Remote sensing of air pollution from space and the application of these for monitoring air quality

Richard Pope (r.j.pope@leeds.ac.uk)[1,2]

1: School of Earth and Environment, University of Leeds, Leeds, UK

2: National Centre for Earth Observation, University of Leeds, Leeds, UK

Summer School on Air Quality and Pollution Prevention - Ghana

Friday 27th October 2023

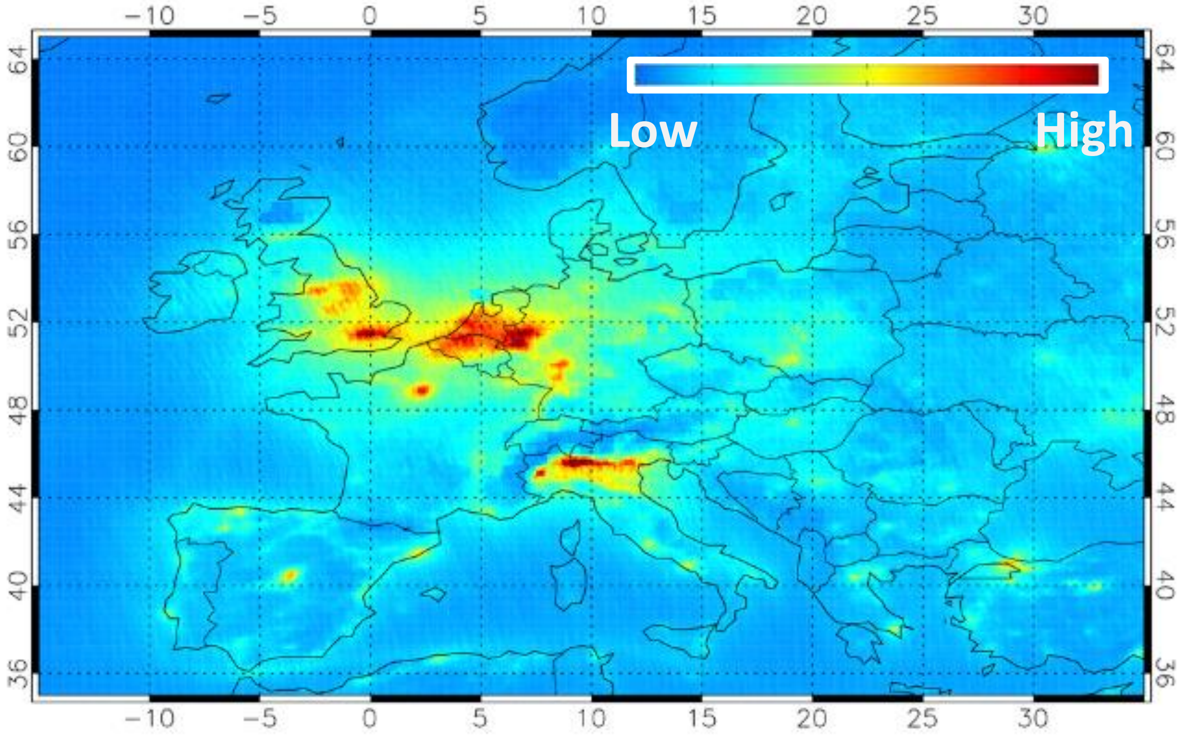
National Centre for Earth Observation
NATURAL ENVIRONMENT RESEARCH COUNCIL

UNIVERSITY OF LEEDS

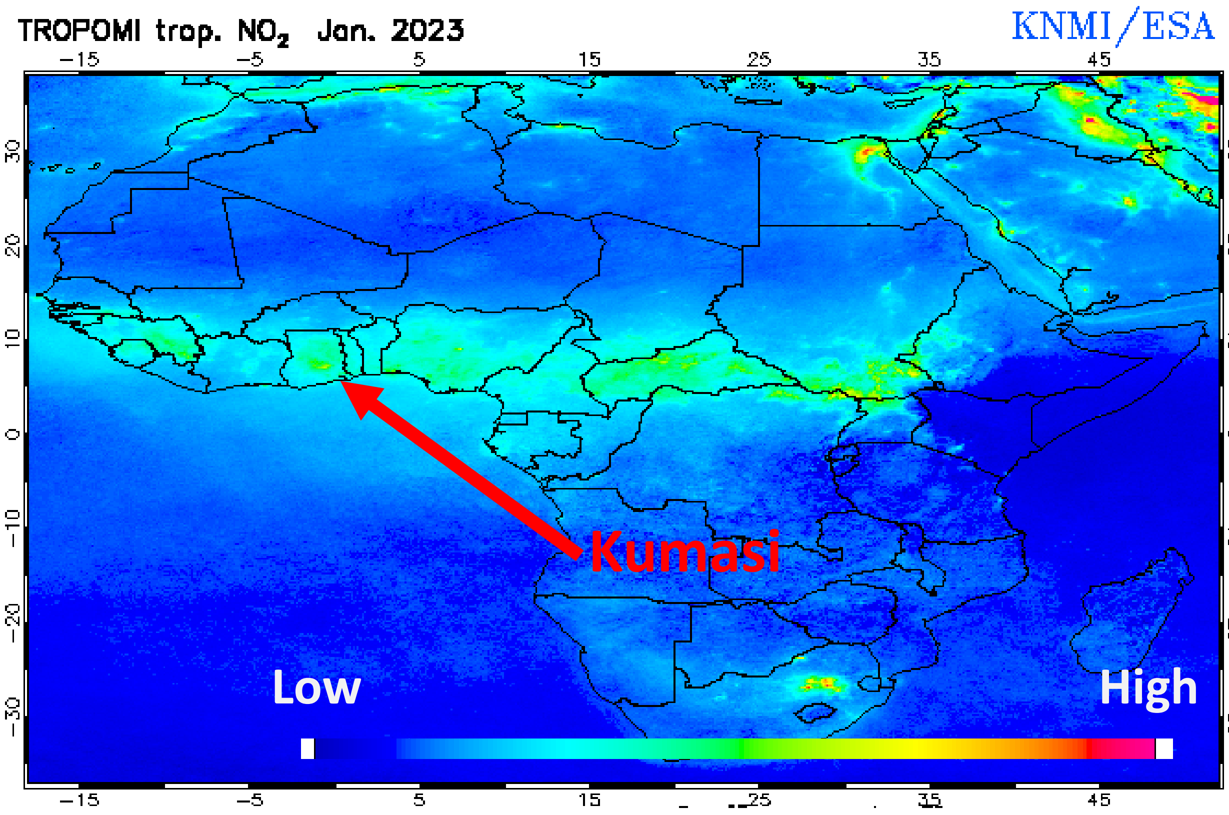
Why do we need satellite measurements?

- Not all measurement locations are accessible (atmosphere, ice, ocean).
- Remote sensing facilitates analysis of long time series.
- Many phenomena require global measurements (e.g. SSTs – ENSO).
- Remote sensing measurements can usually be automated.

What can satellites monitor?



Tropospheric column nitrogen dioxide (NO_2) from the Ozone Monitoring Instrument (OMI) onboard NASA’s Aura satellite.



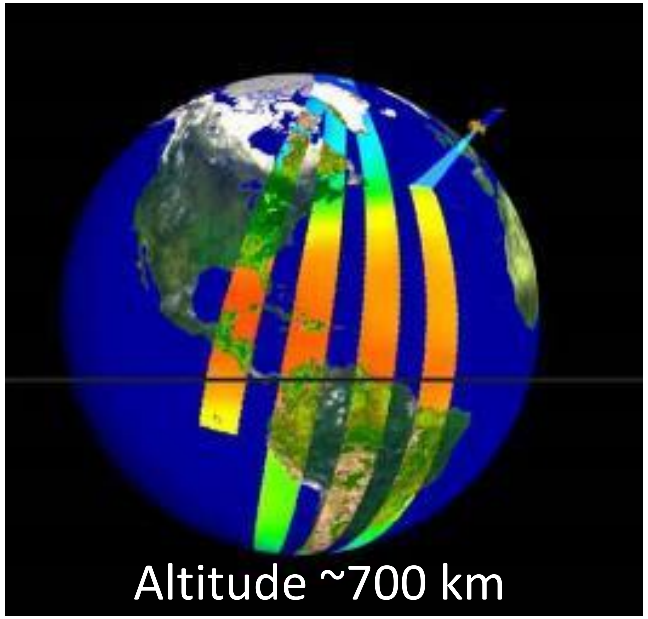
Tropospheric column nitrogen dioxide (NO_2) from the TROPOspheric Monitoring Instrument (TROPOMI) onboard ESA’s Sentinel 5 – Precursor satellite.

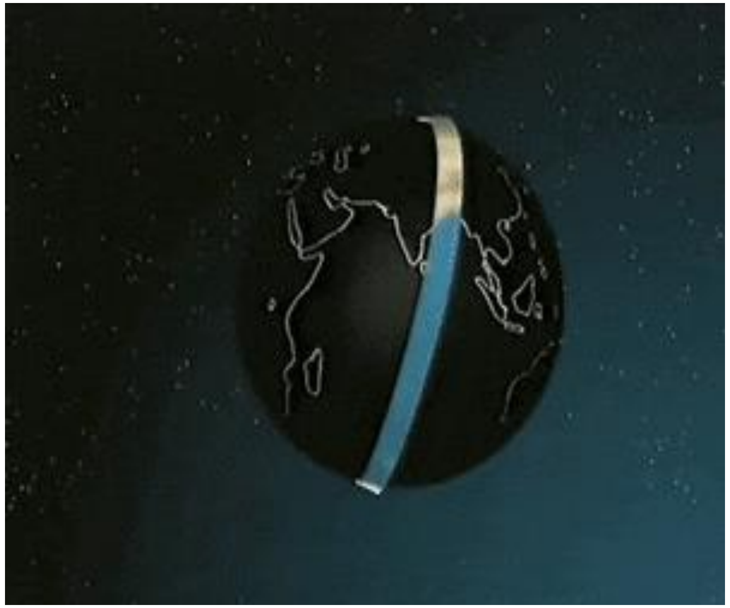
National Centre for Earth Observation
NATURAL ENVIRONMENT RESEARCH COUNCIL

UNIVERSITY OF LEEDS

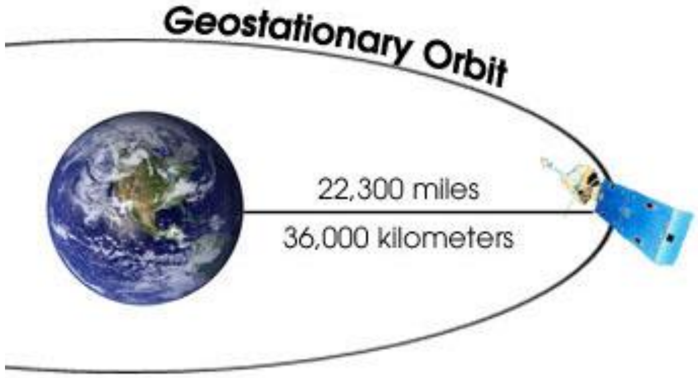
Satellite Orbits Types

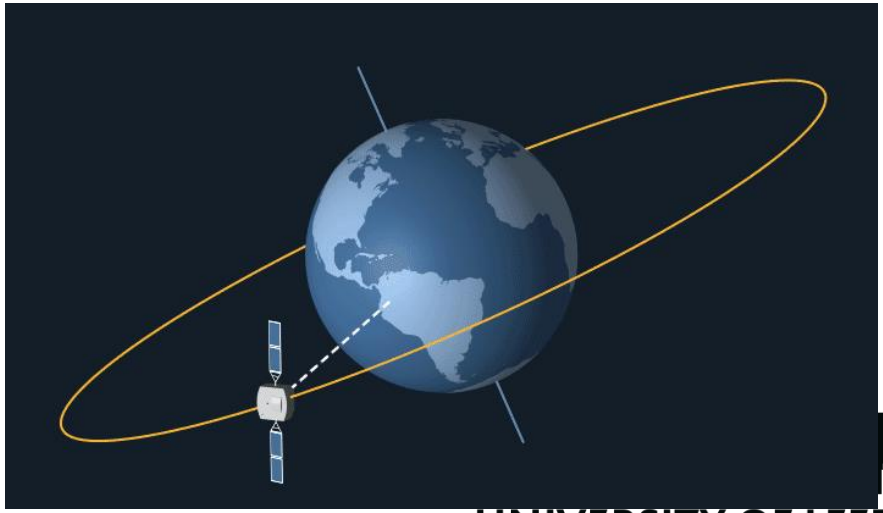
Polar Orbits (1-2 hours):



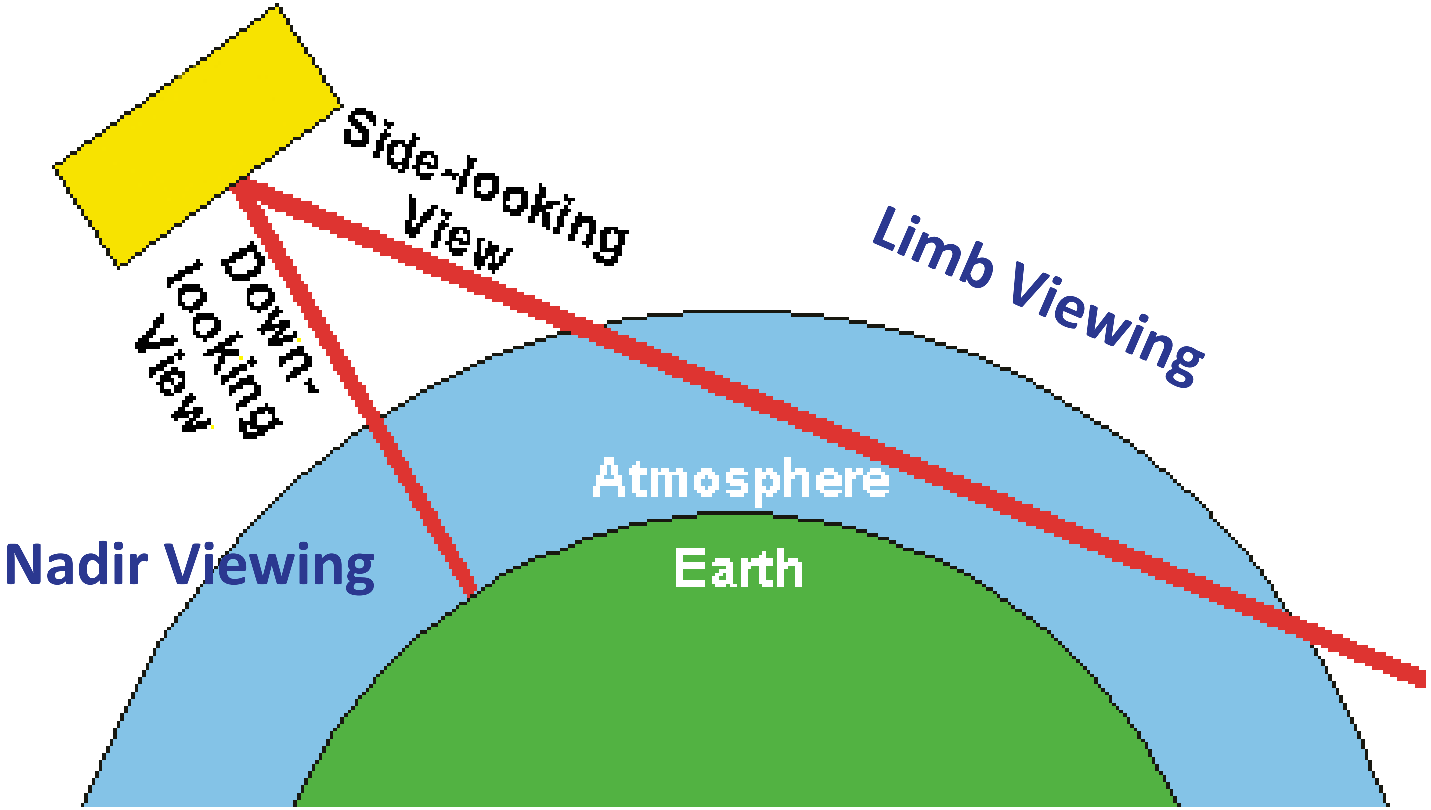


Geostationary Orbits (24 hours):





Satellite Measurements: Viewing Angles



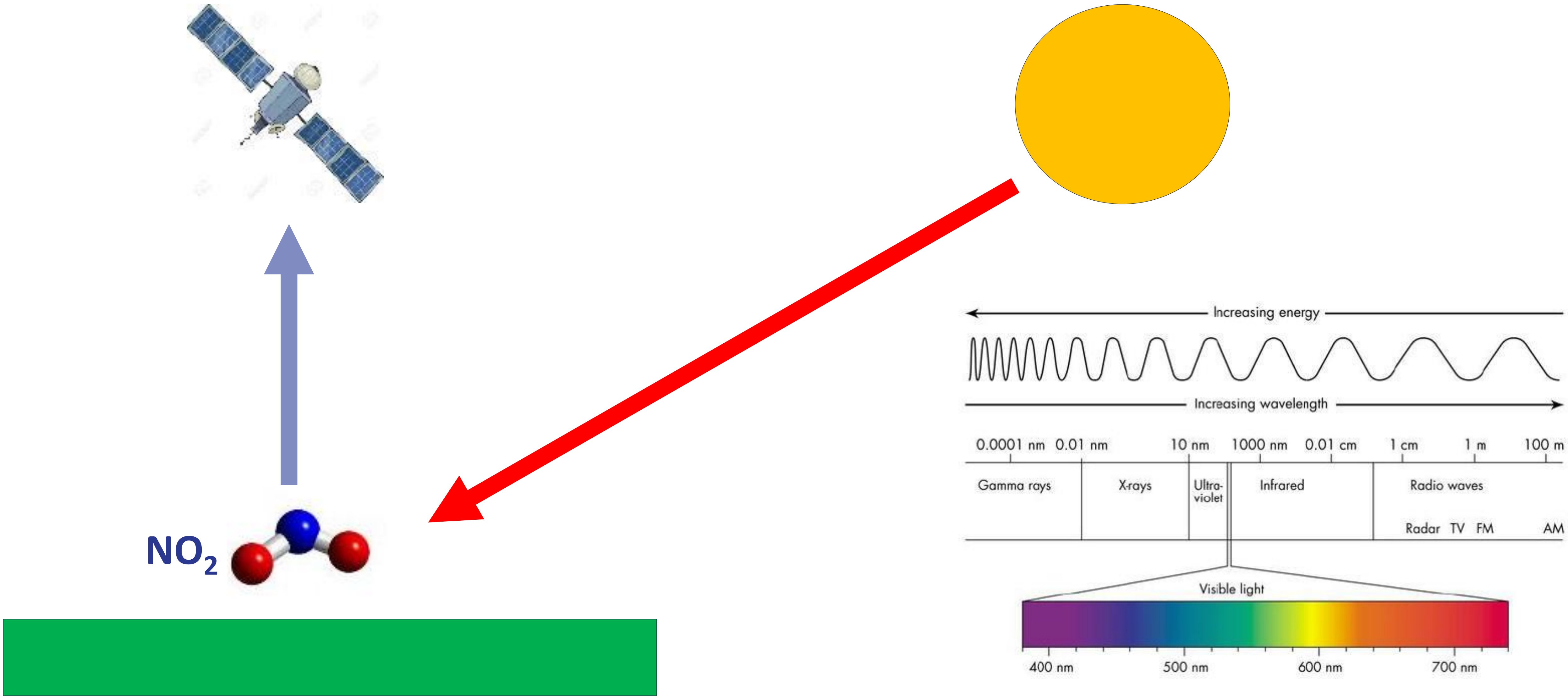
Limb Viewing

- Used for observing the stratosphere and upper troposphere.
- High vertical resolution.
- Low horizontal resolution.
- Clouds are more of an issue.

Nadir Viewing

- Used for obtaining total column amounts.
- High horizontal resolution.
- Low vertical resolution.

Satellite Measurements



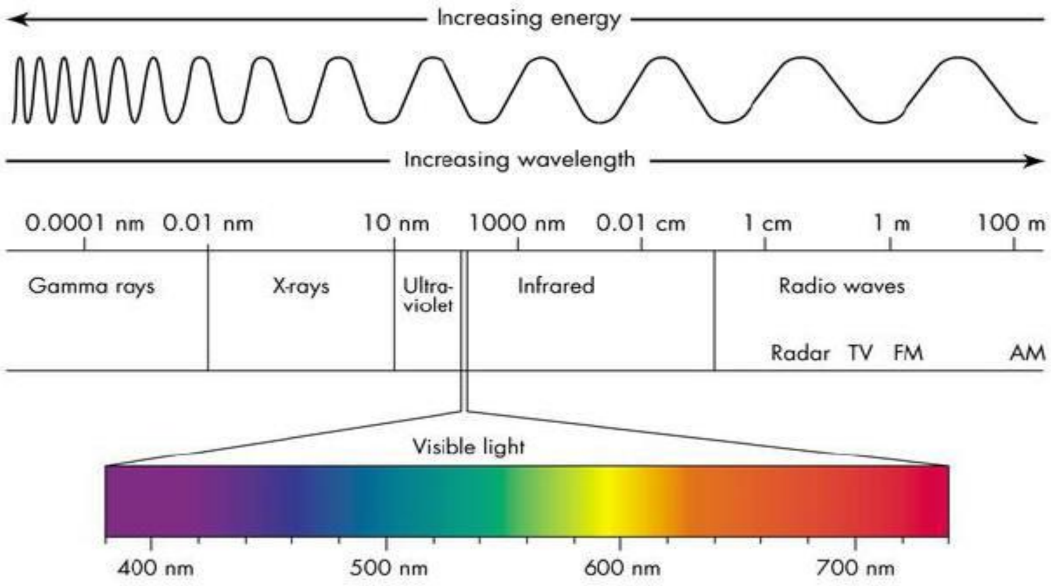
Satellite Measurements: Wavelengths

UV/Vis/NIR:

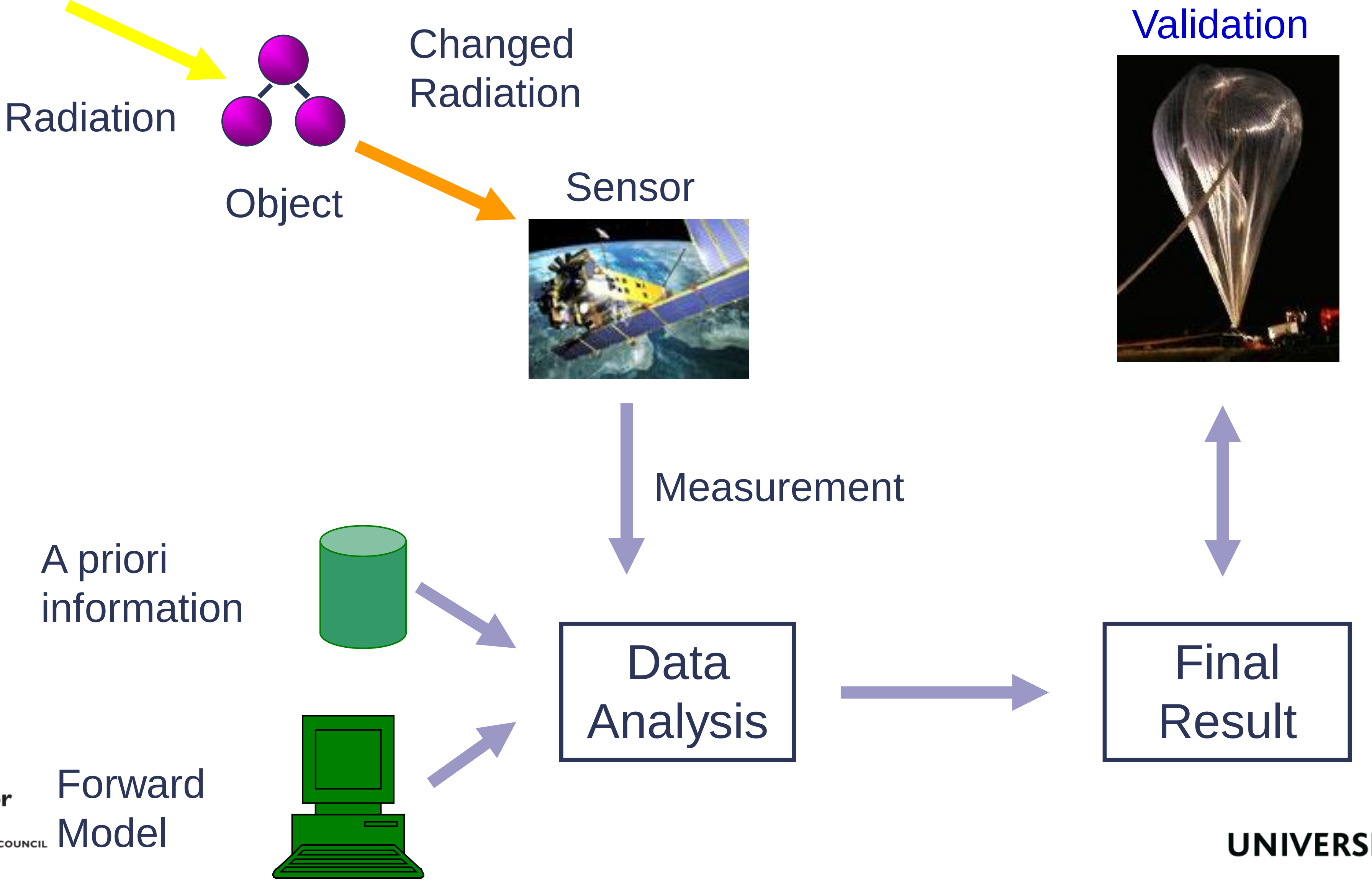
- sensitivity down to surface
- limited number of species
- daytime only
- limited vertical resolution in nadir
- aerosols introduce uncertainties in light path

IR:

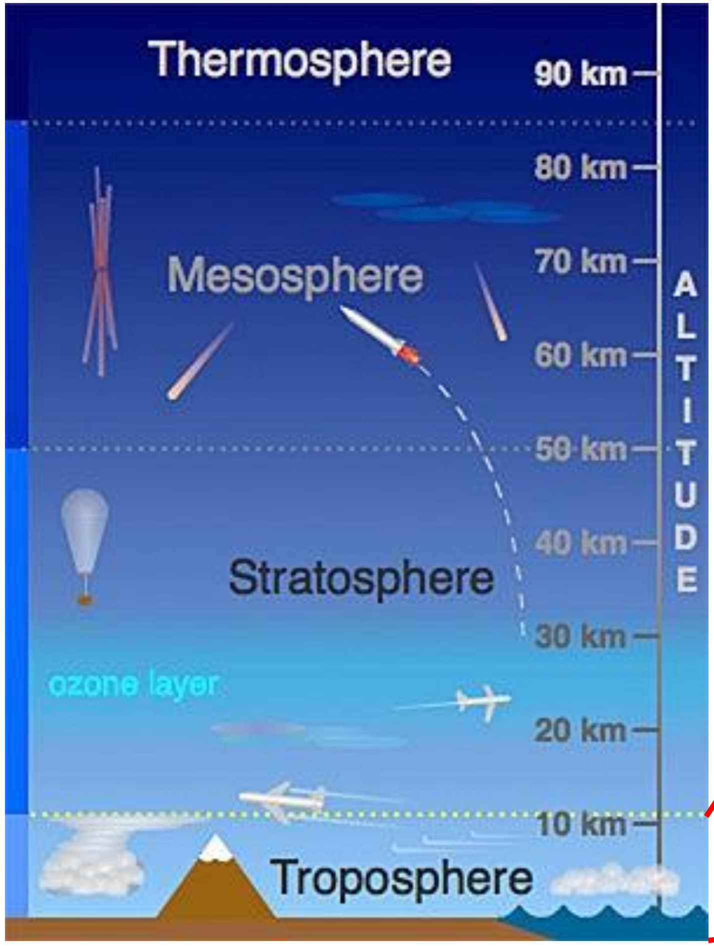
- large number of potential species
- day and night measurements
- some vertical resolution in nadir
- weighted towards middle troposphere
- limited lower troposphere sensitivity



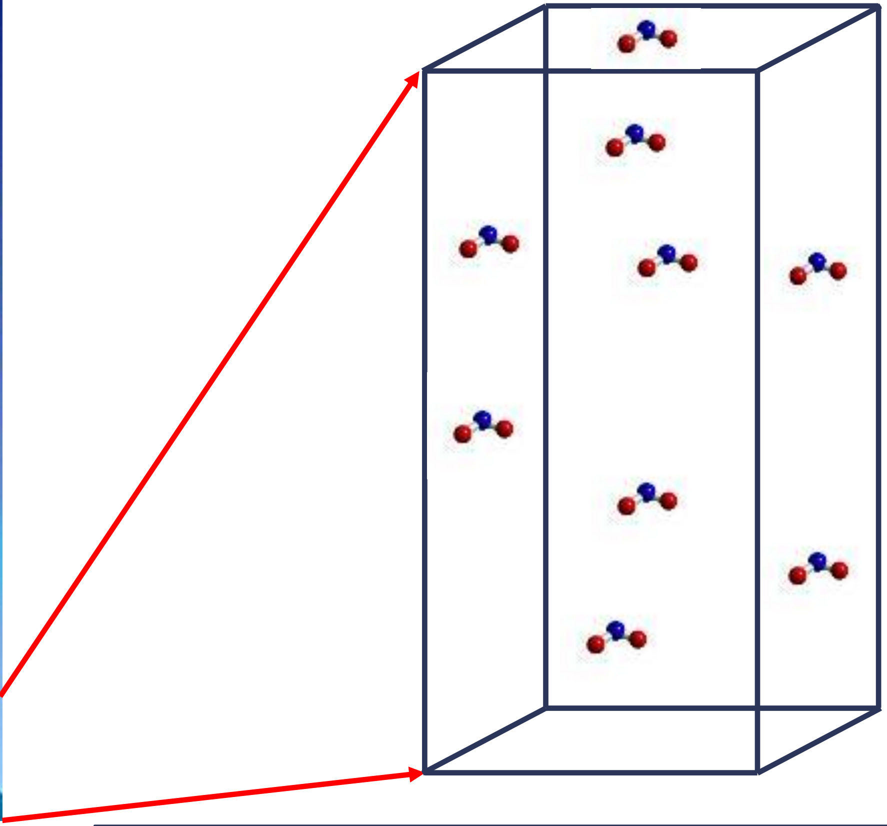
How do satellite retrievals work?



Satellite Measurements: Column Quantities

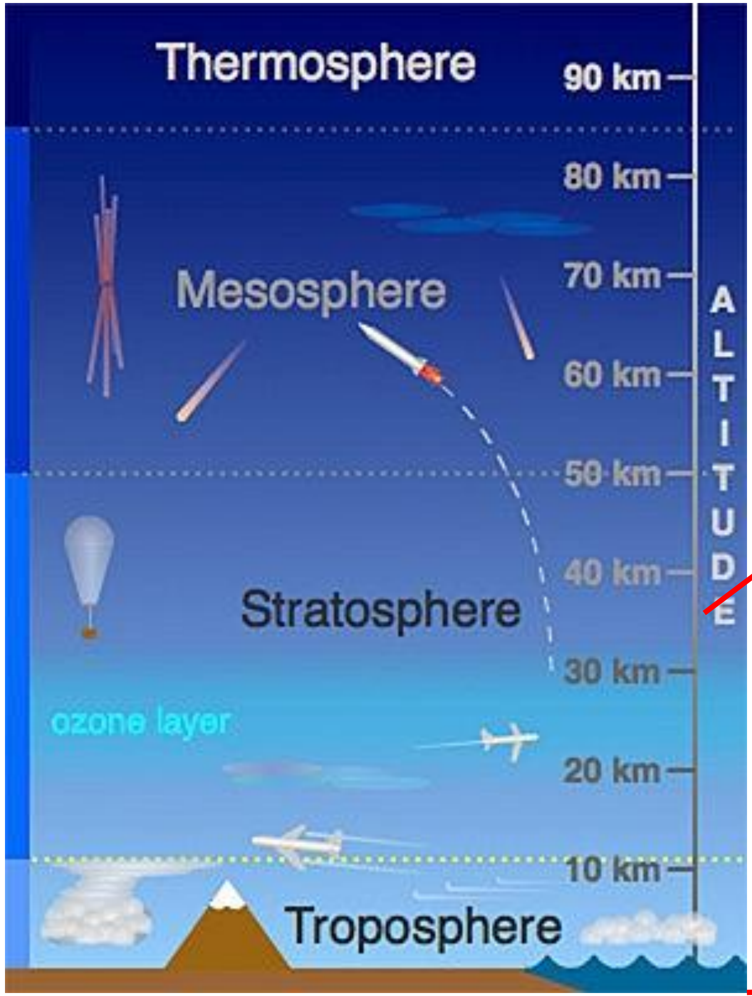


Tropospheric Column NO_2

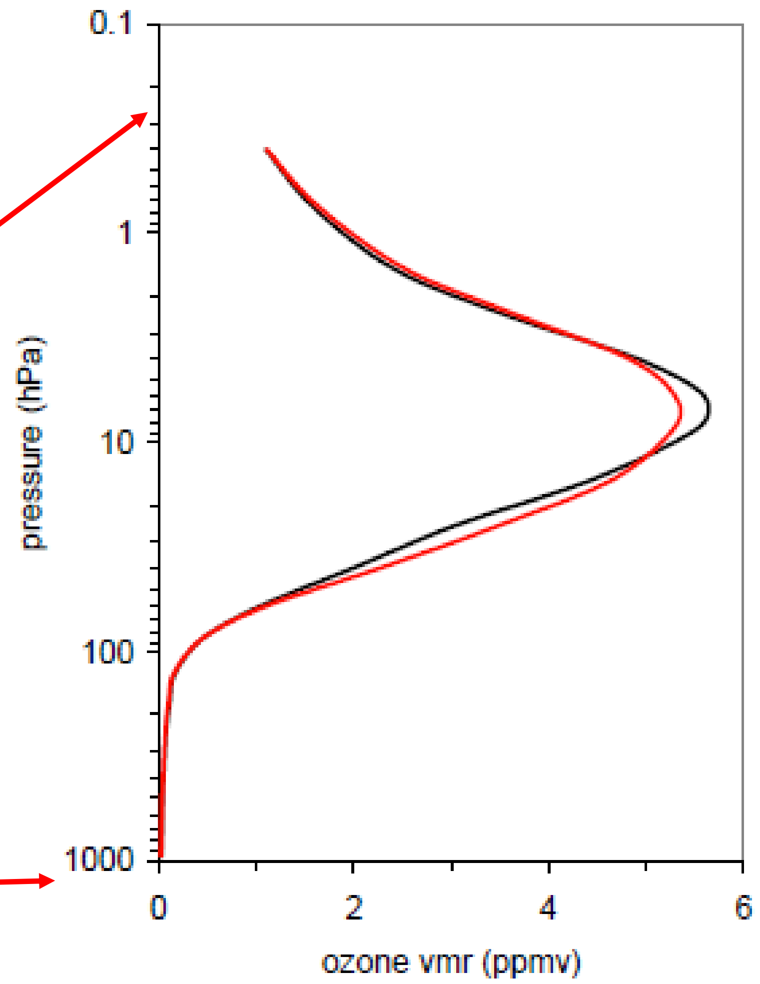


Tropospheric Column Units: 10^{15} molecules/cm^2

Satellite Measurements: Profiles Quantities



Ozone Profiles

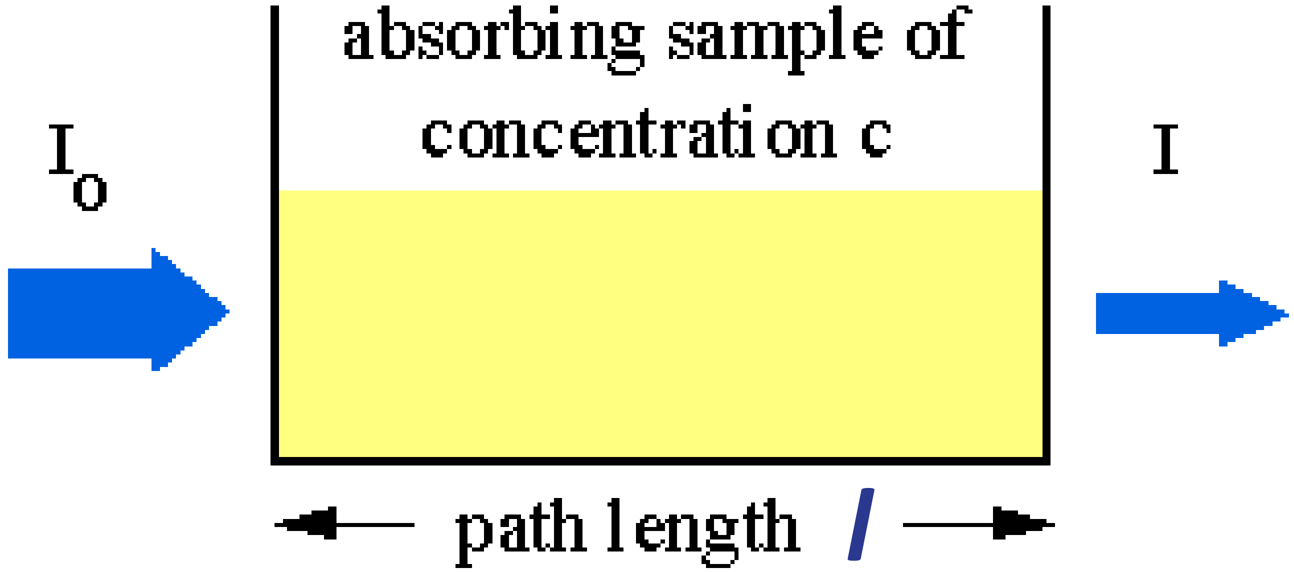


Absorption

The absorption of sunlight (or starlight) through the atmosphere can be used to determine the concentration of key gases which absorb at the wavelength of this radiation (UV/visible). I.e. the *Beer-Lambert law*:

$$I_{tr} = I_0 \, e^{-k\,c\,l} \qquad \text{Slant Column} = c \, . \, l$$

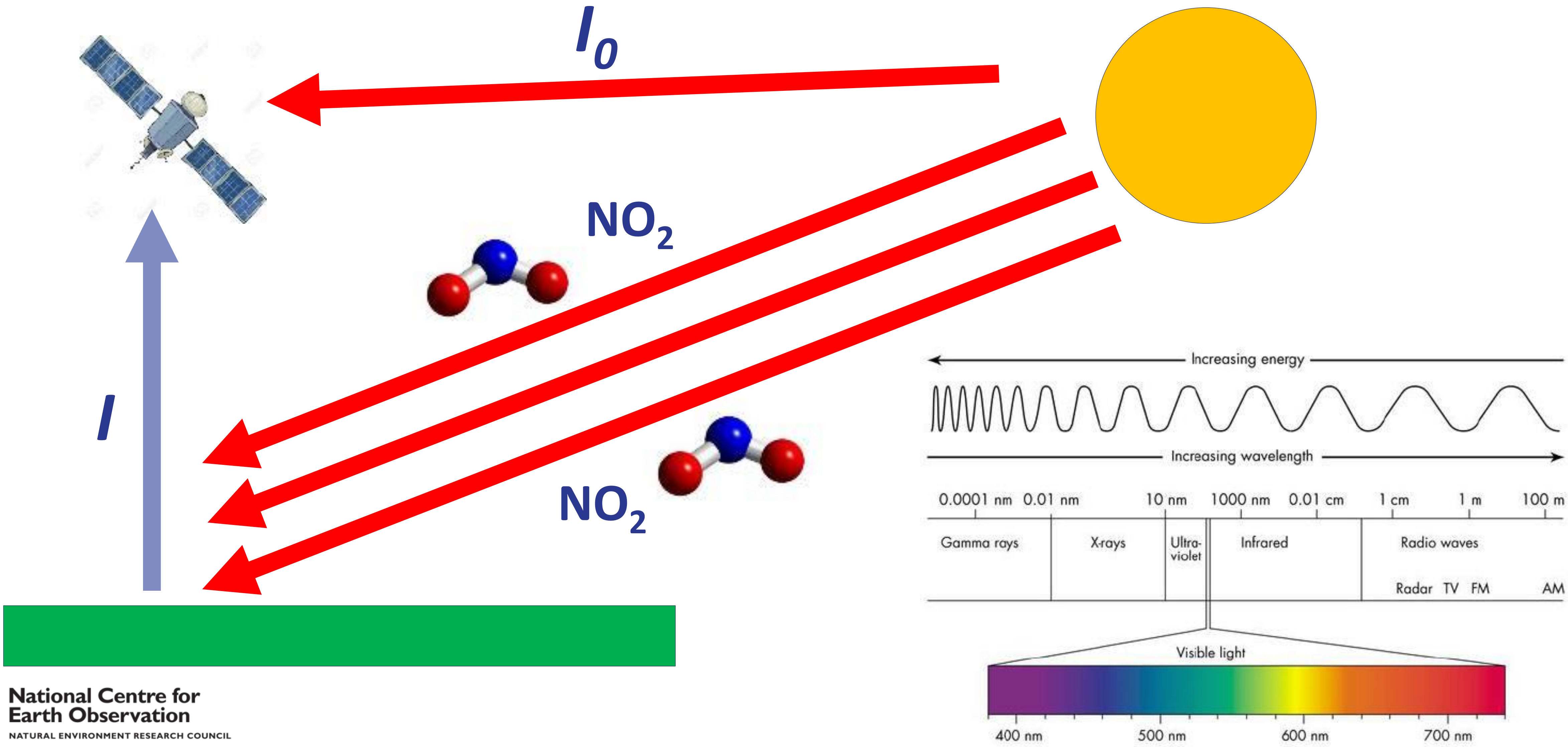
where *k* is the absorption coefficient, *c* is the concentration of the absorber and *l* is the path length.



National Centre for Earth Observation
NATURAL ENVIRONMENT RESEARCH COUNCIL

UNIVERSITY OF LEEDS

Differential Optical Absorption Spectroscopy (DOAS)



Differential Optical Absorption Spectroscopy

The general principle for Differential Optical Absorption Spectroscopy (DOAS) can be represented by:

$$VCD = R(y, b, x_a) = SC(y)/AMF(b, x_a)$$

- *VCD* = vertical column density
- *R* = DOAS retrieval method
- *y* = observed reflectance spectrum
- *b* = forward model parameters
- x_a = trace gas apriori profile
- *SC* = slant column
- *AMF* = air mass factor

We can use an Beer-Lambert law to derive the *SC* and use a radiative transfer model to estimate the *AMF*.

Forward model parameters include e.g. cloud top height, cloud fraction, surface albedo and aerosol optical thickness (i.e. scattering).

Differential Optical Absorption Spectroscopy

$$I_{tr} = I_0 \, e^{-k\,c\,l}$$

Slant Column (*SC*)

→

$$VC = SC/AMF$$

Vertical Column (*VC*)

↓

The air mass factor (AMF) is calculated using a radiative transfer model. It is dependent on variables such cloud fraction, cloud top height, aerosols, surface albedo, solar zenith angle, viewing angle and spectral line strengths.

←

The stratospheric slant column (*SSC*) is normally estimated by a model or from a background region (e.g. Pacific Ocean where *TVC* → 0.0, so the *SC* → *SSC*).

$$TVC = (SC\text{-}SSC)/AMF_{trop}$$

Tropospheric Vertical Column (*TVC*)

Emission

Radiance at Top of the Atmosphere

Radiative transfer equation

$$L_\lambda = \underbrace{\int_0^{top} B_\lambda(T(z)) \frac{\partial \tau_\lambda(z)}{\partial z} dz}_{\text{atmosphere}} + \underbrace{B_\lambda(T_s)\tau_\lambda(0)}_{\text{Surface}}$$

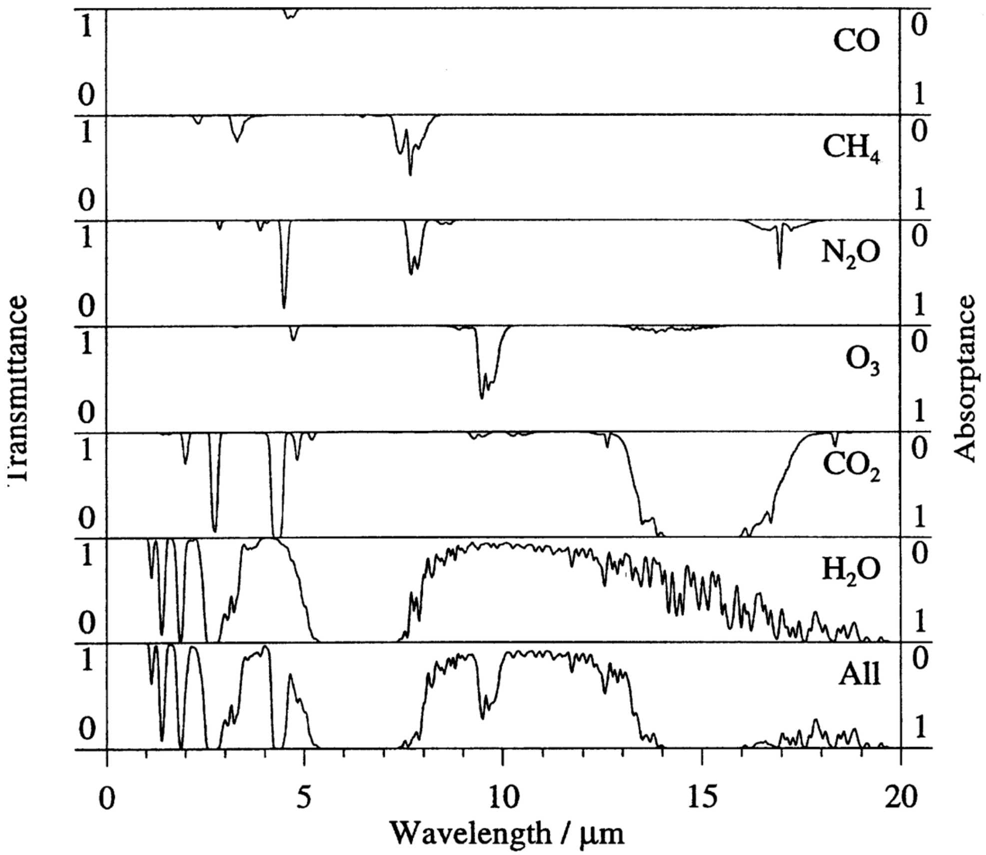
where:

L_λ – Observed radiance
B_λ - Planck function (for wavelength λ) (function of temperature)
T(z) – Atmospheric temperature profile (function of *z* – altitude)
T_s – Surface temperature
$\tau_\lambda(z)$ – Transmittance (at wavelength λ) between *z* and top of atmosphere

Spectroscopy

A given molecule absorbs (and emits) radiation at specific wavelengths related to the properties of the molecule (e.g. frequency of vibration of chemical bonds). In practice these absorption (or emission) 'lines' can overlap with other species. Unless a species is present in a much larger abundance and/or has a much stronger absorption line, it is complicated to separate out the absorption of minor gases from each other.

Although, in theory many gases in the atmosphere could be observed in a given wavelength region, the weak absorption (small abundances) or interference from other absorption limits the possibilities.



Infra-red absorption spectra for 6 strongly absorbing gases and the total absorption for a vertical beam passing through the atmosphere, in absence of clouds.

UV-Vis Nadir Viewing Observations

Satellite	Operational Period	Species
Total Ozone Mapping Spectrometer (TOMS-1, 2 & 3)	1978-2006	O_3
Global Ozone Monitoring Instrument (GOME)	1995-2011	O_3, NO_2, HCHO & BrO
SCanning Imaging Absorption SpectroMeter for Atmospheric CHartographY (SCIAMACHY):	2002-2012	O_3, NO_2, HCHO, CO, SO_2 & BrO
Ozone Monitoring Instrument (OMI)	2004-present	O_3, NO_2, HCHO, SO_2, CHOCHO & BrO
Global Ozone Monitoring Instrument -2 (GOME-2A & B):	2007-present	O_3, NO_2, HCHO, CHOCHO, SO_2 & BrO
Tropospheric Monitoring Instrument (TROPOMI):	2017-present	O_3, NO_2, HCHO & SO_2

* Not a complete list

IR Nadir Viewing Observations

Satellite	Operational Period	Species
Measurement of Pollution in the Troposphere (MOPITT)	1999-present	CO
Tropospheric Emissions Spectrometer (TES)	2005-2018	O_3, CO, PAN, H_2O
Infrared Atmospheric Sounding Interferometer (IASI-A)	2006-2020	O_3, CH_4, CO, NH_3, CH_3OH, H_2O & aerosols
Infrared Atmospheric Sounding Interferometer (IASI-B)	2012-present	O_3, CH_4, CO, NH_3, CH_3OH, H_2O & aerosols
Infrared Atmospheric Sounding Interferometer (IASI-C)	2018-present	O_3, CH_4, CO, NH_3, CH_3OH, H_2O & aerosols
Cross-track Infrared Sounder (CrIS)	2011-present	NH_3, C_5H_8 and others

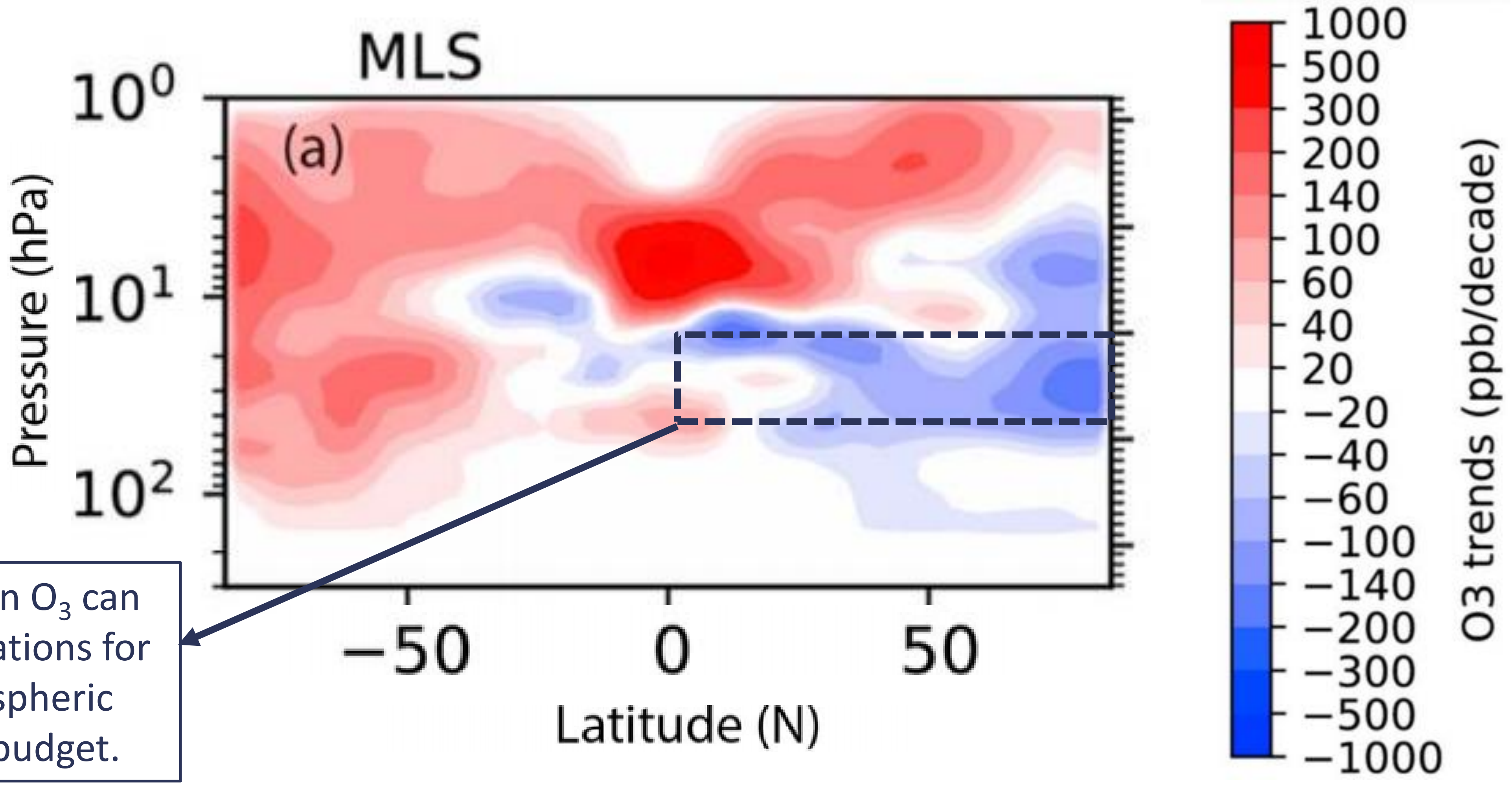
* Not a complete list

Which trace gases and aerosols can we retrieve?

	Limb Sounders	Nadir Sounders
Climate	Stratospheric O_3, OCS, Chlorine Species, N_2O, CFCs & HCFCs	CH_4, Tropospheric O_3, CO_2, Aerosols, BrO
Air Quality	CO, Aerosols, PAN, VOCs, NO_x, UTLS O_3	Tropospheric O_3, VOCs, NO_2, CO, Aerosols, Smoke

Limb Sounder – Climate: Stratospheric Ozone (O_3)

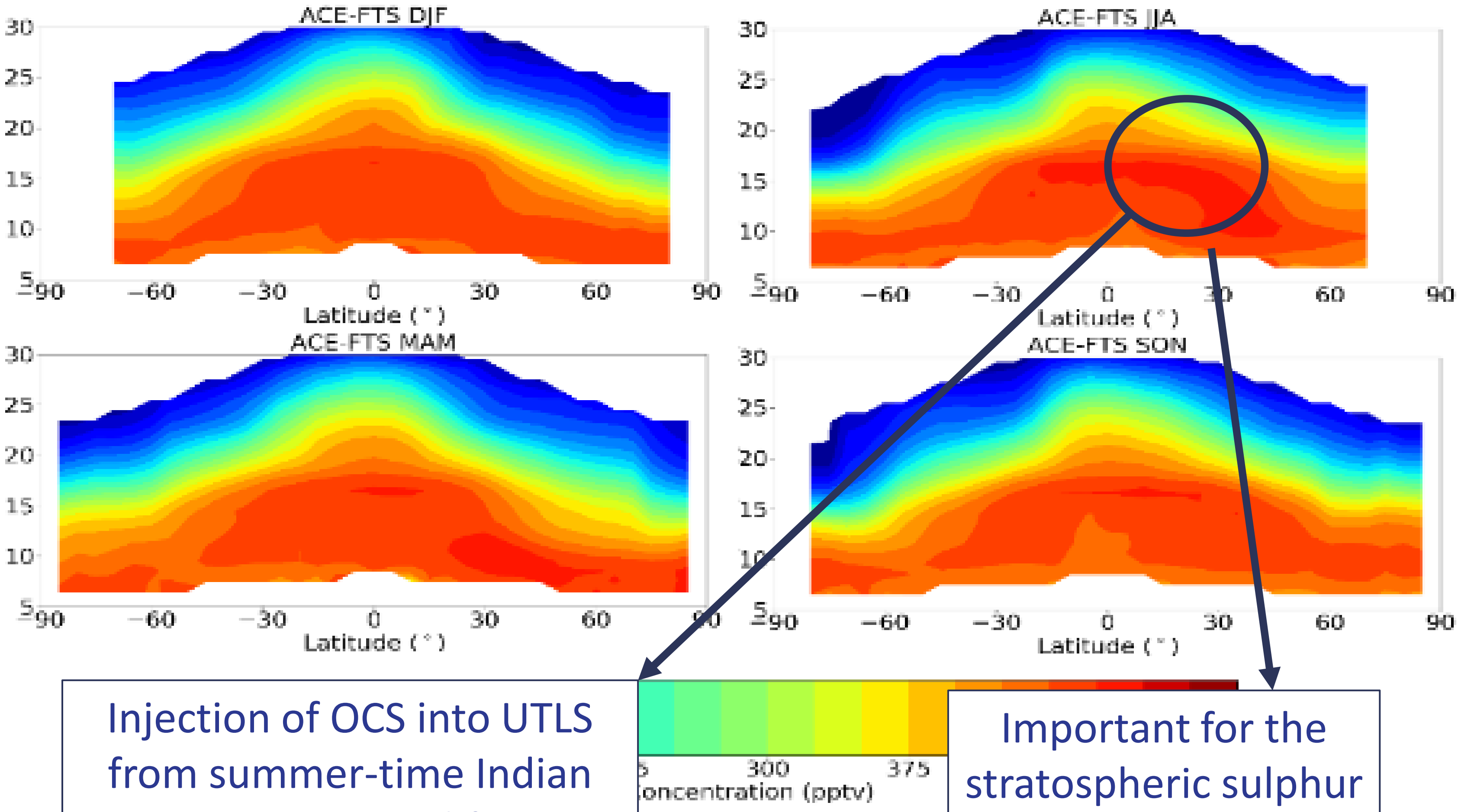
Microwave Limb Sounder (MLS), Aura satellite



Decreases in O_3 can have implications for the atmospheric radiation budget.

Chipperfield et al., (2018), doi.org/10.1029/2018GL078071

Limb Sounder – Climate: Carbonyl Sulphide (OCS)



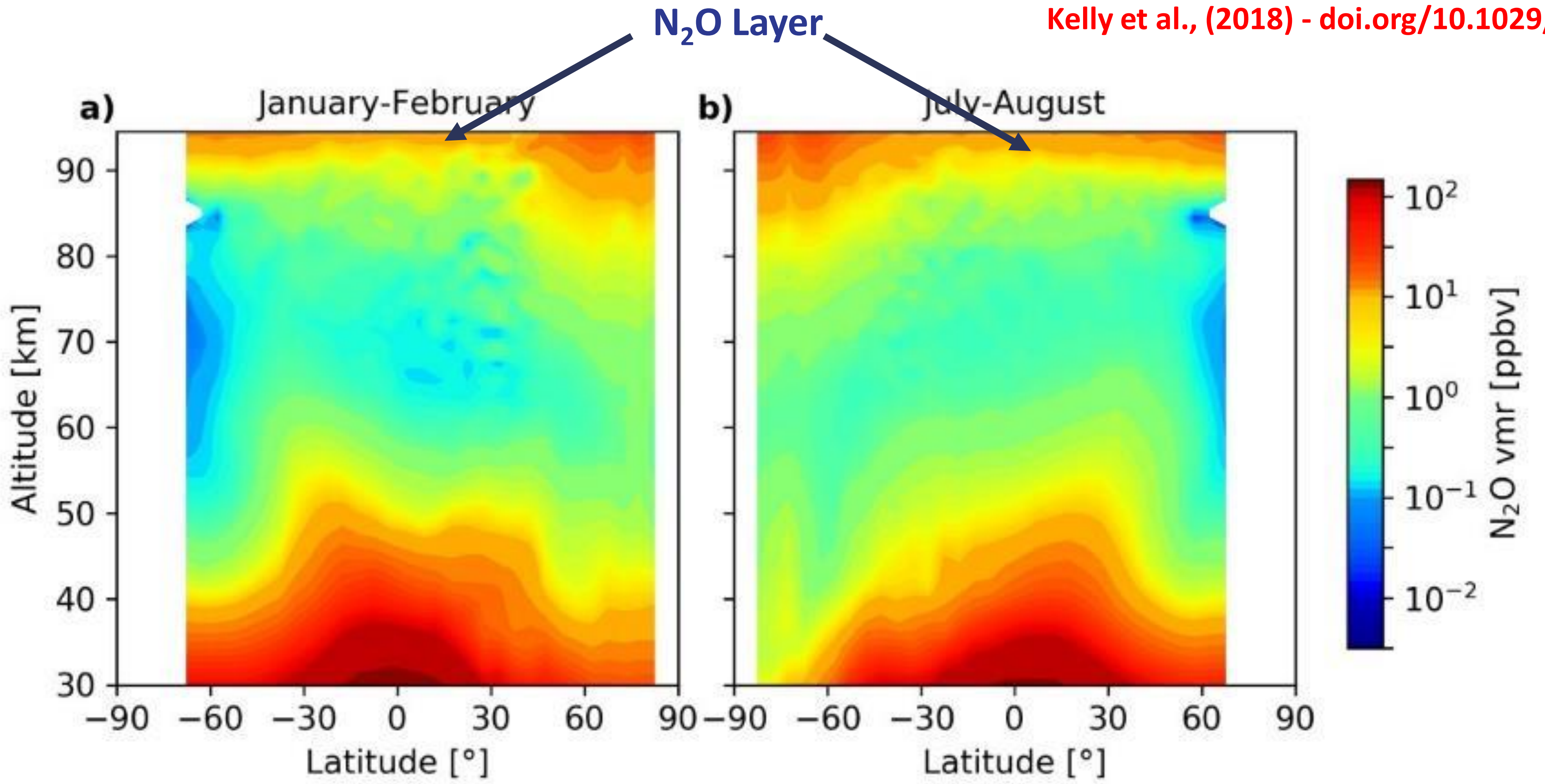
Injection of OCS into UTLS from summer-time Indian Monsoon uplift

Important for the stratospheric sulphur budget

Atmospheric Chemistry Experiment (ACE), SCISAT-1 satellite

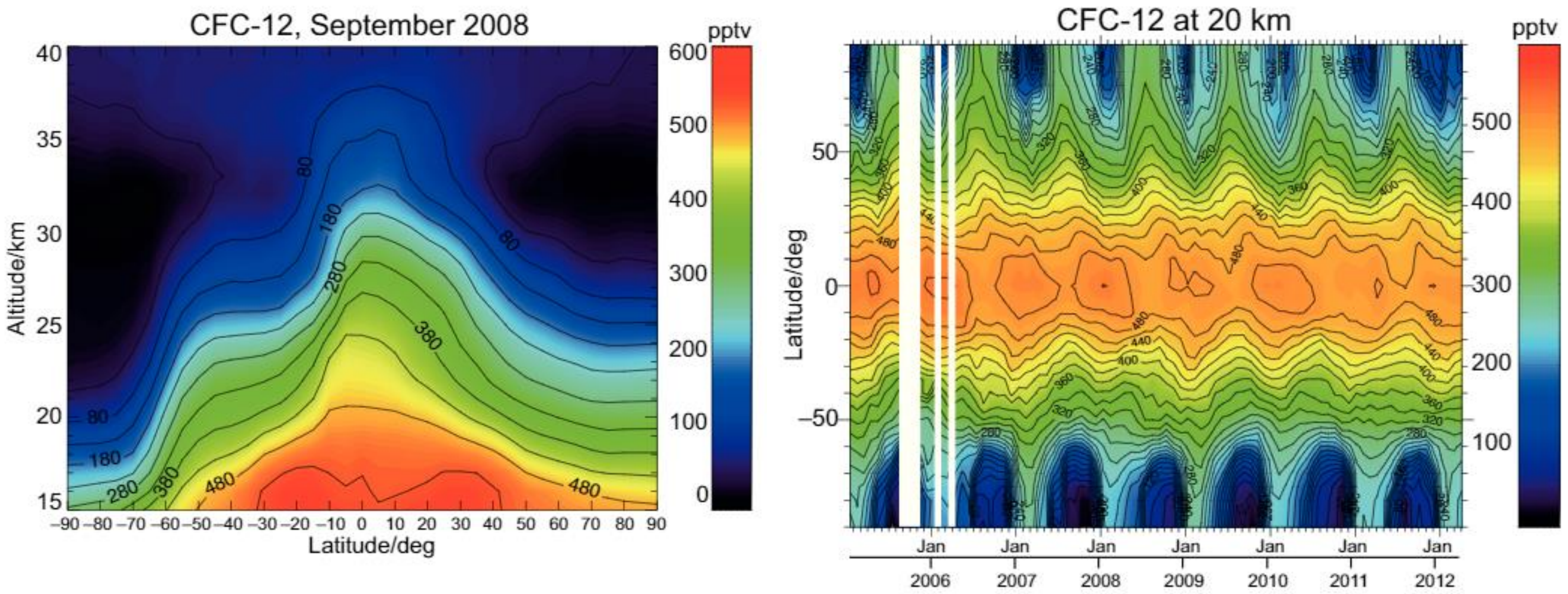
Limb Sounder – Climate: Nitrous Oxide (N_2O)

Kelly et al., (2018) - doi.org/10.1029/2018GL078895



Atmospheric Chemistry Experiment (ACE), SCISAT-1 satellite

Limb Sounder – Climate: CFCs



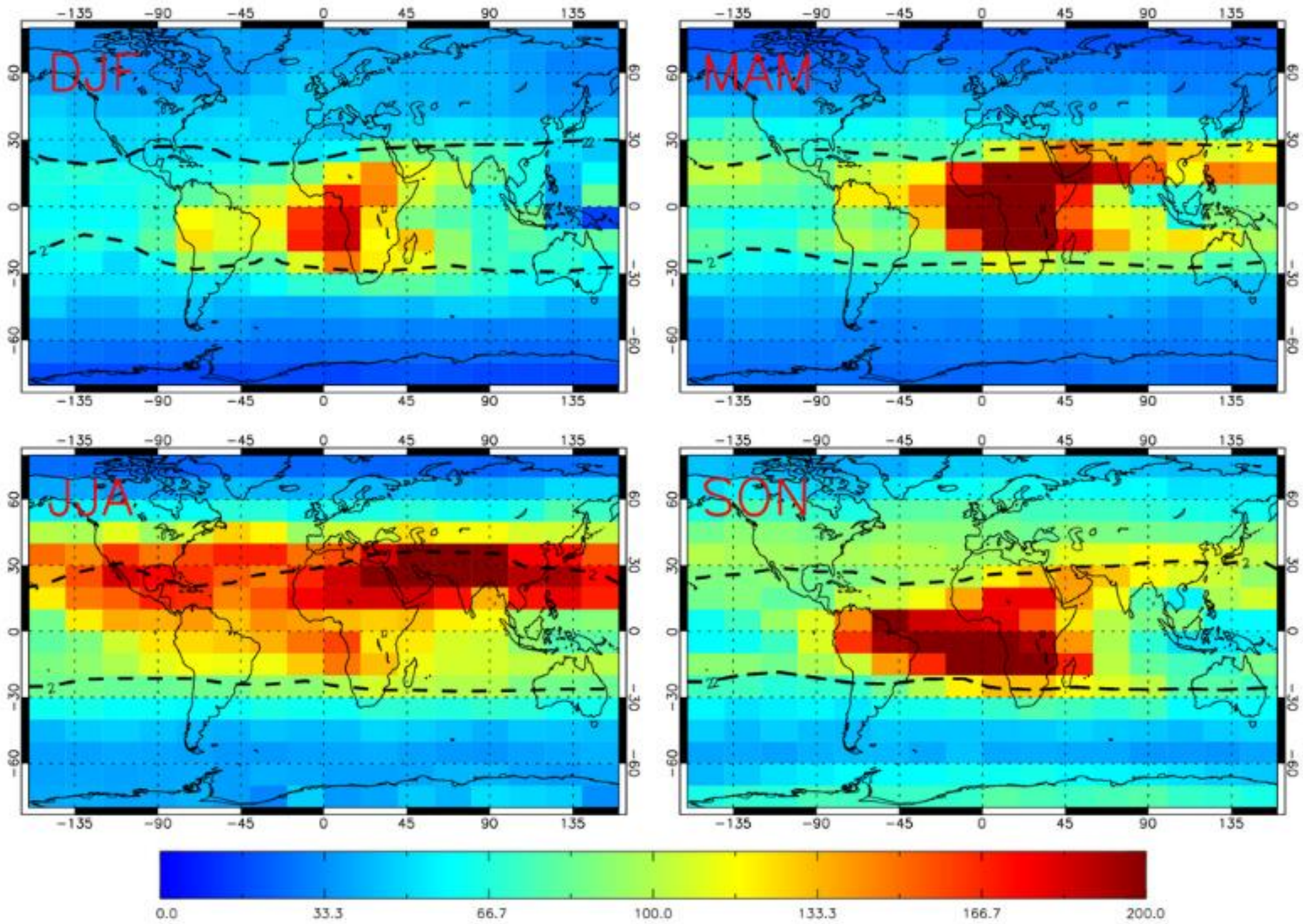
MIPAS measurements of CFC-12, which has implications for the stratospheric chlorine and ozone budgets.

Clarmann (2013), doi: 10.1016/S0187-6236(13)71086-5

Michelson Interferometer for Passive Atmospheric Sounding (MIPAS), ENVISAT satellite

Limb Sounder – Air Quality: **PAN**

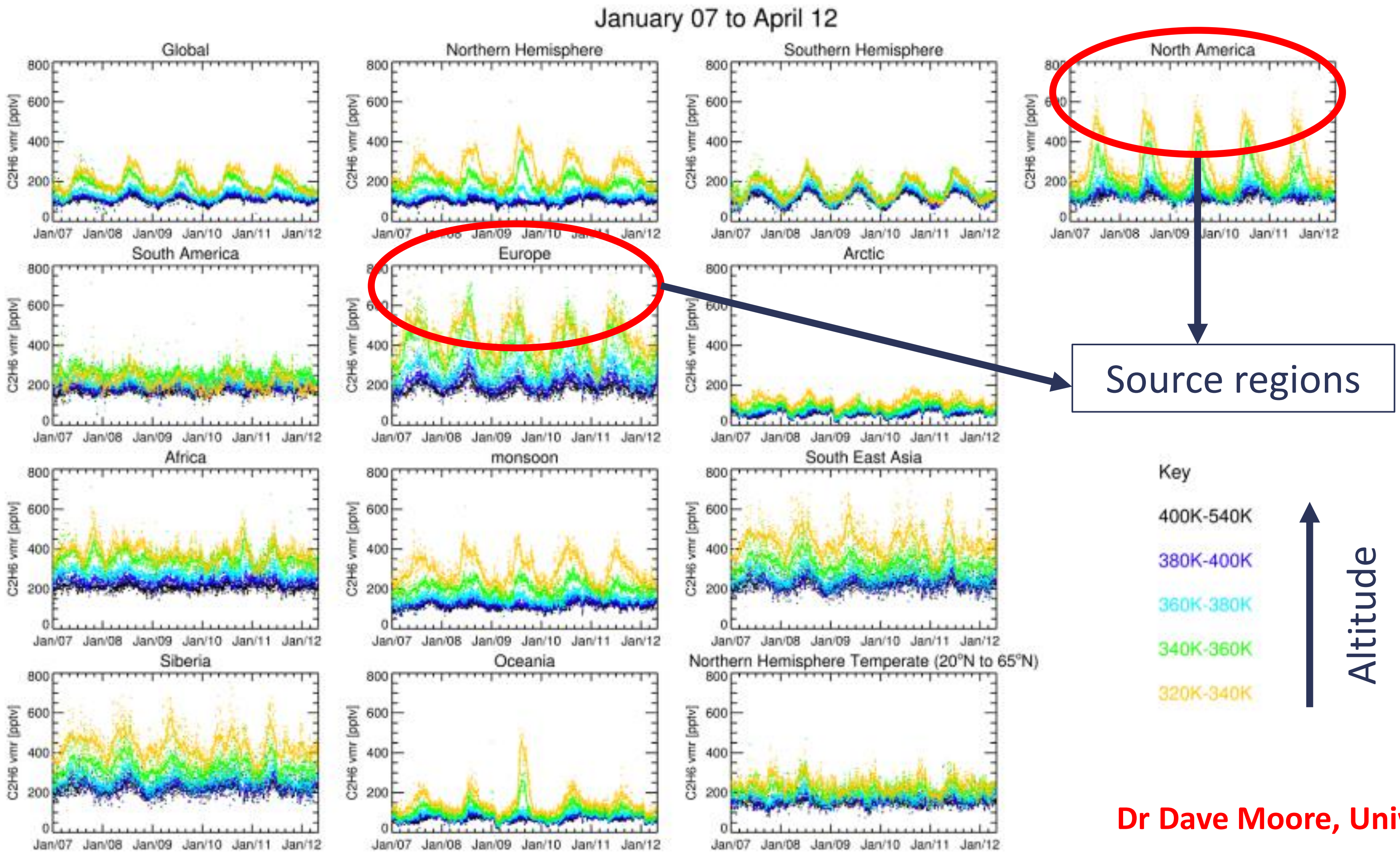
MIPAS Peroxyacetyl Nitrate, PAN, (2007-2008, pptv) at 150 hPa



Pope et al., (2016) – doi.org/10.5194/acp-16-13541-2016

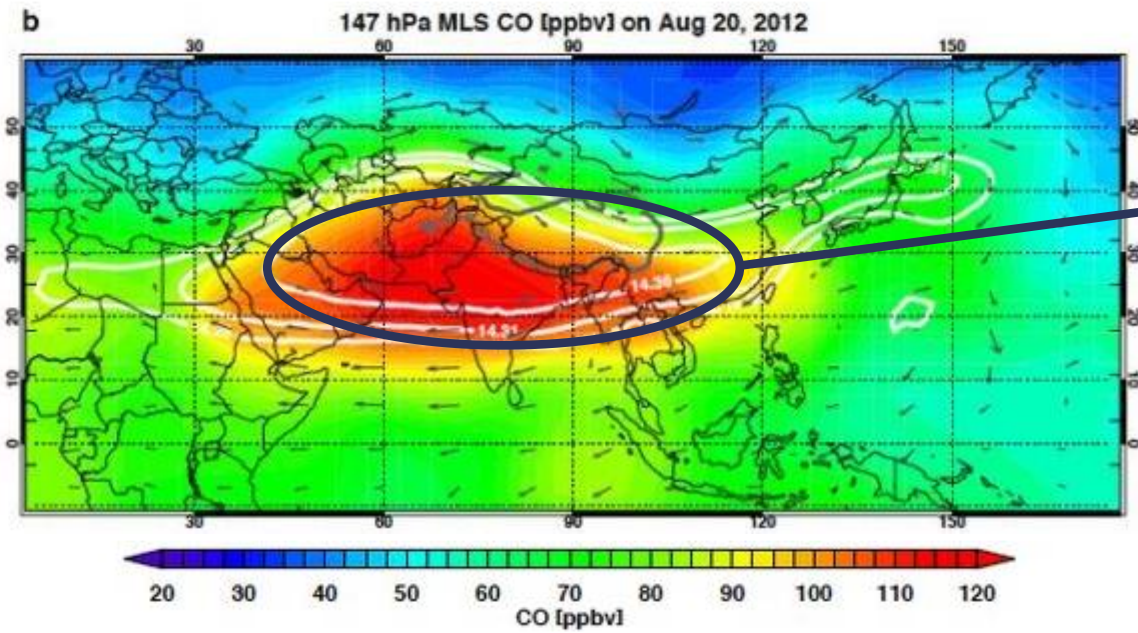
Limb Sounder – Air Quality: Ethane (C_2H_6)

MIPAS Ethane (2007-2012, pptv)

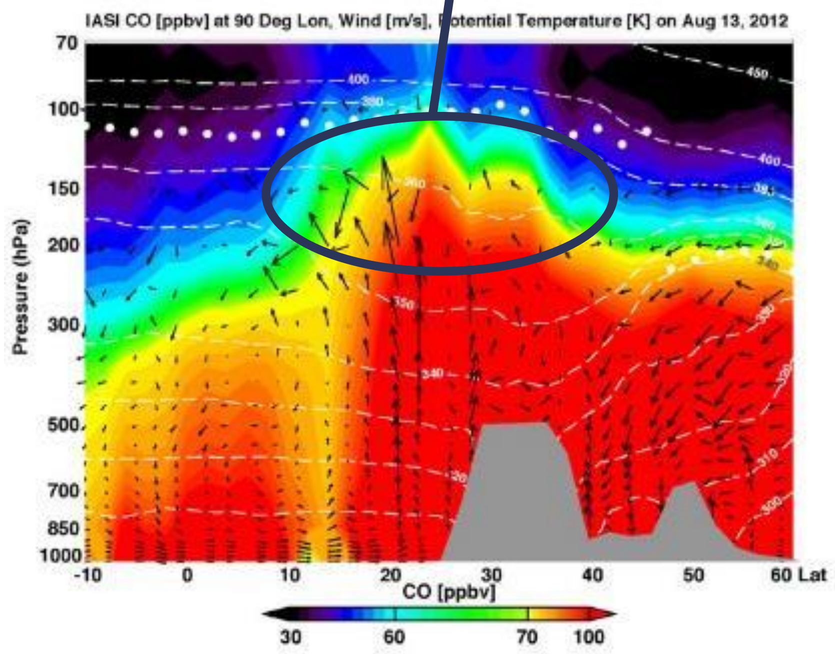


Dr Dave Moore, University of Leicester

Limb Sounder – Air Quality: Carbon Monoxide (CO)



Rapid ascent of pollution into the UTLS from surface



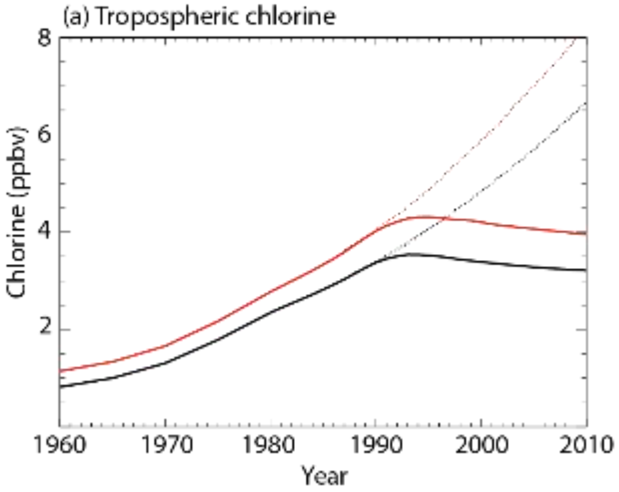
Summer-time Asian Monsoon: MLS CO Observations

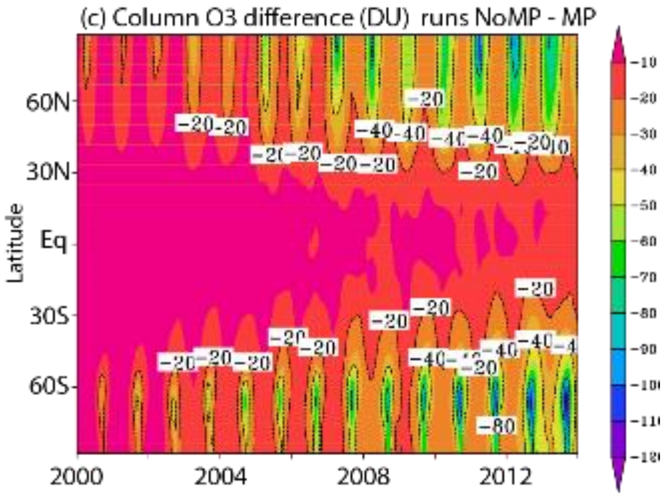
Luo et al., (2017), doi:10.5194/acp-2017-252

Nadir Sounder – Climate: Ozone Hole

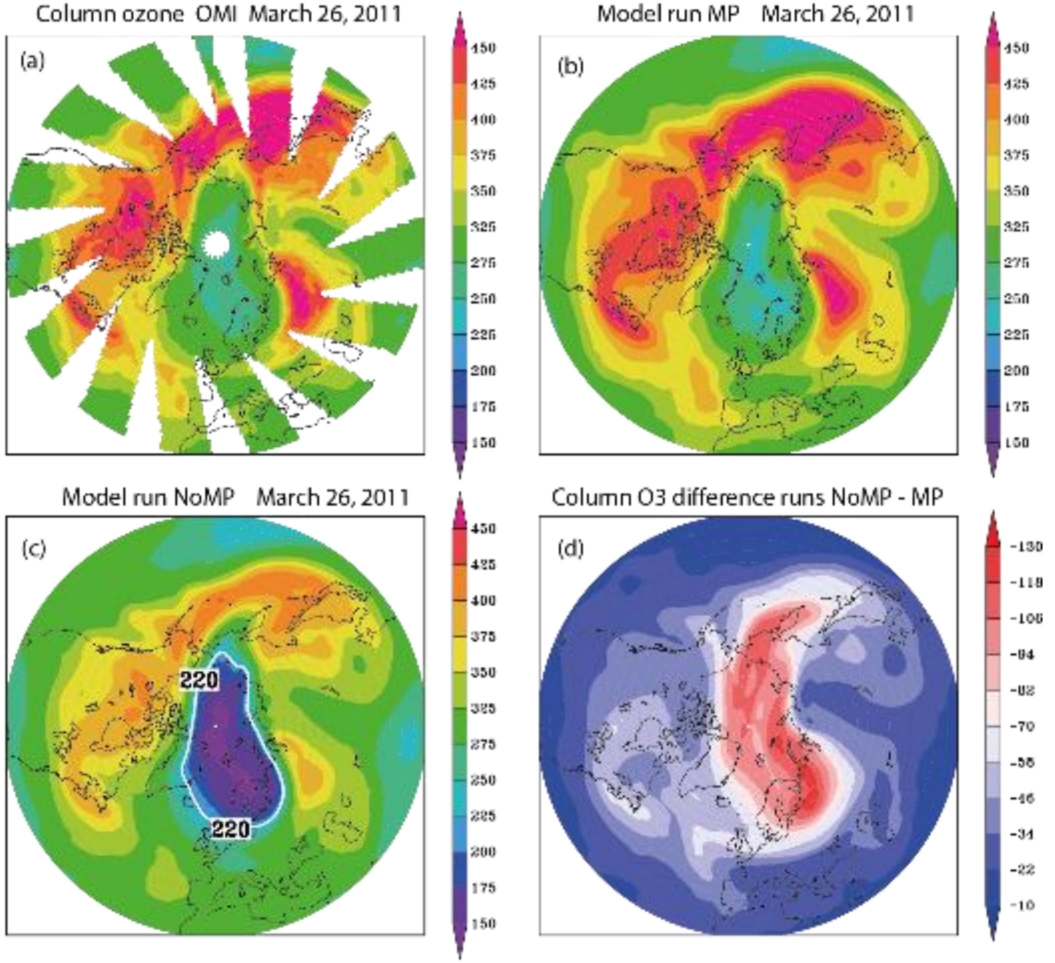
The ‘World Avoided’ by the Montreal Protocol

Chipperfield et al., (2015), doi.org/10.1038/ncomms8233



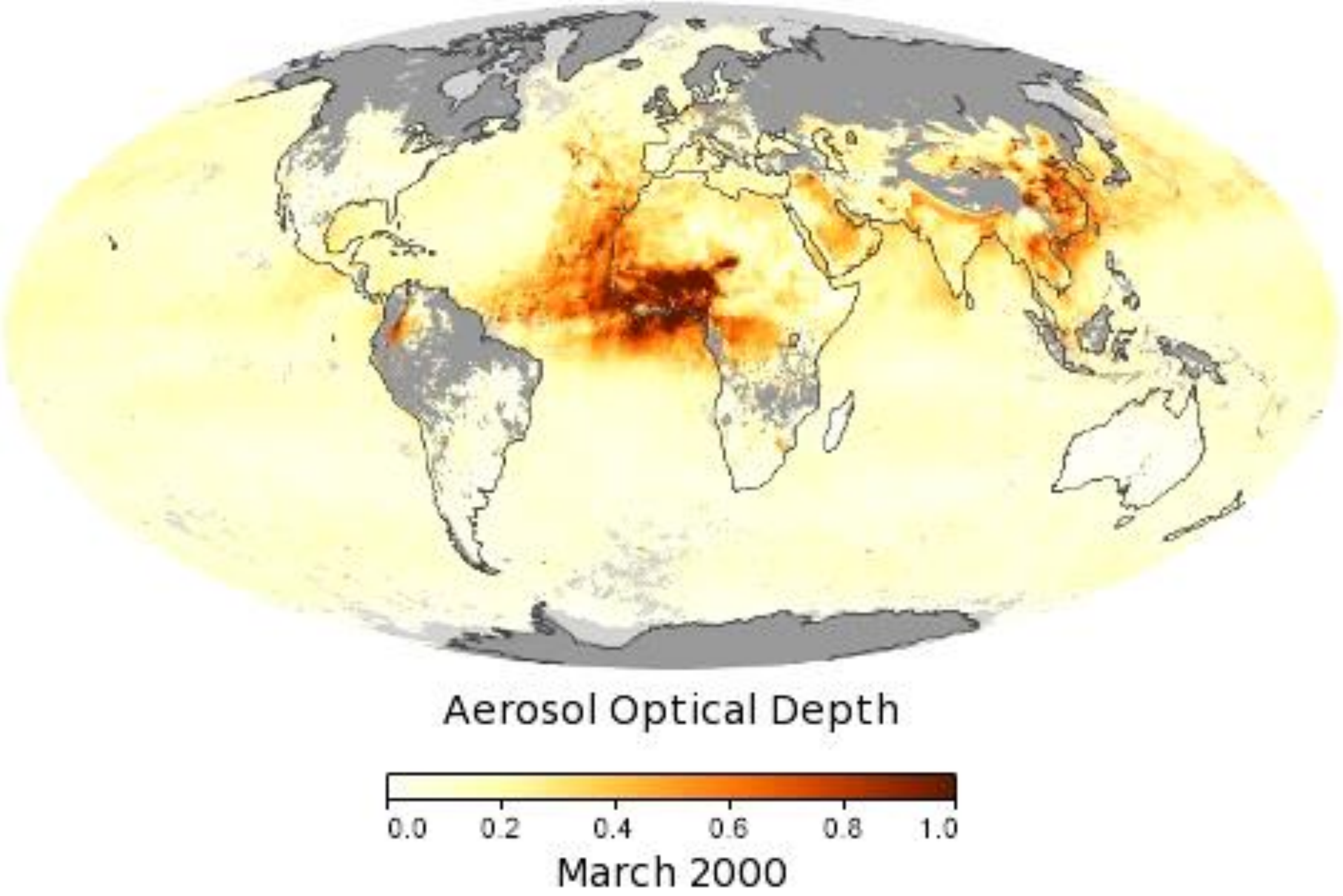


Ozone Monitoring Instrument (OMI), Aura satellite



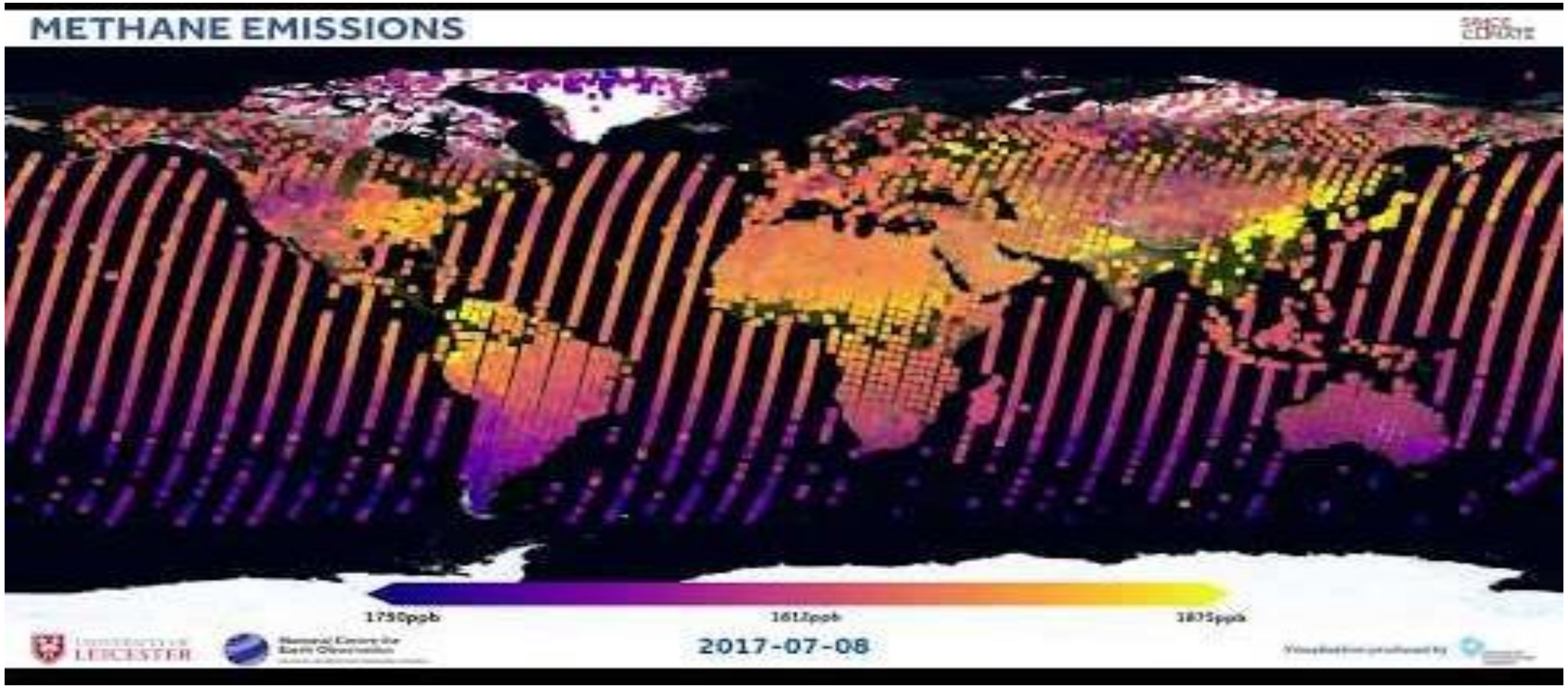
We would have had a deep Arctic Ozone Hole in 2010/11.

Nadir Sounder - Climate: Aerosol Optical Depth (AOD)

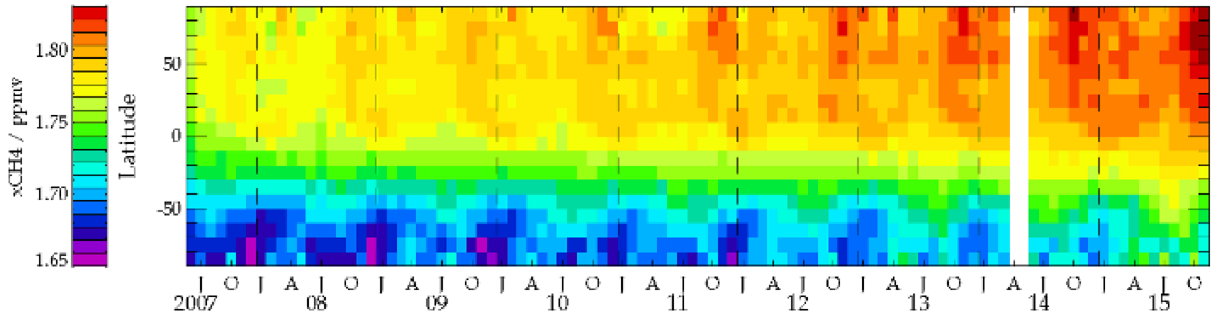


NASA Earth Observatory, https://earthobservatory.nasa.gov/

Nadir Sounder – Climate: Methane (CH_4)



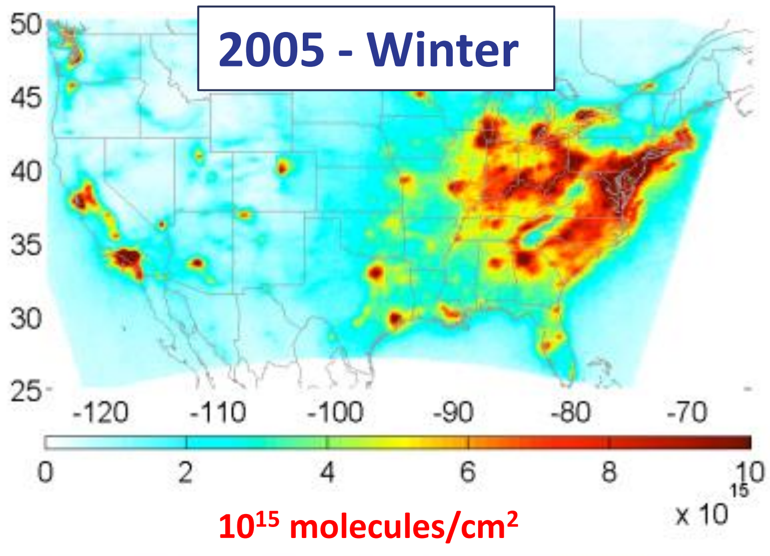
Methane 2007-15 from MetOp-A satellite

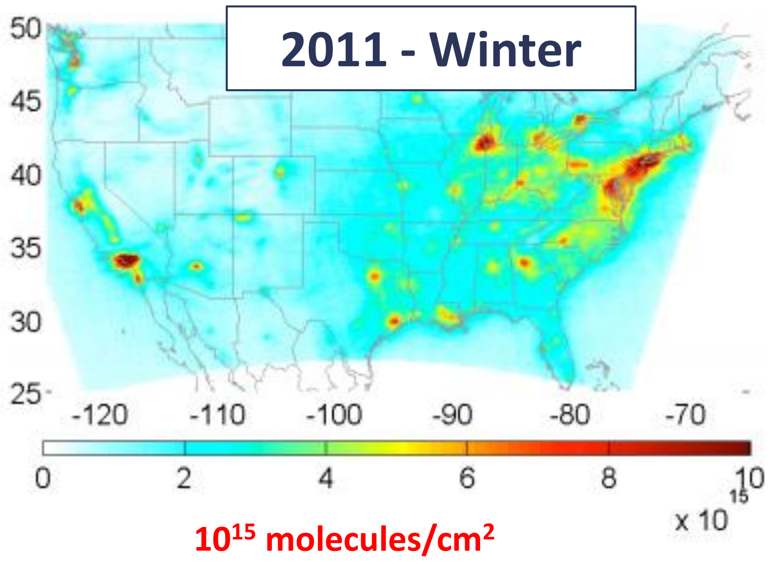


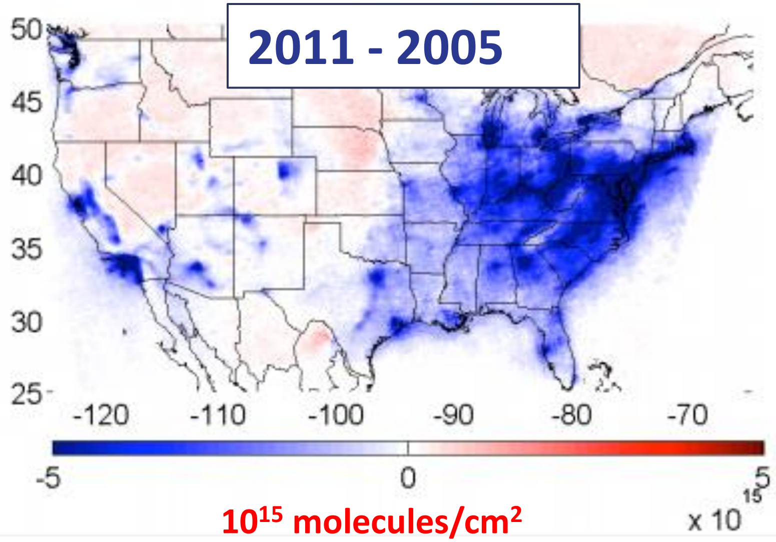
Dr Rob Parker, University of Leicester

RAL Space

Nadir Sounder – Air Quality: NO_2 Trends



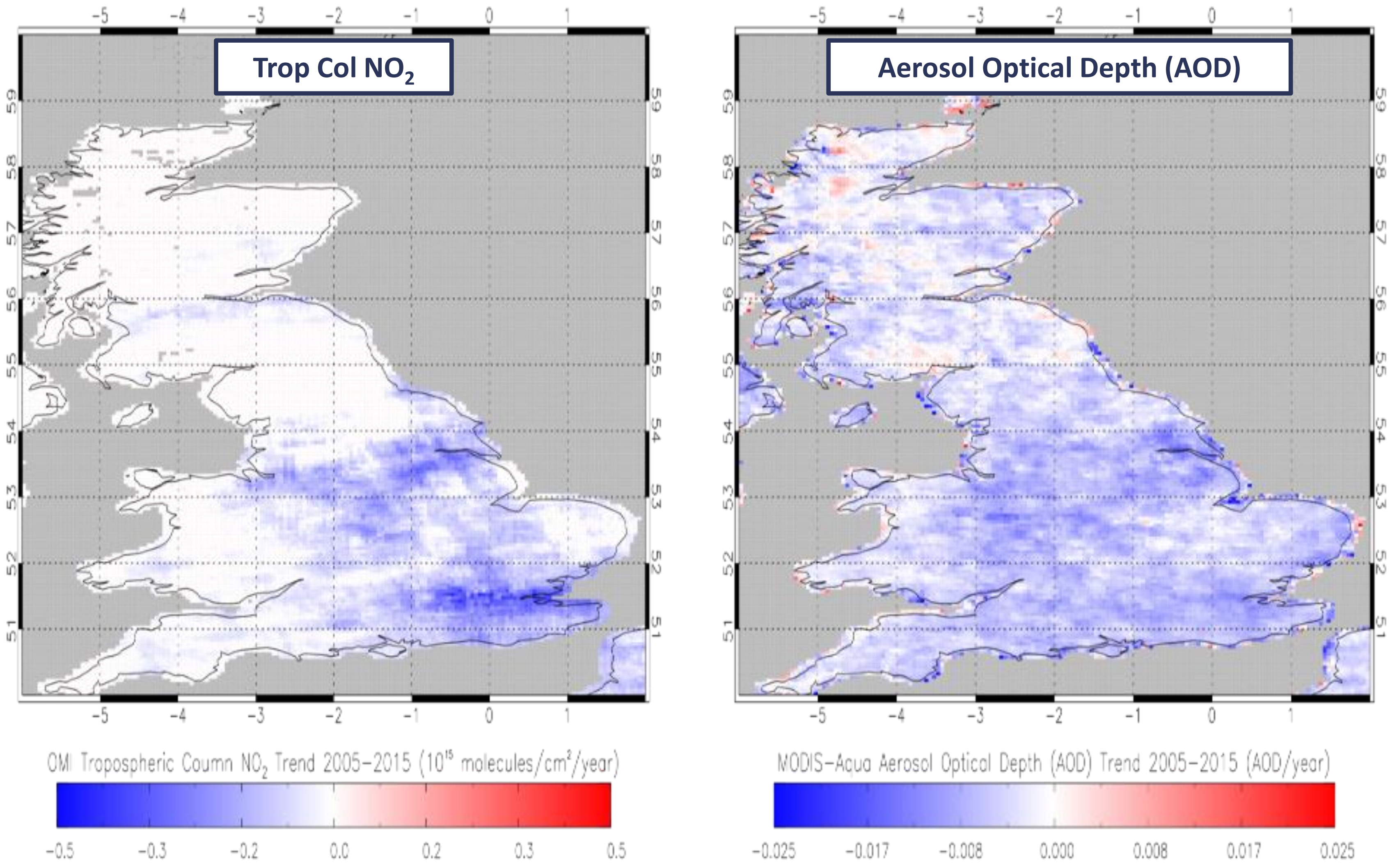




Emissions policies and new technology show decreases in OMI tropospheric column NO_2 over the USA.

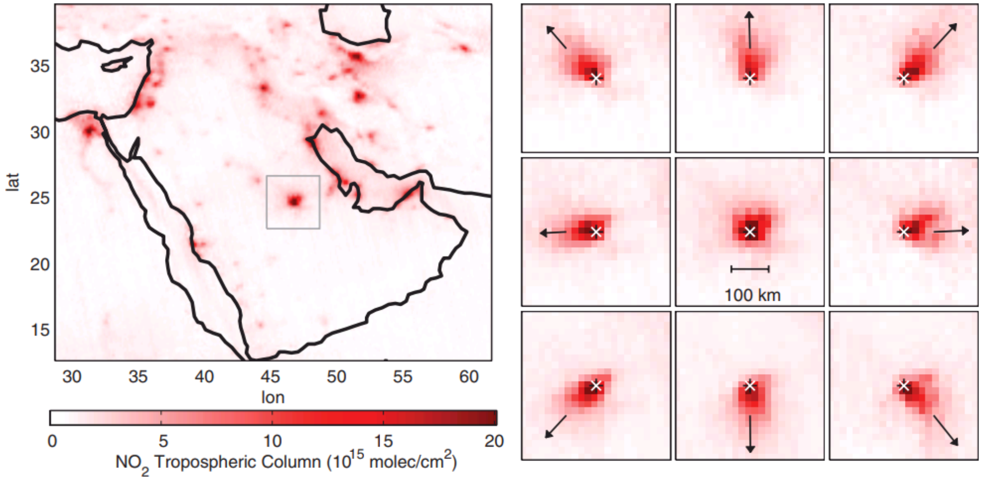
Russel et al., (2012), doi:10.5194/acp-12-12197-2012

Nadir Sounder – Air Quality: UK Trends



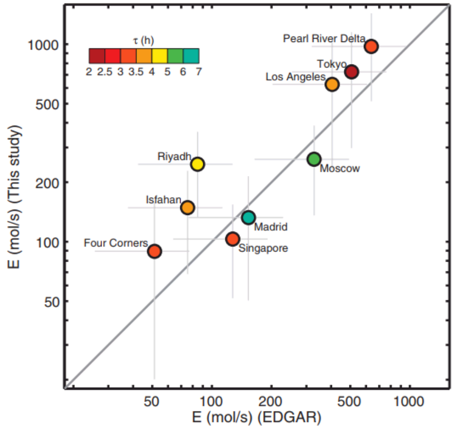
Pope et al., (2018), doi.org/10.1002/asl.817

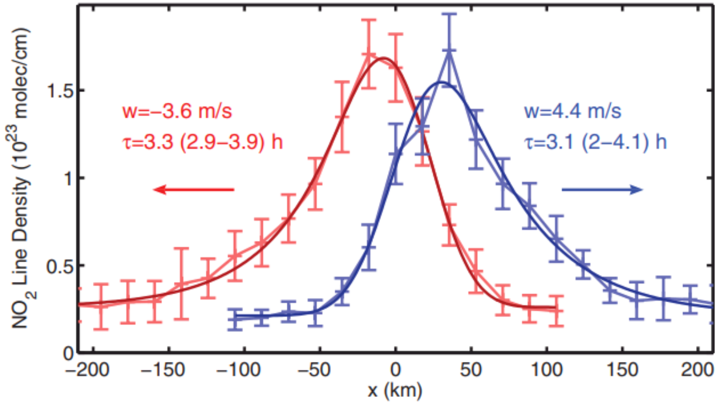
Nadir Sounder – Air Quality: Emission Estimates



By using OMI tropospheric column NO_2 data and model reanalysis wind data, downwind plumes (line densities) from source can be mapped.

Beirle et al., (2011), doi.org/10.1126/science.1207824

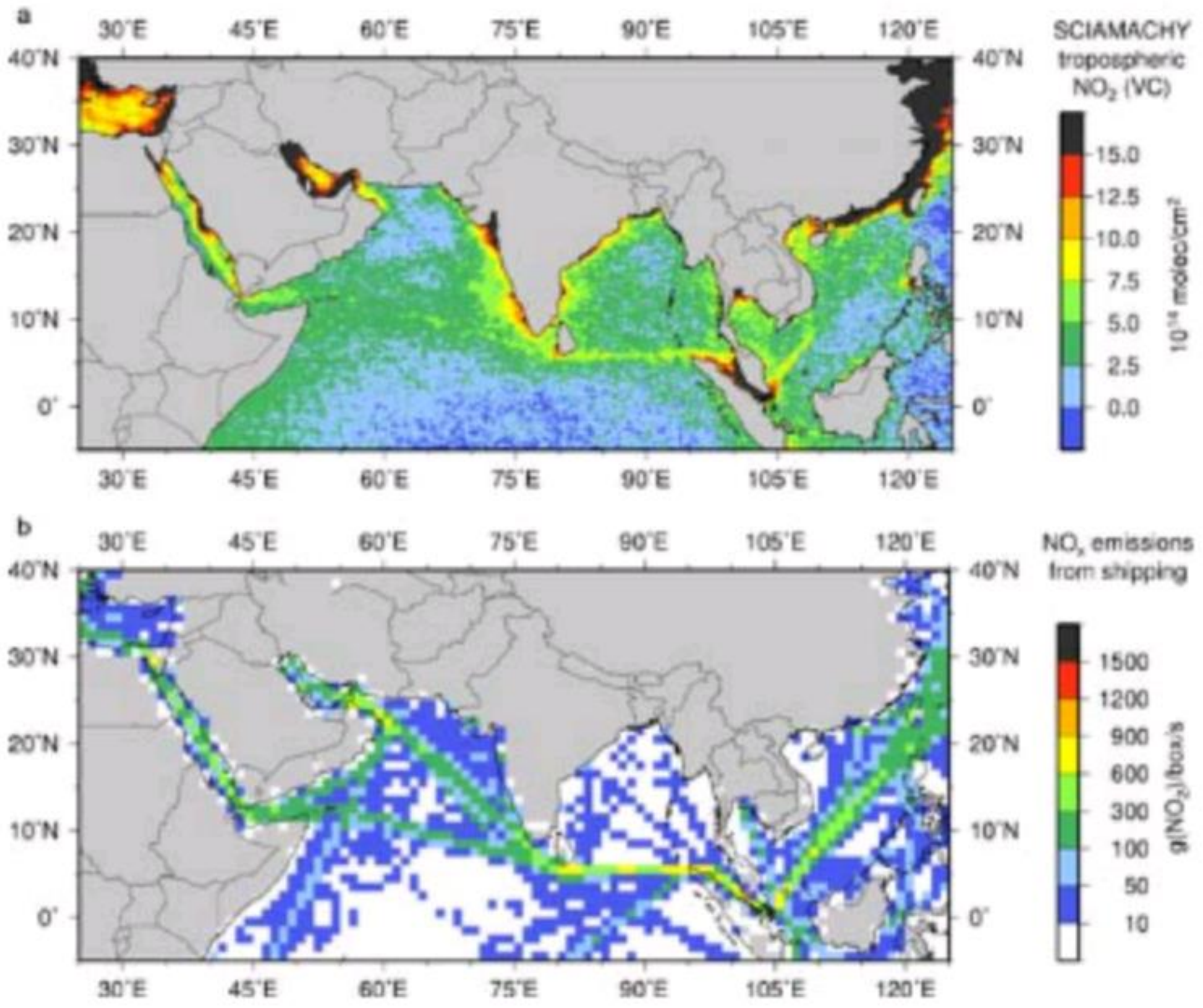




Emissions from satellite compare well with bottom-up derived emission estimates.

Non-linear least squares fit is used to infer the emission rate.

Nadir Sounder – Air Quality: UK Trends



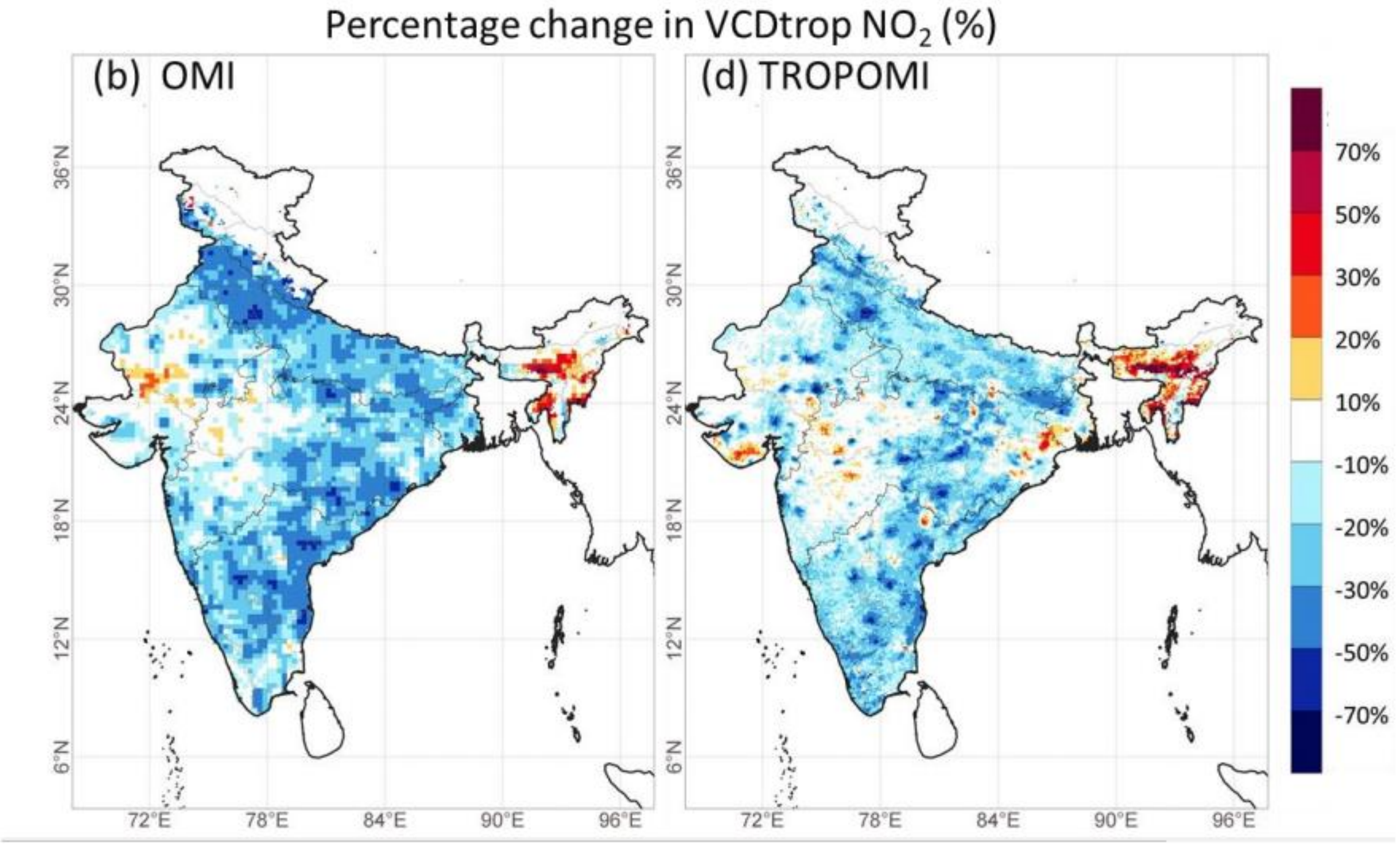
Assuming a NO_2 lifetime and knowledge of the shipping fleet, Richter et al., (2004) derived NO_x emissions from SCIAMACHY data.

Richter et al., (2004), https://doi.org/10.1029/2004GL020822

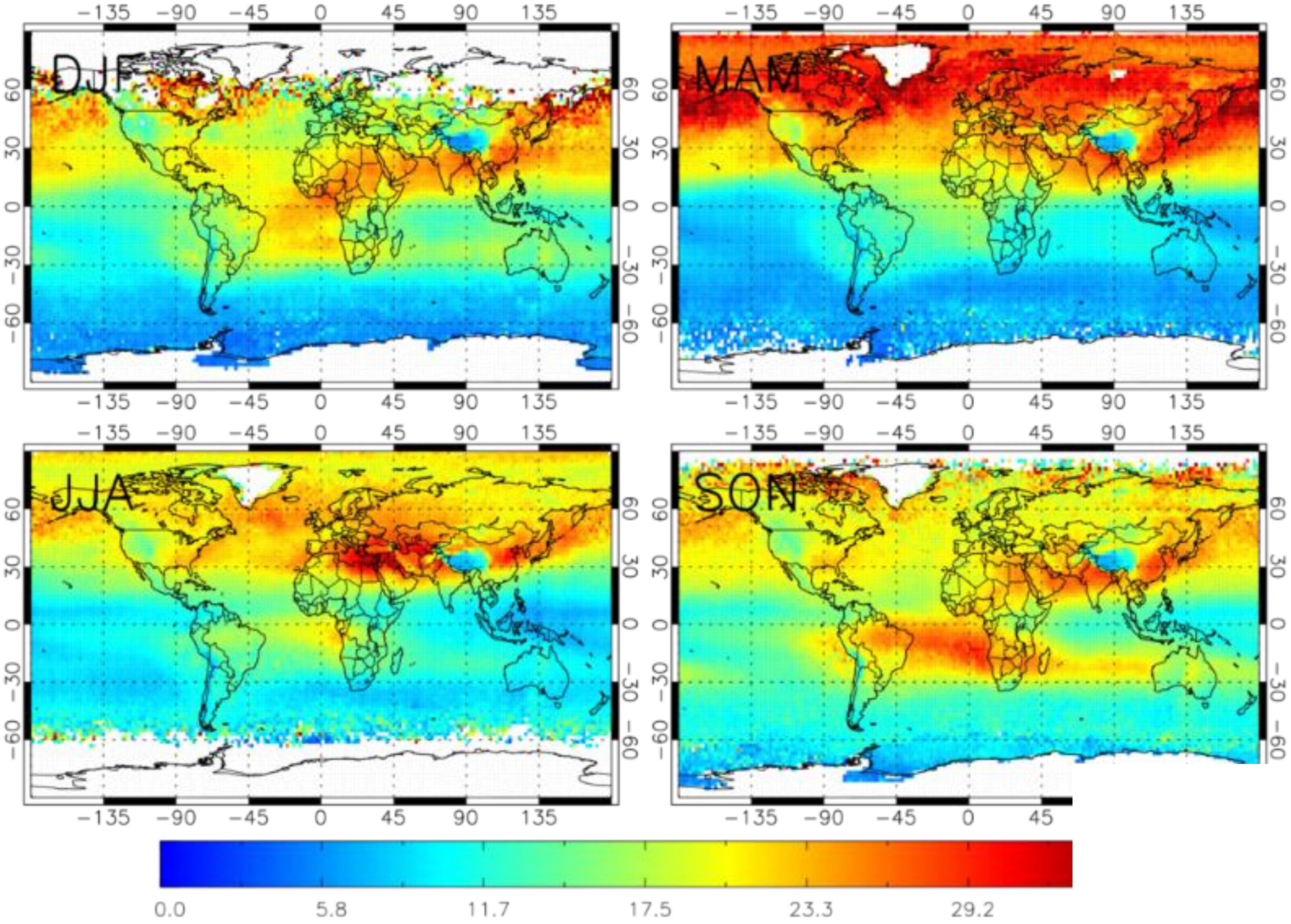
Nadir Sounder – Air Quality: COVID-19

Percentage difference between Lockdown year and previous business as usual years.

Biswal et al., (2020), doi.org/10.5194/acp-2020-1023



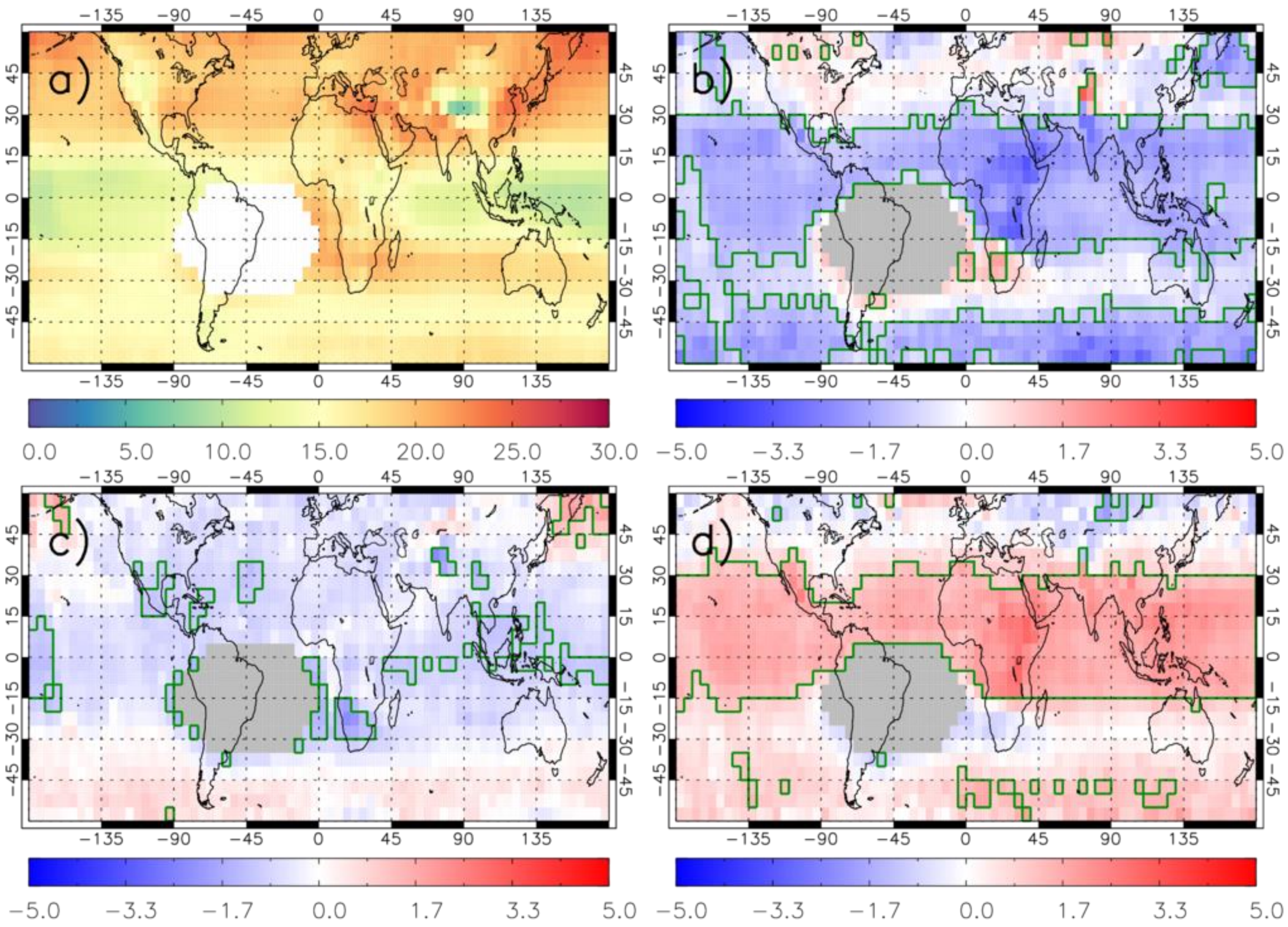
Nadir Sounder – Air Quality: Lower Tropospheric Ozone



OMI Sub-column (0-6 km) O_3 (Dobson Units) – Dr Richard Pope, University of Leeds

Nadir Sounder – Air Quality: Lower Trop Ozone Tendencies

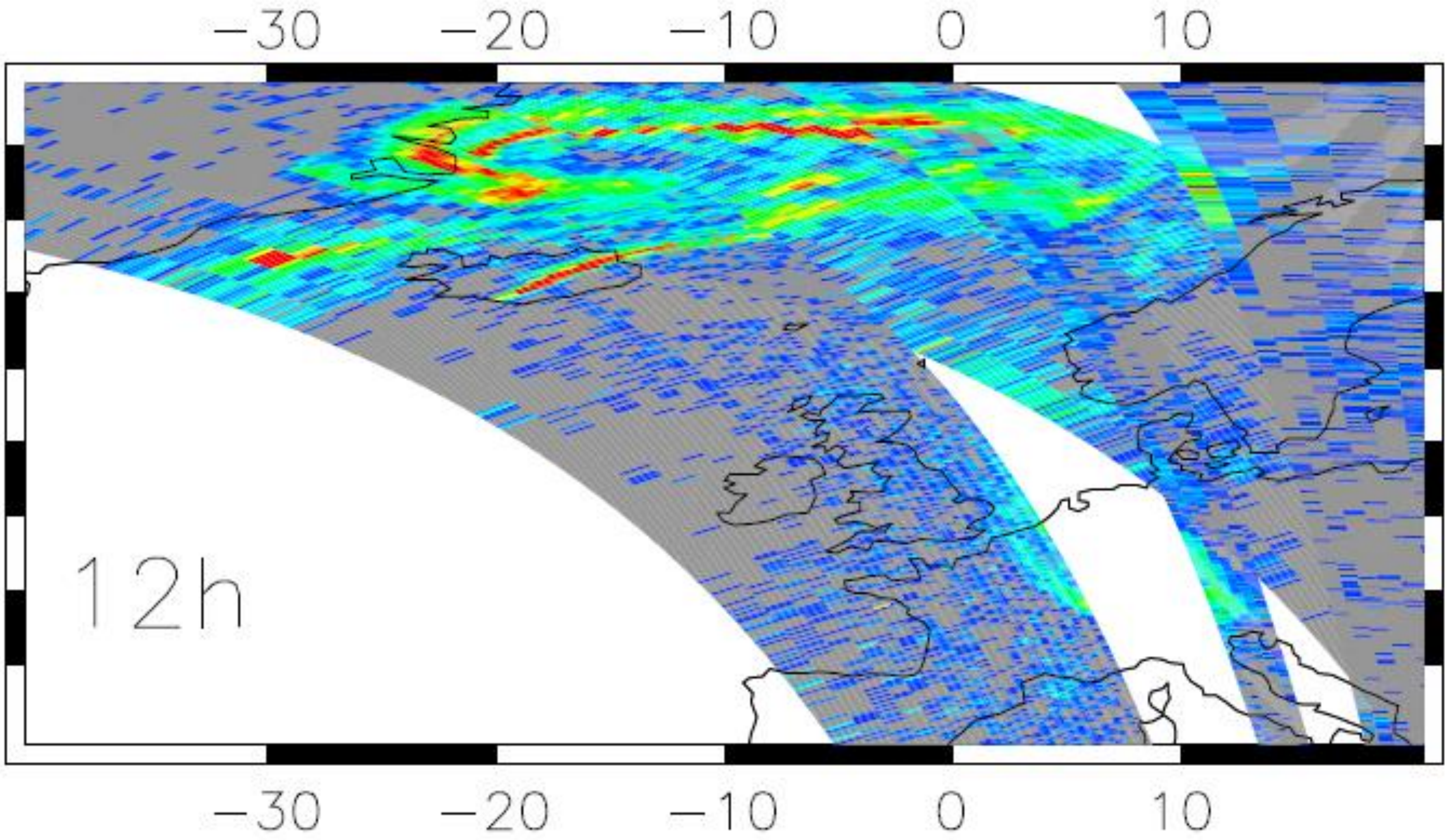
Sub-column (0-6 km) O_3 (Dobson Units) – Dr Richard Pope, University of Leeds



Pope et al., (2023 - accepted), doi: 10.5194/egusphere-2023-1172

Nadir Sounder – Air Quality: Hazards

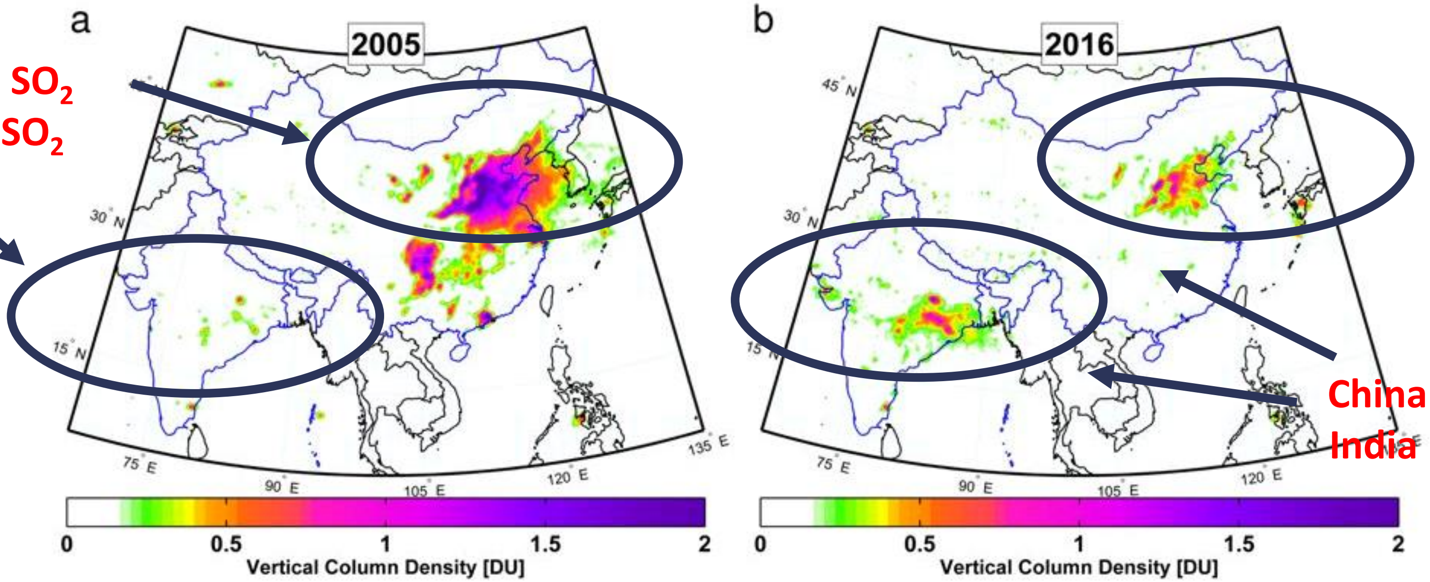
OMI observations of SO_2 from the Icelandic volcano eruption in 2010.



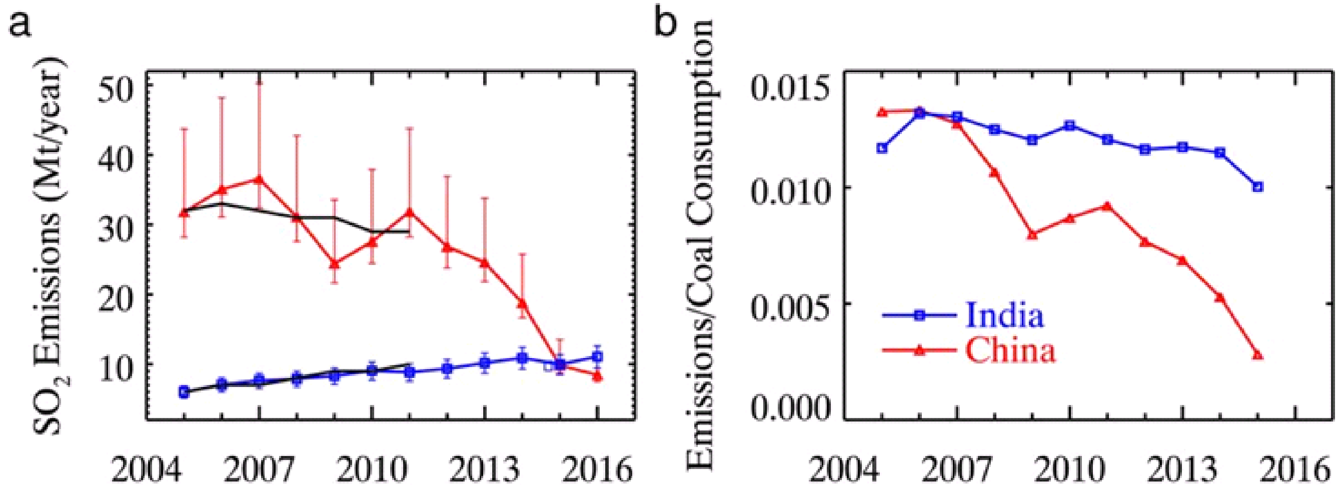
Dr. Nigel Richards, University of Leeds

Nadir Sounder – Air Quality: Emission Changes

China High SO_2
India Low SO_2



China Lower SO_2
India Higher SO_2

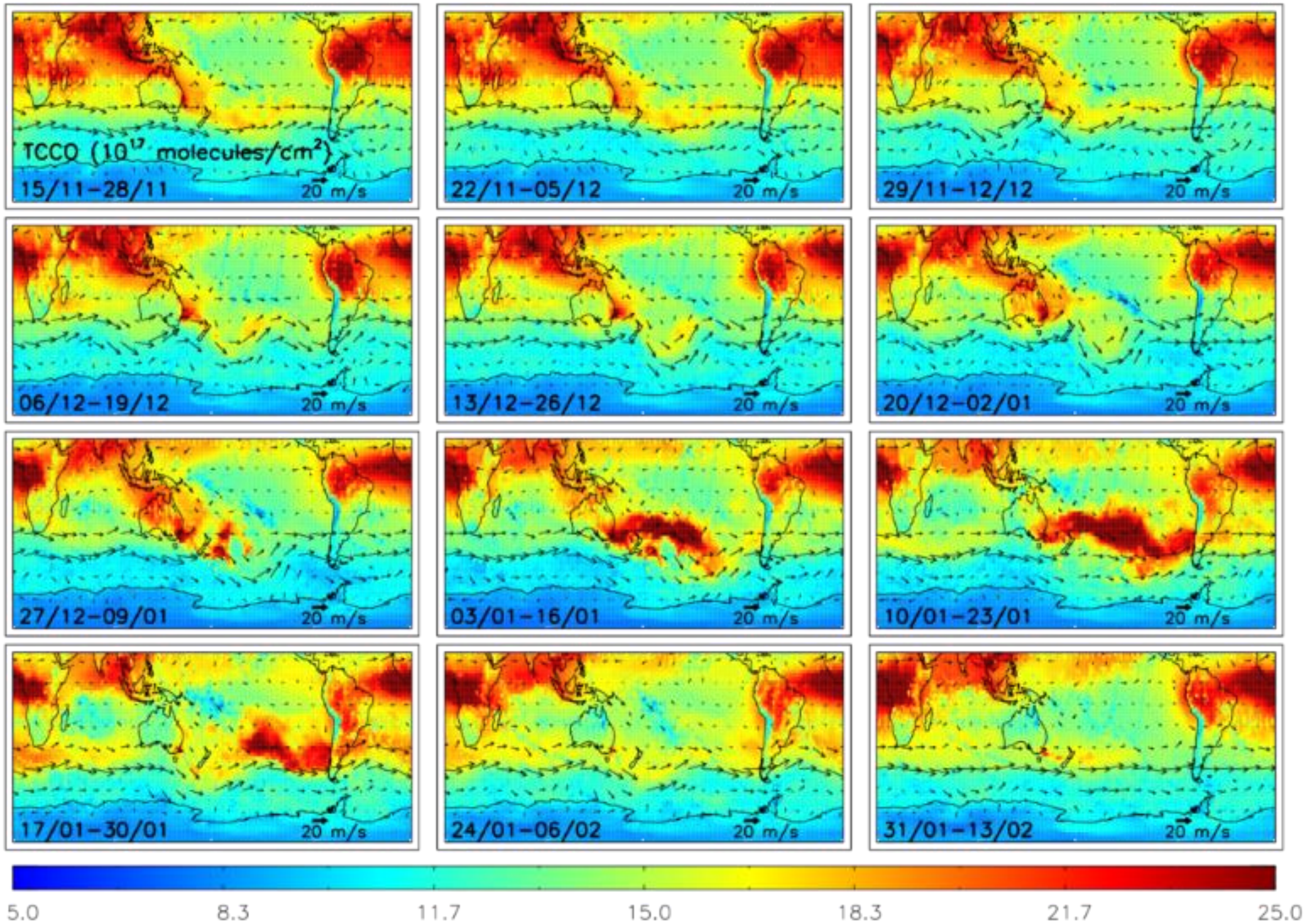


Li et al., (2017), doi.org/10.1038/s41598-017-14639-8

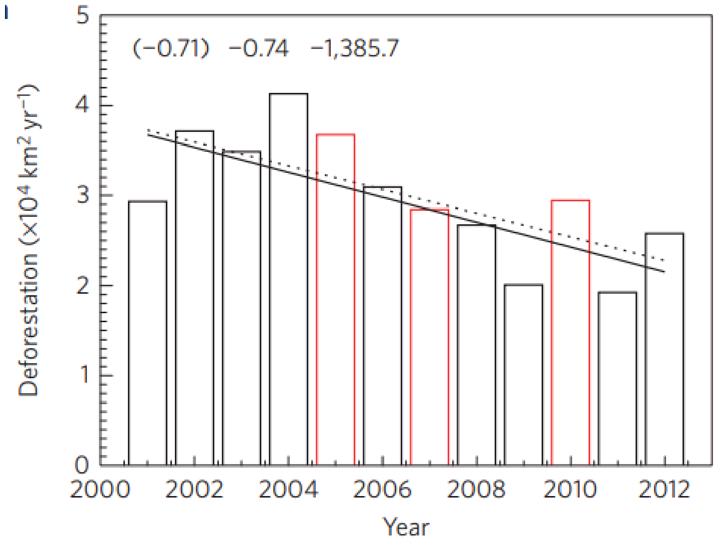
Nadir Sounder – Air Quality: Fire CO

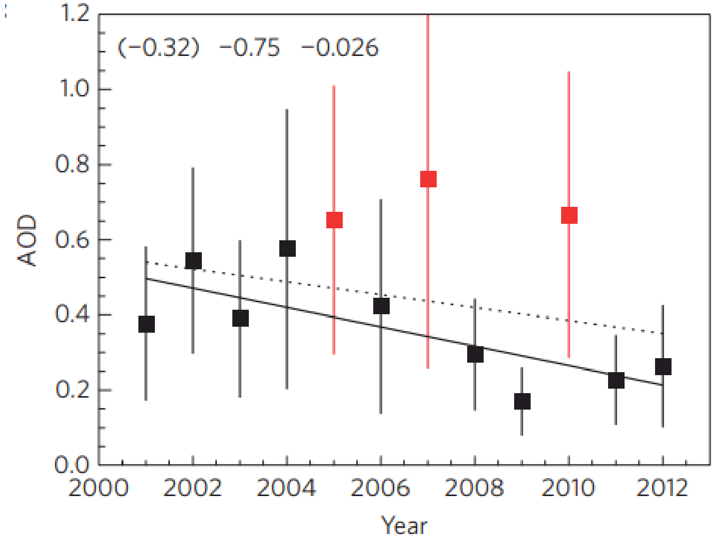
Dr Richard Pope, University of Leeds

IASI Total Column CO – Fire Season 2019/2020

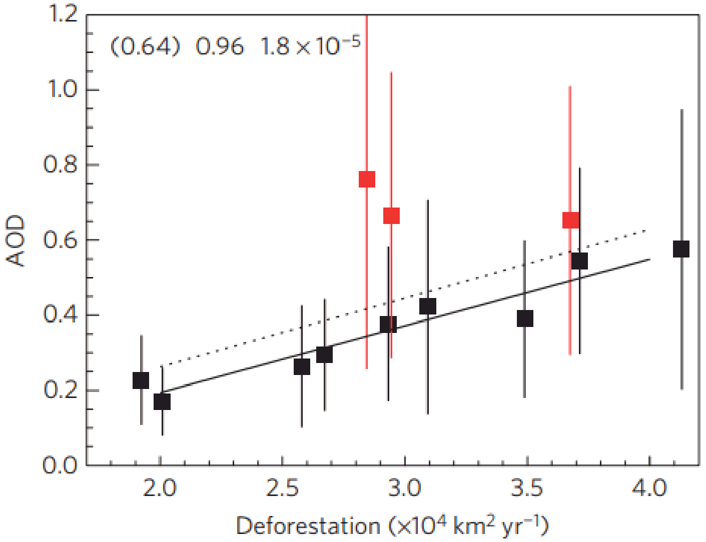


Nadir Sounder – Air Quality: Fire & AOD



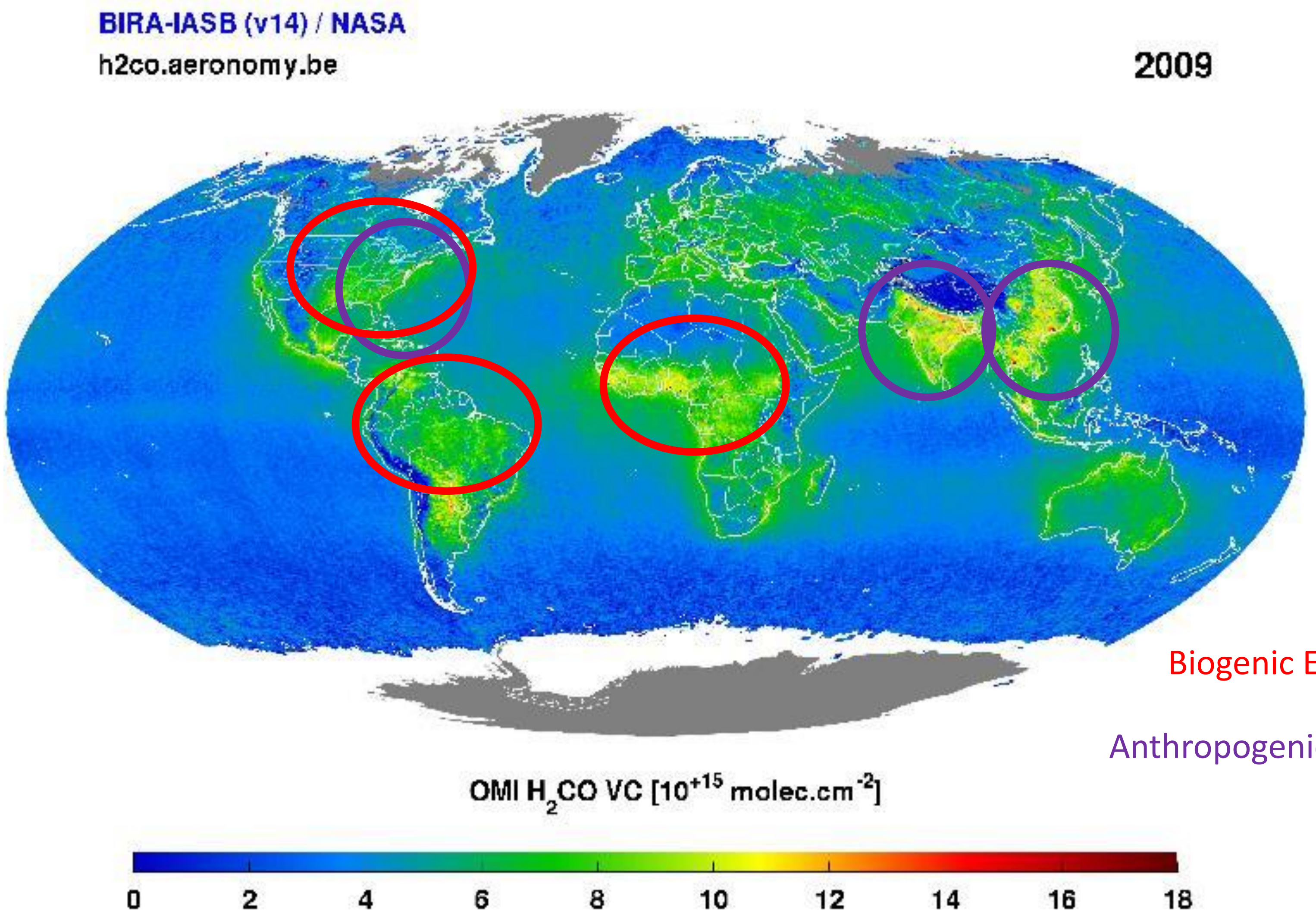


Reddington et al., (2015), doi.org/10.1038/ngeo2535



- Decreases in deforestation fires in the Amazon reduce levels of emitted aerosols (lower satellite retrieved AOD).
- Lower aerosol concentrations lead to improved air quality and less premature deaths.
- Drought years are shown in red: 2005, 2007 and 2010.

Nadir Sounder – Air Quality: Oxidised VOCs



Tropospheric Emissions Monitoring Internet Service (http://www.temis.nl/index.php)

Biogenic Emissions

Anthropogenic Emissions

Nadir Sounder – Air Quality: Methanol

Summer 2018 heat wave yielded enhancements in BVOC emissions, which become oxidised, as seen in IASI methanol measurements.

Dr Richard Pope, University of Leeds