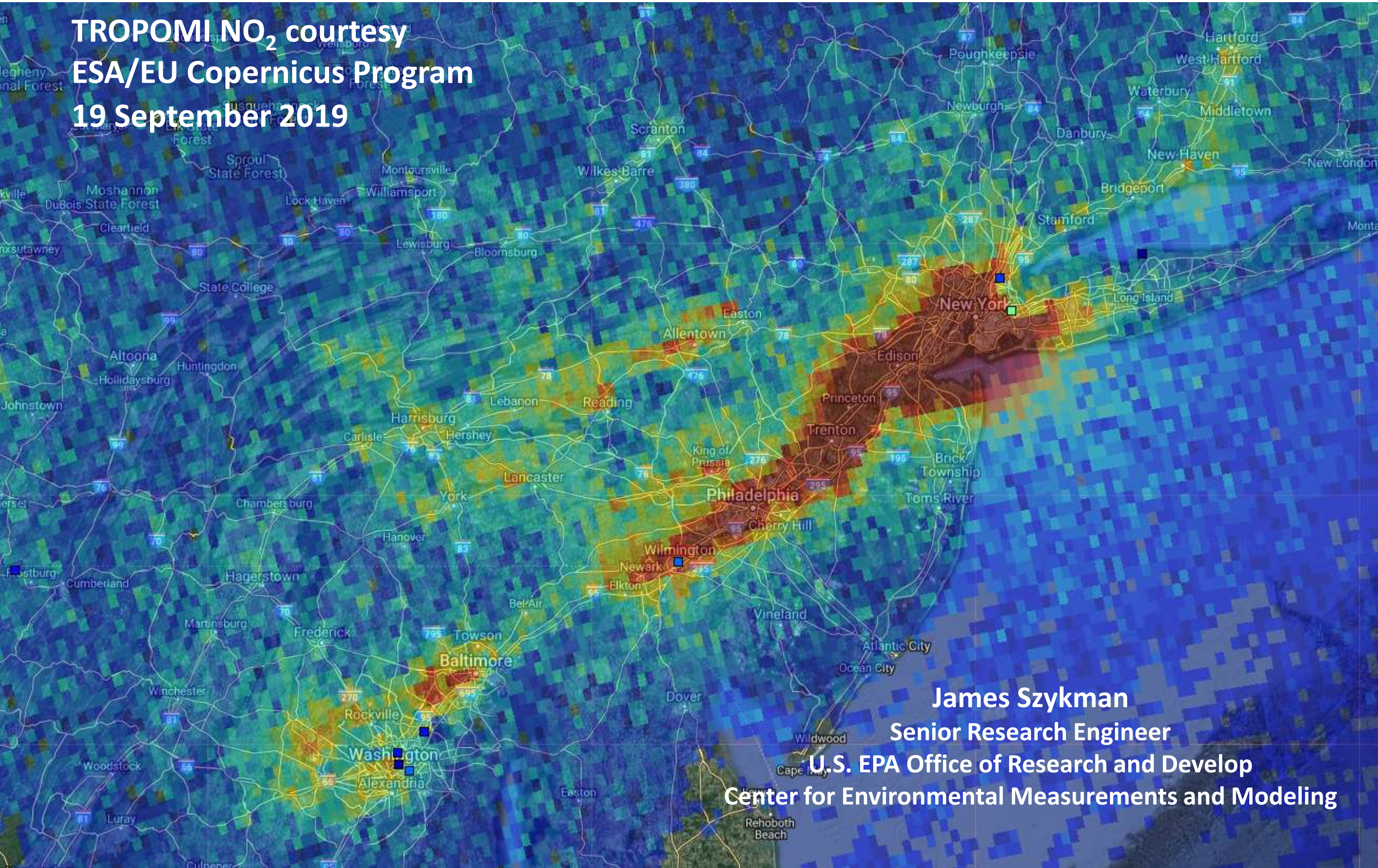
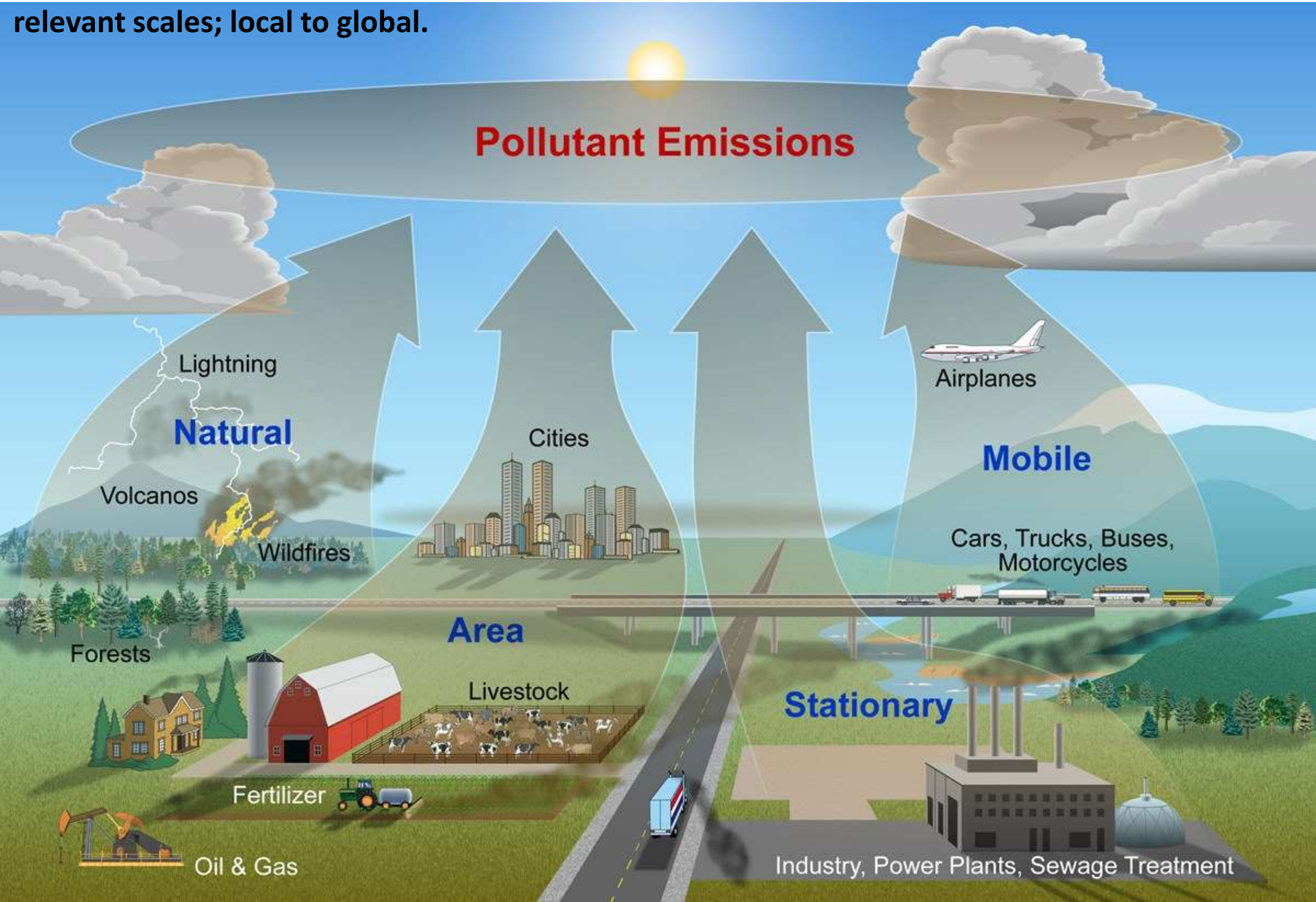
An Integrated Observing System for Air Quality and Recent U.S. Field Campaigns



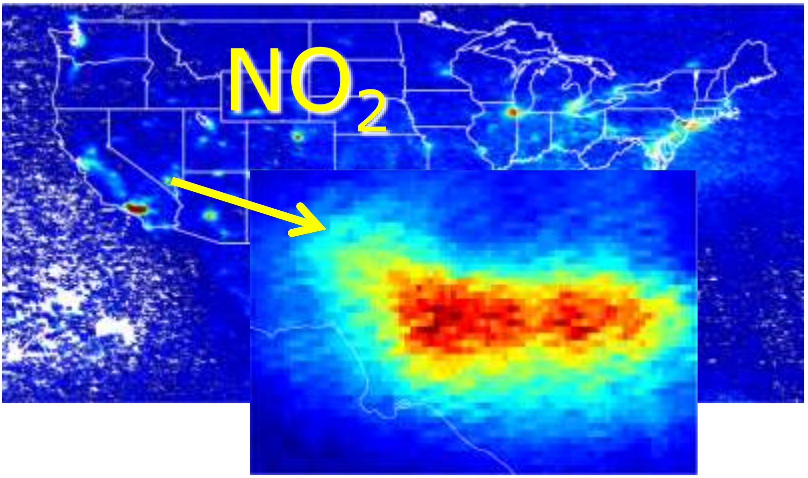
TROPOMI NO_2 courtesy
ESA/EU Copernicus Program
19 September 2019

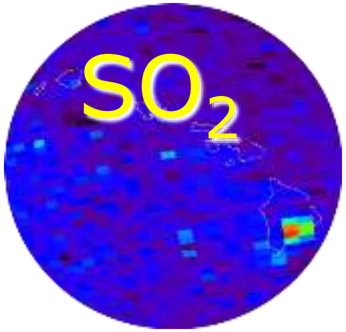
James Szykman
Senior Research Engineer
U.S. EPA Office of Research and Develop
Center for Environmental Measurements and Modeling

While exposure to air pollution occurs near the ground, understanding the complex interaction(s) between pollutant emissions and weather requires measurements which span the **relevant scales; local to global.**

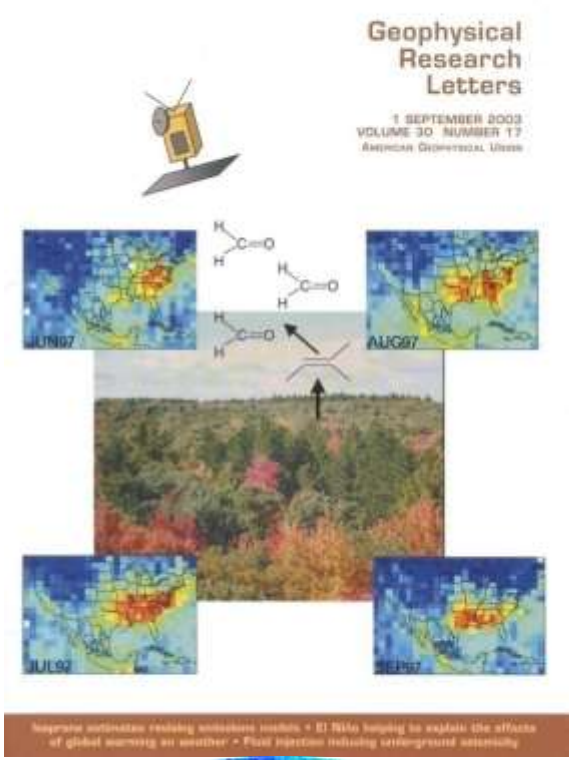


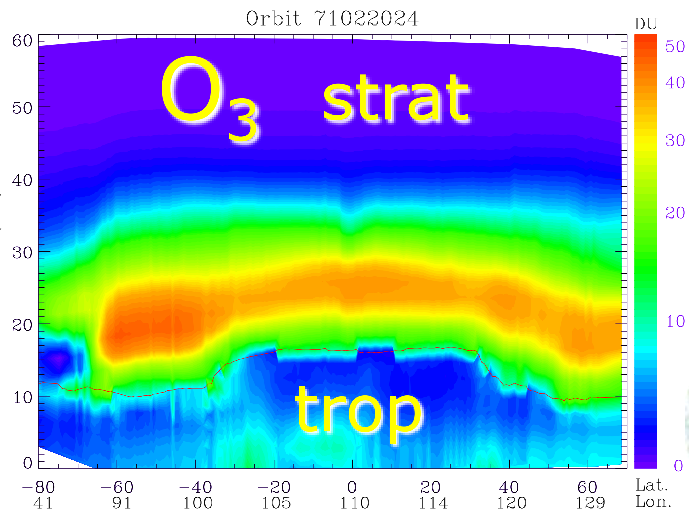
Over four decades sun-synchronous satellites such as TOMS, GOME, SCIA, OMI, have provided a unique view of pollution from Space

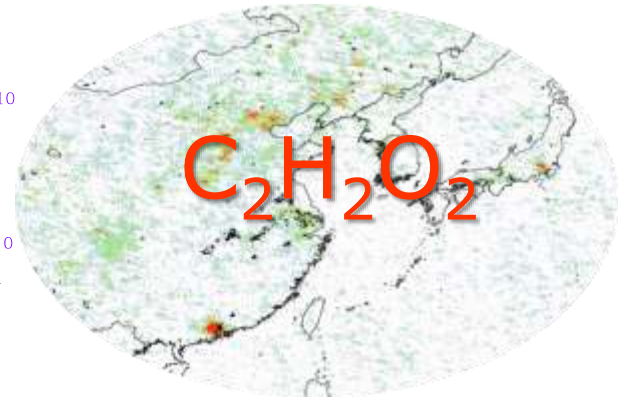


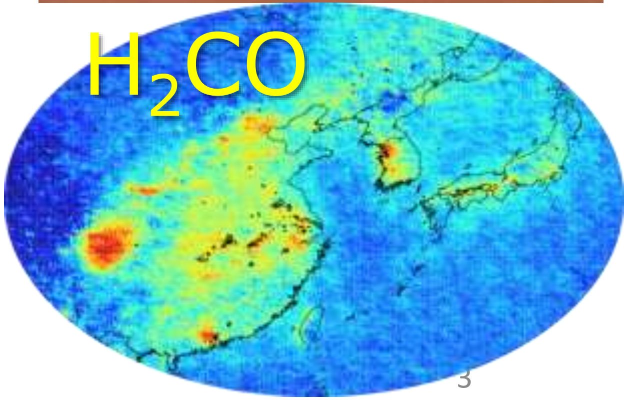


Kilauea activity, source of the VOG event in Honolulu on 9 November 2004



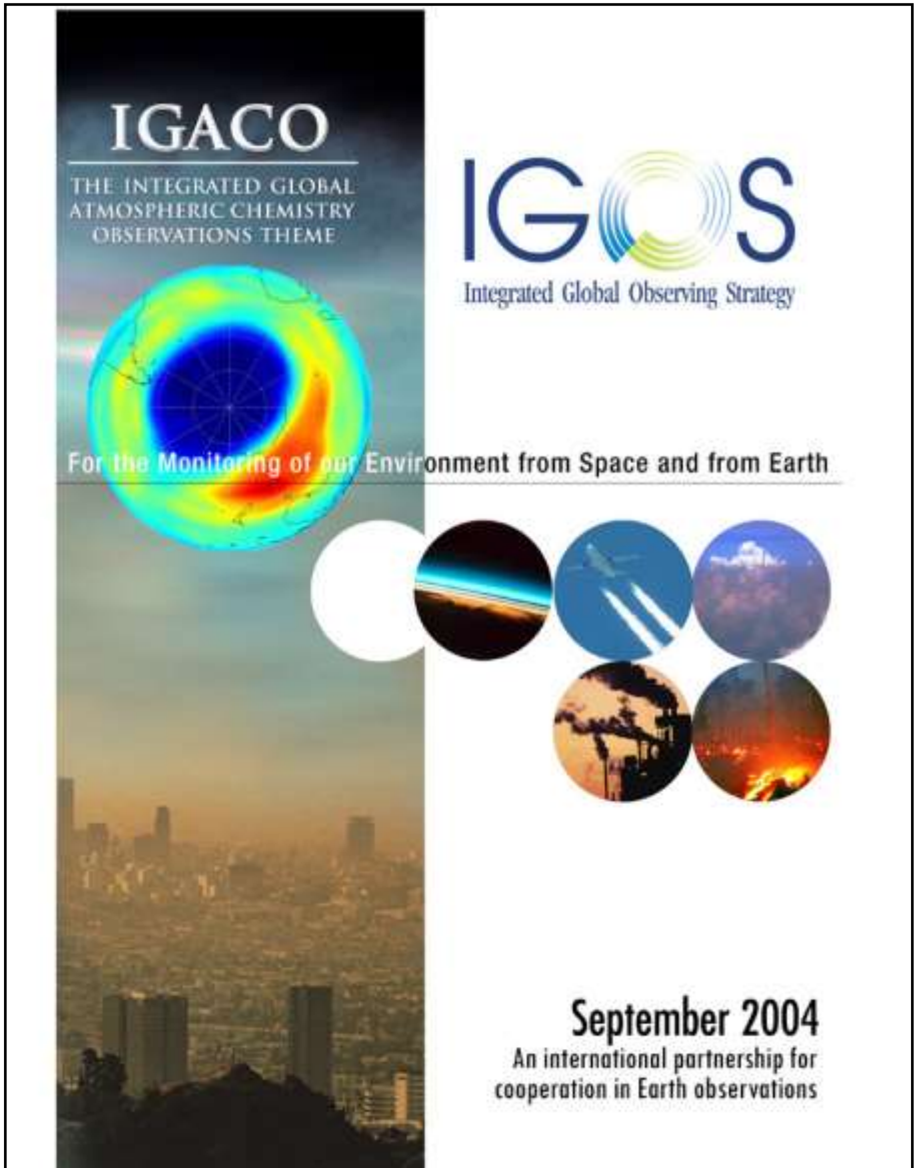






Source: Kelly Chance, SAO

Space Agencies recognized the need for an Integrated Observing System



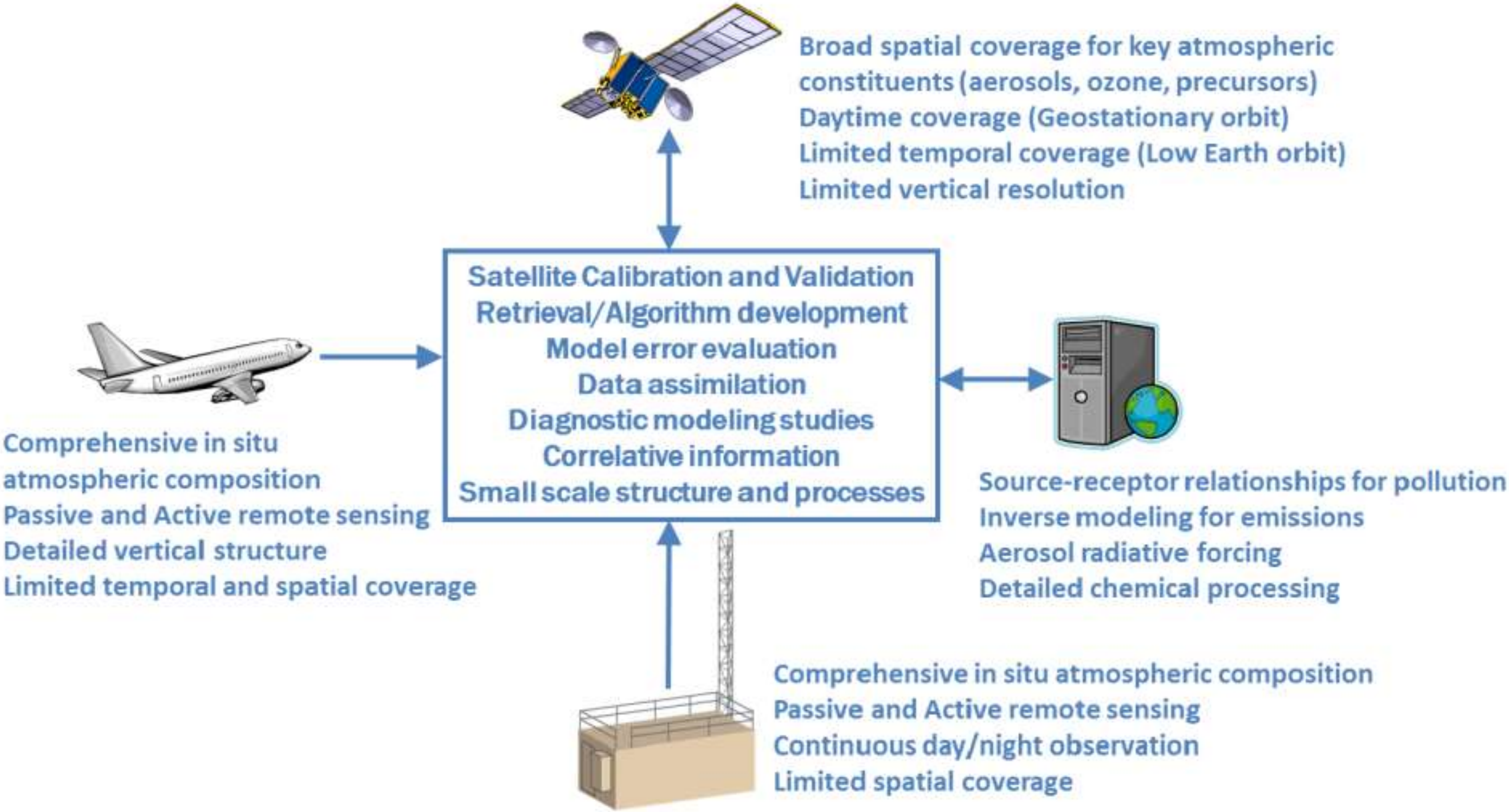
The global long-term observational system for atmospheric composition comprises four components:

- routine ground-based measurements including in-situ, remote sensing and balloon instrumentation;
- systematic aircraft measurements;
- satellite measurements with instrumentation viewing in the nadir and limb directions; and
- a data modelling system with assimilation to provide a comprehensive global picture.

The three measurement components, having different strengths and weaknesses, complement each other, and along with models can enable an improved understanding of:

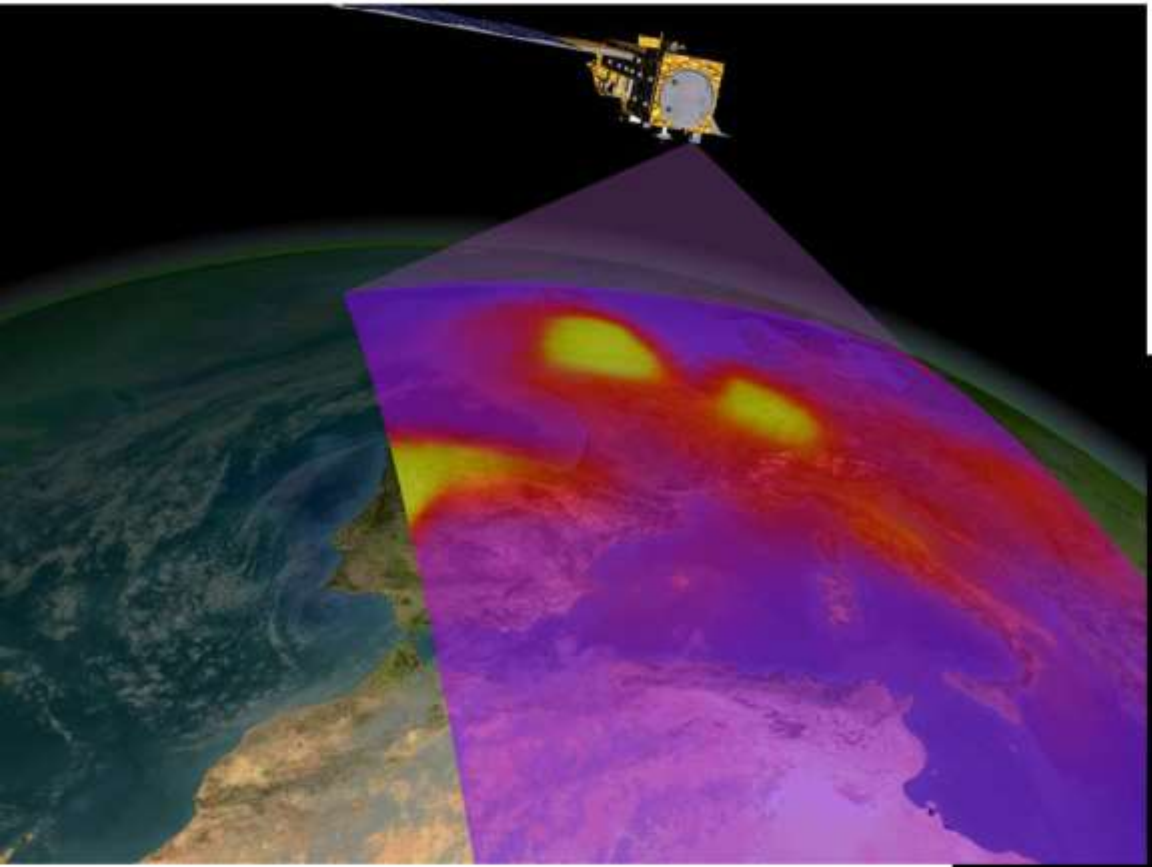
- Emission sources and fluxes
- Pollutant distributions near the surface
- Regional and global transport of pollutants
- Monitoring of pollution trends

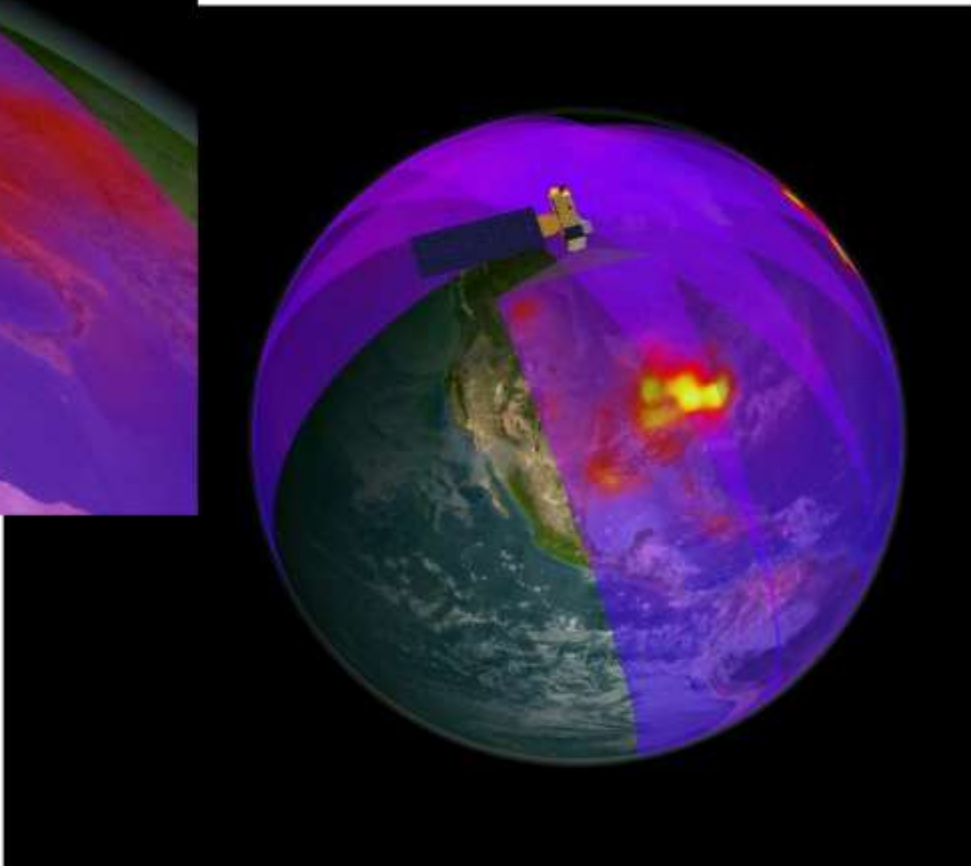
Field campaigns and the Integrated Observing System for Air Quality



Source: Jim Crawford

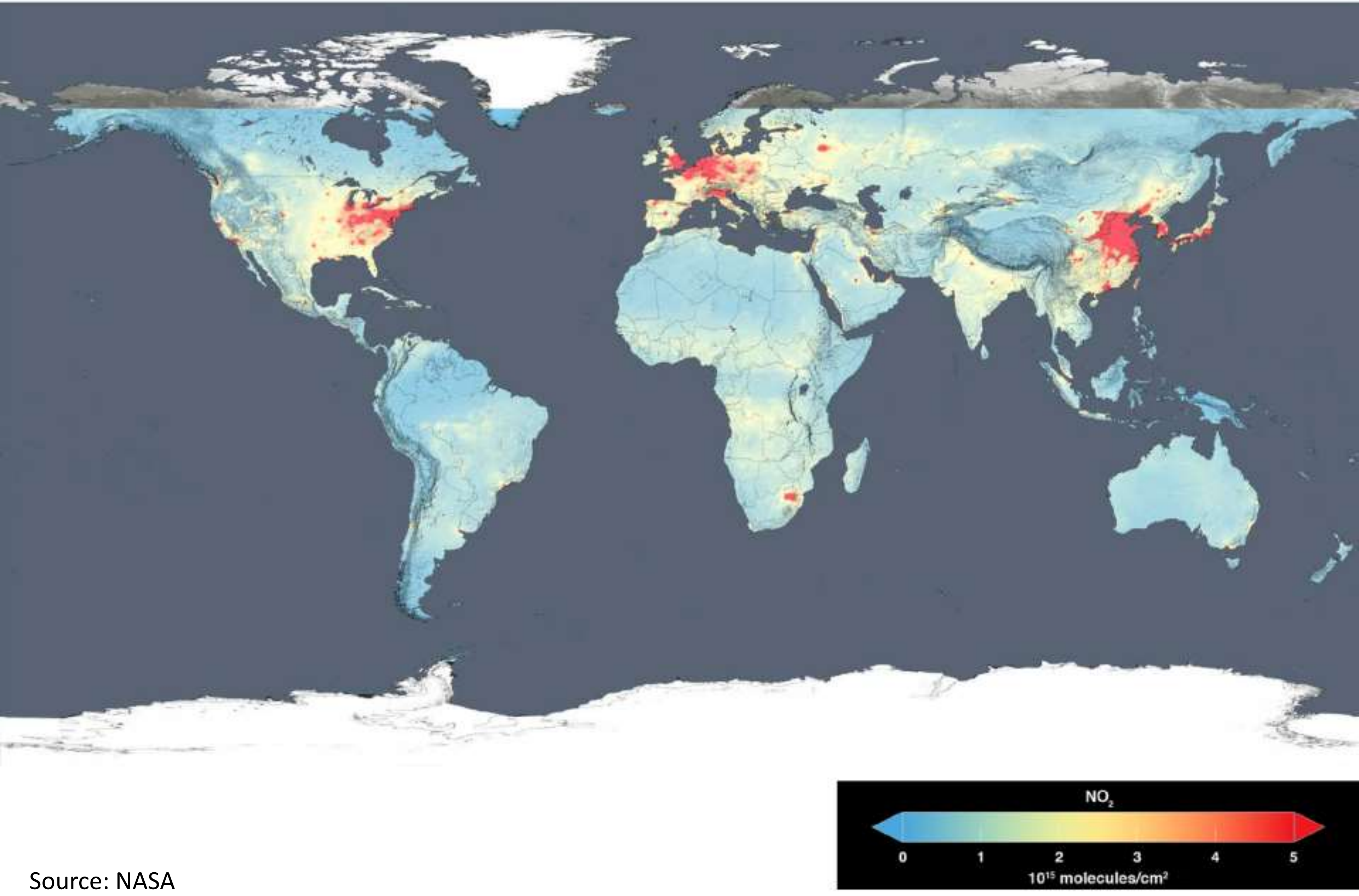
KNMI's OMI Satellite Instrument Mapping Nitrogen Dioxide (NO2)





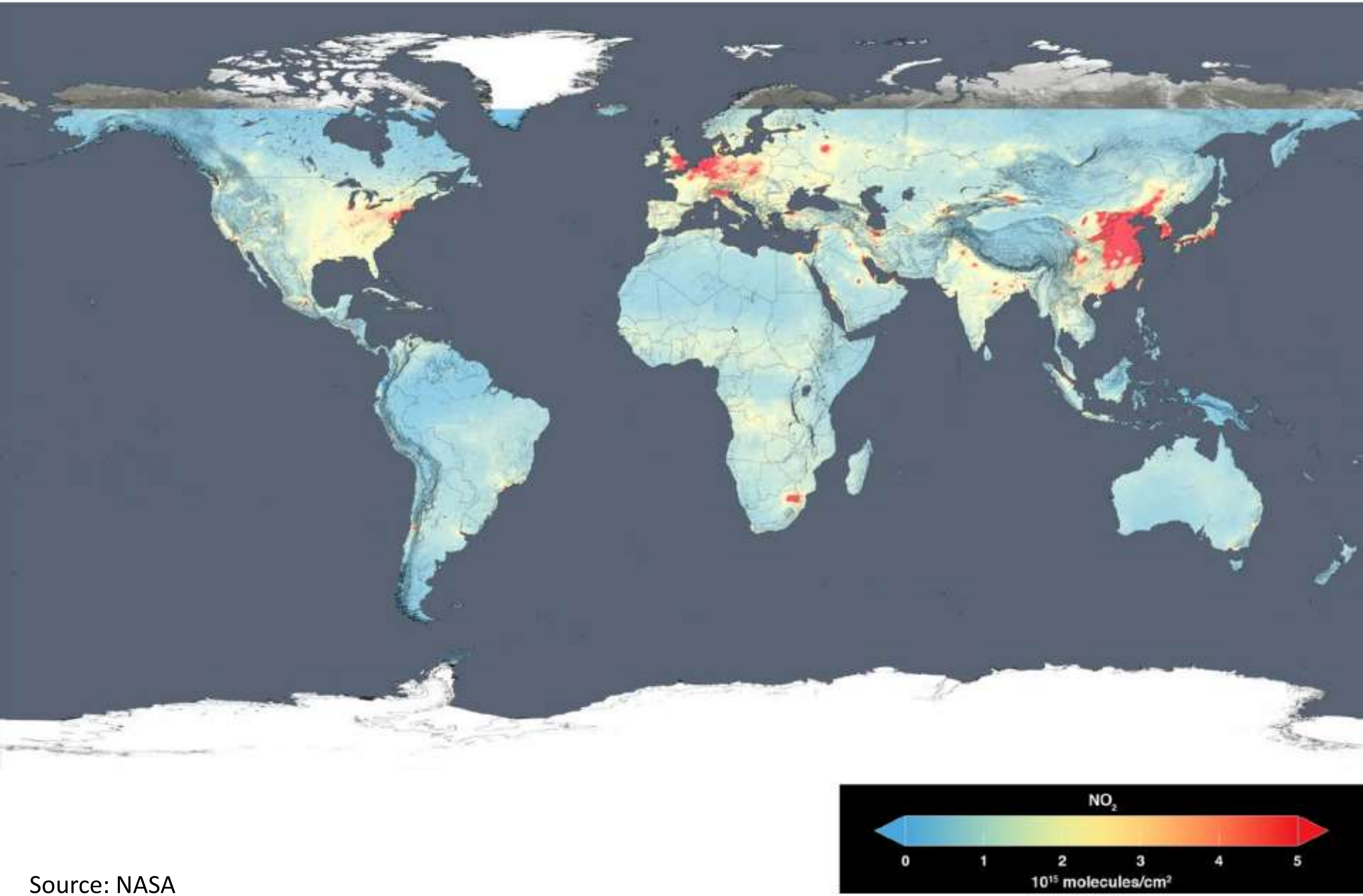
Source: NASA

NASA's OMI NO_2 (2005)



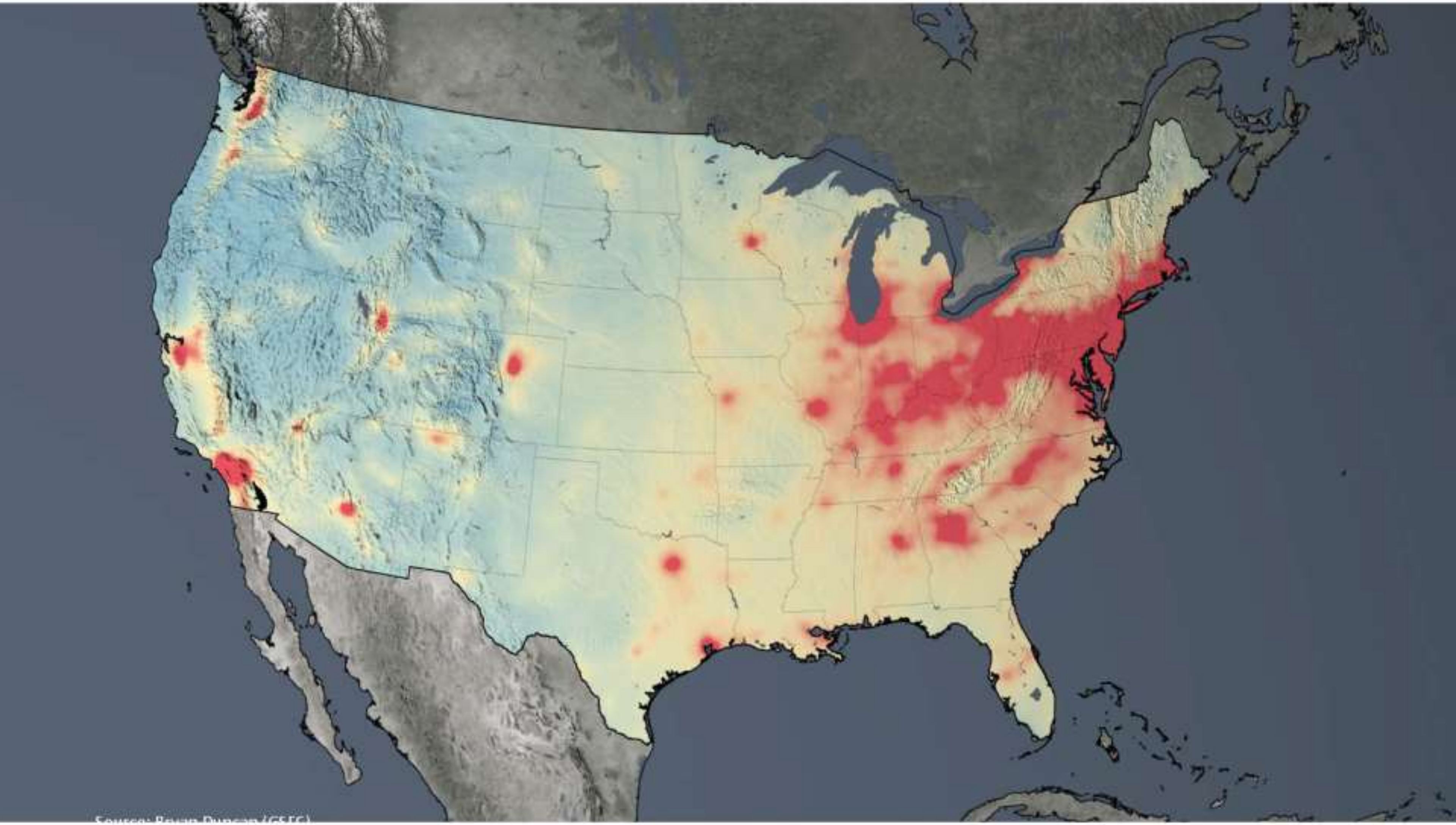
Source: NASA

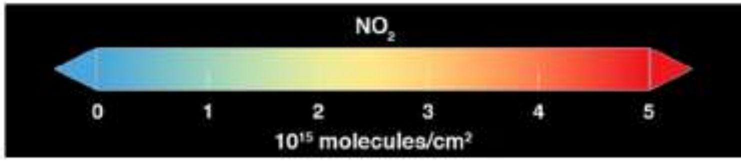
NASA's OMI NO_2 (2014)



Source: NASA

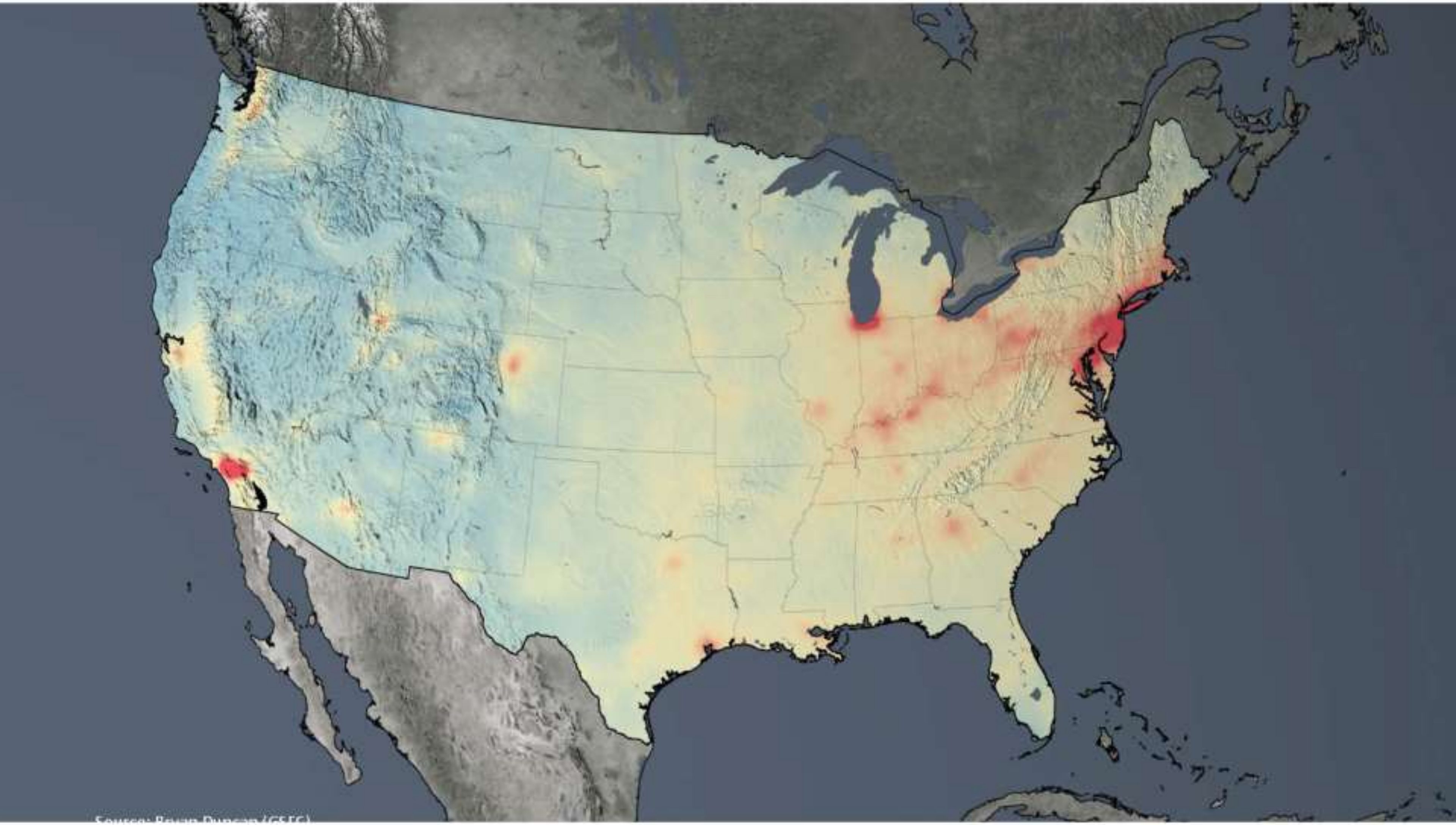
OMI NO_2 for United States (2005)

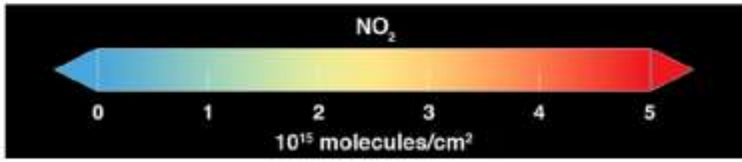




Source: NASA

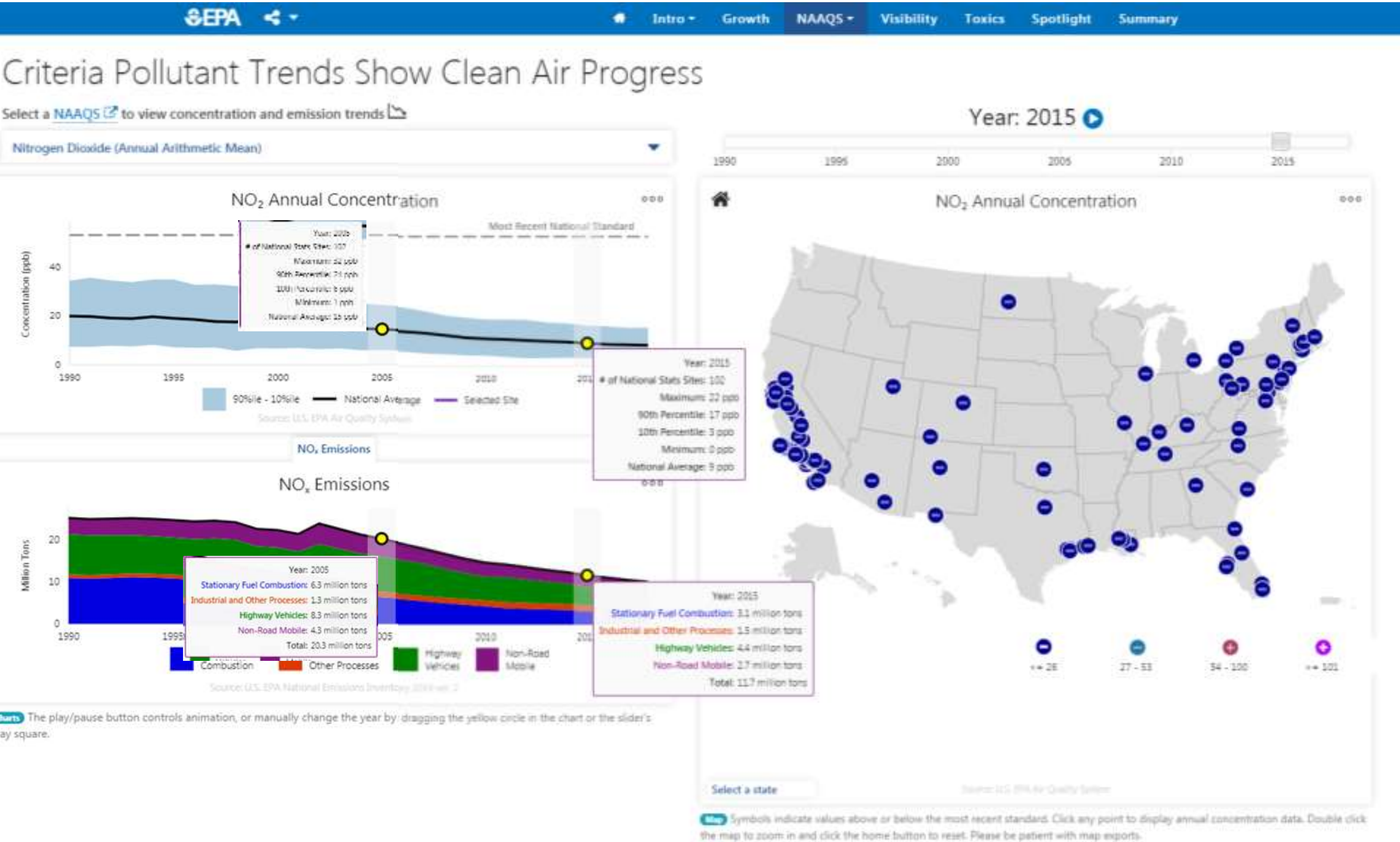
OMI NO_2 for United States (2014)





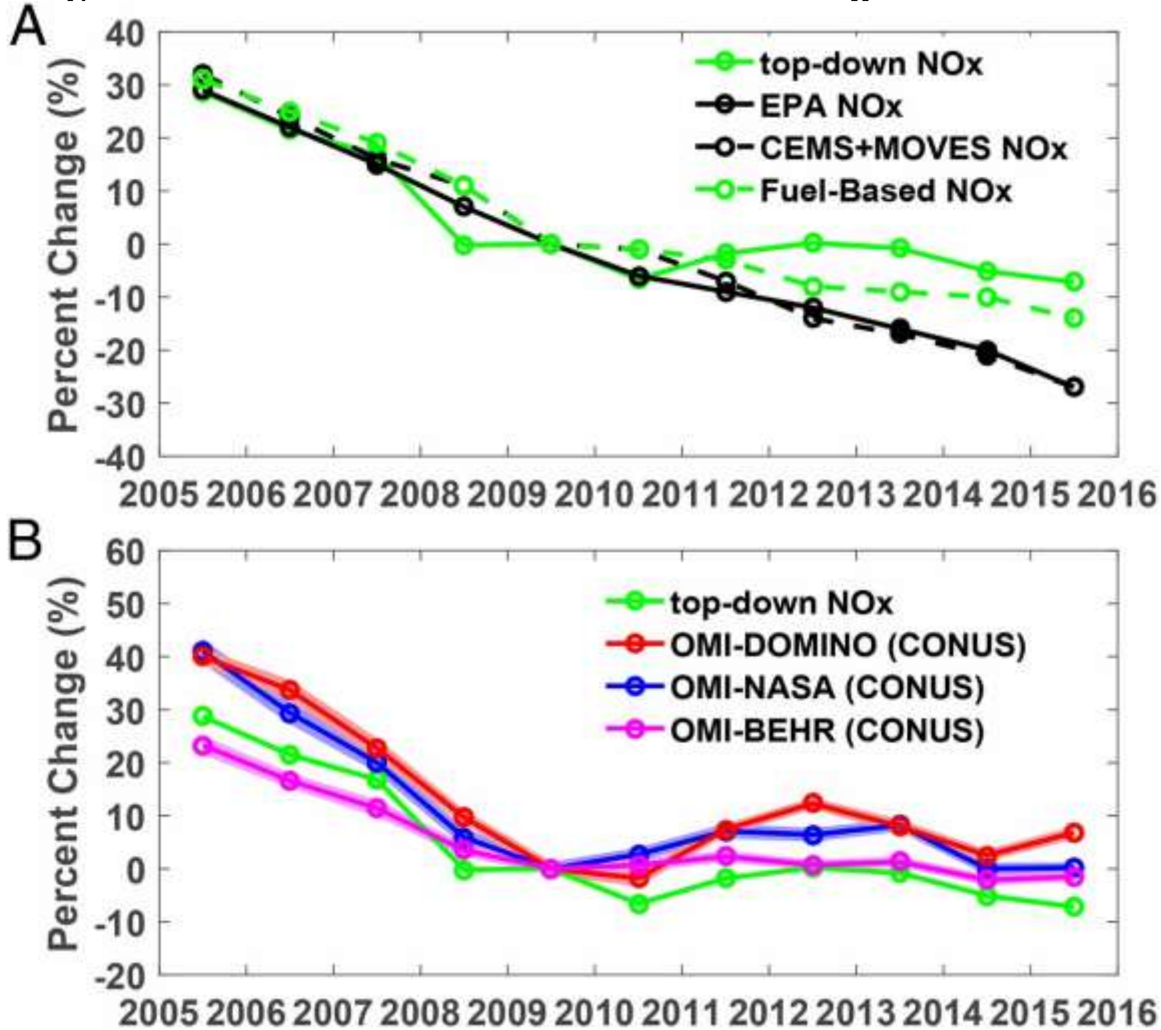
Source: NASA

Long History of U.S Air Quality and Emissions Trends



Source: https://gispub.epa.gov/air/trendsreport/2019/#naaqs_trends

(A) Percent changes (normalized at 2009) of top-down US anthropogenic NOx emission estimates from inverse analysis (green line), EPA's emissions trends report data of NOx (black solid line), revised EPA emission estimates including CEMS and MOVES ...



Zhe Jiang et al. PNAS 2018;115:20:5099-5104

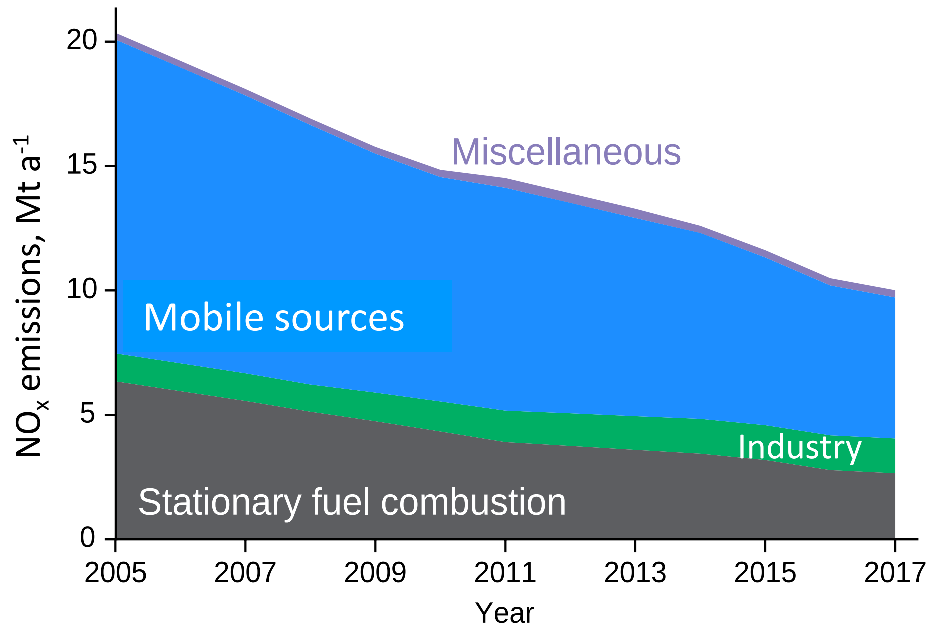
PNAS

Zhe Jiang et at, 2018

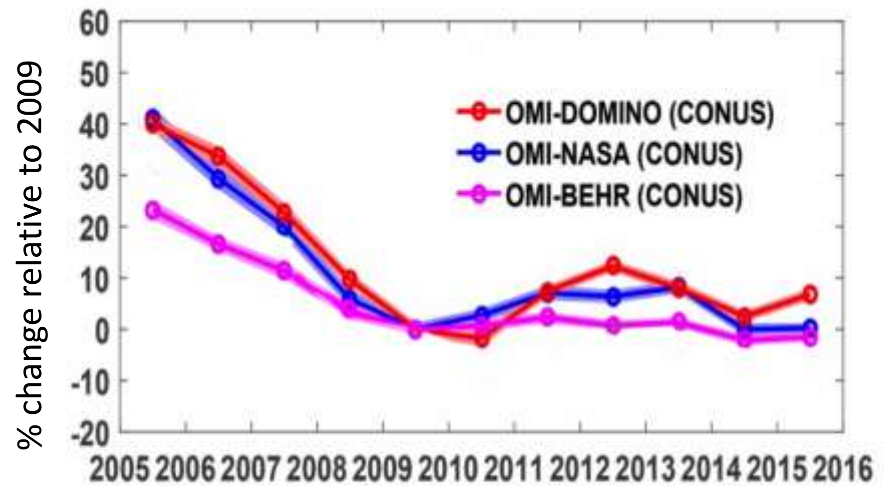
US NO_x emissions have continued to decrease according to EPA…

but OMI tropospheric NO_2 column observations suggest otherwise!

EPA National Emission Inventory (NEI):
53% sustained decrease of NO_x emissions over 2005-2017
EPA, 2018

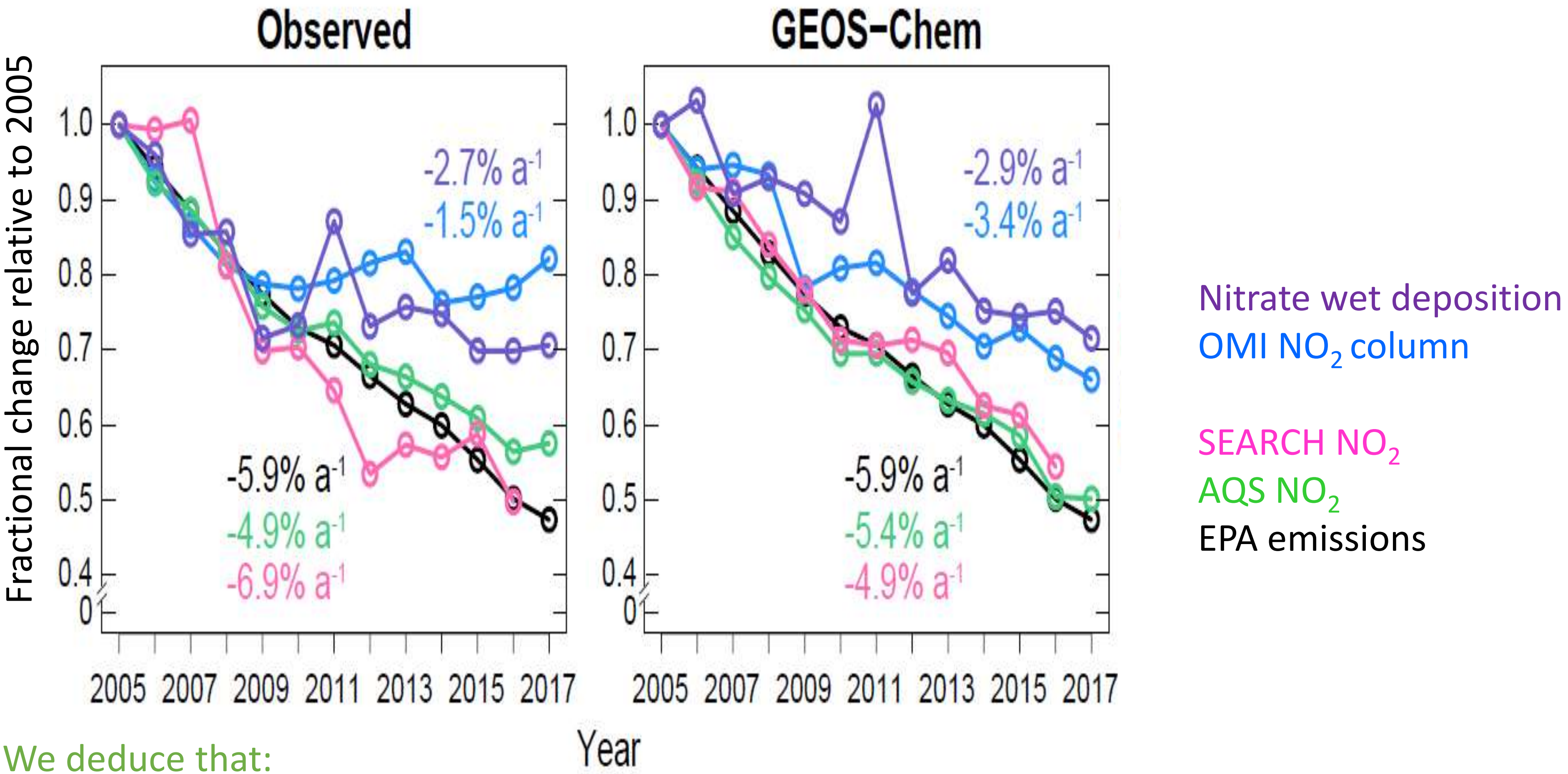


OMI NO_2 columns over CONUS, 2005-2015:
flat after 2009
Jiang et al., PNAS 2018



Source: Atmos. Chemistry Modeling Group-Harvard Univ.

Comparing 2005-2017 relative trends for the different quantities



We deduce that:

- EPA 2005-2017 trend in NO_x emissions is largely correct
- OMI NO_2 columns have strong background influence
- GEOS-Chem underestimates free tropospheric background NO_2

Source: Atmos. Chemistry Modeling Group-Harvard Univ.

Satellite Trends and Spatial Resolution

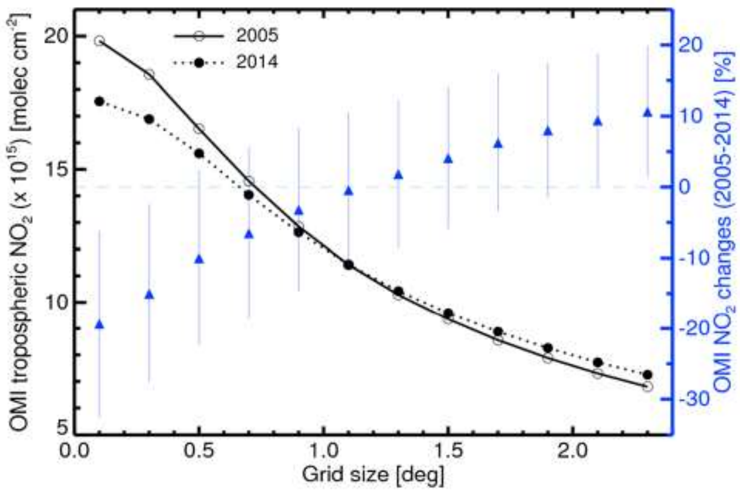
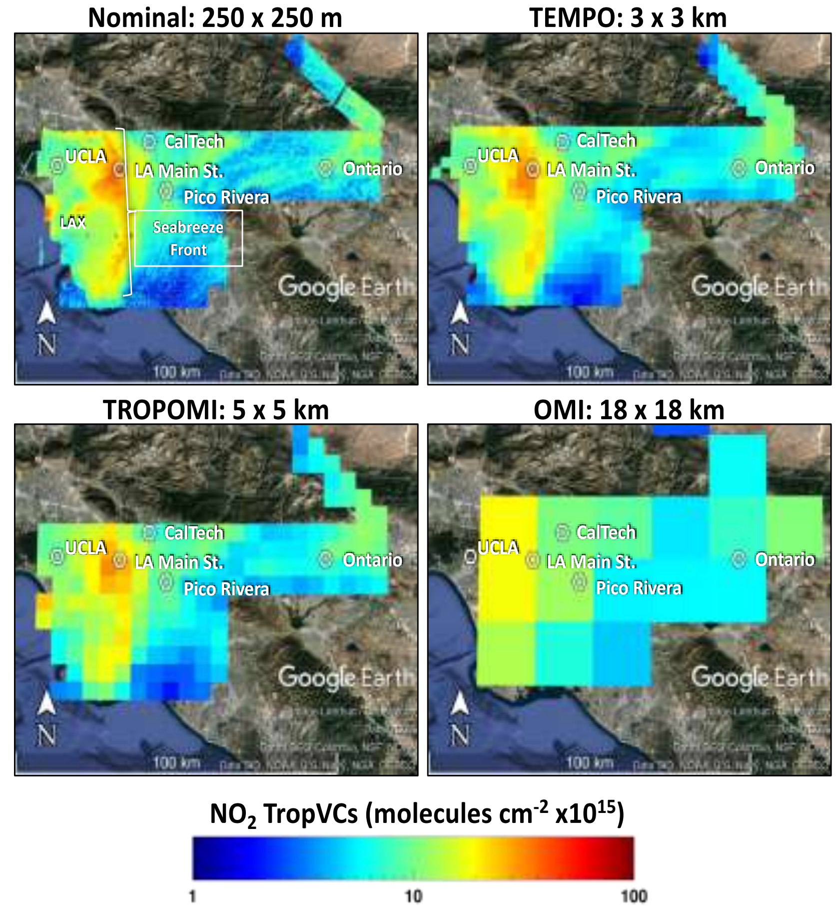


Figure 3. OMI NO_2 levels ($\times 10^{15}$ mol/cm^2) for the Seoul metropolitan area in 2005 (solid black line) and 2014 (dotted black line) as functions of spatial resolution (degrees) centered over central Seoul. The blue triangles show changes (%) in NO_2 levels as a function of spatial resolution between 2005 and 2014; vertical bars represent the 95% confidence interval.



AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Atmospheres

RESEARCH ARTICLE

A space-based, high-resolution view of notable changes in urban NO_x pollution around the world (2005–2014)

Bryan N. Duncan[1], Lok N. Lamsal[1,2], Anne M. Thompson[1], Yasuko Yoshida[1,3], Zifeng Lu[4], David G. Streets[4], Margaret M. Hurwitz[1,5], and Kenneth E. Pickering[1]

https://doi.org/10.5194/amt-2019-161
Preprint. Discussion started: 28 May 2019
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Atmospheric Measurement Techniques Discussions

EGU

Evaluating the impact of spatial resolution on tropospheric NO_2 column comparisons within urban areas using high-resolution airborne data

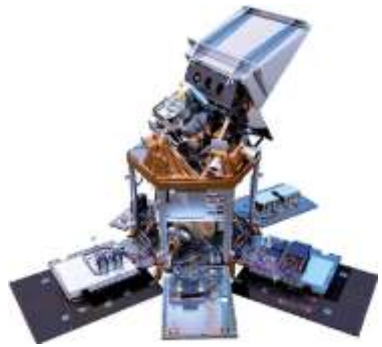
Laura M. Judd, Jassim A. Al-Saadi, Scott J. Janz, Matthew G. Kowalewski, R. Bradley Pierce, James J. Szykman, Lukas C. Valin, Robert Swap, Alexander Cede, Moritz Mueller, Martin Tiefengraber, Nader Abuhassan, David Williams

European Space Agency Sentinel 5 Precursor TROPOspheric Monitoring Instrument (TROPOMI)

esa
European Space Agency

TROPOMI

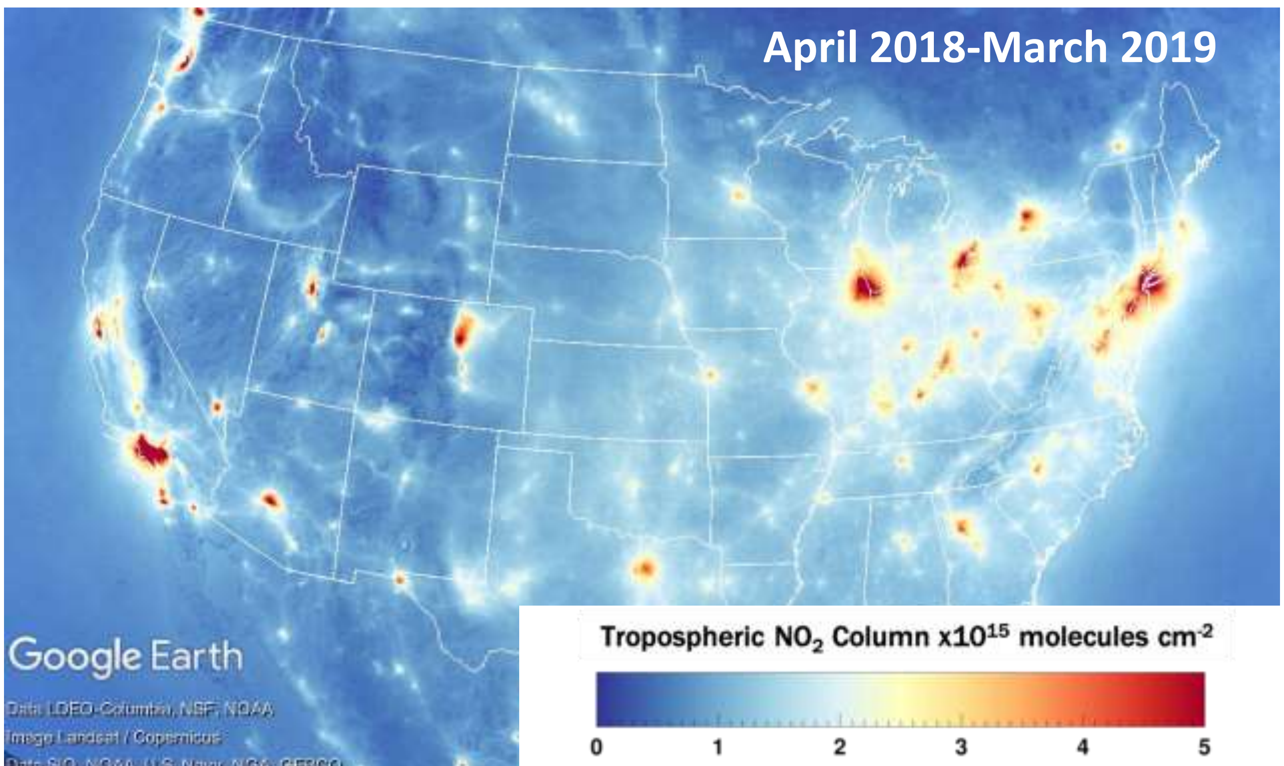
Royal Netherlands Meteorological Institute
Ministry of Infrastructure and the Environment



Continuing the heritage of UV/VIS sun-synchronous satellite instruments (launched October 2017) TROPOMI is first instrument to provide daily views NO_2 (transport/emissions) at city scales across the globe.

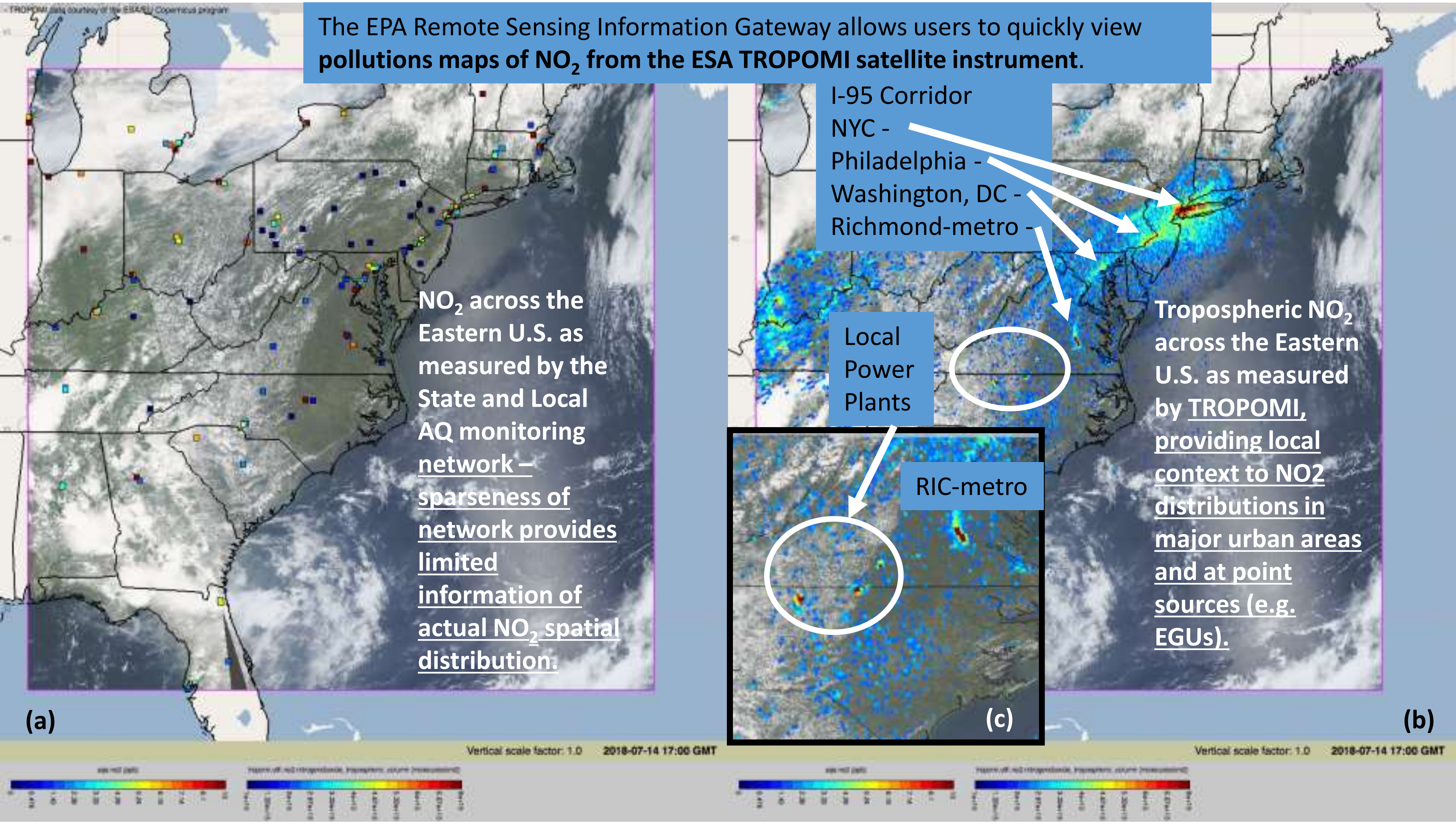
Global Coverage 1 day - TropNO_2 7 km x 3.5 km/5.5 km x 3.5 km July 2019 (~13 times improved spatial resolution over OMI.)

Includes measurements of O3, HCHO, SO_2, CH4, CO, plus other species.

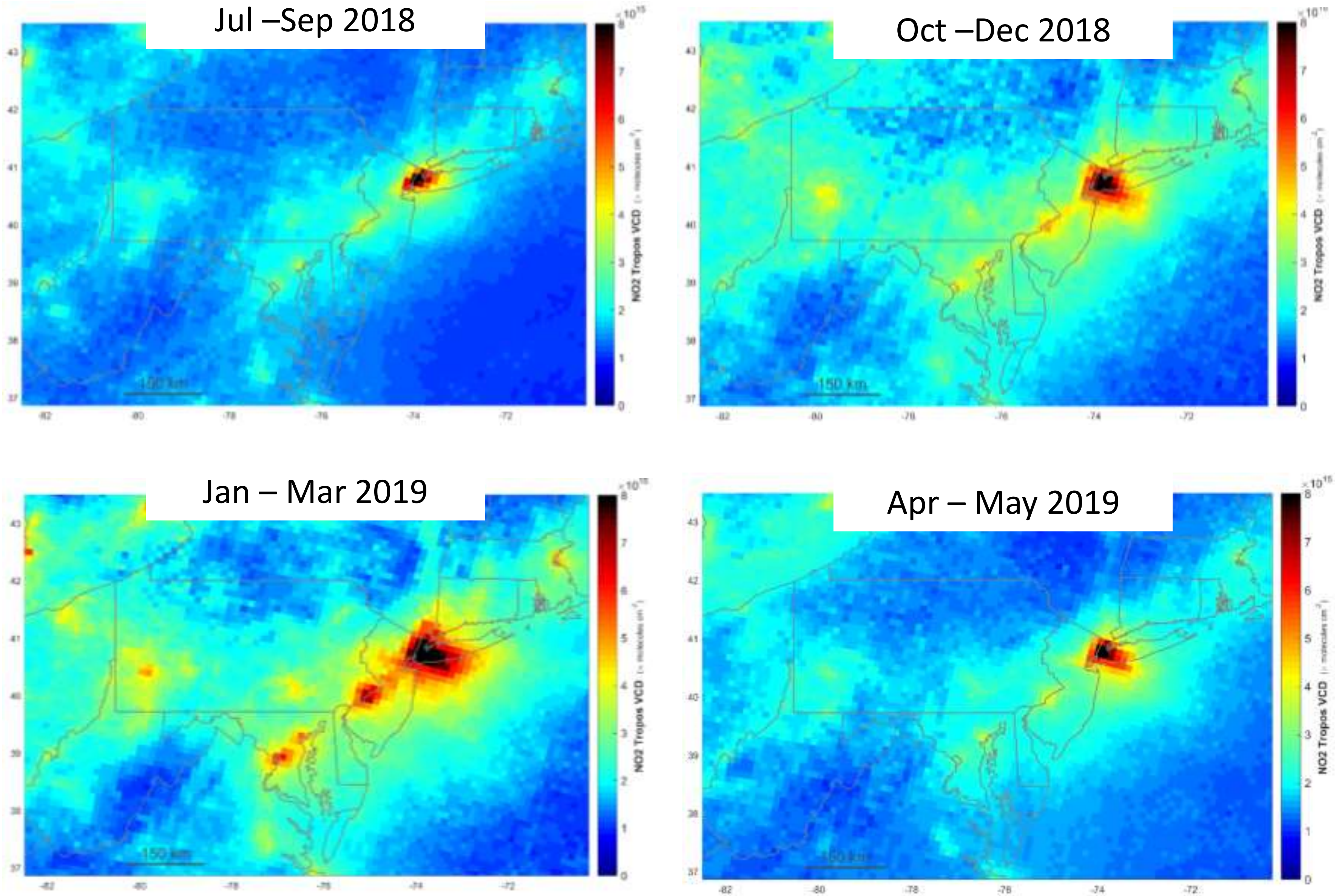


Source:
Laura Judd, NASA LaRC
Henk Eskes, KNMI

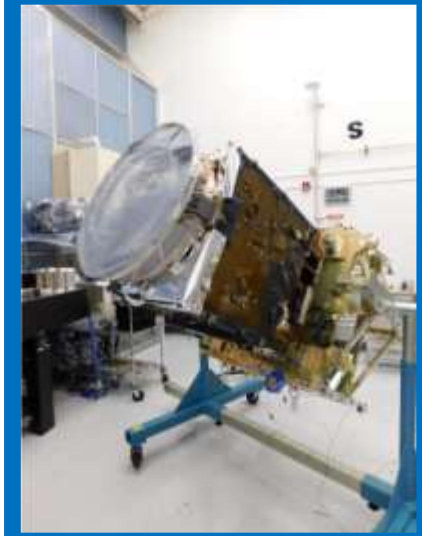
Daily Pollution Motoring from Space has taken a giant leap forward with TROPOMI



S5P Copernicus TROPOMI Tropospheric NO2 Column remapped to CMAQ 12km Grid



Tropospheric Emissions: Monitoring of Pollution –TEMPO Moving to Time Resolved Observations



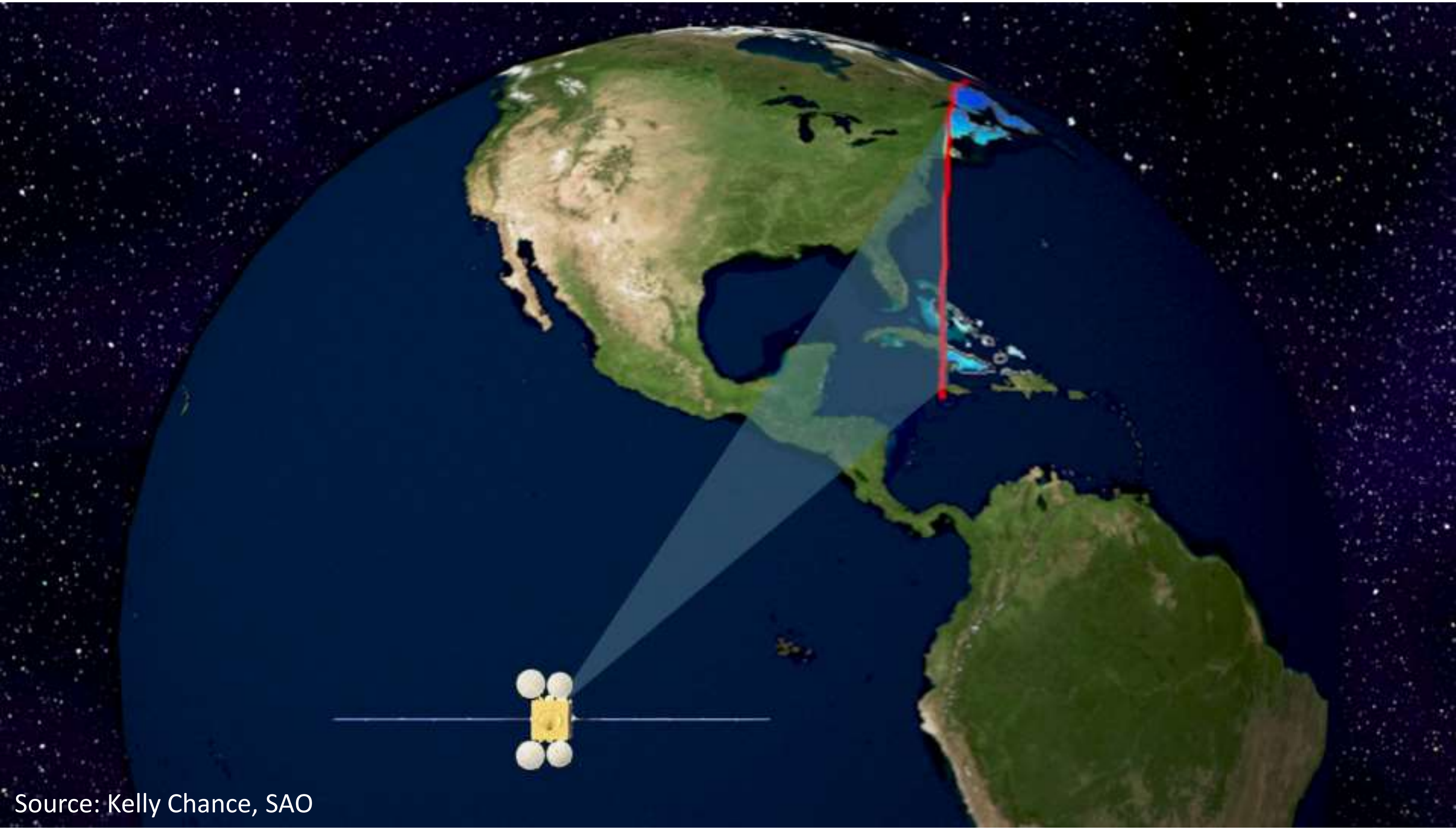
Picture of TEMPO UV/VIS Spectrometer instrument; instrument completed and delivered to NASA - December 2018

PI: Kelly Chance, Smithsonian Astrophysical Observatory
Current other Institutions: EPA, NASA LaRC, NASA GSFC, NOAA, NCAR, Harvard, UC Berkeley, St. Louis U, U Alabama Huntsville, U Nebraska

International collaboration: Korea, Mexico, Canada, Europe

- UV/VIS grating spectrometer (290-490 nm; 540-740 nm) measuring solar backscattered Earth radiance
- Proposed Launch Date: February 2022
- Anticipated Orbital Location: ~91 degrees West Longitude
- Field of Regard (FOR) and duty cycle - Mexico City/Yucatan, Cuba to the Canadian oil sands, Atlantic to Pacific
- Instrument slit aligned N/S and swept across the FOR in the E/W direction, producing a radiance map of Greater North America in one hour
- Spatial resolution - 2.1 km N/S × 4.7 km E/W native pixel resolution (9.8 km2)
- Standard data products and sampling rates: Most sampled hourly, including eXceL O3 (troposphere, PBL)
- NO2, H2CO, C2H2O2, SO2 sampled hourly (average results for ≥ 3/day if needed)
- Ability to do observations at higher time resolution over a dedicated scene

Example of TEMPO hourly NO_2 sweep and Field of View from Geostationary Orbit



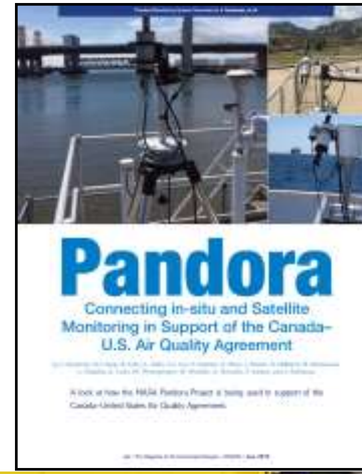
Example of TEMPO Pixel Spatial Resolution as compared to the Global Ozone Monitoring Experiment–2 (GOME-2) and the Ozone Monitoring Instrument (OMI)

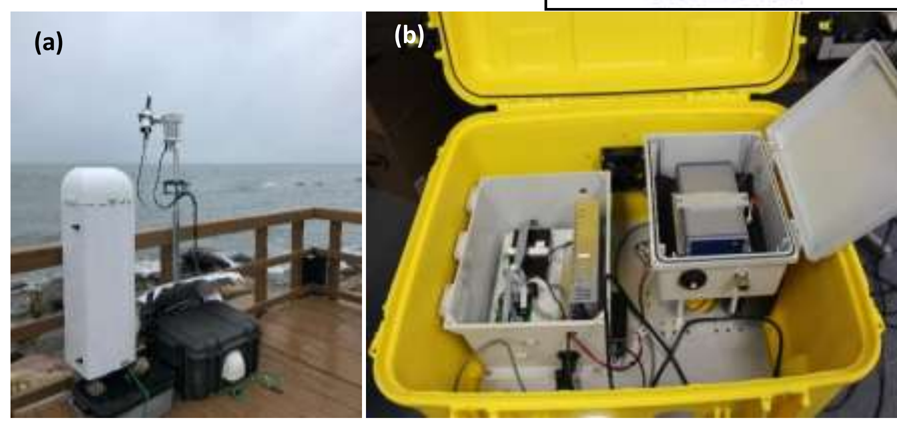
Pandora Spectrometers fill a critical measurement gap for column trace gases

Pandora Ground-Based Spectrometer

- System developed at NASA Goddard by Herman, Cede, and Abuhassan with a focus on satellite validation. Supported and maintained by NASA and ESA.
- Ground-based direct sun/moon & sky scanning remote sensing for air quality and atmospheric composition (1S - ~270 – 530 nm, 0.6 nm; 2S – 400 – 900 nm, 1 nm) provides slant column measurements.
- NRT Standard Operational Products at high frequency (~ 2 mins): Total Column Ozone (+/-15 DU, ~5%); Total Column NO2 (+/-0.05 DU, ~10%) **Optimistically awaiting total column formaldehyde**
- Research products: HCHO column, SO2 column & near surface NO2
- Successfully deployed for multiple field campaigns (e.g. DISCOVER-AQ, KORUS-AQ, LMOS and OWLETS) as well as long-term monitoring.

June 2019 AWMA EM Article →


Pandora
Connecting in-situ and Satellite Monitoring in Support of the Canada–U.S. Air Quality Agreement



Pandora Pictures: (a) enhanced sun tracker; Pan55 deployment at FWS Outer Island in LIS (b) redesigned integrated layout

Recent Pandora Spectrometer Instrument Upgrades

- Enhanced Sun Tracker – Improved reliability, pointing accuracy and greater movement capability
- Replacement of Delrin parts in sensor heads with HCHO free material
- Update to neutral density filters to prevent saturation of signal for impacted UV retrievals
- Enhancements to Blick-O, system main operating software
- Fiber guides added to sensor head to reduce fiber movement/bending, improve stability of signal

Rutgers, NJDEP PAMS site - September 2019

A ESA-US collaboration – Merging validation and surface AQ monitoring networks in USA

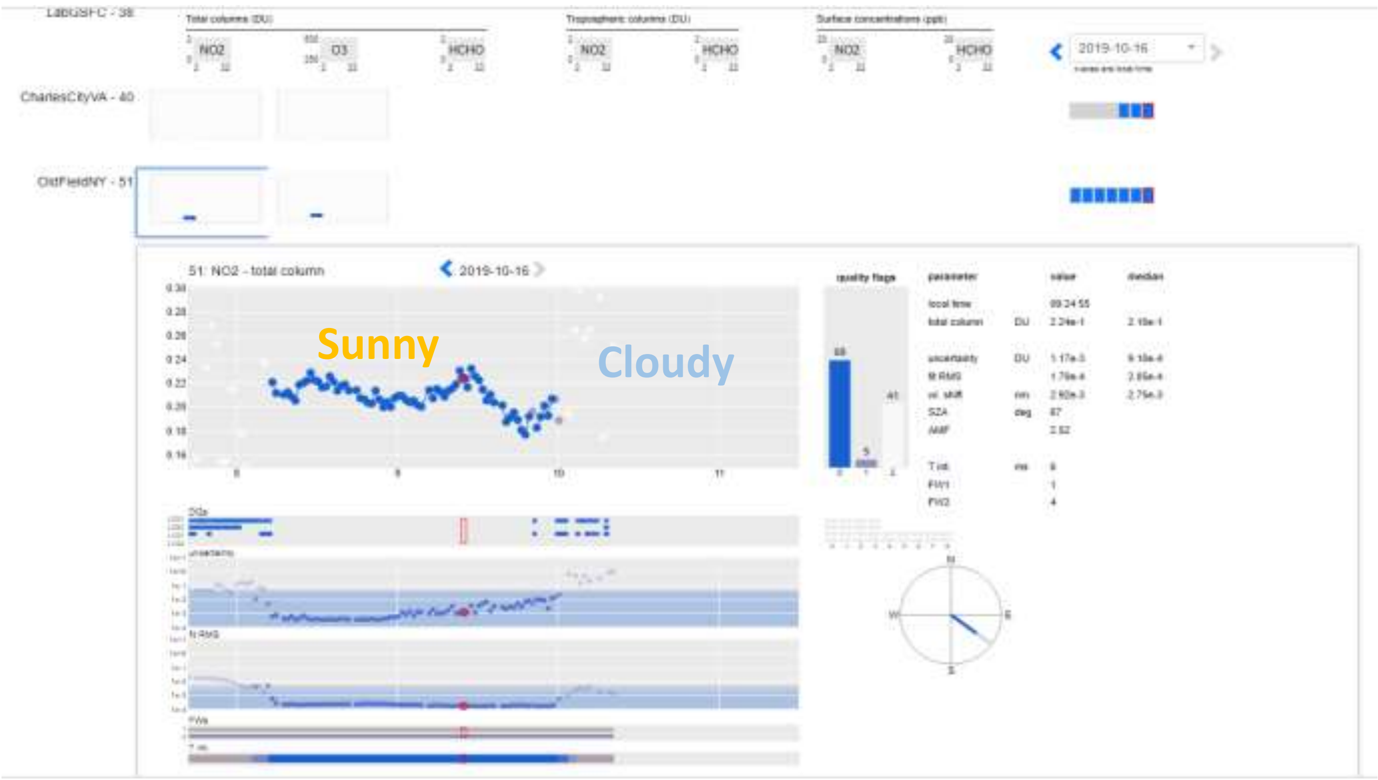
EPA/NASA/ESA Collaboration: TROPOMI L2 Validation in the U.S. Mid-Atlantic Region; An Expanded Ground Validation Network for S5P Validation. (**ESA Proposal ID 28695**)

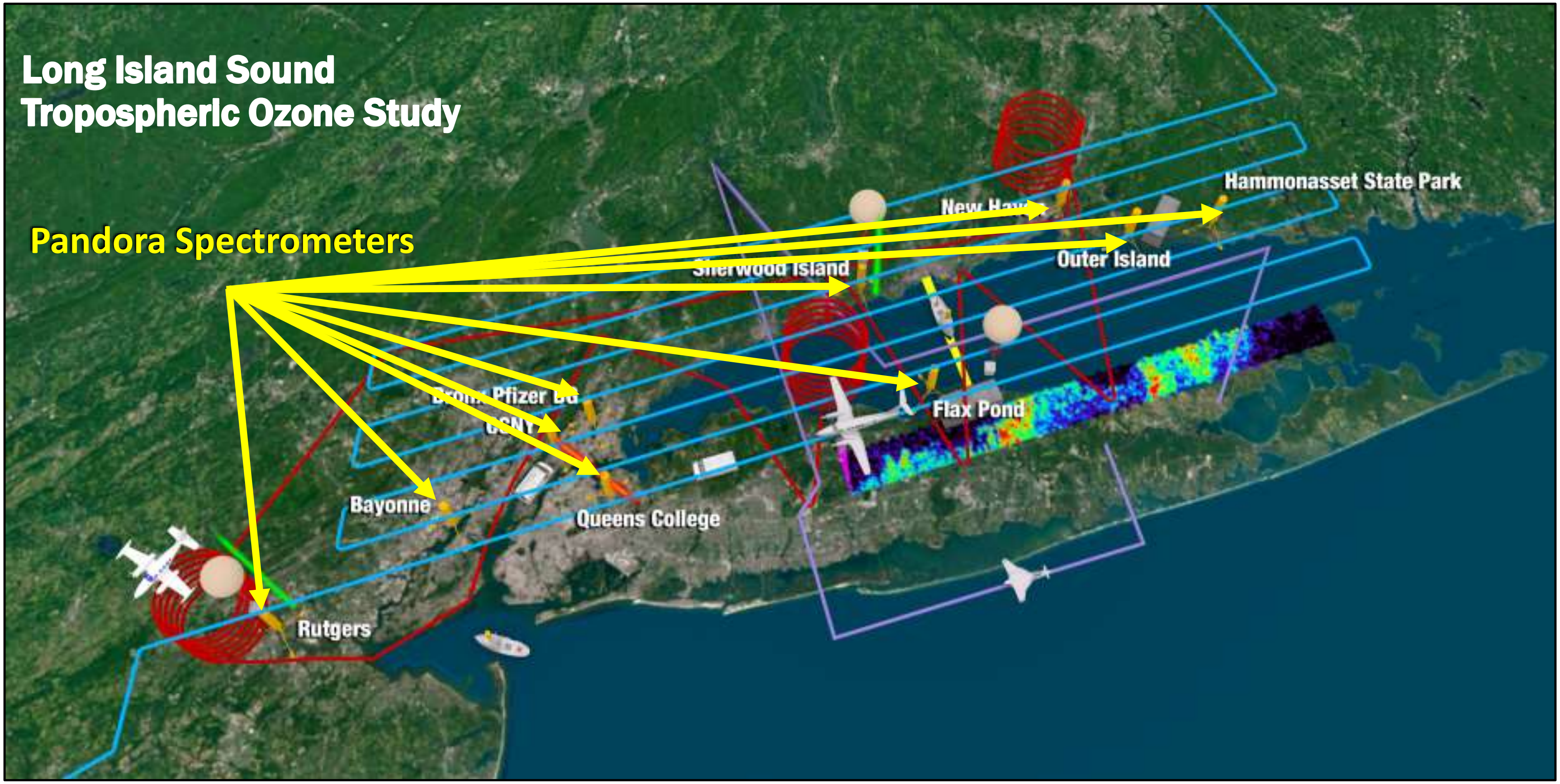
Global distribution of validation instruments as of October 2018

EPA and NASA are integrating validation resources as part of PAMS Enhanced Monitoring Plans at select sites across USA->

Pandora at Flax Pond PAMS site, N. Shore of Long Island
Screenshot captured at 10:30 AM on 2019-10-16

- Up-to-the-minute (almost) data products, QA data and data visualization will soon be publicly available



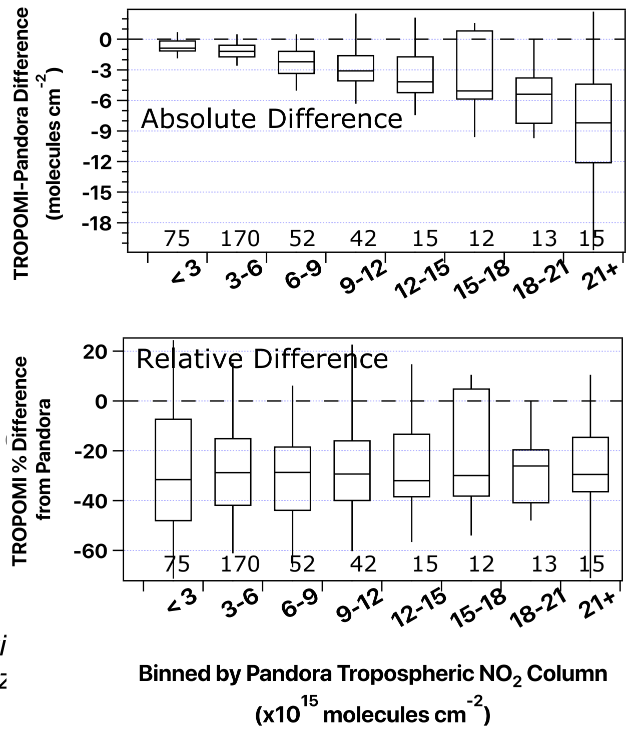

Long Island Sound
Tropospheric Ozone Study
Pandora Spectrometers
Hammonasset State Park
Outer Island
Sherwood Island
Pfizer
Flax Pond
Bayonne
Queens College
Rutgers

TROPOMI Comparisons to PAMS-EMP Pandoras in PGN Network

TROPOMI RPRO/OFFL v1.2.2, v1.3 : 25 June 2018-25 June 2019

TROPOMI Tropospheric NO_2 Column (molecules cm^{-2})

50x1



Verti
Horiz

Queens
Bronx
Bayonne
Flax Pond
Westport
New Haven
Rutgers
Madison
Branford

Coincidence criteria

- *Median Pandora column within ±60 minutes of the TROPOMI measurement that encompasses the site*
- *Site-based offset applied to ensure a common baseline to do aggregate statistics*

The Pandora and TROPOMI are highly correlated with a consistent low bias of ~30% in relation to Pandora.

- *Very similar for other possible temporal windows applied to Pandora data.*

Least polluted bin has median percent difference -0.8×10^{15} molecules cm^{-2} of an interquartile range < 1×10^{15} molecules cm^{-2}

Source: Laura Judd, NASA LaRC

Geostationary Carbon Cycle Observatory (GeoCarb)

GeoCarb Products:

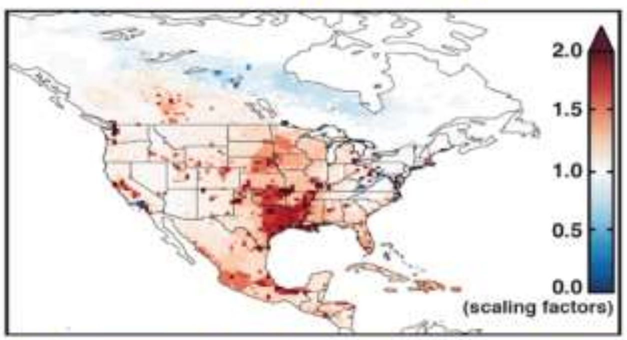
Geostationary measurements of North, Central, South America showing column CO_2, CH_4, CO and Solar Induced Fluorescence (SIF).

GeoCarb accuracy:
0.6% for CH_4 , 0.3% for CO_2 , and 10% for CO

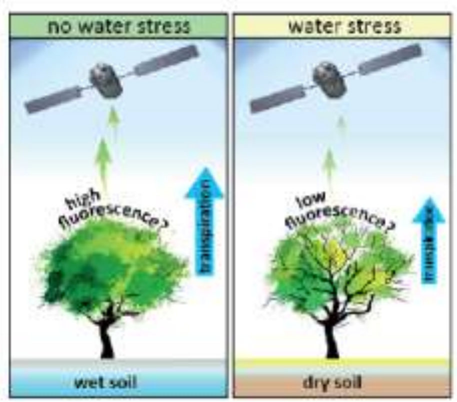
3km x 6km pixel size

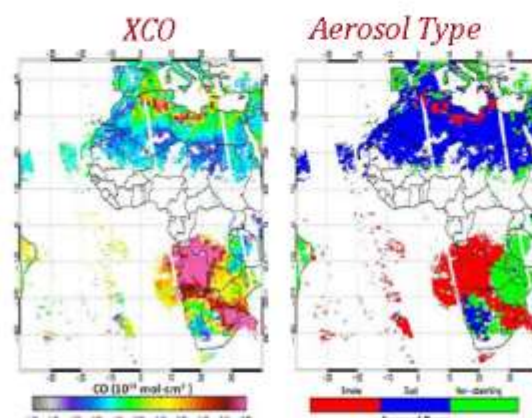
Launch: 2022.

Correction factors for North America



- CONUS anthropogenic emission of 40-43 Tg a^{-1} vs. EPA value of 27 Tg a^{-1}
- Is the underestimate in livestock or oil/gas emissions or both?

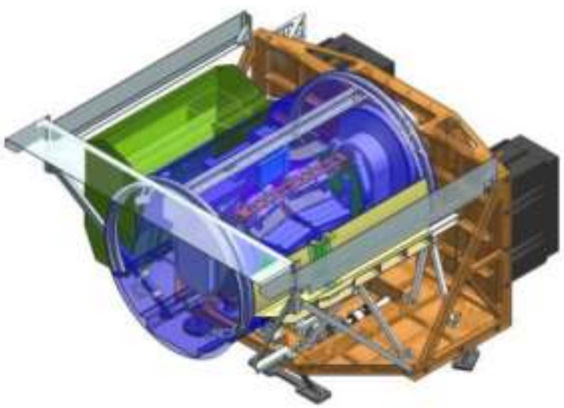




Multi-Angle Imager for Aerosols (MAIA)

- MAIA's objective is to assess the impacts of different size/compositional mixtures of airborne particulate matter (PM) on adverse birth outcomes, premature deaths, and cardiovascular/respiratory disease.

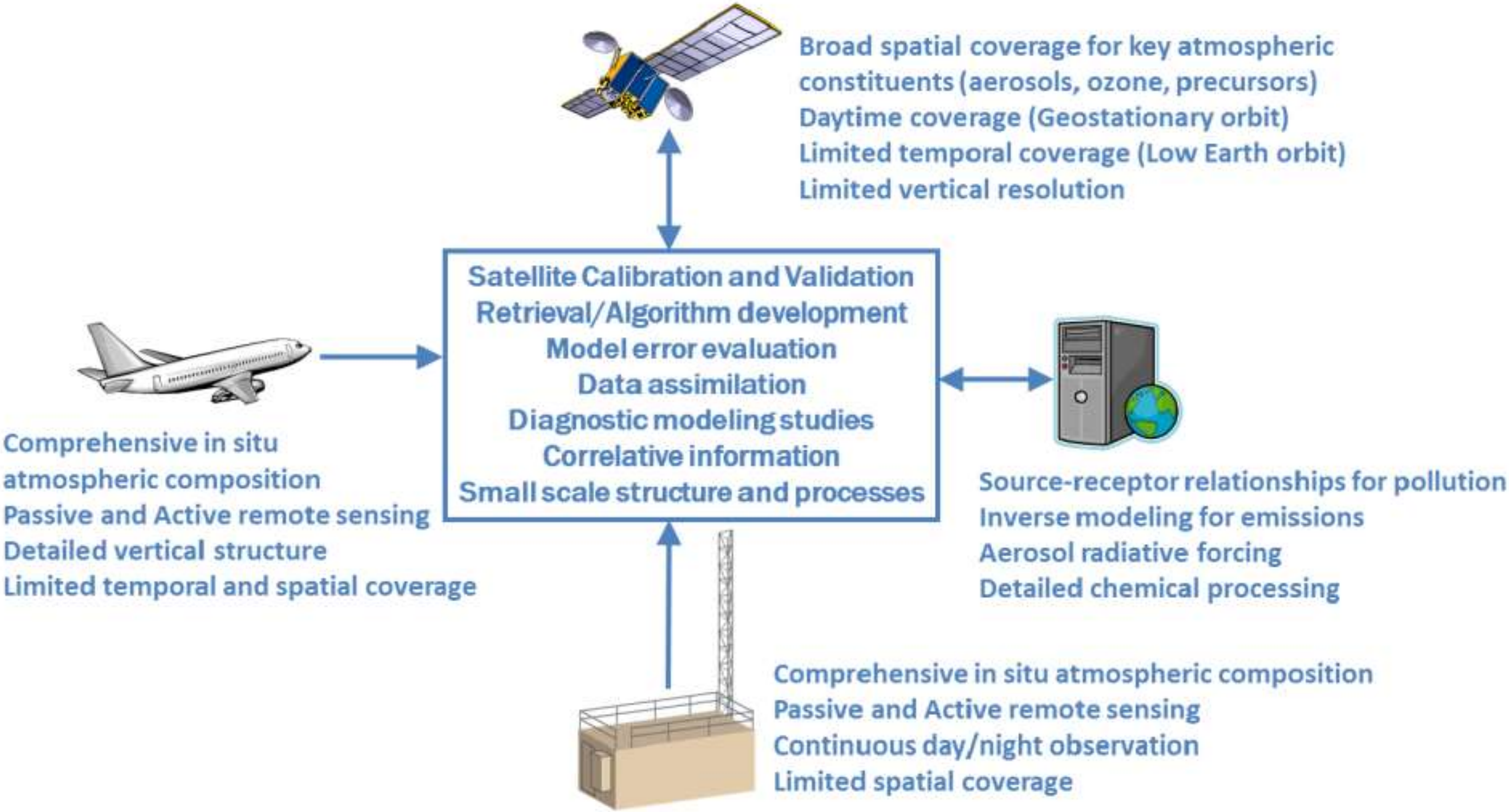
The investigation integrates chemical transport model, surface monitor, and satellite instrument data to map speciated PM at ~1 km scale.



- The MAIA instrument is being built at JPL
  - UV/VNIR/SWIR spectropolarimetric imager on a 2-axis gimbal to routinely observe a set of globally-distributed cities (e.g., Boston, Atlanta, LA, Rome, Tel Aviv, Johannesburg, Taipei, Delhi, Beijing)
- Launch into polar orbit (~2021, 3-year mission)
- Data products include aerosol optical depth, PM_{10}, $PM_{2.5}$, and $PM_{2.5}$ for sulfates, nitrates, black carbon, organic carbon, dust

- Epidemiologists on the MAIA team will use birth, death, and hospital records to associate PM exposure with human health impacts.

Field campaigns and the Integrated Observing System for Air Quality

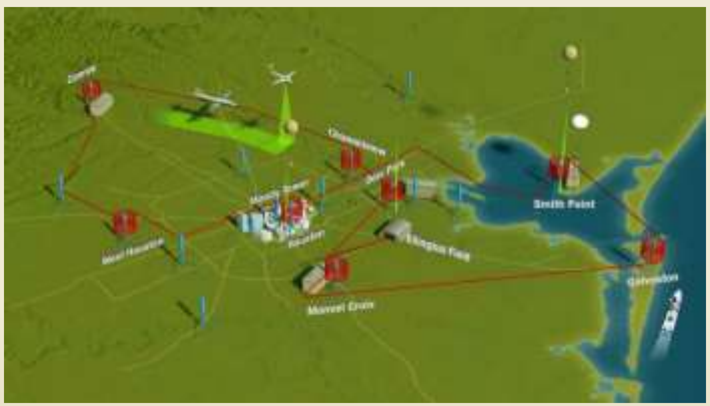


Source: Jim Crawford

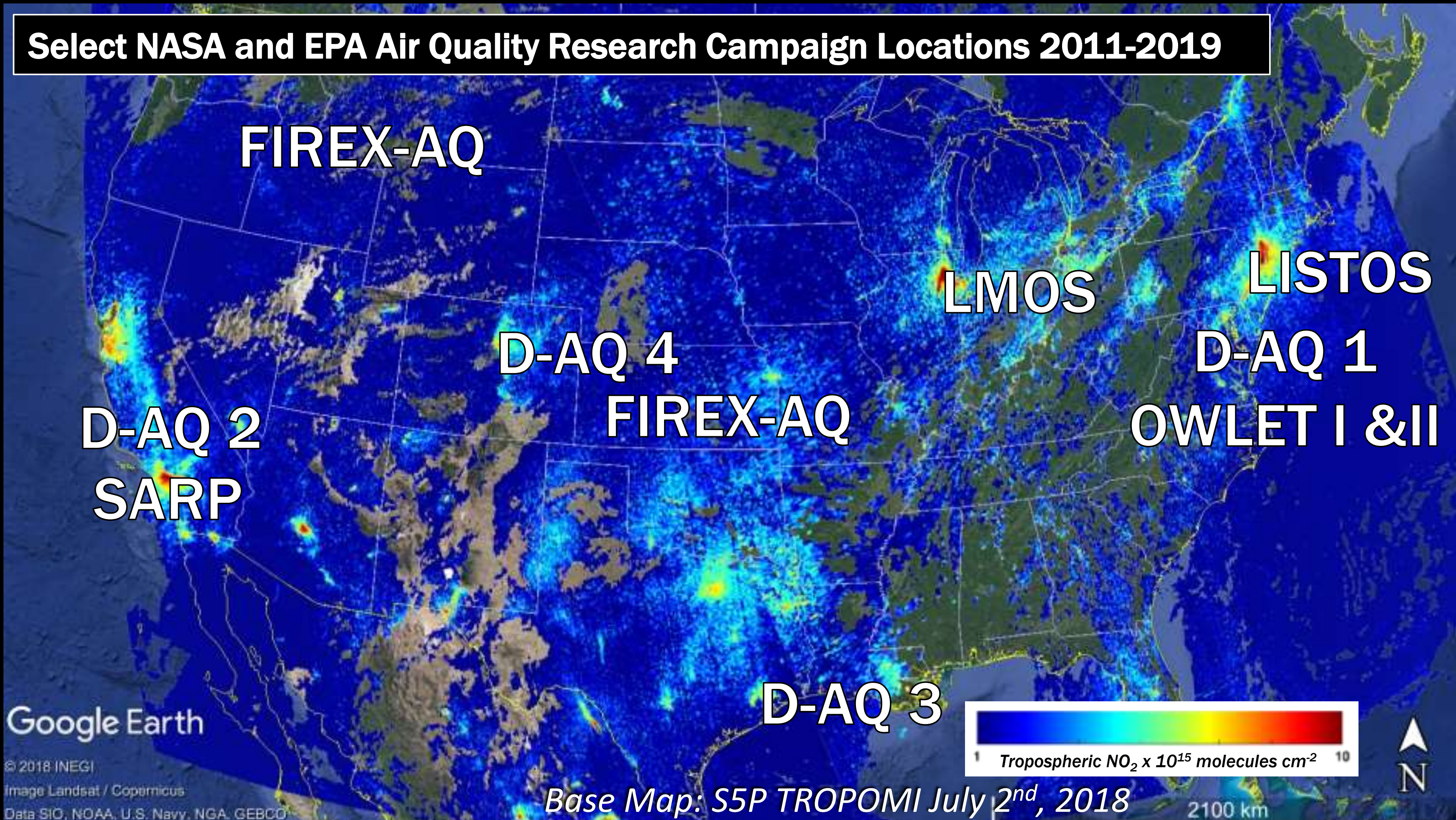
DISCOVER-AQ Ushering in a New Approach to Air Quality Field Campaigns

Systematic and concurrent observation of column-integrated, surface, and vertically-resolved distributions of aerosols and trace gases relevant to air quality as they evolve throughout the day.

San Joaquin Valley, CA – Jan/Feb 2013
Houston, TX – September -2013
Denver, CO – Jul/Aug 2014



Maryland, July 2011


Select NASA and EPA Air Quality Research Campaign Locations 2011-2019
FIREX-AQ
LMOS
LISTOS
D-AQ 4
D-AQ 1
FIREX-AQ
D-AQ 2
OWLET I &II
SARP
D-AQ 3
Google Earth
© 2018 INEGI
Image Landsat / Copernicus
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
1
Tropospheric NO_2 x 10^{15} molecules cm^{-2}
10
N
Base Map: S5P TROPOMI July 2nd, 2018
2100 km

Synchronized Multi-Day Ozone Lidar Measurements in Support of the OWLETS-2 and LISTOS

John Sullivan, T. Berkoff, G. Gronoff, T. McGee, G. Sumnicht, L. Twigg, W. Carrion, J. Sparrow

Science Questions:

- **What are the mechanisms (low boundary layer, chemistry, weather) that produce high ozone over the Chesapeake Bay and Long Island Sound?** ***The synergy of TOLNet lidars, balloon-borne, and surface measurements at during OWLETS-2 and LISTOS directly revealed differences in controlling factors related to air quality episodes***

- **How can measurements be better utilized (in conjunction with chemical transport models) to connect ground level pollutants to satellites in the upcoming framework of the NASA TEMPO instrument?** ***Repeated high-resolution TOLNet measurements under a variety of atmospheric conditions will help provide the atmospheric science community with the tools to better evaluate chemical transport models that will feed into TEMPO a priori.***

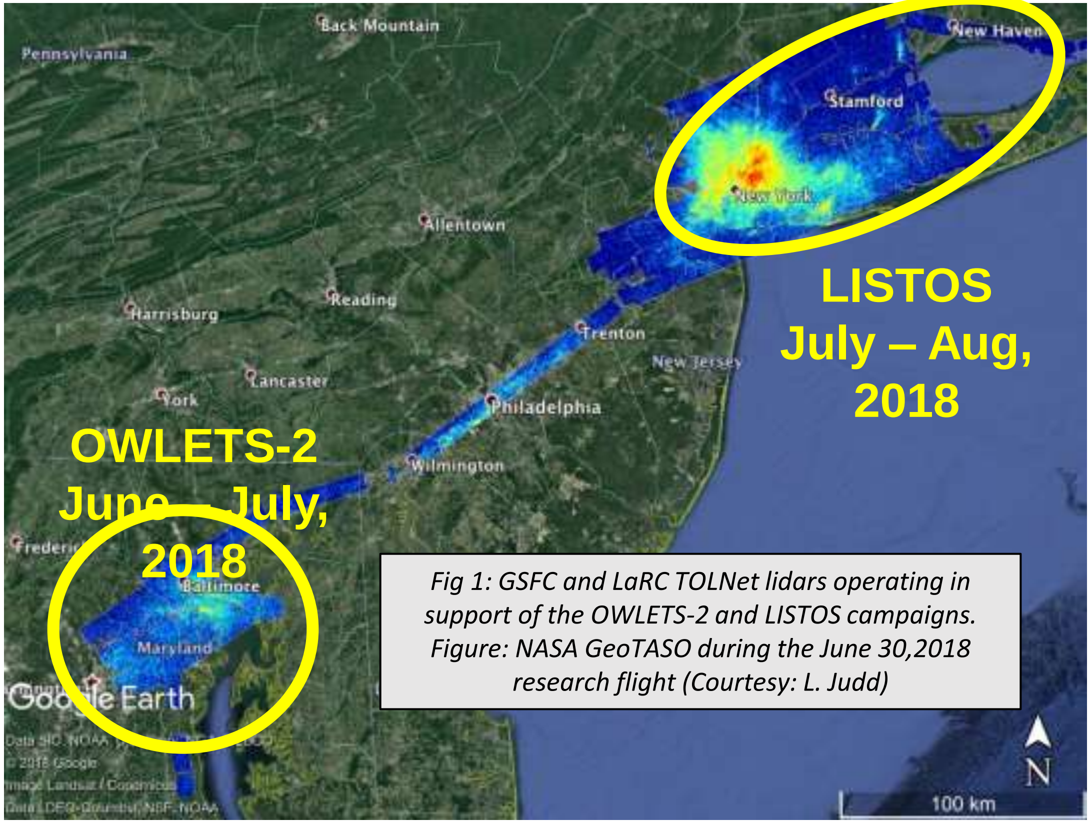


Fig 1: GSFC and LaRC TOLNet lidars operating in support of the OWLETS-2 and LISTOS campaigns. Figure: NASA GeoTASO during the June 30,2018 research flight (Courtesy: L. Judd)

Synchronized Multi-Day Ozone Lidar Measurements in Support of the OWLETS-2 and LISTOS

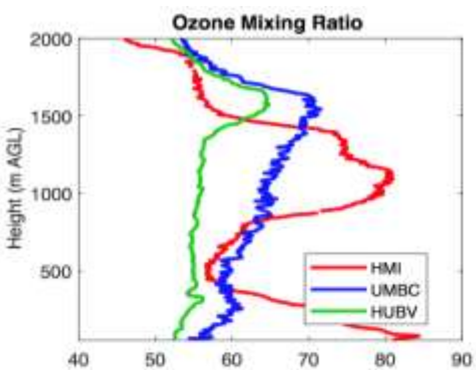
John Sullivan, T. Berkoff, G. Gronoff, T. McGee,
G. Sumnicht, L. Twigg, W. Carrion, J. Sparrow

Background:

•**OWLETS-2** is a follow-on study to better understand the behavior of ozone and related trace gases across the water land transition zone in the upper portion of the Chesapeake Bay

– ***Fig 1: 4 days of continuous TOLNet measurements from Hart Miller Island (HMI) and University of Maryland, Baltimore County (UMBC)***

•At coastal boundaries, significant water-land gradients can occur due to difference in surface deposition, boundary layer height, and cloud coverage from water to land



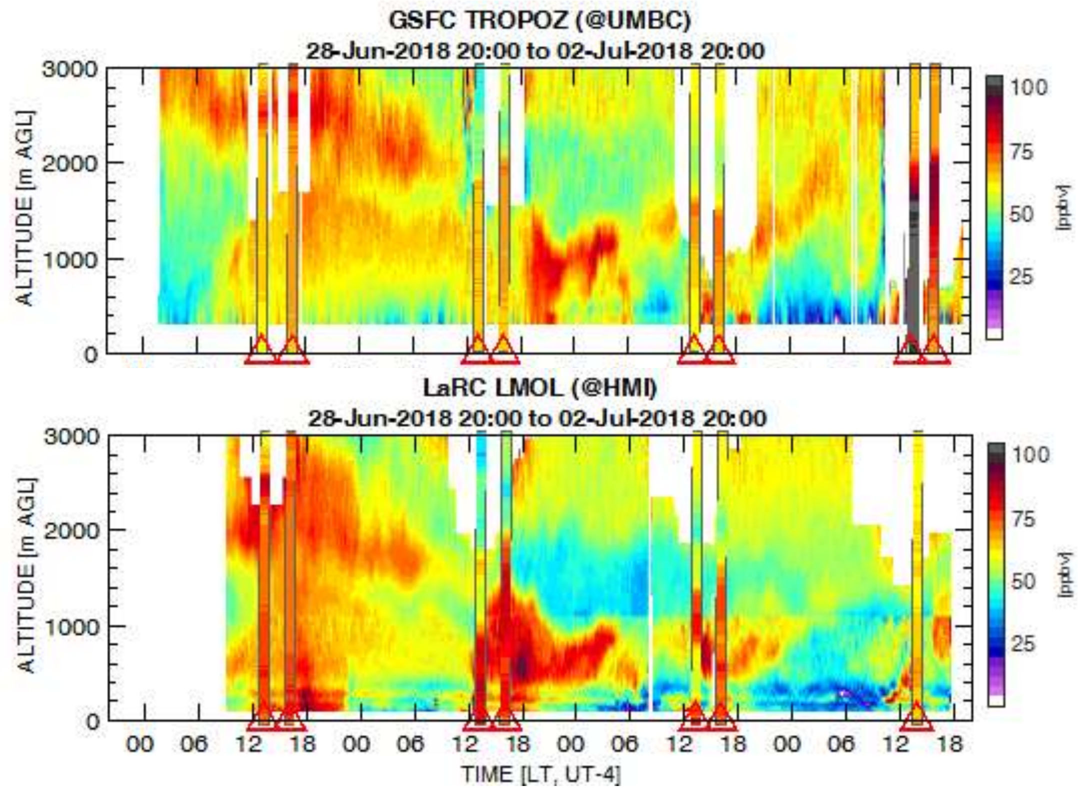
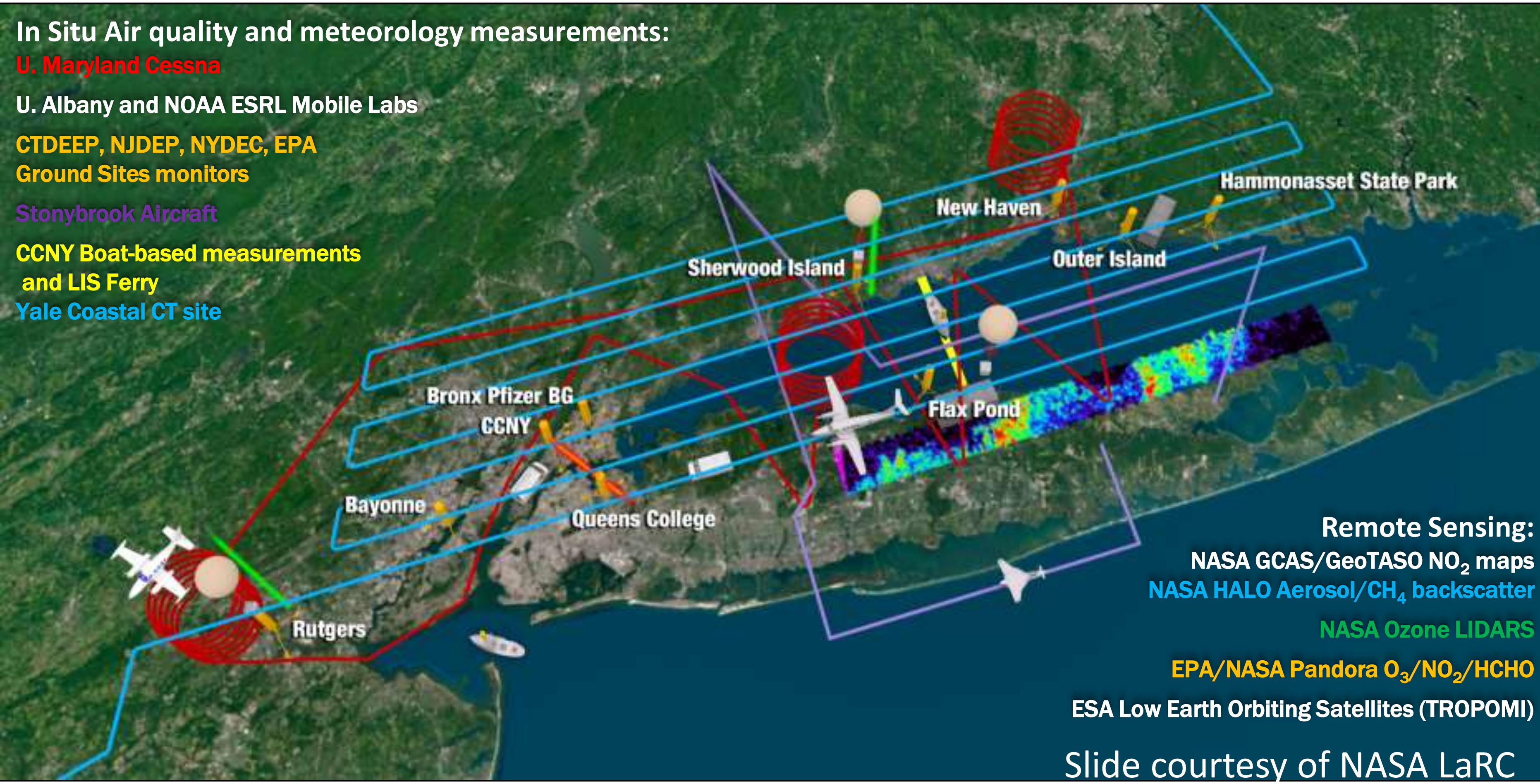


Fig 1: (left) Simultaneous ozonesondes launches at multiple sites during OWLETS-2
Fig 2: (right): GSFC and LaRC TOLNet lidars operating continuously for 4 days during OWLETS-2 campaign.

Mockup of the Integrated Observing Strategy for LISTOS



Airborne Mapping Spectrometers: LaRC/GSFC Partnership

Scott Janz, NASA GSFC Instrument PI; LaRC Aircraft and Science

GeoTASO

- <u>Geo</u>stationary <u>T</u>race gas and <u>A</u>erosol <u>S</u>ensor <u>O</u>ptimization
- Flown during all Studies
- UV-VIS
- Large—300+lbs

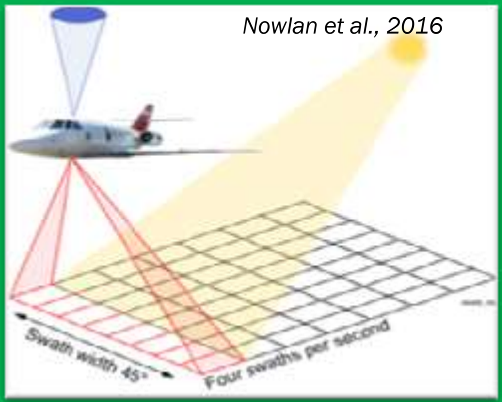
GCAS

- <u>GEOCAPE</u> <u>A</u>irborne <u>S</u>pectrometer
- Flown during LISTOS
- UV-VIS-NIR
- Small— ~100 lbs

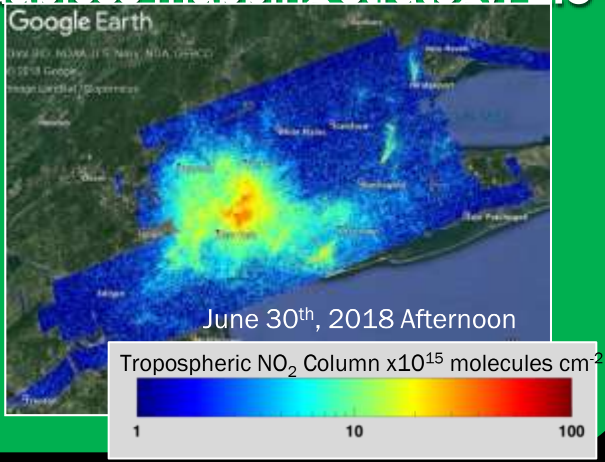
Used to improve and validate retrievals for future geostationary observations of air quality (e.g. TEMPO)

Both operate in a push-broom mode recording high spectral resolution visible spectra for NO_2 retrievals at ~250 x 250 m resolution

Also capable of retrieving HCHO



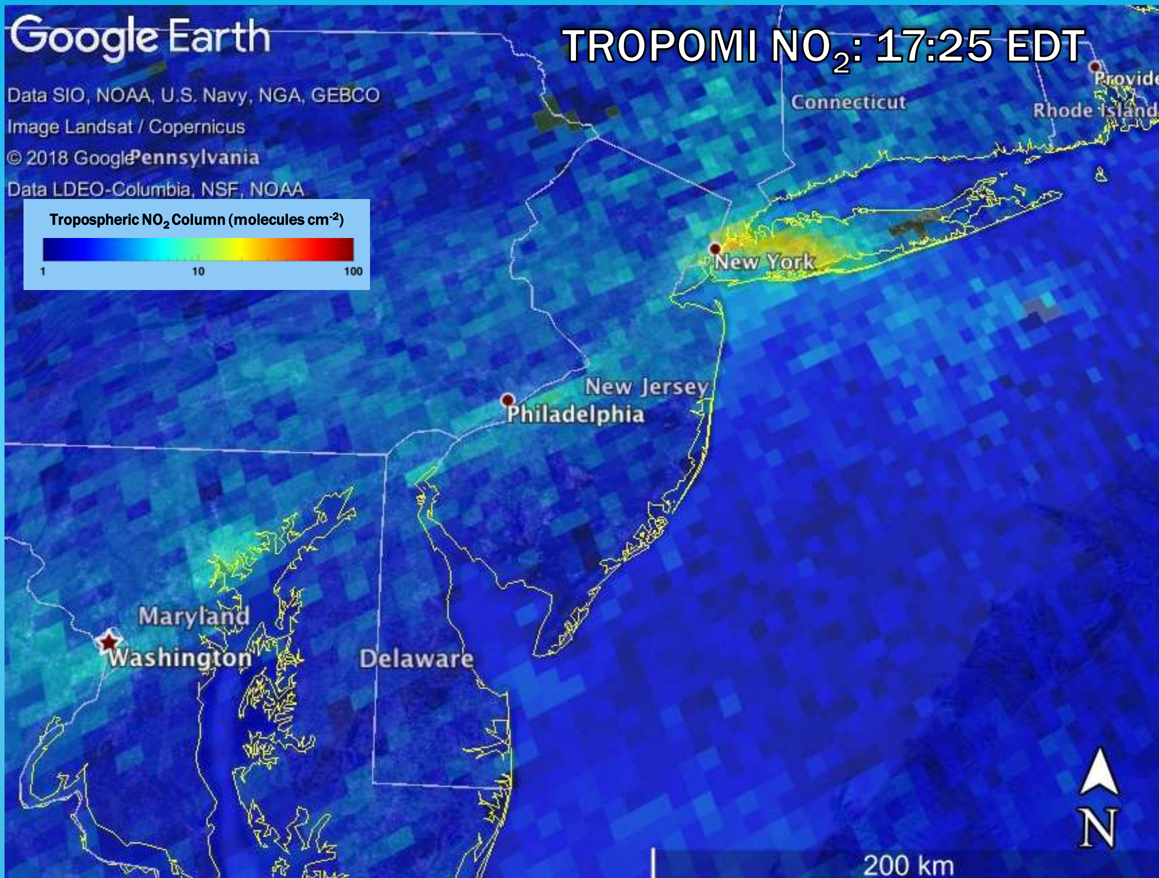
Gapless mapping strategy: 1.5-4



Source: Laura Judd, NASA LaRC

LIS O_3 Event: August 28th, 2018

Preliminary Results :



In the afternoon…

NASA's airborne spectrometer, GCAS, is able to pick up signatures from single point sources [e.g. powerplants, airports, traveling corridors]

3km NAM analysis from 17UTC highlights emissions extending downwind with a convergence zone along the CT Coast

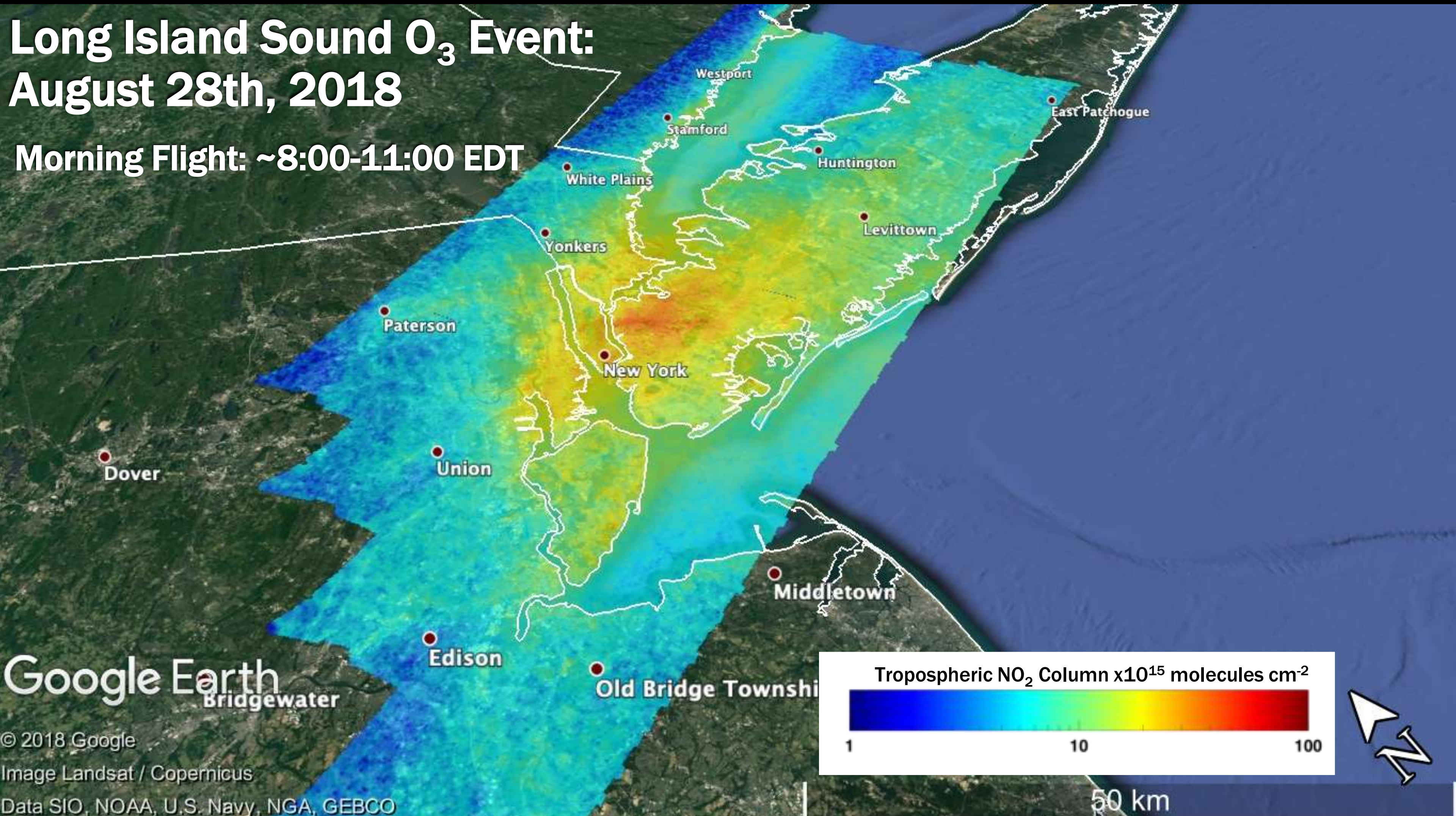
17:25 UTC overpass of TROPOMI correlates with the distribution of NO_2 observed by GCAS.

Regionally, TROPOMI shows enhanced NO_2 along the I95 corridor…
…with the highest values originating from **NYC**

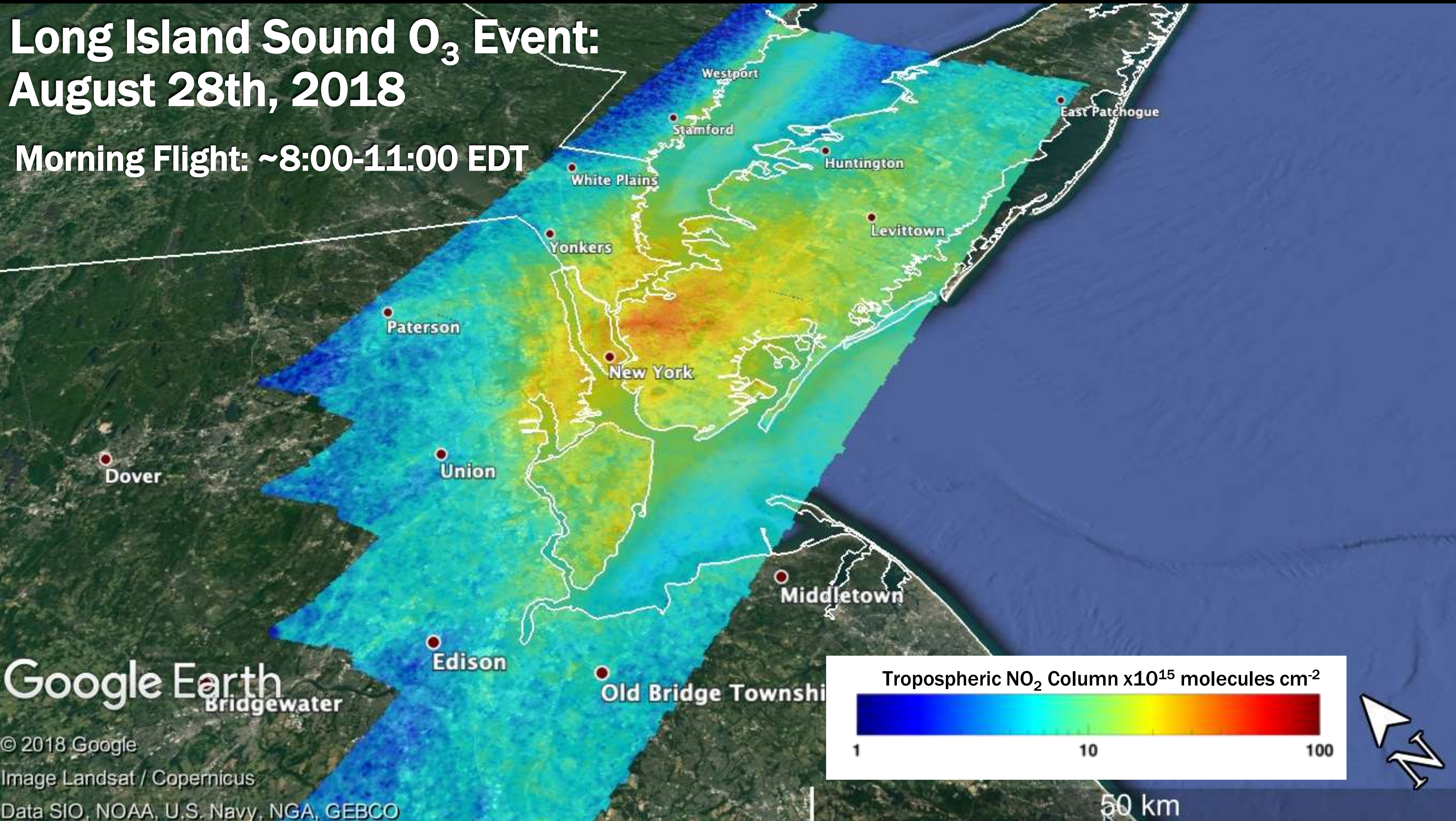
Source: Laura Judd, NASA LaRC

Long Island Sound O_3 Event: August 28th, 2018

Morning Flight: ~8:00-11:00 EDT



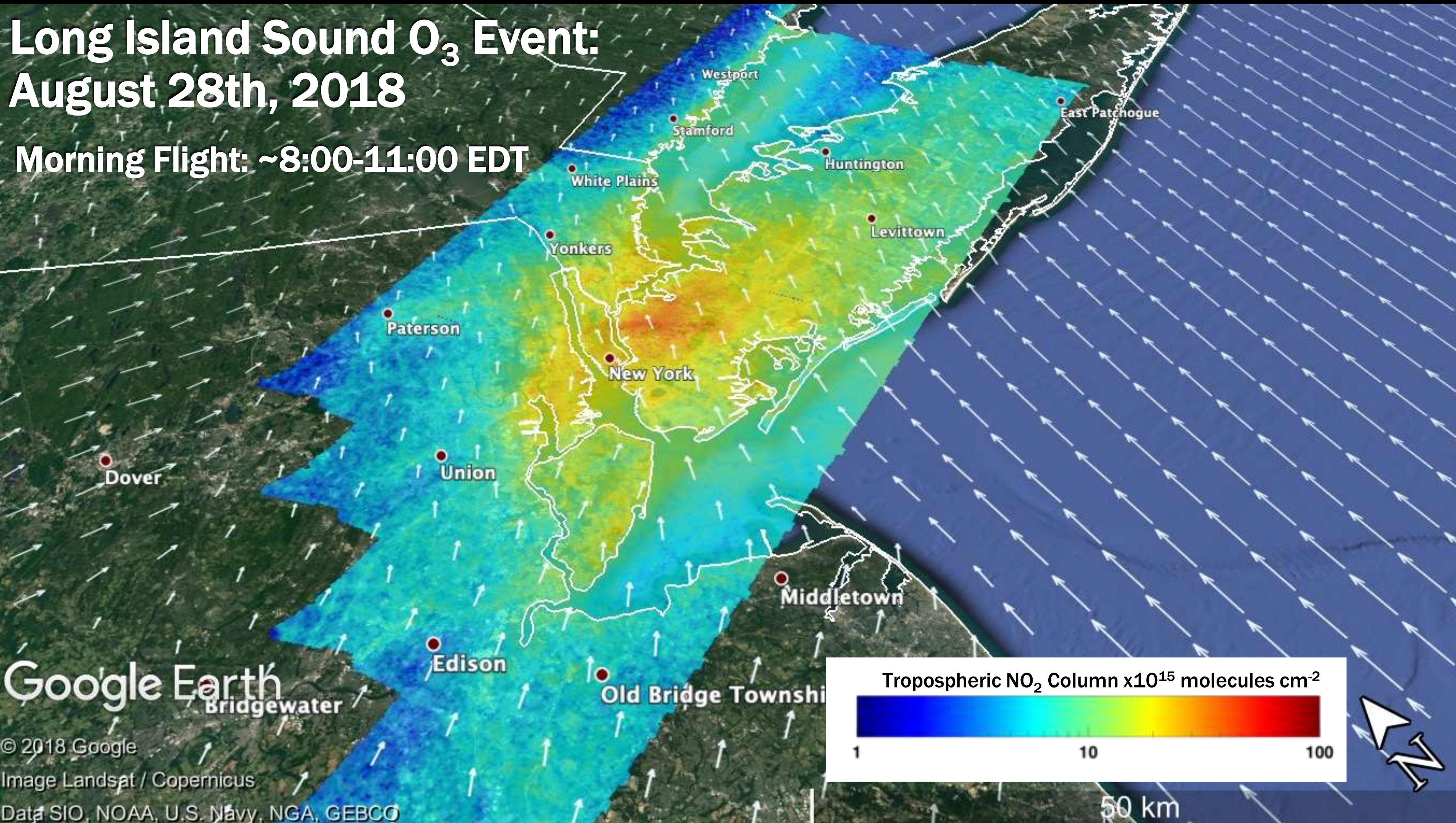
Source: Laura Judd, NASA LaRC



Source: Laura Judd, NASA LaRC

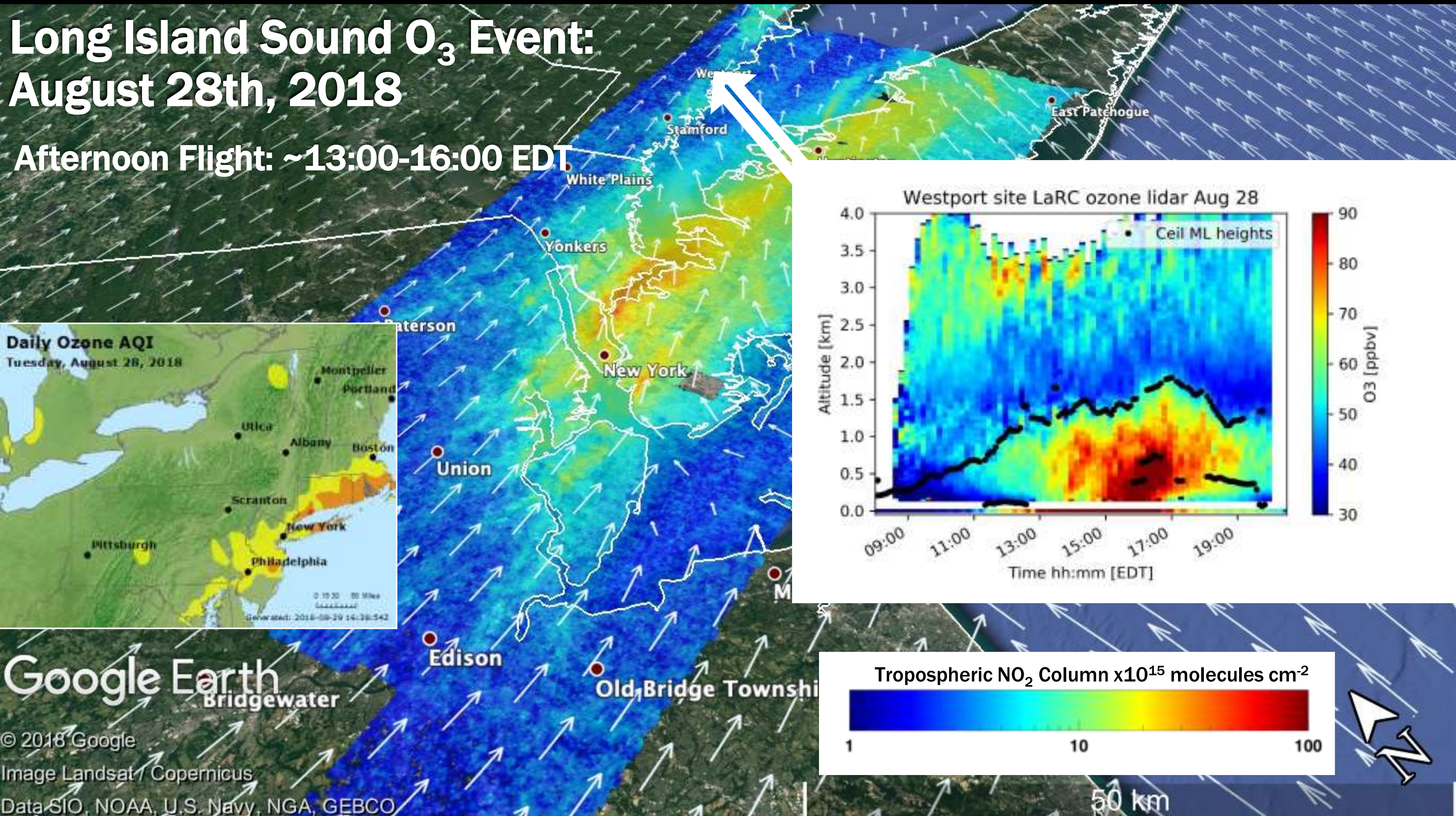
Long Island Sound O_3 Event: August 28th, 2018

Morning Flight: ~8:00-11:00 EDT



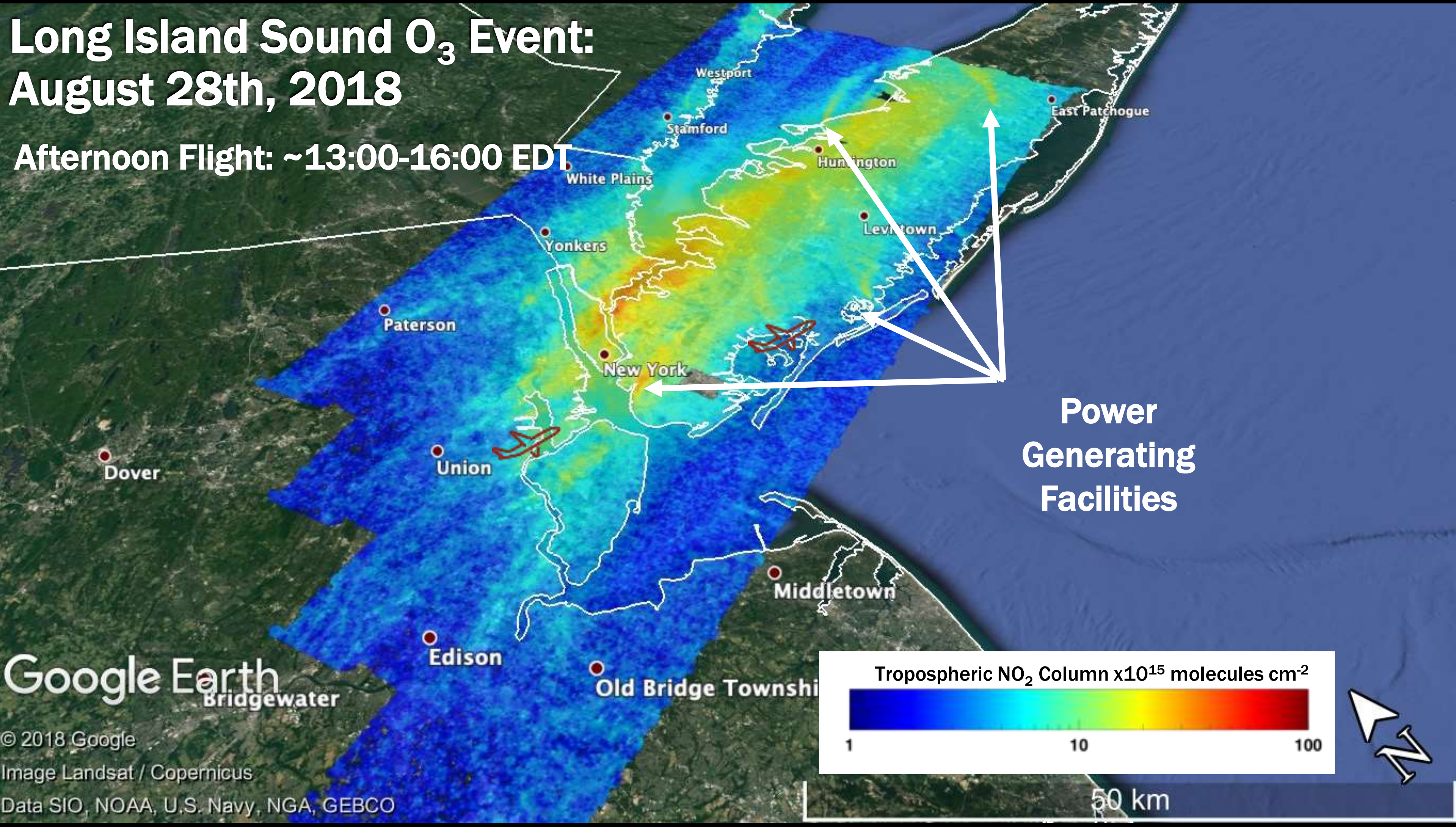
Long Island Sound O_3 Event: August 28th, 2018

Afternoon Flight: ~13:00-16:00 EDT



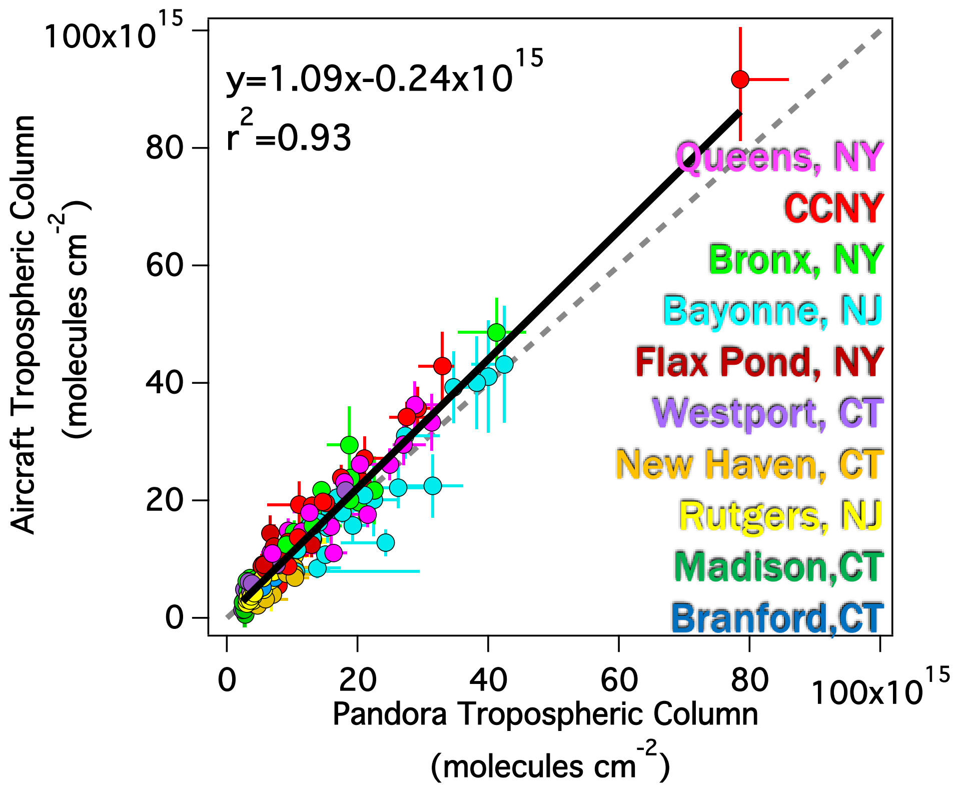
Long Island Sound O_3 Event: August 28th, 2018

Afternoon Flight: ~13:00-16:00 EDT



Source: Laura Judd, NASA LaRC

Comparison of GeoTASO and Pandora Tropospheric Column NO_2 Evaluating Variability Effects on Validation Measurements

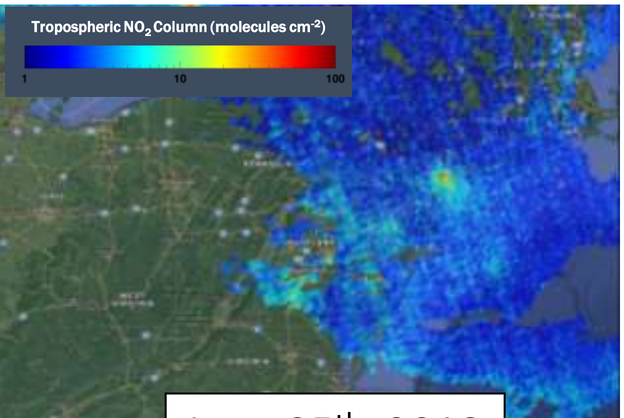


With over 200 coincidences with Pandora spectrometers, GCAS/GeoTASO vertical column observations are very well correlated.

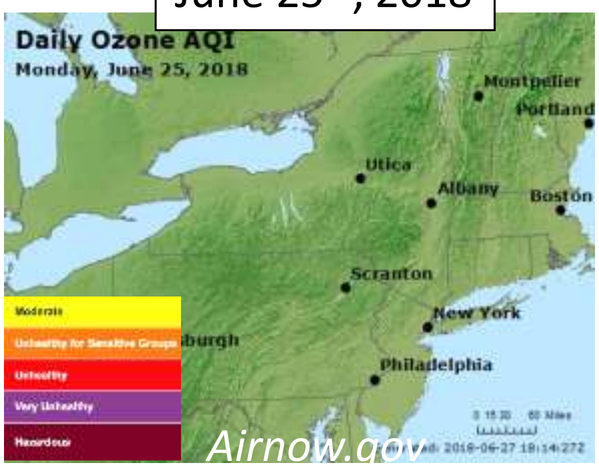
Much of the variability in this comparison is likely real spatiotemporal variability.

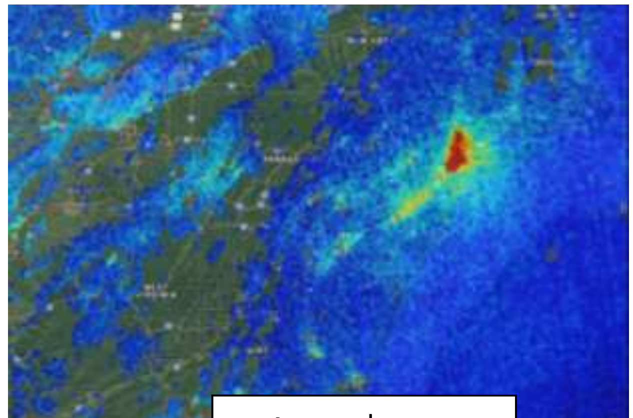
Source: Laura Judd, NASA LaRC

Connecting Air Quality from Space to Surface Air Quality: Examples from ESA TROPOMI NO_2 and EPA AirNow AQI

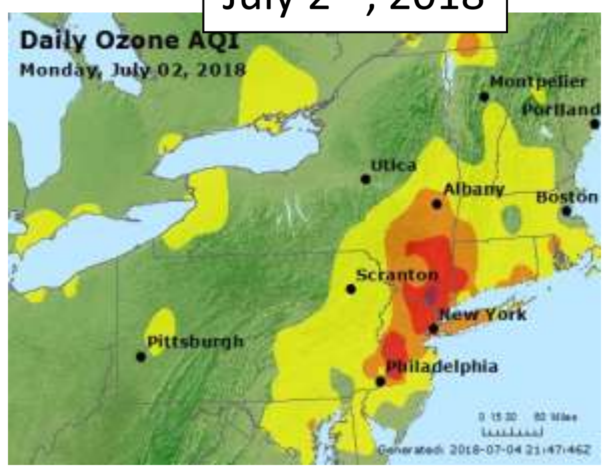


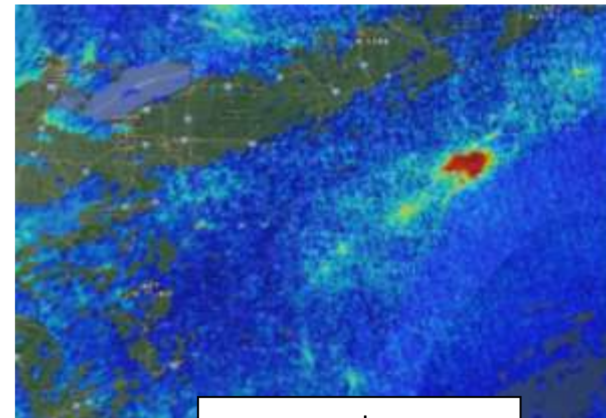
June 25th, 2018





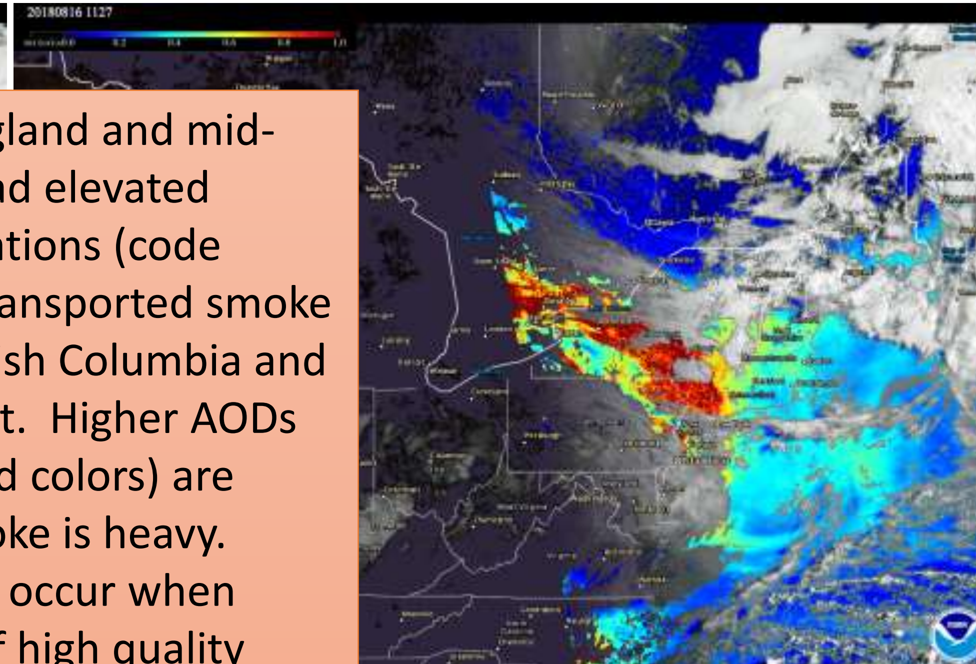
July 2nd, 2018





July 10th, 2018

GOES-16/ABI GeoColor and AOD: August 16, 2018 (11:42-16:12 UTC)



Philadelphia, PA		Daily $PM_{2.}$
Observed August 16		75 (Mode
August Climatology	Median	45 (Goo
	95th %ile	70 (Mode
Health Standard		100 (thresho

Parts of New England and mid-Atlantic states had elevated PM2.5 concentrations (code yellow) due to transported smoke from fires in British Columbia and Pacific Northwest. Higher AODs (shown in hot red colors) are areas where smoke is heavy. Gaps in AOD can occur when retrieval is not of high quality (e.g., adjacent to cloud etc.). GeoColor imagery provides additional guidance to forecasters where the smoke is and 5-minute refresh rate helps in observing its transport.

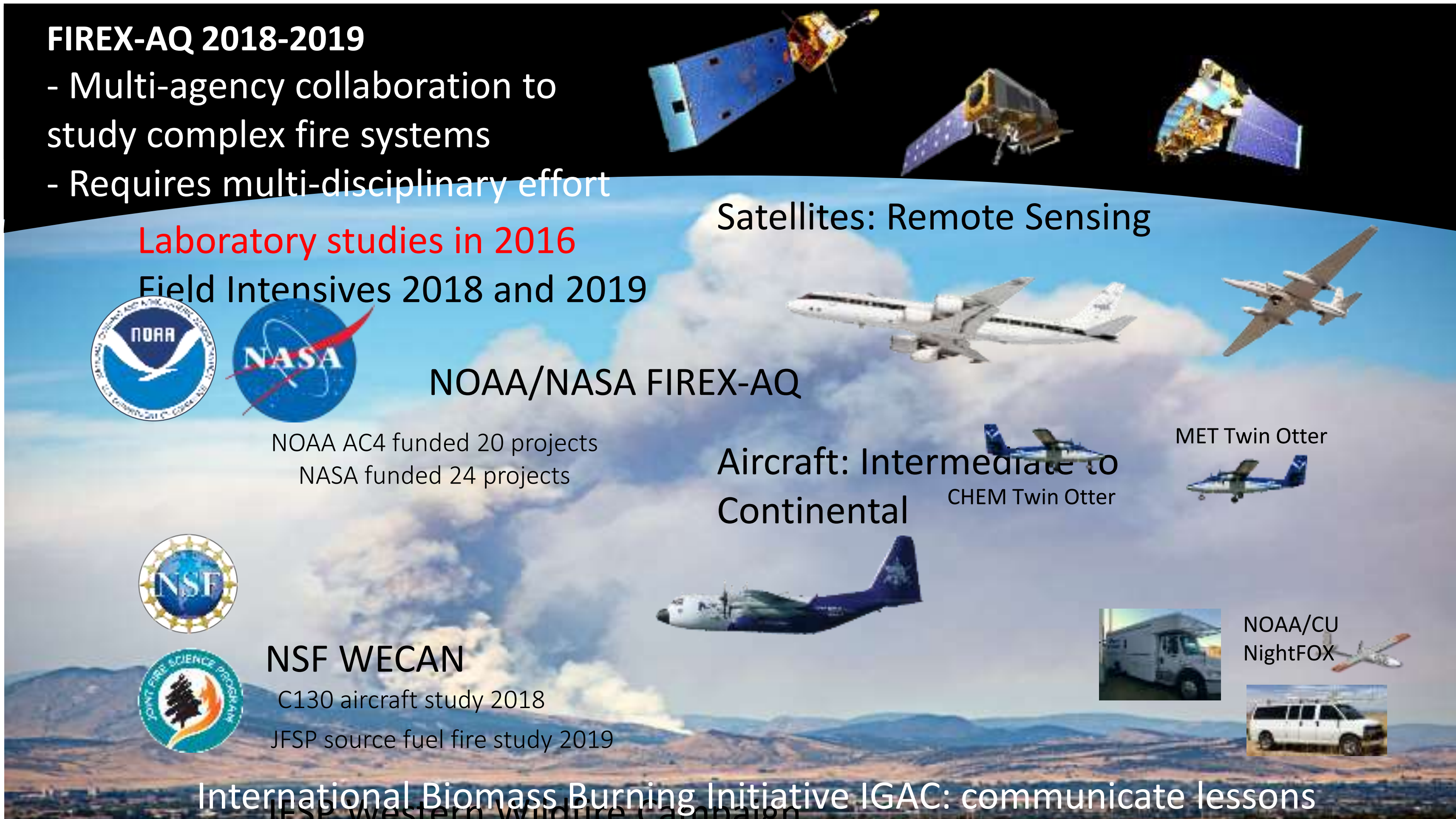
ornia's wildfires is reaching Washington

y **Jason Samenow**, Weather editor

ugust 16

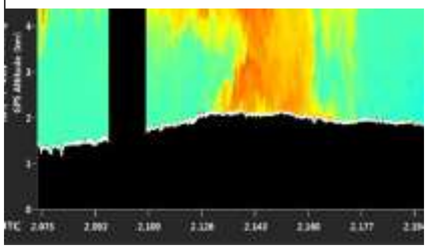
Source: Shobha Kondragunta, NOAA NESDIS

FIREX-AQ Coordinated Activities 2018-2019

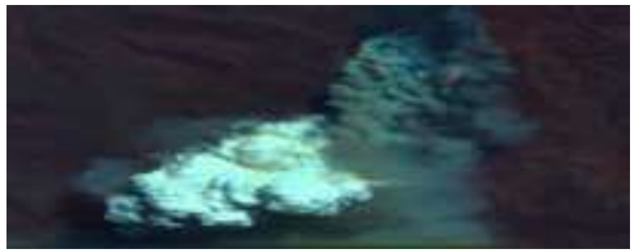


Mobile Ground Sites: Local

HSRL smoke distribution and properties

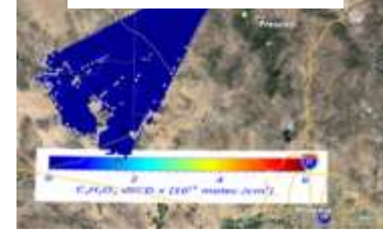


AirMSPI plume rise and optical properties

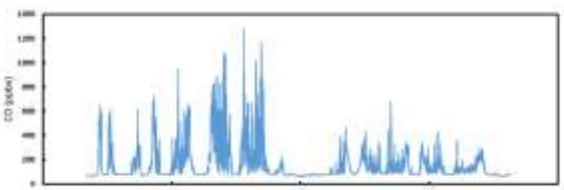


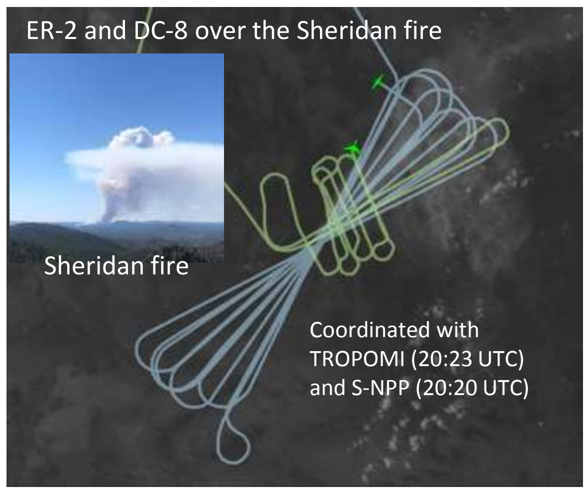
eMAS Fire Radiative Power

GCAS Trace Gas Remote Sensing



In situ CO for plume

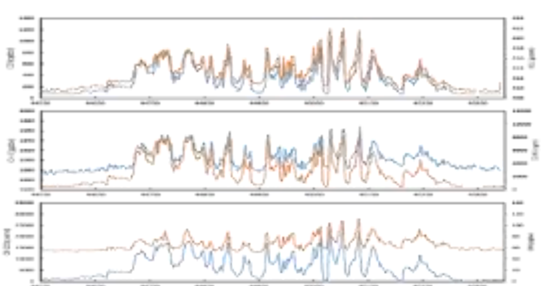




MASTER Fire Radiative Power

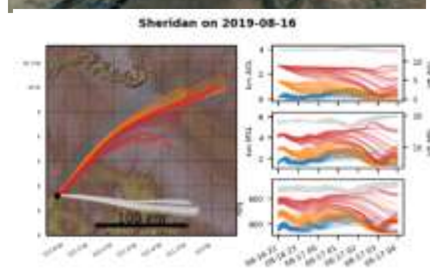
MODIS and VIIRS Active Fire Counts

In situ trace gases and aerosols for emission factors and chemistry

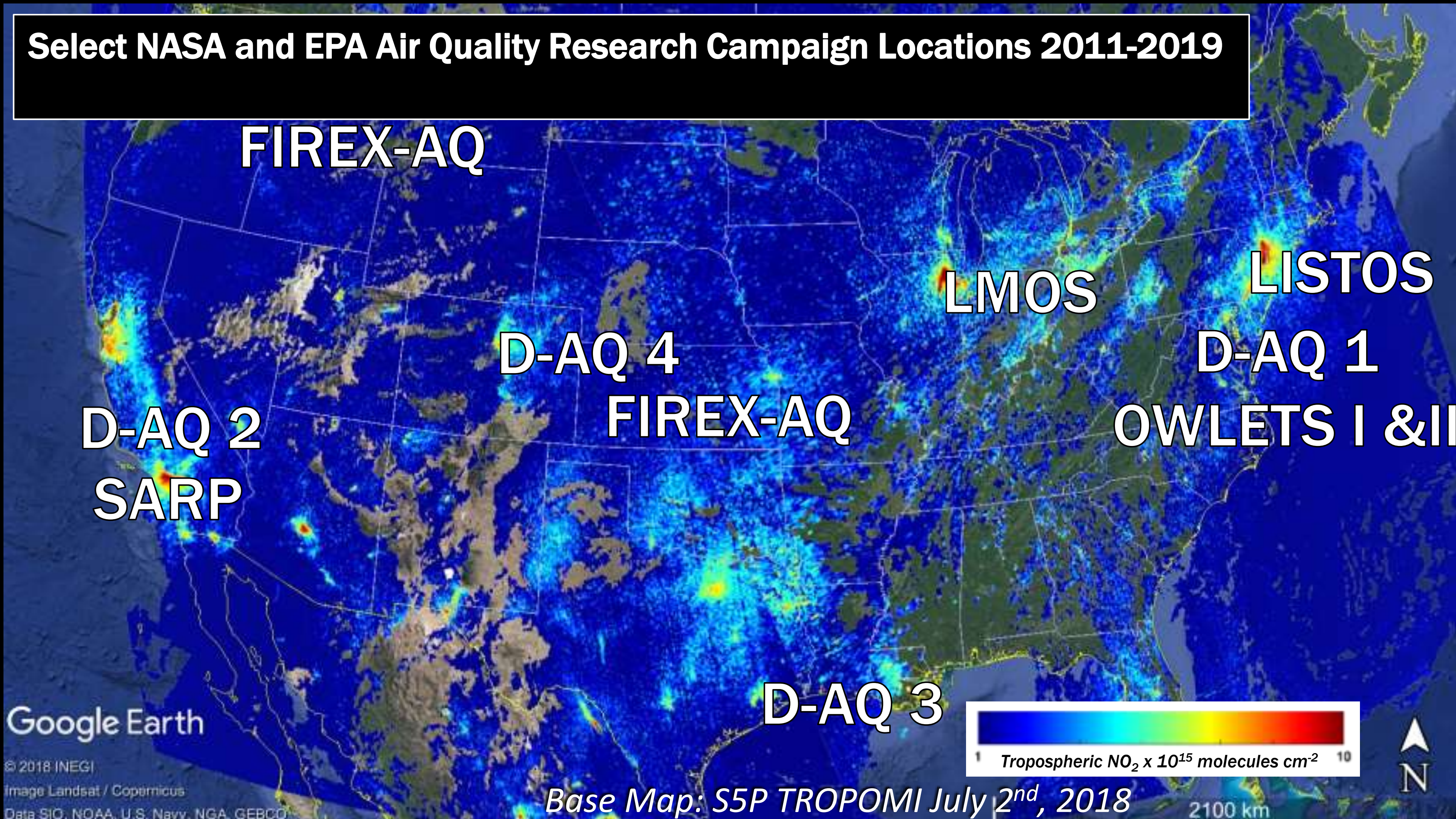


Integrated Observations of the Sheridan Fire

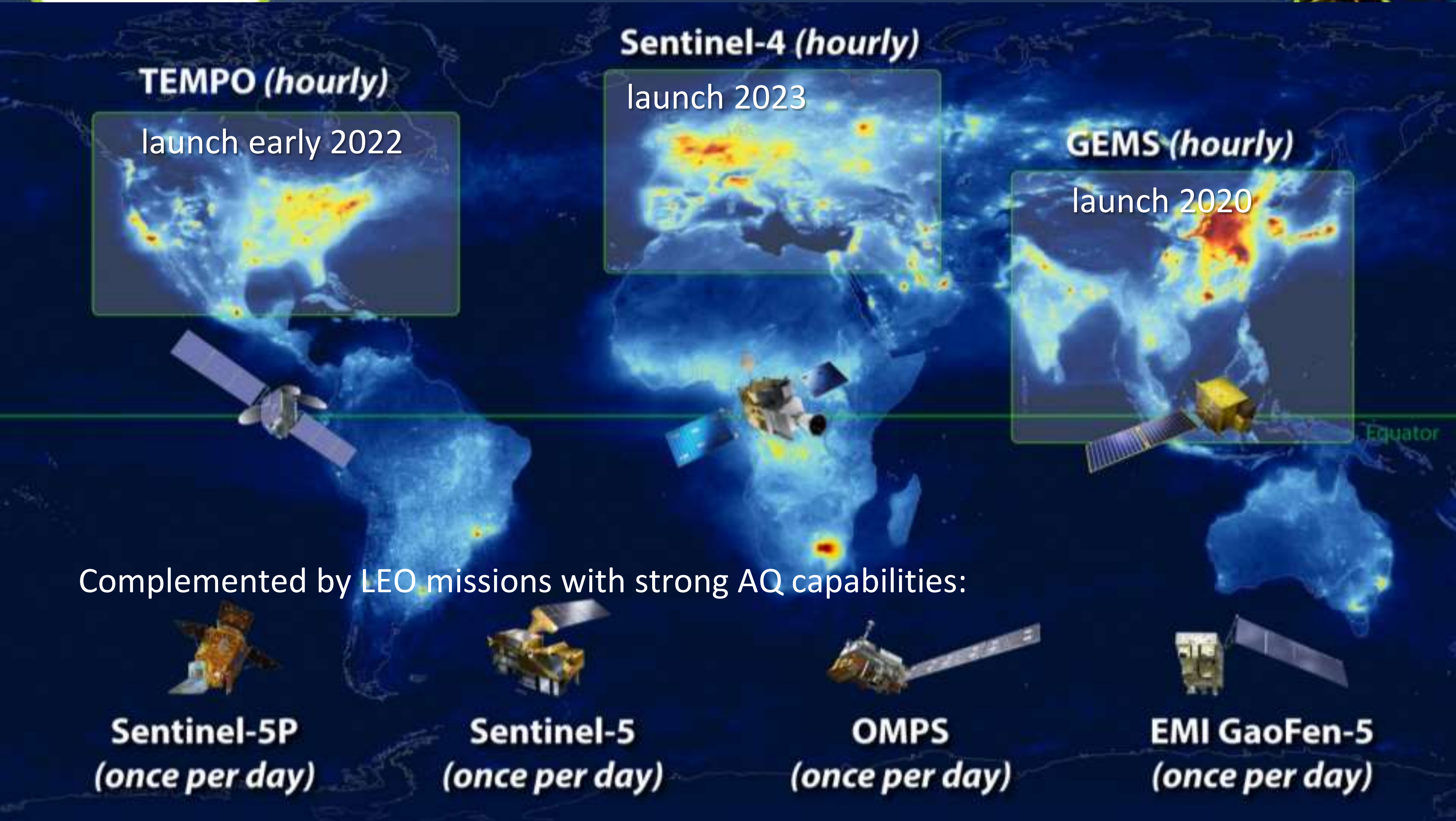
Plume transport forecast



State and Local Agencies resources (personnel and infrastructure) were critical to the success of these campaigns and serve as the anchor for the AQ Integrated Observing System



Geostationary Air Quality (Geo-AQ) Constellation: TEMPO + Sentinel-4 + GEMS



Graphic: NASA LaRC
NO_2 Image: KNMI/ESA

Space Agencies are actively coordinating under CEOS on the Atmospheric Composition Virtual Constellation and Air Quality Activities

- The Committee on Earth Observations Satellites (CEOS) developed the concept of virtual, space-based constellations in support of Group on Earth Observations objectives consistent with IGACO Theme report and as the space component of the Global Earth Observation System of Systems
    - A Virtual Constellation (VC) is a coordinated set of space and/or ground segment capabilities from different partners that focuses on observing a particular parameter or set of parameters of the Earth system
    - Best-efforts structure: CEOS VCs leverage inter-Agency collaboration and partnerships while maintaining the independence of individual CEOS Agency contributions
- In 2011, AC-VC members delivered a seminal white paper recommending coordination of emerging geostationary satellite missions for observing global air quality
- In 2019 CEOS endorsed whitepaper on ‘Geostationary Satellite Constellation for Observing Global Air Quality: Geophysical Validation
- CEOS member Agencies, primarily NASA and NOAA in the U.S., are now undertaking activities to support implementation of the recommendations
- In the U.S. DISCOVER-AQ, LMOS, OWLETS, LISTOS are viewed as successful capacity building activities conducted national (US EPA, NOAA), and regional-state (LADCO, NESCAUM, MDE, CDPHE, TCEQ, NJDEP, NYDEC, CTDEEP) and university partners

Source: Jay Al-Saadi, NASA LaRC

Final Thoughts

The measurement assets for a North American Integrated Observing System (ISO) for Air Quality will be in place by 2022.

Continued coordination among MJOs, Federal, State, Local, and Tribal agencies, along with the Universities is Critical to realize the vision.

PAMS Enhanced Monitoring Plans should be viewed as a opportunity for local IOS-AQ

Data placed in an open archive is a necessary step, but doesn't answer the critical policy-relevant-science questions

Development of an analysis capacity is crucial for success of the IOS-AQ to be realized, and LMOS, OWLETS (I &II), and LISTOS are hopefully helping to build necessary capacity

Acknowledgements

This work leverages funding across the U.S. EPA Air-Energy Research Program, NASA Tropospheric Composition Program, NASA Pandora Project, TEMPO EV-I mission, and ESA Pandonia Global Network

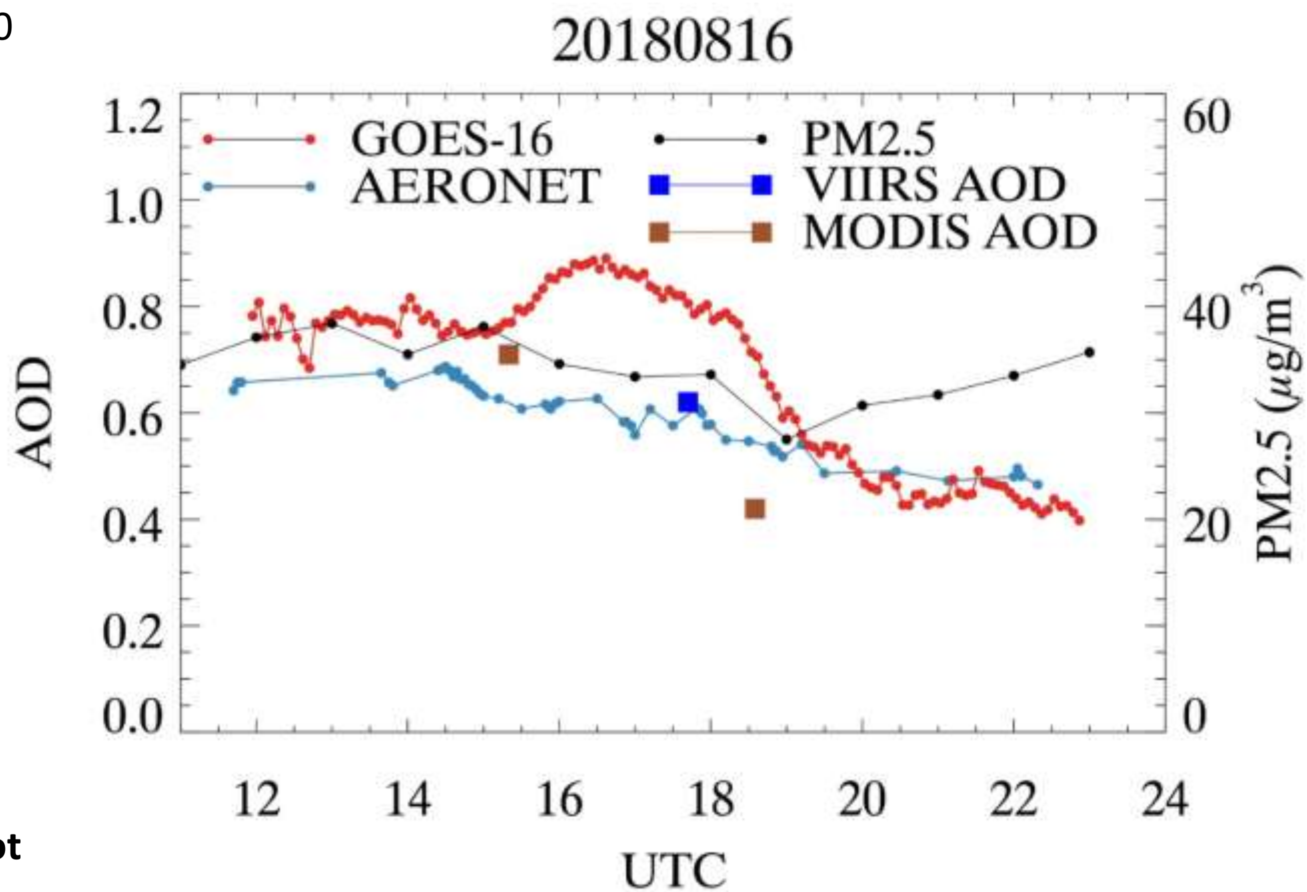
Diurnal Profile of AOD and PM2.5 at CCNY

CCNY was on the receiving end of some of the smoke (*transport of smoke shown in previous slide*). AODs were high and PM2.5 higher than 30 ug/m3 all day.

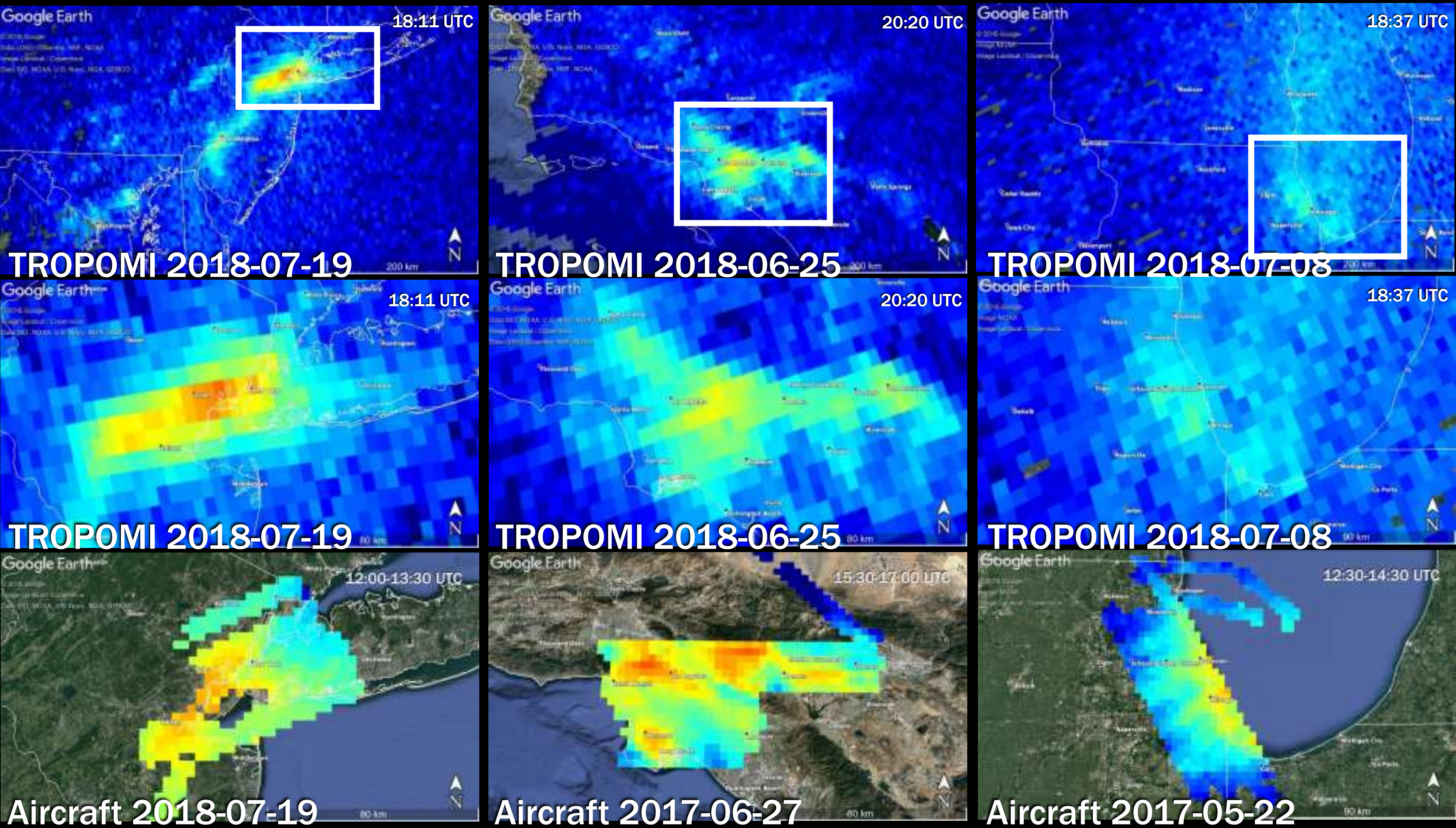
Note how continuous ABI observations are. First time ever observational frequency matches ground measurements. **ABI products are breaking the temporal barrier.**

Note also One VIIRS and two MODIS observations

Investigating the hump in ABI AOD between 15 and 19 UTC. **ABI band 2 calibration bias not applied and could be the cause.**



Source: Shobha Kondragunta, NOAA NESDIS and Fred Moshary, CCNY



Source: Laura Judd, NASA LaRC