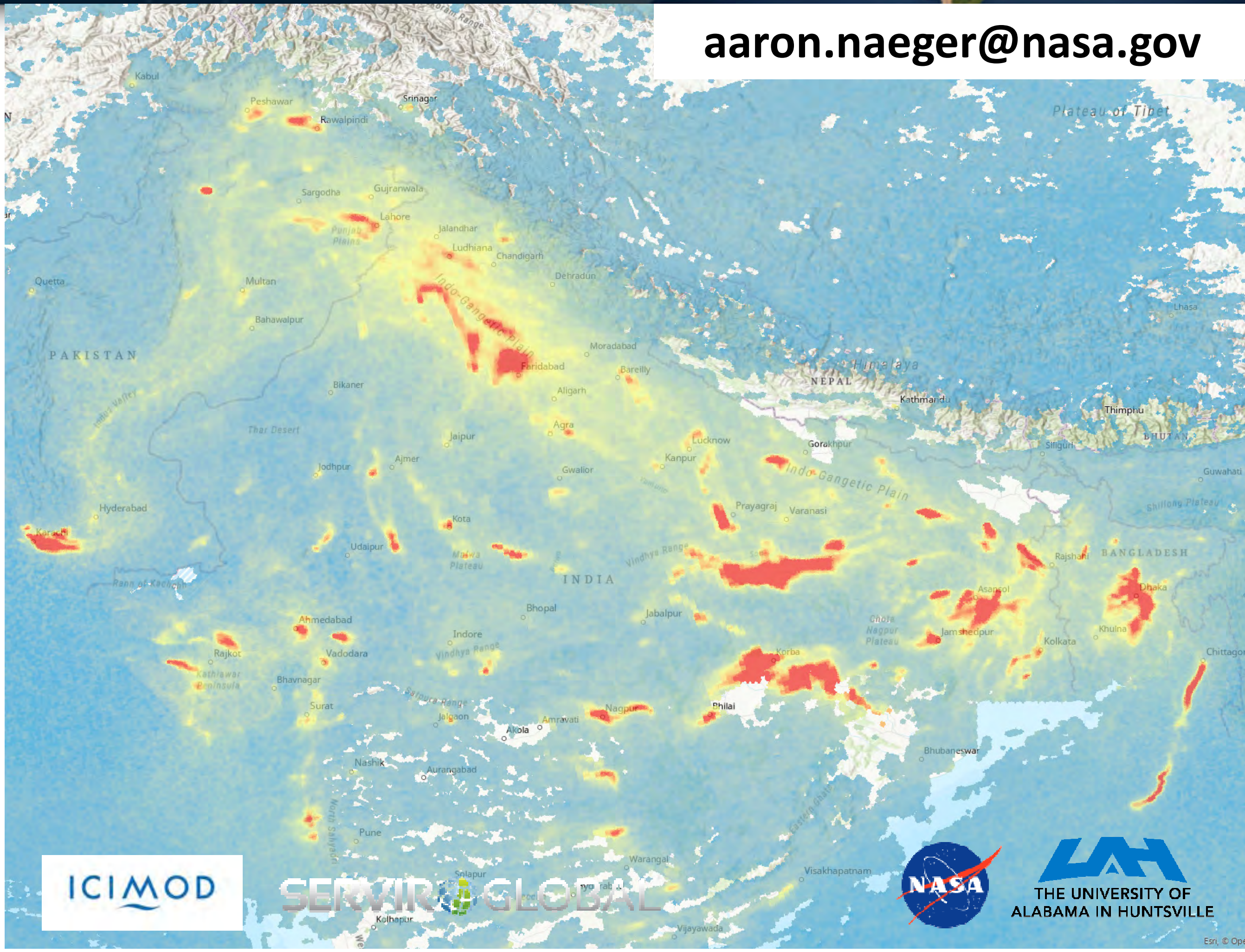
Remote Sensing of Trace Gases and Value-Added Products

aaron.naeger@nasa.gov



Aaron Naeger

Earth System Science Center, University of Alabama in Huntsville (UAH), Huntsville, AL

Co-I's (ASTs):
Jonathan Case, ENSCO Inc.
Kevin Fuell, Earth System Science Center, UAH
Michael Newchurch, UAH

Project Objectives

1. **Intelligently fuse information from state-of-the-art satellite sensors to develop comprehensive products for advancing real-time air pollution & fog monitoring capabilities**
2. Design a tailored chemical transport model framework for providing accurate AQ, fog/smog, and temperature/stability forecasts
3. Build a lagrangian dispersion model informed by our tailored products to aid in the rapid response to extreme AQ/disaster events
4. Implement the satellite- and model-based AQ products into applicable Decision Support Systems, and develop customized end-user training

Overarching Project Goal:

Deliver an advanced air quality monitoring & forecasting toolkit for providing accurate and timely alerts/warnings to the public

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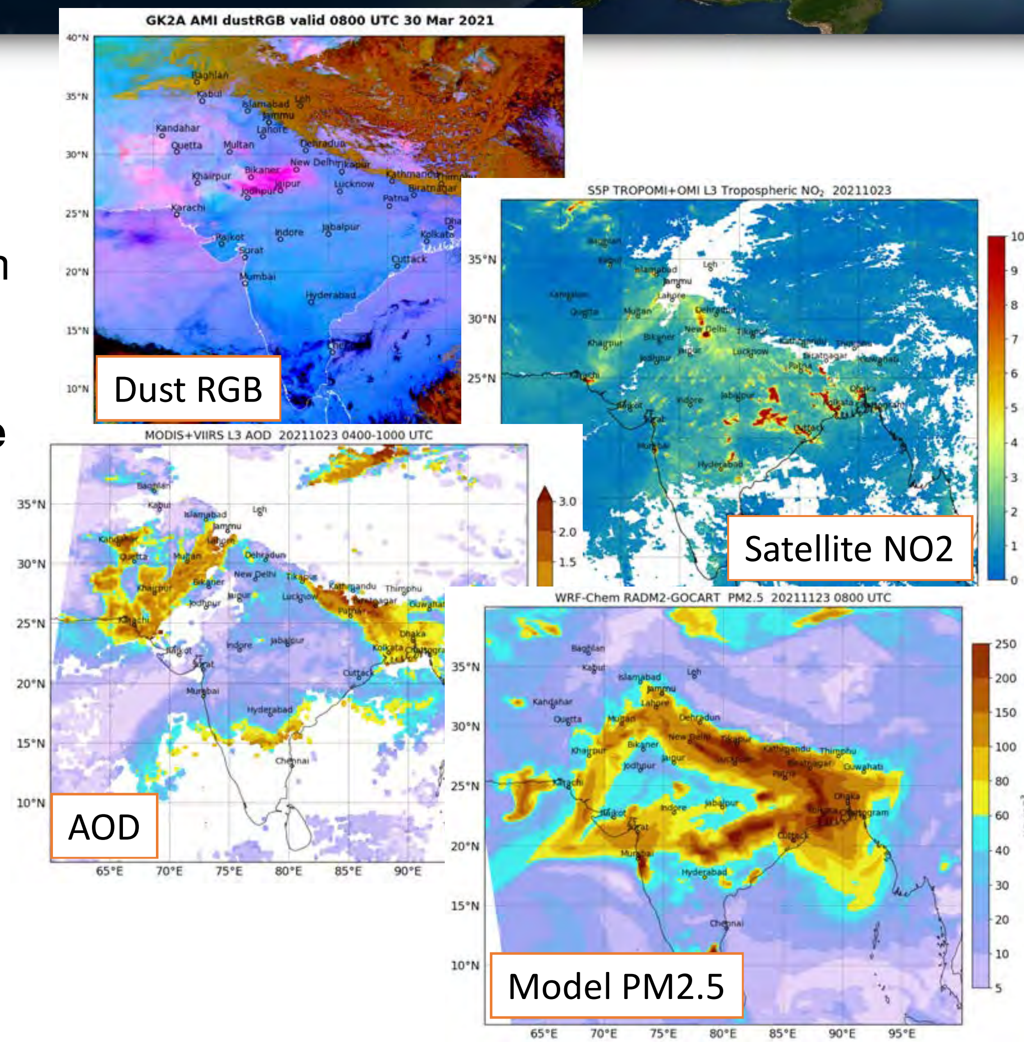
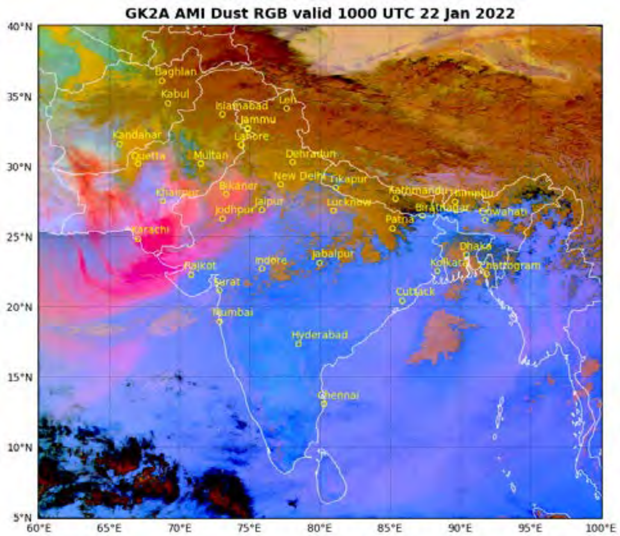
Key Products & Tools

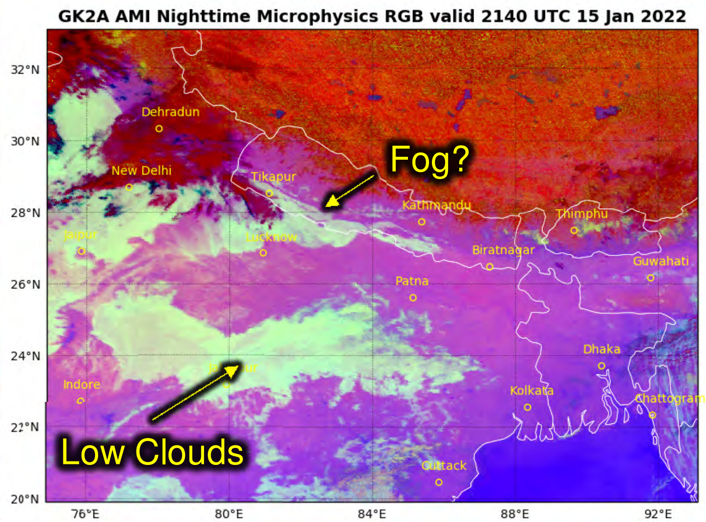
1. Suite of Red-Green-Blue (RGB) products from the geostationary Advanced Meteorological Instrument (AMI) for monitoring diurnal evolution of dust, fires, smoke and fog
2. **High-level (L2+) trace gas and aerosol products developed from composite satellite and model data to track air pollution in the troposphere and surface layer**
3. High-resolution chemical transport model for accurately predicting AQ in the HKH region and providing timely warnings to the public
4. Dispersion model designed for efficiently predicting dust pollution concentrations and enabling rapid response to dust storms



Recap from Yesterday

- ❑ Presented several different AMI RGB products that can and should be utilized in conjunction for aiding pollution, smog, smoke, and fog conditions





- ❑ Today will provide details on an additional RGB product (True Color), fire detection algorithm, and conclude with details on trace gas products

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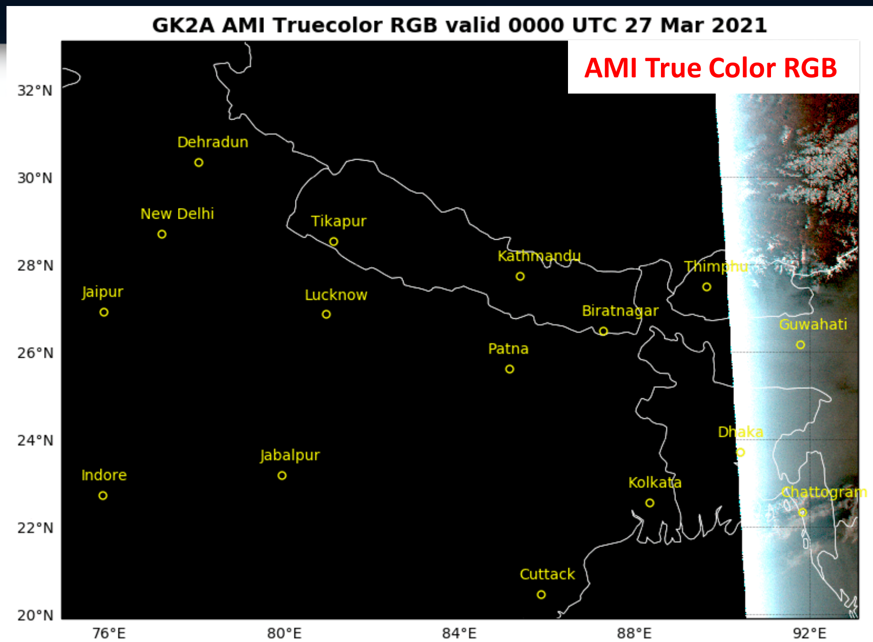
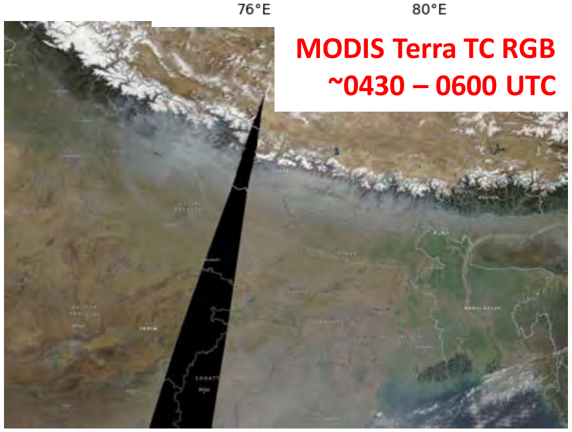
Dust RGB Training Guides

https://weather.msfc.nasa.gov/sport/training/articles/202111231606_Dust-RGB-Basics-for-AMI/

True Color (TC) RGB

True Color RGB - Introduction





- ❑ Uses the three visible channels of AMI to monitor aerosols, clouds, and vegetation
- ❑ Designed to imitate how the human eye would see the scene

Benefits:

- ❑ Easy to interpret
- ❑ Aerosols usually distinguishable from clouds
- ❑ Different aerosol types can have different color shades (i.e., ash, smoke, dust)
- ❑ Aids in fire detection and smoke monitoring

Limitations:

- ❑ Only valid during the daytime
- ❑ At high zenith angles during evening, pollution can appear worse than real conditions
- ❑ The Green band for AMI (0.51 µm) is slightly shifted from visible reflectance peak
  - ▪ Differences in vegetation color less apparent for AMI than MODIS / VIIRS

AMI True Color RGB – Features & Use Case

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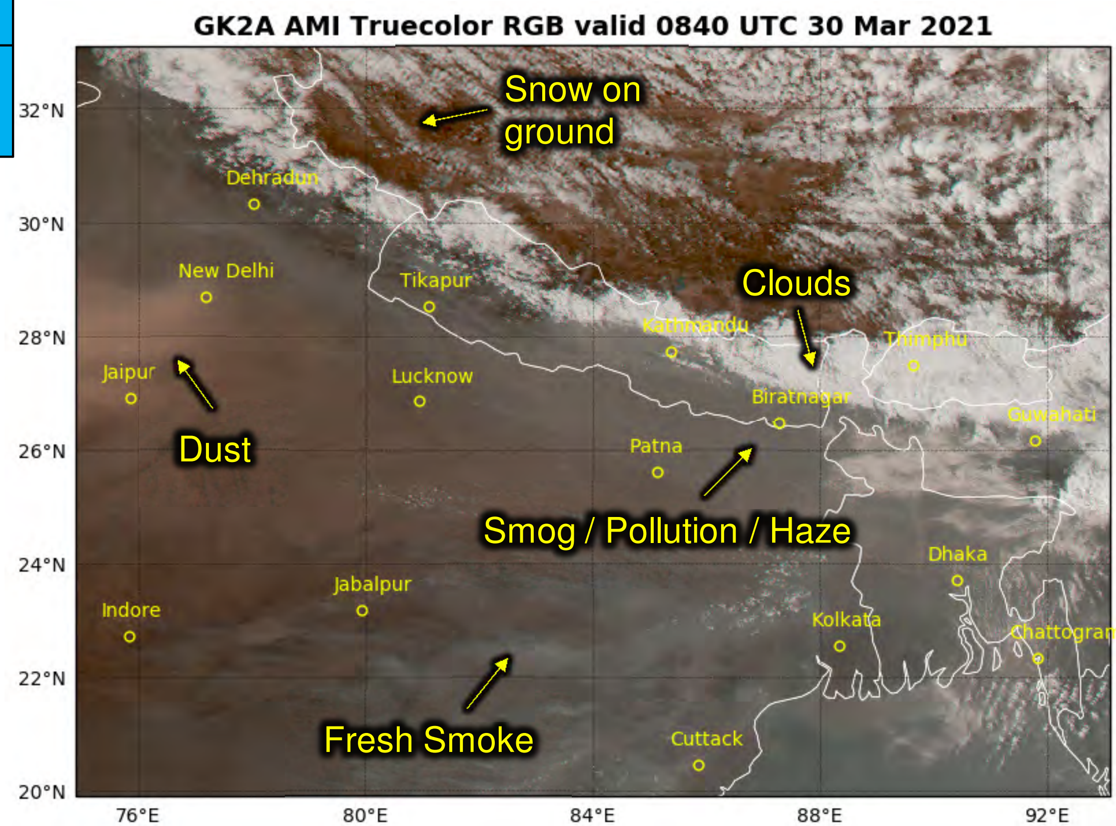
Red	*Green*	*Blue*
$VIS_{0.64}$ (0 to 1.0 refl)	$VIS_{0.51}$ (0 to 1.0 refl)	$VIS_{0.47}$ (0 to 1.0 refl)

- TC RGB tracks dust and smoke pollution on 30 March 2021
- Dust appears in a brownish tone
- Smog and haze appear grey
- Fresh smoke can appear grey with some bluish tone
- Clouds and snow on ground appear white
- "Dirty clouds" can be apparent in HKH region

Different shades of aerosols in TC RGB can be difficult to discern in HKH due to the complex pollutant mixtures that often impact the region.

Using other RGBs can help!



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True Color RGB – 31 March 2021

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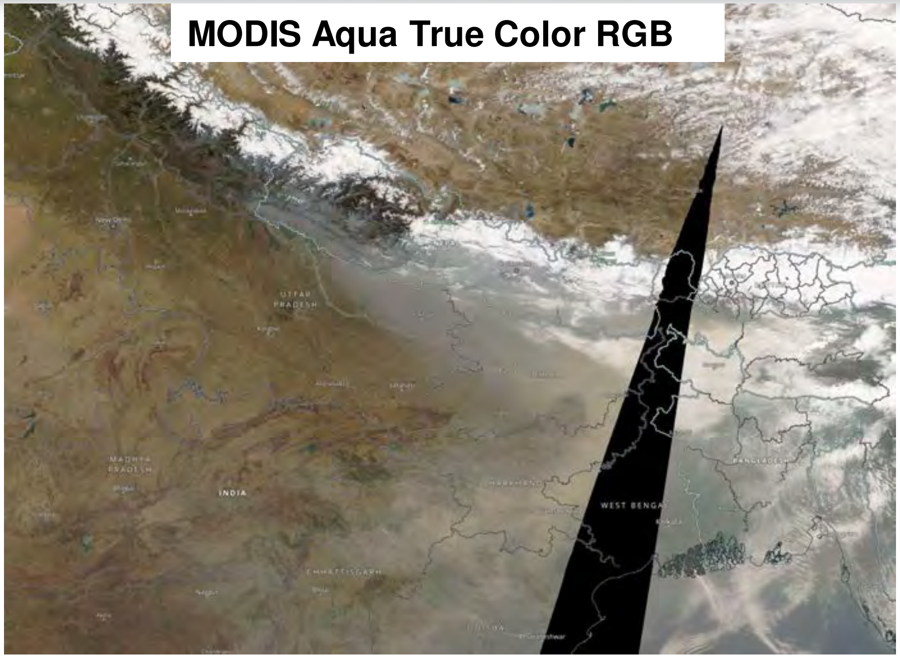

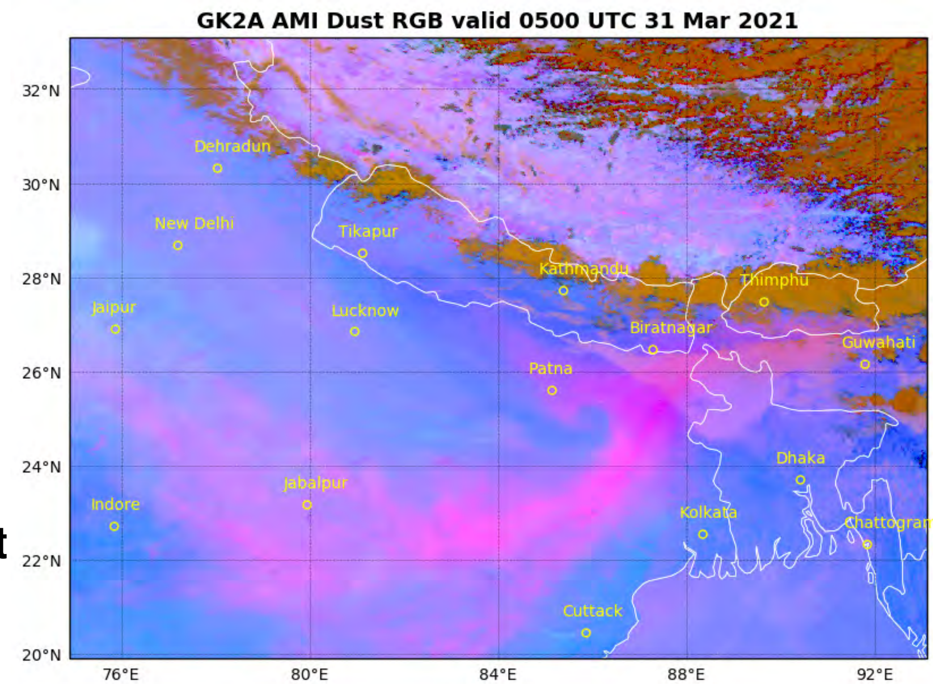

Combining information from RGB product suite can help better understand evolution of different pollutants in the atmosphere

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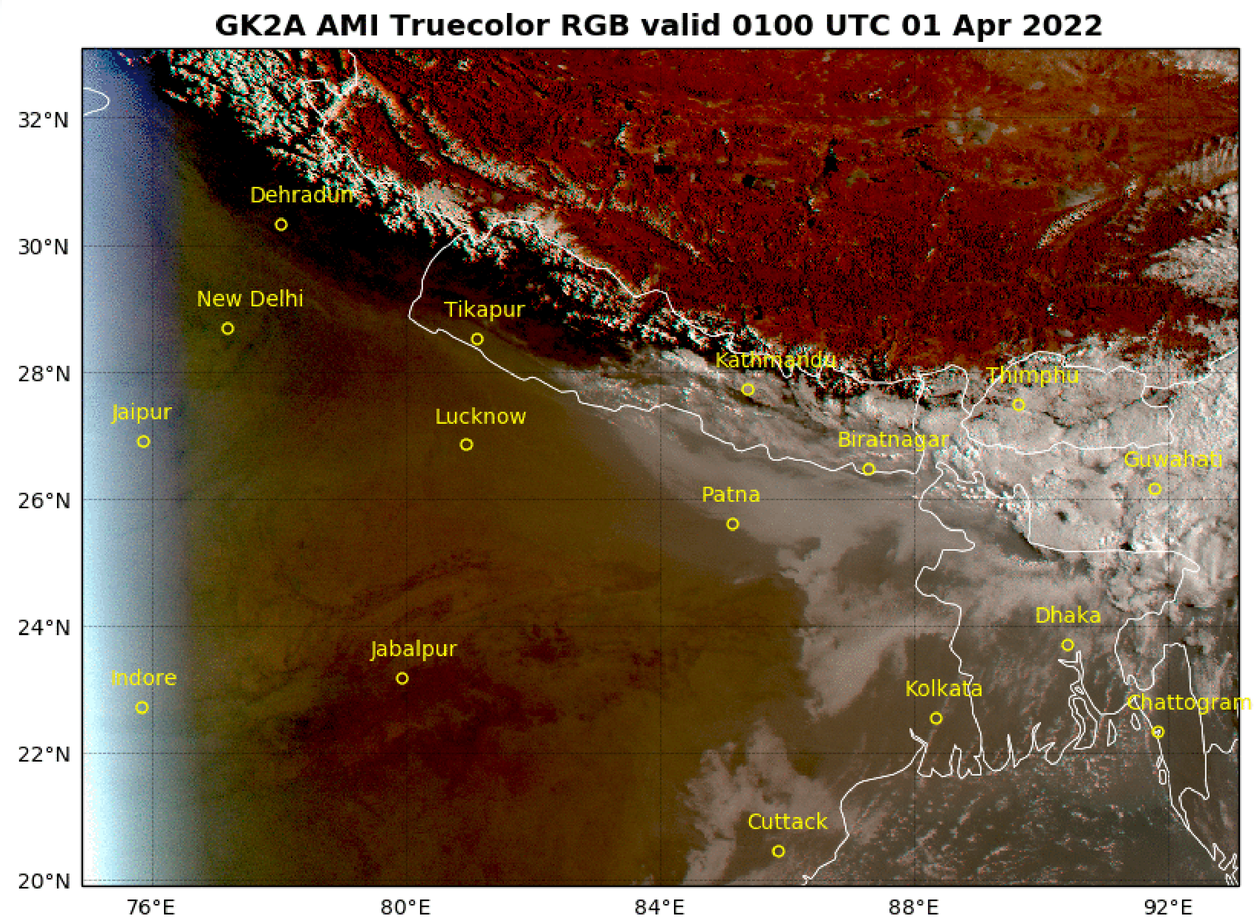
AMI True Color RGB – Recent Example



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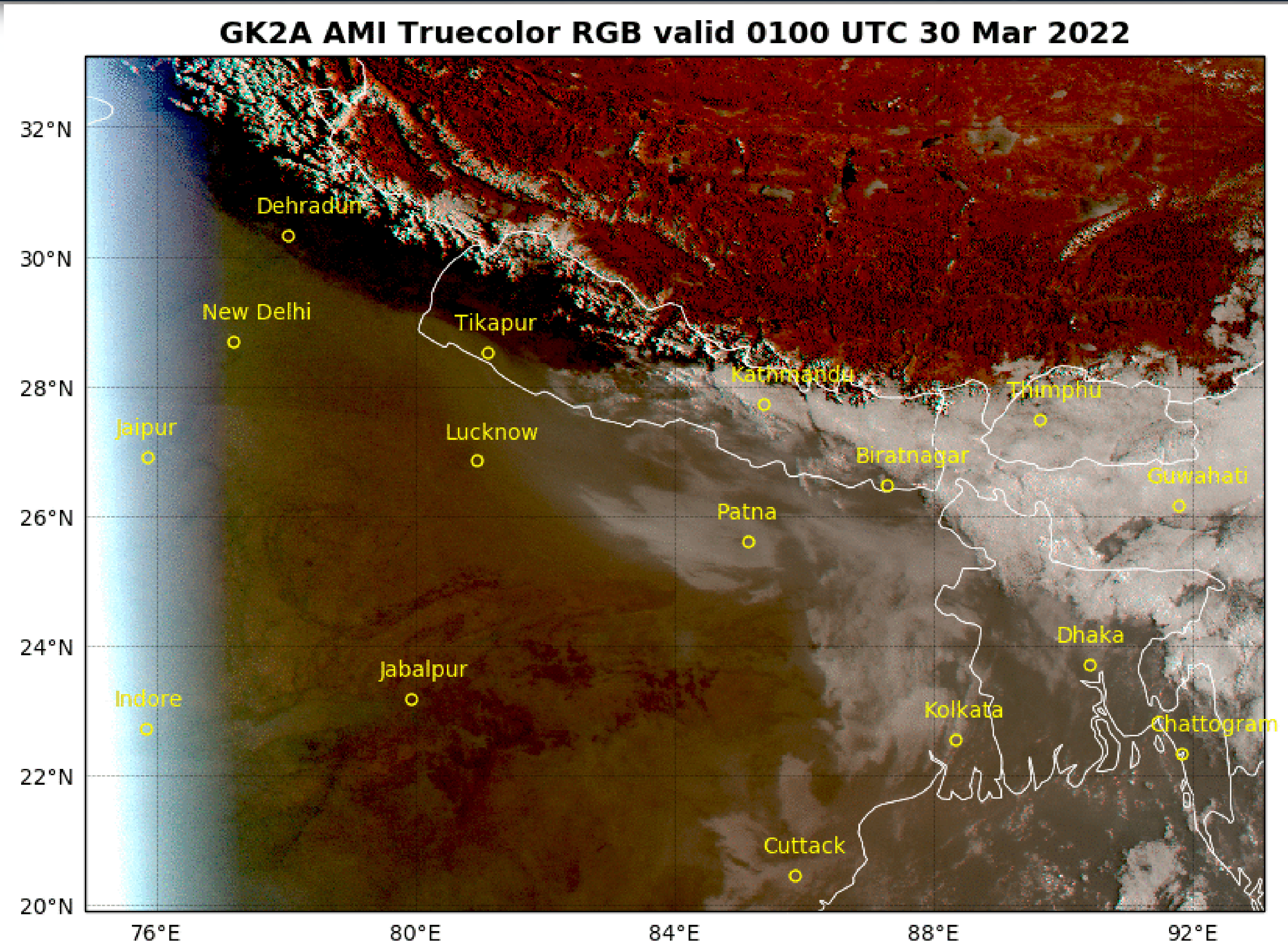
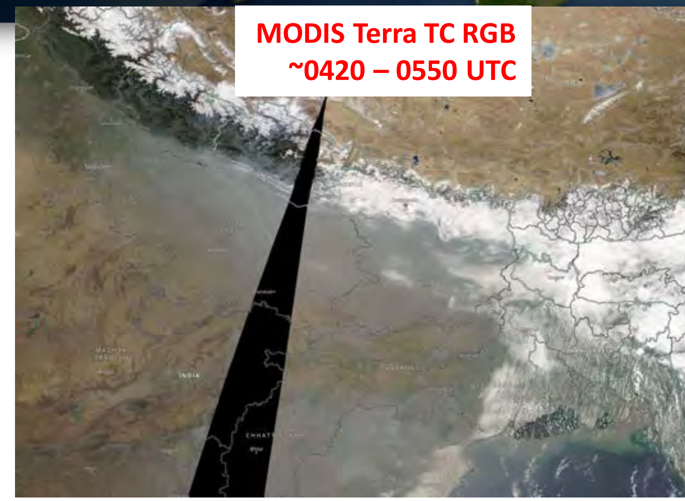
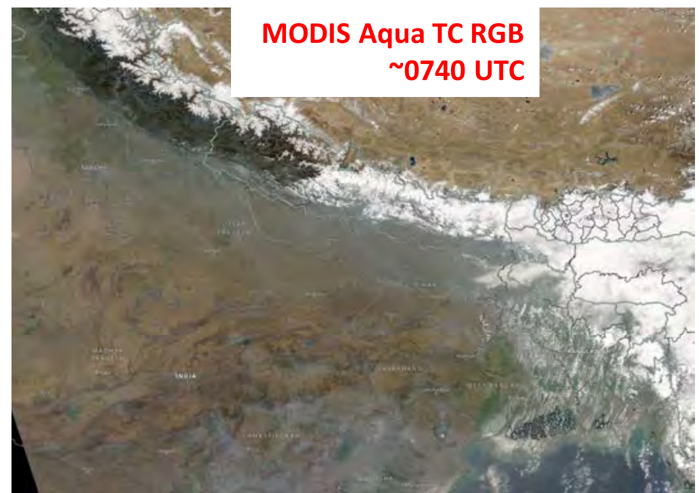
AMI True Color RGB – Recent Example



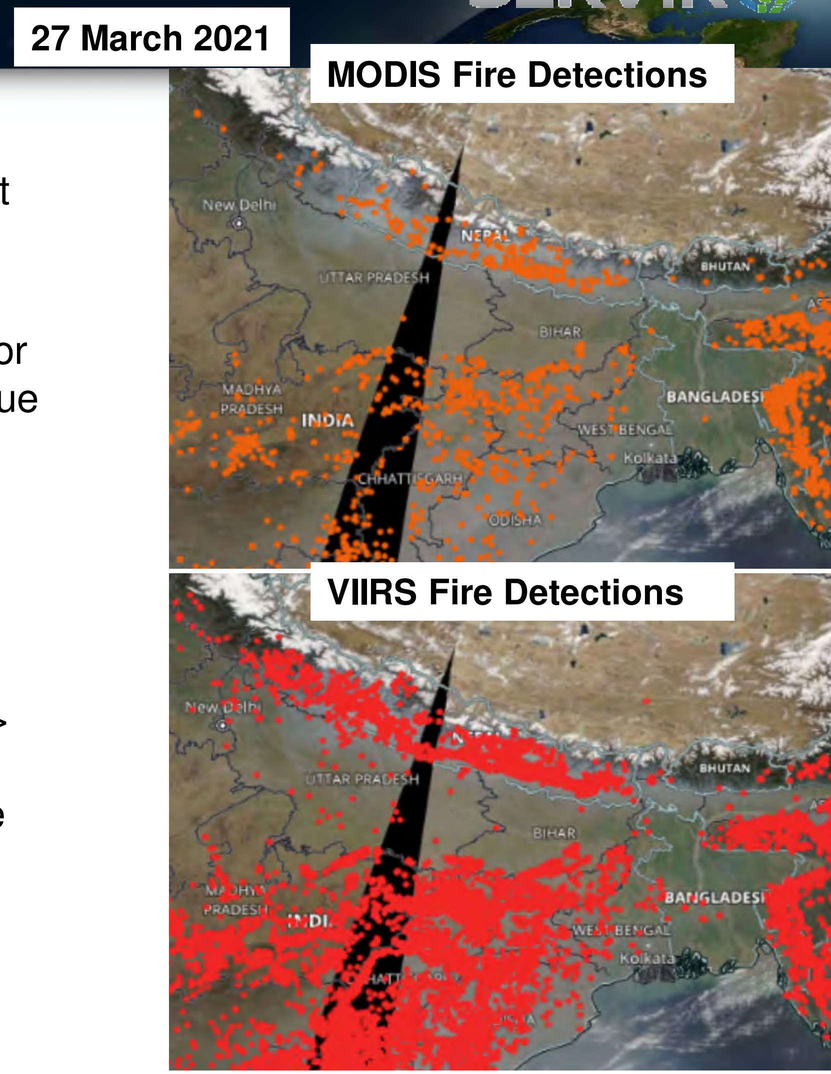




Fire Detections

Fire Detection – Introduction

- MODIS and VIIRS have high spatial resolution (1 km for MODIS, 375 m for VIIRS) for detecting small scale fires, but lack the temporal resolution for monitoring fires throughout the day
- AMI has sufficiently high temporal resolution (10 minutes) for daytime monitoring of fires, but can often miss small fires due to its coarser spatial resolution (> 4 km over HKH)
- A range of different fire detection methods have been implemented using various satellite sensors (e.g., MODIS, VIIRS, GOES, AHI) with a common theme being the application of the SW 3.9 μm band
- Stringent threshold tests relying on the 3.9 μm band (e.g., > 60 K) alone have been implemented for GOES, but these simple methods are only applicable to high-intensity wildfire events
- We develop a more intensive methodology for AMI fire detection using a series of band threshold tests along with auxiliary data to detect smaller scale, lower intensity fires



AMI Fire Detection – Methods

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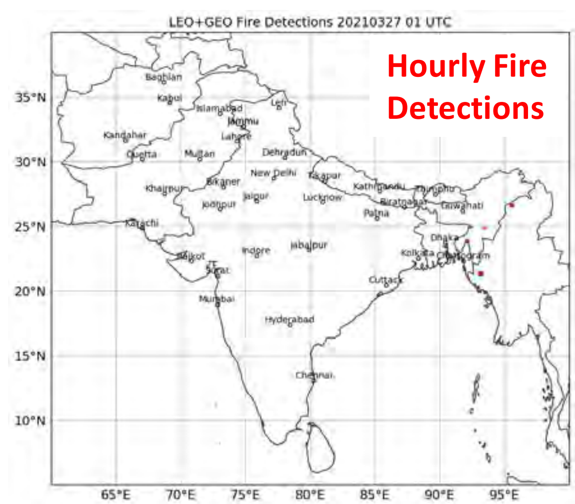
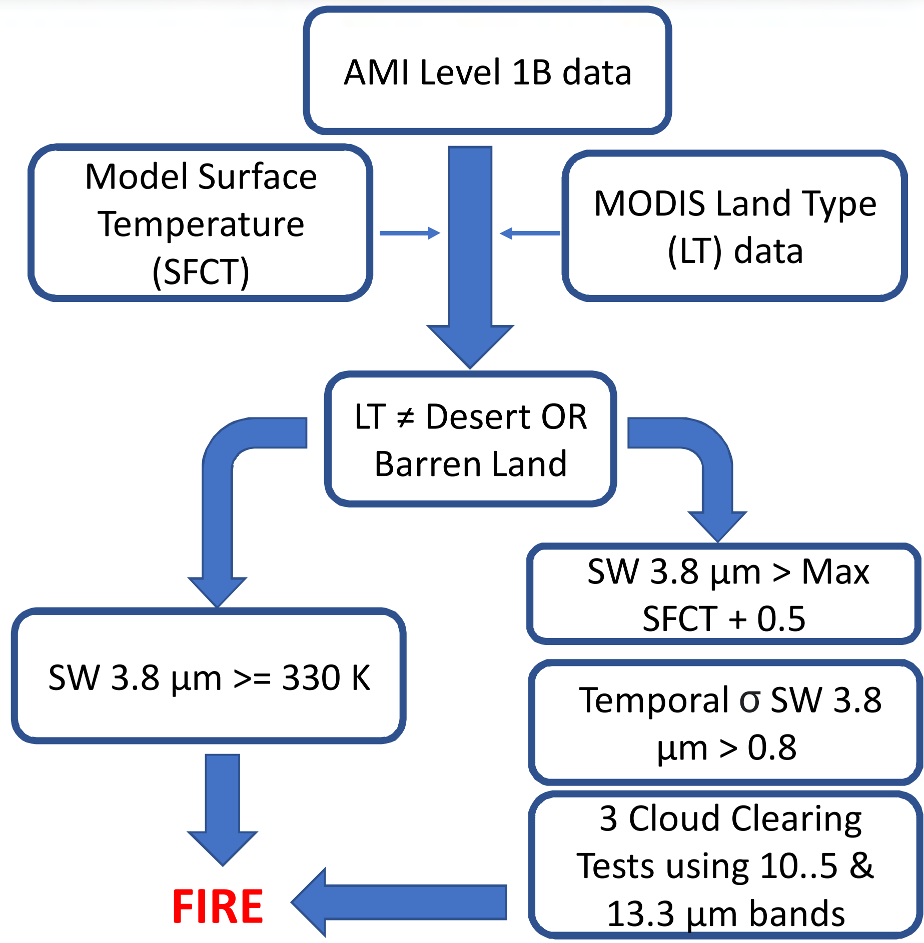
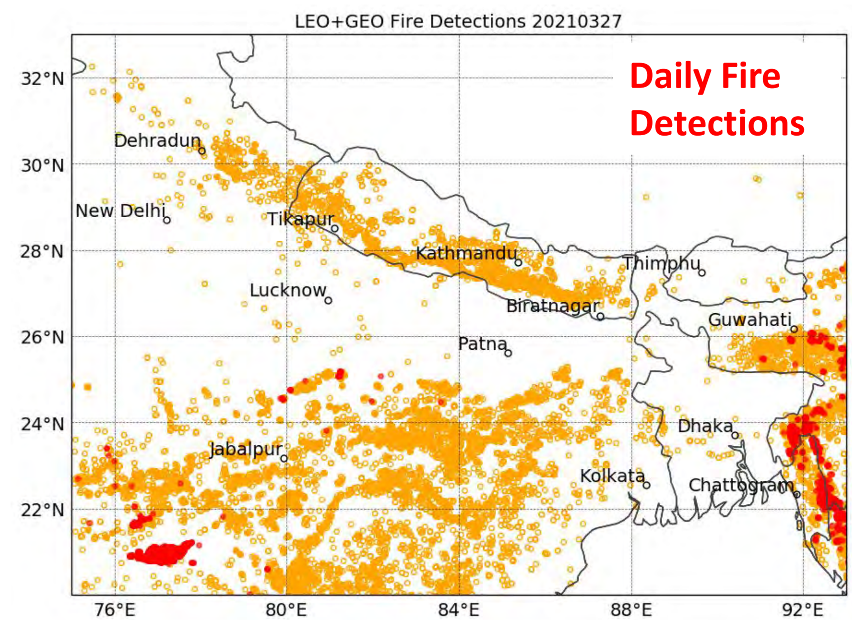
- ❑ AMI fire detection method is applied every 10 minutes!
- ❑ Hourly fire detection maps are a composite of the 10-minute AMI detections and MODIS fire detections in the 1-hour time window
- ❑ Daily fire detection maps are a composite of all AMI, MODIS, and VIIRS fires throughout the daytime
  - ▪ VIIRS is likely to have minor impact on fire detection map due to 3-hour latency





AMI Fire Detection – Results and Validation

- Algorithm was first tested in Spring 2021
- Initial validation efforts highlighted the good performance of the product
  - AMI detected numerous fire hot spots in the morning prior to MODIS and VIIRS observations
- As expected, MODIS and VIIRS detect many more fires compared to AMI due to higher spatial resolution
- Daily composite map of MODIS, VIIRS, and AMI fire detections show full extent of fires in region
- Additional validation efforts have commenced this spring to ensure methods are applicable across extended periods in operational setting



AMI can provide valuable information on evolution of fires and smoke over HKH

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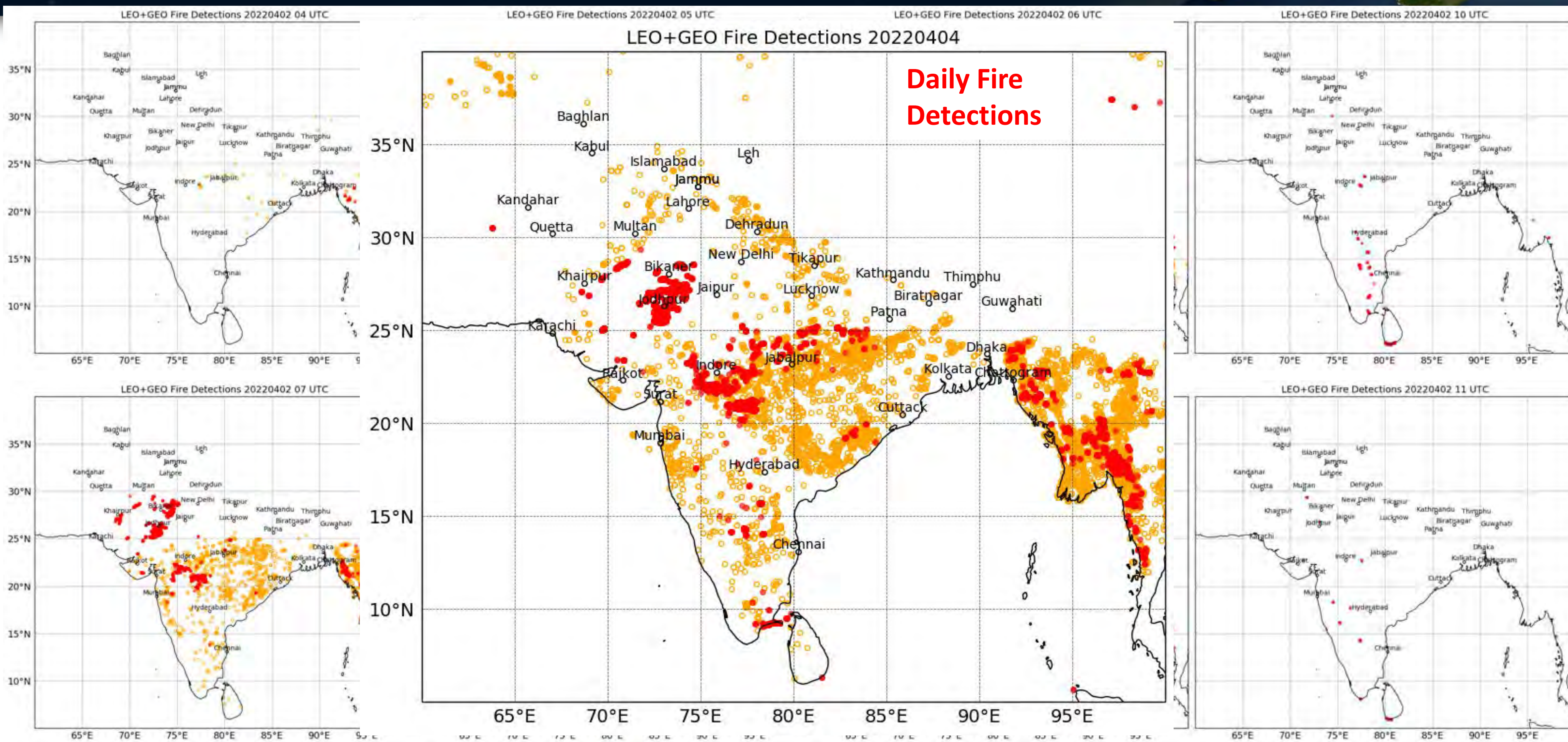
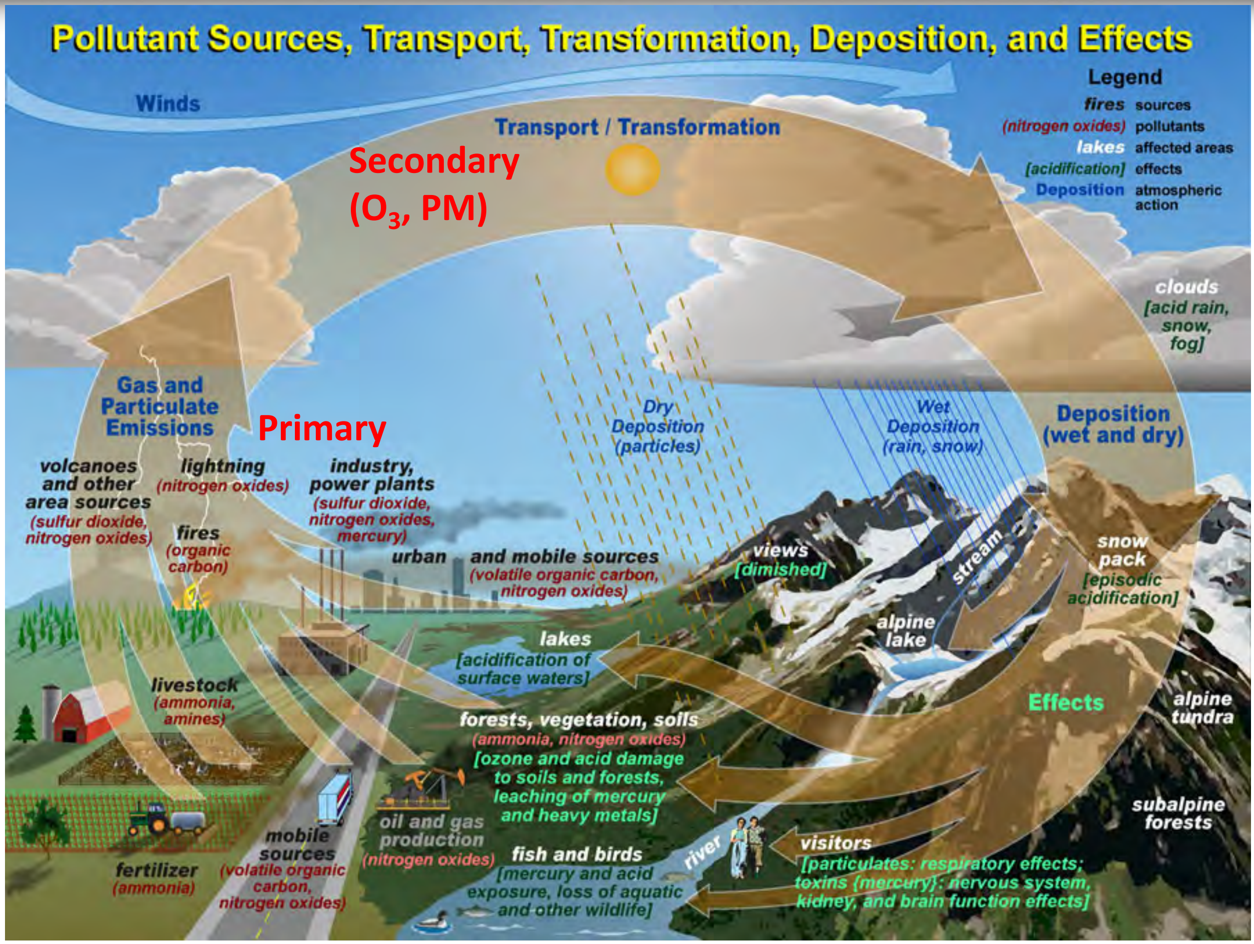
AMI Fire Detection – Recent Event



Discussion, Q&A
Break

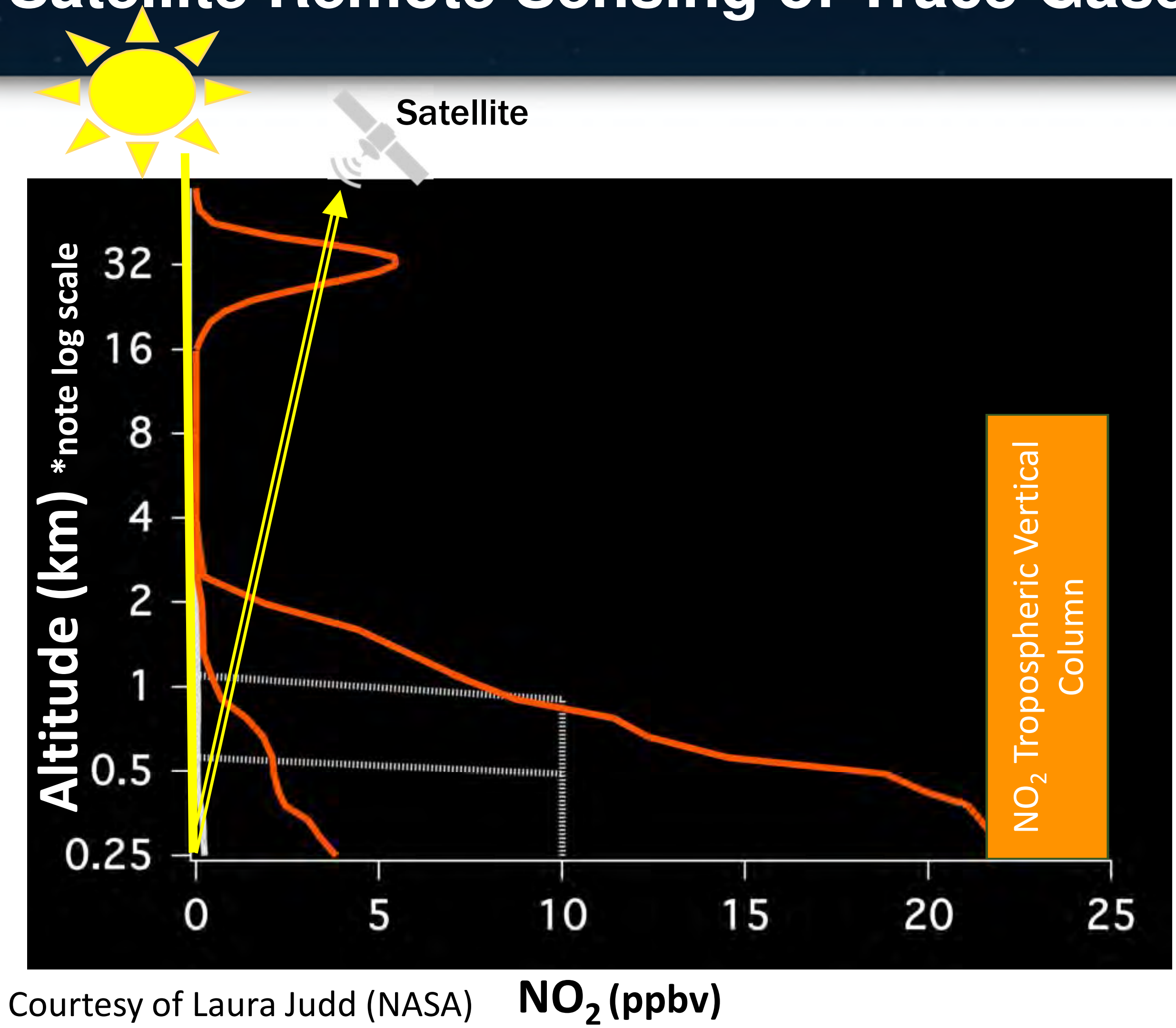
Introduction to Satellite Spectrometer Instruments

Air Pollution is a complex problem!



Credit: https://www.fws.gov/refuges/AirQuality/sources.html

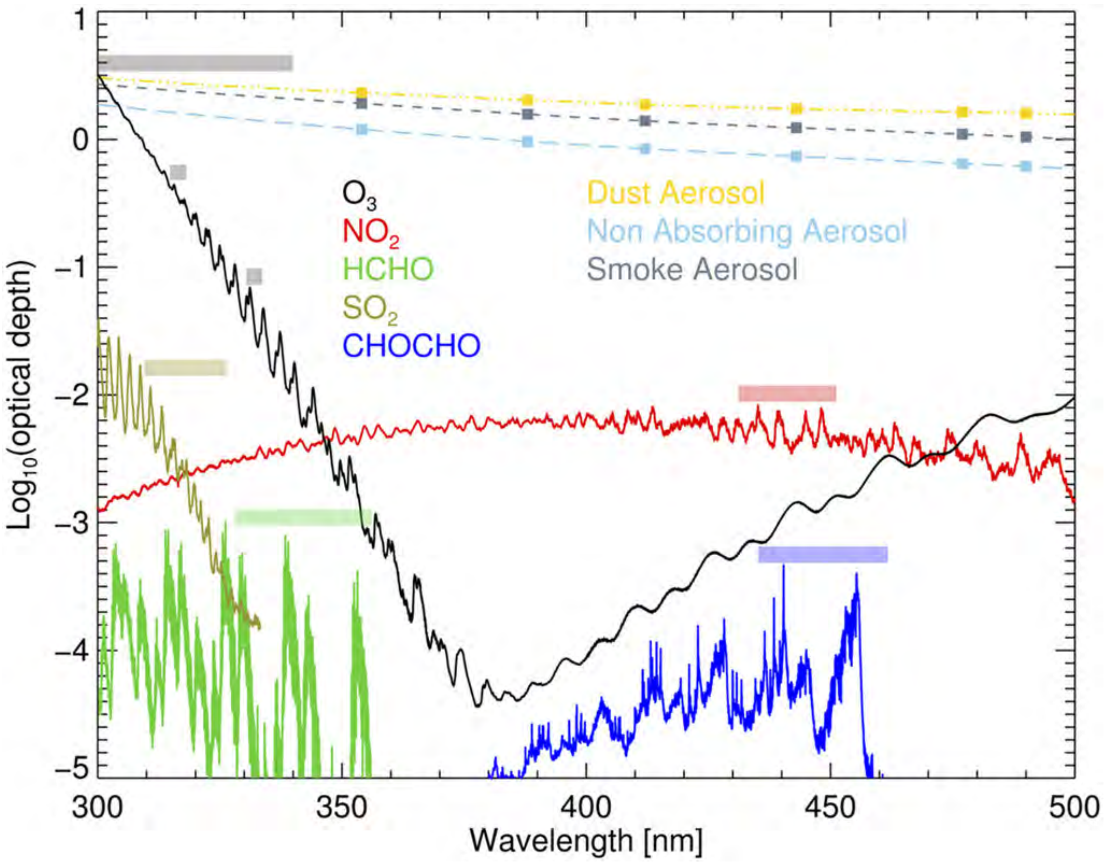
Satellite Remote Sensing of Trace Gases



Courtesy of Laura Judd (NASA)

- Satellites can only 'remotely sense' trace gas columns (e.g., NO2) by looking at absorption signatures in the light spectrum (Differential Optical Absorption Spectroscopy)
- Trace Gas Column Density: Integrated molecular density of gas through the vertical
- In situ monitors measure molecular density or mixing ratio at the surface

Satellite Remote Sensing of Trace Gases



Kim et al. (2020)

Optical depth spectra of aerosols and trace gases in example spectral range of satellite spectrometer for typical GEO measurement geometry. Different colors represent species for vertical optical depths (line).

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Legacy LEO orbit

- Spectrometer instruments aboard satellites are designed to measure trace gas pollutants (e.g., NO2, SO2, HCHO, O3, CO)
- Space-borne spectrometers currently providing publicly available data are aboard low-earth orbit (LEO) satellites, limited to mid-day overpass times
- NASA Ozone Monitoring Instrument (OMI), a UV-VIS spectrometer, has been operating since 2004.

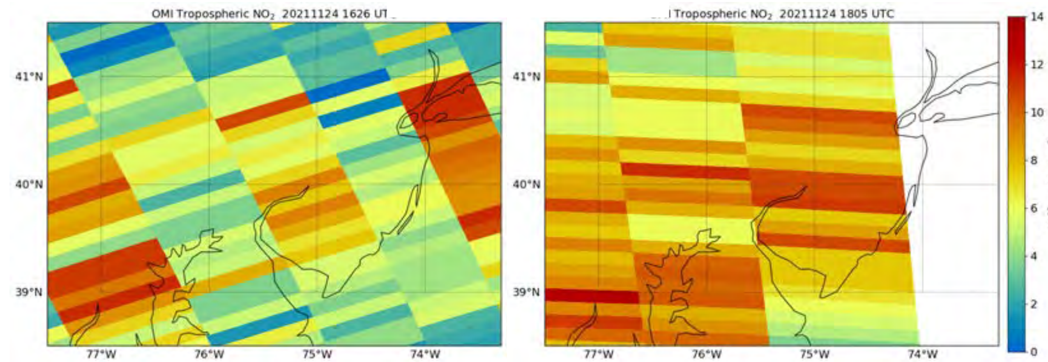
Figure Credit: https://svs.gsfc.nasa.gov/

Satellite Trace Gas Measurements – Spatial Resolution!

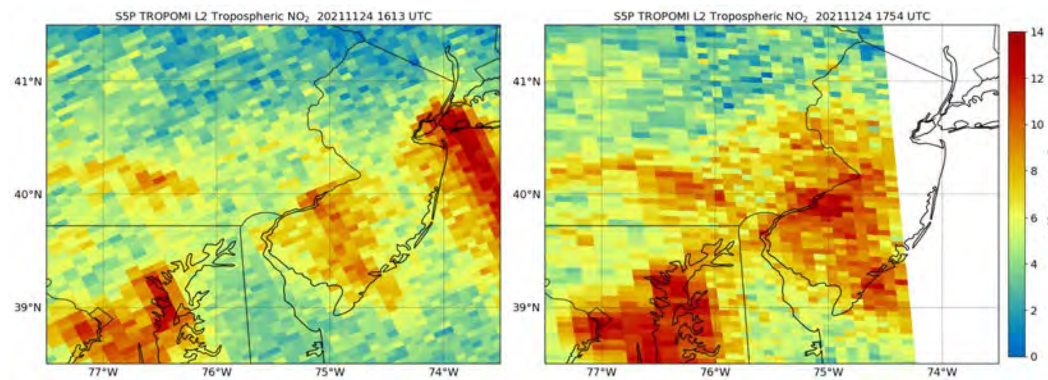
MODIS True Color RGB

- ❑ … 13 … of … d by
- ❑ … as … 5 … atmosphere
- ❑ **TROPOMI provides unprecedented pollution observations from space!**

OMI NO2



TROPOMI NO2



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OMI vs TROPOMI – Spectral Characteristics

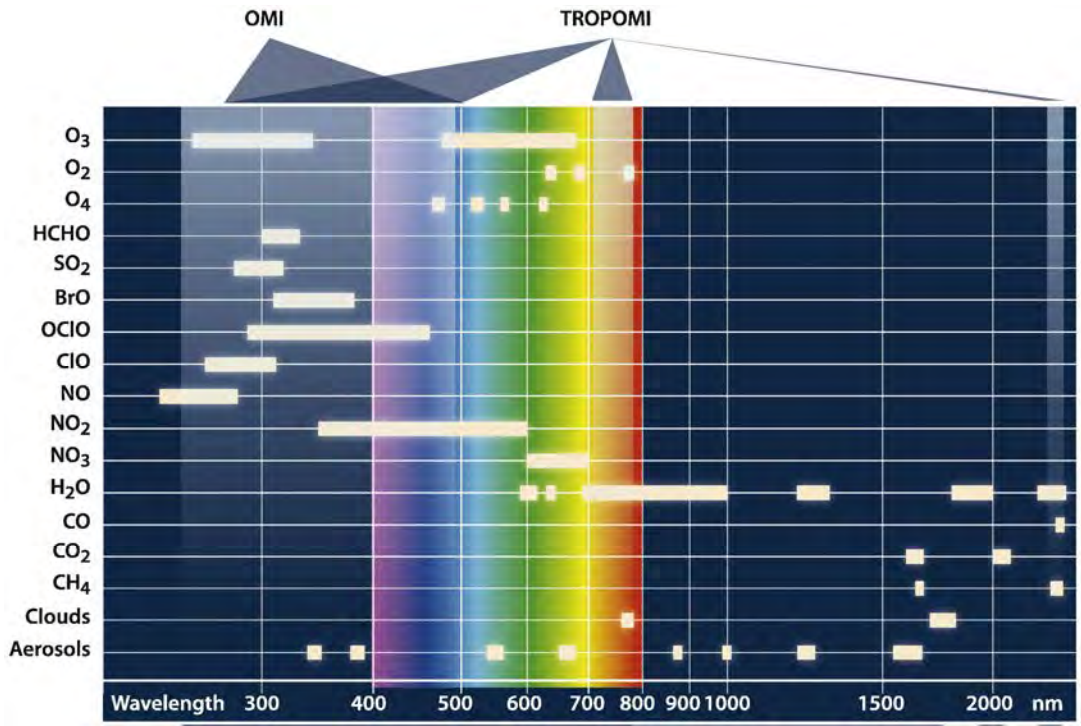
https://space.oscar.wmo.int/instruments/

OMI

Spectral range	No. of channels	Spectral resolution
270 - 314 nm	390	0.63 nm
306 - 380 nm	390	0.42 nm
350 - 500 nm	780	0.63 nm

TROPOMI

Spectral ranges	Number of channels	Spectral resolution
270-495 nm	1200	0.55 nm
710-775 nm	600	0.55 nm
2305-2385 nm	800	0.25 nm



Veefkind et al. (2012)

TROPOMI provides more information on air pollution by measuring in the UV, VIS, NIR, & SWIR, including CO, CH4, and additional aerosol properties (Aerosol Layer Height)

Trace Gas Products

OMI vs TROPOMI – Data Products

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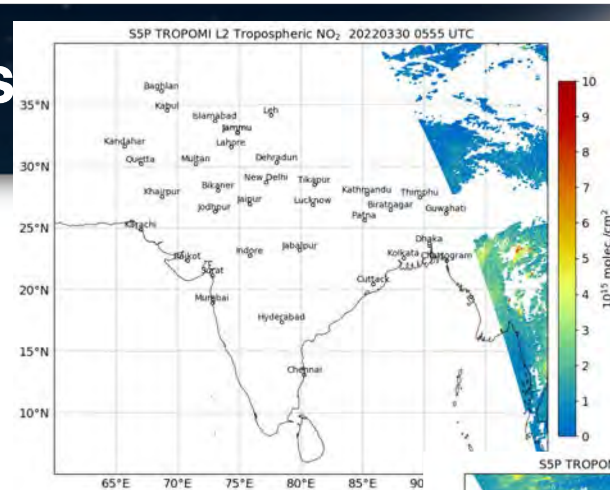
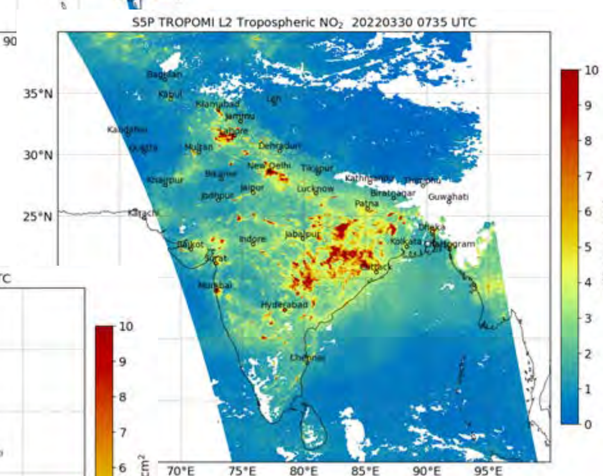
TROPOMI

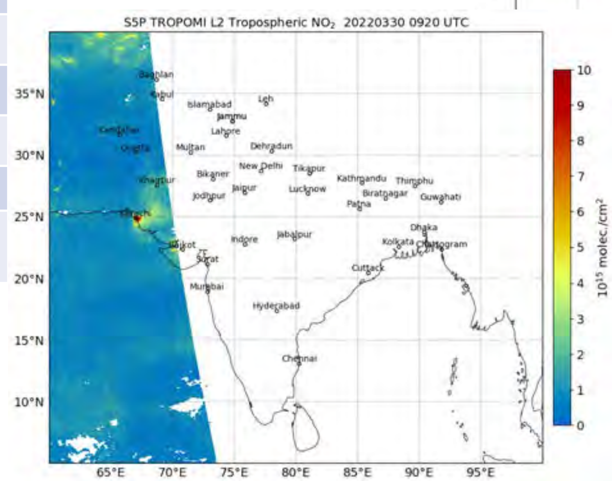
Level	Product	Major Outputs	Res km^2
L2	Cloud	Cloud fraction, cloud pressure	5.5 x 3.5
	O_3 Profiles	O3 profile, stratospheric, tropospheric O3 column, errors	28.0 x 28.0
	Total O_3	Total O3	5.5 x 3.5
	NO_2	Total and tropospheric columns	5.5 x 3.5
	HCHO		5.5 x 3.5
	SO_2	Total columns	5.5 x 3.5
	CO		7.0 x 7.0
	CH_4		5.5 x 7.0
	Aerosol Layer Height	Mid-level pressure	5.5 x 3.5
	UV Aerosol Index	Aerosol Index	5.5 x 3.5

Products in Red are also provided by OMI but at reduced spatial resolution of 13 x 24 km^2 at nadir



TROPOMI swaths over HKH





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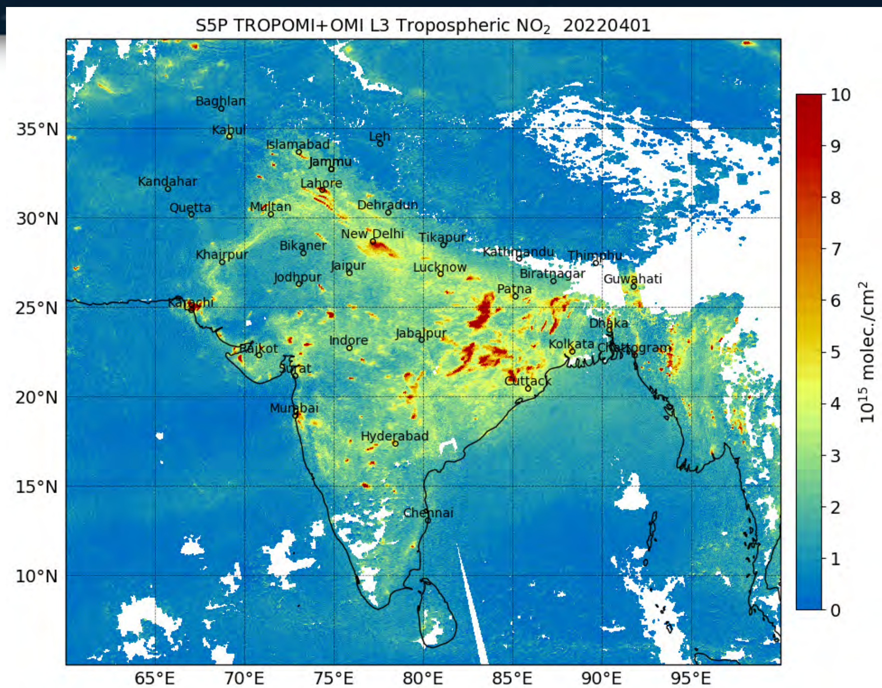
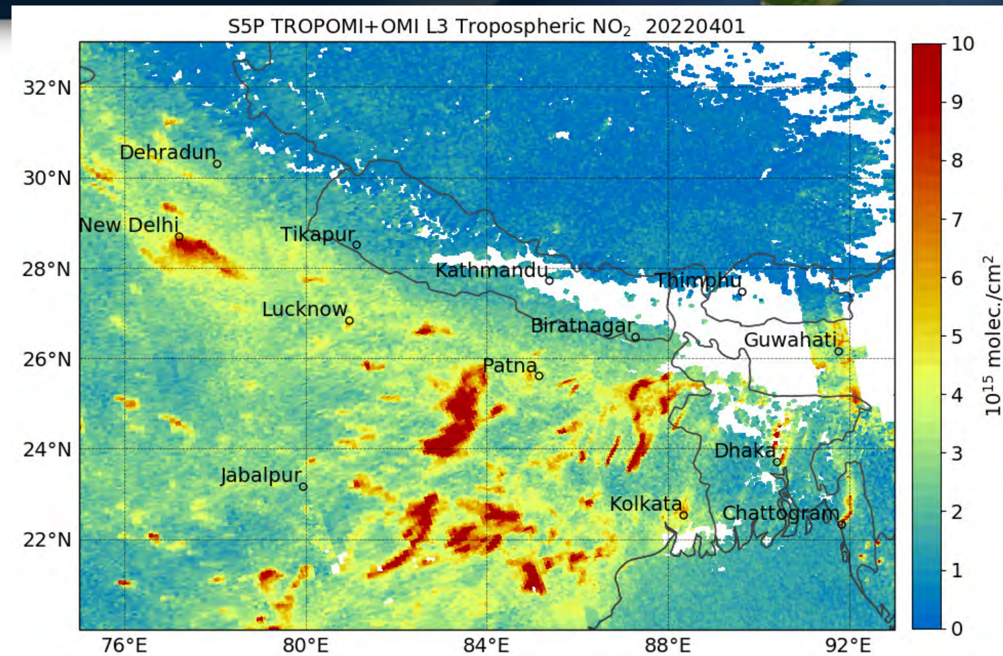
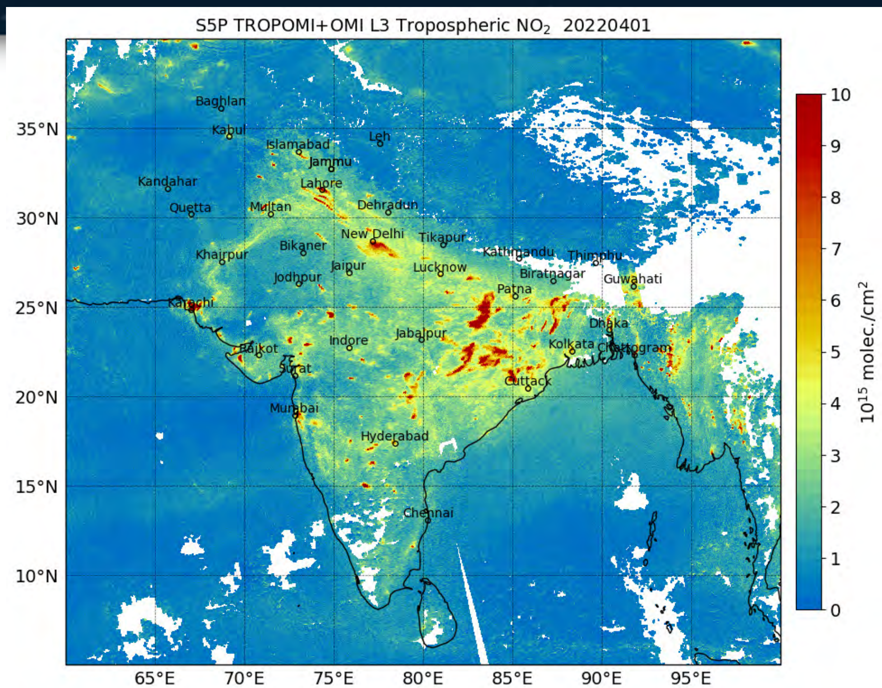
TROPOMI+OMI Level 3 NO2 Product

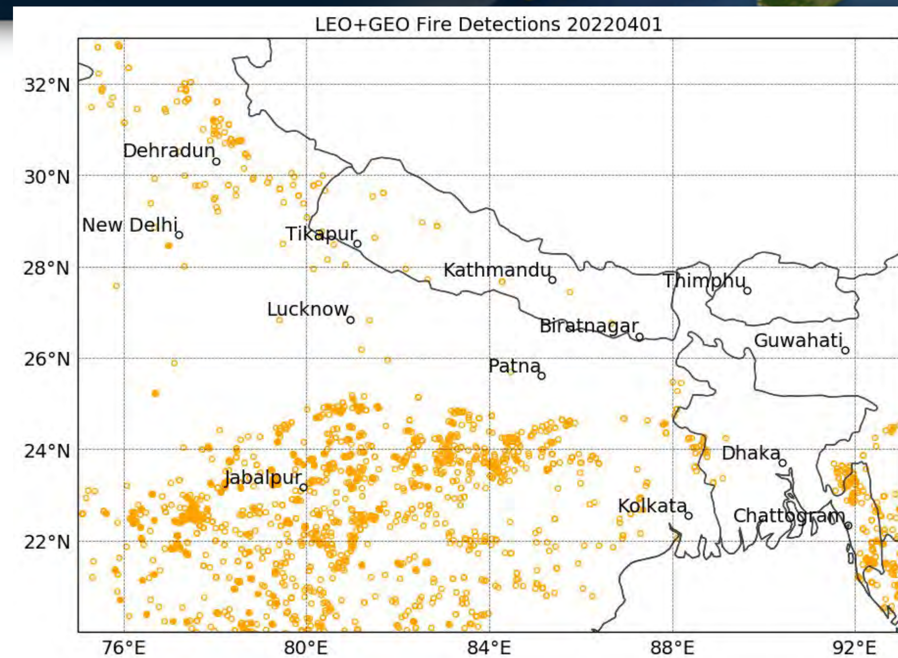




- Level 2 swath data stitched together using quality assurance measures (e.g., cloud fraction > 50%, partially snow/ice covered scenes, errors) to retain only high quality data
- Spatial weighting interpolation routine applied to remap to regular grid of 0.02°
- High NO2 tropospheric VCDs due to various emissions sources including fire, power plant, and fire emissions

TROPOMI+OMI Level 3 NO2 Product





- Level 2 swath data stitched together using quality assurance measures (e.g., cloud fraction > 50%, partially snow/ice covered scenes, errors) to retain only high quality data
- Spatial weighting interpolation routine applied to remap to regular grid of 0.02°
- High NO2 tropospheric VCDs due to various emissions sources including transportation, urban, power plant, and fire emissions

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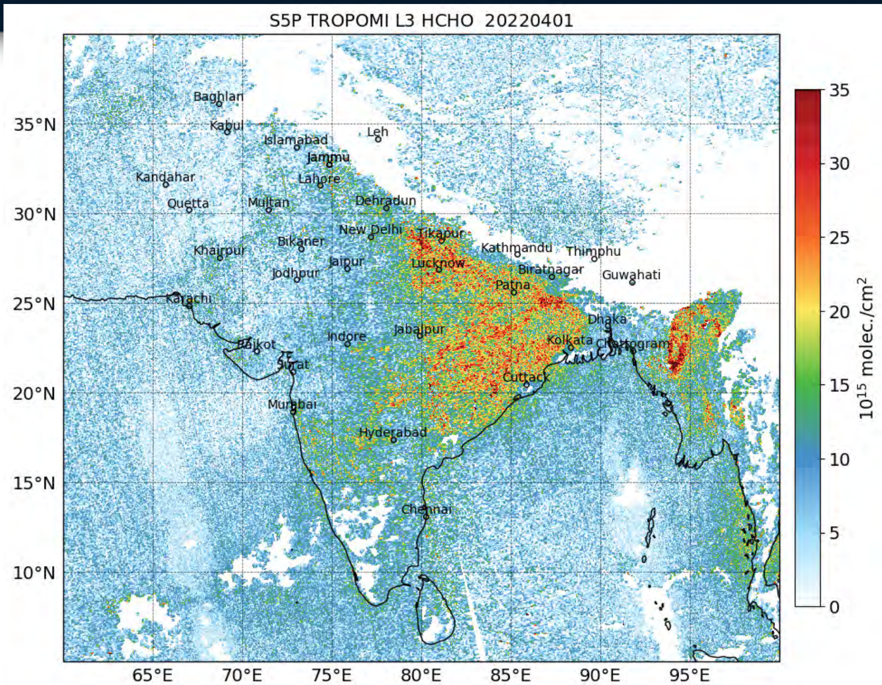
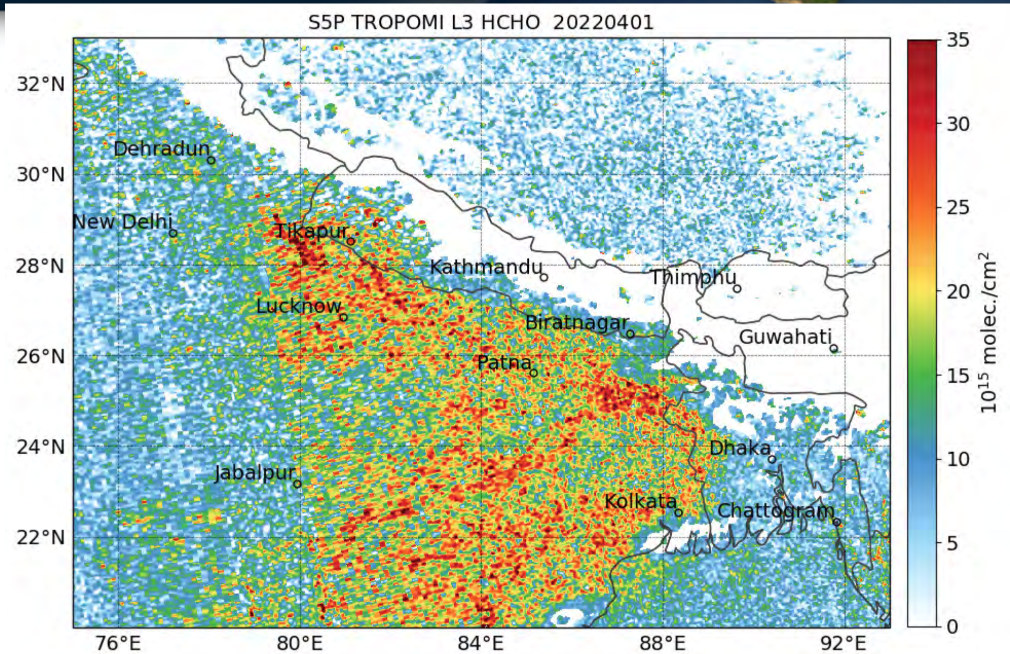
TROPOMI Level 3 HCHO Product





- Similar procedure as NO2 for generating Level 3 HCHO Product, except destriping method applied using previous two days of HCHO data over the middle of the Pacific Ocean
- HCHO retrievals from space are noise sensitive and error prone, but TROPOMI has good enough sensitivity to resolve real and important HCHO features
- Vegetation, fires, traffic and industrial sources can all result in localized enhancement in HCHO
- Strong signals of HCHO within smoke plumes have been observed across HKH

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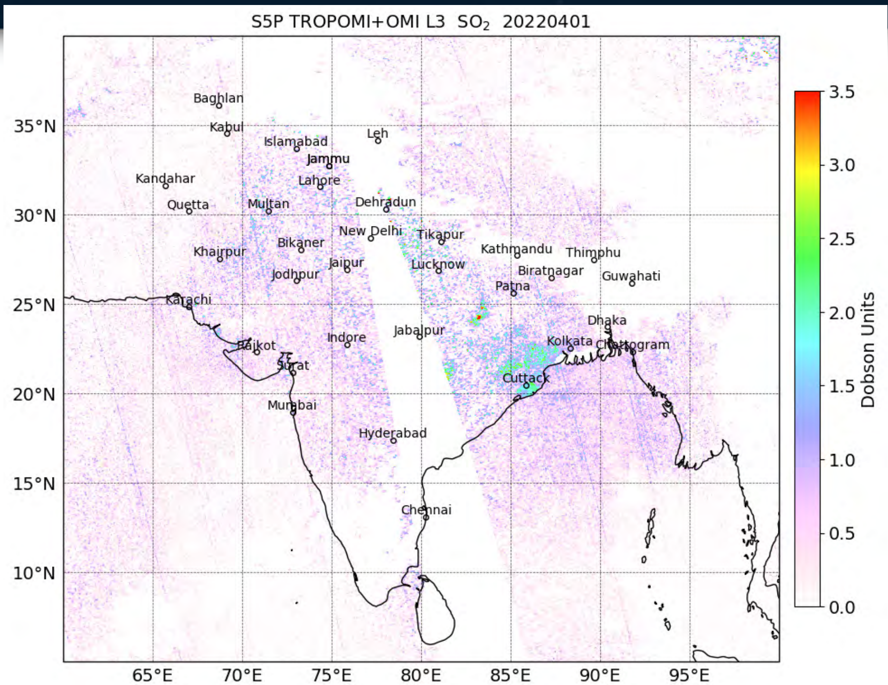
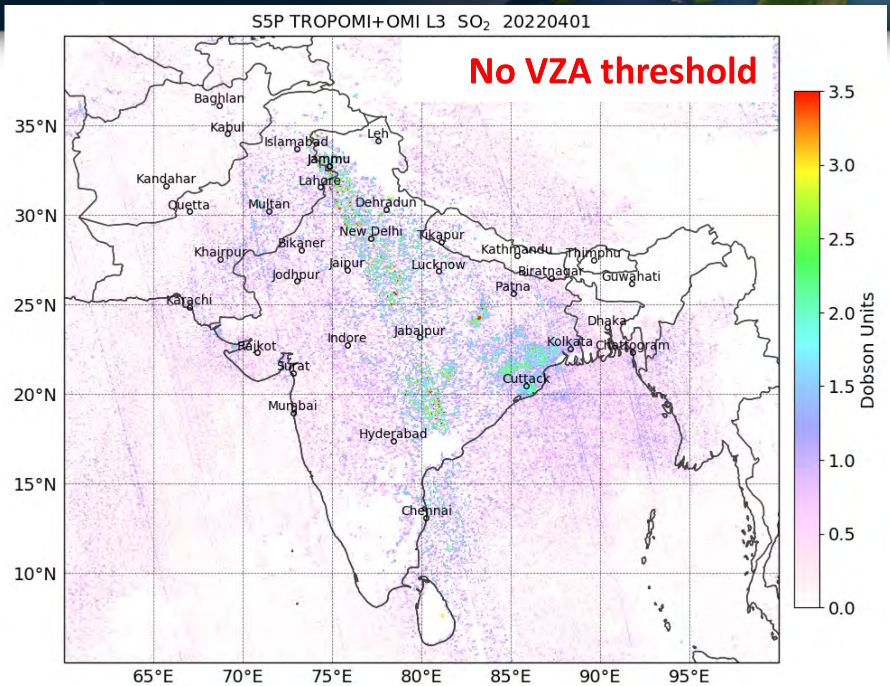
TROPOMI+OMI Level 3 SO2 Product





- Some stricter quality control measures are applied for SO2, such as disregarding SO2 pixels associated with viewing zenith angle > 60°
- Noisy retrievals at high viewing zenith angles lead to false signals of SO2 and potentially poor interpretation by users

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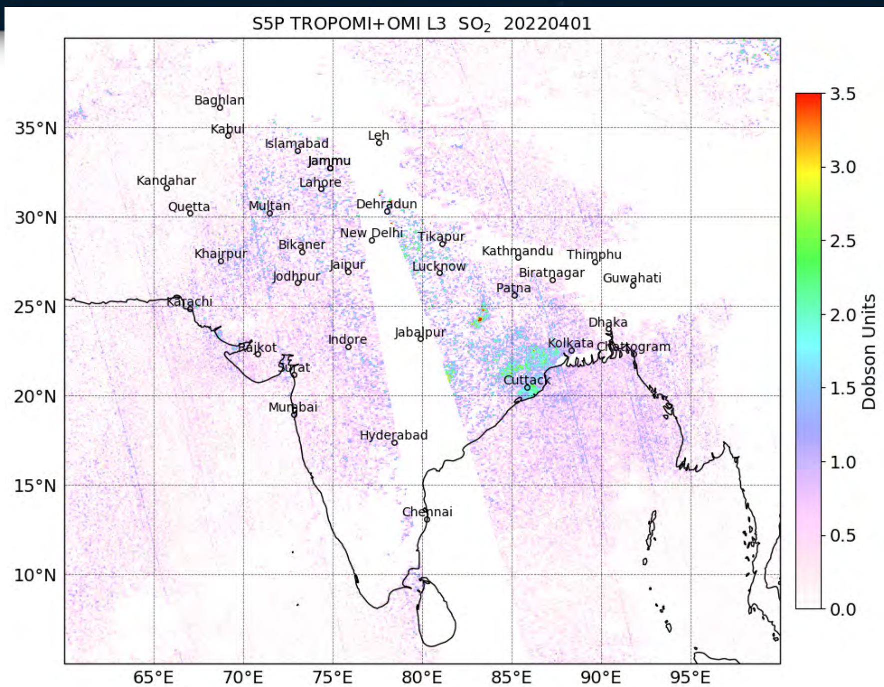
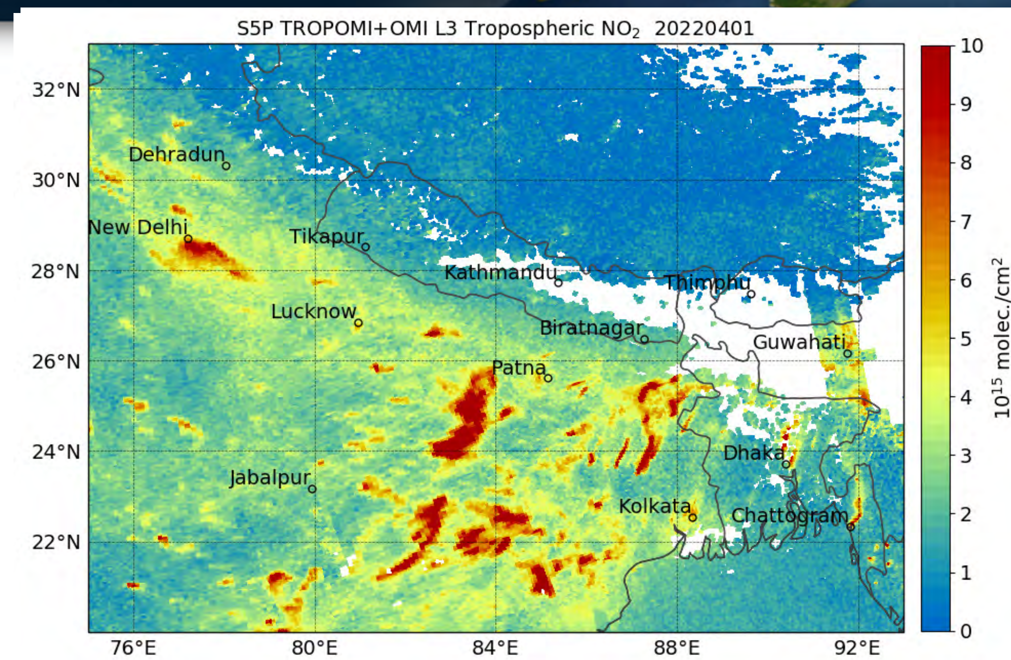
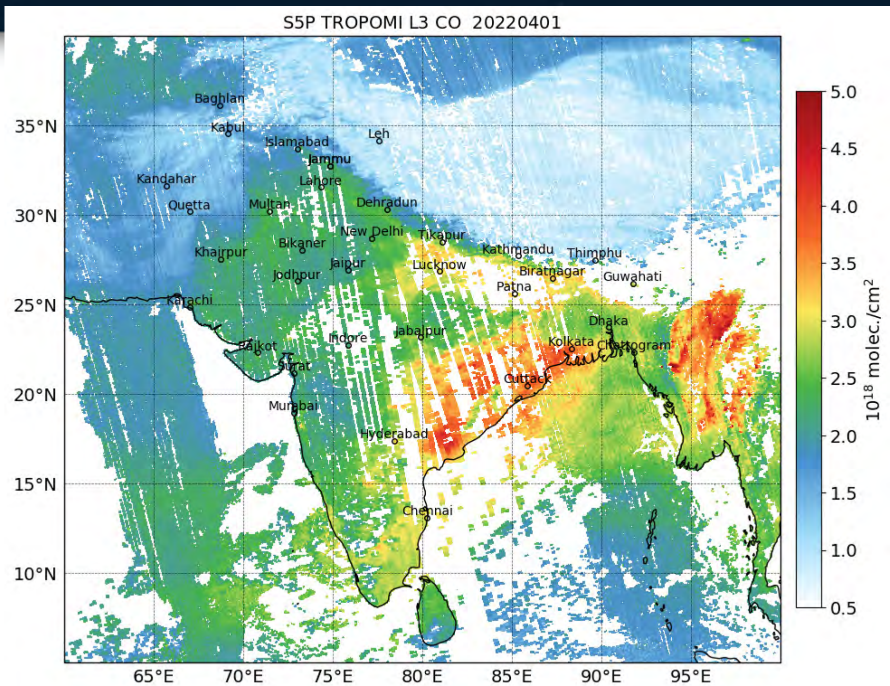
TROPOMI+OMI Level 3 SO2 Product

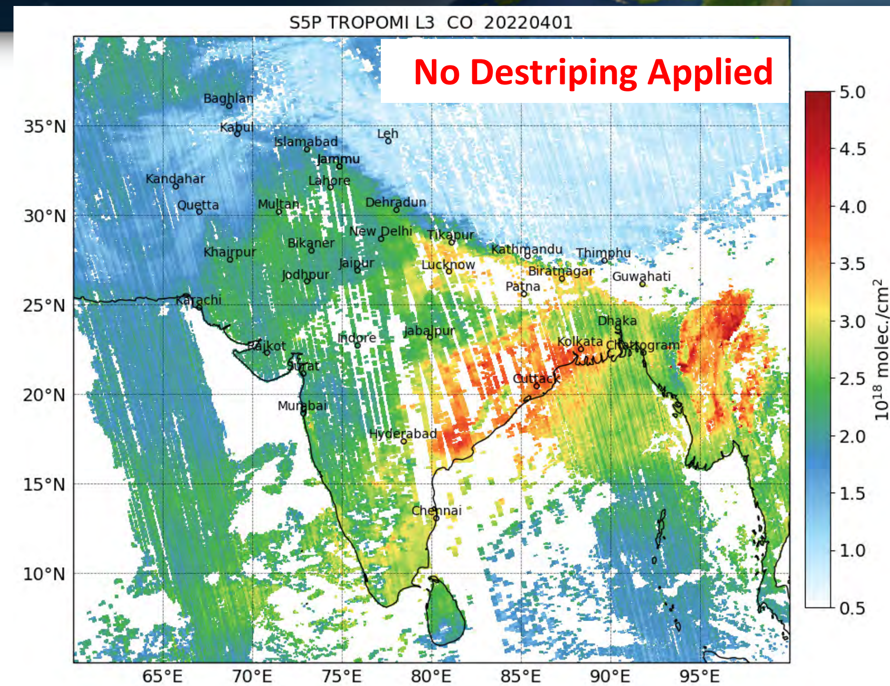




- Only ~30% of emitted SO2 comes from natural sources (e.g., volcanoes), as the majority is of anthropogenic origin such as power plants
- We have found many distinct SO2 and NO2 signals from coal fired power stations in the HKH region

TROPOMI Level 3 CO Product





- Striping pattern in CO retrievals from spectrometers is a well recognized issue, which can make it difficult to decipher the detection of small scale sources and estimate fire emissions
- We apply destriping technique that applies 7 days of previous CO data over the central Pacific to significantly reduce the striping issue

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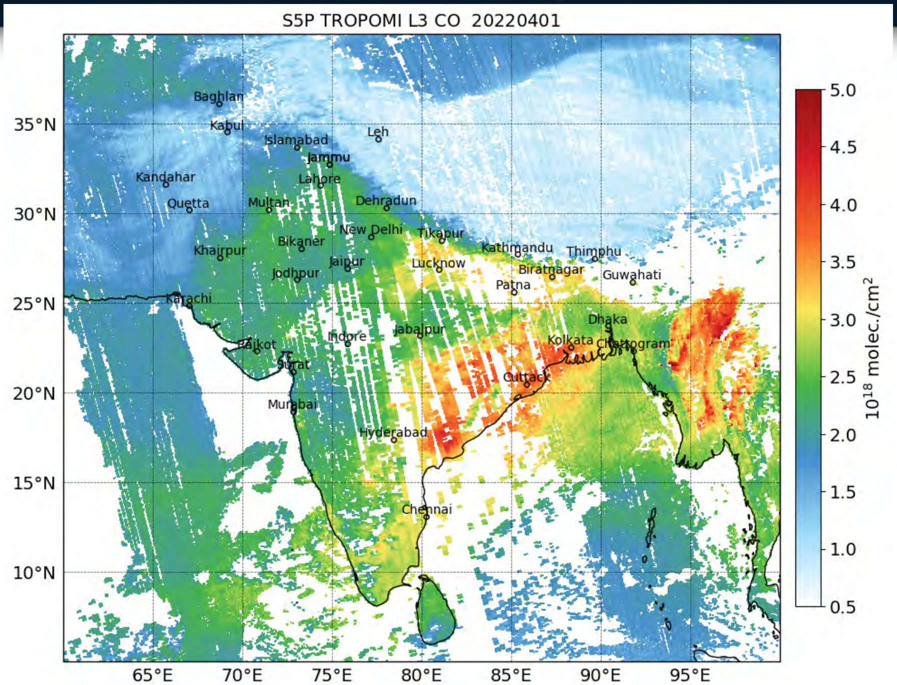
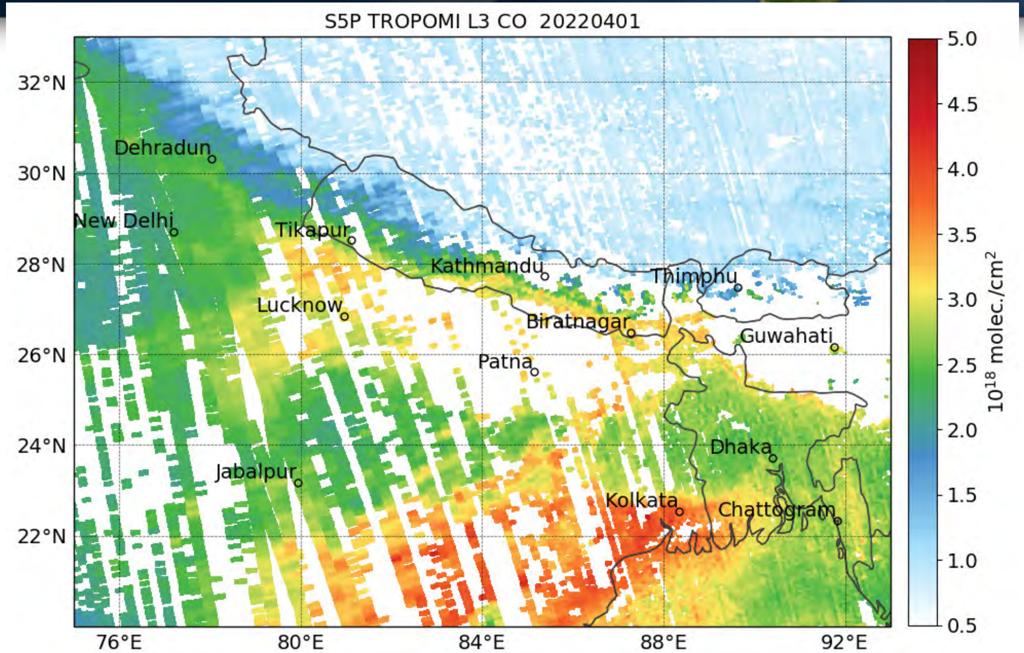
TROPOMI Level 3 CO Product





- Main sources of CO are combustion of fossil fuels, biomass burning, and atmospheric oxidation of methane, etc.
- During active burning seasons over HKH, we have observed high CO VCDs from TROPOMI in the regions of smoke
- Excellent tracker of smoke pollution in the region

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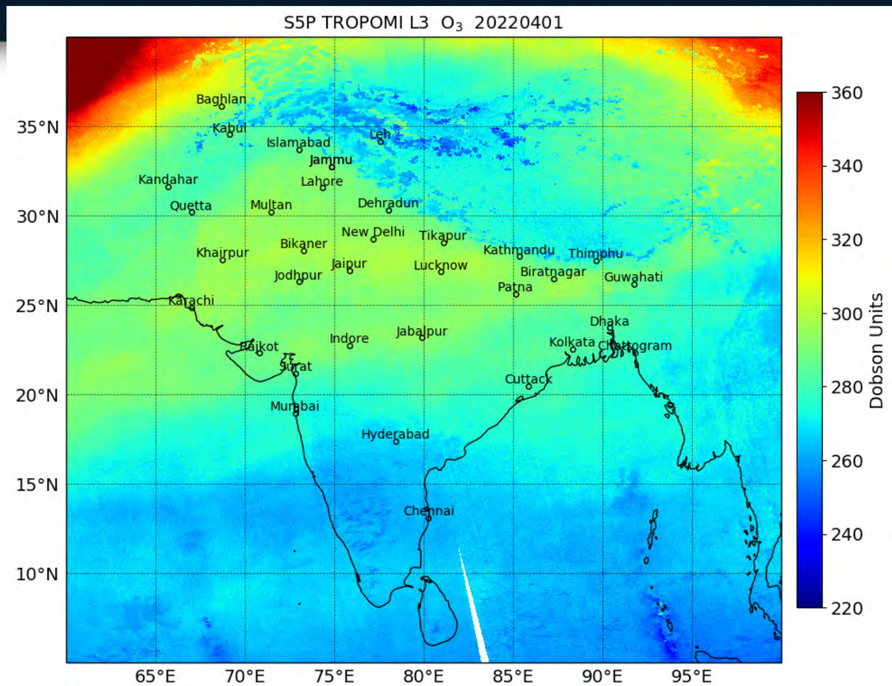
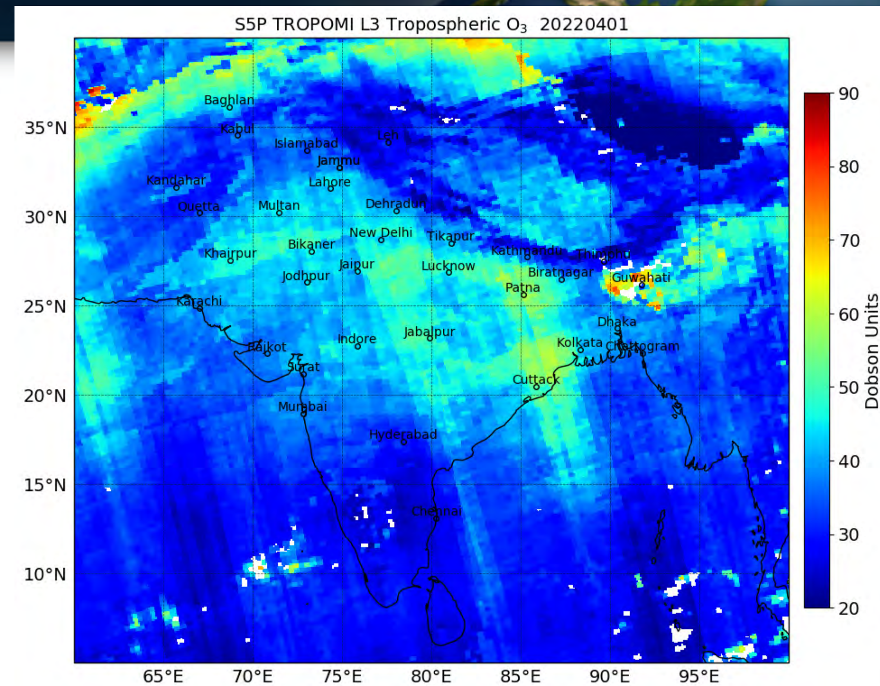
TROPOMI Level 3 O3 Products





- Ozone is a long-lived secondary pollutant in that atmosphere, which can be harmful to human and vegetation health at high concentrations
- Stratospheric ozone intrusions contributes to ozone abundance in troposphere, but ozone is also produced through precursor emissions (NOx) and chemical reactions, leading to smog
- TROPOMI has new capability of distinguishing ozone concentrations in the tropospheric layer
- Level 3 O3 tropospheric product is at reduced spatial resolution of 0.08°

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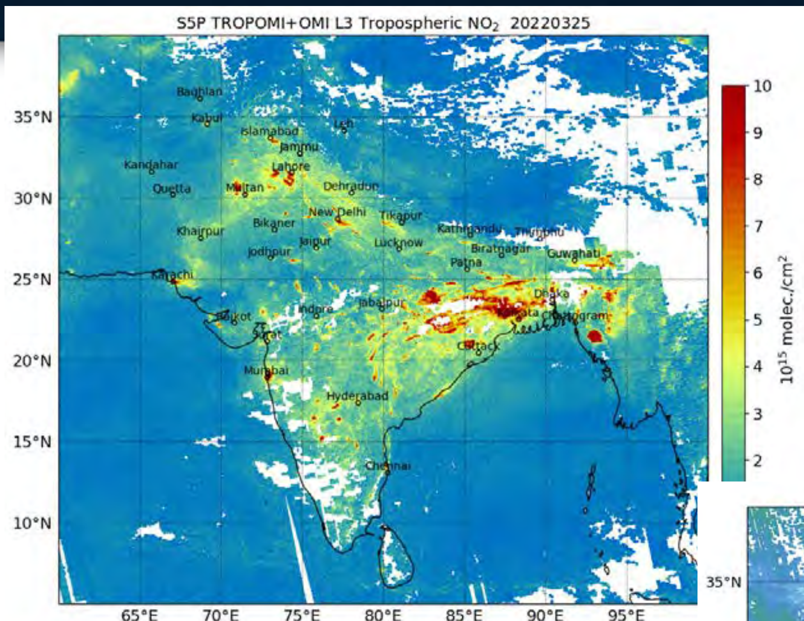
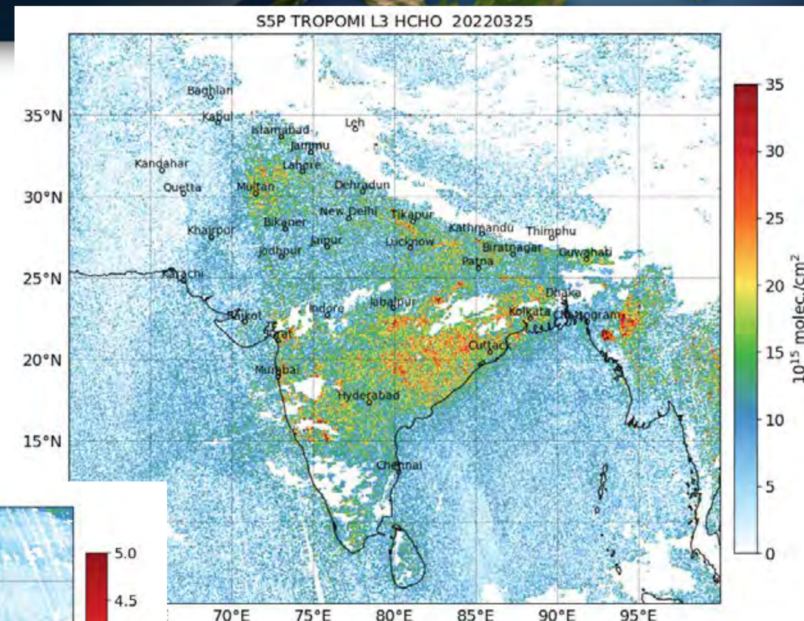
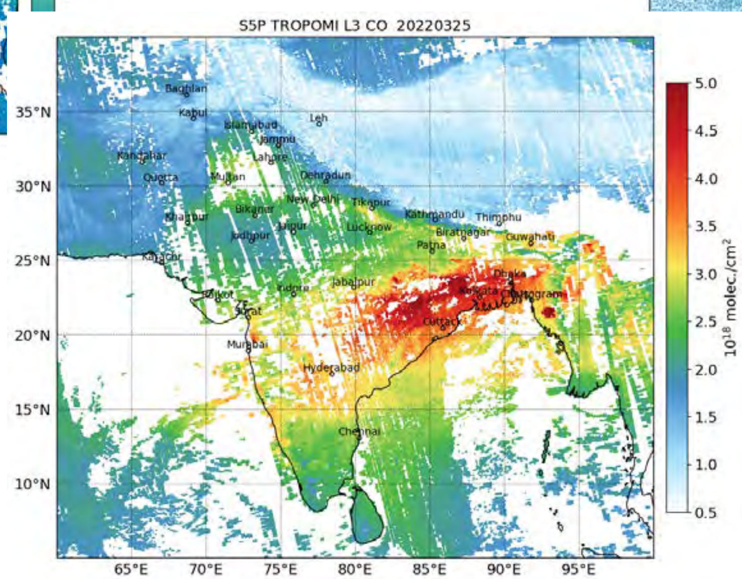
25 March 2022 - Smoke Pollution Event

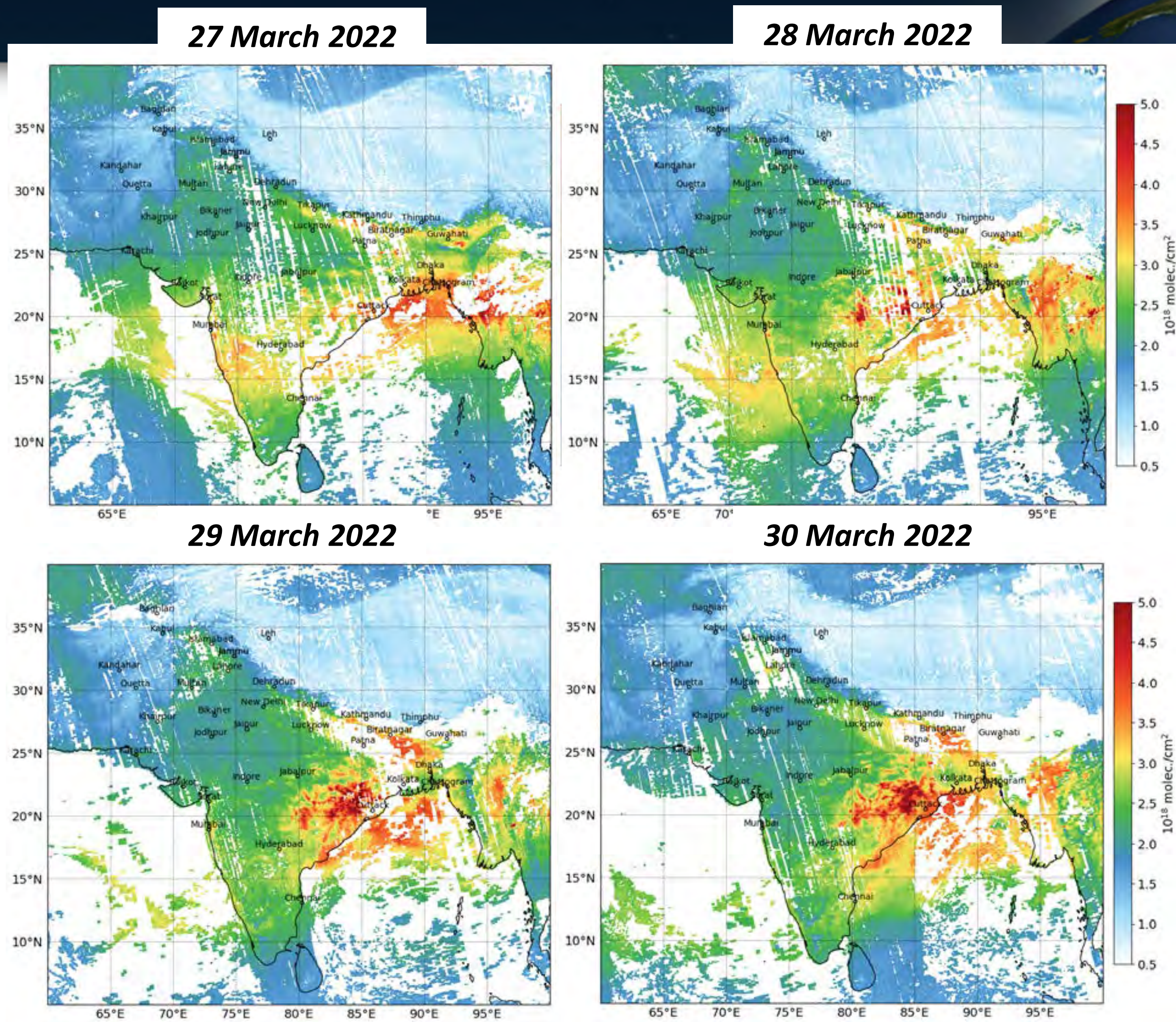






Suite of advanced trace gas products from new generation satellite instruments can aid in characterizing emissions, pollutant mixtures, and associated air quality impacts

Smoke and CO



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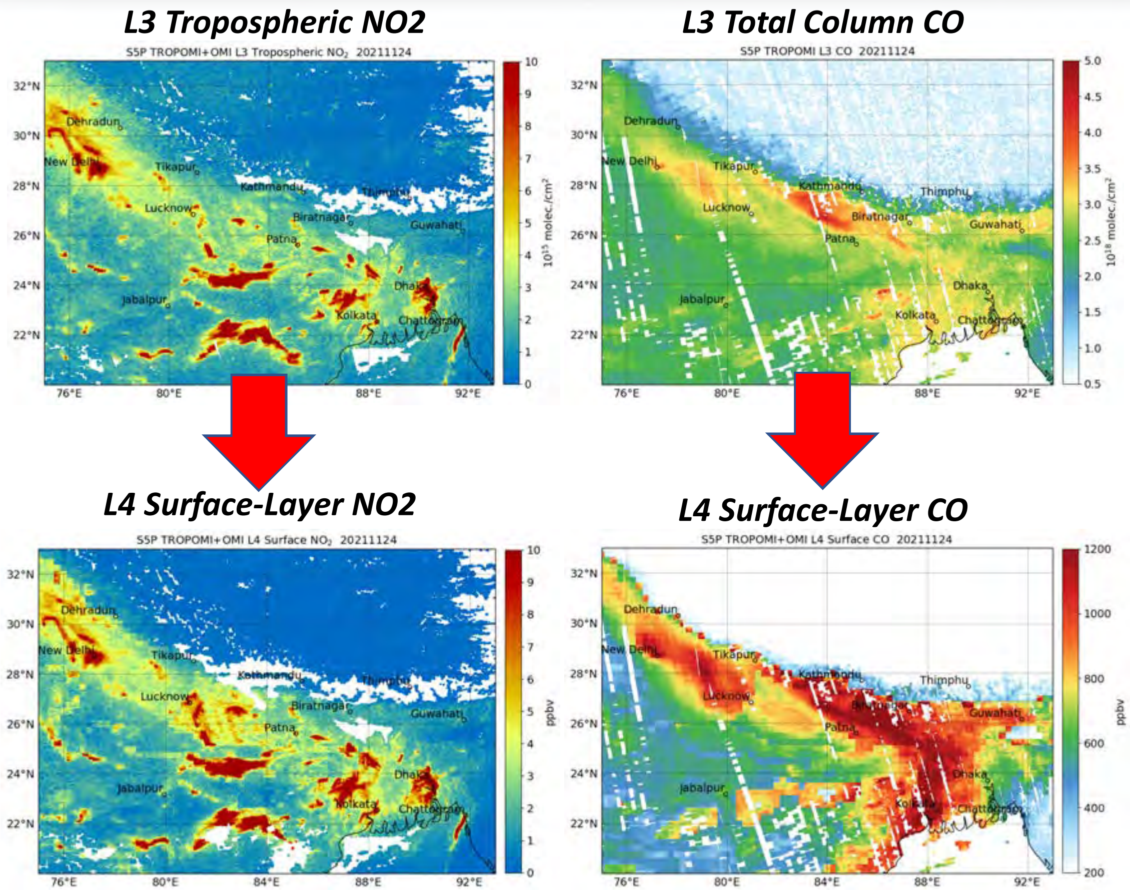
Level 4 Trace Gas Products - Methods



- L4 products fuse L3 TROPOMI+OMI products and model data to estimate trace gas pollution at the surface where people live!
- The current L4 products are utilizing model profile information from the NASA Goddard GEOS Composition Forecasting System (GEOS-CF) at 0.25° grid spacing
- L4 products are produced once per day on regular 0.02° grid

Brief Method Description:

1. Model remapped to 0.02° grid
2. Calculate VCDs and surface-level concentrations from the model data
3. Multiply the observed trace gas VCD by the ratio of model surface and VCDs
4. Convert the values to appropriate units (ppbv) to arrive at surface-layer pollution maps

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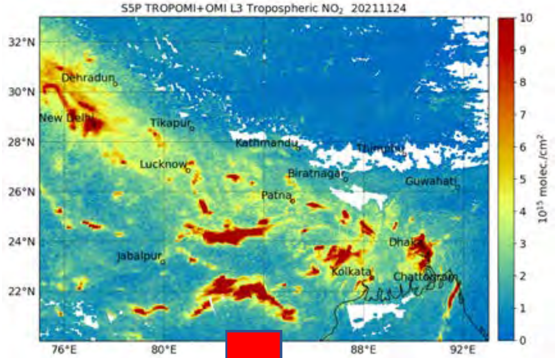
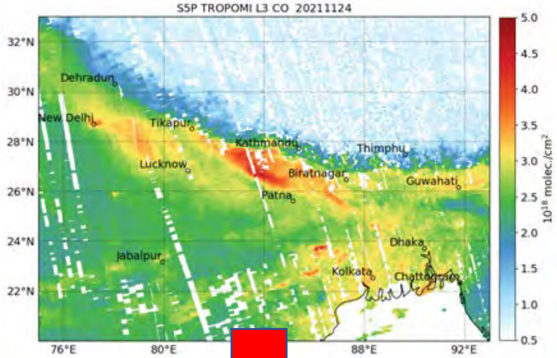
Level 4 Trace Gas Products - Analysis

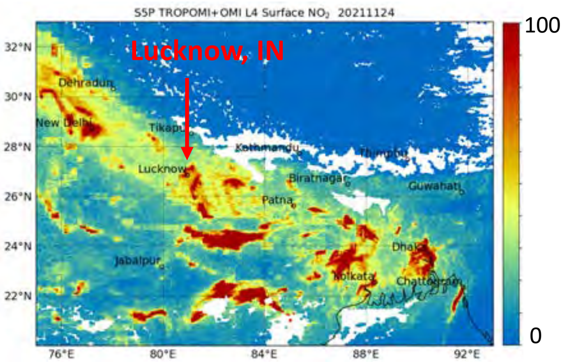
L3 Tropospheric NO2



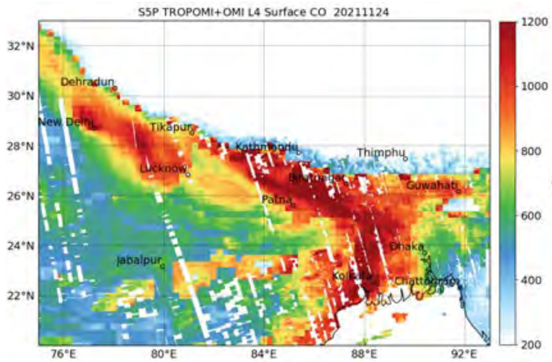
L3 Total Column CO



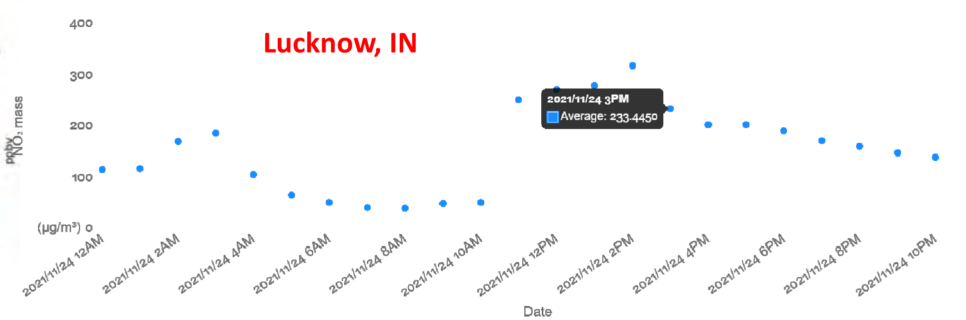
L4 Surface-Layer NO2



L4 Surface-Layer CO



- ❑ L4 product shows adequate agreement to NO2 measured at the Lucknow site
- ❑ Underestimation may be related to current application of GEOS-CF model data
- ❑ Improvements expected after fully transitioning to our AQ model (WRF with Chemistry)

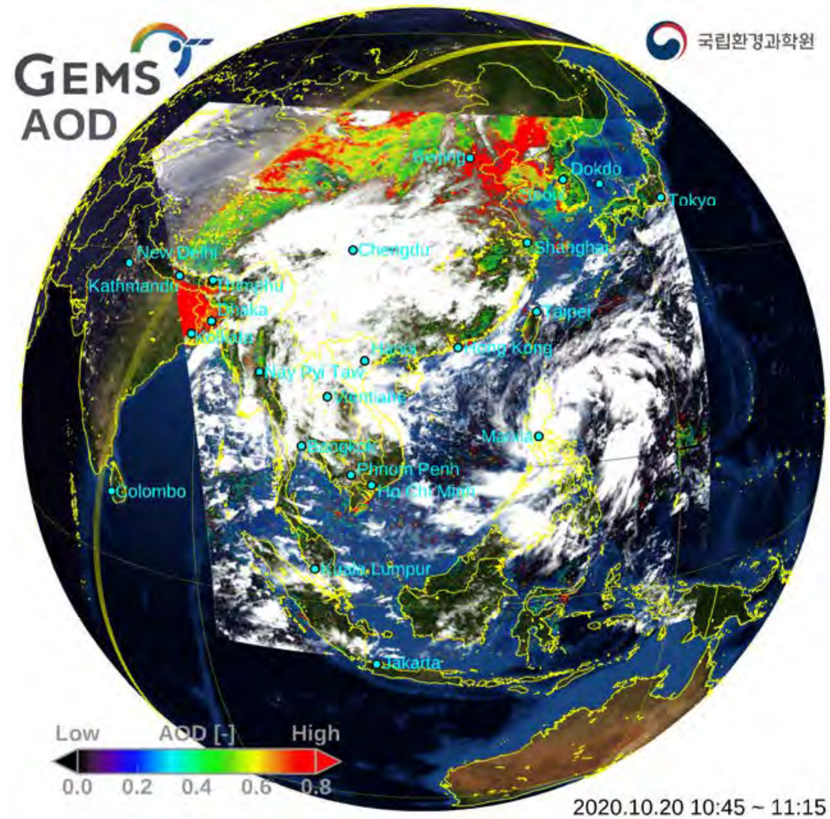


Satellite Trace Gas Measurements – Temporal Resolution!

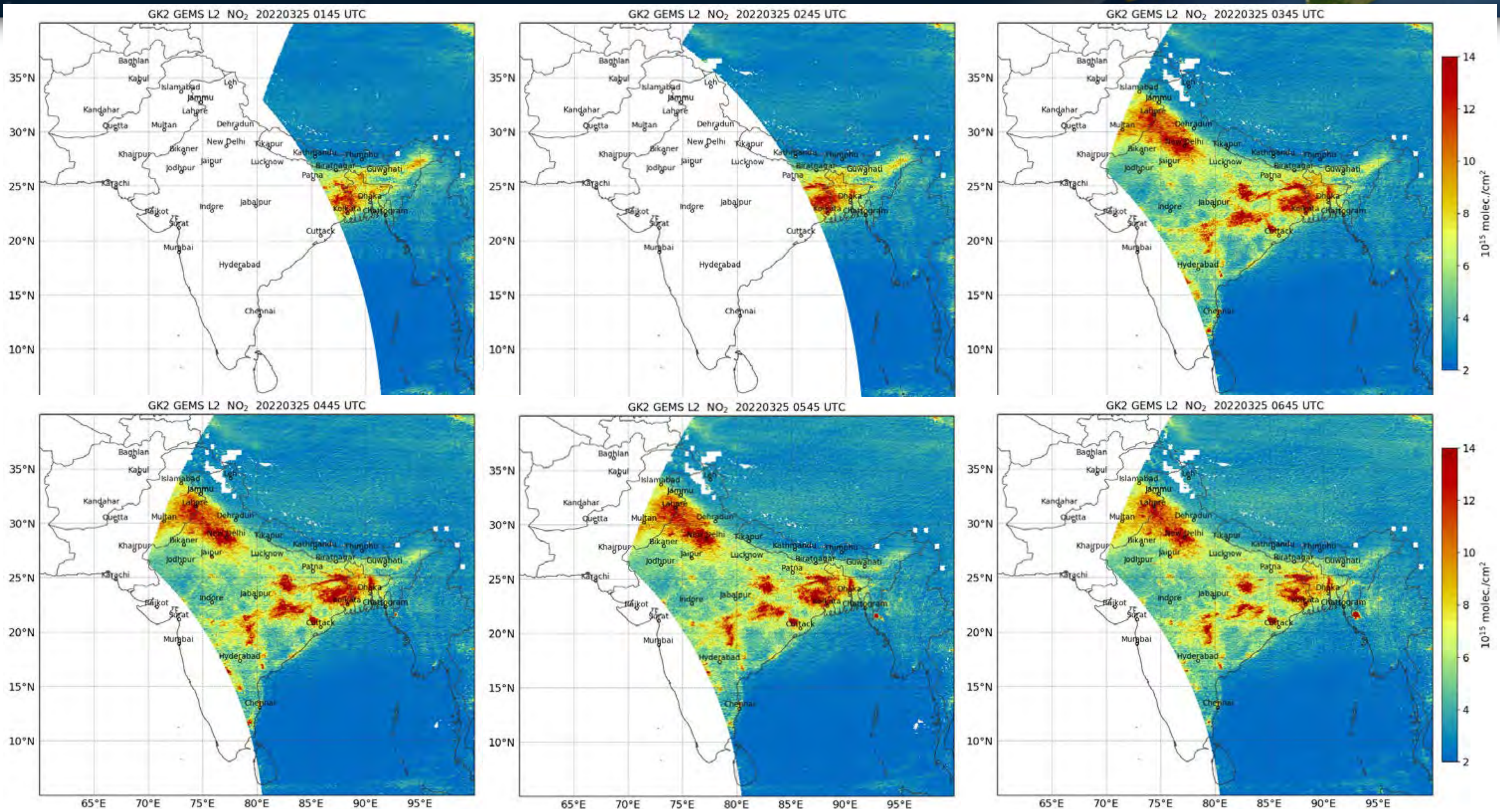
Product		Importance	Min	Max	Nominal	Accuracy	Window (nm)	Spatial resolution (km × km) at Seoul	SZA (°)	Algorithm
NO_2	TROP	O_3/aerosol precursor	1 × 10^{13} molecules cm^{-2}	4 × 10^{17} molecules cm^{-2}	1 × 10^{14} molecules cm^{-2}	1 × 10^{15} molecules cm^{-2}	432–450	7 × 8 × 2 px	<70	DOAS[a]
	STRAT									
SO_2		Aerosol precursor	8 × 10^{15} molecules cm^{-2}	4 × 10^{17} molecules cm^{-2}	1 × 10^{16} molecules cm^{-2}	1 × 10^{16} molecules cm^{-2}	310–326	7 × 8 × 4 px × 3 h	<50	DOAS[a]-PCA[b] hybrid[c]
		Volcano	0 DU	100 DU	—	—	310–340	7 × 8		
HCHO		VOC proxy	8 × 10^{4} molecules cm^{-2}	6.2 × 10^{16} molecules cm^{-2}	5 × 10^{15} molecules cm^{-2}	1 × 10^{16} molecules cm^{-2}	328.5–356.5	7 × 8 × 4 px	<50	DF[d]
CHOCHO			1 × 10^{14} molecules cm^{-2}	1 × 10^{15} molecules cm^{-2}	5 × 10^{14} molecules cm^{-2}	1 × 10^{15} molecules cm^{-2}	435–461	7 × 8 × 4 px	<50	DF[d]
O_3	TROP	Oxidant, pollutant	20 DU	50 DU	30 DU	20%	300–340	7 × 8	<70	OE[e]
	STRAT	Ozone layer	180 DU	450 DU	270 DU	5%	300–340			OE[e]
	Total		200 DU	500 DU	300 DU	3%	317.5, 331.2 331.2, 340, 380			TOMS[f]
Aerosol	AOD	Air quality, climate	0	3.6	0.54	20% or 0.1 at 400 nm	354, 388, 412, 443, 477, 490	3.5 × 8	<70	LUT, OE[g]
	UVAI		–7	7	0.35	—				LUT[g]
	SSA		0.82	0.99	0.90	—				LUT, OE[g]
	AEH		0 km	6 km	1.19 km	—	477	7 × 8		O_2–O_2[h]
Cloud	ECF	Retrieval, climate	0	1	—	5%	300–500	7 × 8	<70	O_2–O_2[h,i]
	CCP		100 hPa	1,013 hPa	—	5%	477			
	CRF		0	1	—	—				
Surface reflectivity		Retrieval, environment	0	1	—	—	300–500	3.5 × 8	<70	Multi-λ, Min reflectivity[j]
UVI	UVI	Public health	0	15	—	—	354	7 × 8	<70	LUT[k]
	VitaD									
	DNA									
	Plant									

[a] Platt (1994); [b] Li et al. (2013); [c] Yang (2019); [d] Chance et al. (2000), Gonzalez Abad et al. (2016), Kwon et al. (2017, 2019); [e] Rodgers (2000), Liu et al. (2010), Bak et al. (2013); [f] Haffner et al. (2015), McPeters et al. (2015); [g] Torres et al. (2013), Kim et al. (2018), Jeong et al. (2016), Kim et al. (2007), Kaufman et al. (1997); [h] Park et al. (2016); [i] Acarreta et al. (2004), Stammes et al. (2008), Veefkind et al. (2016); [j] Vasilkov et al. (2017), Lee et al. (2018); [k] Lindfors et al. (2018)

Kim et al. (2020)



GEMS NO2 Products



NASA Worldview

https://worldview.earthdata.nasa.gov/

Products over HKH

https://weather.msfc.nasa.gov/sport/servir/

Lead in to Aerosols and Modeling Tomorrow

AMI Aerosol Optical Depth Product