September 6, 2019

WRF-Chem Fire tracer at 5km a.s.l.



RO₃QET Huntsville



Ozone Water Land Environmental Transition Study (OWLETS-1) Hampton Roads Region 2017

Sullivan et al., "The Ozone Water–Land Environmental Transition Study", BAMS 2019

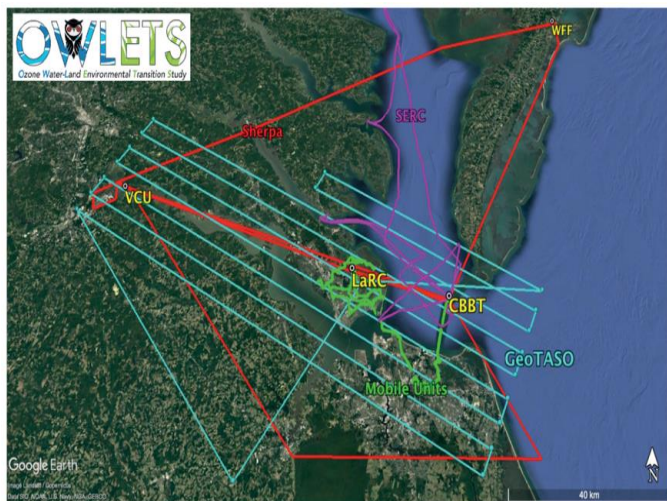


Fig. 1. Overview of OWLETS ground sites, mobile unit pathways, research cruise routes, and aircraft sorties.

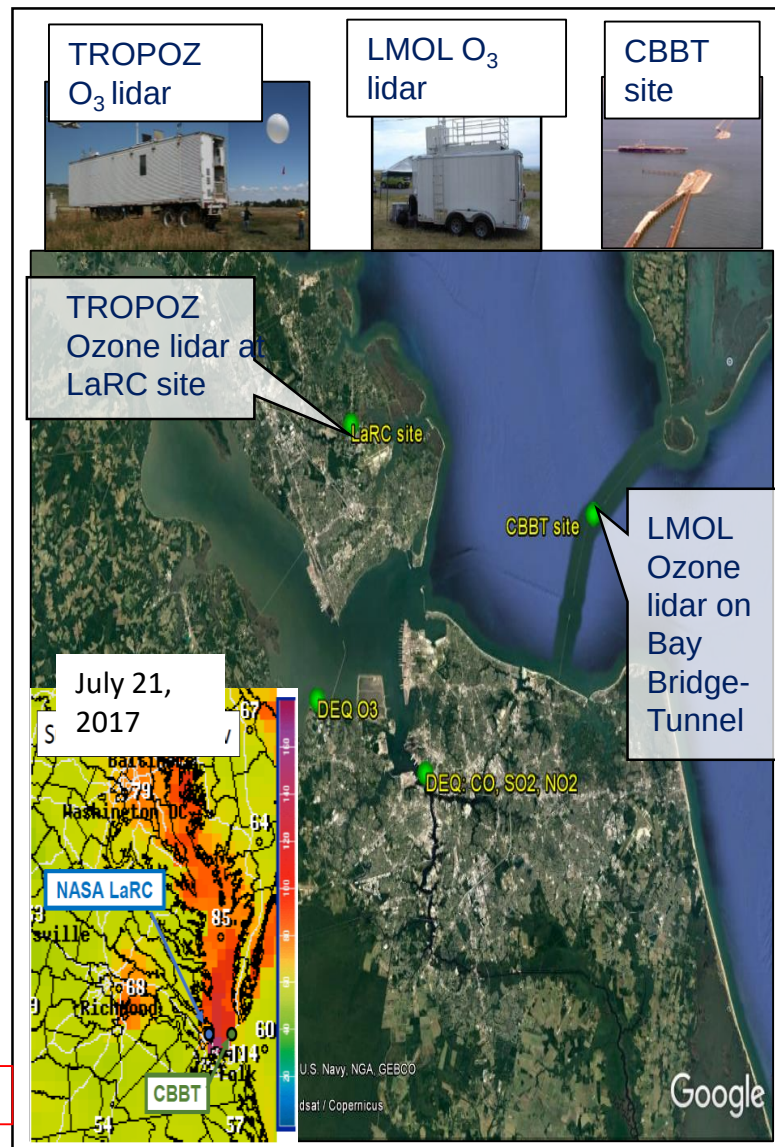
12 days of measurements from July 7 to Aug 2, 2017

- Two TOLNet ozone lidars (CBBT & LaRC)
- UAS/drone (CBBT or LaRC)
- Simultaneous ozonesonde launches (LaRC & CBBT)
- Mobile Cars (2)
- VA DEQ sites
- PANDORA (CBBT & LaRC)
- Surface in-situ measurements
- Two Sherpa aircraft flights (July 19, 20)
- Three GeoTASO aircraft flights (July 7, 8)
- Two days SERC research vessel (July 17, 18)

OWLETS data archive:

<https://www-air.larc.nasa.gov/missions/owlets/index.html>

Initial seed funding for OWLETS-1 provided by NASA Science Innovation Fund Award



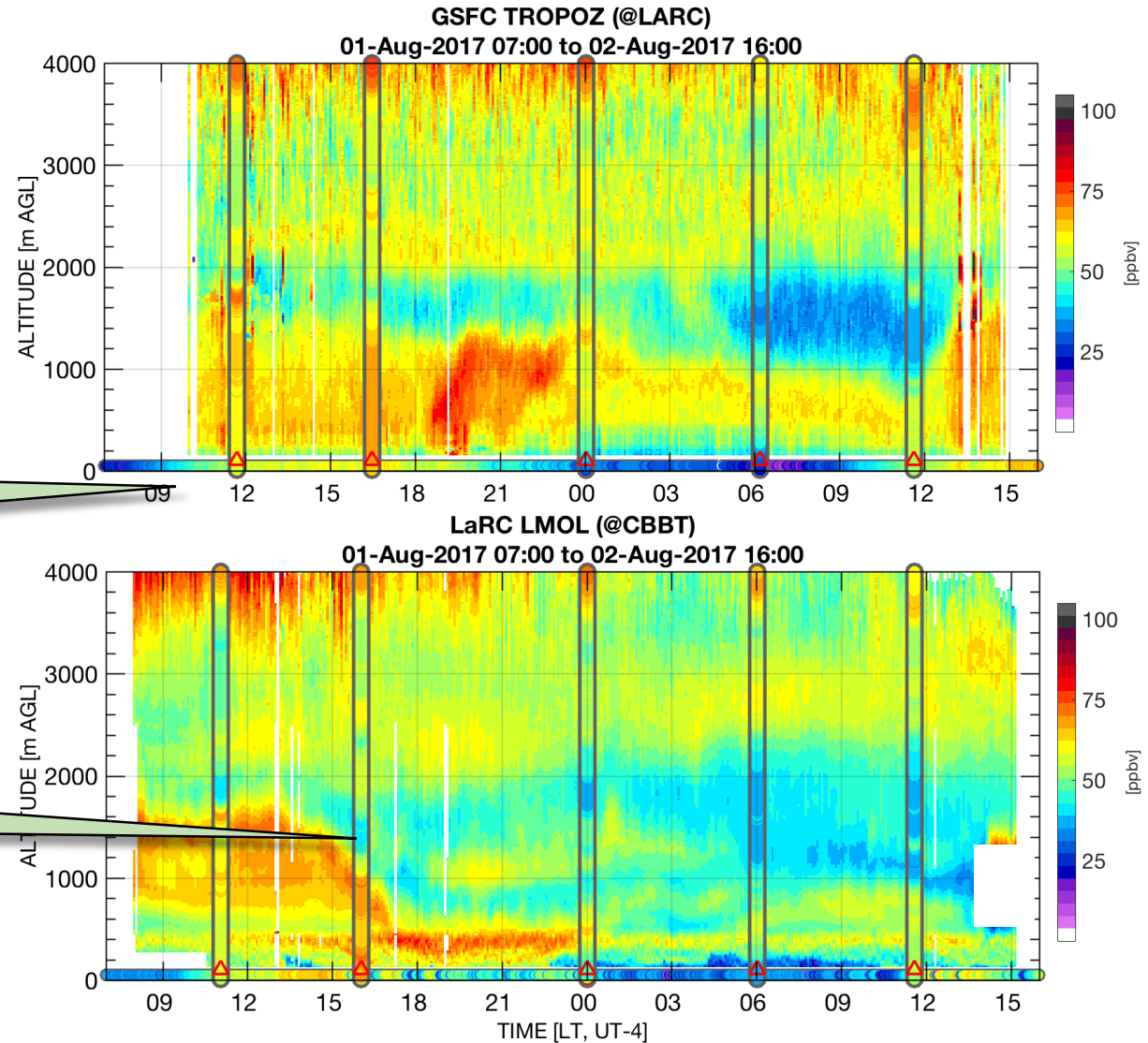


On-Land

Surface O₃

Over-Water

O₃-sonde



Courtesy John Sullivan
John.t.Sullivan@nasa.gov

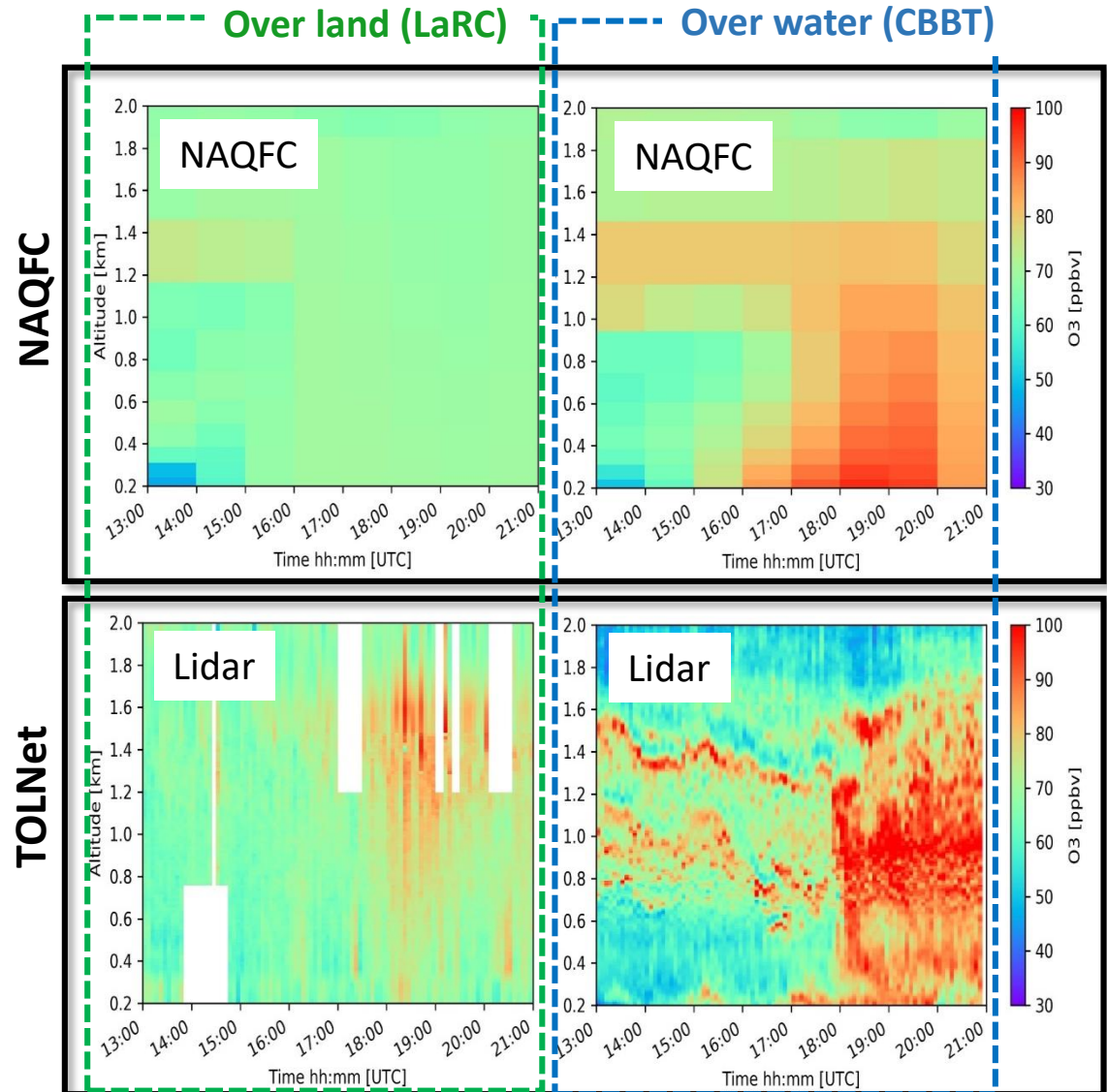
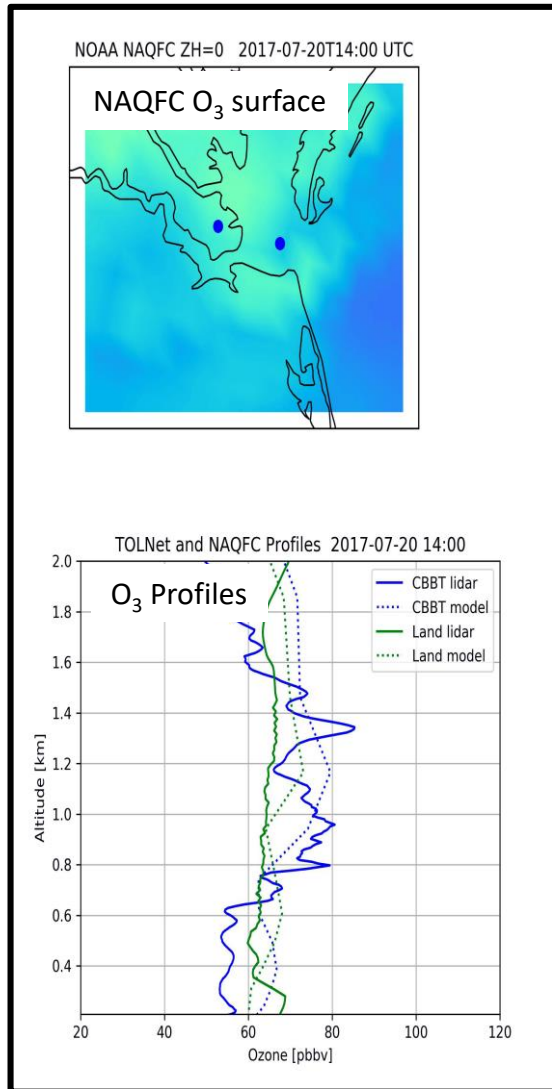


OWLETS-1 Campaign: July 20, 2017 NAQFC Model & TOLNet Lidar Ozone Intercomparison Example

Berkoff et al, AGU 2019

July 20, 2017

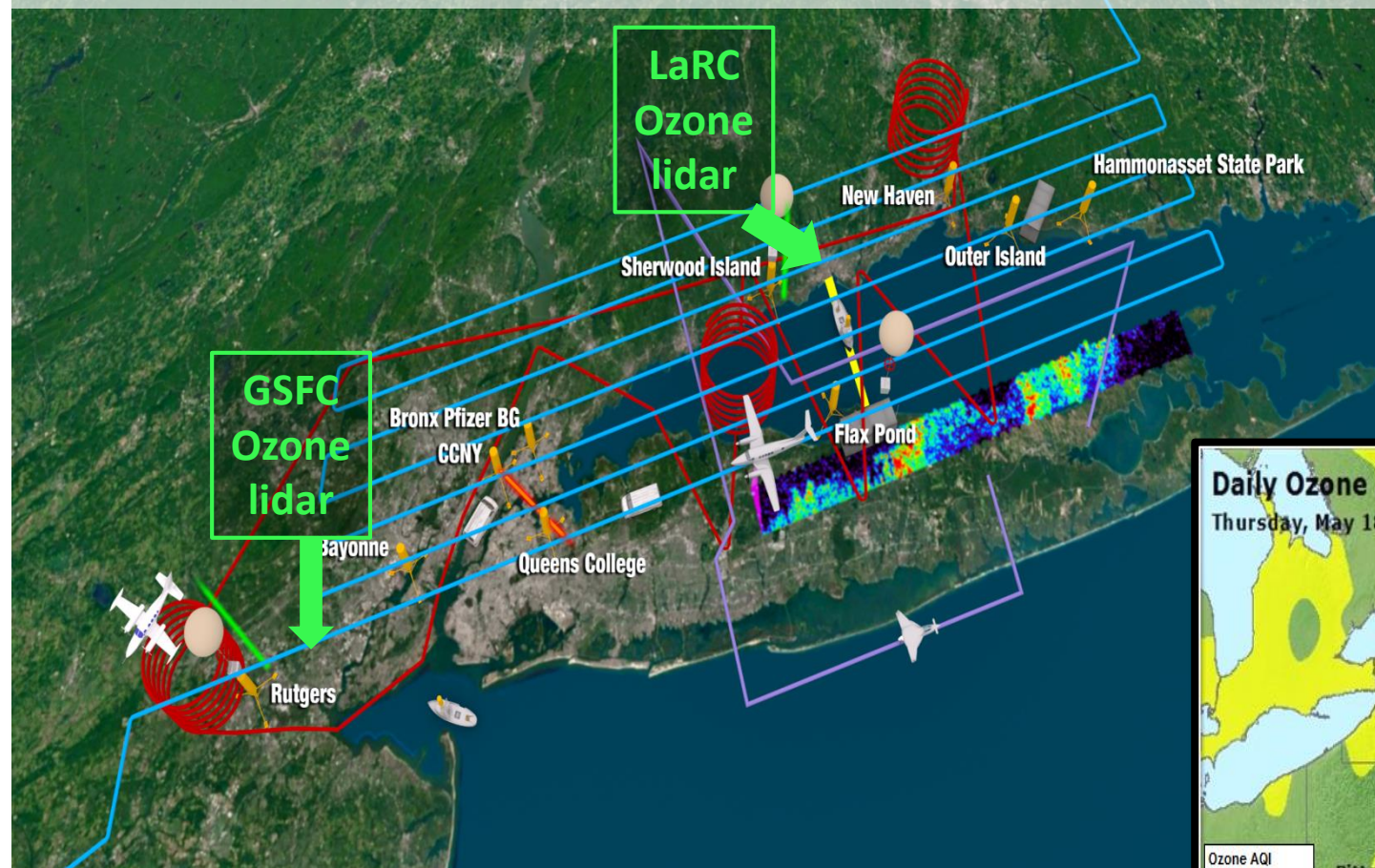
Ozone profiles July 20, 2017





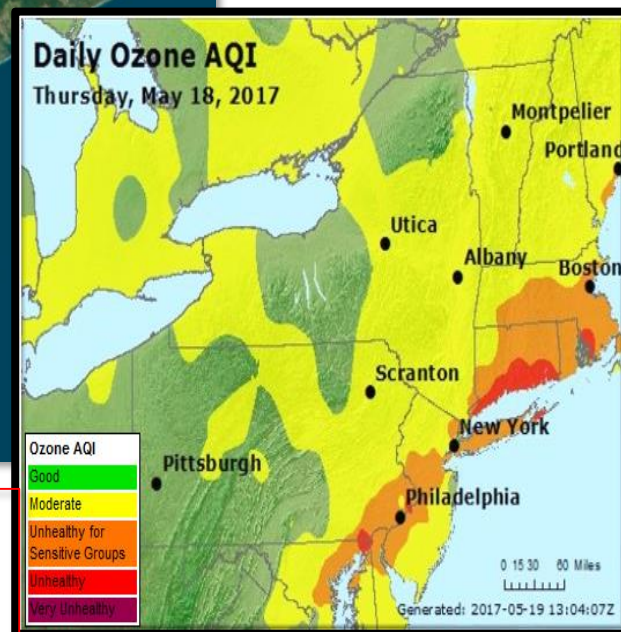
Long Island Sound Tropospheric Ozone Study (LISTOS)

Miller et al., "Overview of the Long Island Sound Tropospheric Ozone Study (LISTOS)", AGU Fall Meeting, 2018



Summer 2018:

- Multiple aircraft
- Marine vessels
- Automobiles
- Ground lidars
- Sounding systems
- In-situ sensors
- Pandora sun-spectrometers
- Aeronet sun-photometers
- Radiosonde/Ozonesondes



Campaign description website:

<http://www.nescaum.org/documents/listos>

LISTOS Campaign Aug 24-25, 2018: Langley Airborne HALO and Langley Mobile Ozone Lidar Measurements of Wildfire Transport

Tim Berkoff et al. NESCAUM LISTOS Meeting April 2019 & Liqiao Lei et al., EGU Meeting May 2020

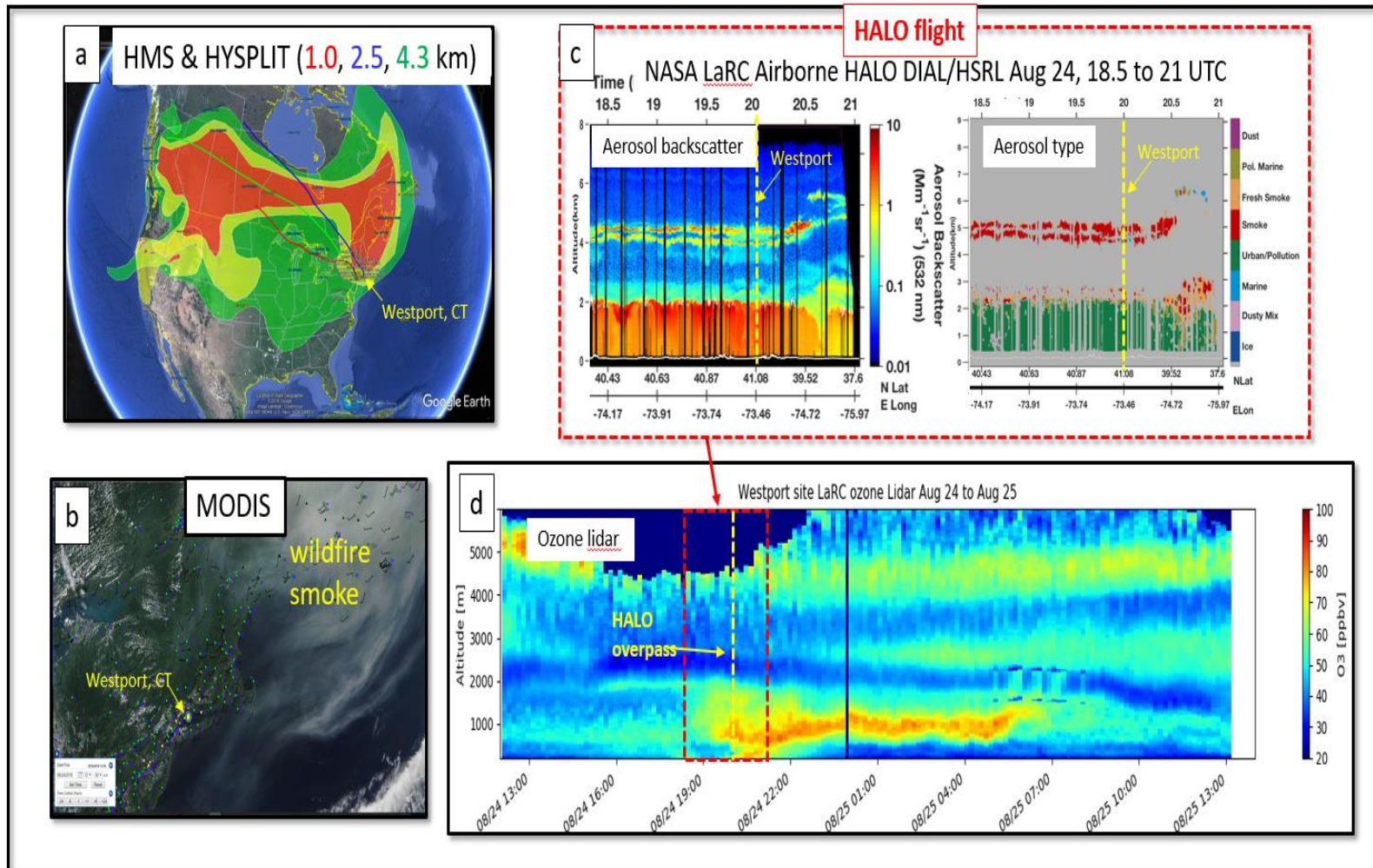


Figure: Aug 24-25, 2018 wildfire transport event during LISTOS showing **a**) NOAA HMS reporting of satellite observed smoke over the North America also with HYSPLIT back-trajectories from Westport, CT, **b**) Aqua/MODIS afternoon true color image, **c**) Aug 24 aerosol profile data from the NASA LaRC airborne HALO lidar and identifying aloft smoke aerosol, and **d**) Aug 24-25 O₃ curtain time series measured by the NASA LaRC lidar located at Westport, CT, showing aloft O₃ layers as a result of wildfire emission transport.



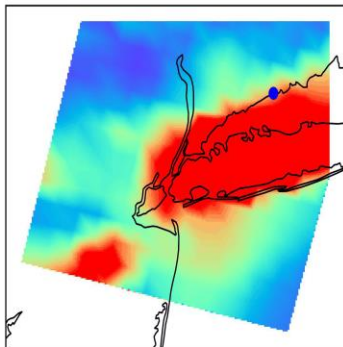
LISTOS Aug 28, 2018, Westport Connecticut site: O₃ Lidar Inter-comparison with NAQFC forecast model

Berkoff et al, TOLNet STM 2019

NOAA NAQFC surface forecast

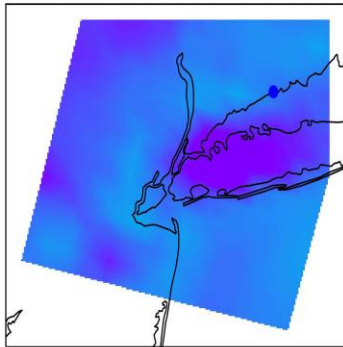
O₃ Vertical Profiles Westport, CT

NO₂
NOAA NAQFC NO2 Z=0 2018-08-28T13:00 UTC



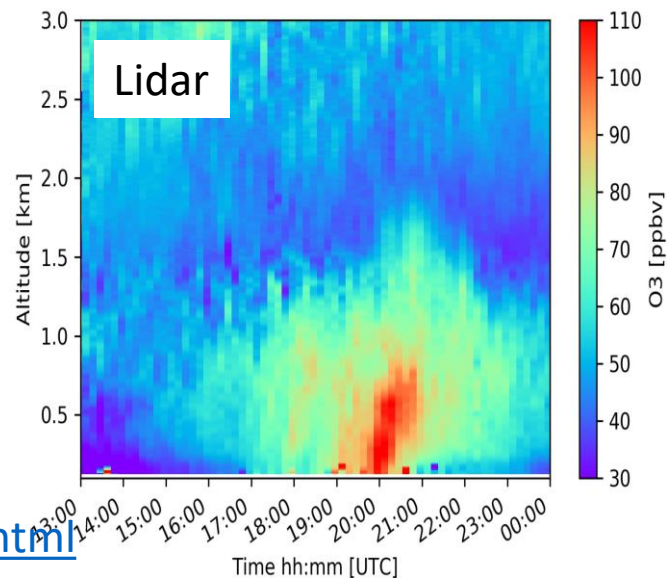
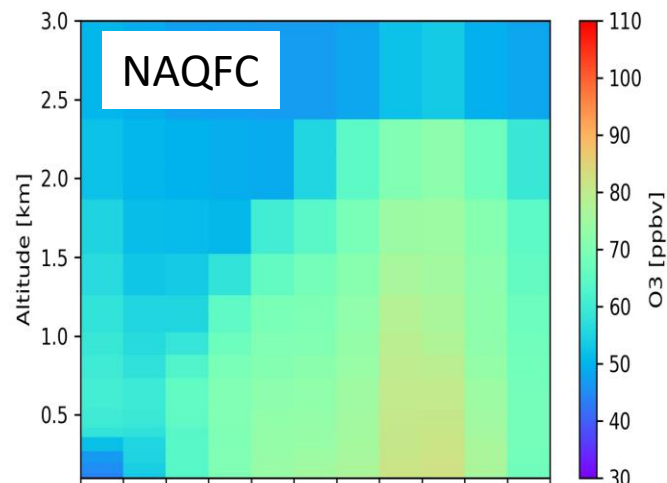
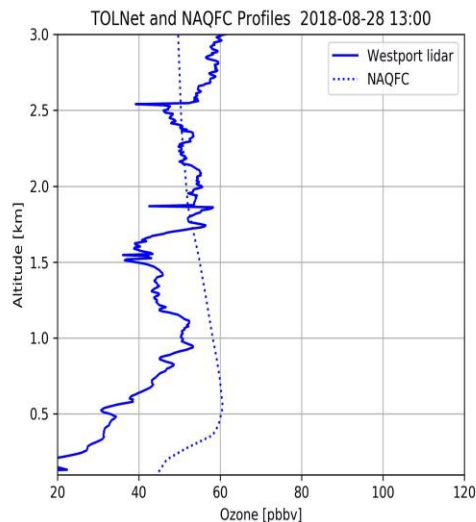
O₃

NOAA NAQFC ZH=0 2018-08-28T13:00 UTC



PRELIMINARY

TOLNet (solid),
NAQFC (dashed)



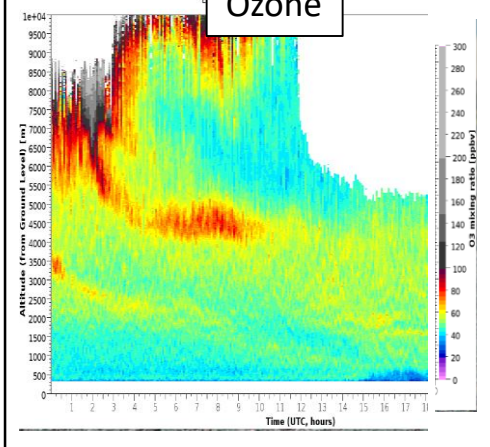
O₃ lidar data available in the LISTOS archive:
<https://www-air.larc.nasa.gov/missions/listos/index.html>



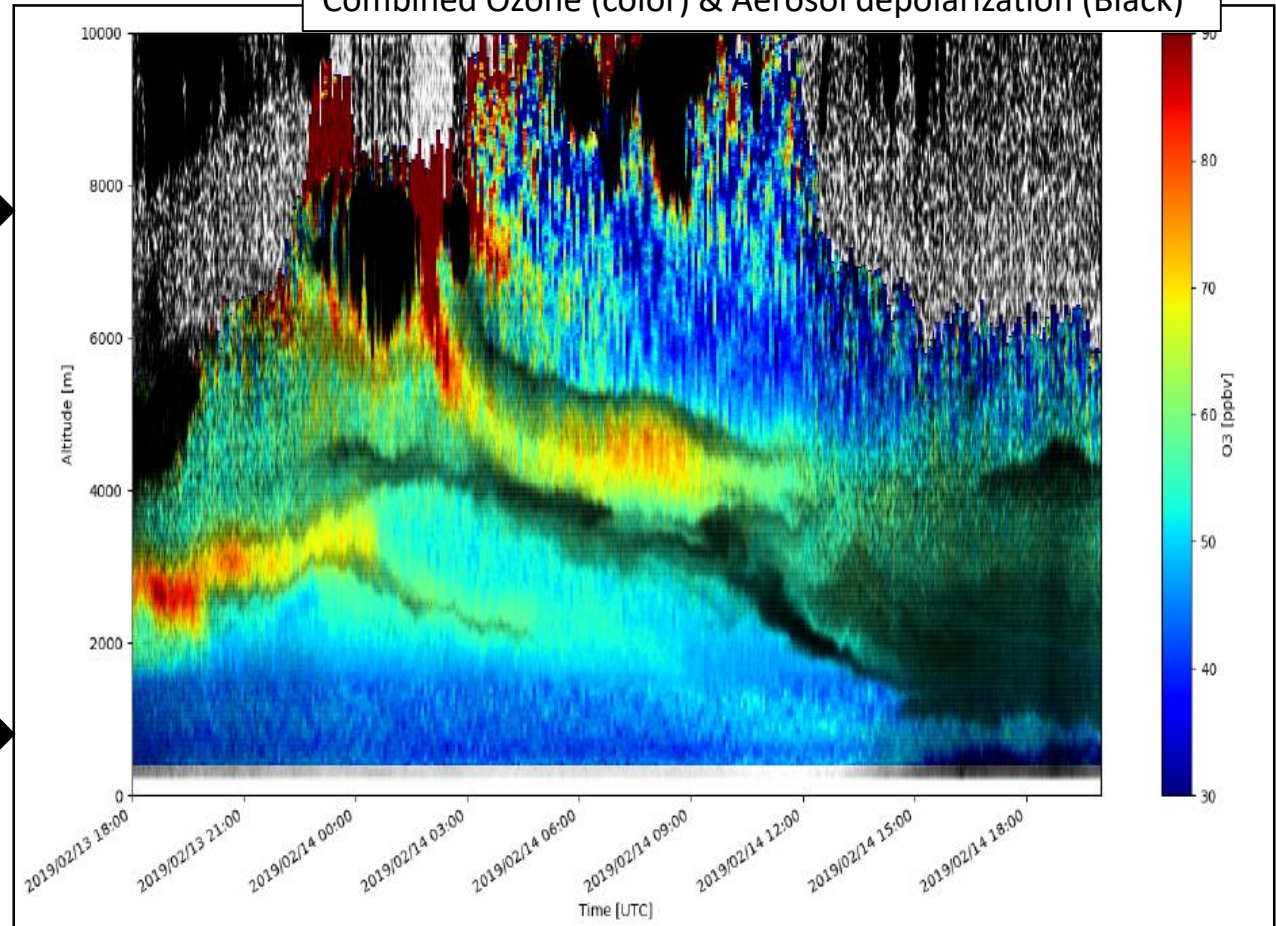
Feb 14, 2019 Stratospheric Intrusion Event: TOLNet Lidar Data (ozone) and co-located Micropulse Lidar (aerosol)

Gronoff et al, "Lidar Observation and Modeling of a Stratospheric Intrusion above Hampton, Virginia"
Today! Wed Jan 15 @ 2:15 pm, Rm 209

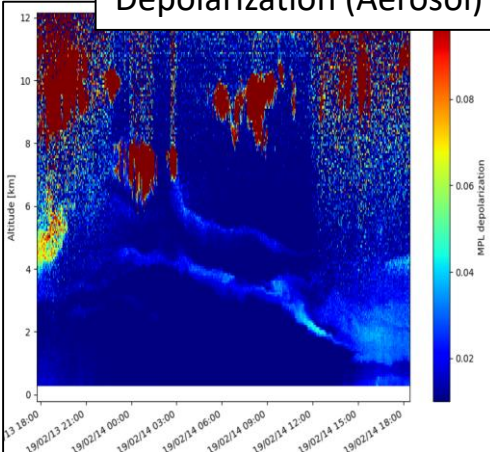
Ozone



Combined Ozone (color) & Aerosol depolarization (Black)



Depolarization (Aerosol)



TOLNet

Tropospheric Ozone LIDAR Network



Conclusions

1. The spatio-temporal characteristics of prevalent atmospheric trace gas and aerosol structures exhibit substantial variability.
2. Lidars can measure this spatio-temporal structure in a few places over limited times.
3. Space-borne sensors can measure these structures in hourly resolution across a continent.
4. The synergy of space-borne sensors with ground based (and aircraft) lidars and other sensors afford the best approach to measuring and diagnosing important air-quality structures and processes in a modeling framework.
5. The challenge for the air-quality community is to define the intersection of space-borne and ground-based air-quality measurements.

TOLNet

Tropospheric Ozone LIDAR Network



**6th Annual TOLNet Meeting
with
2nd Annual OWLETS
6-8 May 2019
College Park, MD USA**

