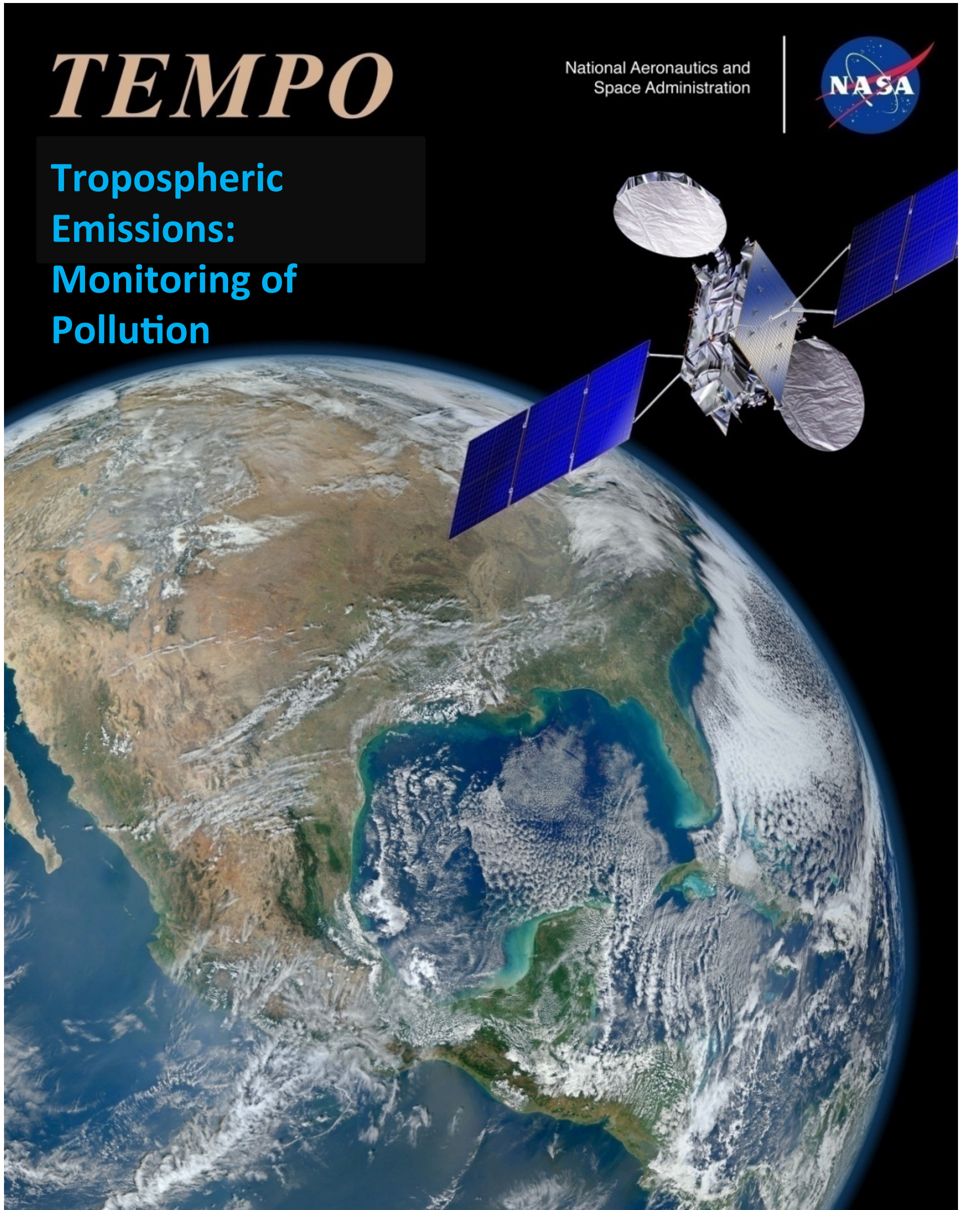
TEMPO, keeping the beat with Air Quality



Tropospheric Emissions: Monitoring of Pollution

Kelly Chance (Smithsonian Astrophysical Observatory, PI)

Presented at the 12/12/12 CIMSS Science Symposium by Brad Pierce (NOAA/NESDIS)

yeah... yeah... yeah...

TEMPO is part of NASA's Earth Venture Instrument program that includes small, targeted science investigations designed to complement NASA's larger research missions. TEMPO is NASA's first Earth Venture Instrument award under the agency's Earth System Science Pathfinder program.

Completed in 2017 at a cost of not more than $90 million, TEMPO will share a ride on a commercial satellite as a hosted payload with a target launch in 2019

- TEMPO spectroscopic measurements in the ultraviolet and visible provide a tropospheric measurement suite that includes the key elements of tropospheric air pollution chemistry: *ozone (O_3), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), formaldehyde (H_2CO), glyoxal ($C_2H_2O_2$), water vapor (H_2O), aerosols, cloud parameters, and UVB radiation.*

- TEMPO provides much of the atmospheric measurement capability recommended for GEO-CAPE in the 2007 National Research Council Decadal Survey, Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond. TEMPO will launch at a prime time to be a *component of a global GEO constellation for pollution monitoring, with a major focus on intercontinental pollution transport, along with Europe (Sentinel-4) and Asia (Geostationary Environment Monitoring Spectrometer)*.

Smithsonian Astrophysical Observatory

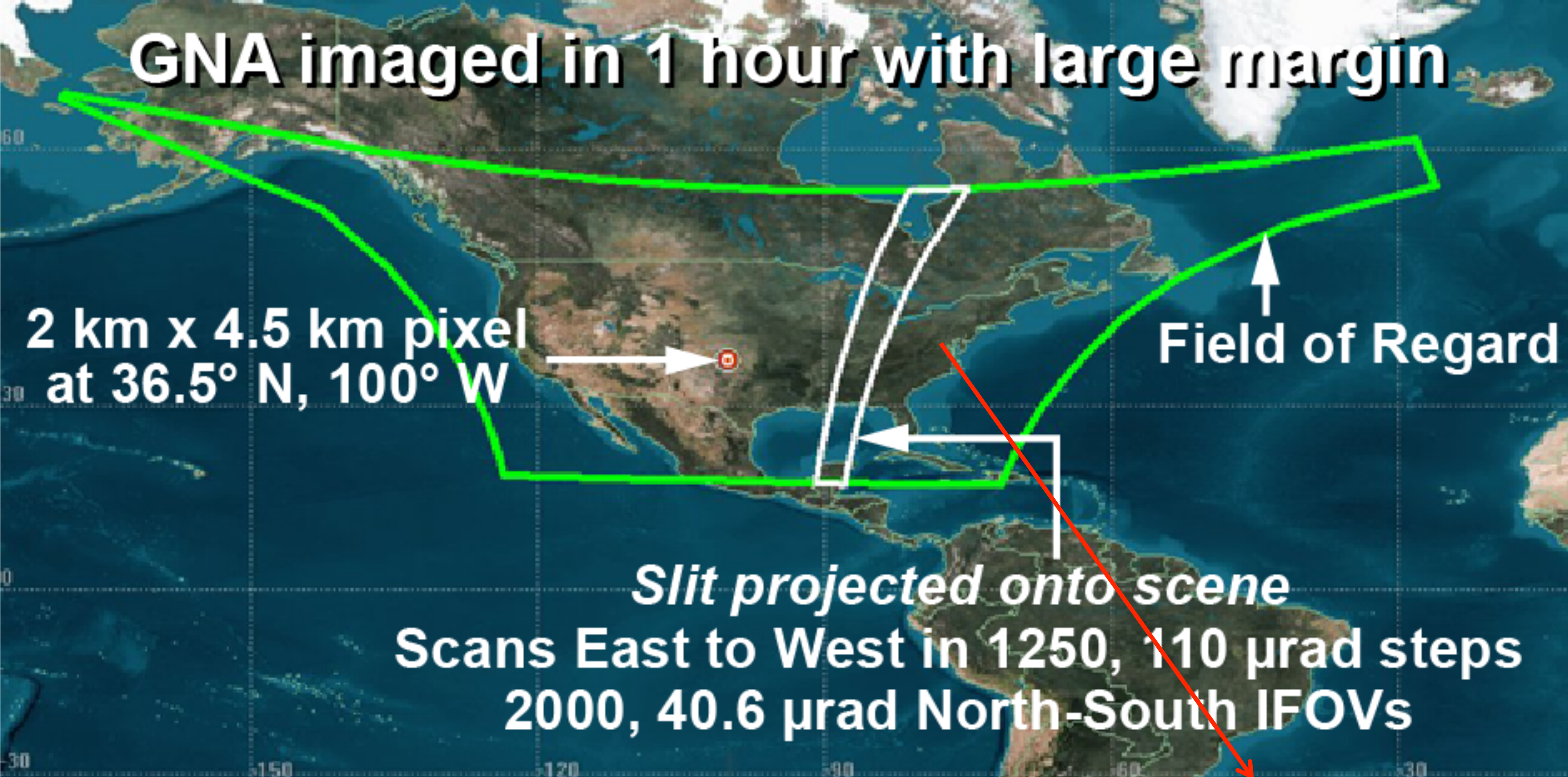
Sun-synchronous nadir heritage*

Instrument	Detectors	Spectral Coverage [nm]	Spectral Resolution [nm]	Ground Pixel Size [km^2]	Global Coverage
GOME (1995-2011)	Linear Arrays	240-790	0.2-0.4	40×320 (40×80 zoom)	3 days
SCIAMACHY (2002-2012)	Linear Arrays	240-2380	0.2-1.5	30×30/60/90 30×120/240 (depending on product)	6 days
OMI (2004)	2-D CCD	270-500	0.42-0.63	15×30 - 42×162 (depending on swath position)	daily
GOME-2a,b (2006, 2012)	Linear Arrays	240-790	0.24-0.53	40×40 (40×80 wide swath; 40×10 zoom)	near-daily
OMPS-1 (2011)	2-D CCDs	250-380	0.42-1.0	50×50 250×250 (depending on product)	daily

*Thanks to the late Dieter Perner of MPI

Previous experience (since 1985 at SAO and MPI)

Scientific and operational measurements of pollutants O_3, NO_2, SO_2, H_2CO, $C_2H_2O_2$ (& CO, CH_4, BrO, OClO, ClO, IO, H_2O, O_2-O_2, Raman, aerosol, ….)

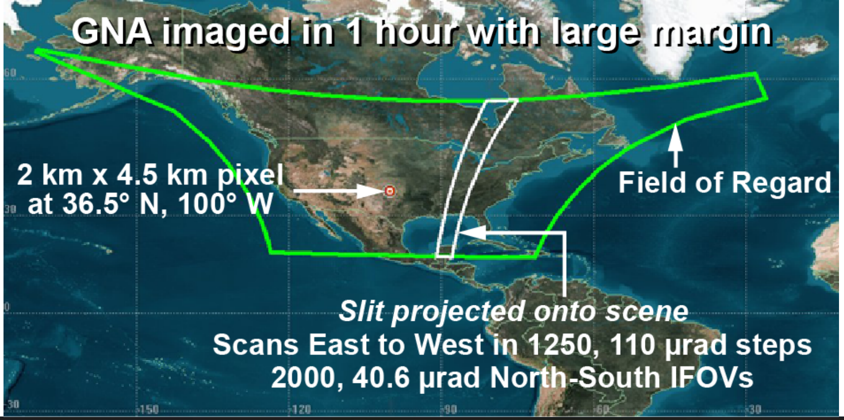


355 times GOME-2 spatial resolution
50 times OMI spatial resolution

Smithsonian Astrophysical Observatory

Each 2 km × 4.5 km pixel is a 2K element spectrum from 290-690 nm!

GEO platform selected by NASA for viewing greater North America



KEY INSTRUMENT CHARACTERISTICS

Requirements		Comment
Field of Regard	GNA	Mexico City to Canada tar sands & Atlantic to Pacific
Imaging Time	1 hr	1250 scan positions with 2.8 sec integration
Footprint N/S	2.0 km	Native pixel achieved by 44 cm telescope effective focal length
Footprint E/W	4.5 km	
Spectral Range	290-690 nm	1,024 spectral channels matched to 2k focal plane
Spectral Resolution	0.6 nm	Achieved by spectrometer design
Spectral Sampling	0.2 nm	

Heritage-based grating spectrometer efficiently achieves the requirements derived directly from the Science Traceability Matrix.

Species	λ Band nm	SNR Reqs	SNR Predict	EOL Margin
SO_2	305-345	1297	1820	40%
H_2CO	327-354	487	2094	330%
NO_2	423-451	1233	1910	55%
$C_2H_2O_2$	433-457	1350	2331	73%
O_3 (UV)	303-345	1122	1635	46%
O_3 (Vis)	546-648	958	1254	31%
AOD	354, 388	1000	1596	60%

Substantial margins for predicted signal-to-noise ratios are the foundation for a low-risk program.

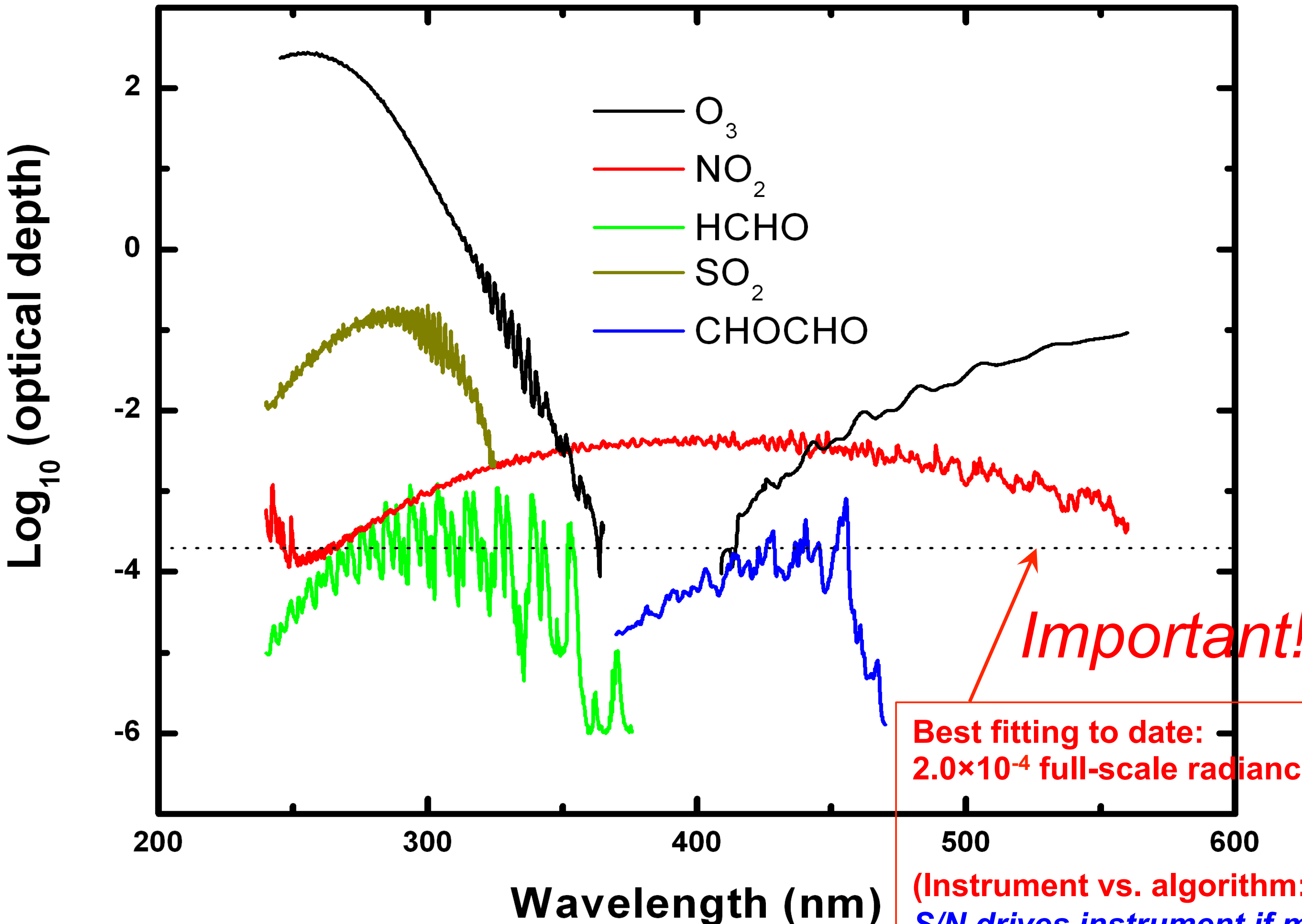
INSTRUMENT COMPLEMENT

TEMPO moves high heritage LEO hardware to GEO following a low-risk build philosophy. The high design maturity of the TEMPO spectrometer is leveraged from LEO-proven heritage from OMPS, SAGE III, and SBUV, as well as from GEO studies and risk reduction activities. This, coupled with substantial performance margins, results in a low-risk, compact configuration ideally matched to deliver a high value science product.

Requirements	TEMPO		
	Current Best Estimate	Contingency	Maximum Expected Value
Mass (kg)	92	17%	107.9
Average Power (W)	81.6	22%	99.4
Downlink Rate (Mbps)	8.95		
Volume (l x w x h)	1.02m x 1.07m x 0.96m		

The low resource requirements for TEMPO can be accommodated by any of the commercial GEO buses over GNA, ensuring flexibility to selection of a host platform.

Optical Depths for Typical GEO Measurement Geometry

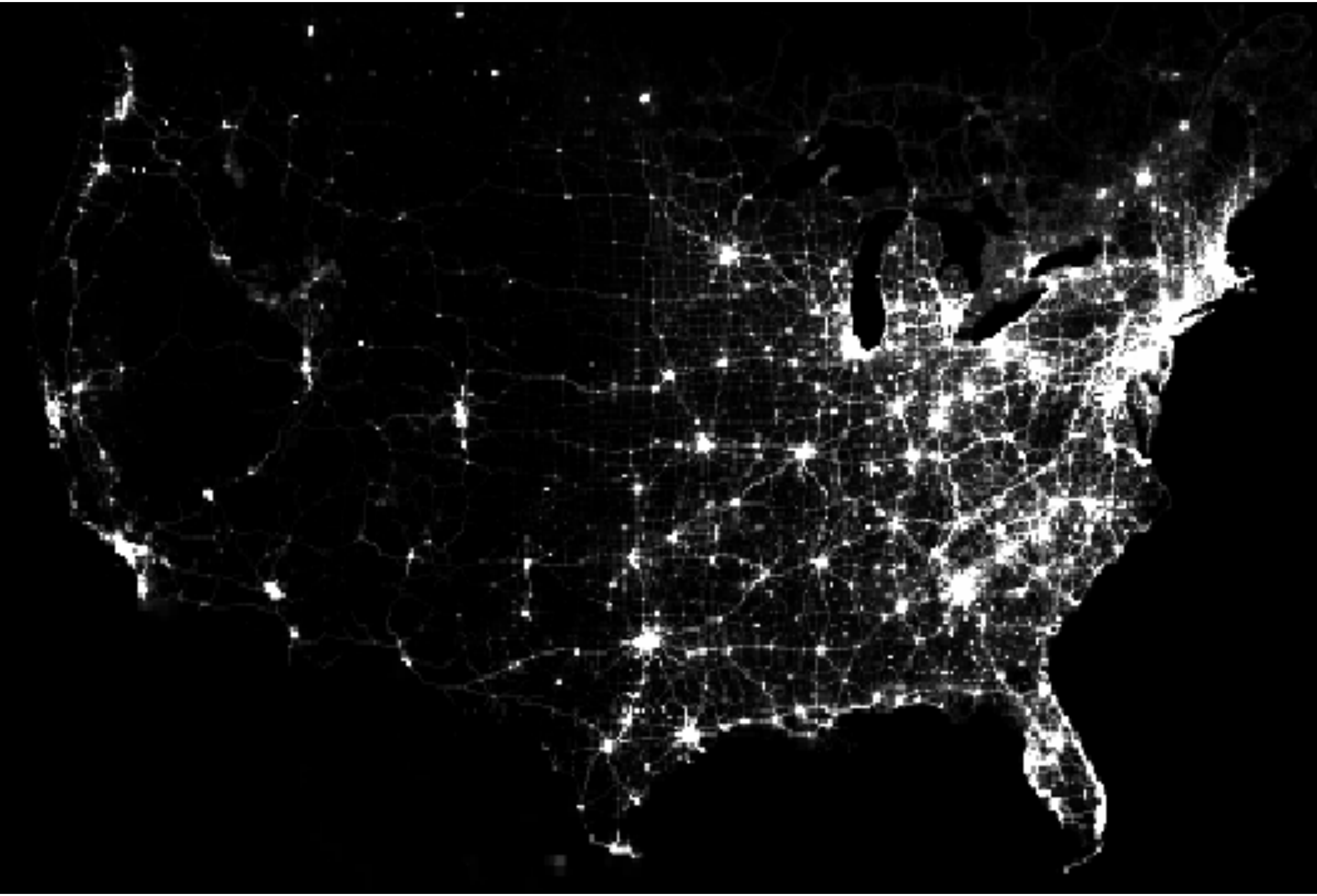


Best fitting to date:
2.0×10^{-4} full-scale radiance

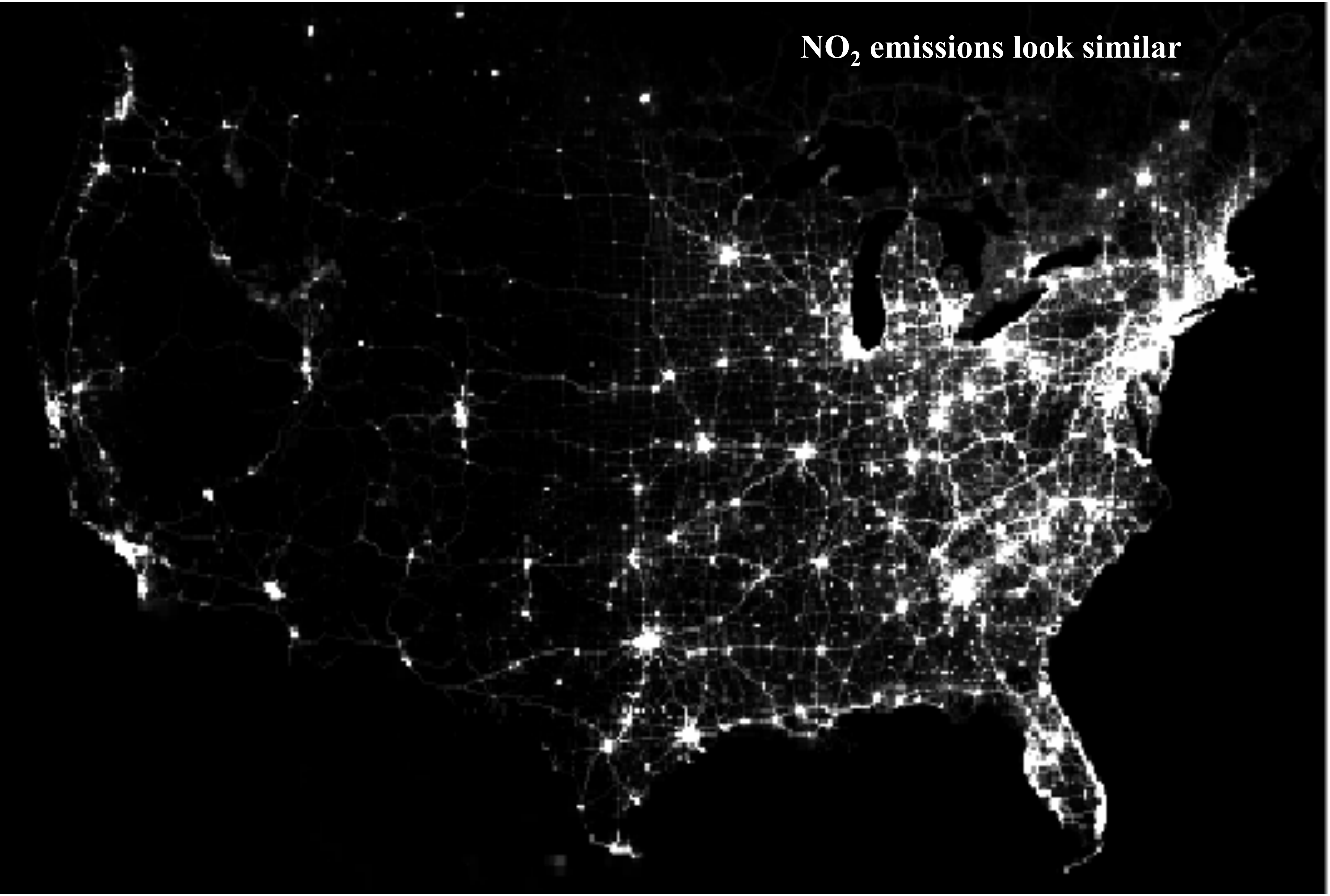
(Instrument vs. algorithm: *Tied!*
S/N drives instrument if meas. requirements can be met

Composite assembled from data acquired by the [Suomi NPP satellite] in April and October 2012 using [Visible Infrared Imaging Radiometer Suite] (VIIRS) "day-night band"

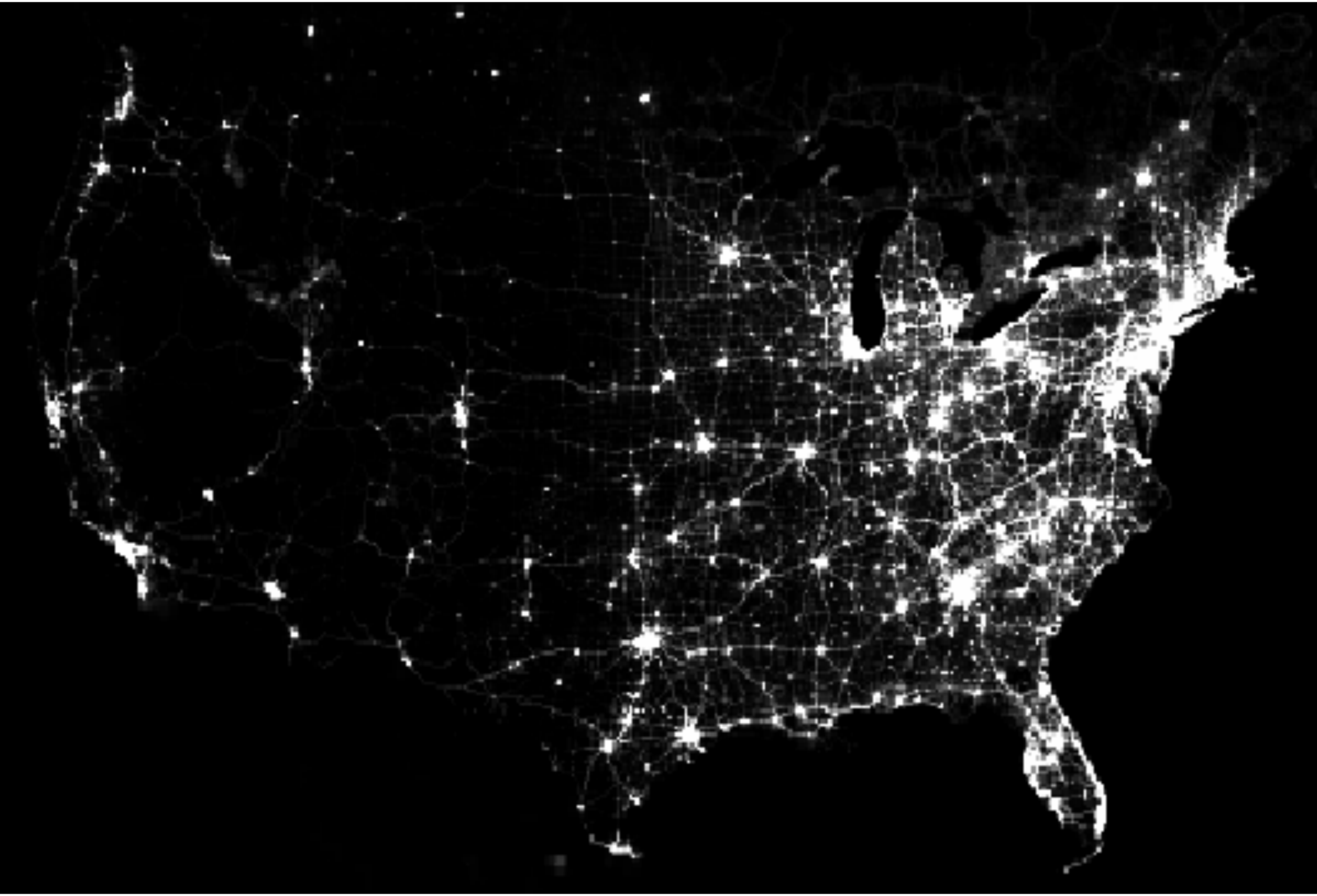
What’s this?



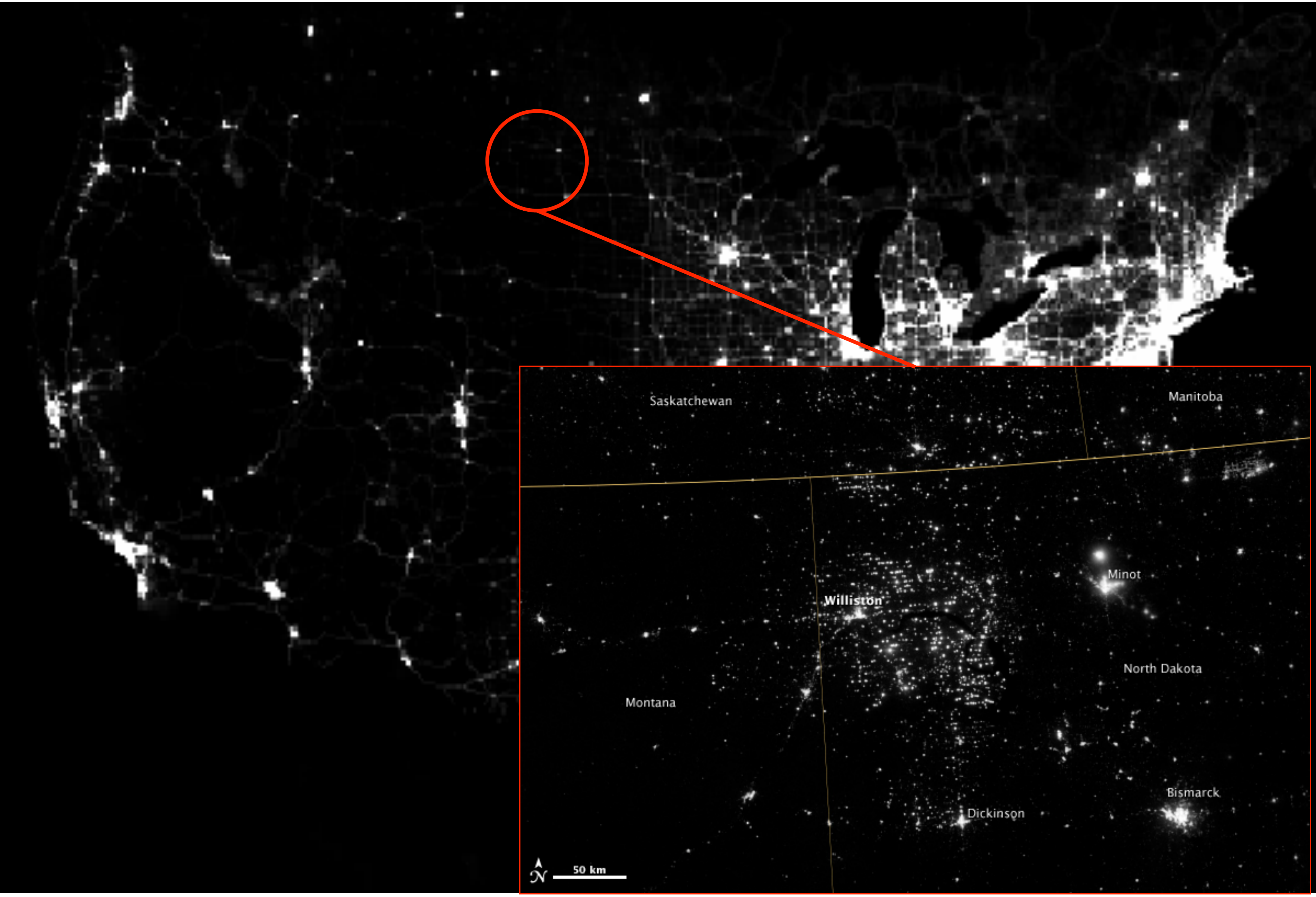
What's this -> 1999 National Emission Inventory (NEI) Carbon Monoxide (CO) emissions



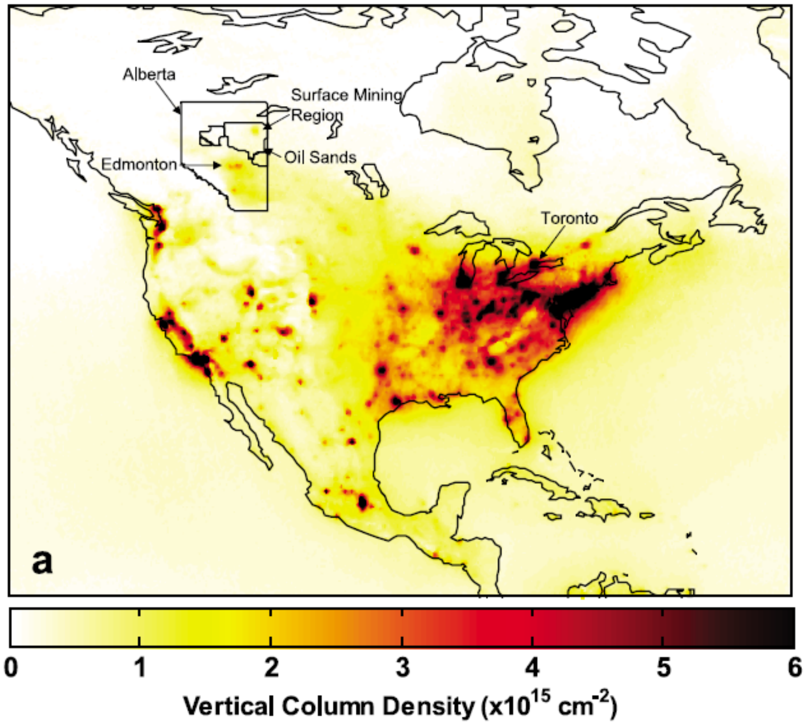
What’s missing?

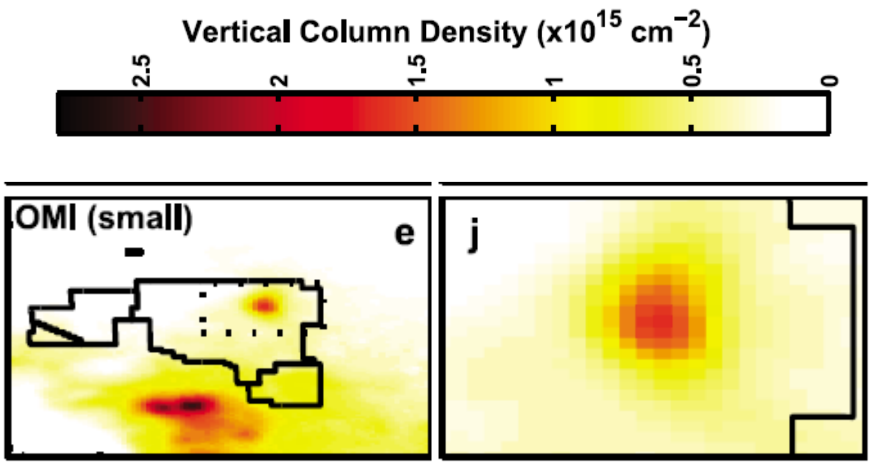


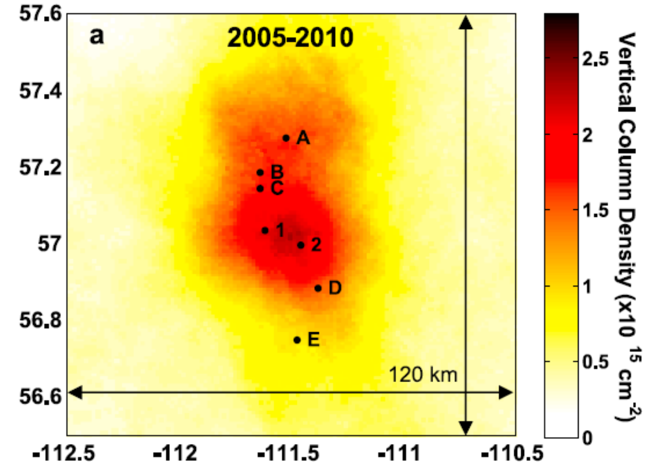
What's missing ->Natural Gas flares from oil production at the Bakken shale formation.

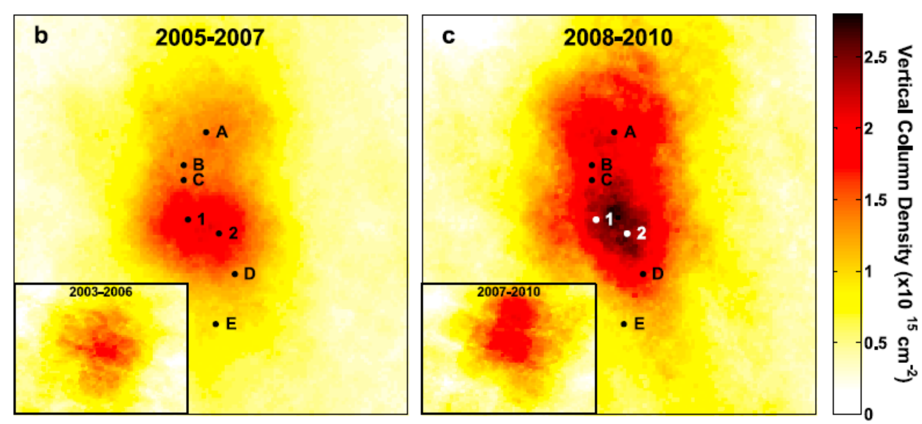


OMI NO_2 trends over the Canadian oil sands









McLinden, C. A., et al. (2012), Air quality over the Canadian oil sands: A first assessment using satellite observations, Geophys. Res. Lett., 39, L04804, doi:10.1029/2011GL050273.

TEMPO measurements will capture spatial structure in NO_2 emissions that are not captured by current LEO observations

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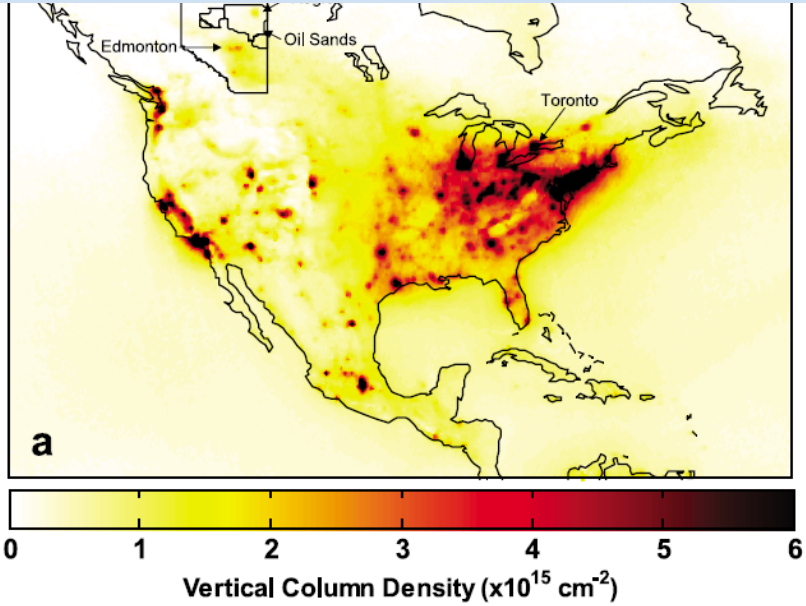

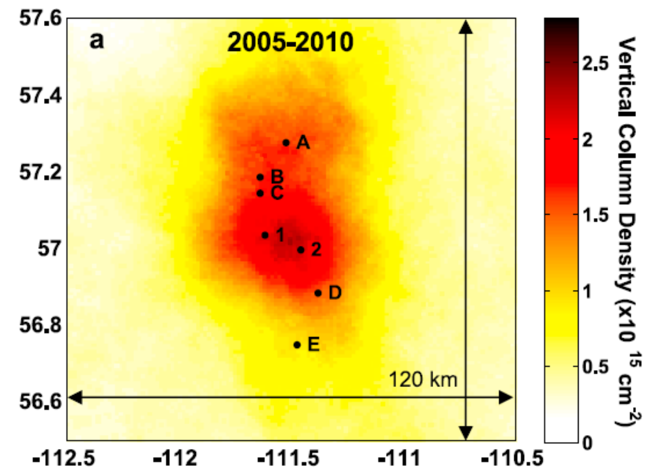

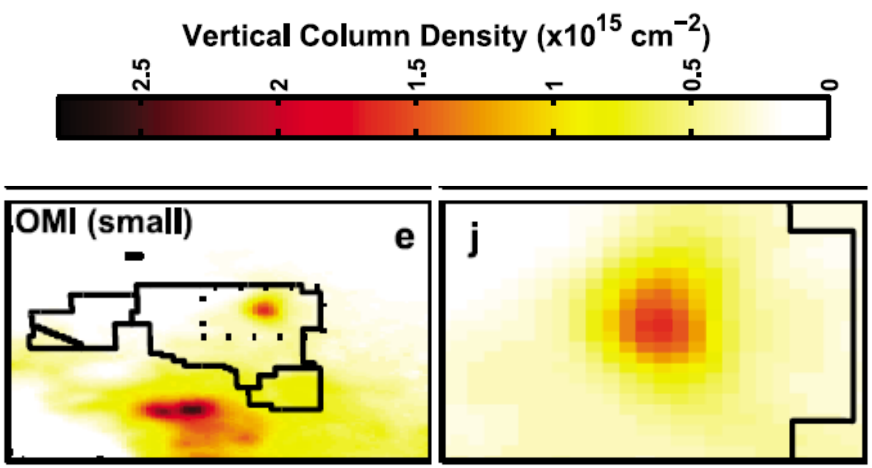

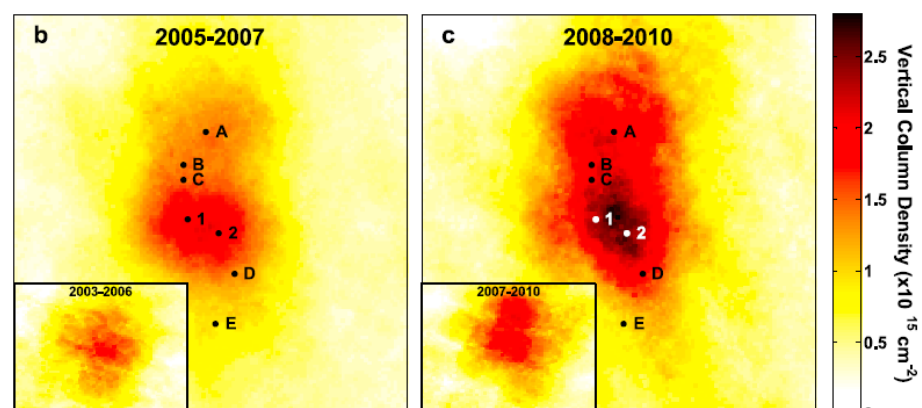

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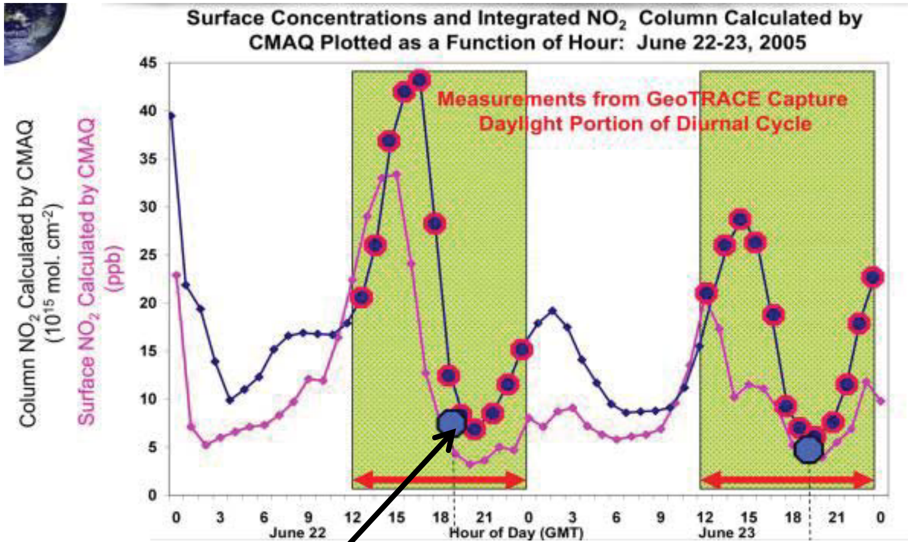
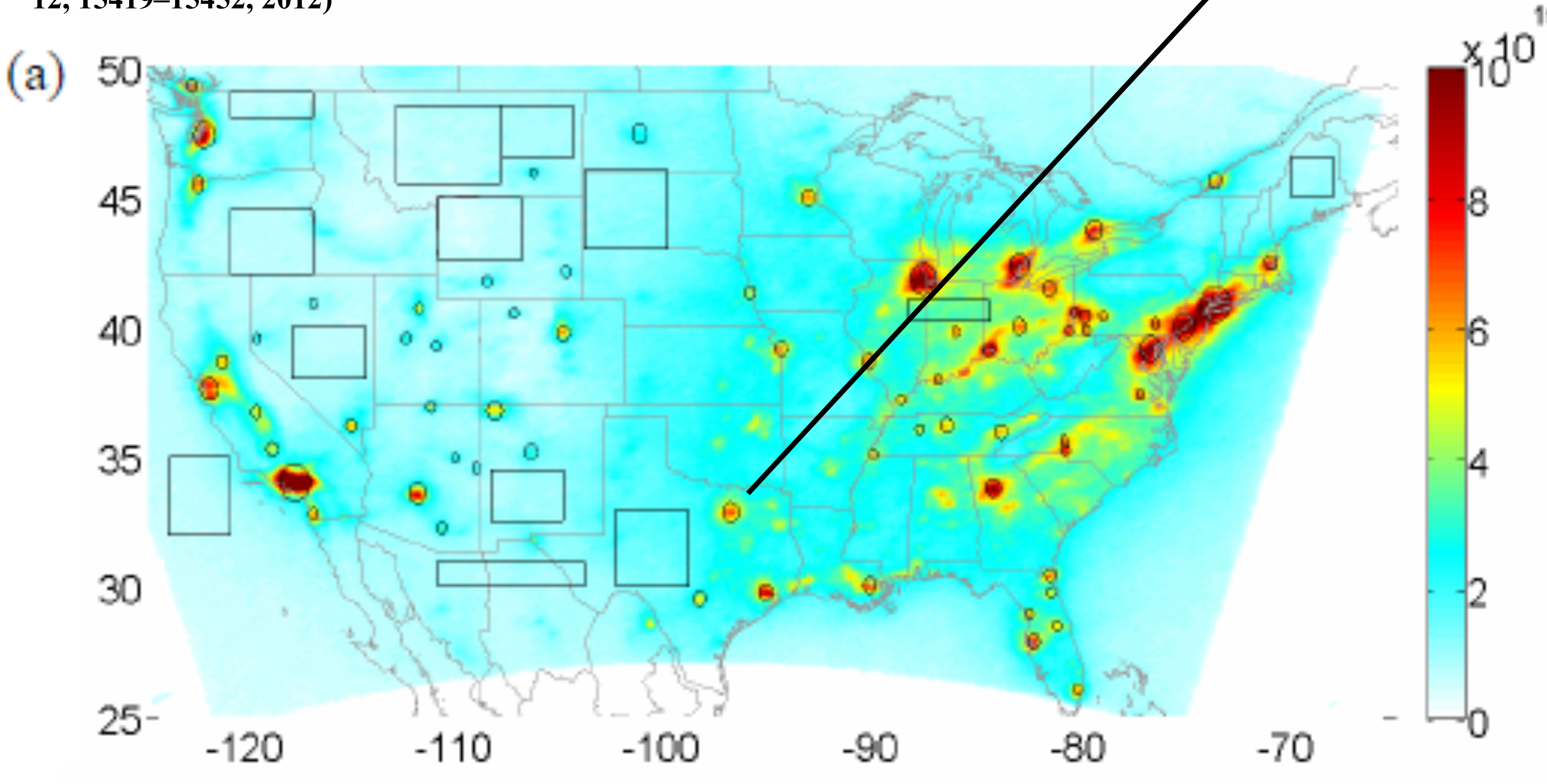
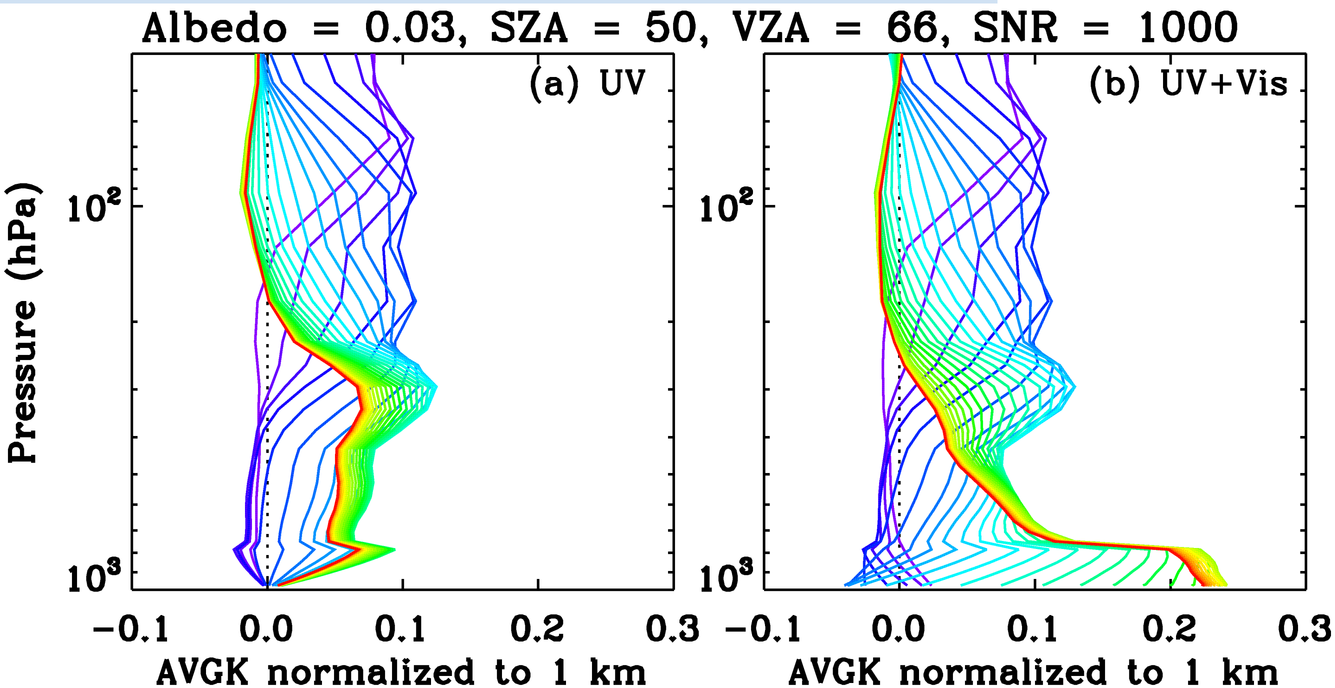
TEMPO measurements will capture the diurnal cycle of NO_2 that is missed by current LEO observations



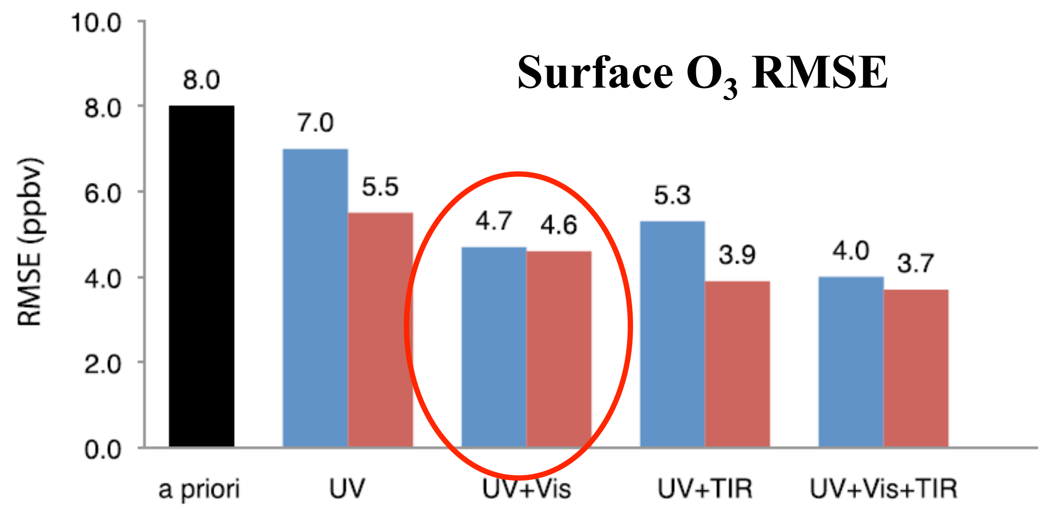
Average summertime (April–September) OMI BEHR NO2 column densities for 2005, (From Russell et al., Atmos. Chem. Phys. Discuss., 12, 15419–15452, 2012)



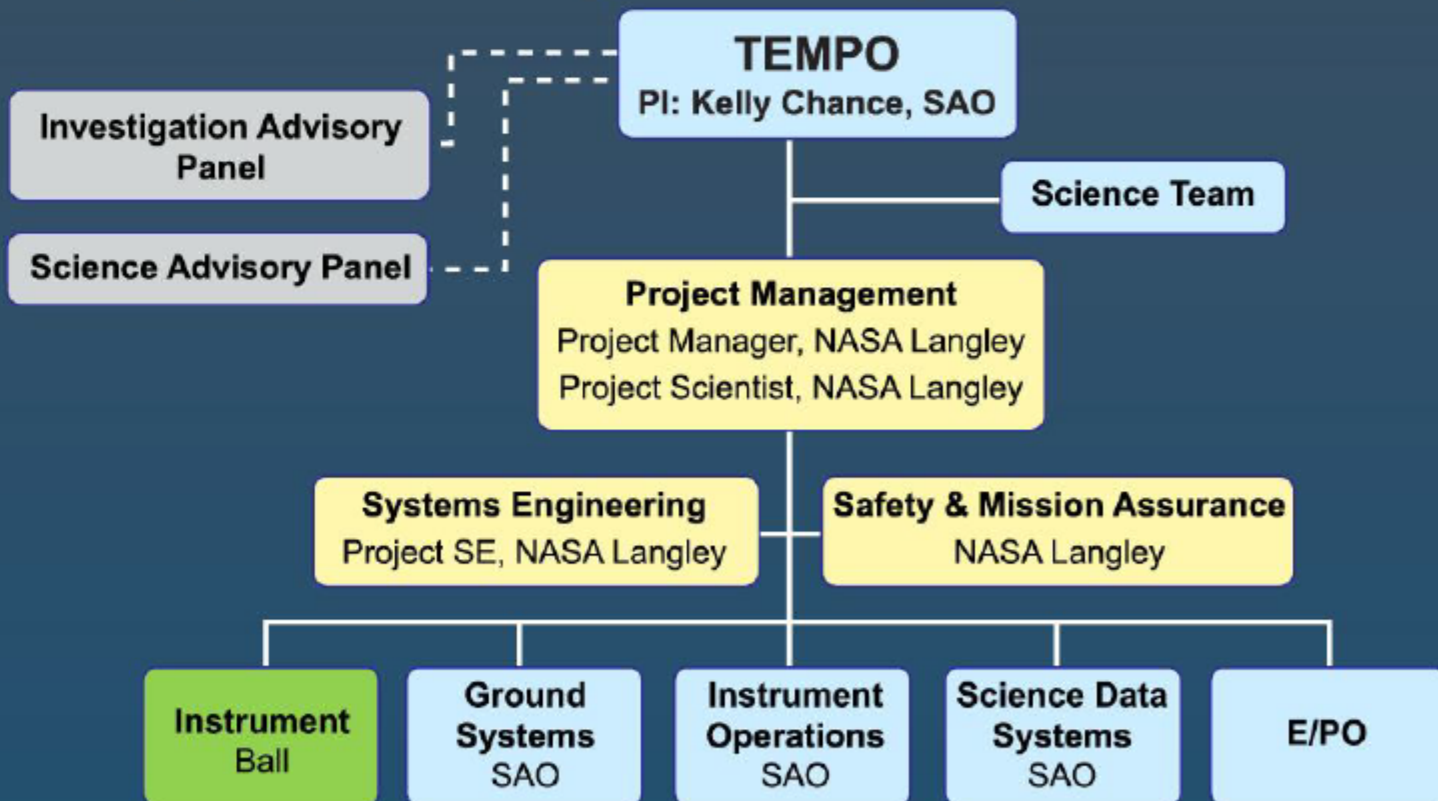
TEMPO UV-Vis observations significantly improve sensitivity to O3 near the surface over the use of UV only



Zoogman et al. (2011) used an OSSE framework to demonstrate substantial improvement in comparison with surface ozone concentrations when UV+Vis measurements, such as from TEMPO, are assimilated



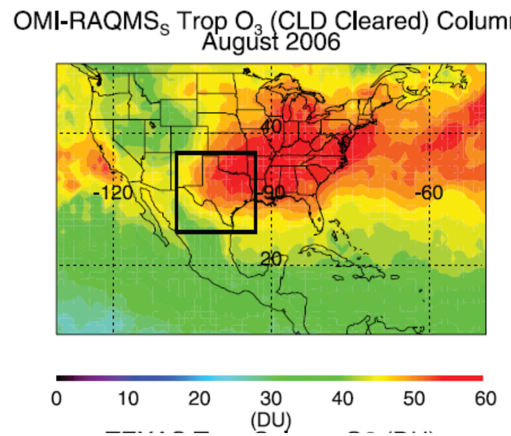
INVESTIGATION ORGANIZATION provides clear lines of authority with accountability and ownership.

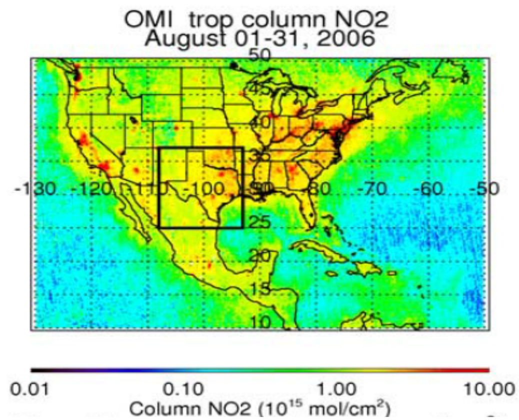


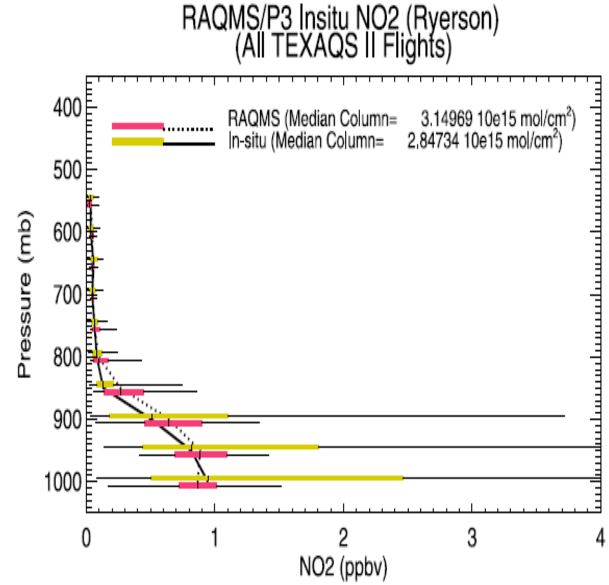
TEMPO Science Team: Data product developers, in bold, conduct TEMPO space-based validation with other satellites

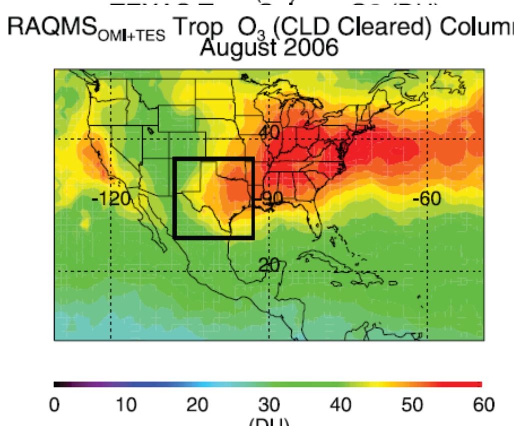
Team Member	Institution	Role	Responsibility
K. Chance	SAO	PI	Overall science development; **Level 1b, H_2CO, $C_2H_2O_2$**
X. Liu	SAO	Deputy PI	Science development, data processing; **O_3 profile, tropospheric O_3**
J. Carr	Carr Astronautics	Co-I	**INR Modeling and algorithm**
M. Chin	GSFC	Co-I	**UV aerosol product, AI**
R. Cohen	U.C. Berkeley	Co-I	NO_2 validation, atmospheric chemistry modeling, process studies
D. Edwards	NCAR	Co-I	VOC science, synergy with carbon monoxide measurements
J. Fishman	St. Louis U.	Co-I	Education/Public outreach
D. Flittner	LaRC	Project Scientist	Overall project development; STM; instrument cal./char.
J. Herman	UMBC	Co-I	Validation (PANDORA measurements)
D. Jacob	Harvard	Co-I	Science requirements, atmospheric modeling, process studies
S. Janz	GSFC	Co-I	Instrument calibration and characterization
J. Joiner	GSFC	Co-I	**Cloud, total O_3, TOA shortwave flux research product**
N. Krotkov	GSFC	Co-I	**NO_2, SO_2, UVB**
M. Newchurch	U. Alabama Huntsville	Co-I	Validation (O_3 sondes, O_3 lidar)
R.B. Pierce	NOAA/NESDIS	Co-I	AQ modeling, data assimilation
R. Spurr	RT Solutions, Inc.	Co-I	Radiative transfer modeling for algorithm development
R. Suleiman	SAO	Co-I, Data Mgr.	Managing science data processing, **BrO, H_2O, and L3 products**
J. Szykman	EPA	Co-I	AIRNow AQI development, validation (PANDORA measurements)
O. Torres	GSFC	Co-I	**UV aerosol product, AI**
J. Wang	U. Nebraska	Co-I	Synergy w/GOES-R ABI, **aerosol research products**
J. Leitch	Ball Aerospace	Collaborator	Aircraft validation, instrument calibration and characterization
R. Martin	Dalhousie U.	Collaborator	Atmospheric modeling, air mass factors, AQI development
D. Neil	LaRC	Collaborator	GEO-CAPE mission design team member
J. Kim	Yonsei U.	Collaborators, Science Advisory Panel	Korean GEMS, CEOS constellation of GEO pollution monitoring
J. McConnell	York U. Canada		CSA PHEOS, CEOS constellation of GEO pollution monitoring
B. Veihelmann	ESA		ESA Sentinel-4, CEOS constellation of GEO pollution monitoring

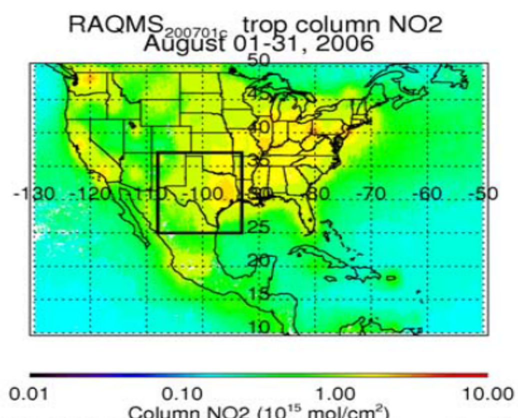
At CIMSS, RAQMS and WRF-CHEM chemical data assimilation activities will utilize TEMPO O3 and NO2 measurements to improve air quality forecasting capabilities

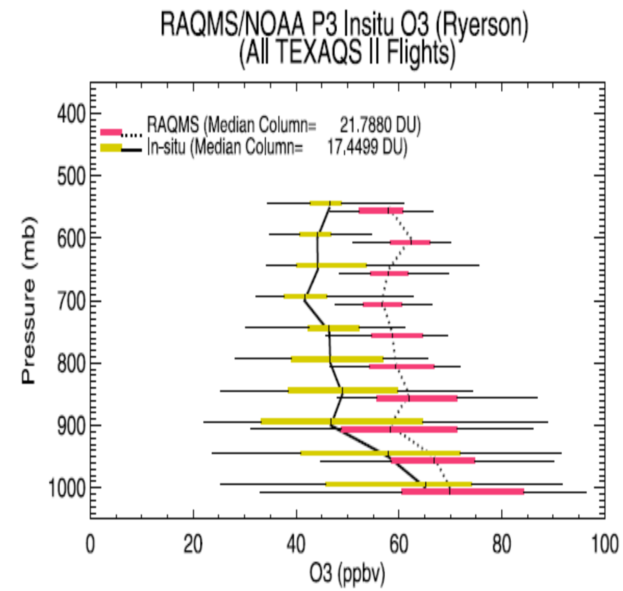


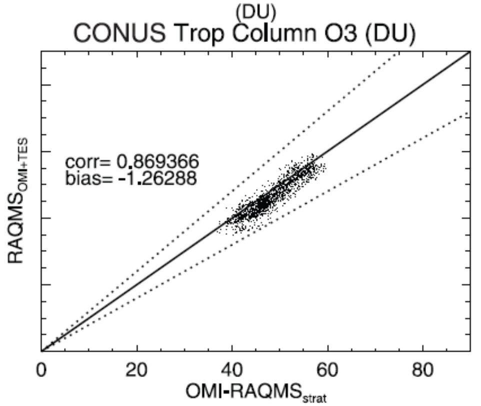


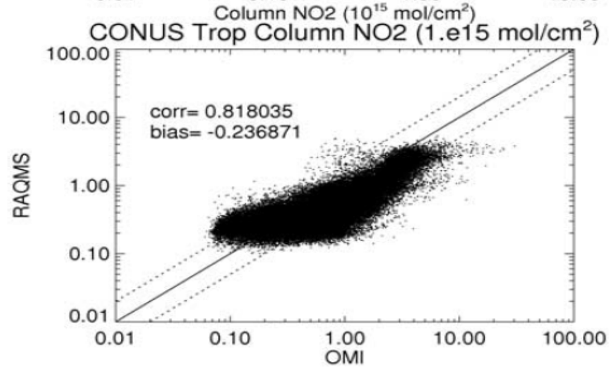












Alignment with 2007 Decadal Survey

The NRC 2007 Decadal Survey "Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond" recommended missions including Geostationary Coastal and Air Pollution Events (GEO-CAPE). The atmosphere part of GEO-CAPE is recommended to include the measurements proposed here.

TEMPO makes all the requisite GEO-CAPE UV/visible measurements, including O_3, NO_2, H_2CO, and aerosols (plus several additional species including SO_2). Together with the proposed IR instrument for CO measurements, all GEO-CAPE atmospheric requirements for North America are fulfilled.

Global Observations: International Cooperation

- Continuous global observations can be provided by a constellation of at least 3 geostationary satellites
- Harmonization of currently planned geostationary missions would enable an integrated global observing system fulfilling the visions of GEO/GEOSS and IGOS Atmospheric Chemistry and Coastal themes
  - *ESA Sentinel 4 on MTG, **2017** (AQ)*
  - *MEST/ME MP-GeoSat, **2017** (AQ, OC)*
  - *NASA GEO-CAPE, **2020?** (AQ, OC)*
  - *CNES OCAPI **????** (OC)*
- The US component of this global constellation could be effectively achieved by coordinating GEO-CAPE to align with ESA and MEST observations
  - *Cost must fit within NASA Earth Science mission budget profiles*

Figure courtesy Doreen Neil, NASA

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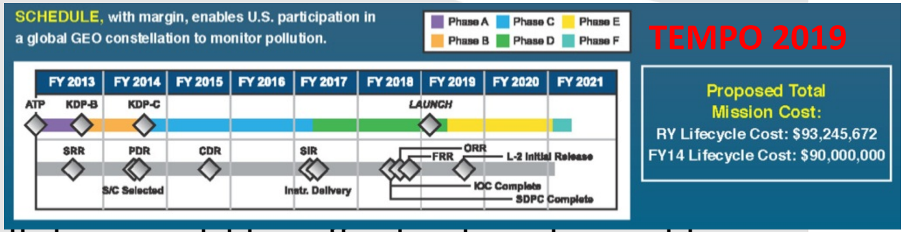

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Figure courtesy Doreen Neil, NASA

Global Observations: Internationa

US Geostationary IR sensor would complete the integrated global observing system!

ed by

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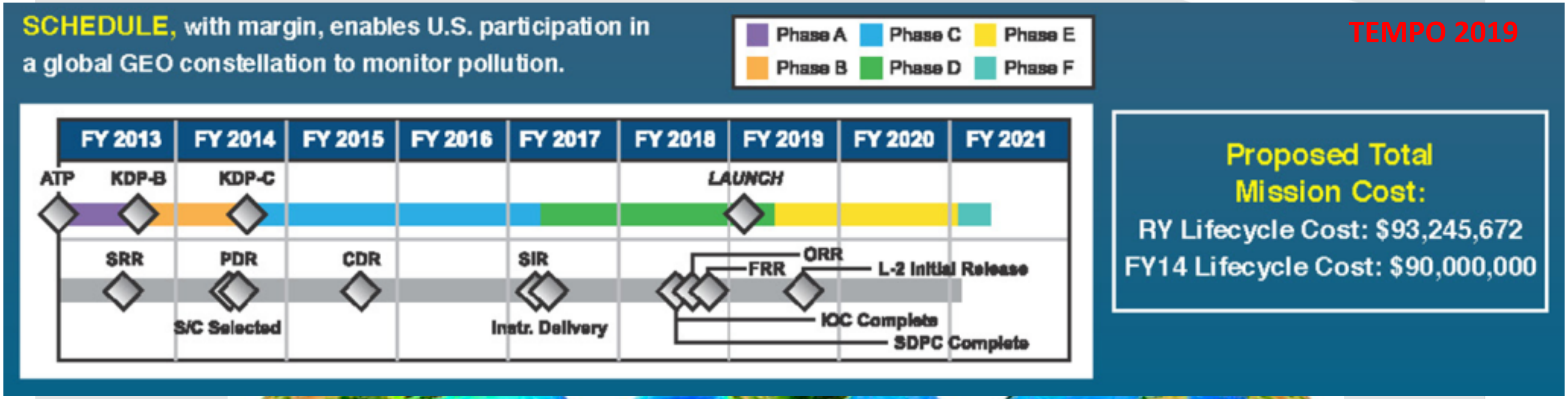

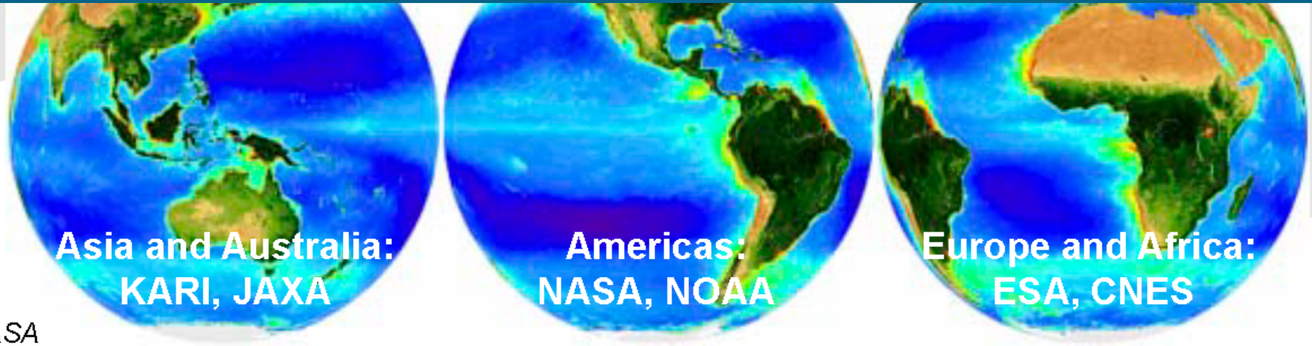

Figure courtesy Doreen Neil, NASA