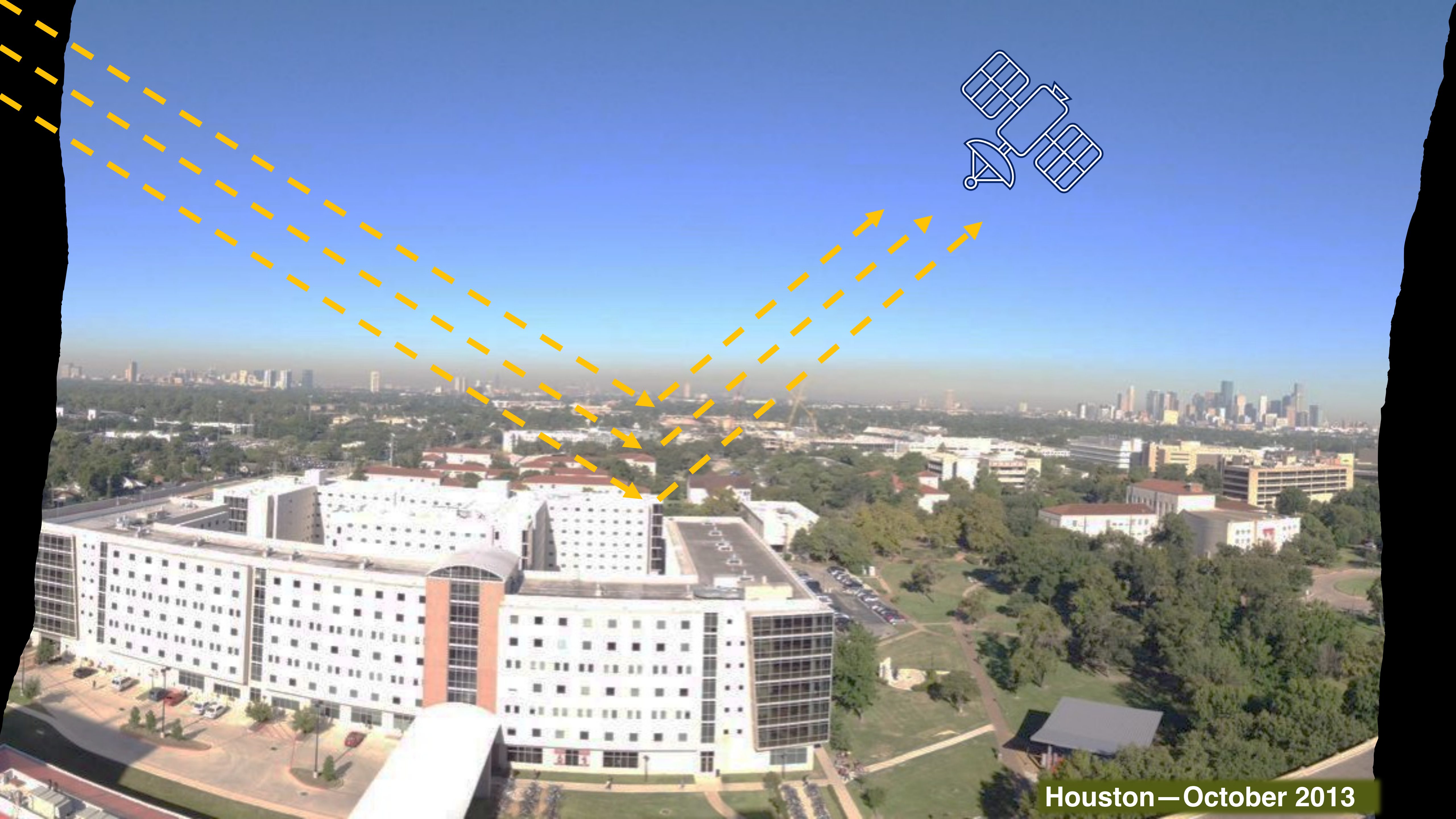
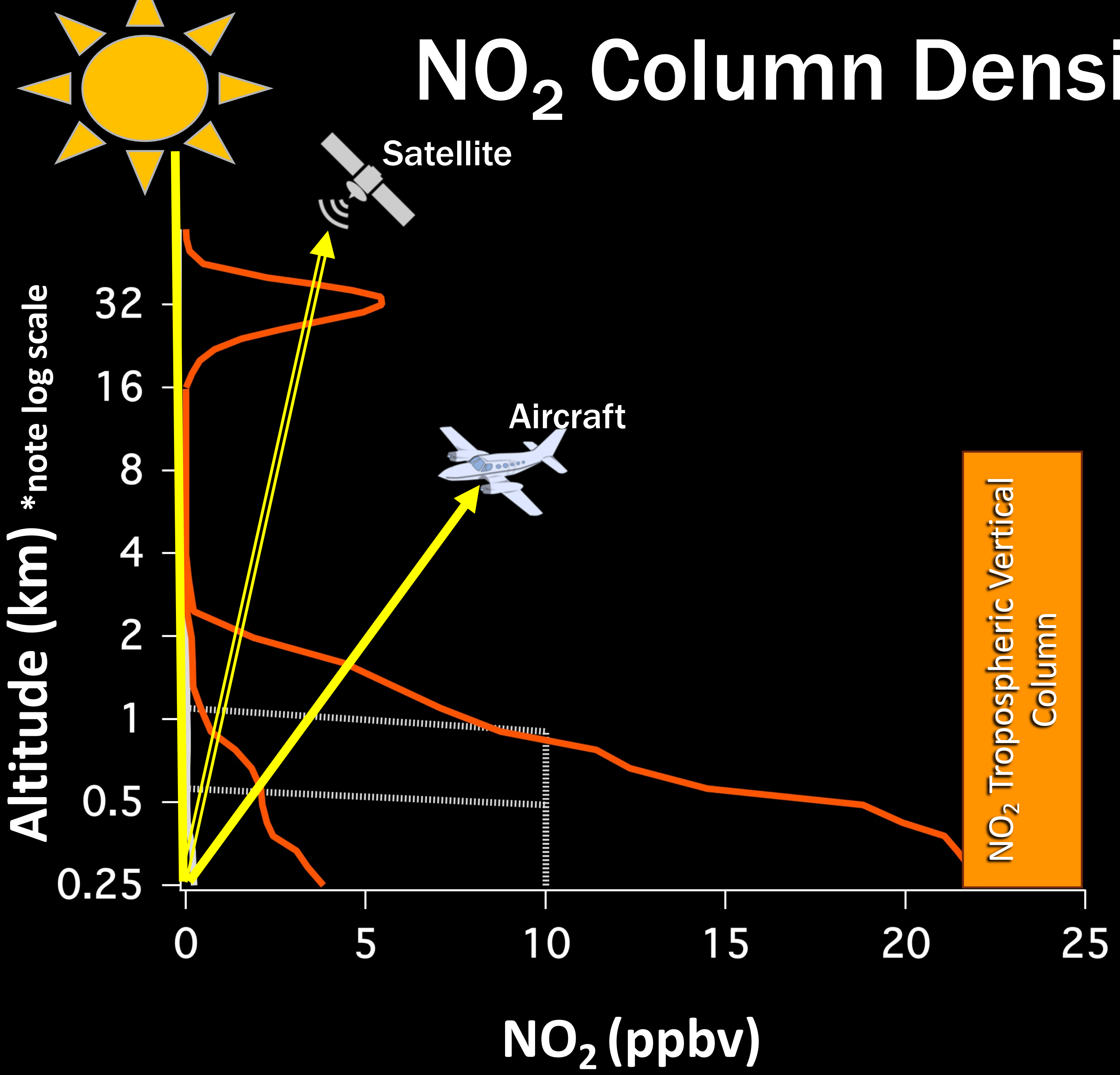
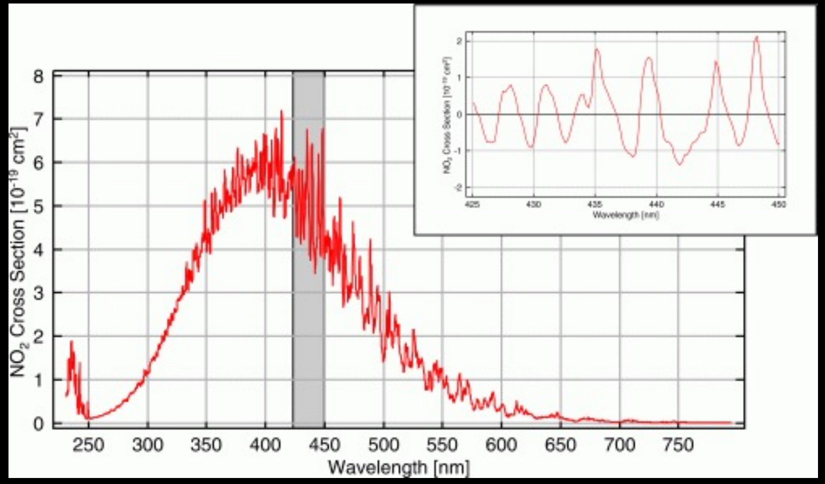
Unveiling the Air We Breathe at New Scales: a Focus on Geostationary-like Observations during Airborne Field Campaigns

Laura Judd, PhD – NASA LaRC


Houston—October 2013

NO_2 Column Density





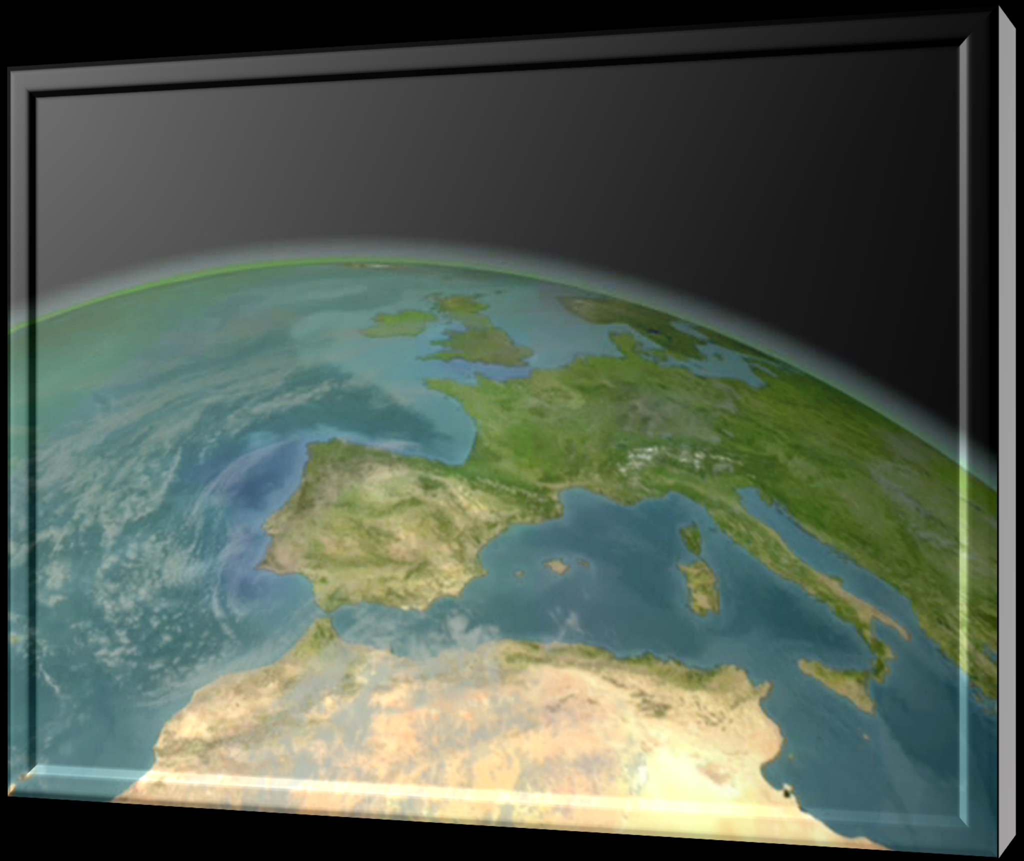
Satellites and GeoTASO/GCAS can only 'remotely sense' NO_2 columns by looking at the its absorption signatures in the blue part of the light spectrum (via Differential Optical Absorption Spectroscopy[1]).

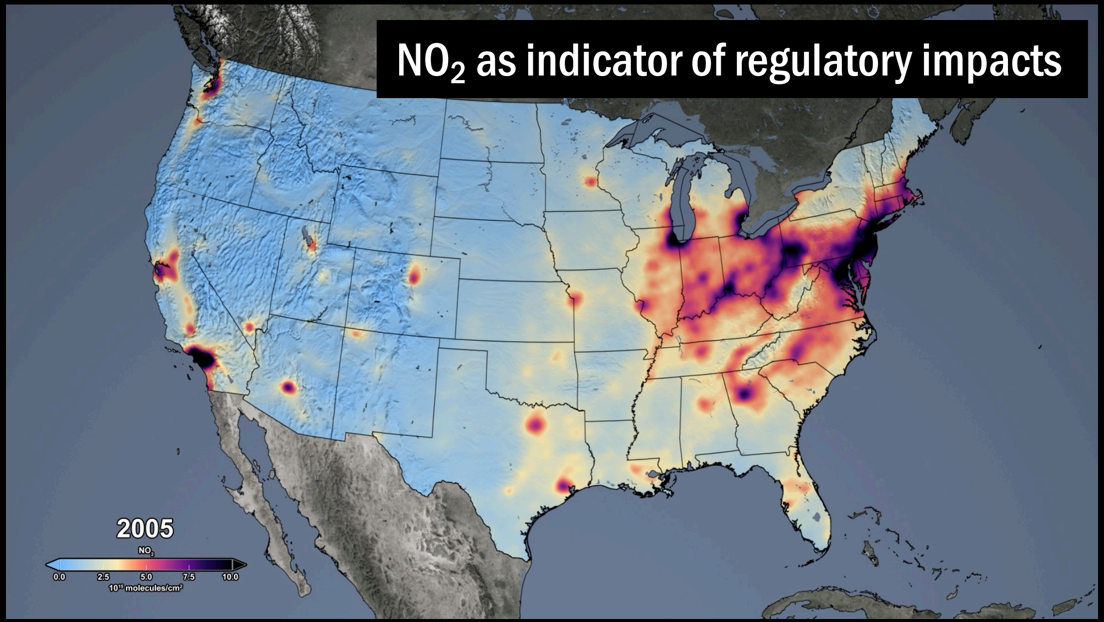
Surface NO_2: molecular density or mixing ratio directly measured at the surface by an in situ monitor

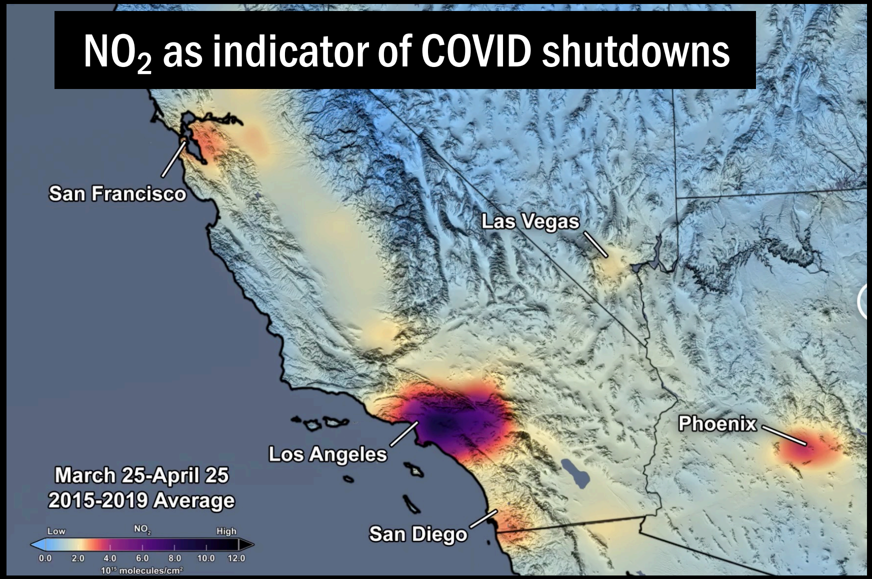
NO_2 Column Density: Integrated molecular density of NO_2 through the vertical

1: Platt, U., & Stutz, J. (2008). Differential optical absorption spectroscopy: principles and applications ; with 55 tables. Berlin: Springer.

Air Quality Measurements in Low-Earth Orbit (LEO)- e.g., OMI

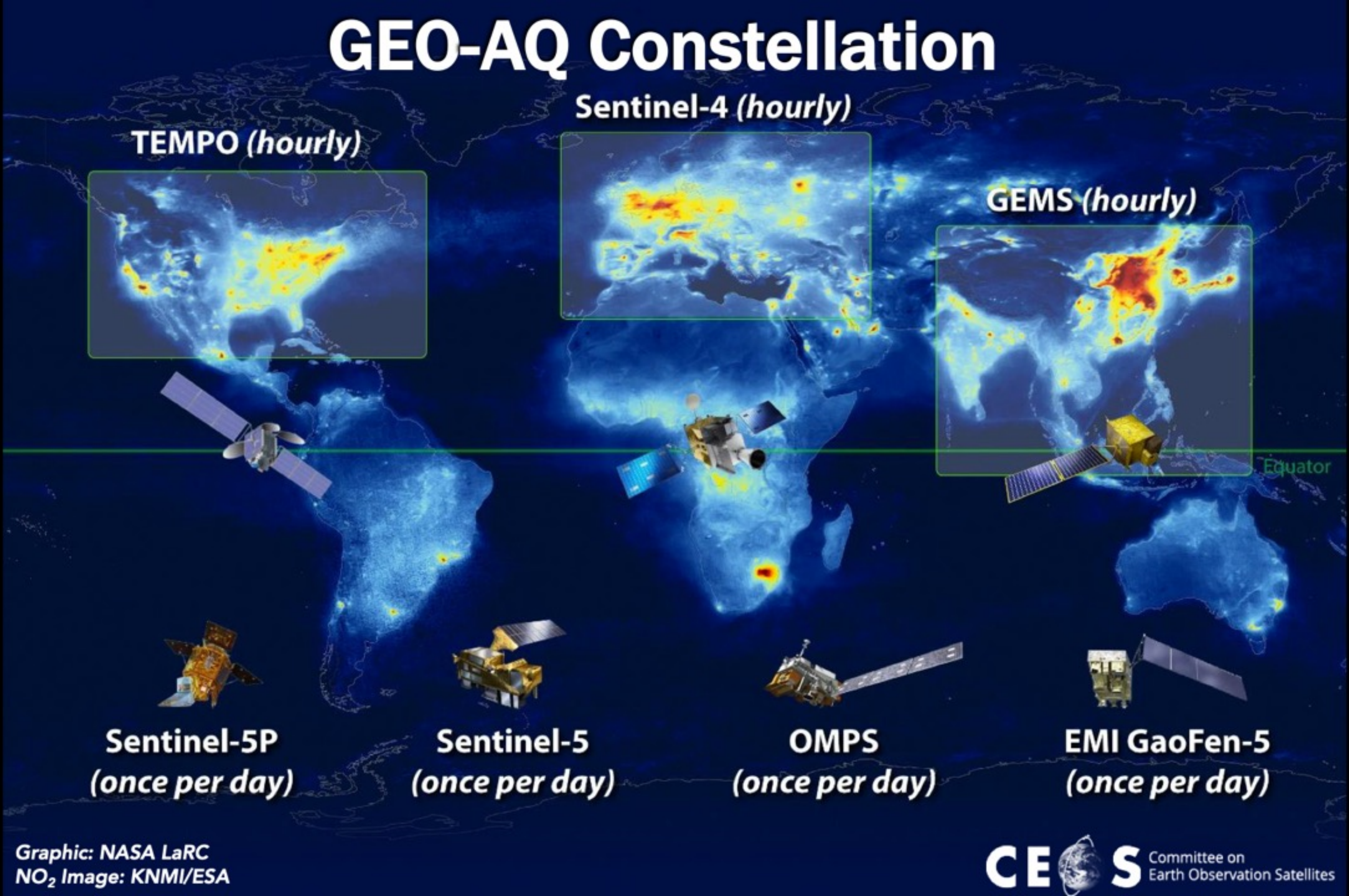






- UV-VIS Spectrometer operating 2004-present
- Overpasses once-per-day typically around 13:30 LT
- NO_2 column density is retrieved using the DOAS method
- Also retrieves O_3, HCHO, SO_2, etc.

Figure Sources: https://svs.gsfc.nasa.gov/ & https://airquality.gsfc.nasa.gov


GEO-AQ Constellation
TEMPO (hourly)
Sentinel-4 (hourly)
GEMS (hourly)
Equator
Sentinel-5P
(once per day)
Sentinel-5
(once per day)
OMPS
(once per day)
EMI GaoFen-5
(once per day)
Graphic: NASA LaRC
NO2 Image: KNMI/ESA
CEOS Committee on Earth Observation Satellites

TEMPO

Launching in 2022

<u>TEMPO Mission Leads:</u>

Principal Investigator:

Kelly Chance, Smithsonian Astrophysical Observatory

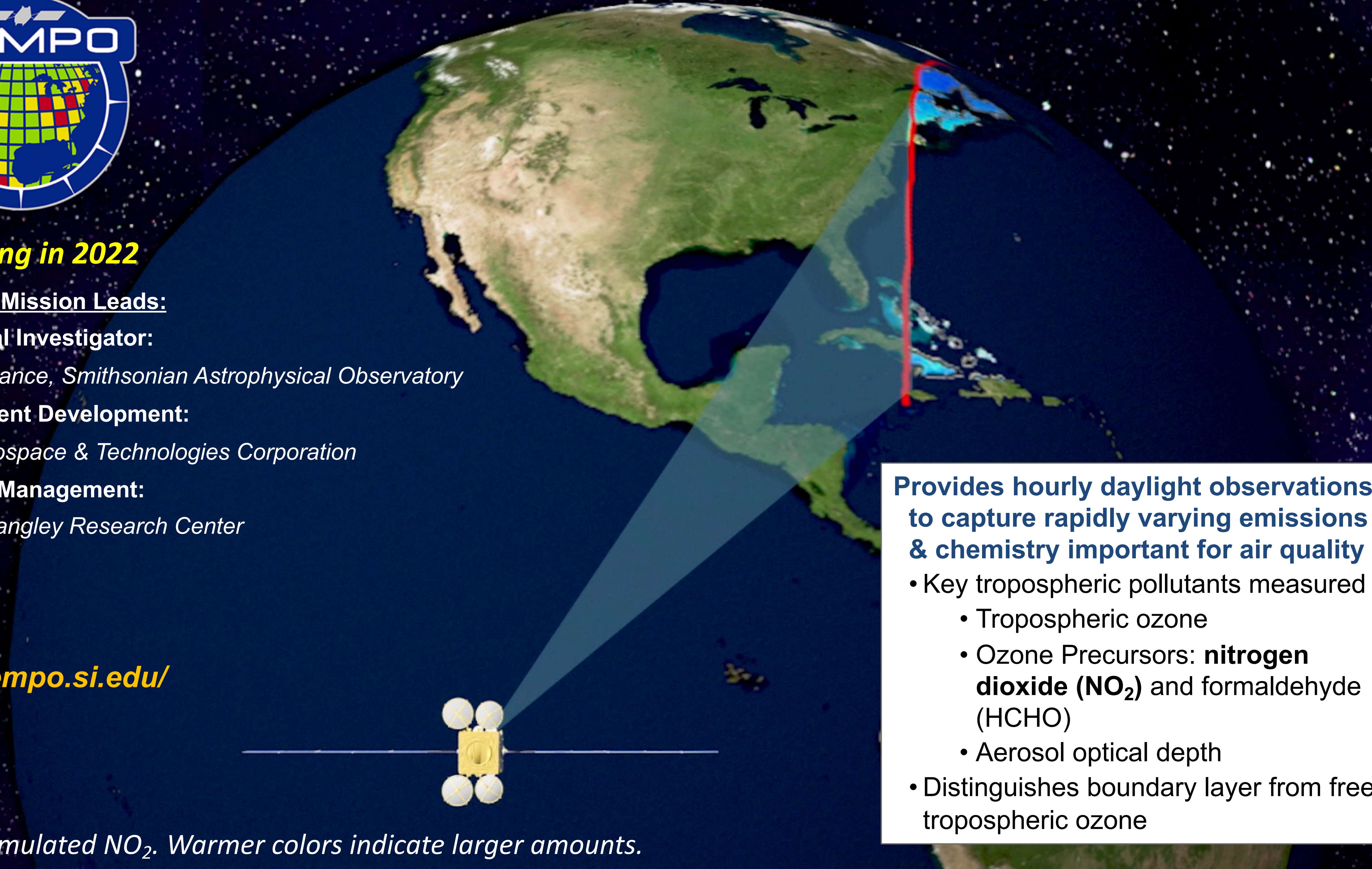
Instrument Development:

Ball Aerospace & Technologies Corporation

Project Management:

NASA/Langley Research Center

http://tempo.si.edu/



Model-simulated NO_2. Warmer colors indicate larger amounts.

Provides hourly daylight observations to capture rapidly varying emissions & chemistry important for air quality

- Key tropospheric pollutants measured
  - Tropospheric ozone
  - Ozone Precursors: **nitrogen dioxide (NO_2)** and formaldehyde (HCHO)
  - Aerosol optical depth
- Distinguishes boundary layer from free tropospheric ozone

GeoXO Constellation

(Preliminary, pending program approval)

GEO-West

Visible/Infrared Imager
Lightning Mapper
Ocean Color

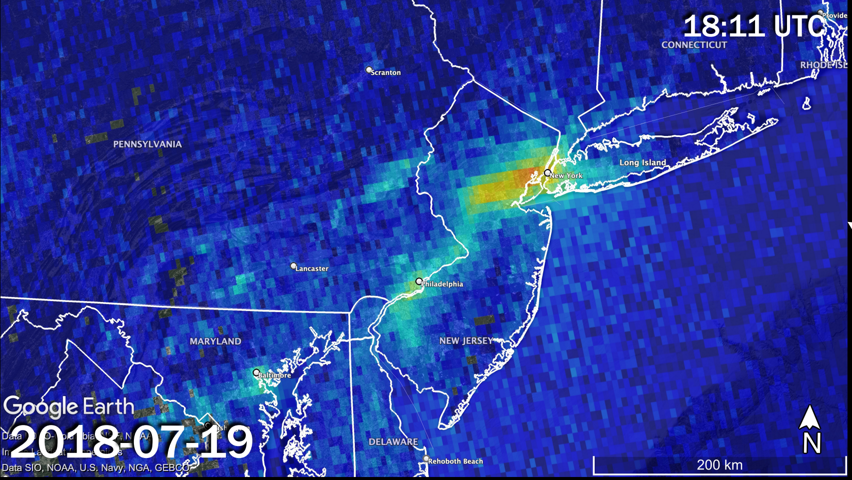
GEO-Central

Hyperspectral Infrared Sounder
Atmospheric Composition
Partner Payload

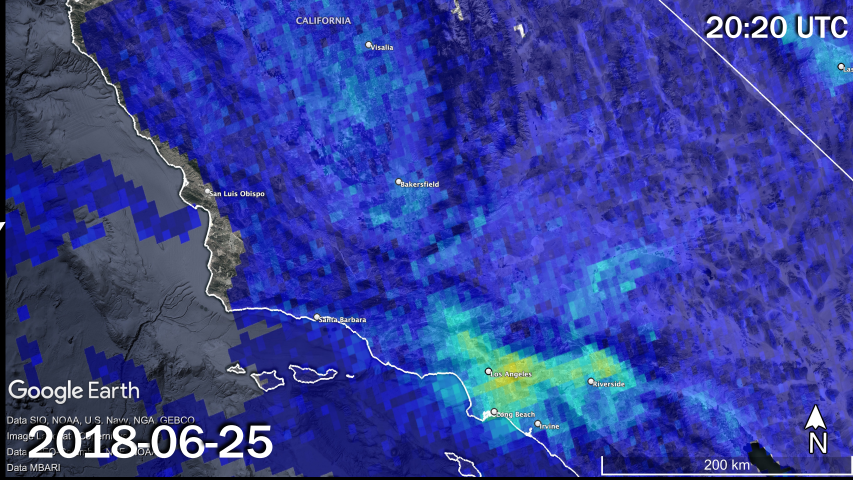
GEO-East

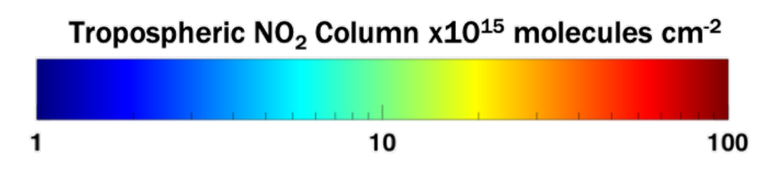
Visible/Infrared Imager
Lightning Mapper
Ocean Color

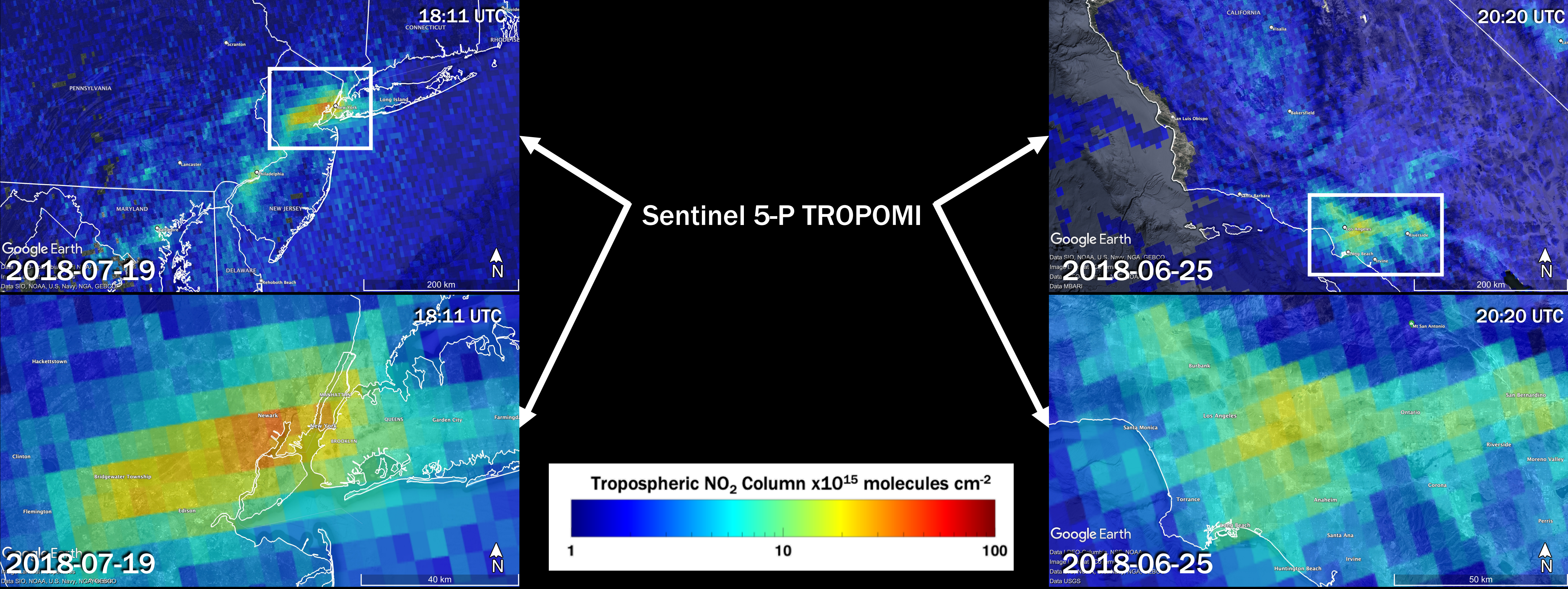
https://www.nesdis.noaa.gov/GEO-XO



Sentinel 5-P TROPOMI






Sentinel 5-P TROPOMI
18:11 UTC
2018-07-19
PENNSYLVANIA
CONNECTICUT
Scranton
Long Island
New York
Lancaster
Philadelphia
MARYLAND
NEW JERSEY
Baltimore
DELAWARE
Rehoboth Beach
200 km
N
Google Earth
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
18:11 UTC
Hackettstown
MANHATTAN
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New York
QUEENS
Garden City
BROOKLYN
Clinton
Bridgewater Township
Flemington
Edison
2018-07-19
40 km
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2018-06-25
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Moreno Valley
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Torrance
Anaheim
Perris
Long Beach
Santa Ana
Irvine
Huntington Beach
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Tropospheric NO_2 Column x10^{15} molecules cm^{-2}
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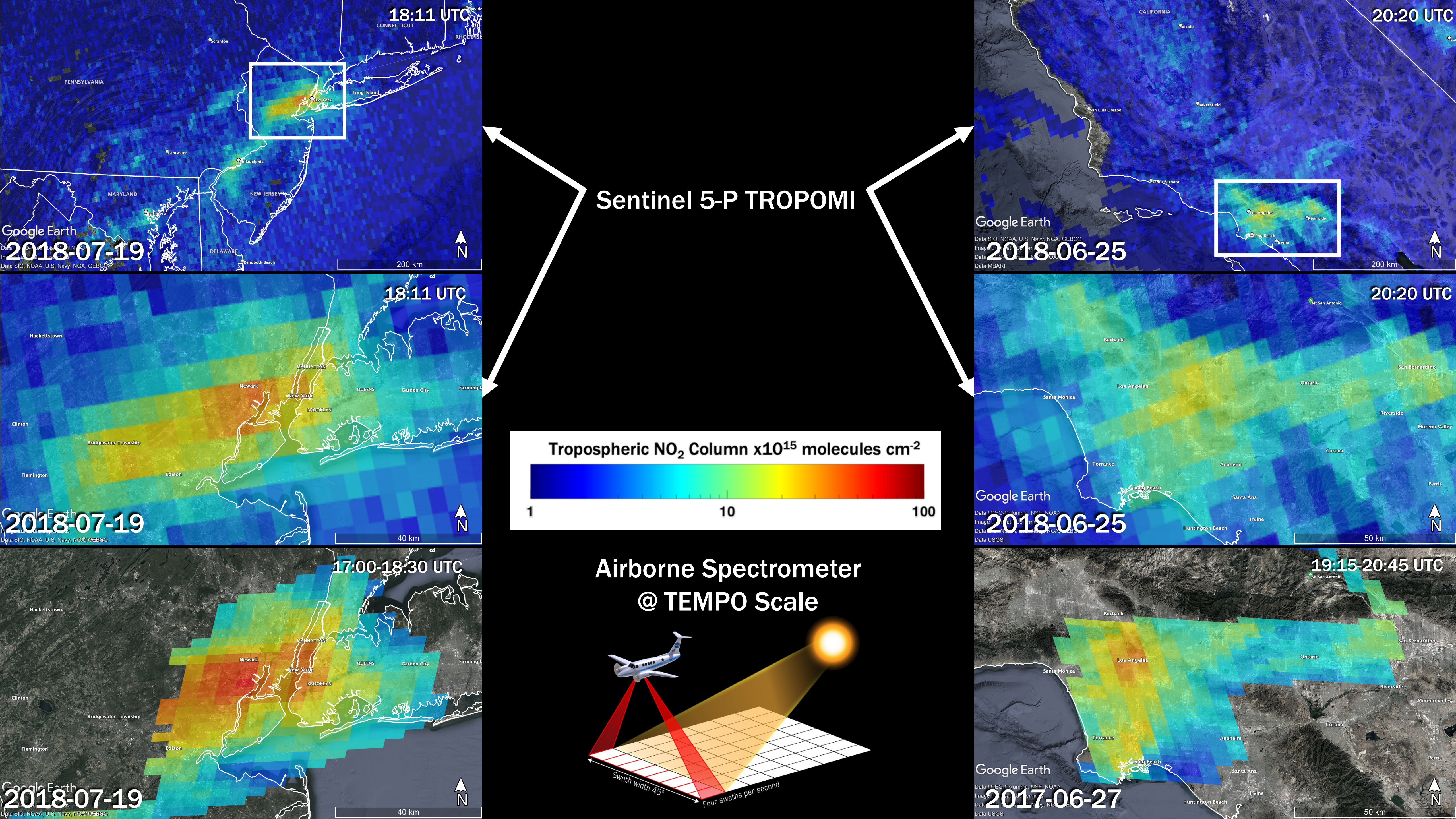
Sentinel 5-P TROPOMI
Airborne Spectrometer
@ TEMPO Scale
Tropospheric NO_2 Column x10^{15} molecules cm^{-2}
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2018-07-19
18:11 UTC
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20:20 UTC
2018-06-25
20:20 UTC
2018-06-25
19:15-20:45 UTC
2017-06-27
200 km
40 km
50 km
Swath width 45°
Four swaths per second
Google Earth
PENNSYLVANIA
MARYLAND
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DELAWARE
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Philadelphia
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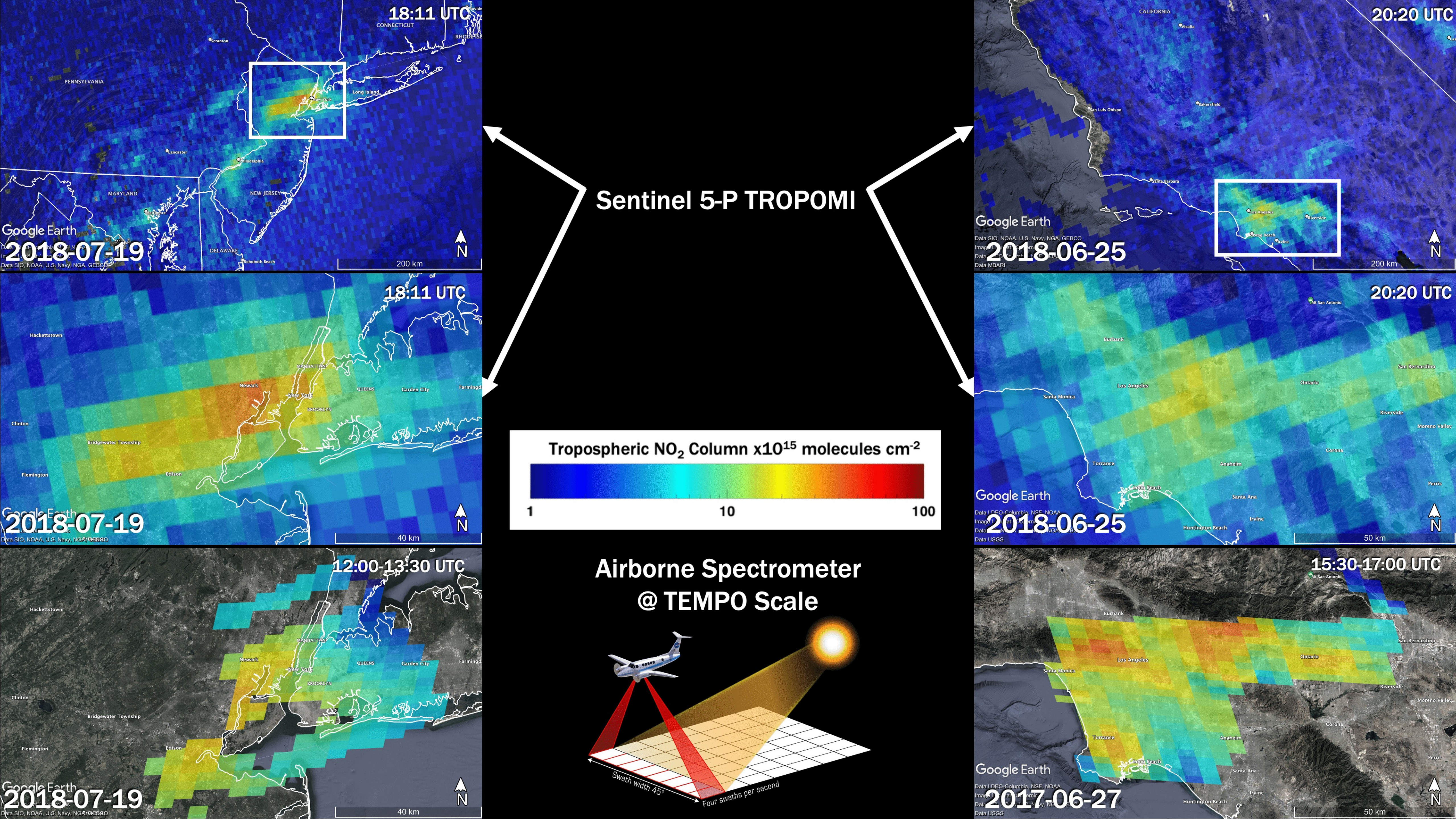
San Bernardino
Moreno Valley
Perris



Sentinel 5-P TROPOMI
18:11 UTC
2018-07-19
Google Earth
200 km
18:11 UTC
2018-07-19
40 km
12:00-13:30 UTC
2018-07-19
40 km
20:20 UTC
2018-06-25
Google Earth
200 km
20:20 UTC
2018-06-25
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15:30-17:00 UTC
2017-06-27
50 km
Tropospheric NO$_2$ Column x10^{15} molecules cm^{-2}
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Airborne Spectrometer
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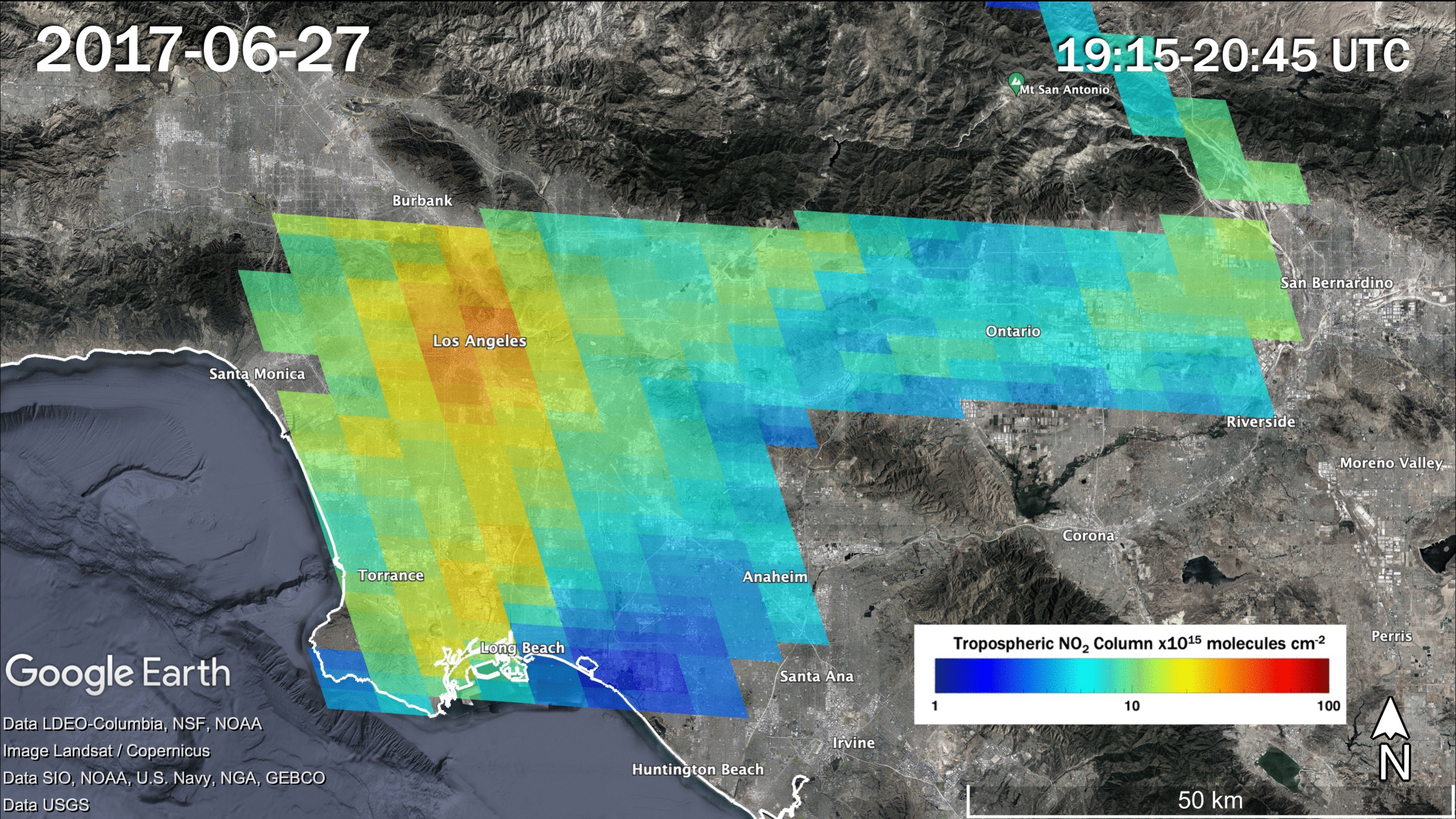
Mt San Antonio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19:15-20:45 UTC
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Moreno Valley
Corona
Torrance
Anaheim
Perris
Long Beach
Santa Ana
Irvine
Huntington Beach
Tropospheric NO_2 Column x10^{15} molecules cm^{-2}
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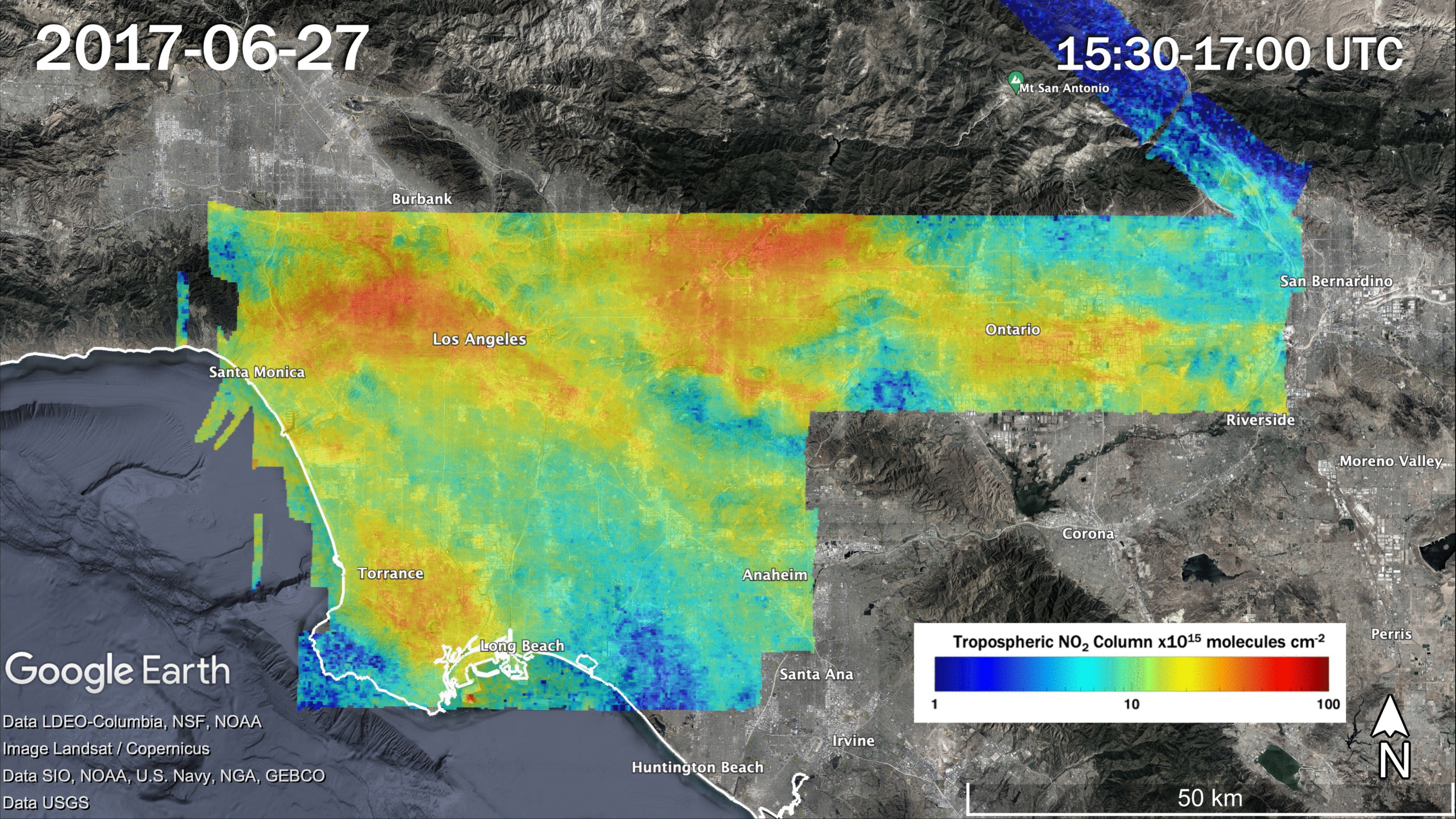
Google Earth
Data LDEO-Columbia, NSF, NOAA
Image Landsat / Copernicus
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Data USGS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Anaheim
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Santa Ana
Perris
Irvine
Huntington Beach
Tropospheric NO2 Column x10^15 molecules cm^-2
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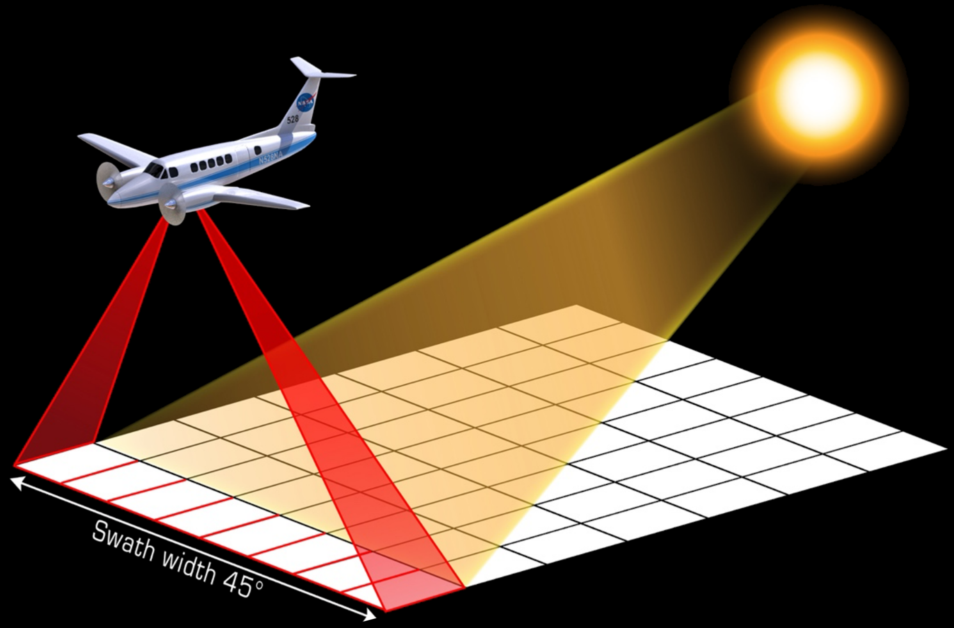
100
N
50 km
Google Earth
Data LDEO-Columbia, NSF, NOAA
Image Landsat / Copernicus
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Data USGS

NASA GCAS/GeoTASO Airborne Spectrometers

- Think of it as an airborne TEMPO simulator
- Primarily been used to collect preparatory measurements for geostationary air quality observations as well as emissions mapping
- Observes from the bottom of an airplane with a field of view of ~7 km at a nominal altitude of 28,000 feet executing gapless mapping over areas of interest
- Measures spectra in the UV-VIS-(NIR) at high spectral and spatial resolution from which trace gas columns can be remotely retrieved (NO_2 and HCHO) (nominally 250 m x 250 m)

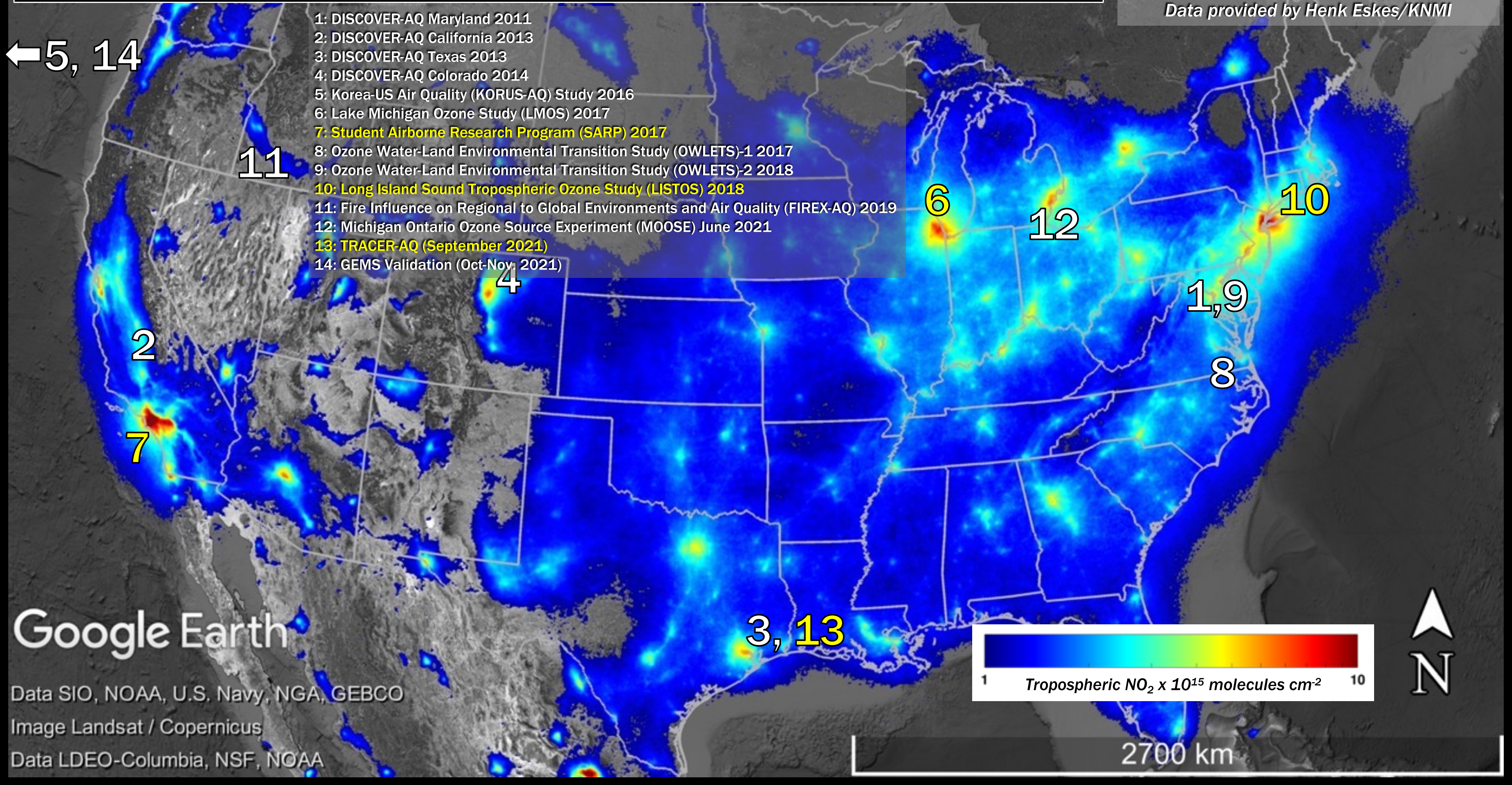


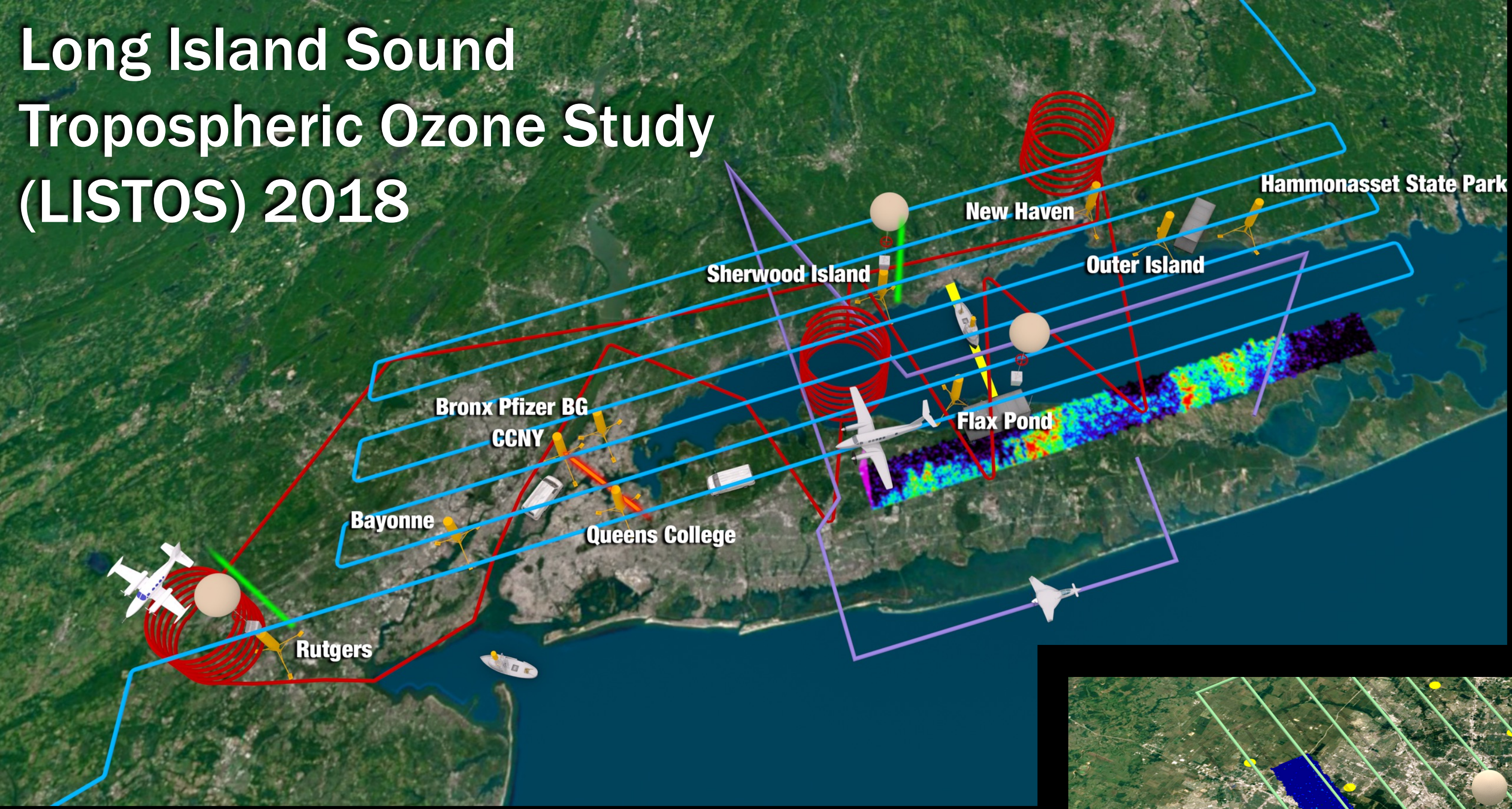
Sampling strategy for the airborne spectrometers operating in a push-broom configuration (adapted from Nowlan et al., 2016)

Some References:

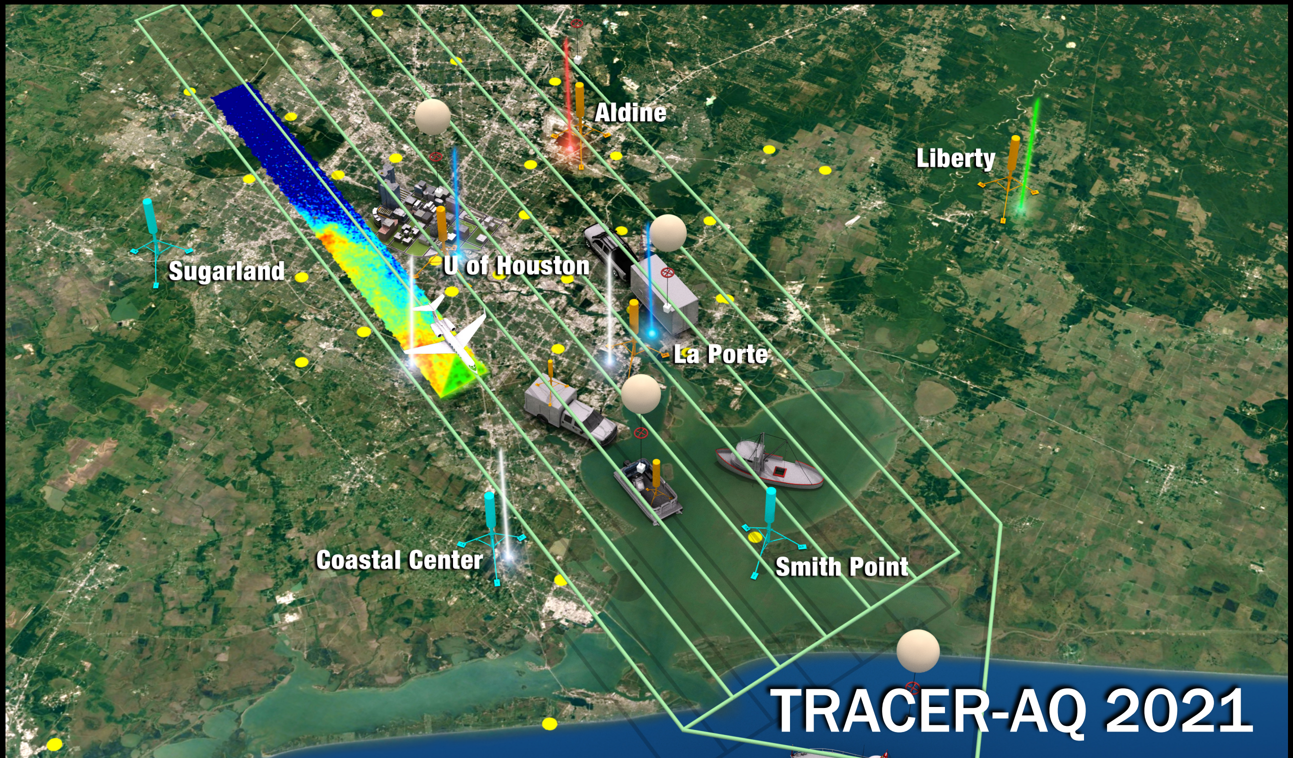
Kowalewski & Janz, 2014: doi:10.1117/12.2062058
Leitch et al., 2014: doi: 10.1117/12.2063763
Nowlan et al., 2016: doi:10.5194/amt-9-2647-2016
Nowlan et al., 2018: doi:10.5194/amt-2018-156
Judd et al., 2019: doi: 10.5194/amt-12-6091-2019
Judd et al., 2020: doi: 10.5194/ amt-13-6113-2020

NASA-Associated Air Quality Remote Sensing Campaigns 2011-Present





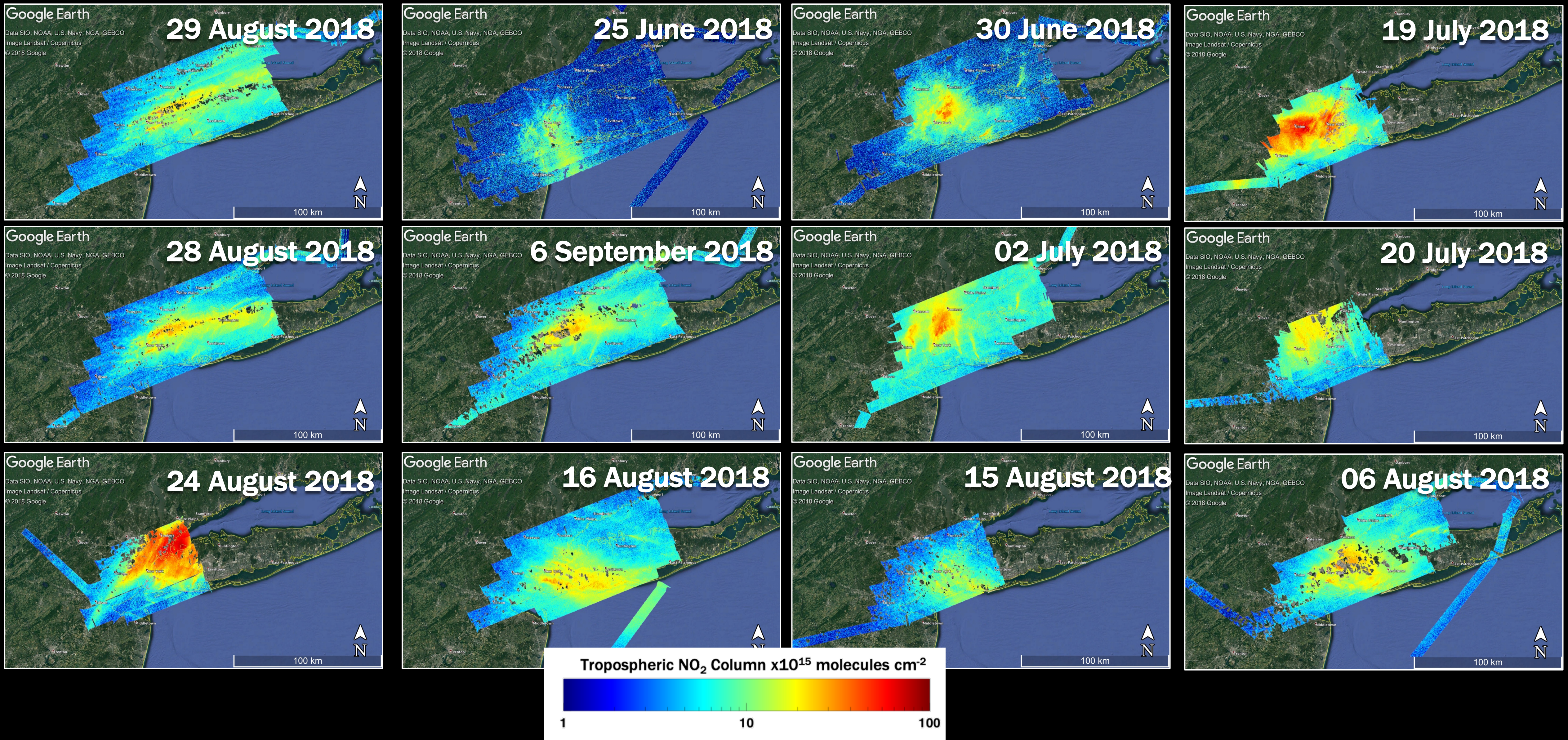
Building an integrated observing strategy



1. **Column Measurements:**
   - surface aircraft, satellite
2. **Vertical Profile Measurements:**
   - aircraft, lidars, sondes
3. **Nose-level Measurements:**
   - vehicle, boat, stationary, including regulatory monitors
4. **Model Analysis:**
   - forecasting & evaluation

2018 Long Island Sound Tropospheric Ozone Study

What was historically perceived as a larger scale issue opened eyes toward the perspective of local influence



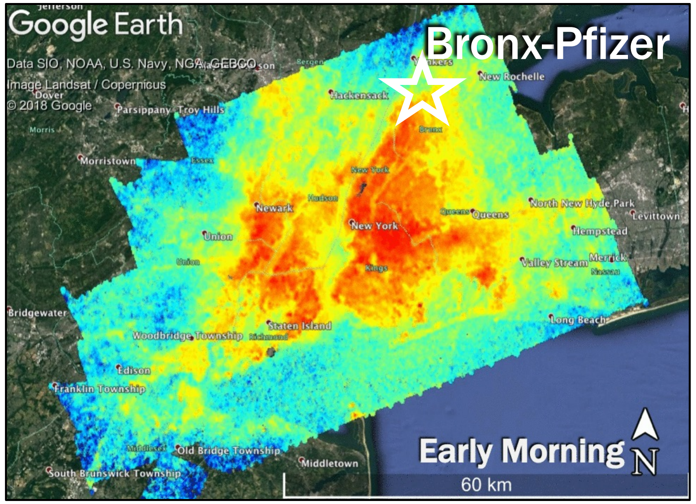
Pandora Spectrometers

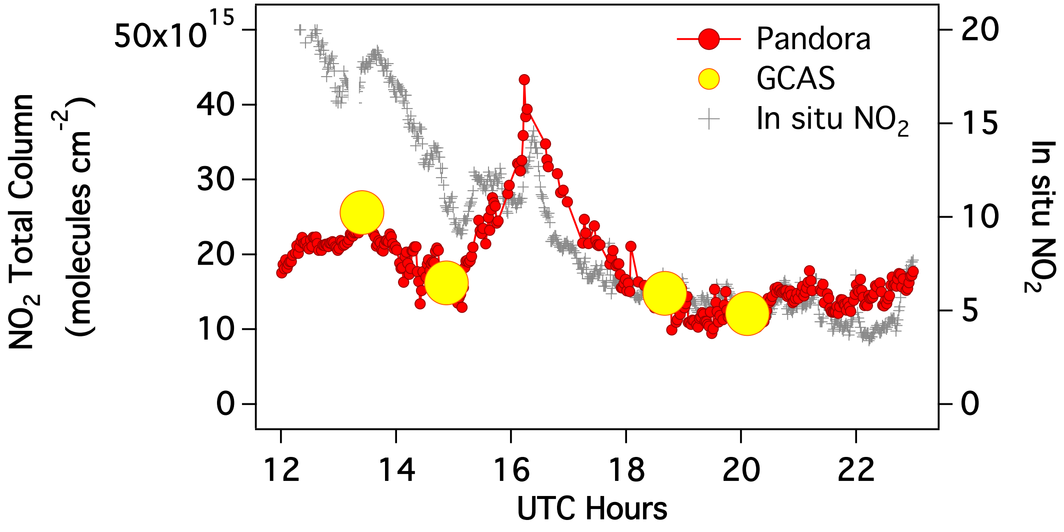
Ground-based UV-VIS spectrometer system collecting spectra in which trace-gas column densities can be retrieved continuously throughout the day.

Operational products are NO_2 and O_3
Research products include HCHO and others

Developed at NASA GSFC and is primarily used for satellite validation activities, supporting science through NASA EV Missions and R&A Activities and EPA-PAMS Enhanced Monitoring upper air measurements.

Friday, July 20th, 2018

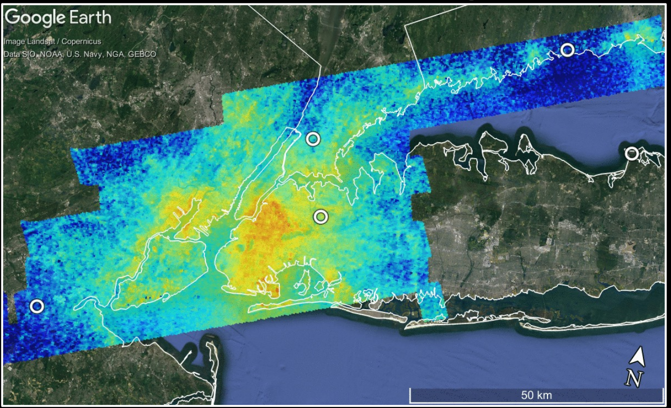


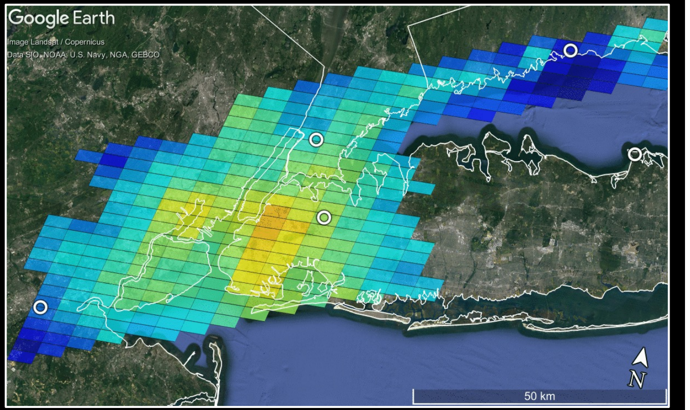


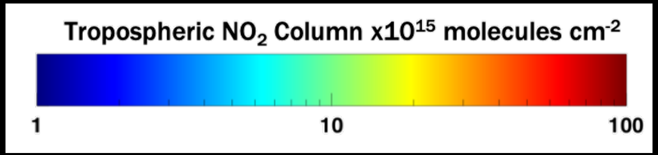
Links: https://www.pandonia-global-network.org/ & https://pandora.gsfc.nasa.gov/

Pandora-Aircraft-TEMPO Comparisons

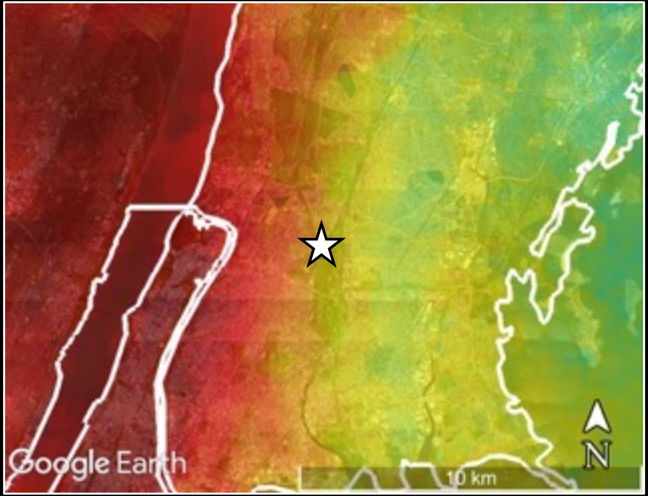
24 August 2018: 4 raster animation

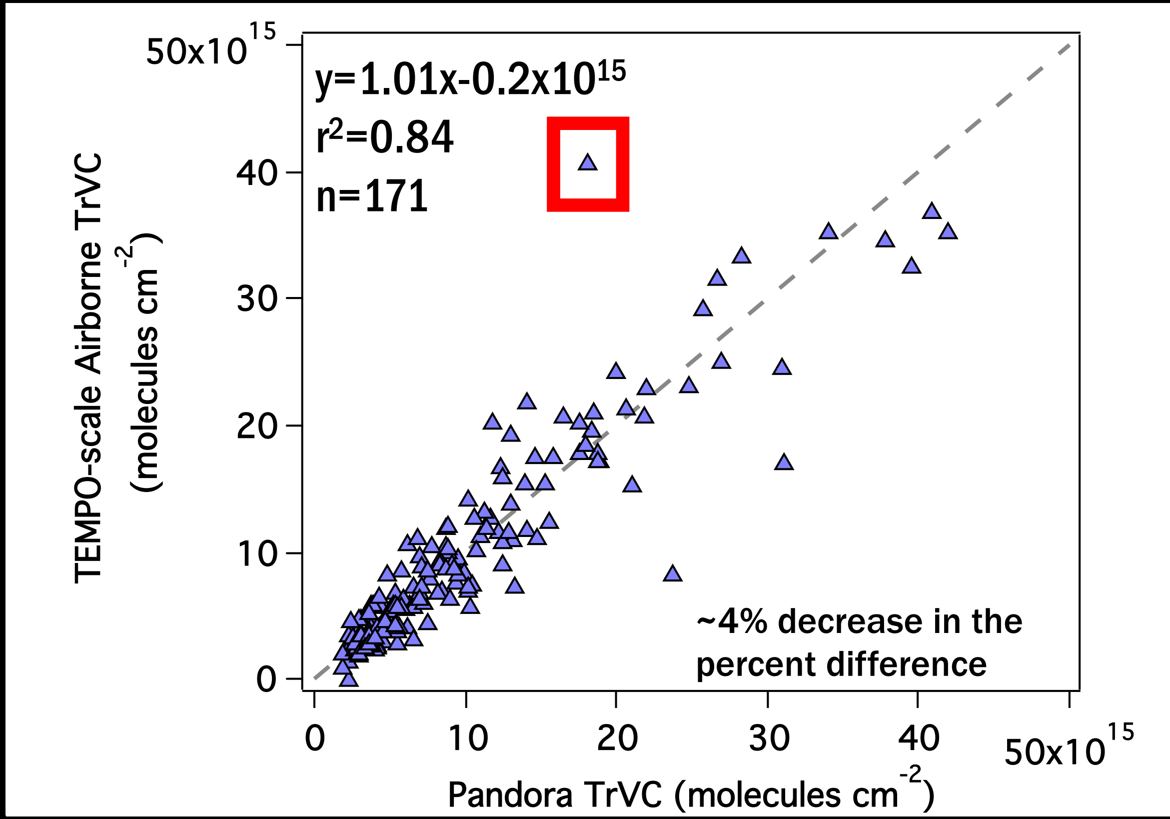






Bronx Pandora: July 2nd AM

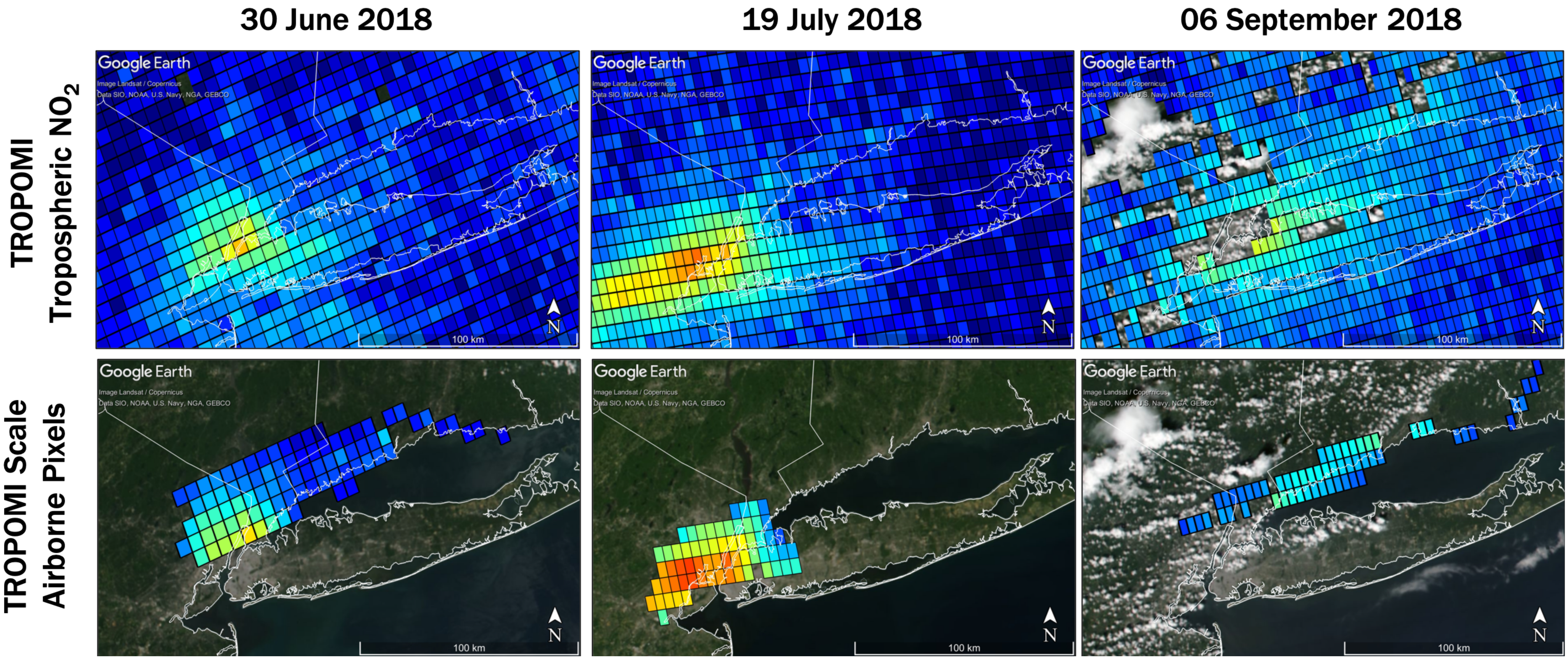




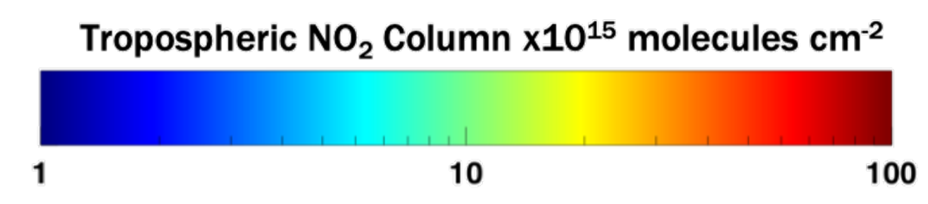
Two Challenges

1. Spatial heterogeneity: Less of an issue than before but still can lead to mis-matches in areas with strong gradients
2. Temporal heterogeneity: the high temporal resolution of Pandora and the hourly measurements from TEMPO could help in identifying large changes over the hour time-frame

TROPOMI CRF < 50% and airborne data within a ± 30-minute from overpass and area mapped > 75%



From Judd et al., 2020: https://doi.org/10.5194/amt-13-6113-2020



Airborne v. TROPOMI v1.2

Slant-to-slant:

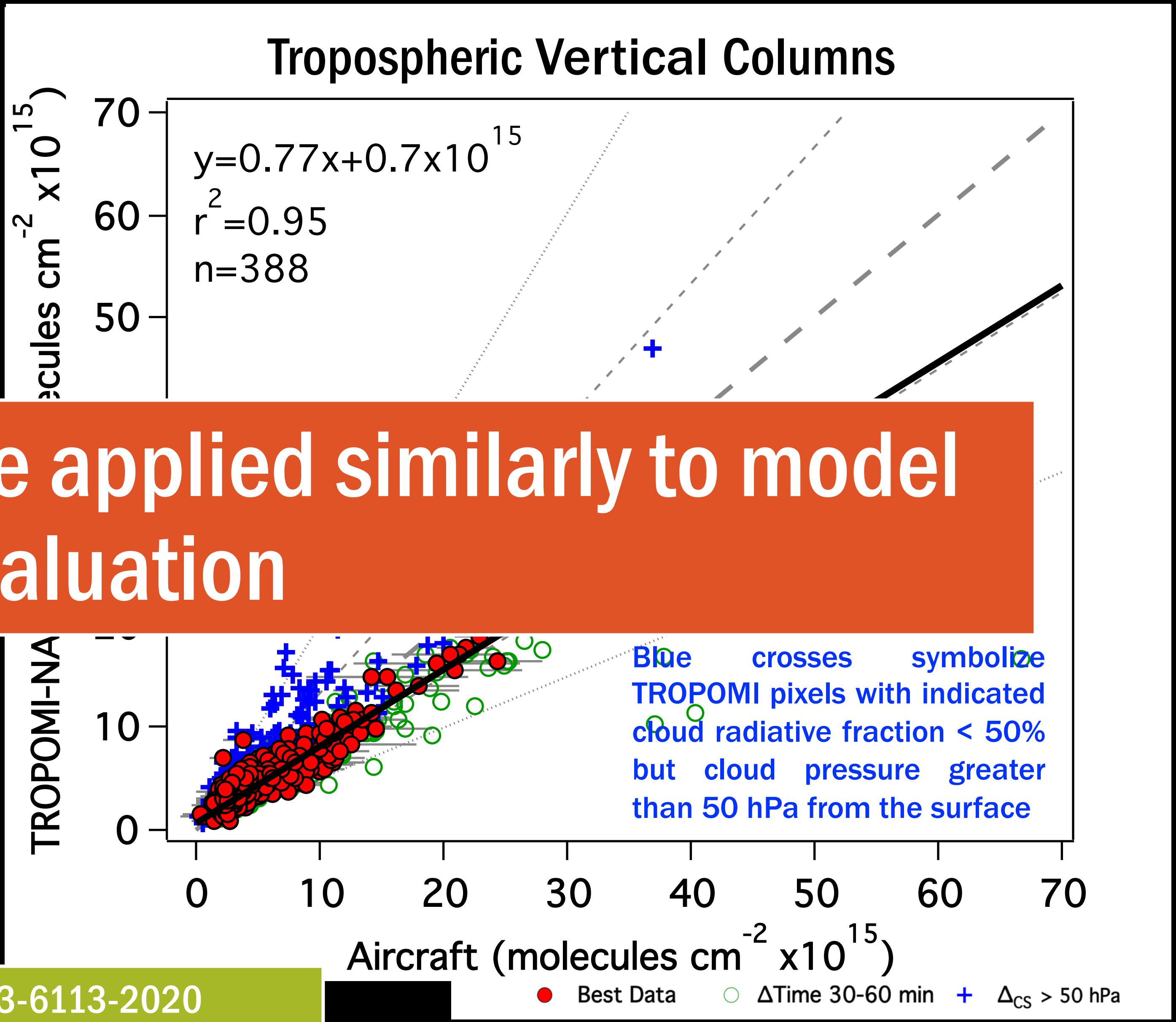
- Very high correlation indicating that satellite and aircraft are sampling largely similar slant columns (at least near the surface where most of the pollution is located)
- Correlation drops when the temporal window is opened from ± 30 to ± 60 minutes (r^2=0.91)

Vertical-to-vertical:

- Slo…
  tha…
  the…
- Bia…
  resolution in the TROPOMI retrieval (1° x 1°)

Vertical-to-vertical with NAMCMAQ 12 km analysis”

- Percent bias improves to -7%
- Outliers related to cloud pressure height seem to become important when higher resolution data is used (all stats are in manuscript)



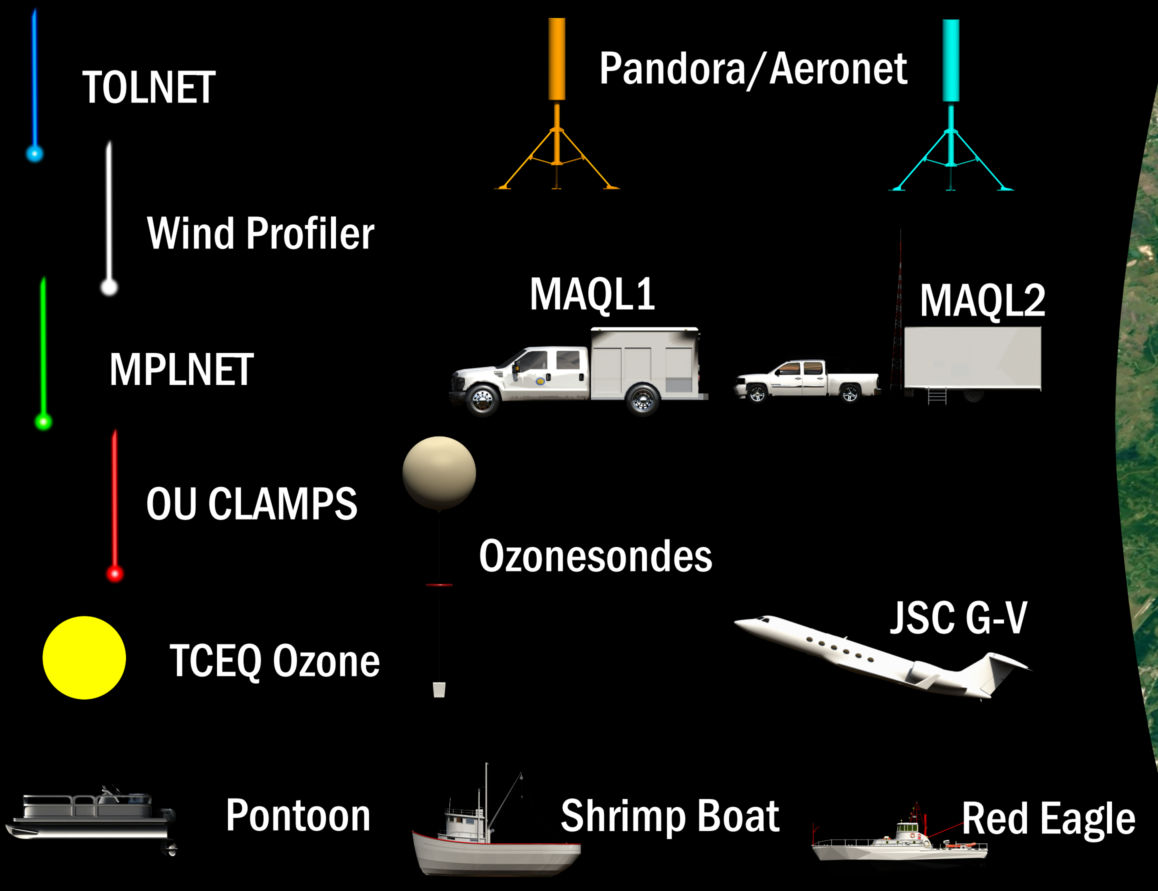
Methodology could be applied similarly to model evaluation

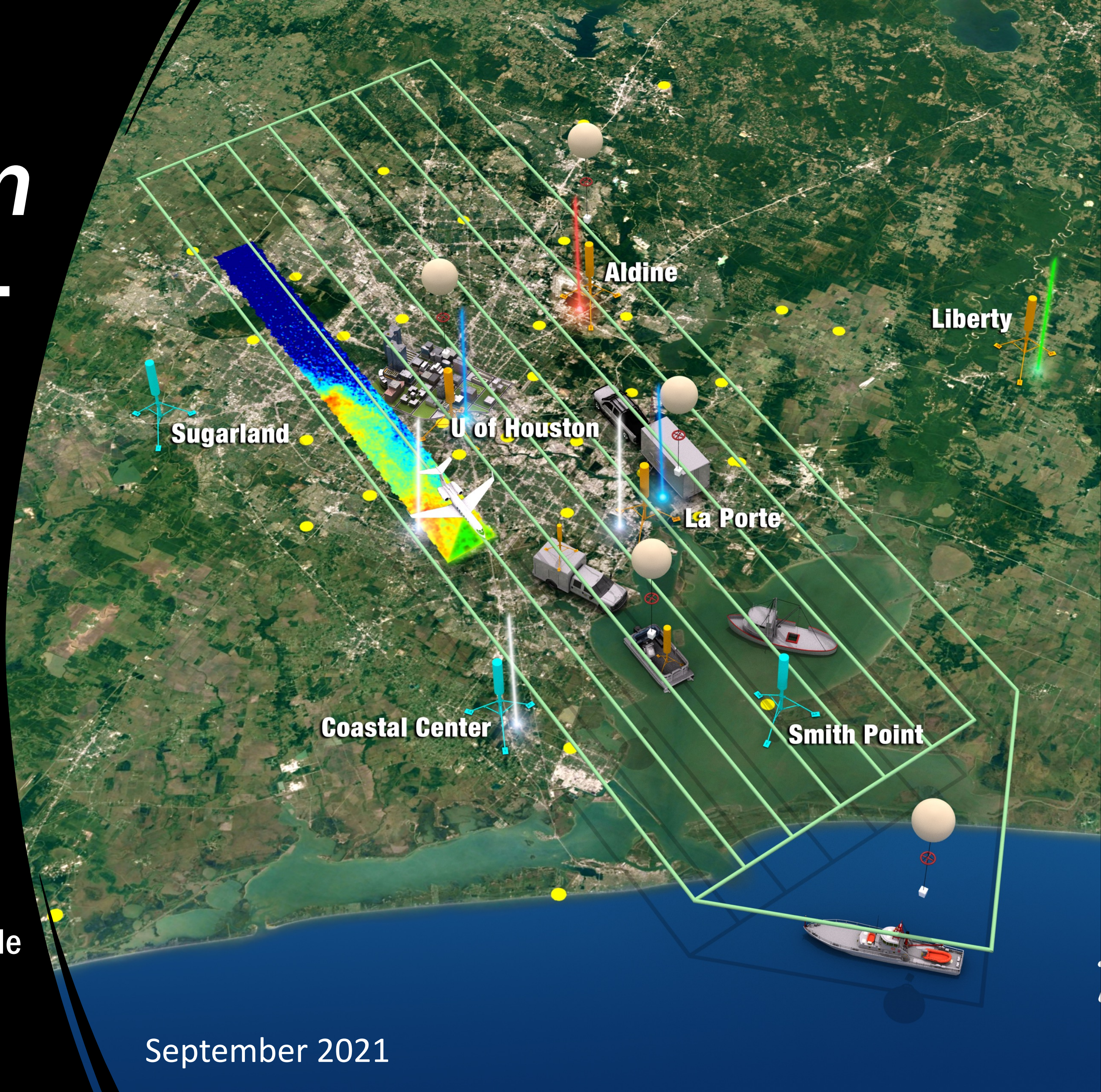
From Judd et al., 2020: https://doi.org/10.5194/amt-13-6113-2020

Unless noted: Stats are applied to red points
Ignore blue points for now.

Airborne v. TROPOMI

TRACER-AQ Observing System





TRACER-AQ Links to TEMPO

Focus Area 1: Ozone Photochemistry and Meteorology

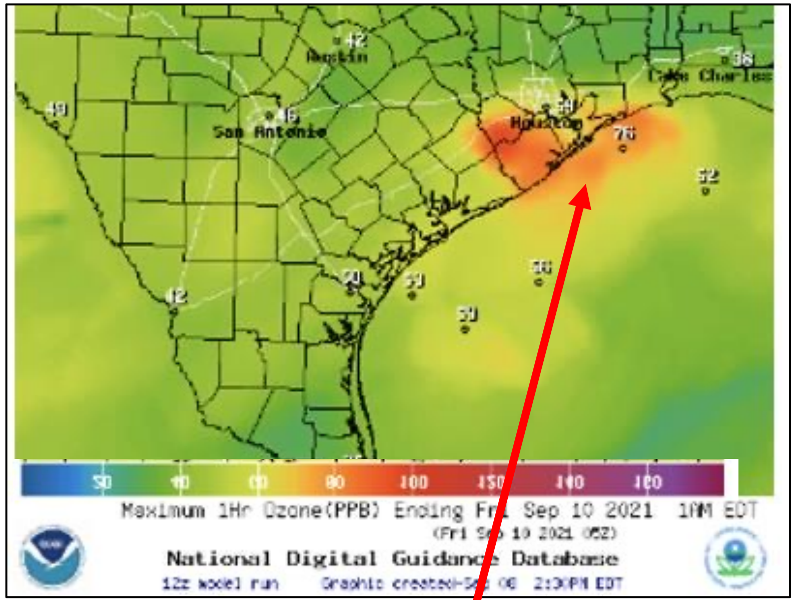
Focus Area 2: Modeling and Satellite Evaluation

Focus Area 3: Intersection of Air Quality and Socioeconomics Factors

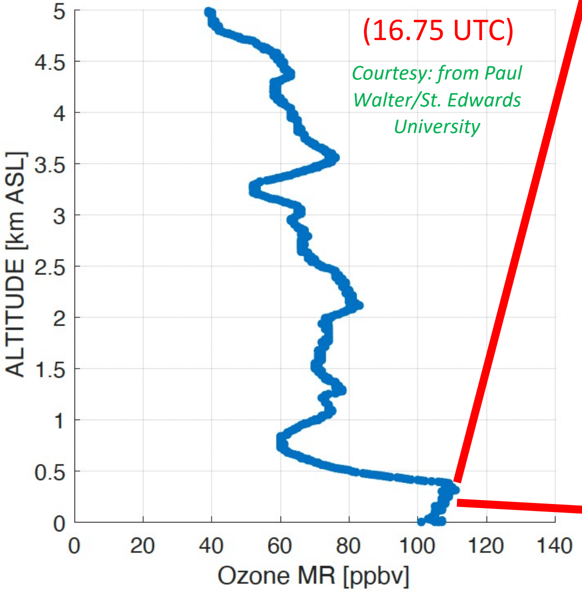
During TRACER-AQ, the data collected helped characterize the current state of ozone air quality and impact of meteorology in Houston during three separate events.

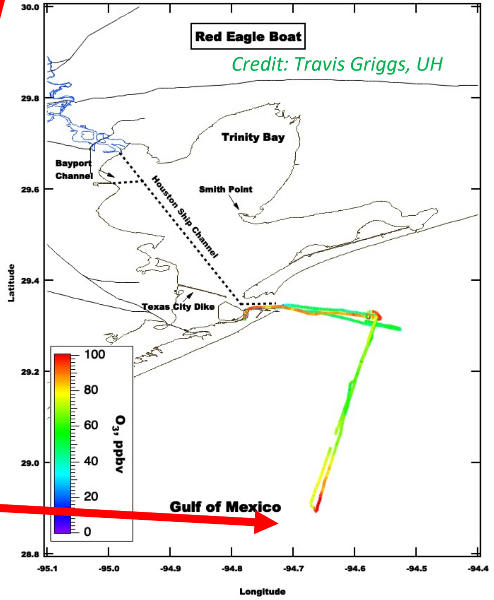
Highlights include, but are not limited to:

- Steep horizontal and vertical gradients in ozone over the water
- Boat/offshore emissions
- Influence of synoptic patterns on emission spatial patterns and providing perspective of where to expect ozone



Offshore ozone observations (sonde + in situ) September 9th, 2021





Not shown are hints of low-level ozone feature from the HSRL2 observations.

TRACER-AQ Links to TEMPO

Focus Area 1: Ozone Photochemistry and Meteorology

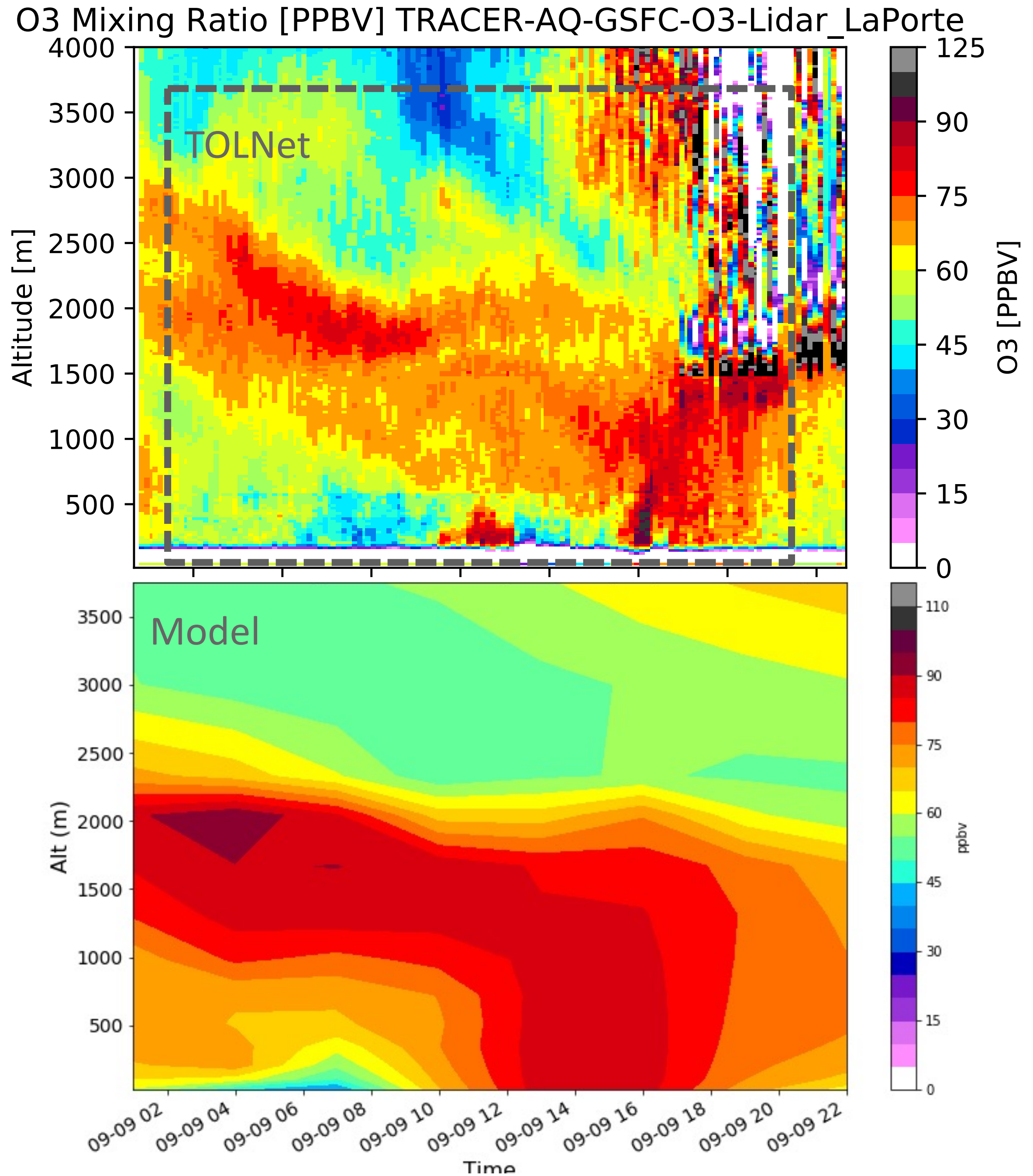
Focus Area 2: Modeling and Satellite Evaluation

Focus Area 3: Intersection of Air Quality and Socioeconomics Factors

During TRACER-AQ, the data collected provide enhanced observations for evaluating air quality forecasts/models (e.g., over water ozone).

Aircraft data can also be used to create proxy-data for TEMPO for assessing the temporal evolution of O3, HCHO, and NO_2 and the impact of spatial resolution on the analysis.

These product retrievals will use GEOS-CF as a priori as a test for future TEMPO product validation/evaluations.



Preliminary Modeling (WRF-GC) Analysis of TRACER-AQ Observations –Yuxuan Wang (UH)

TRACER-AQ Links to TEMPO

Focus Area 1: Ozone Photochemistry and Meteorology

Focus Area 2: Modeling and Satellite Evaluation

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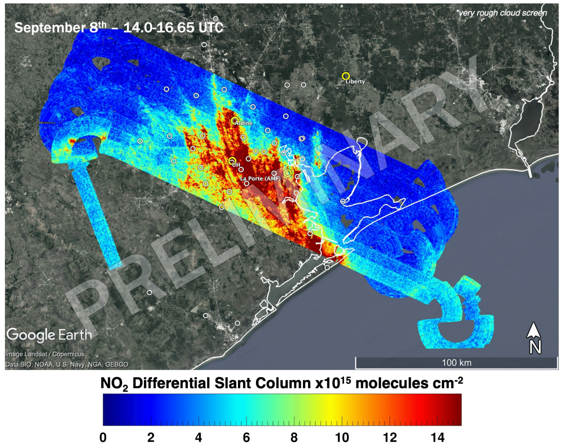
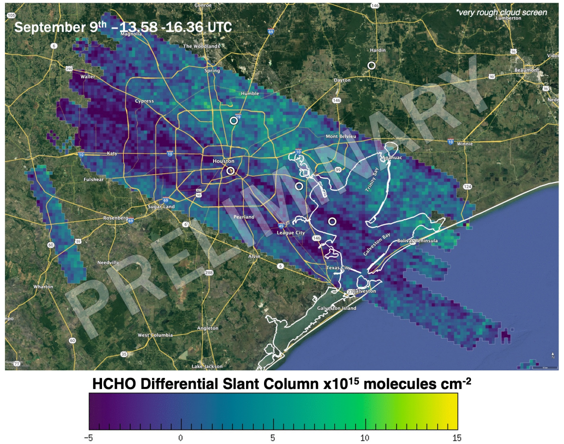
During TRACER-AQ, the aircraft collected 27 raster maps over the Houston area over 10 fight days and 1 over offshore platforms over the Gulf of Mexican.

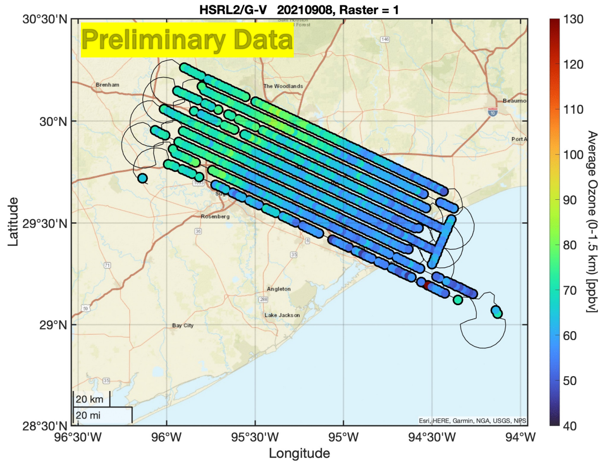
GCAS NO2 DSC



GCAS HCHO DSC



HSRL2 0-1.5km ozone



Example flight from September 8th, 2021 showing the diurnal evolution of NO_2, HCHO, and Ozone

Preliminary data courtesy of GCAS and HSRL2 teams

TRACER-AQ Links to TEMPO

Focus Area 1: Ozone Photochemistry and Meteorology

Focus Area 2: Modeling and Satellite Evaluation

Focus Area 3: Intersection of Air Quality and Socioeconomics Factors

During TRACER-AQ, the airborne, mobile, and dense ground networks will be used to update the work of identifying air quality disparities with GCAS in Houston as documented by Demetillo et al. (2020) as well as expand analysis to HCHO and O_3.

The data collected by the instruments on the airborne platform can be used to create TEMPO proxy datasets for this analysis which expand from once per day observations with TROPOMI to how disparities evolve throughout the day.

NO_2 was 37% higher for non-whites and Hispanics living in low-income tracts compared to whites living in high-income tracts in September 2013. (Demetillo et al., 2020: https://dx.doi.org/10.1021/acs.est.0c01864)

Preliminary observations from a single day in TAQ indicate that these NO_2 disparities persist throughout all times of the day.

Results with TROPOMI show that a 65% reduction in diesel NO_x emissions will reduce NO_2 inequality by 50% in Houston. (Demetillo et al., 2021:https://doi.org/10.1029/2021GL094333)

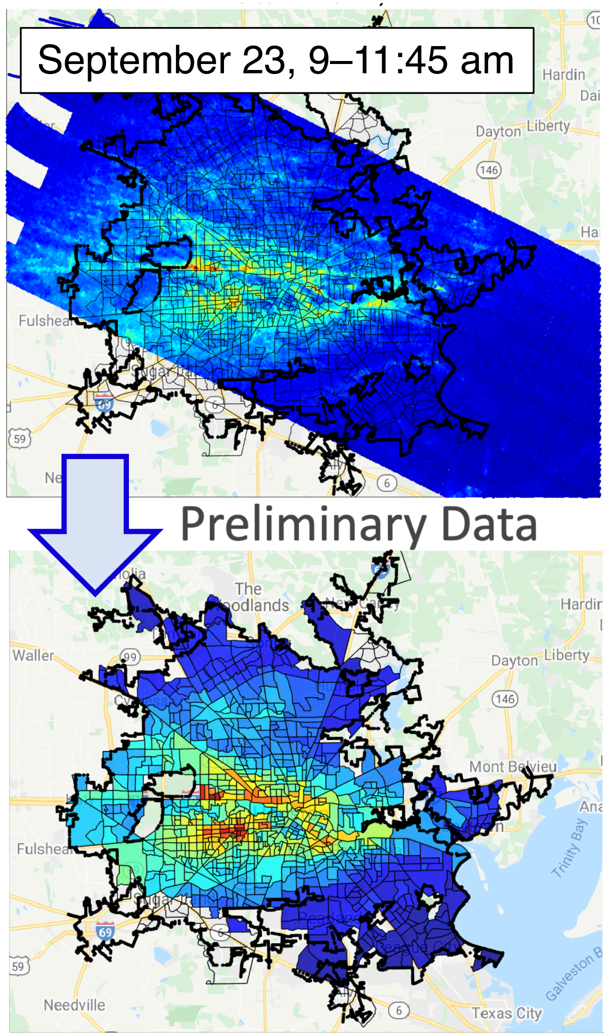
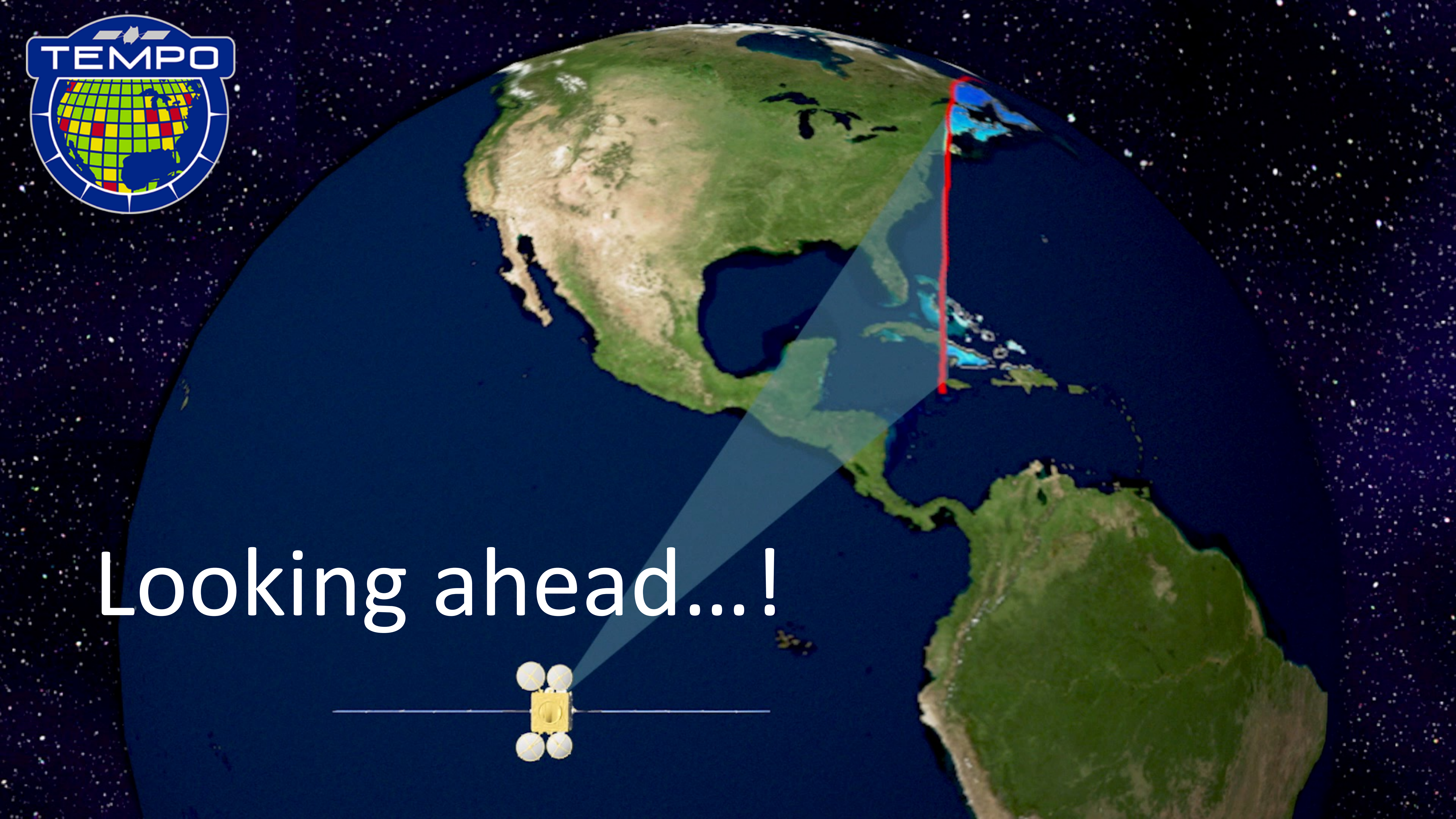


Figure demonstrates how airborne data is remapped to census tracts in Houston

Credit for this work to Angelique Demetillo and Sally Pusede, UVA


TEMPO
Looking ahead…!

Synergistic TEMPO Air Quality Science (STAQS)

In July-August 2023, STAQS seeks to integrate TEMPO satellite observations with traditional air quality monitoring to improve understanding of air quality science and increase societal benefit.

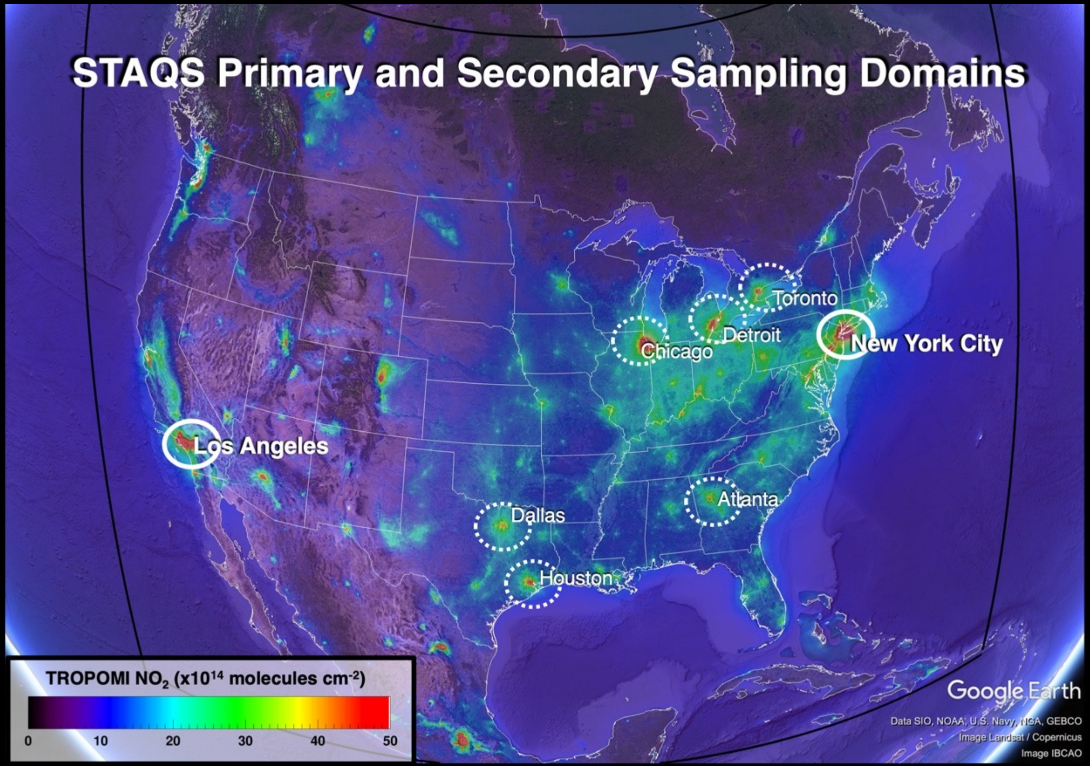
Science Objectives

1) Evaluating TEMPO level 2 products geo-physically, spatially, and temporally
2) Interpreting the temporal and spatial evolution of air quality events tracked by TEMPO
3) Improving temporal estimates of anthropogenic, biogenic, and fire emissions
4) Assessing the benefit of assimilating TEMPO data into chemical transport models
5) Linking air quality patterns to socio-demographic data

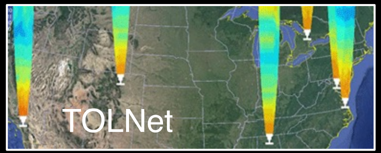
Collaborative activities:

- NOAA Atmospheric Emissions and Reactions Observed from Megacities to Marine Areas (AEROMMA)
- NOAA Coastal Urban Plume Dynamics Study (CUPiDS)
- Greater New York (NY) Oxidant, Trace gas, Halogen, and Aerosol Airborne Mission (GOTHAAM)

Annual average of TROPOMI NO_2 overlaid with the currently planned primary (solid circles) and secondary (dotted circles) sampling domains during STAQS within the TEMPO field of regard (black outline).



Includes deployment of airborne and ground-based remote sensing observations

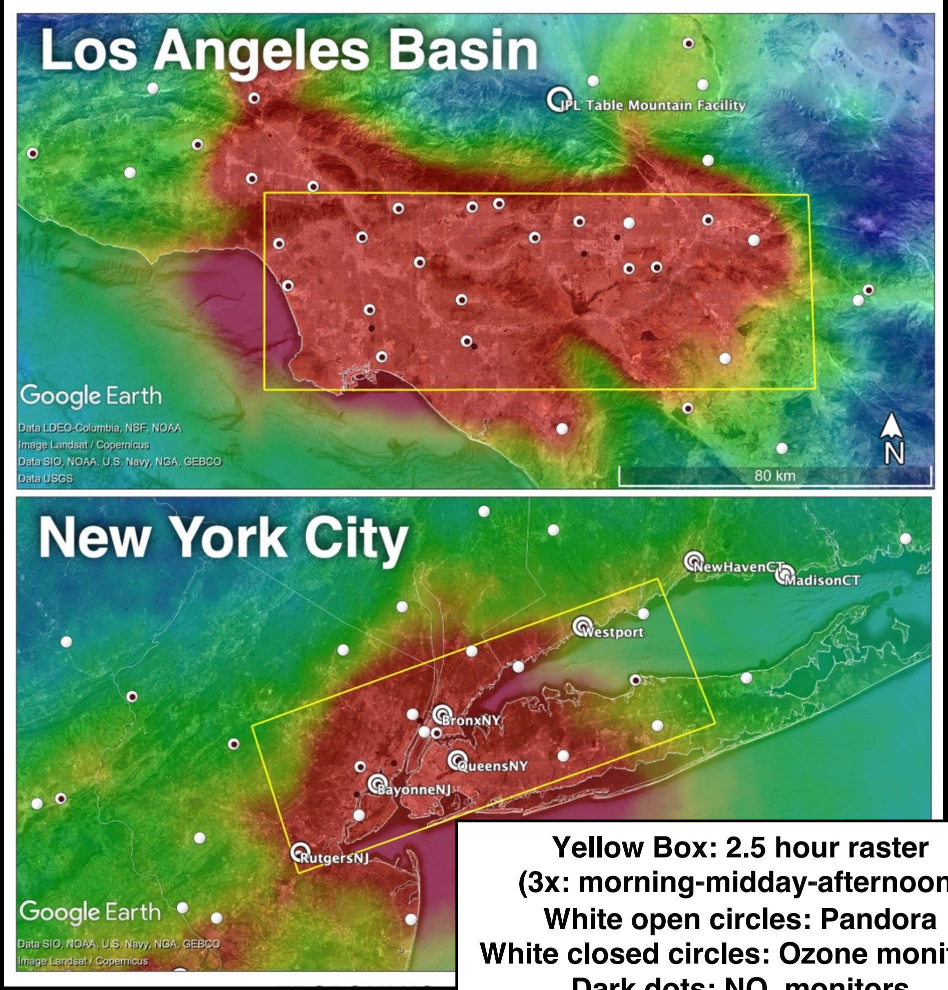


Interested in connecting with the STAQS team? laura.m.judd@nasa.gov and john.t.sullivan@nasa.gov

Synergistic TEMPO Air Quality Science (STAQS)

Build an integrated observing system consisting of ground-, airborne-, and satellite-based platforms.

Below are the existing measurements and capabilities of G-V coverage in the two primary domains of LA and NYC.

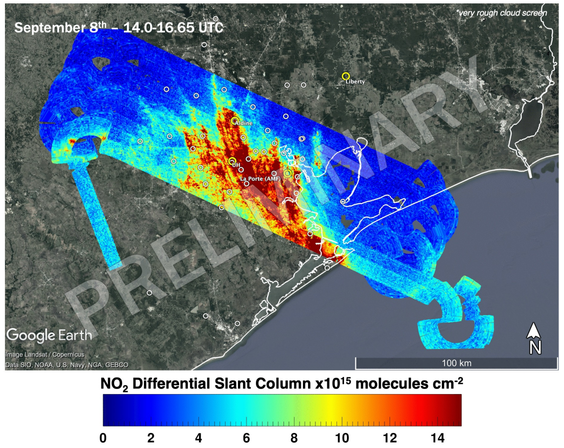


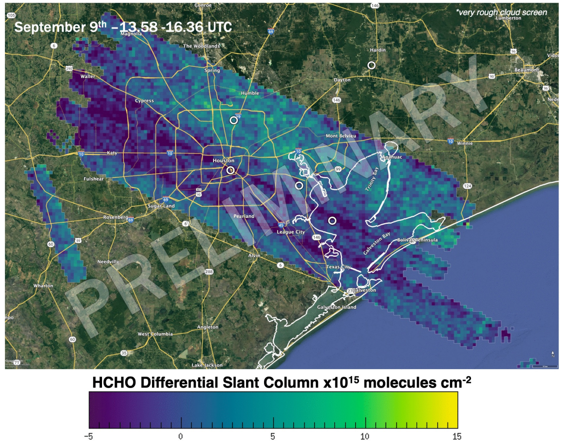
Yellow Box: 2.5 hour raster
(3x: morning-midday-afternoon)
White open circles: Pandora
White closed circles: Ozone monitors
Dark dots: NO_2 monitors

Prioritize repeated systematic sampling in a predefined domain during morning, midday, and afternoon times

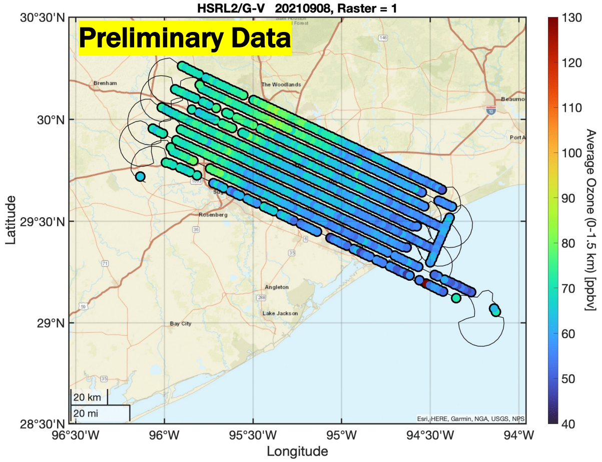
Below is an example of G-V GCAS/HSRL2 data during TRACER-AQ

GCAS NO_2 DSC





HSRL-2 0-1.5km ozone



Example flight from September 8th, 2021 showing the diurnal evolution of NO_2, HCHO, and Ozone

Not shown: HSRL aerosol products

Preliminary data courtesy of GCAS and HSRL-2 teams

Thanks for you attention!

Follow up questions? laura.m.judd@nasa.gov

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