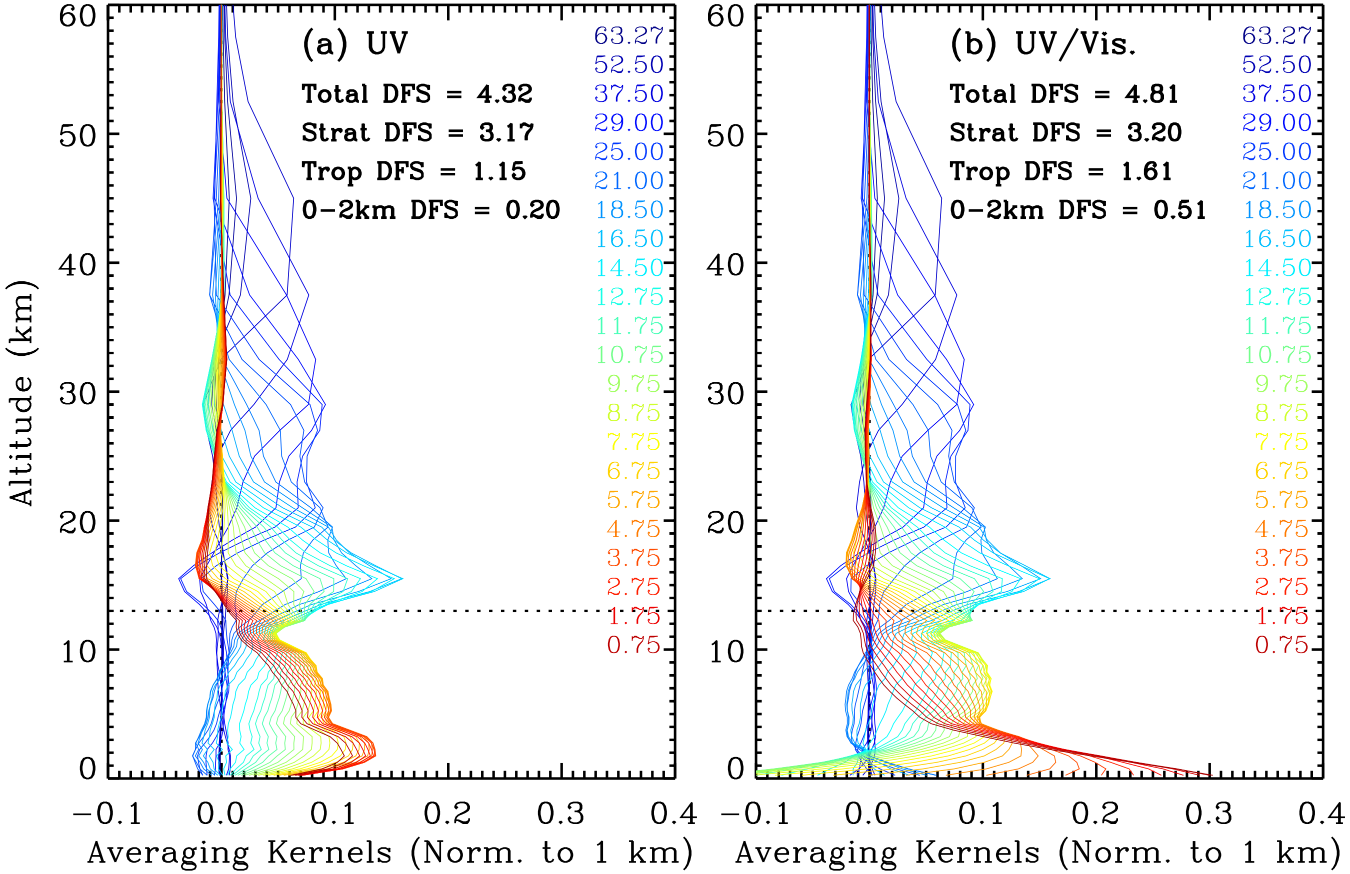
Building the Pathway from TEMPO to GeoXO

Joint Science Meeting for TEMPO, GeoXO ACX, & TOLNet

TOLNet for Improved TEMPO Validation and Science Results

Matthew Johnson, Thierry Leblanc
Andrew Langford, Claudia Bernier
Fred Moshary, Ruben Delgado, Kevin Strawbridge
Shi Kuang

TEMPO Ozone Profile and Tropospheric O_3 Algorithm

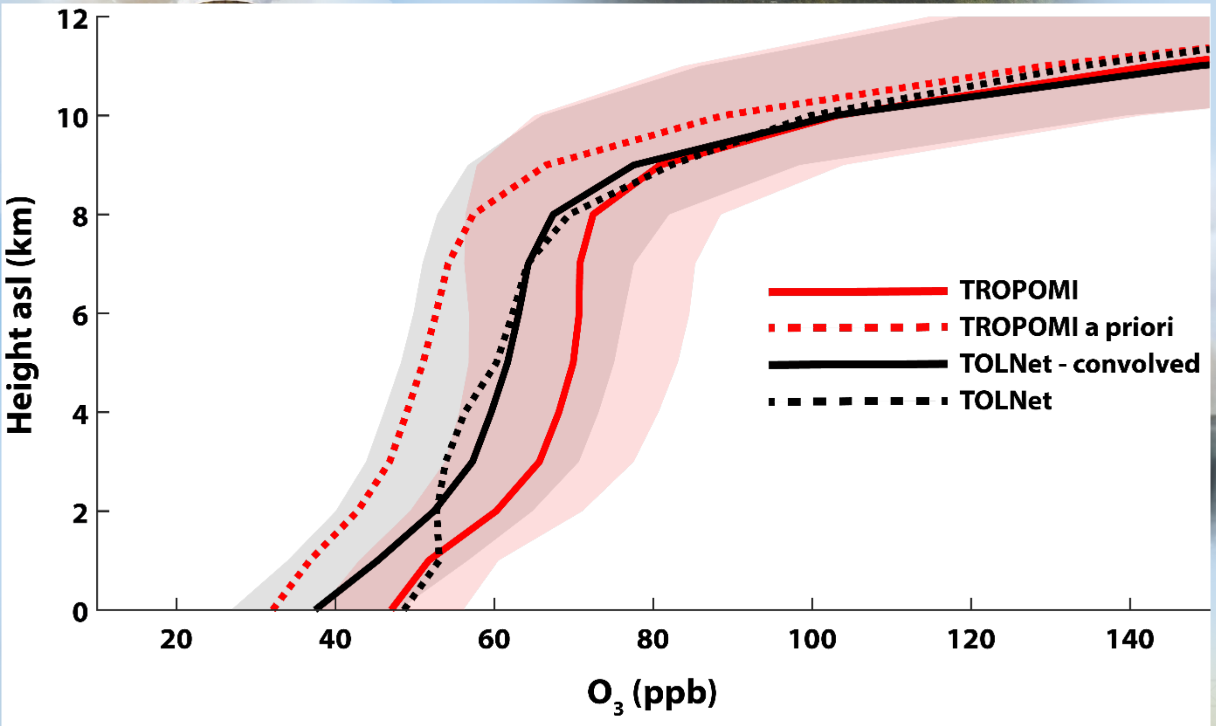


- SZA=25, VZA=45, AZA=86, SNR with 4 pixels coadded
- Under ideal conditions (4-pixel coadded): 3-5 total DFS with up to ~1.5 in the troposphere, and up to ~0.5 DFS in 0-2 km with ~6 km vertical resolution.

- Optimal Estimation (OE): 293-345 nm, 540-650 nm
- Retrieve partial O_3 columns at ~24 layers (bottom layer is 0-2 km above surface) as well as total, stratospheric, and tropospheric O_3 columns.
- A priori: a combination of tropopause-based climatology (Bak et al., 2013) with diurnally-resolved GEOS-CF data

Building the Pathway from TEMPO to GeoXO

Joint Science Meeting for TEMPO, GeoXO ACX, & TOLNet



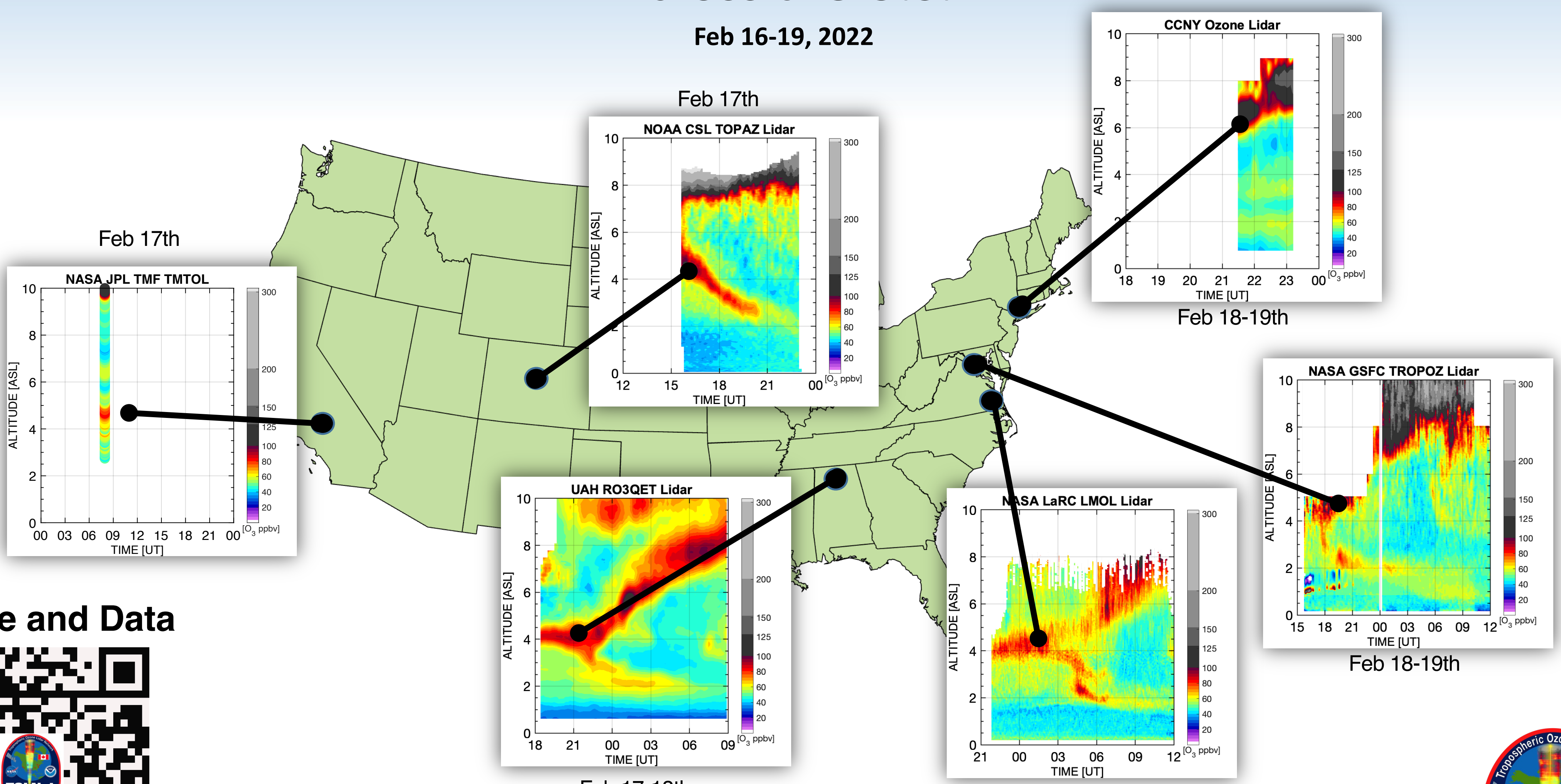
TOLNet for Improved TEMPO Validation and Science Results: Validation Data Synthesis

Matthew Johnson

NASA Ames Research Center

Network Wide Observations of Stratospheric Intrusions Across the U.S.

Feb 16-19, 2022



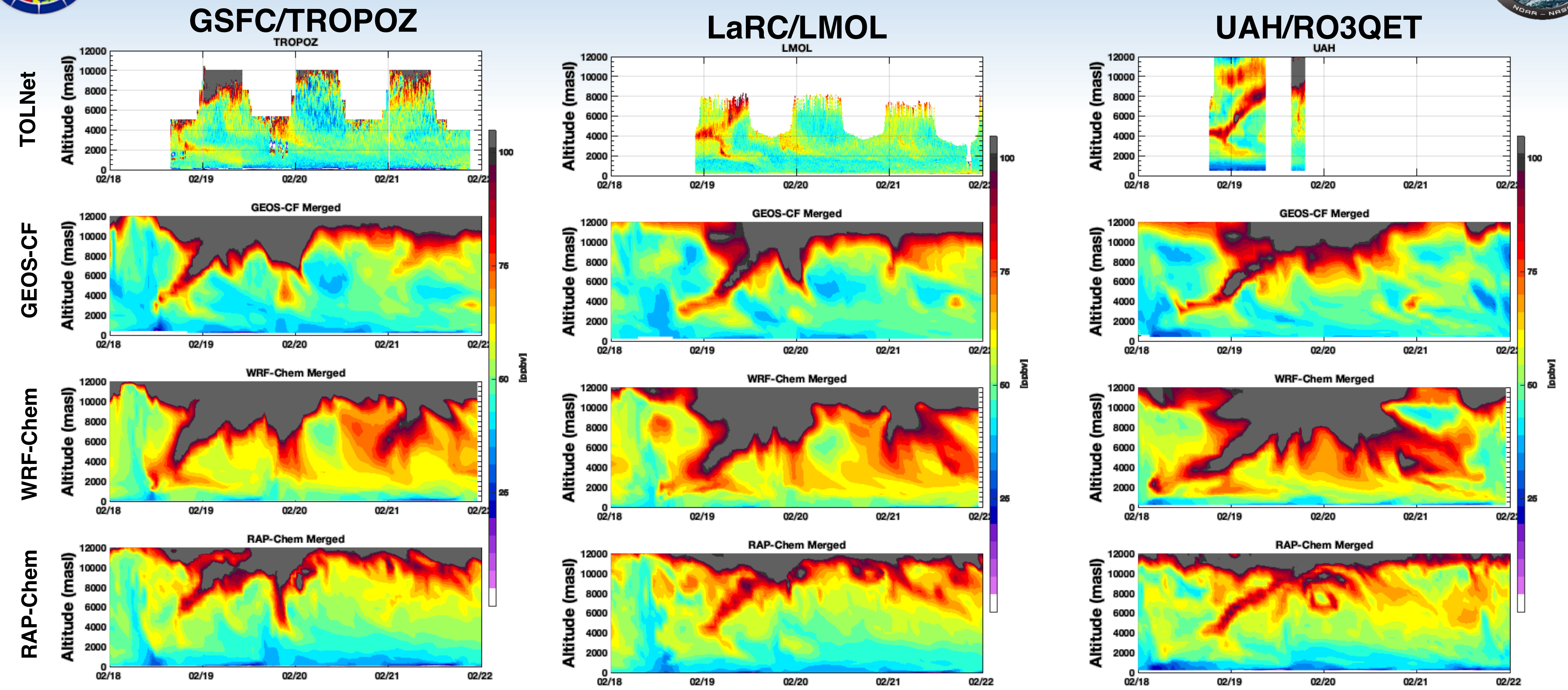
Website and Data

Air Quality (AQ) Forecast Alerts for TOLNet

- TOLNet provides data relevant for both scientific studies and satellite validation.
- Automated forecast system: daily AQ forecast email alerts are distributed to lidar teams to indicate times of AQ events (e.g., boundary layer O_3 enhancements, wildfires, stratospheric intrusions) to help determine ideal times to make observations.
- Models included:
  - WRF-Chem: 48-hour forecasts
  - RAP-Chem: 36-hour forecasts (06Z and 18Z)
  - GEOS-CF: 120-hour (5-day) forecasts; useful for long-range planning
  - NAQFC: 72-hour forecasts
  - HRRR-Smoke: 48-hour forecasts of wildfire smoke
- Determine times to make observations of “clean” and “polluted” conditions for use in TEMPO validation.
- Observations of “clean” and “polluted” conditions needed for robust satellite validation.

Stratospheric Intrusion Forecast Alert for TOLNet

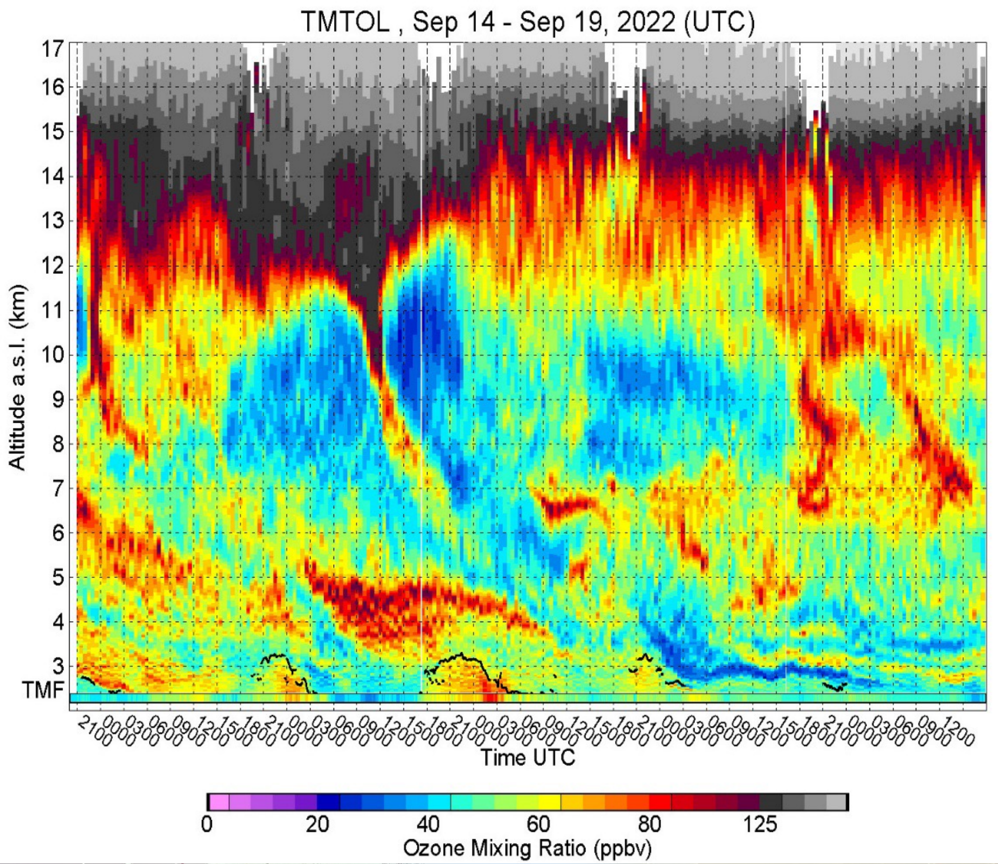
Feb 18-22, 2022



- ➢ **AQ forecasts proved vital in coordinating the network-wide observations of the stratospheric intrusion.**
- ➢ **Daily, multi-model AQ forecast alerts being provided to 8 TOLNet lidar systems for TEMPO validation observations.**

Building the Pathway from TEMPO to GeoXO

Joint Science Meeting for TEMPO, GeoXO ACX, & TOLNet

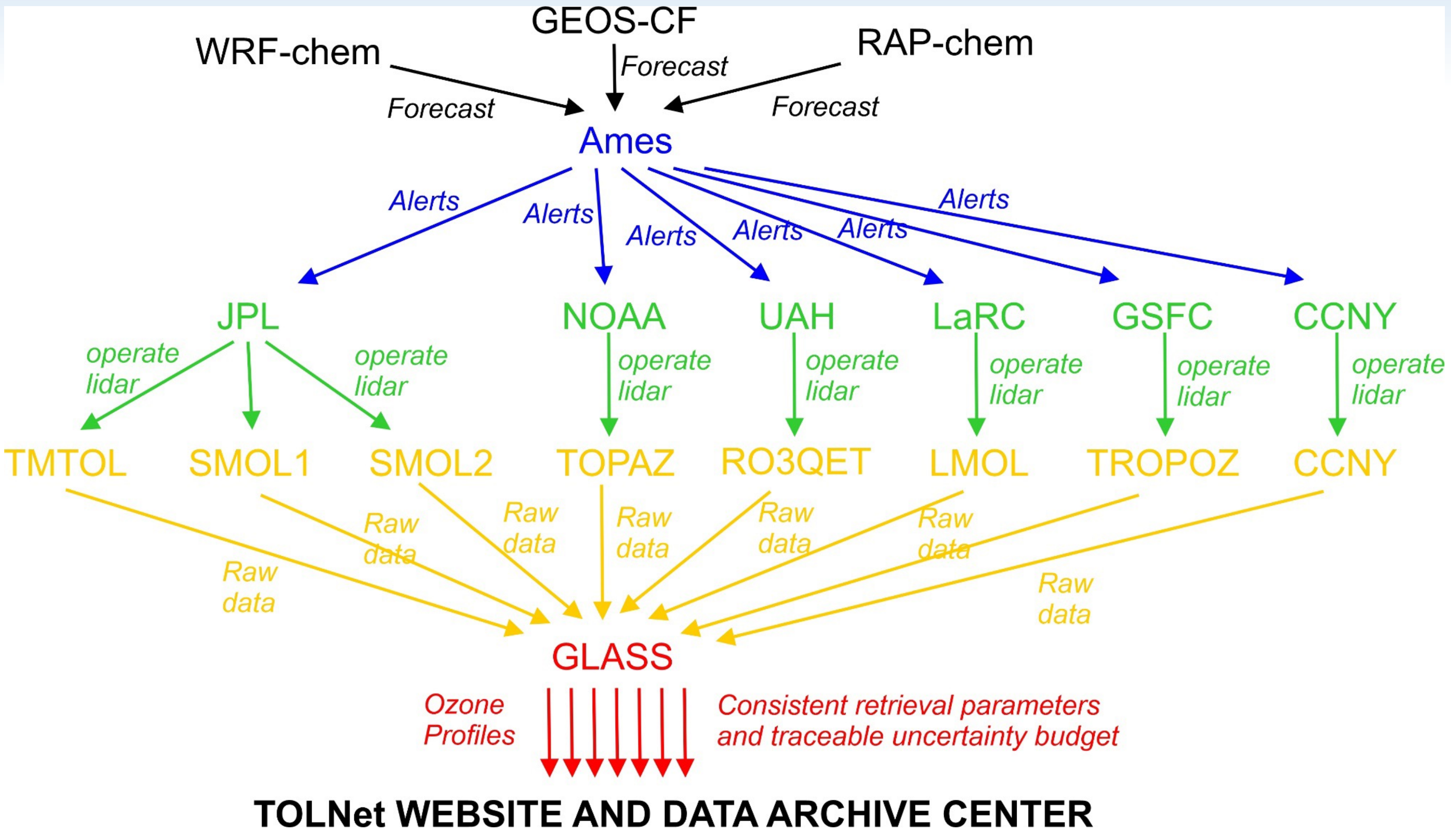


TOLNet Lidar Data Centralized Processing

Thierry Leblanc

NASA Jet Propulsion Laboratory
California Institute of Technology

TOLNet-wide ozone profile production flow in case of a special event Forecast Alert



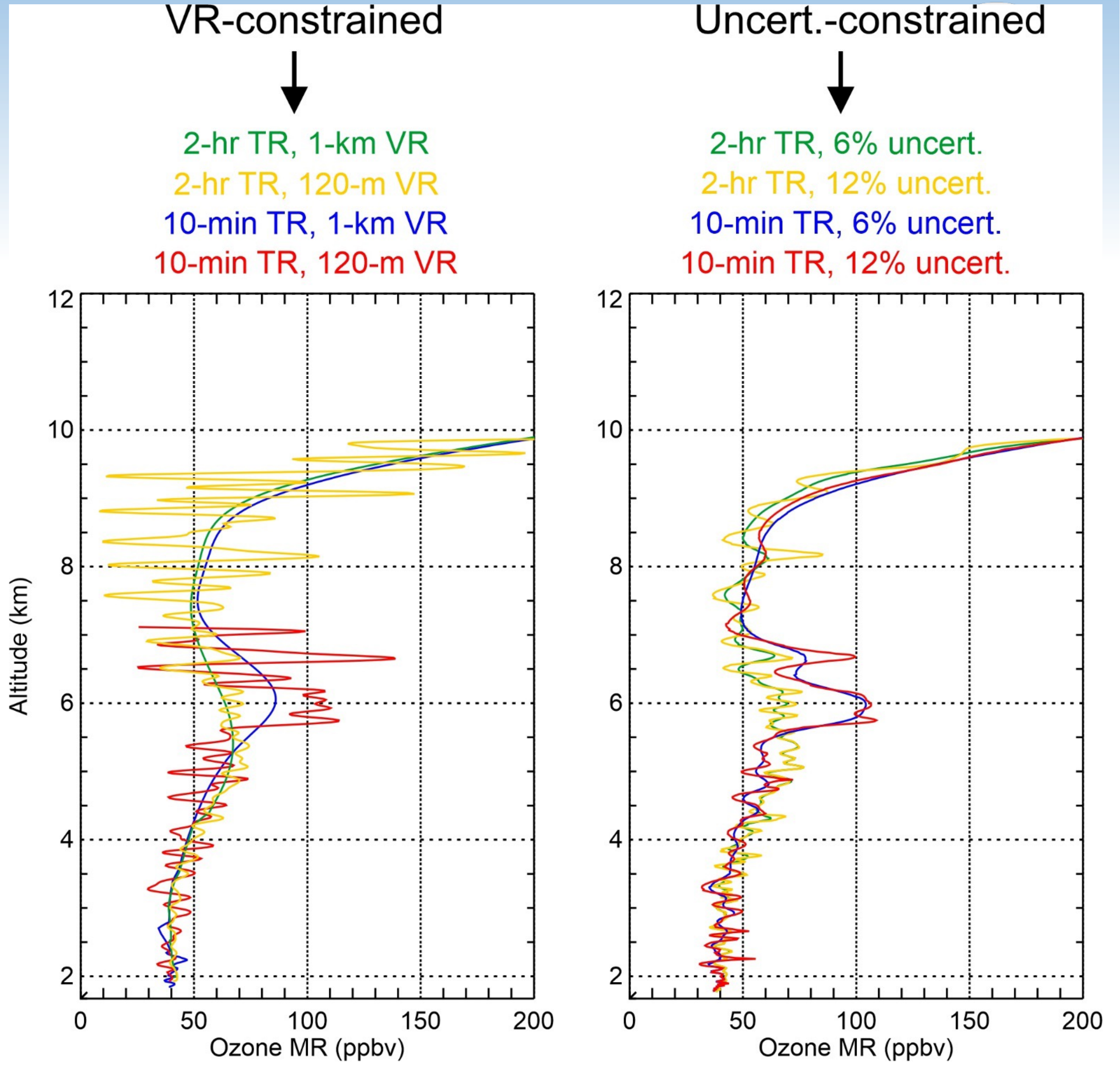
- **A similar alert system can be set up for TEMPO routine and/or special Ops.**

Tailored resolution and uncertainty requirement

Uncertainty, VR and TR can be tuned up to optimize validation needs

VR = Vertical Resolution

TR = Temporal Resolution



Lidar’s unique capability

Lidars can (and will) catch strong temporal and vertical gradients

Examples on figure show spatio-temporal scales of

Δt = 1 hour

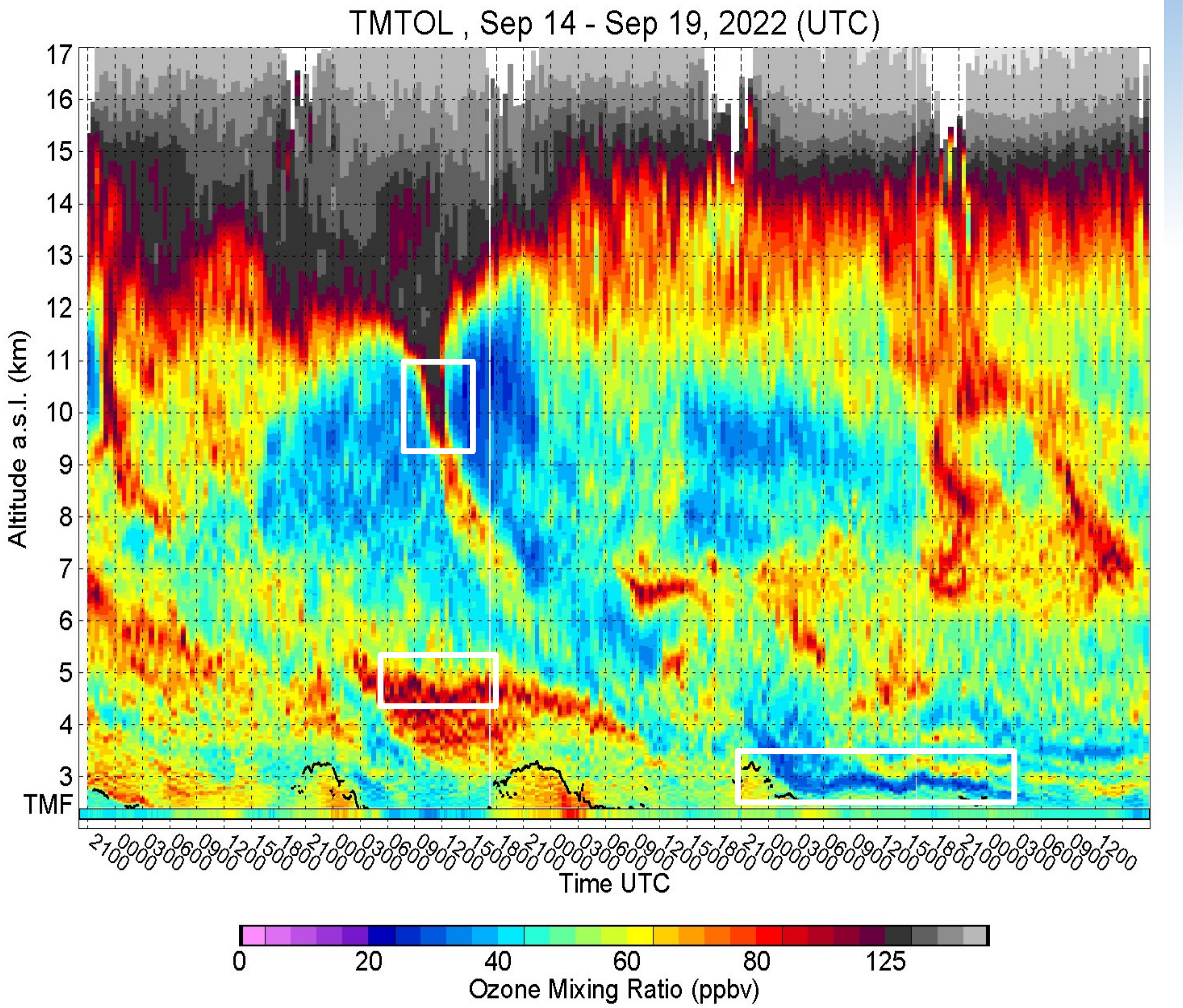
Δz = 0.5 km

How short of a time interval?

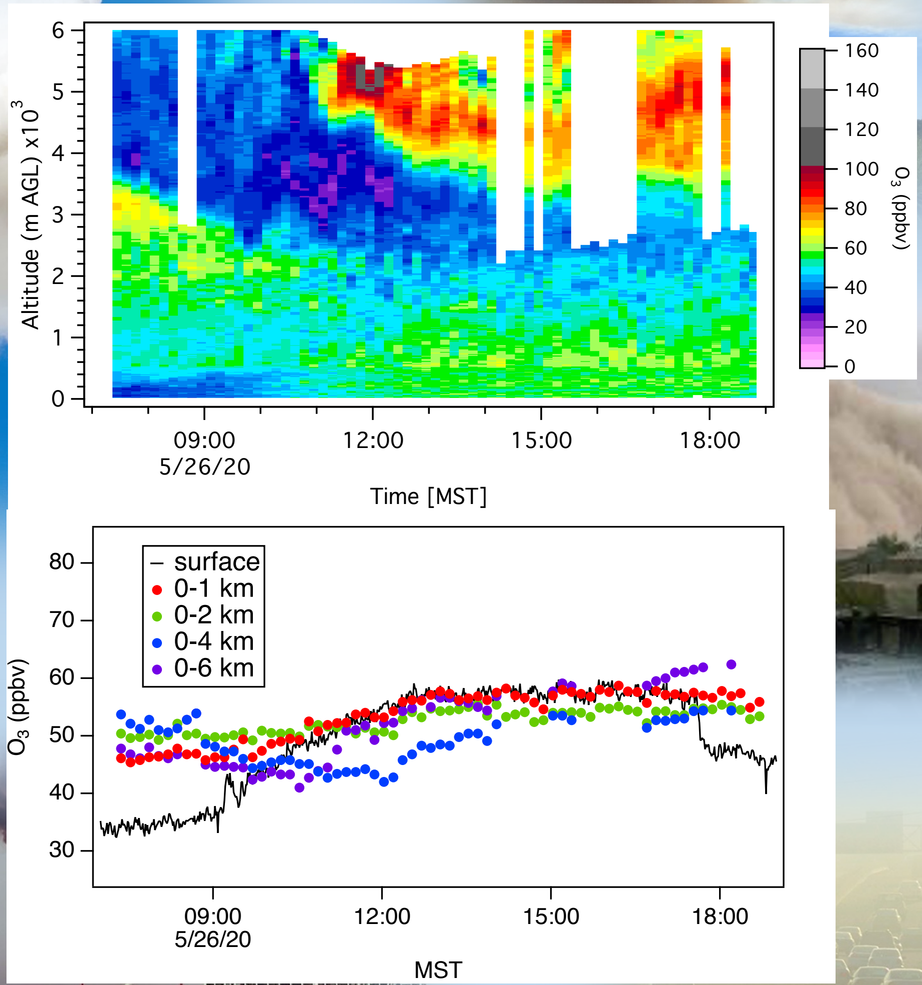
… and how shallow of a layer?

do we need for TEMPO Validation?

➔ 20-min TR and 0.1 to 2 km VR should suit most situations



Joint Science Meeting for TEMPO, GeoXO ACX, & TOLNet



TOLNet Lidar Data Campaigns and Understanding Ozone Representativeness

Andy Langford/NOAA CSL, Claudia Bernier/UH

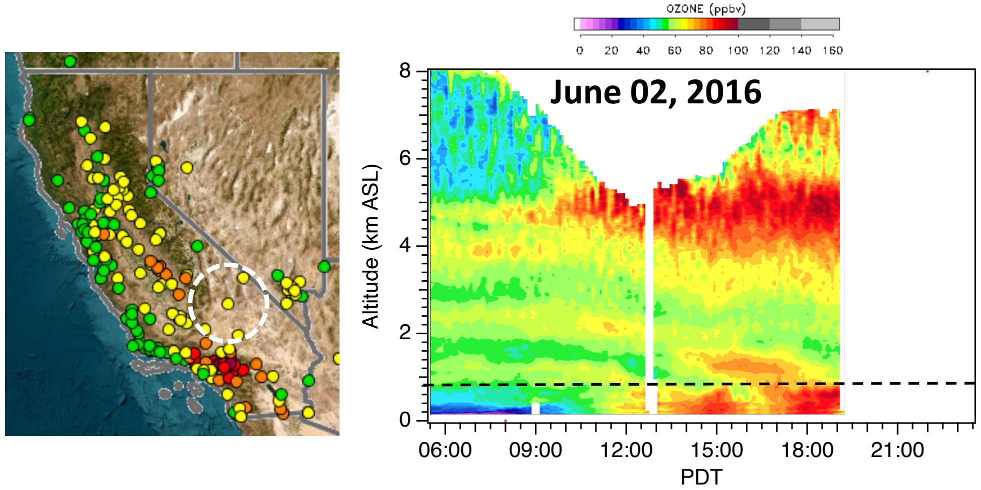
How will TOLNet measurements of atmospheric processes, especially within a campaign environment, contribute to understanding TEMPO vertical (0-2km, 0-10km), horizontal, and temporal gradient capabilities?

TOLNet lidars can characterize elevated layers that will complicate attribution of TEMPO 0-2 km O_3 product

CABOTS 2016

Visalia (San Joaquin Valley)

- **Strong latent heating and subsidence inhibit vertical mixing and PBL growth.**

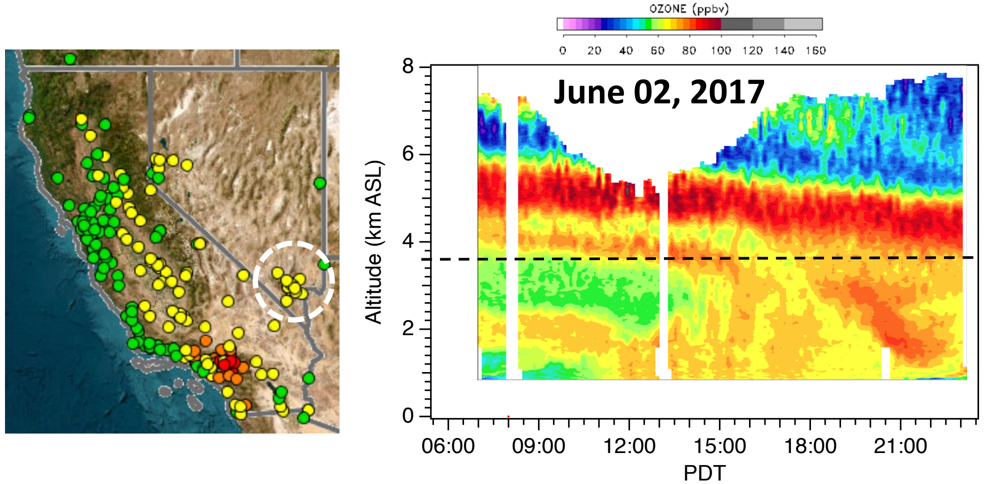


Asian pollution passes over shallow (≤1 km) PBL *and* the Sierra Nevada.

FAST-LVOS 2017

Las Vegas (Mojave Desert)

Weak latent heating allows PBL to reach depths of 5 km or more.

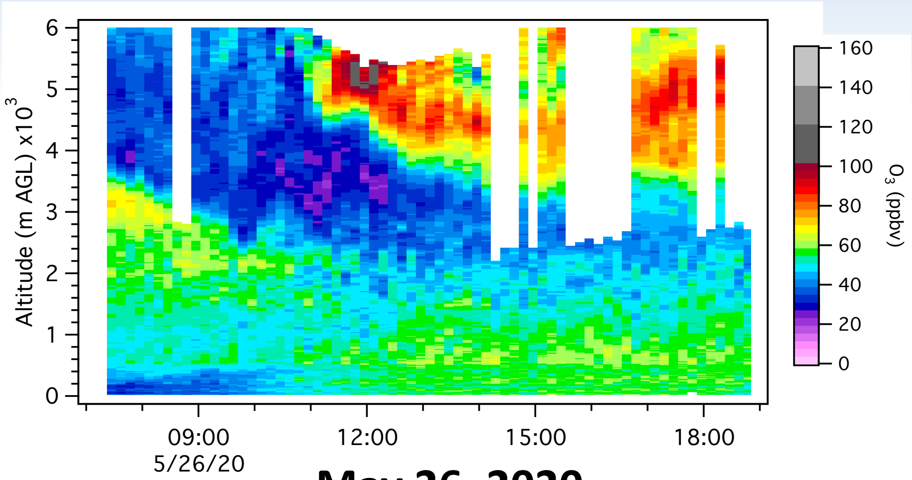


Asian pollution entrained by deep (≥3.5 km) PBL to mix with local pollution.

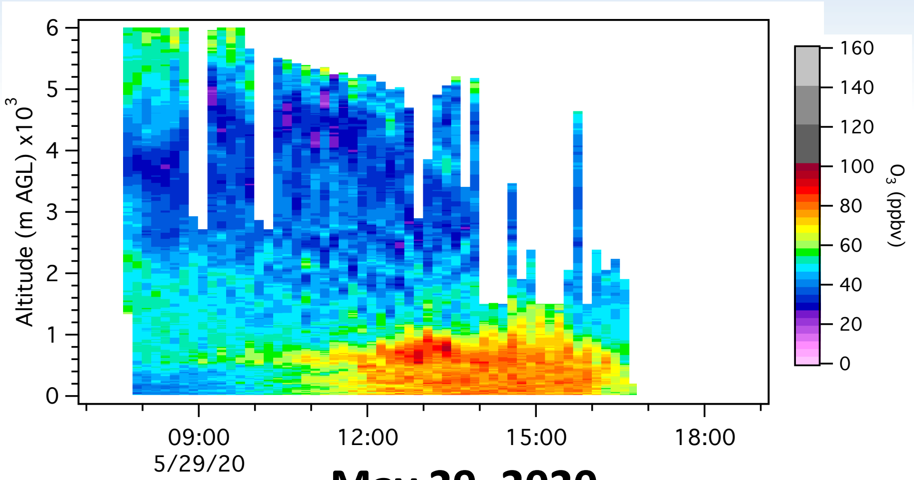
TOLNet lidars can help constrain the TEMPO lower tropospheric O_3 product

1. How do GEOS-CF forecasts compare to measurements?

TOPAZ lidar measurements from Boulder

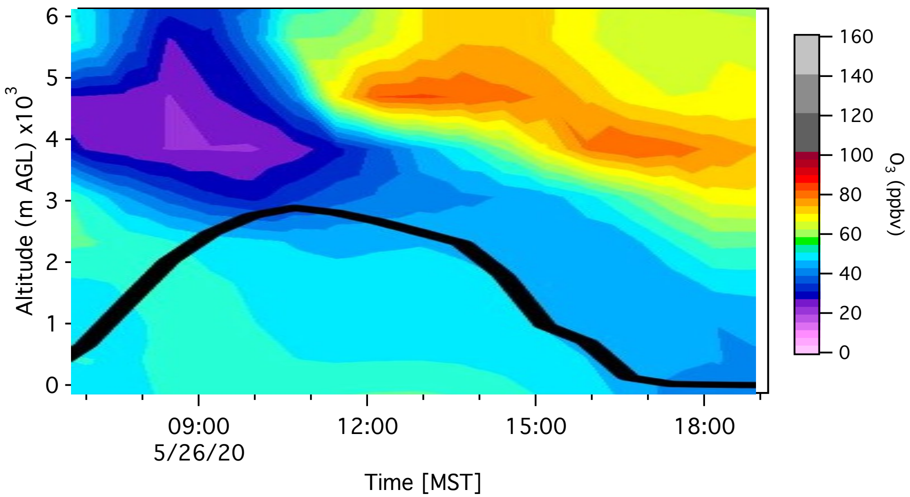


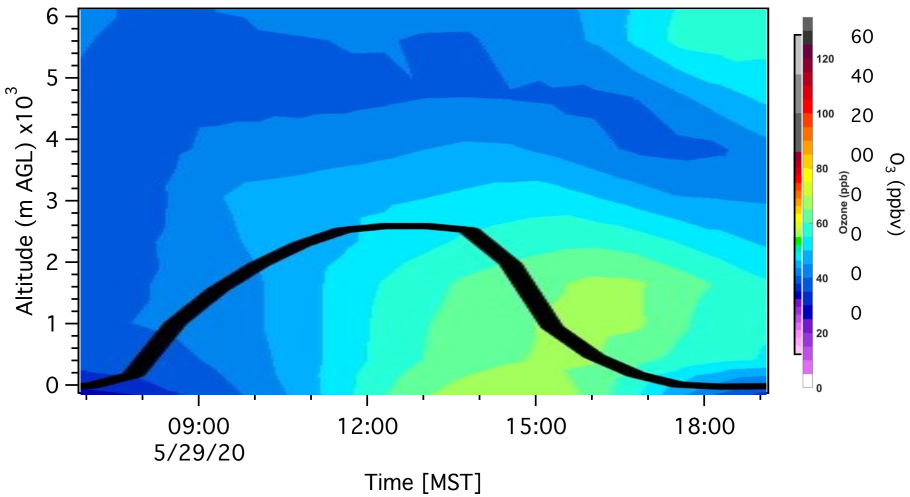
May 26, 2020



May 29, 2020

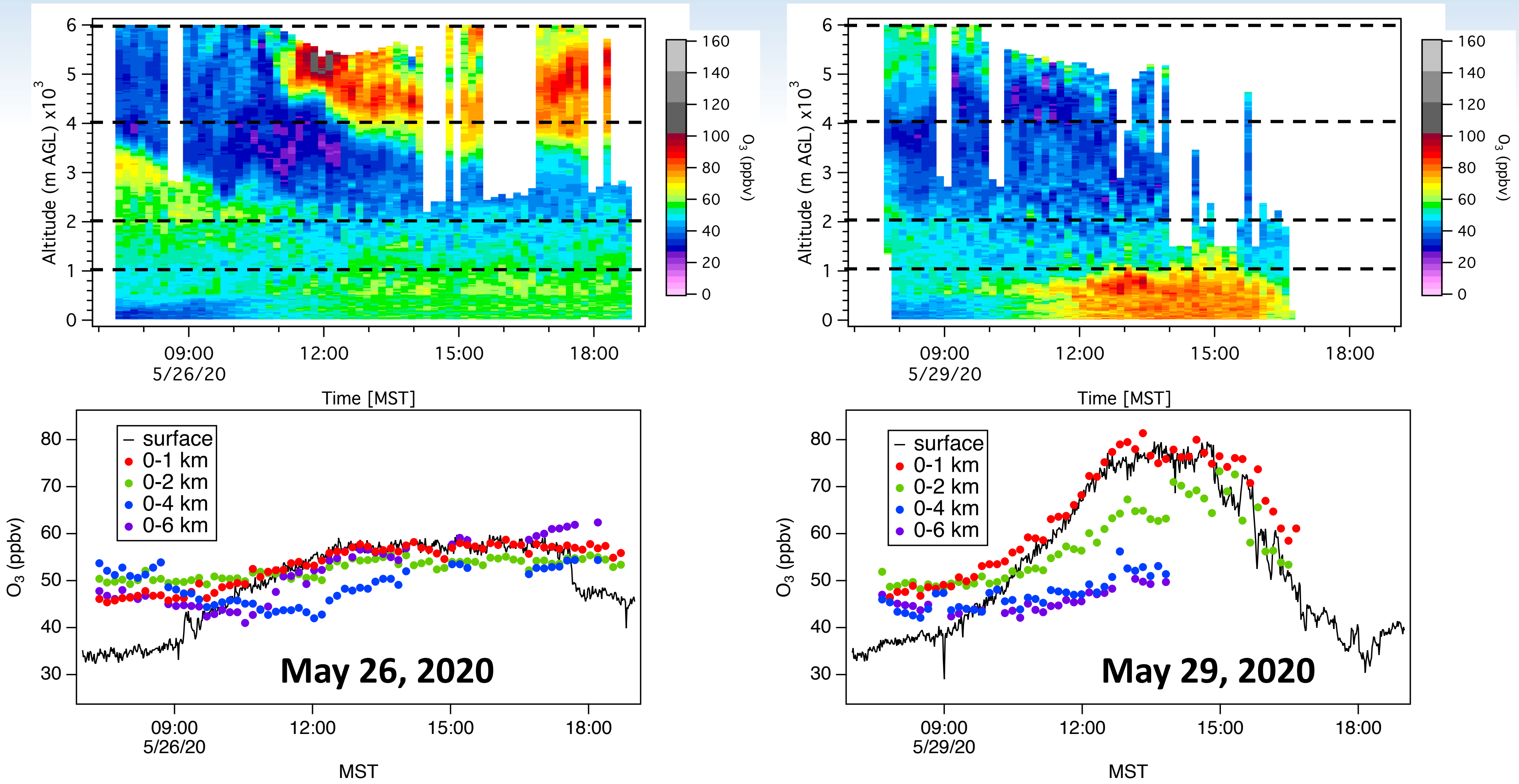
GEOS-CF Ozone (ppb) - TOPAZ - initialized 12UTC 20200526
Forecast provided by NASA GMAO; Emma Knowland





TOLNet lidars can help constrain the TEMPO lower tropospheric O_3 product

2. How do partial ozone columns compare to surface measurements?

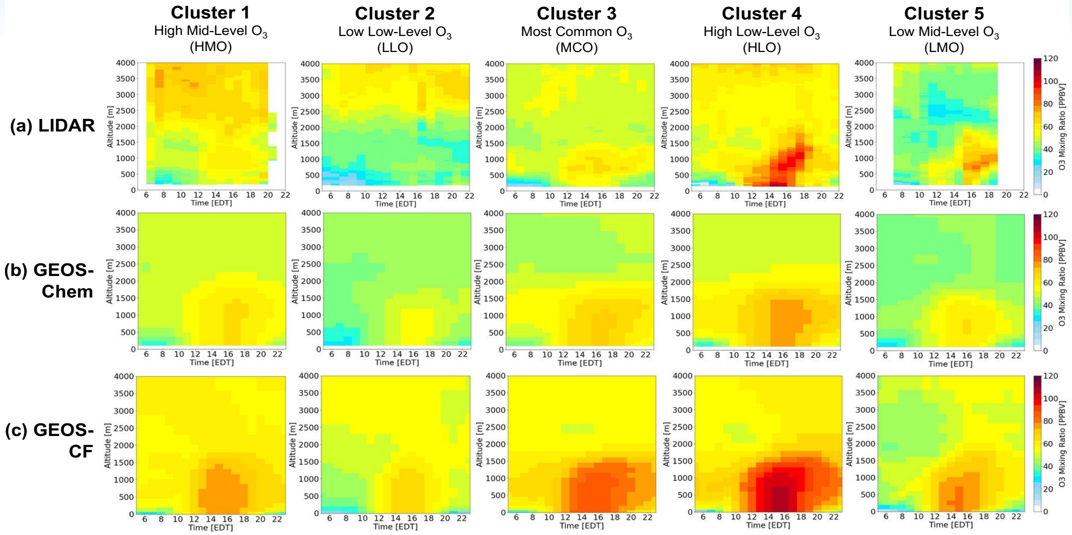


- 0-1 and 0-2 km columns agree well
- 0-4 km column low by 10 ppbv
- 0-6 km column right - for the wrong reasons!

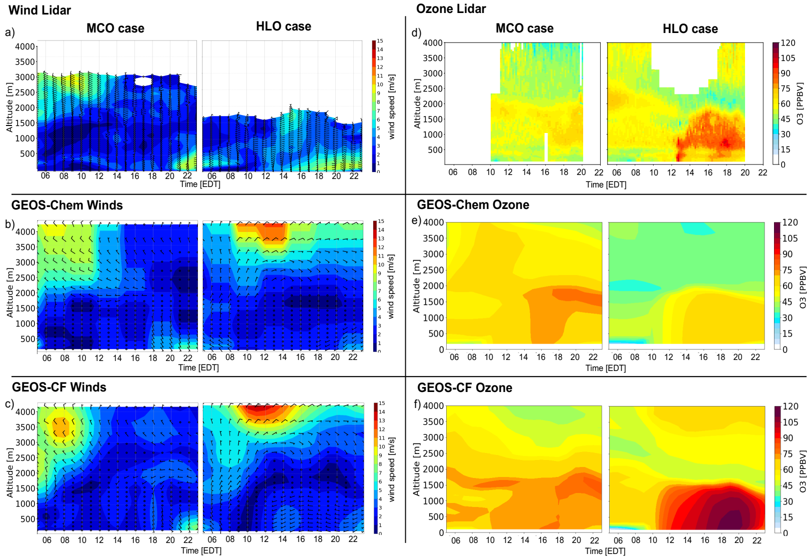
- 0-1 km column agrees well
- 0-2 km column low by 15 ppbv low.
- 0-4 and 0-6 km columns low by 25 ppbv

How TOLNet measurements of atmospheric processes, especially within a campaign environment, contribute to understanding TEMPO vertical (0-2km, 0-10km), horizontal, & temporal gradient capabilities?

Ozone lidar campaign clusters vs. GEOS-Chem & GEOS-CF



- Developed clustering method based on lidar O_3 curtain profiles from OWLETS 1 & 2, LISTOS
- Clusters highlight model limitations

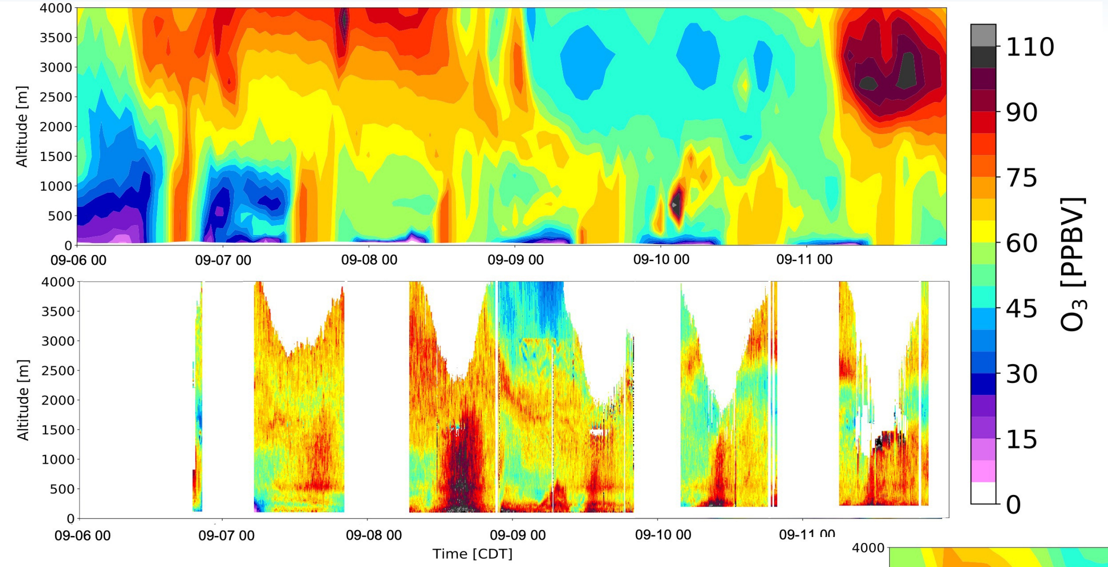


- Use cluster to evaluate specific case studies – sea/bay breeze possible cases
- Method useful in understanding air quality patterns, more readily evaluate models
- For future work - investigate TEMPO retrievals using lidar & models to assess the ability of satellite retrievals (e.g., TEMPO) to monitor O_3 over such complex environments

Recently published: *Bernier, C., Wang, Y., Gronoff, G., Berkoff, T., Knowland, K. E., Sullivan, J. T., Delgado, R., Caicedo, V., and Carroll, B.:, Atmos. Chem. Phys., 22, 15313–15331, https://doi.org/10.5194/acp-22-15313-2022, 2022.*

How TOLNet measurements of atmospheric processes, especially within a campaign environment, contribute to understanding TEMPO vertical (0-2km, 0-10km), horizontal, & temporal gradient capabilities?

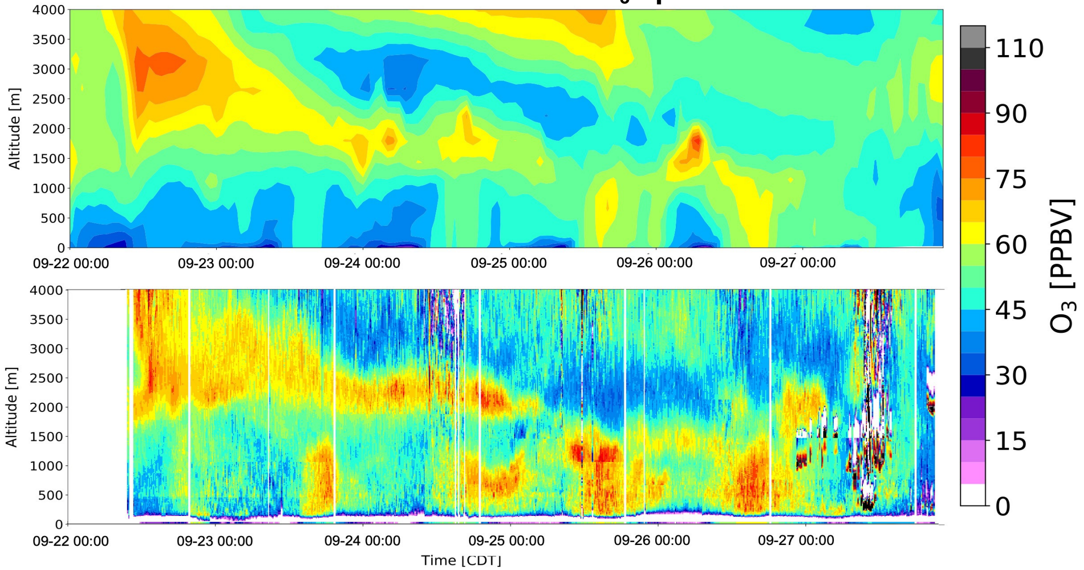
Ozone lidar vs. WRF-Chem during TRACER-AQ



O_3 episode 1: UH Campus - LMOL

- Recent work evaluating lidar measurements & WRF-Chem model (4km) capability during two O_3 episodes from TRACER-AQ
- Will allow for intercomparison between model – lidar – satellite

O_3 episode 2: La Porte - GFSC



Building the Pathway from TEMPO to GeoXO

Joint Science Meeting for TEMPO, GeoXO ACX, & TOLNet

TOLNet for Improved TEMPO Validation and Science Results

Fred Moshary- CCNY

Kevin Strawbridge-Env Canada

Ruben Delgado- Hampton U

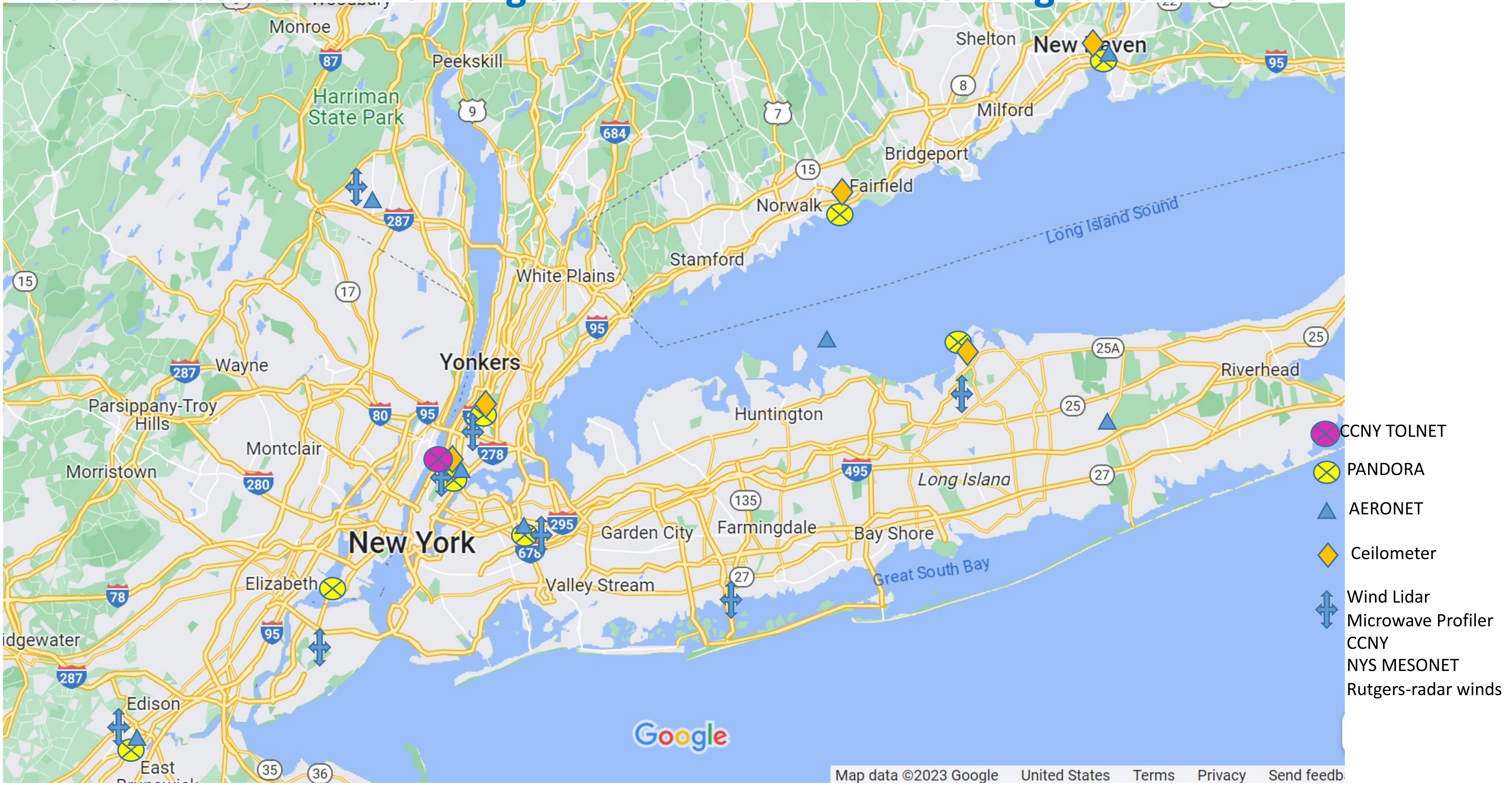
The City College of New York

NOAA-CESSRST CENTER FOR EARTH SYSTEM SCIENCES AND REMOTE SENSING TECHNOLOGIES

How can the higher spatiotemporal resolution of TOLNet/lidar/ceilometer ozone and aerosol measurements combine with TEMPO measurements to improve our knowledge and understanding of these atmospheric constituents?

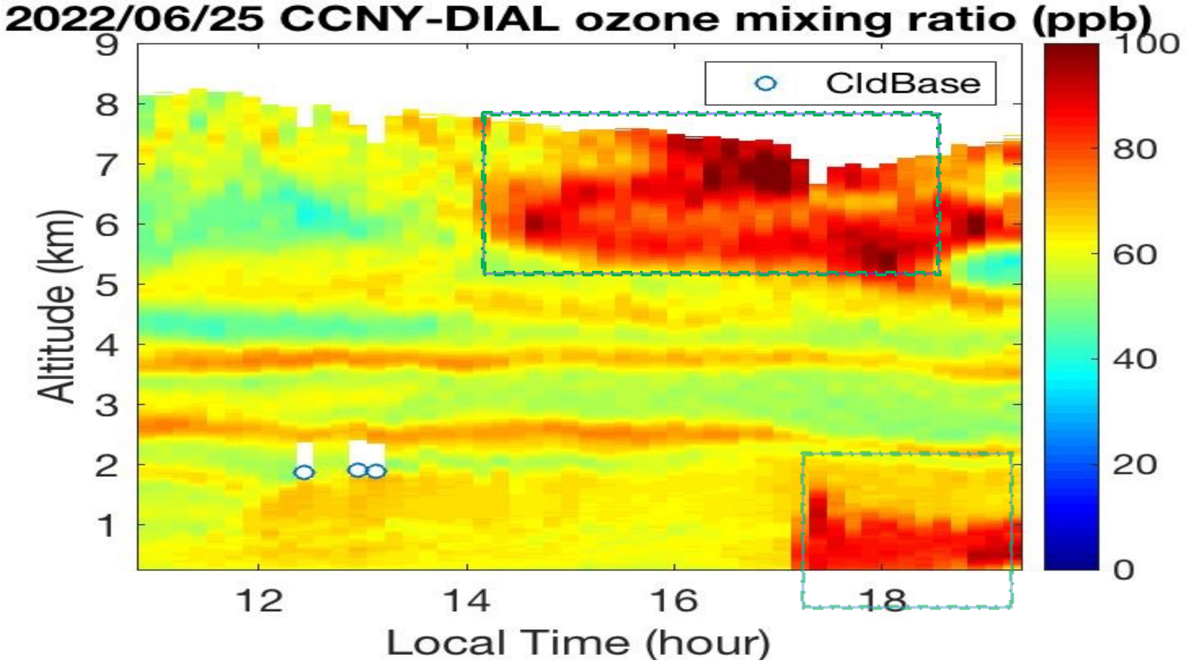
- PBL height
- Vertical distribution within the PBL and aloft
- Aerosol Optical Properties (Multiwavelength Lidar)
- Connecting nighttime to daytime (transitions)
- Capture atmospheric dynamics (e.g. sea breeze impacts)
- Plume transport and impacts on surface air

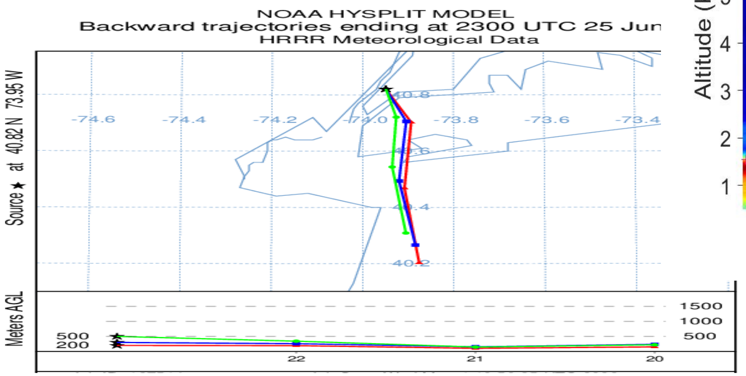
Extensive concentration of ground-based remote sensing observations

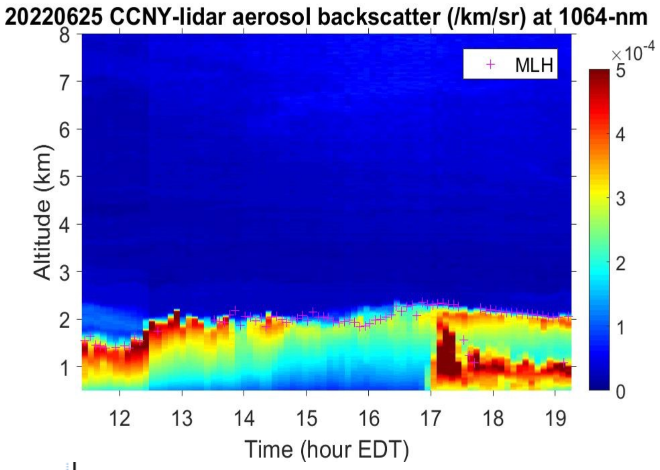


Case-Sharp increase of near-surface O_3 in the late afternoon (sea-breeze effect)

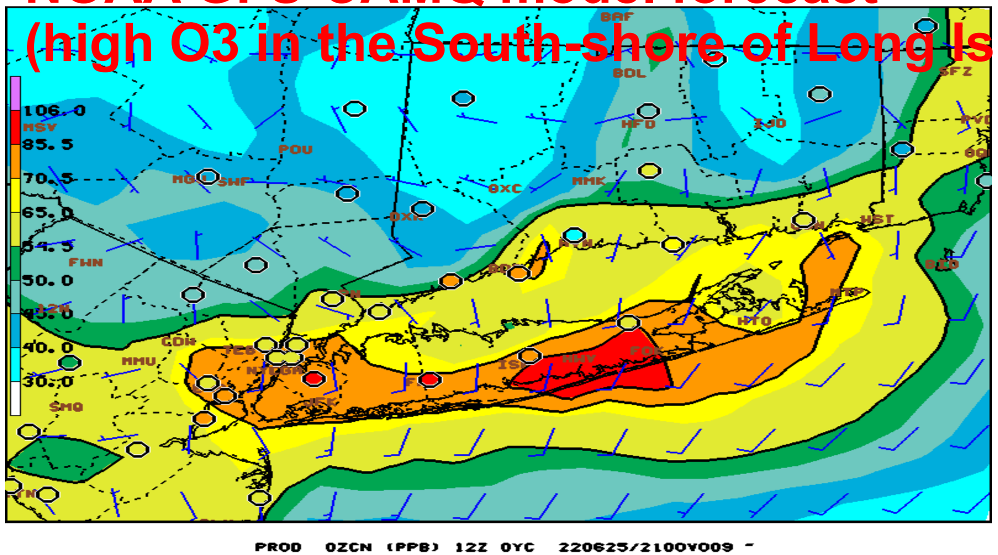
Prevailing NW winds in NYC before 17:00, more O3 in the southern Long Island and NY/NJ Bight

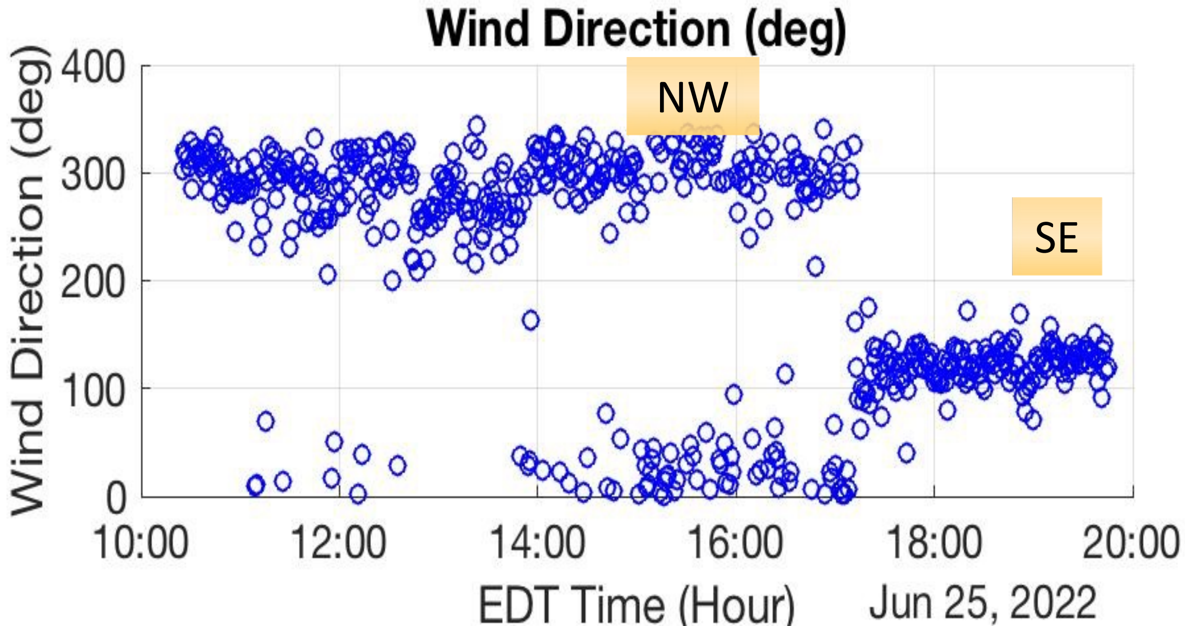




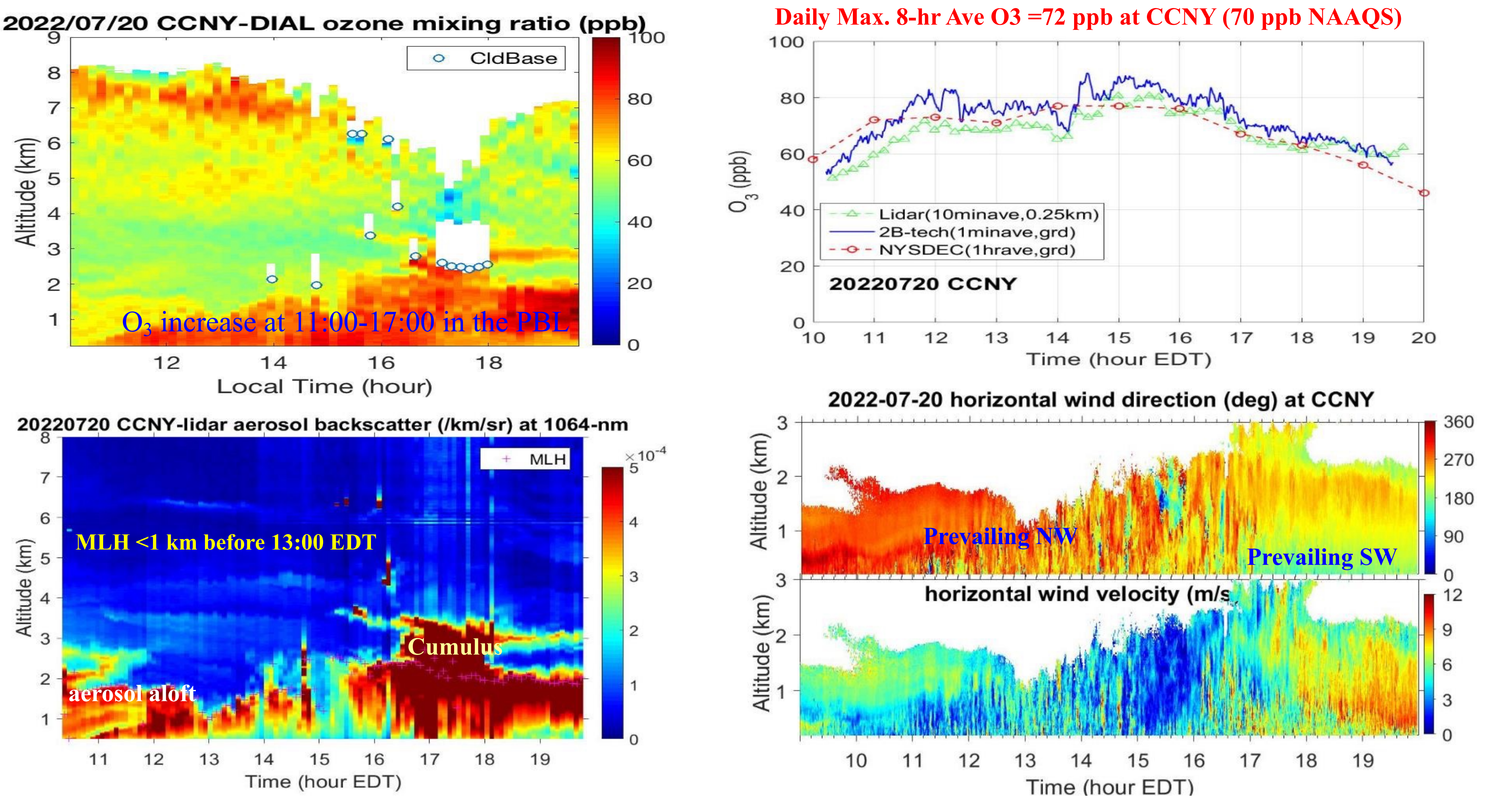


NOAA GFS-CAMQ model forecast (high O3 in the South-shore of Long Island

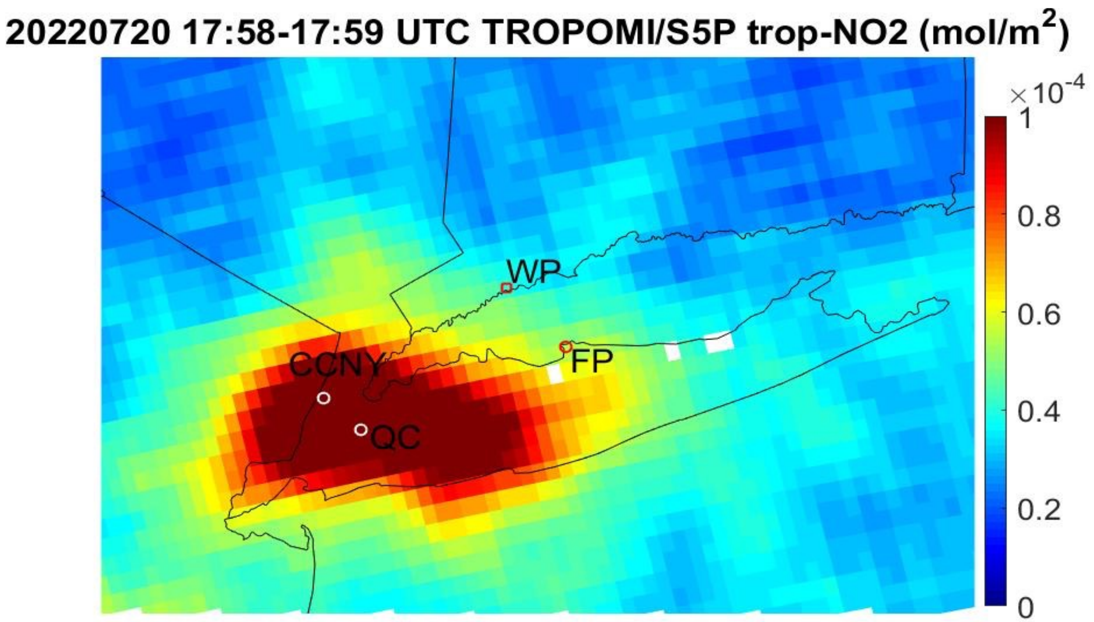


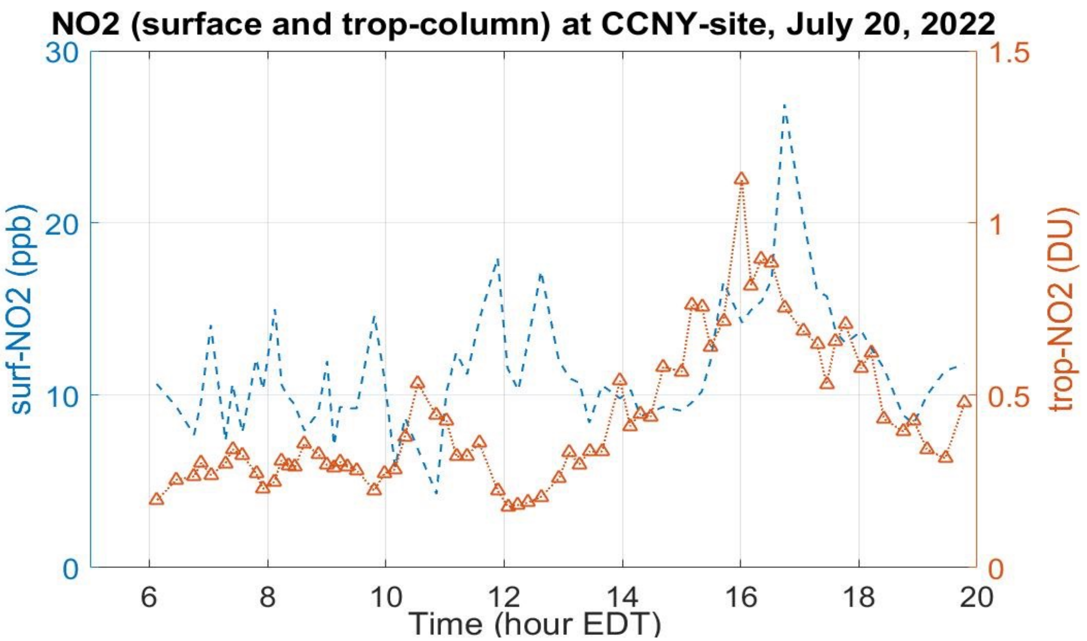


High O_3 formation at noon in the low PBL on July 20, 2022(T_{max}=35.36°C heat-wave day)

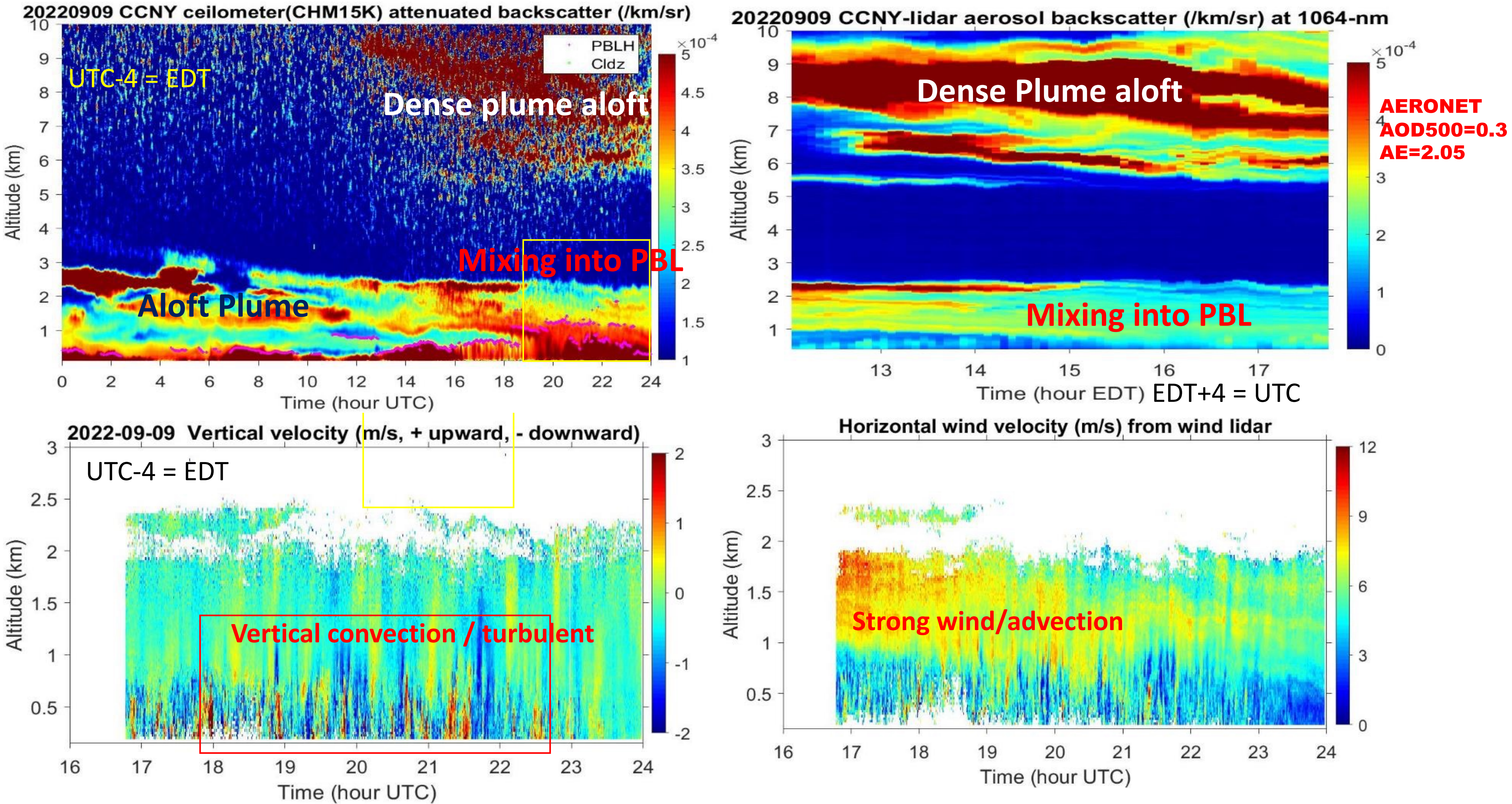


Case: Heat-wave day, July 20, 2022

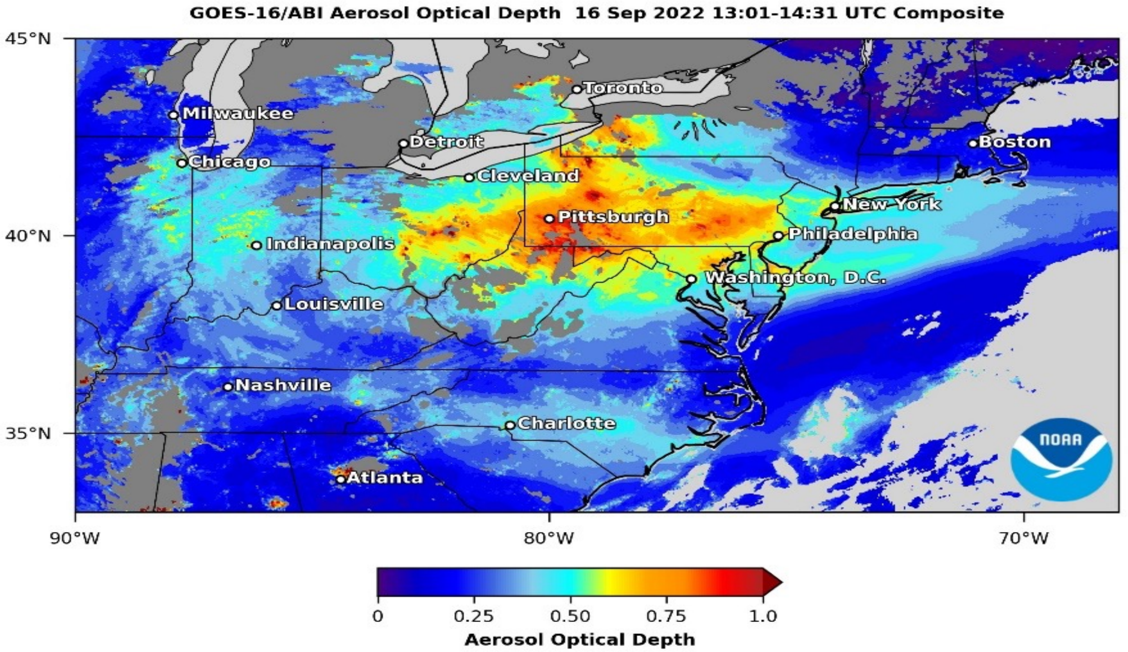


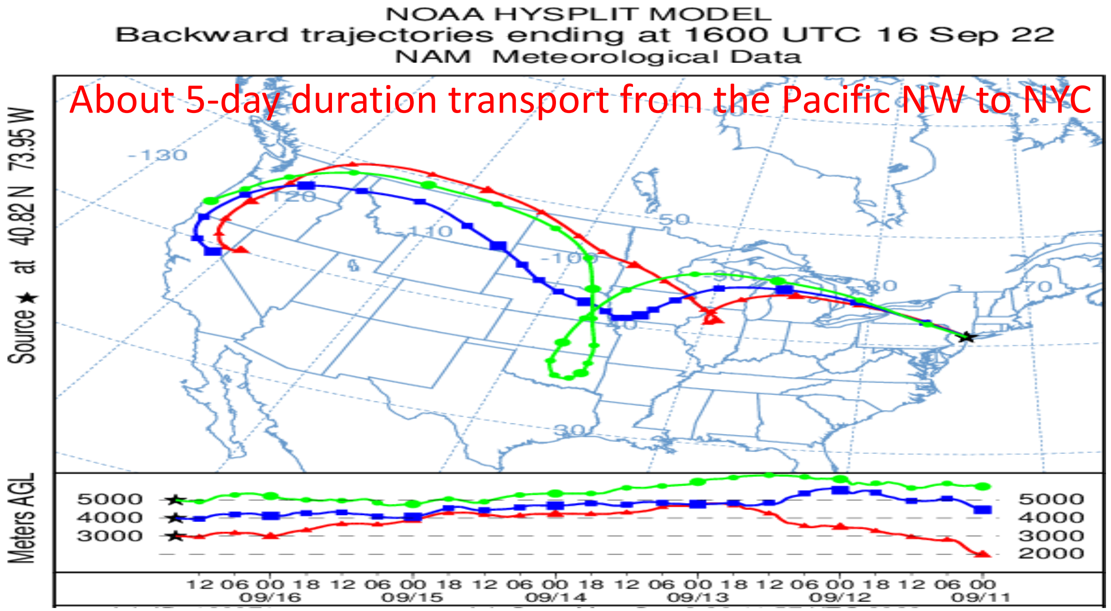


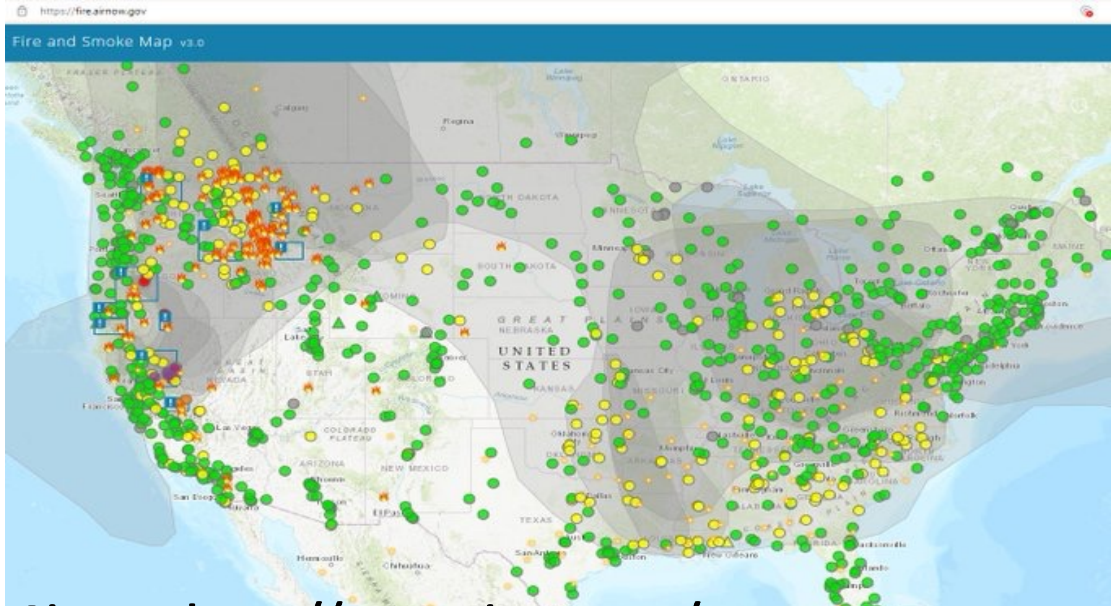
Smoke Plume Mixing into PBL on Sep.9, 2022



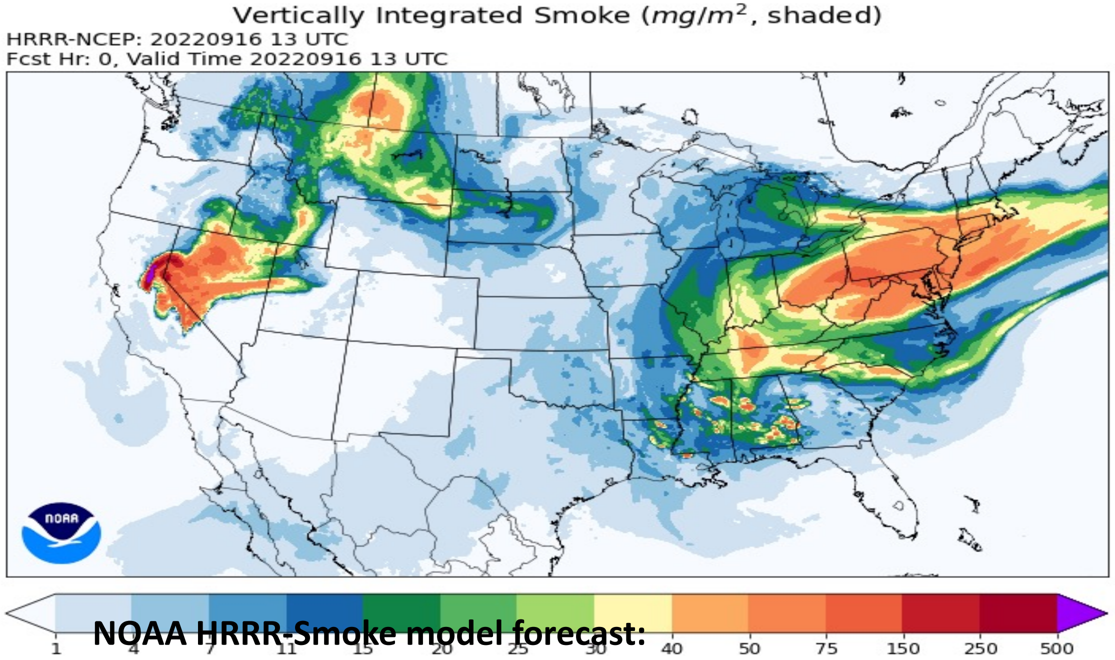
NOAA satellite GOES-16 AOD and smoke transport to NYC area







Airnow: https://www.airnow.gov/



NOAA HRRR-Smoke model forecast:
https://rapidrefresh.noaa.gov/hrrr/HRRRsmoke/

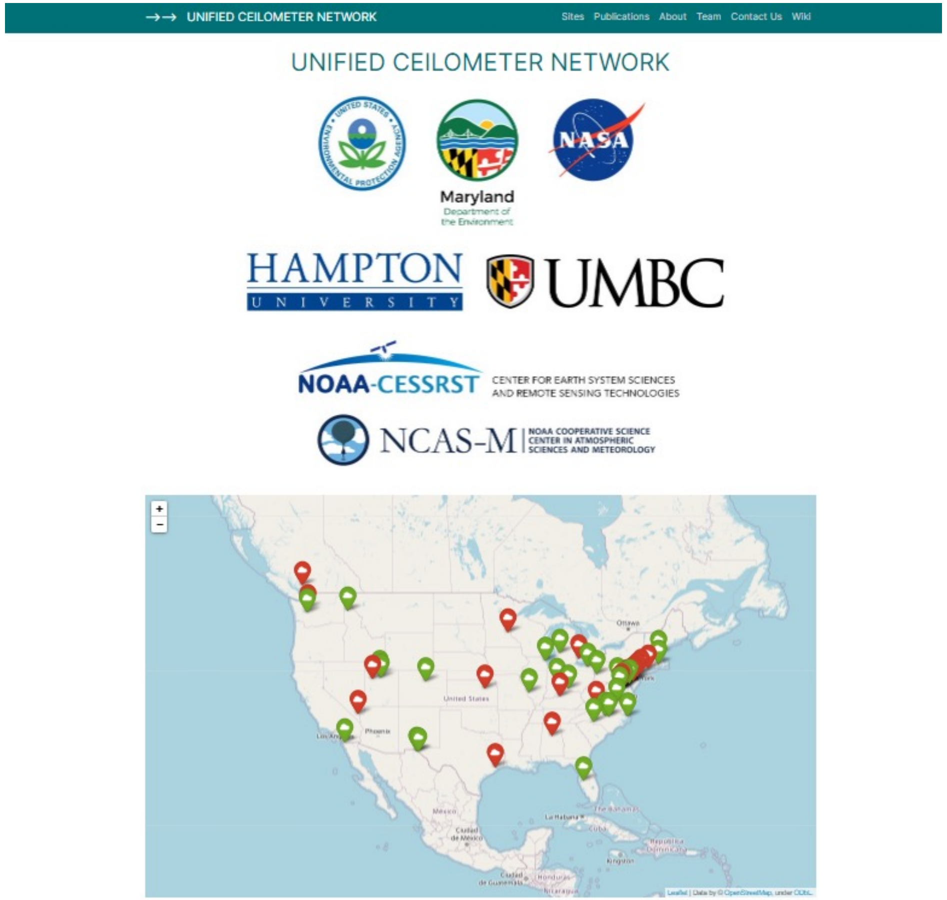
Unified Ceilometer Network (UCN)

- Engaged with 34 local and state environmental agencies, 5 federal agencies (US EPA, NASA, NOAA, USDA, ARMY), 11 MSIs and 1 international (Environment and Climate Change Canada). Over 50 sites in North America.

- Supporting Photochemical Assessment Monitoring Stations (PAMS) program: Hourly Mixing Layer Height requirement.

- Relate Column Observations (Satellite and Ground) to Surface Conditions for Aerosols and Trace Gases

  - Do boundary layer depth, humidity, long-range transport and surface type appear to influence these correlations?
  - Differences and similarities in the diurnal cycles of surface and column observations.



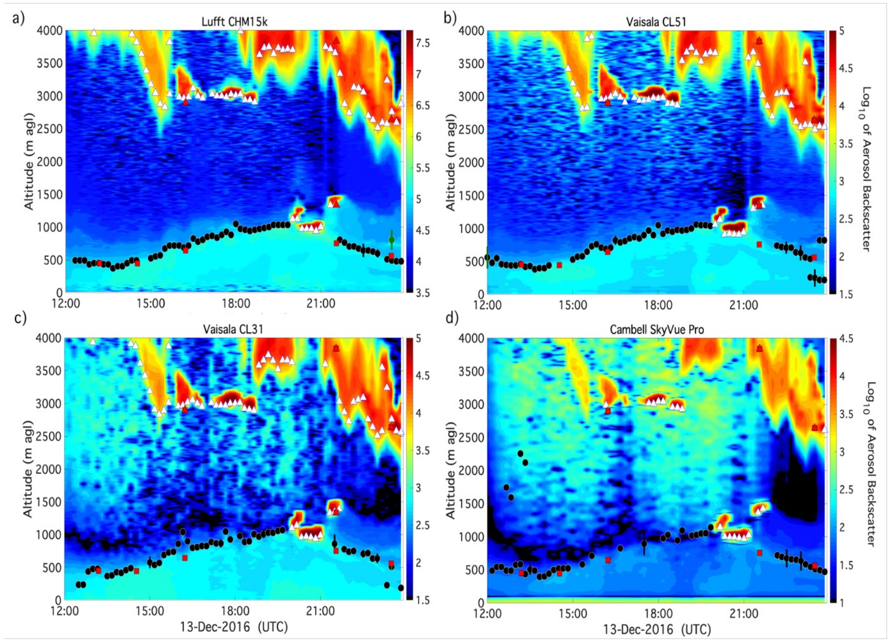
https://ucn-portal.org

UCN Data Products

- **Near real-time data processing of particle pollution**
  - Fire Weather, Dust Storms and Volcanic Ash
- **Standardized retrieval algorithms for heterogeneous network**
  - Automated PBL algorithm corrects for signal quality, screens for precipitation and cloud layers, and provides PBLH uncertainties.
- **Ceilometers collocated with AQ/Met sensors:**
  - 40 US EPA locations (PAMS+Ncore): Sites with continuous boundary layer profiling collocated with Ambient air database (met, $PM_{2.5}$, O_3,NO_2, NOx, speciated VOCs and $PM_{2.5}$).
  - A select number of sites host Pandora spectrometers as an enhanced monitoring instrument.

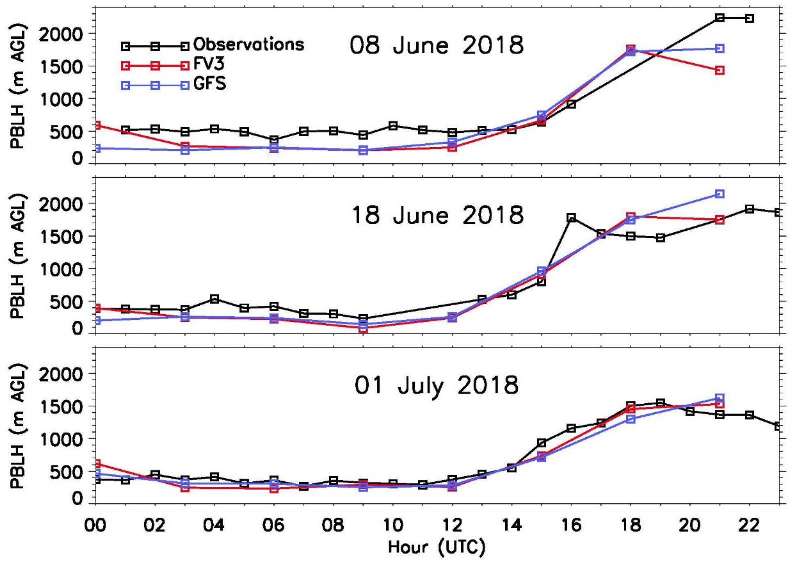
PBL Automated Outputs:

- Cloud-base heights
- Precipitation flags
- Filtered PBL heights (NSL, RL, MLH)
- Uncertainties for PBL heights

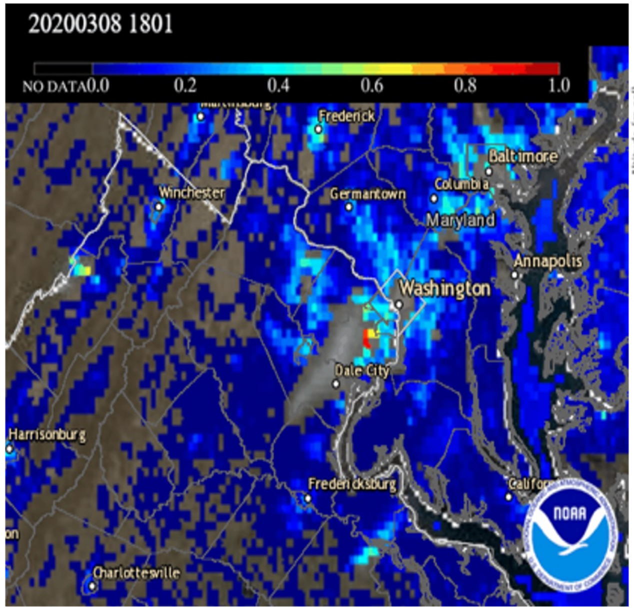


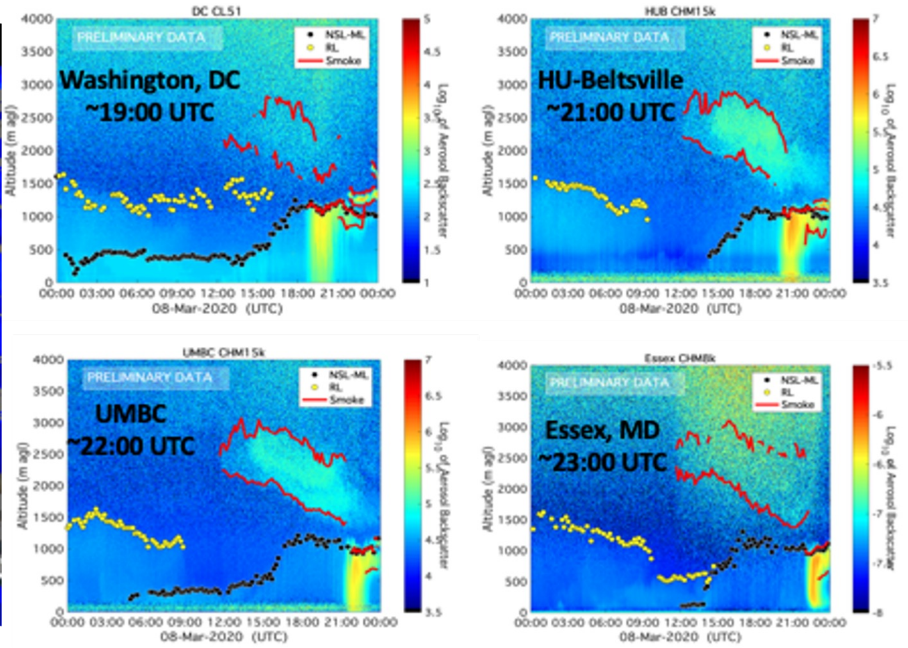
Caicedo et al. (2020)
https://doi.org/10.1175/JTECH-D-20-0050.1

Verification/Validation of Models and Satellite Products



PBL Height:
Ceilometer vs NOAA FV3 and GFS model
(Loughner et al. 2019)





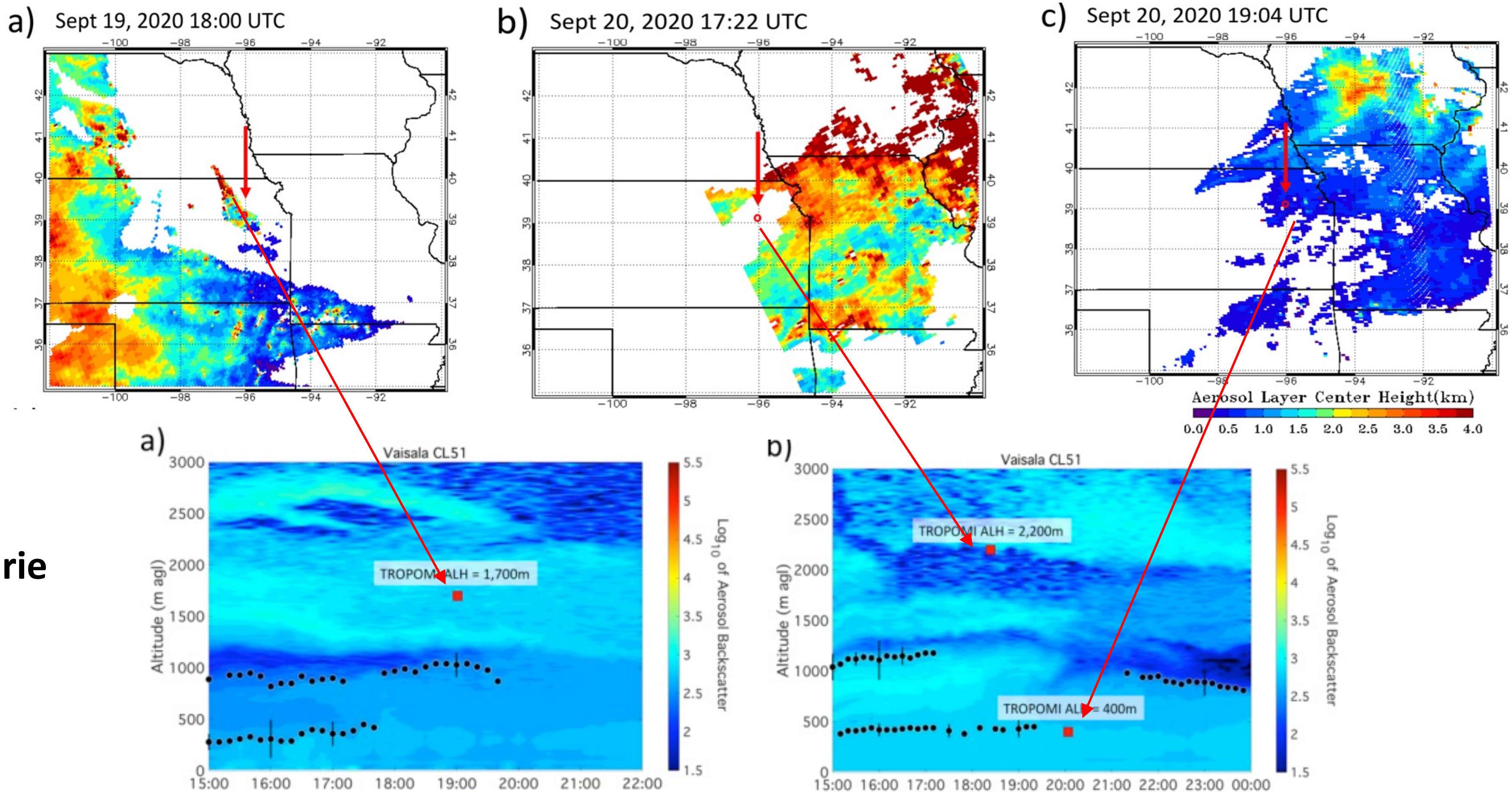
Smoke transport within PBL observed by ceilometers network supplementing GOES-16/ABI AOD
Huff et al. 2021
https://doi.org/10.1175/JTECH-D-20-0162.1

Air Quality Case Studies and Exceptional Event Analysis

Verification/Validation of Models and Satellite Products

TROPOMI Aerosol Layer Heights

U.S. Region 7 CL51 at Konza Prairie Site



The UCN site in Konza Prairie, Kansas (EPA Region 7: 39.1022°N, 96.6096°W Bottom a-b) captured the evolution of the smoke plume transport. Ceilometer planetary boundary layer heights were calculated at the times of TROPOMI measurements and contrasted against TROPOMI ALH (Top a-c).

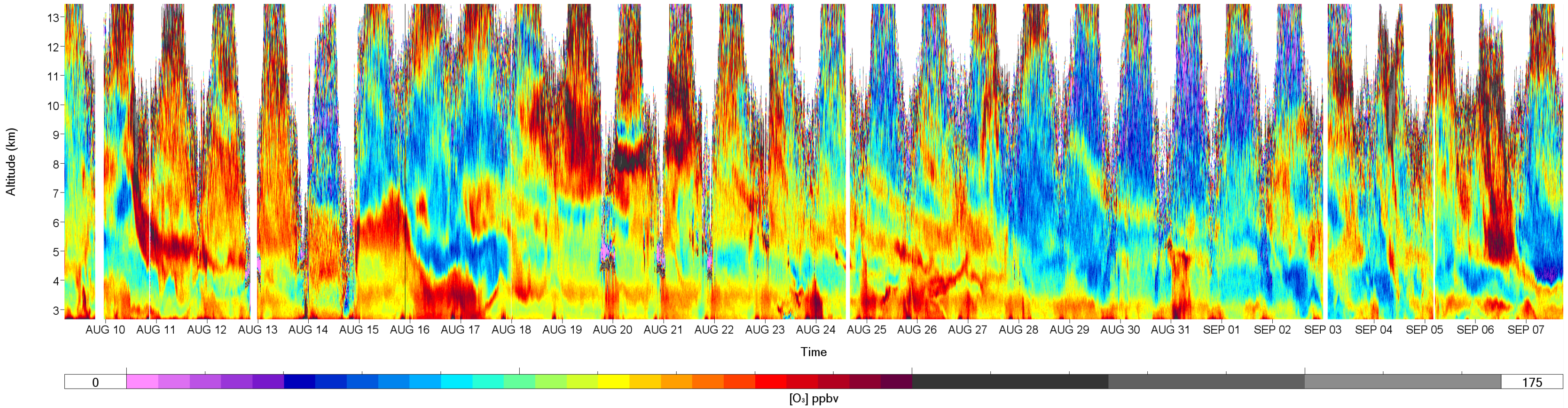
Source: Caicedo (CIRES)/Wang (Univ. Iowa)

Synergistic approach of using TOLNet and TEMPO (plus Ceilometers, AERONet, PANDORAs, MPLNet)

General Comments:

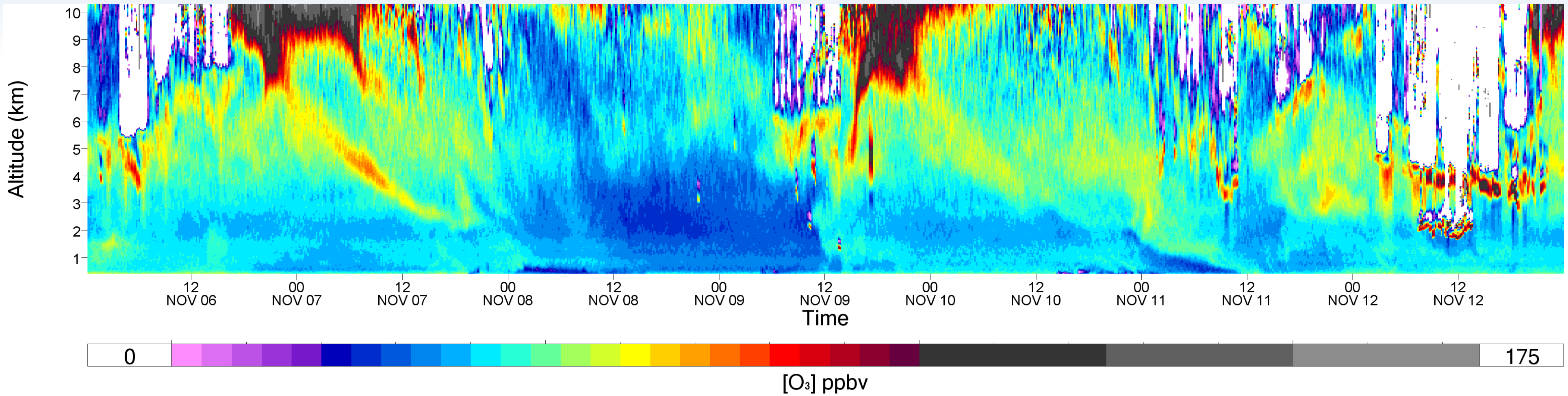
- Since lidars are active instruments then can operate 24/7 – some of the TOLNet systems are fully autonomous or can be operated remotely allowing continuous multi-day observations (except during precipitation)
  - Allows one to observe “phenomena” that otherwise you may have missed – normally may not operate in those conditions – removes some sampling bias
  - Fill in the gaps between the TEMPO days of observation
    - Break-up of the PBL
    - Important in process studies – opportunity to link models with lidar and TEMPO observations
- TEMPO hourly data over the same geographical grid square provides a very unique opportunity when combined with high resolution lidar data
  - Validation of TEMPO ozone, aerosol, water vapor products (seasonal - eg. Snow)
  - Health studies
  - Climate studies
  - Process studies

30 days of Ozone observations

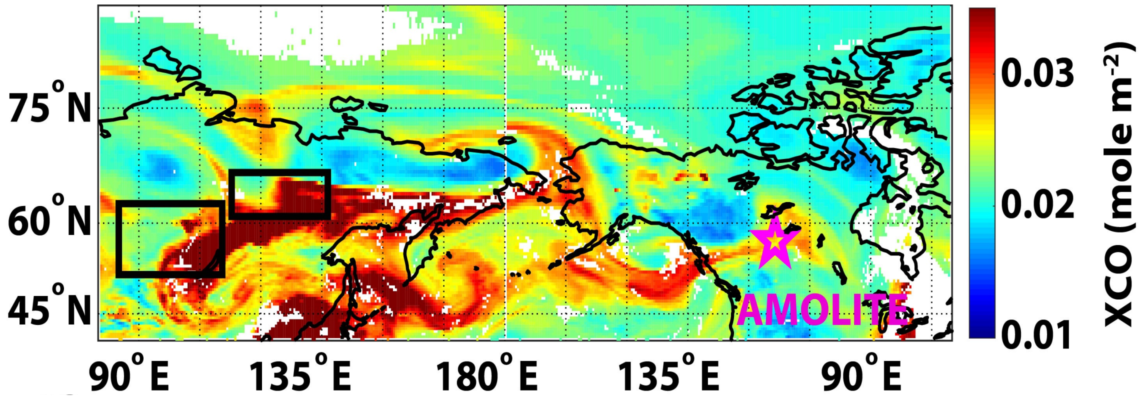


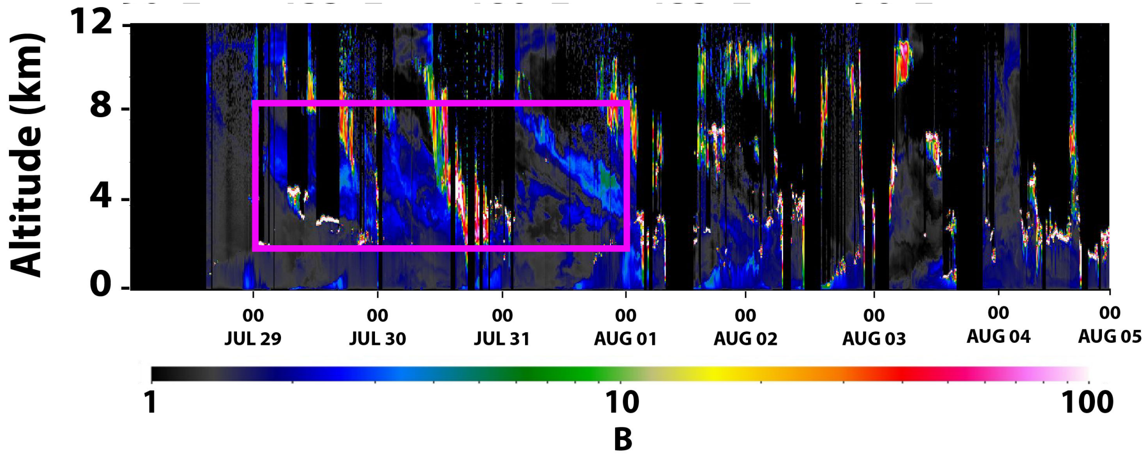
Ozone:

- Study of stratospheric/tropospheric transport (STT)
  - The vertical resolution of the lidar and the horizontal capability of TEMPO gives a unique opportunity to study the magnitude and frequency of STT events



- Ozone generated by forest fires



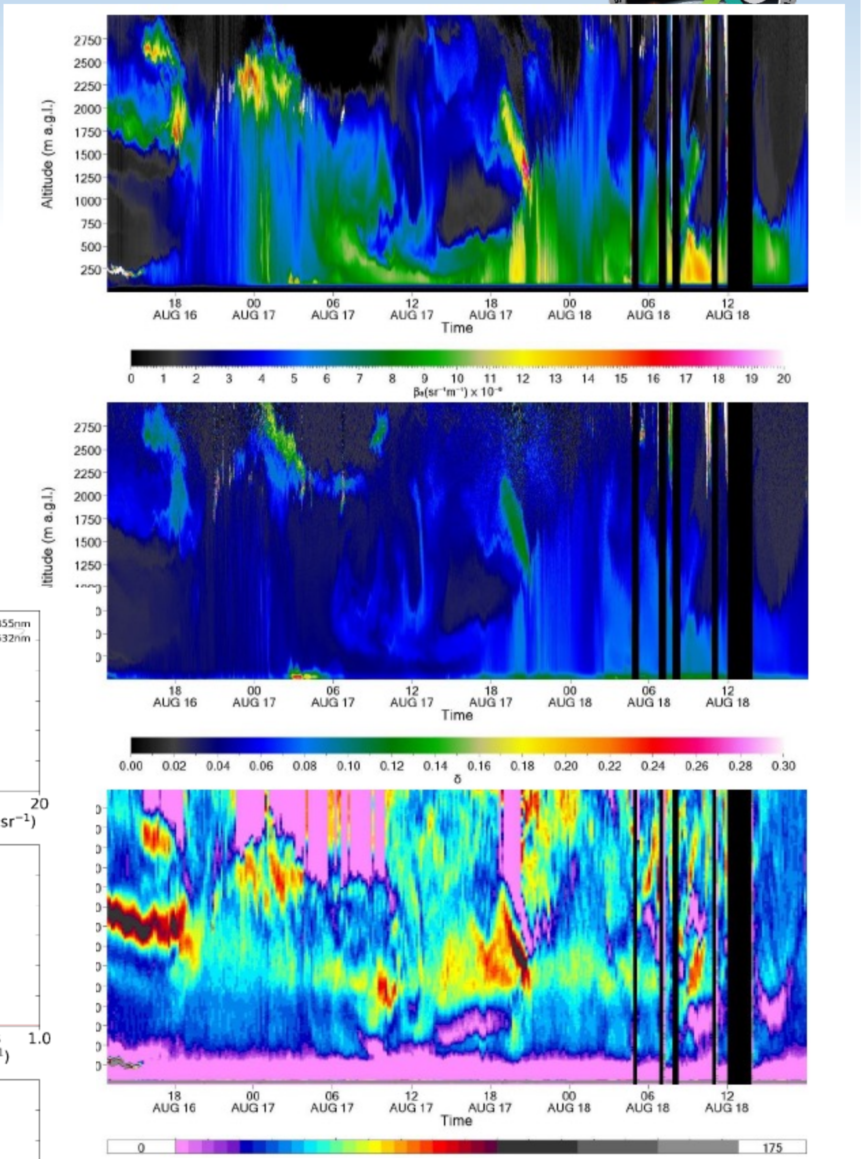


GEOS-CF XCO (mole m^{-2}) on July 29, 2019 (top) and AMOLITE aerosol backscatter ratio (B) between July 28 and August 5, 2019 (bottom). The magenta star and box highlight the location of AMOLITE and the large aerosol lamina observed by the system, respectively.

Aerosols:

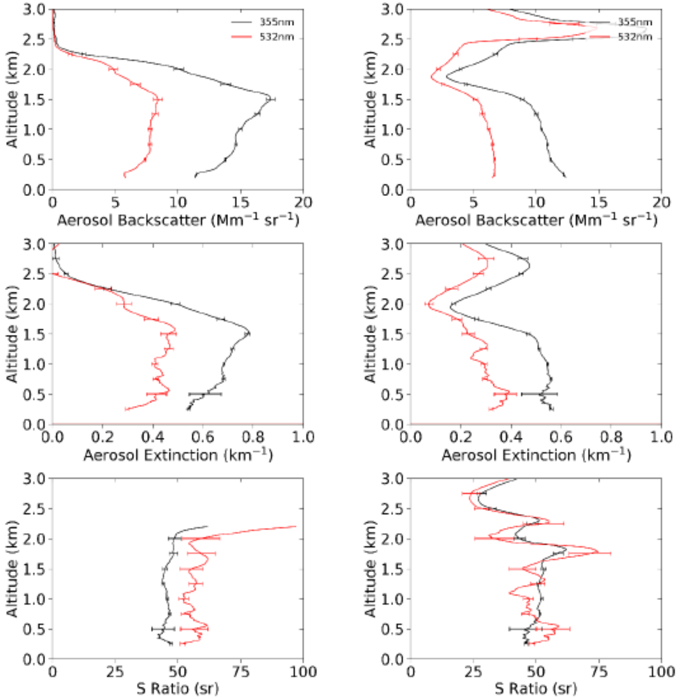
- PBL height
  - Lidar can validate PBL height TEMPO product
  - Important parameter in air quality index products – forecasting
- Aerosol optical depth (AOD)
  - AERONET can give optical closure
  - Lidar can determine AOD of individual aerosol layers
- Identifying types of aerosols on a regional level
  - Magnitude and frequency of occurrence of smoke, dust etc.
  - Some TOLNet systems have enhanced aerosol capabilities
    - Polarization, S ratio, angstrom coefficient, color ratio

Forest fire plume



Seasonal variability of PBL height

Bscatt, Exctinction, S ratio



Joint Science Meeting for TEMPO, GeoXO ACX, & TOLNet



How can TOLNet/airborne/mobile measurements of horizontal gradients of ozone and aerosols complement TEMPO column measurements?

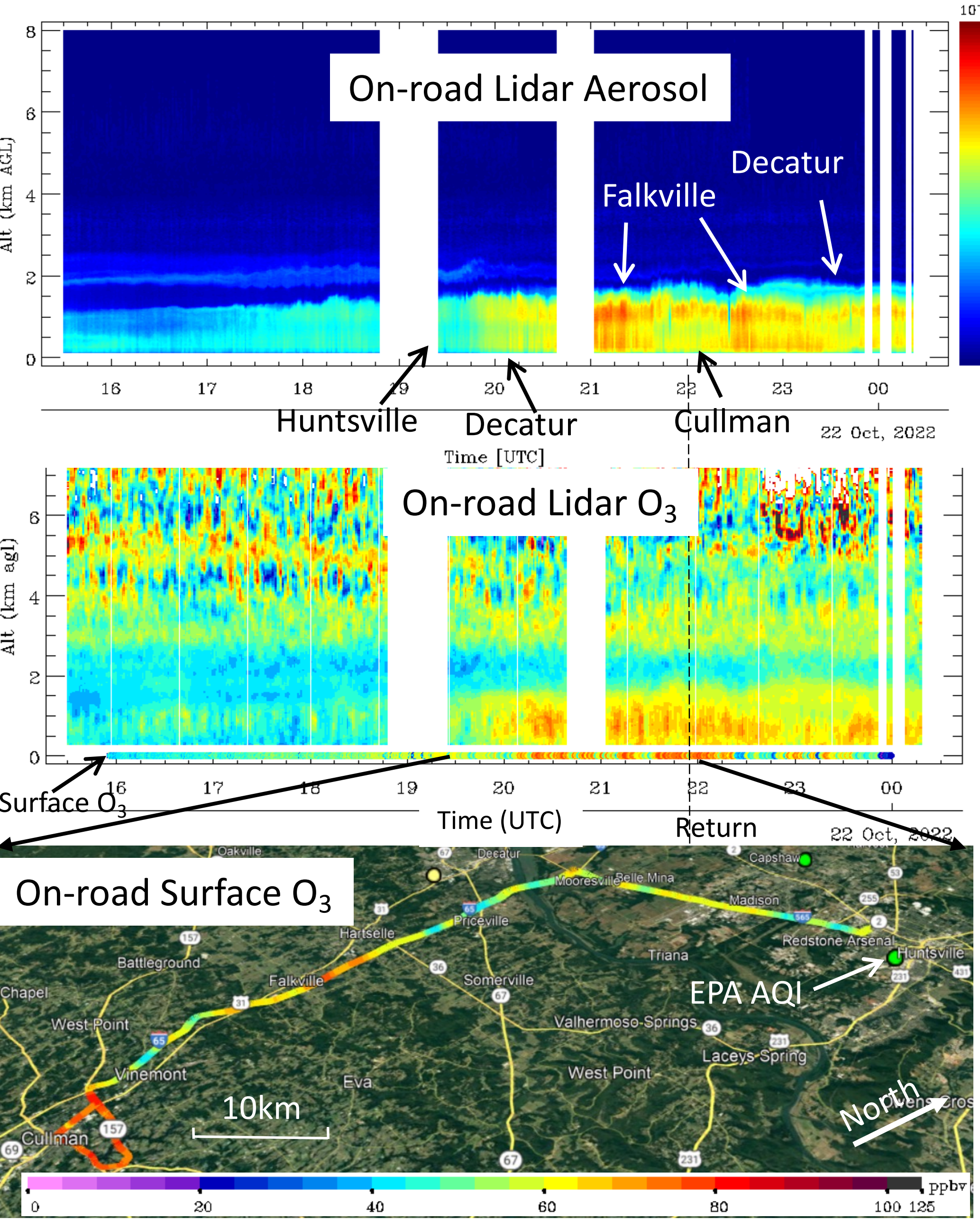
Shi Kuang, Mike Newchurch, Todd McKinney, Paula Tucker, Darby Stevenson, Mason Mills, Susan Alexander

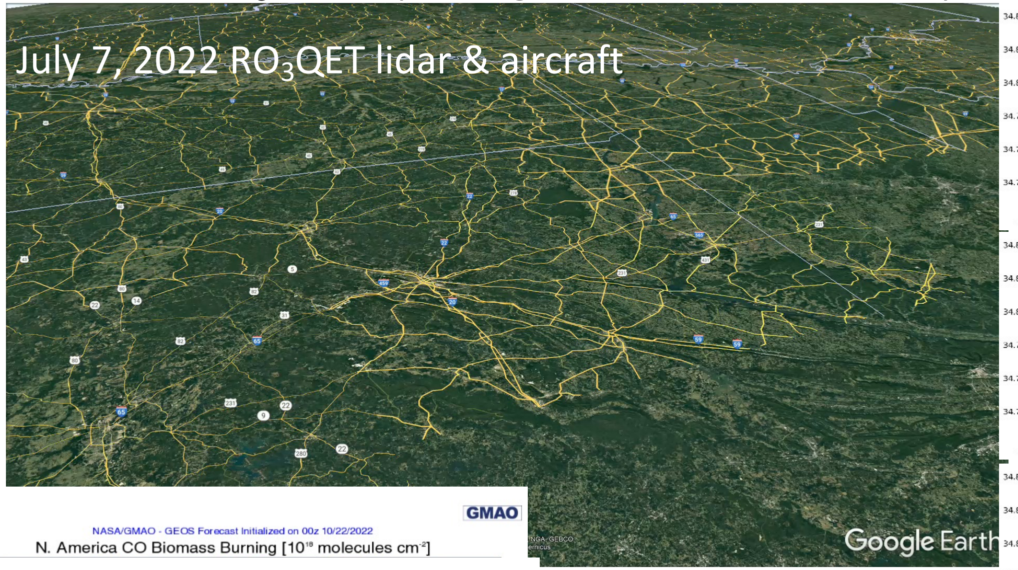
University of Alabama in Huntsville

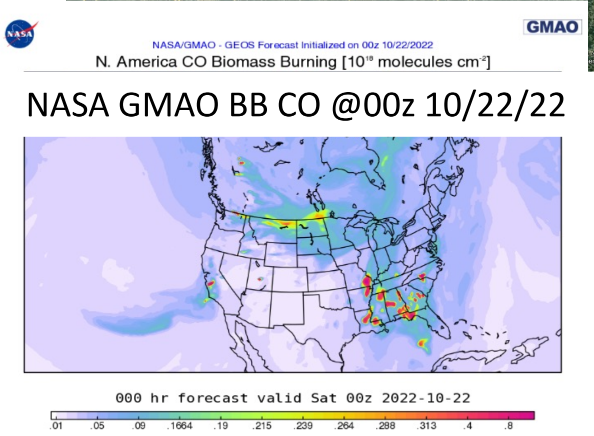


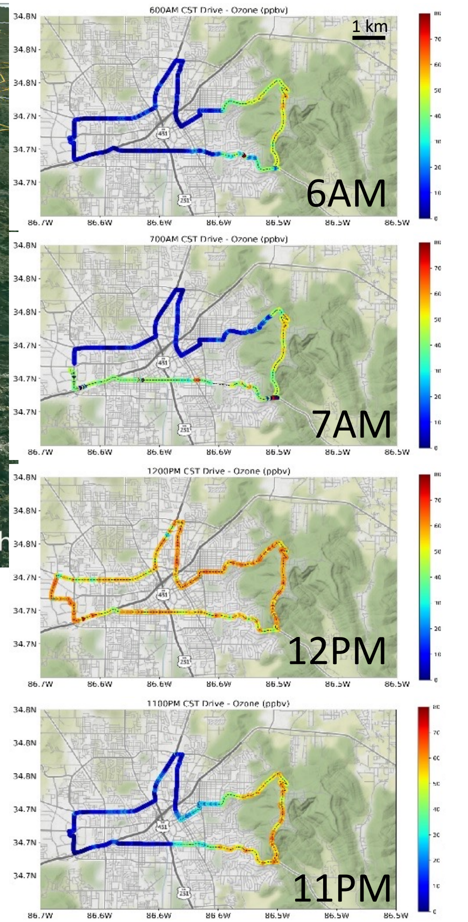
Measuring Horizontal Gradients by the TOLNet UAH lidar

1. TOLNet mobile lidar O_3 and aerosol products suggest horizontal gradients in PBL due to local fire burns. The air quality impact from local agriculture fires can be addressed by high-resolution TEMPO products.
2. PBL dynamics strongly influence the surface impact of PBL O_3 and aerosol concentrations.
3. Interpretation of the relationship between TEMPO PBL O_3 retrievals and surface O_3 will require significant correlative study.



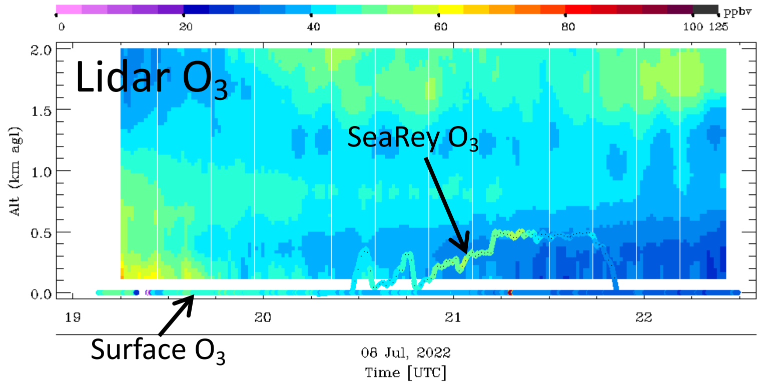






Steep Horizontal Ozone and Aerosol Gradients due to Sea Breeze

1. Air pollutant removal and enhancement due to sea/gulf breeze have been observed at coastal sites. We should quantify the ability of TEMPO to measure the steep horizontal gradients resulting from these smaller-than-synoptic-scale processes.
2. The combination of surface instruments, lidars, and aircraft measurements provides critical information to assess TEMPO precision, accuracy, and application to air-quality diagnoses and forecasting.
3. We should expect to find steep gradients in many constituents at TEMPO and sub-TEMPO scales.



What did we learn in the past campaigns and how will we measure?

- Platform and method: traditionally airborne (quick); mobile lidar or in situ sensors (slower, but inexpensive); multiple lidars or sondes at nearby locations; drone attached sensor; potentially horizontal scanning lidar.
- Choice of locations: coastal areas, regions with possible transition between NOx and VOC sensitive, regions with large local emissions such as local agriculture fire burns.

- Large O_3, NOx, NOy, VOC gradients due to complicated emissions (ships, power plants, petrochemical industrial) at Houston were measured during the Texas Air Quality Study (Ryerson et al. 2003), primarily using **airborne** observations.
- During DISCOVER-AQ, large horizontal O_3 gradients were investigated due to bay breeze at Chesapeake Bay using **ozonesondes** and **aircraft** (Stauffer et al. 2015). Inhomogeneous O_3 production rates at Houston were studied using **airborne** (P-3B) data and **CMAQ** model (Mazzuca et al. 2016). In DISCOVER-AQ Texas Study (Caicedo et al. 2019), **airborne HSRL and TOPAZ** were used to capture aerosol/O_3 cross sections associated the Gulf breeze.
- During LISTOS campaign, Zhang et al. (2020) carried out on-road observations of O_3, NO_2, and VOC at NYC Long Island and found the large O_3 gradients (18 ppb/km) associated with the sea breeze cycling using **CMAQ**, **DWL**, and **Hysplit** etc. At the same location, Couillard et al. (2021) showed similar large O_3 gradients at upper air due to bay breeze and LLJ, but using **O_3 DIAL**, **ozonesondes**, and **airborne** data.
- During OWLETS 1 and 2, horizontal gradients at water-land interface due to sea/bay breeze at Chesapeake Bay was investigated furtherly using more platforms including **TOLNet DIALs**, **ozonesondes**, **airborne** payload, **2B POM** etc. (Caicedo et al. 2021, Sullivan et al. 2019)