Thermal IR satellite missions for air quality

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CEOS Atmospheric Composition Virtual Constellation AC-VC-16

NASA and NOAA Operational Atmospheric Chemistry Products

Chris Barnet

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NOAA/JPSS Senior Advisor for Atmospheric Sounding
Science and Technology Corporation, STC

May 27, 2020
Update for CEOS AC-VC

Space-borne operational hyperspectral *thermal sounders* to be discussed today

- There are 5 operational thermal sounder suites at NASA or NOAA

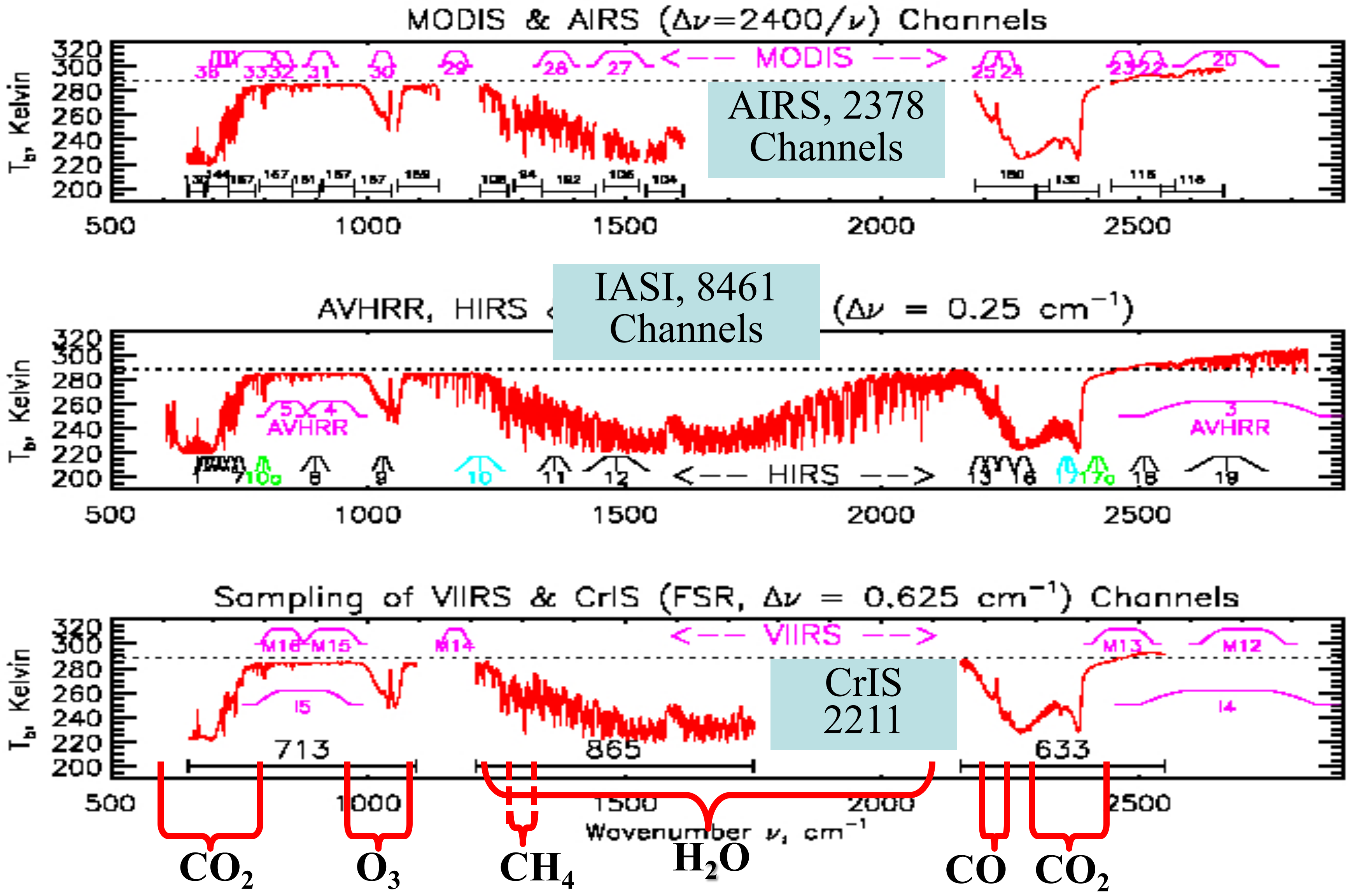
Satellite	Instruments	Overpass	Launch dates
Aqua	AIRS, AMSU	1:30 **	2002
Metop	IASI, AMSU, MHS	9:30	2006, 2012, 2018
S-NPP, JPSS	CrIS, ATMS	1:30	2011, 2017, …

- There are numerous differences in these sounding suites
  - **Instruments are different**
    - Spectra resolution, sampling and noise
    - Spatial sampling
    - Degradation over time
  - **Algorithm differences**
    - NOAA algorithms became operational ~1-2 year after launch and have asynchronous maintenance schedules (e.g., training datasets are different)
    - 9:30/1:30 orbits co-location w/ in-situ is different (affects tuning/regression training and makes validation more difficult)
  - **Sensitivity to a-priori assumptions**
    - Sensitivity to meteorology (e.g., clouds at 9:30 vs 1:30 am/pm)
    - Sensitivity to seasonal and climate changes (e.g., 10% increase in CO_2, 2002-2020)

Trace Gas products were not the primary design criteria of the modern satellite sounding suite

** in early 2022 Aqua will drop out of A-train // begins a 6 year drift to 5:30

Spectral Coverage of Thermal Sounders & Imagers (Aqua, Metop-A,B,C, Suomi-NPP, NOAA-20+)



MODIS & AIRS ($\Delta\nu=2400/\nu$) Channels

AIRS, 2378 Channels

AVHRR, HIRS ($\Delta\nu$ = 0.25 cm^{-1})

IASI, 8461 Channels

Sampling of VIIRS & CrIS (FSR, $\Delta\nu$ = 0.625 cm^{-1}) Channels

CrIS 2211

Operational sounding products using the “CAPS” algorithm

	NASA CLIMCAPS	**NOAA NUCAPS**
A-priori	MERRA-2 for T(p), q(p), O3(p)	Global regression (i.e.,model independent)
Error propagation	Eigenvector expansion of full 2-D covariance	1-D diagonal w/ specified vertical “oscillation”
Supported systems	• S-NPP full mission • NOAA-20 full mission • Aqua full mission, end of 2020	• Metop –A, -B, -C • S-NPP FSR • NOAA-20
Latency	~1 month (wait f/ MERRA)	Real time (~30 minutes)
Averaging Kernels?	YES – fully supported	Not operational, but can provide via science code

NUCAPS = NOAA-Unique Combined Atmospheric Processing System

CLIMCAPS = Community Long-term Infrared Microwave Coupled Atmospheric Product System

Operational and experimental retrieval products from NUCAPS & CLIMCAPS

Trace gas profile products

Retrieval Product	Spectral Region (cm^{-1})
Ozone, O_3	990 – 1070
Carbon Monoxide, CO	2155 – 2220
Methane, CH_4	1220 – 1350
Carbon Dioxide, CO_2	660 – 760 2200 – 2400

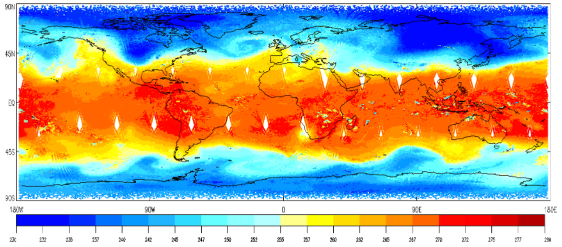
Experimental trace gas products

Nitric Acid, HNO_3	760 – 1320
Nitrous Oxide, N_2O	1290 – 1300 2190 – 2240
Volcanic Sulfur Dioxide, SO_2	1343 – 1383

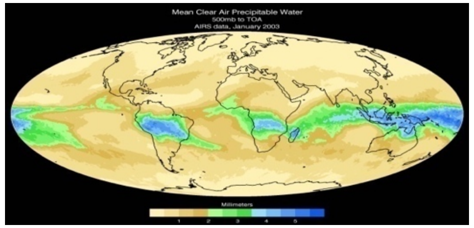
Single-FOV detection flags

Isoprene (C_5H_8)	893.8
Ethane (C_2H_6)	822.5
Propylene (C_3H_6)	911.9
Ammonia (NH_3)	966.25 + 928.75

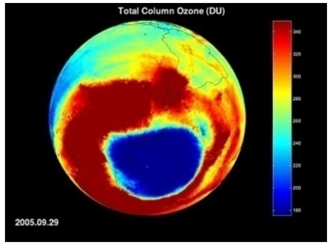
500 hPa Temperature



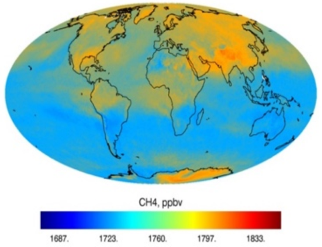
500 hPa Water Vapor



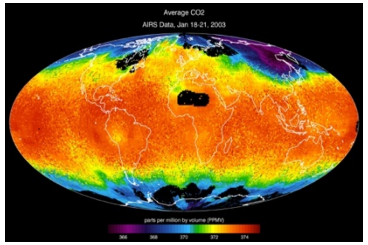
Ozone



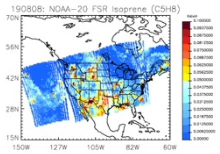
Methane



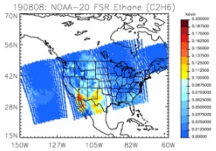
Carbon Dioxide



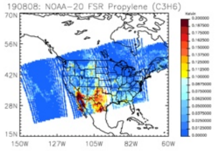
Isoprene



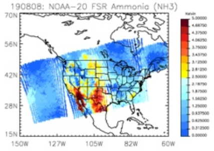
Ethane



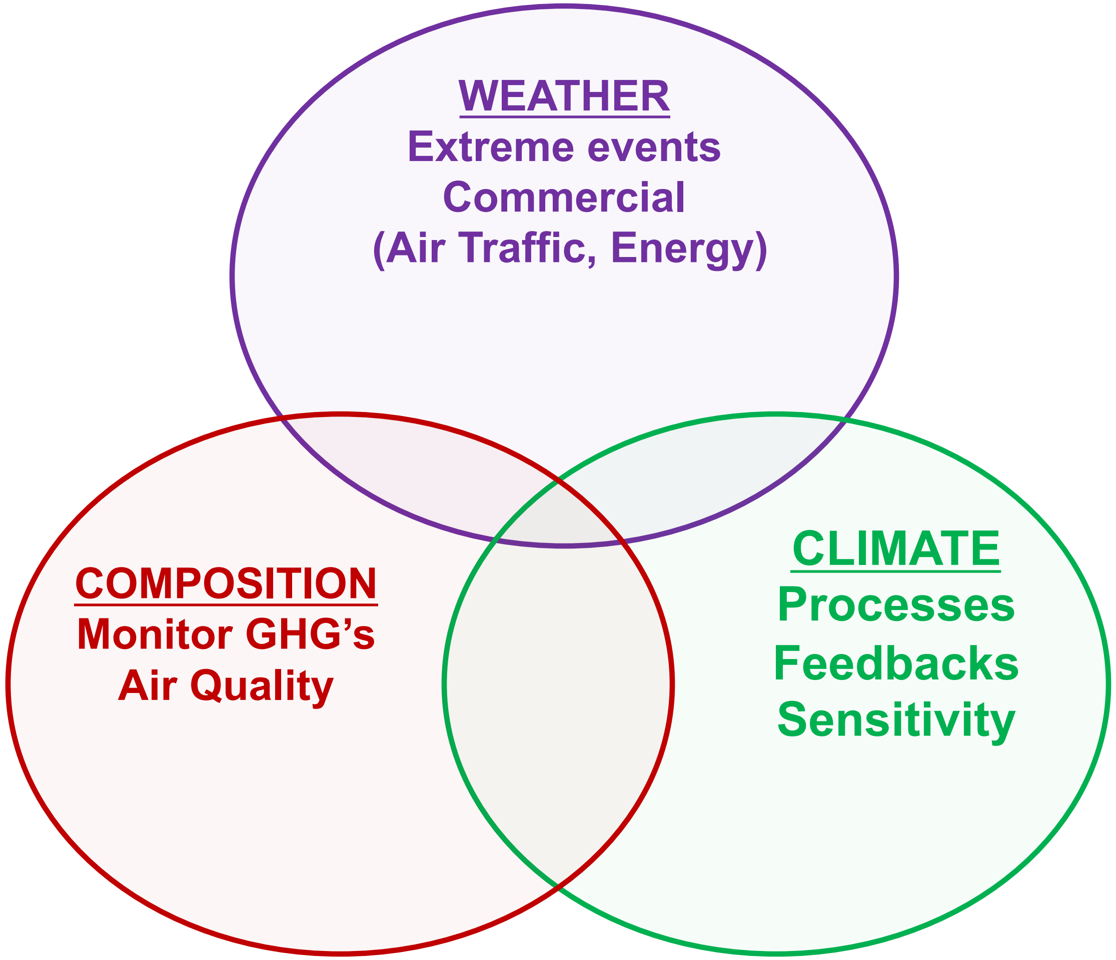
Propylene



Ammonia



Together these algorithms can ***contribute*** to the needs of three communities



WEATHER
Extreme events
Commercial
(Air Traffic, Energy)

COMPOSITION
Monitor GHG's
Air Quality

CLIMATE
Processes
Feedbacks
Sensitivity

Applications we are **NOT** targeting with NUCAPS & CLIMCAPS.

Topic	Potential applications for thermal sounding products
Long term GHG trends	• For GHG-relevant gases we have very low information content. • We relax to a-priori assumptions so we only see ~50% of the signal. • Large cross-talk between CO2/T, N2O/T, CH4/q, etc. • Recommend using other products for trends • For example, Larrabee Strow's radiance anomaly product (also funded by NASA TASNPP)
GHG Emissions Monitoring	• We have very low (and variable) sensitivity in the PBL • Most of our PBL information content comes from a-priori assumptions. • We complement the information content of passive solar sensors.
High spatial resolution approaches for trace gases.	• Clouds are still a major obstacle for infrared sounding. • NU/CLIMCAPS are intended as global quick look products. • NU/CLIMCAPS can be used as "triggers" for more advanced algorithms • could use CLIMCAPS to launch specialty algorithms (e.g., NASA TASNPP or AC4 funded algorithms, MUSES, etc.)

Applications we are targeting with NUCAPS & CLIMCAPS.

Topic	Potential applications for thermal sounding products
T(p), q(p) sounding and data assimilation	Knowledge of CO2, O3, HNO3, N2O needed to derive T(p) Knowledge of CH4, N2O, SO2 needed to derive q(p)
GHG Monitoring	Enhance the boundary layer sensitivity of passive solar retrieval products.
Ozone	Ozone hole; intrusions and mid-trop O3 (Langford 2018 Atmos. Env); LS O3 trends (Ball 2018 ACP, Wargan 2018 GRL); CO/O3 ratio (Anderson 2016 Nat.Comm)
Carbon Dioxide (CO2)	Seasonal cycle amplitude (Barnes 2016 JGR), Clear bias and diurnal “rectifier” effects (Corbin 2008 JGR), and stratospheric/troposphere CO2 gradient. Evaluation of transport models (mixing into mid-trop, etc.). Note that separability of T/CO2 is significantly improved with use of Merra-2 a-priori and with AMSU/ATMS O2 bands for T(p)
Carbon Monoxide	Long-term trends of CO (Worden 2013 ACP). Impact on OH (Gaubert 2017 GRL), Seasonal cycle (Park 2015 JGR) and CO/CO2 emission factors (Wang 2009 ACP)
Methane (CH4)	Monitoring of Amazon CH4 (Bloom 2016 ACP), Changes to Arctic emissions (Shakhova 2010 Science, Thornton 2016 GRL)
Other trace gases	Nitric Acid, Nitrous Oxide, Sulfur Dioxide are supported with experimental retrievals. Ammonia, Isoprene, Ethane, and Propylene are potentially useful as tracer-tracer correlations, emission ratios (errors tend to cancel), source type identification, etc.

CLIMCAPS Version.2 at NASA GES-DISC for full missions of S-NPP and JPSS-1

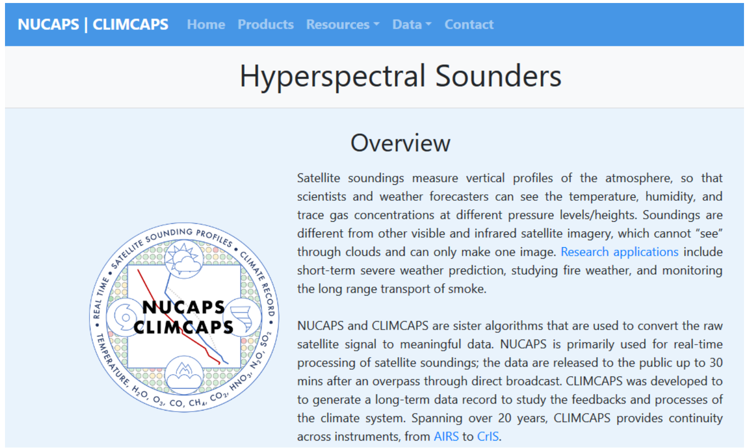
Short Name	DOI	Description
SNDRSNIML2CCPRETN	10.5067/9HR0XHCH3IGS	Geophysical state derived from Suomi-NPP ATMS + CrIS NSR
SNDRSNIML2CCPCCRN	10.5067/CNG0ST72533Z	Cloud Cleared Radiances derived from Suomi-NPP CrIS NSR
SNDRSNIML2CCPRET	10.5067/62SPJFQW5Q9B	Geophysical state derived from Suomi-NPP ATMS + CrIS FSR
SNDRSNIML2CCPCCR	10.5067/ATJX1J10VOMU	Cloud Cleared Radiances derived from Suomi NPP CrIS FSR
SNDRJ1IML2CCPRET	10.5067/LESQUBLWS18H	Geophysical state derived from JPSS-1 (NOAA-20) ATMS + CrIS
SNDRJ1IML2CCPCCR	10.5067/KE4WCXM829A3	Cloud Cleared Radiances derived from JPSS-1 (NOAA-20) CrIS

Note: NSR = Nominal Spectral Resolution, FSR = Full Spectral Resolution

For More Information

NUCAPS and CLIMCAPS Landing Page, Located at:

https://weather.msfc.nasa.gov/nucaps



Hyperspectral Sounders

Overview

Satellite soundings measure vertical profiles of the atmosphere, so that scientists and weather forecasters can see the temperature, humidity, and trace gas concentrations at different pressure levels/heights. Soundings are different from other visible and infrared satellite imagery, which cannot "see" through clouds and can only make one image. Research applications include short-term severe weather prediction, studying fire weather, and monitoring the long range transport of smoke.

NUCAPS and CLIMCAPS are sister algorithms that are used to convert the raw satellite signal to meaningful data. NUCAPS is primarily used for real-time processing of satellite soundings; the data are released to the public up to 30 mins after an overpass through direct broadcast. CLIMCAPS was developed to to generate a long-term data record to study the feedbacks and processes of the climate system. Spanning over 20 years, CLIMCAPS provides continuity across instruments, from AIRS to CrIS.

Product descriptions,
Data access,
FAQ's and more

Open Access Publications

(Smith and Barnet 2019 Remote Sensing) CLIMCAPS Algorithm paper

https://www.mdpi.com/2072-4292/11/10/1227

(Smith and Barnet 2020 Atm. Meas. Tech.) CLIMCAPS Information Content

https://www.atmos-meas-tech-discuss.net/amt-2020-71/

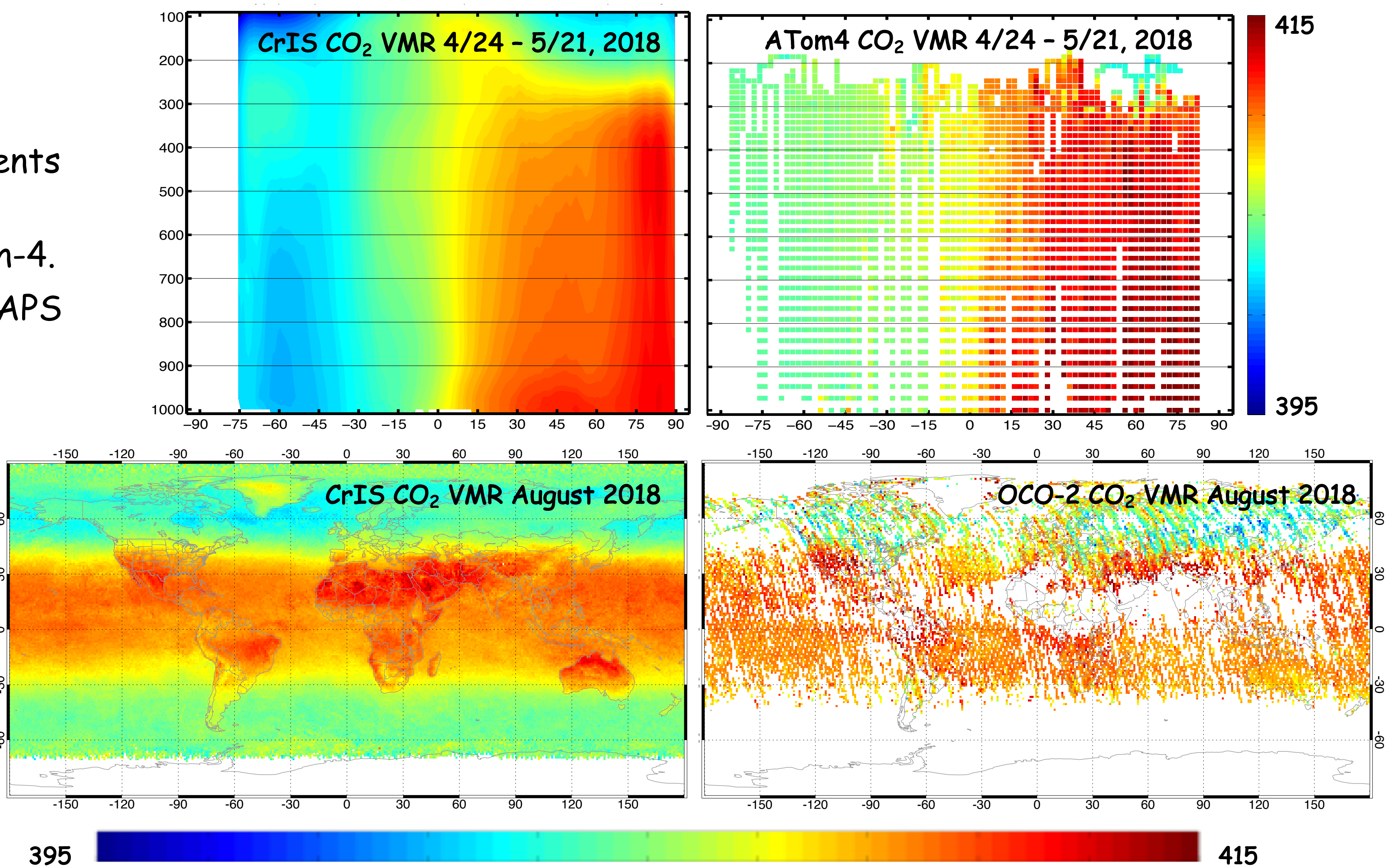
(Esmaili et al. 2020 Remote Sensing) NUCAPS Hazardous Weather Applications

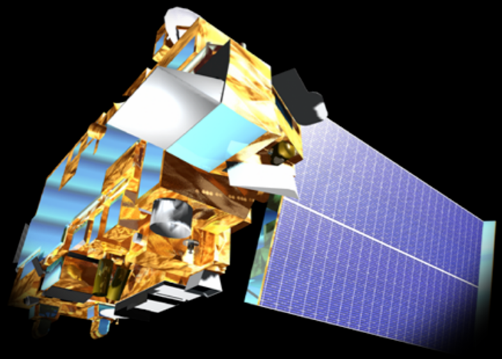
https://www.mdpi.com/2072-4292/12/5/886

S-NPP CrIS new CO_2 and Comparisons with ATom and OCO-2

Juying Warner and Zigang Wei (UMD) and NOAA NUCAPS team

- A priori and/or 1st guess using
  - Carbon Tracker;
  - ESRL surface measurements
- Top CO_2 curtains, and left new NUCAPS and right ATom mission-4.
- Bottom CO_2 maps, and left NUCAPS and right OCO-2.



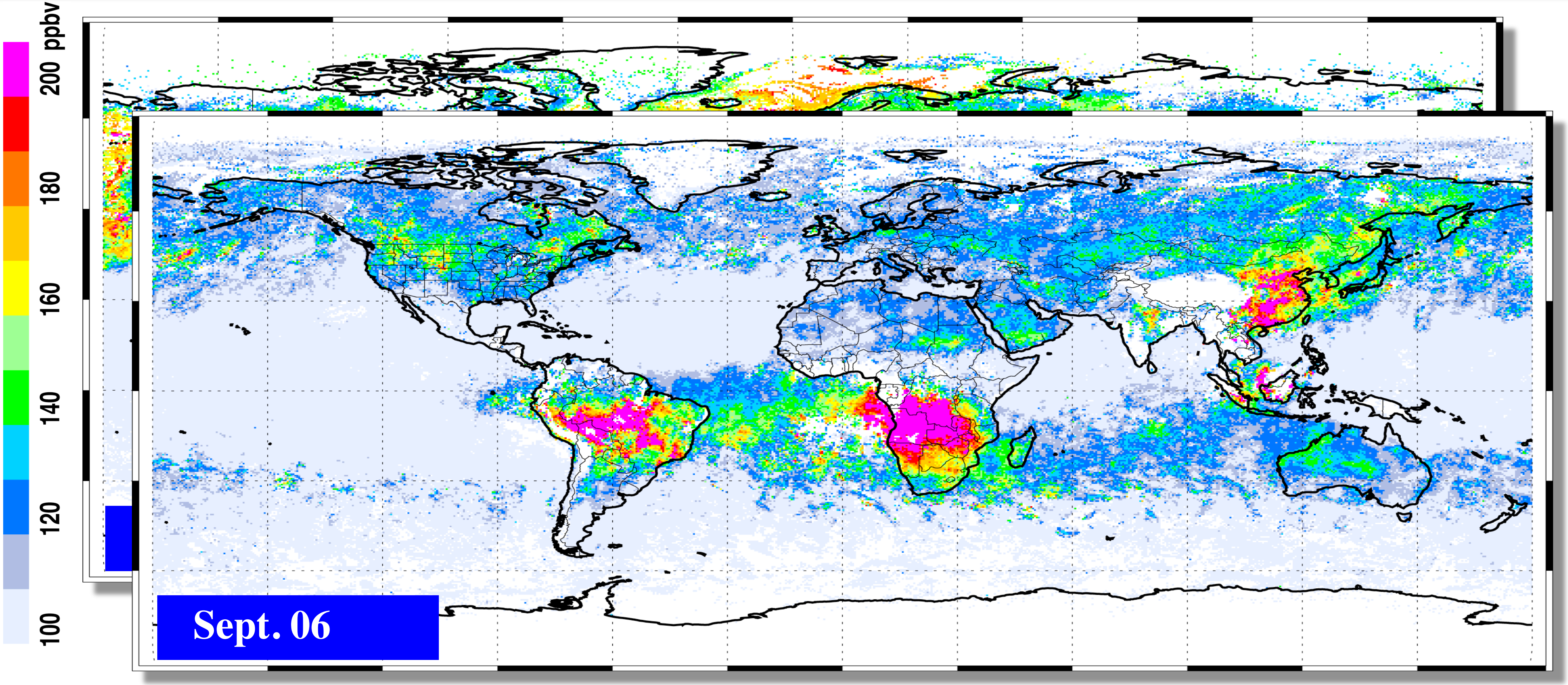


MOPITT’s twenty years of tropospheric pollution measurements from space

David Edwards and the MOPITT Science Team

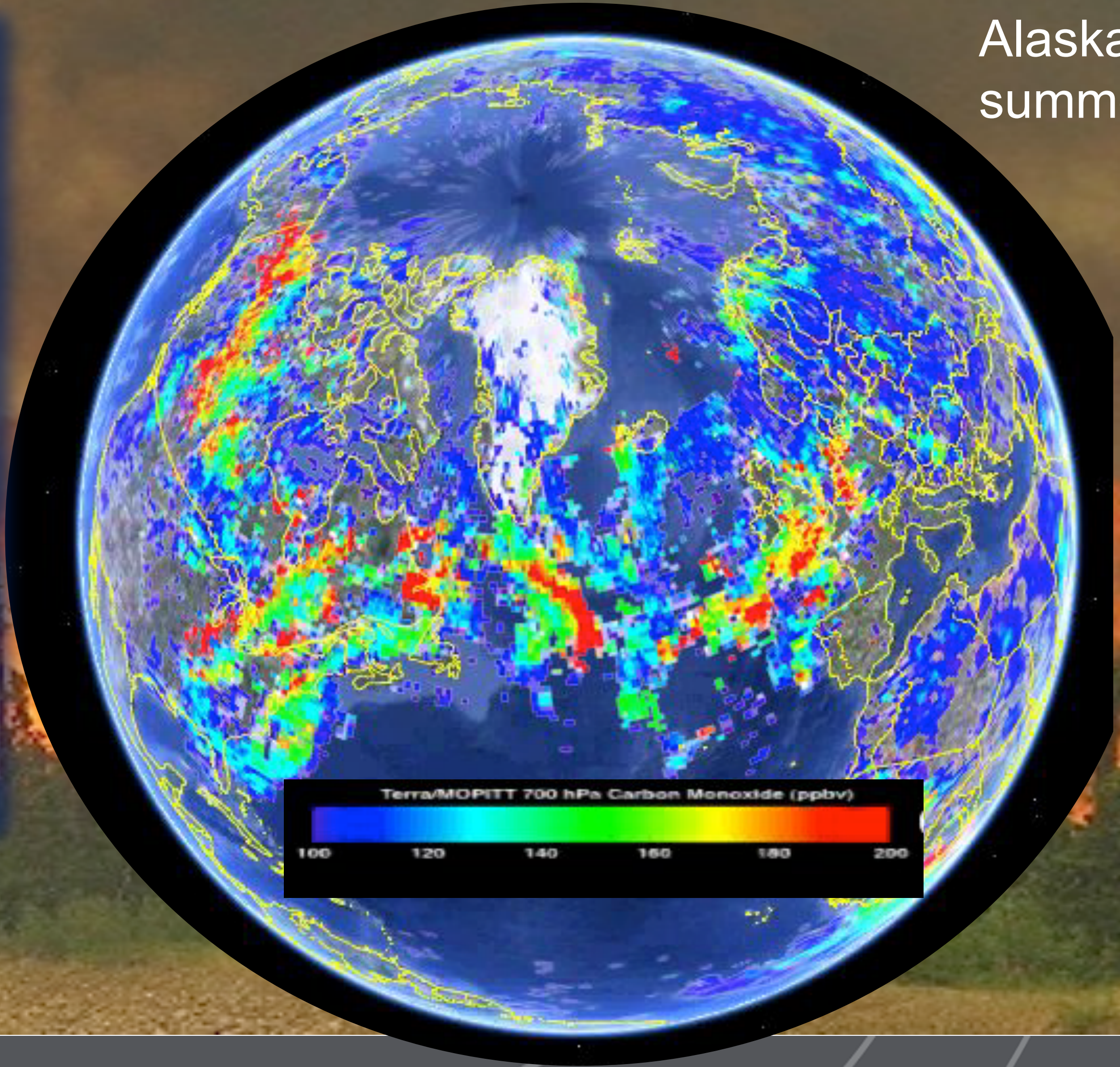
This material is based upon work supported by the National Center for Atmospheric Research, which is a major facility sponsored by the National Science Foundation under Cooperative Agreement No. 1852977.

Seasonal & interannual CO variability



Long range & intercontinental pollution transport

- Inverse modeling showed that the Alaska fires emitted about as much CO as did human-related activities in the continental USA during the same time period, about 30 Tg CO June-August
- Because of the wildfires, ground-level ozone concentrations increased by 25% or more in parts of the northern continental USA and by 10% as far away as Europe

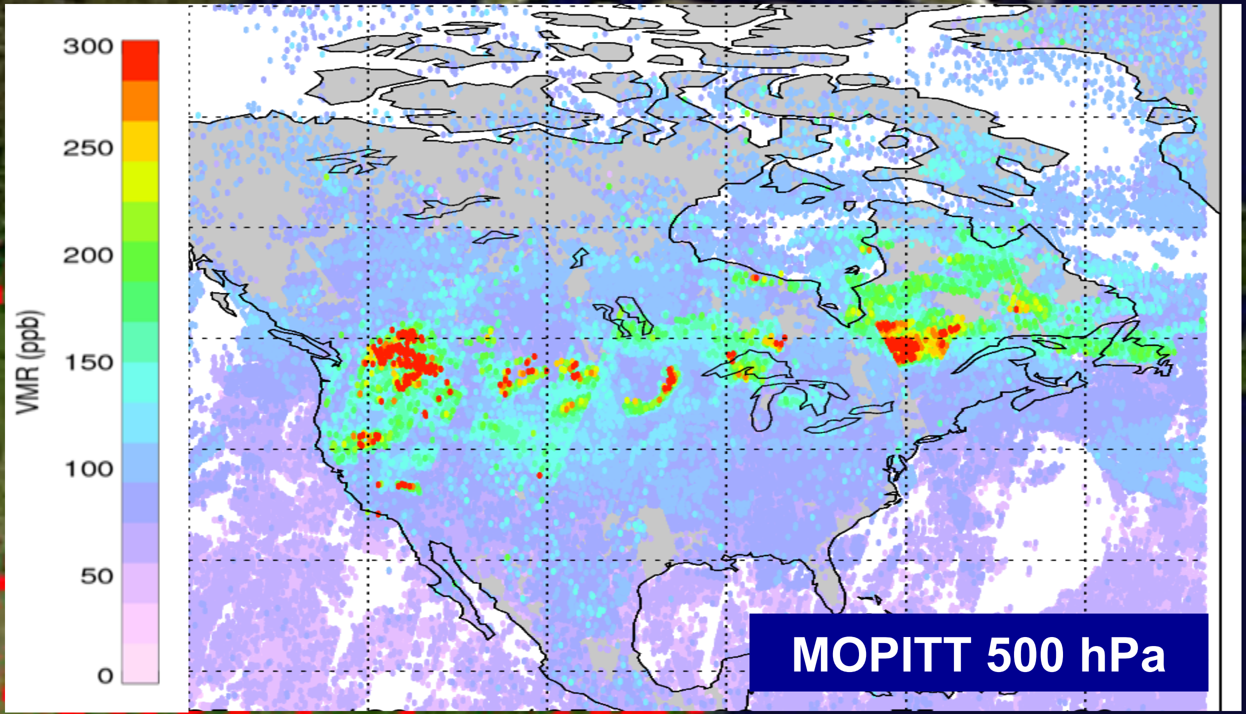


Alaska wildfires, summer 2004

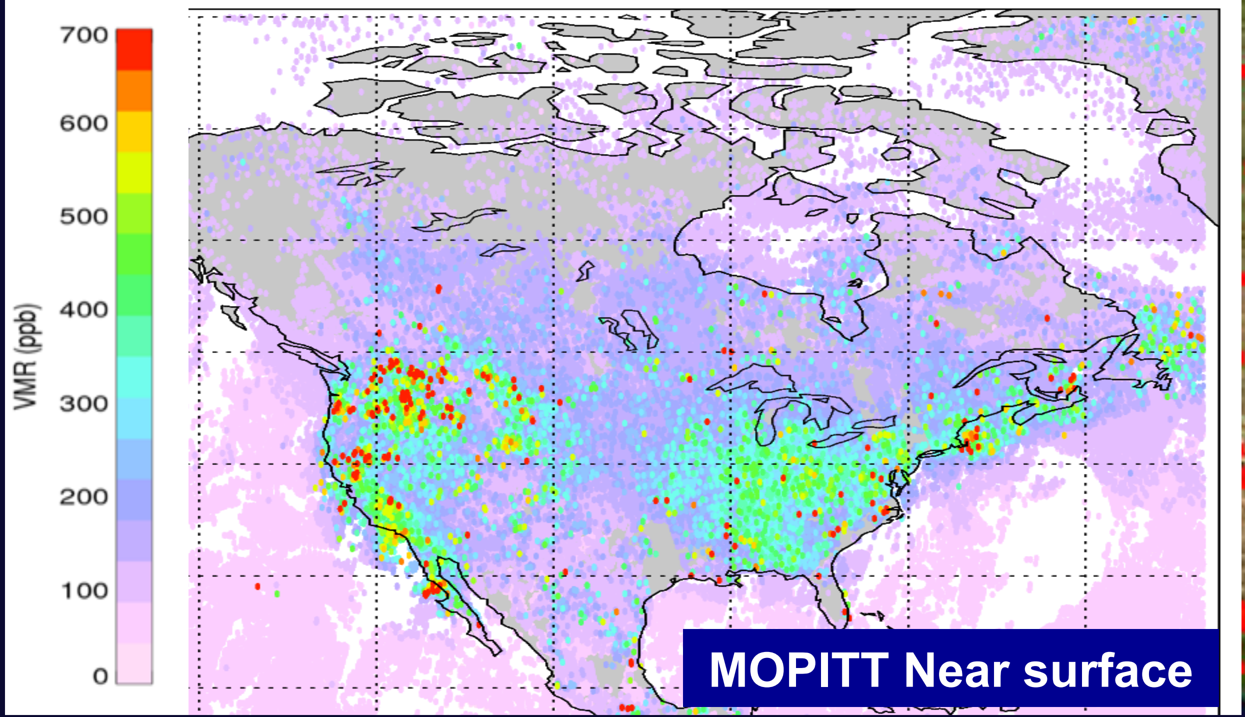
Pfister et al., JGR, 2006

MOPITT multispectral CO retrievals provide profile information

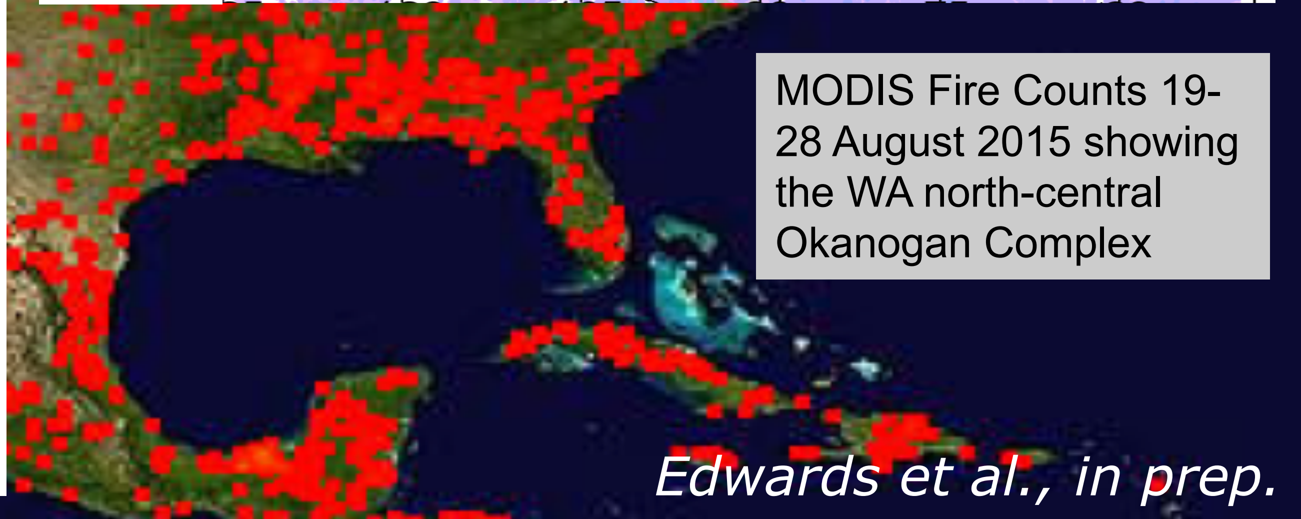
MOPITT multispectral CO retrievals provide profile information that can distinguish fire source regions from free troposphere long-range transport of pollution. Washington State fires 20-27 August, 2015



MOPITT 500 hPa



MOPITT Near surface



MODIS Fire Counts 19-28 August 2015 showing the WA north-central Okanogan Complex

Edwards et al., in prep.

MOPITT CO zonal average & deseasonalized anomaly

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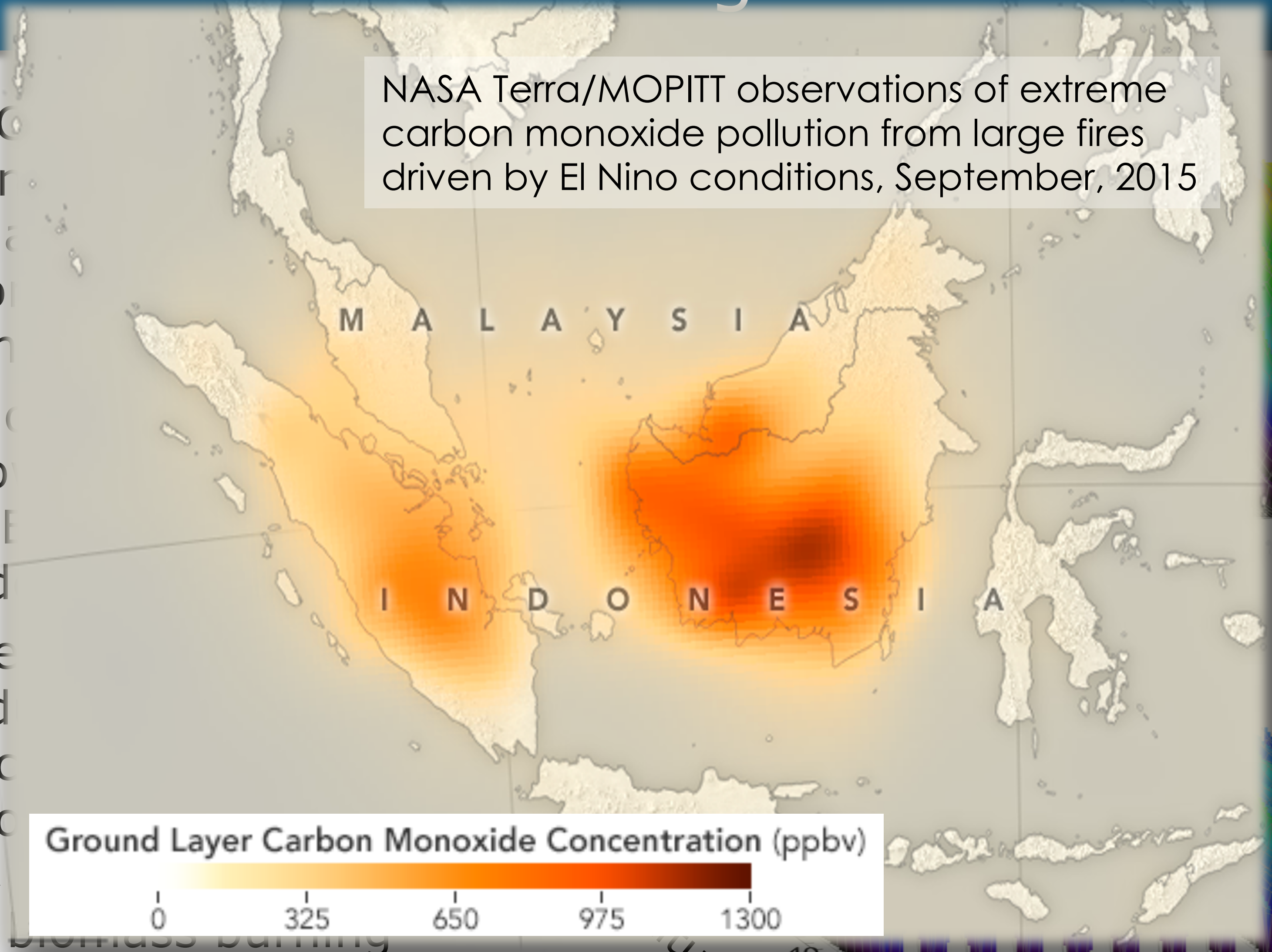
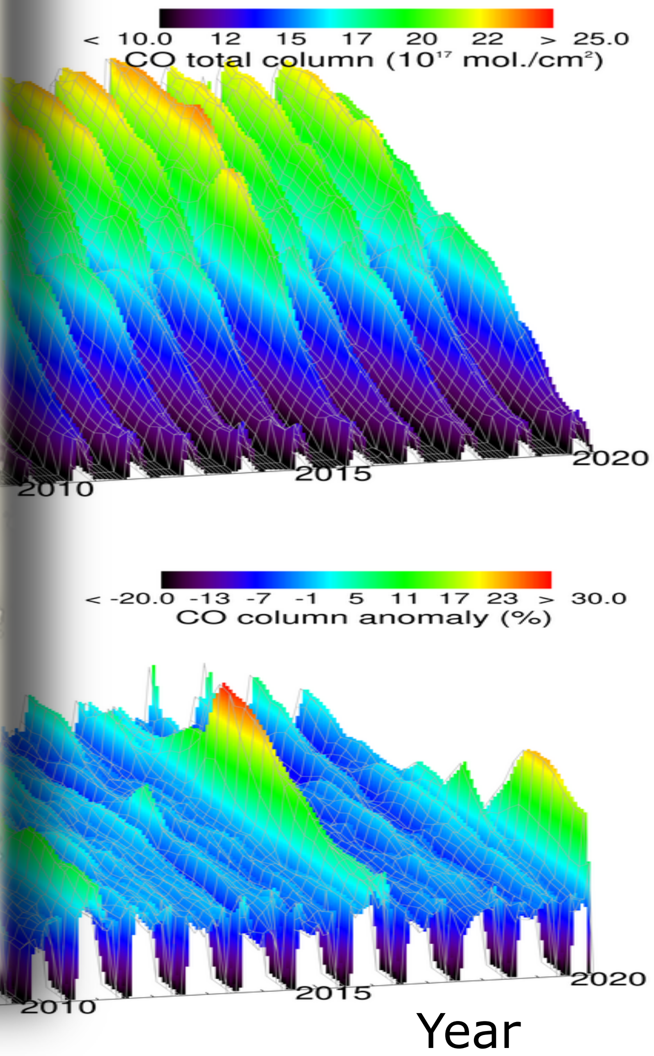
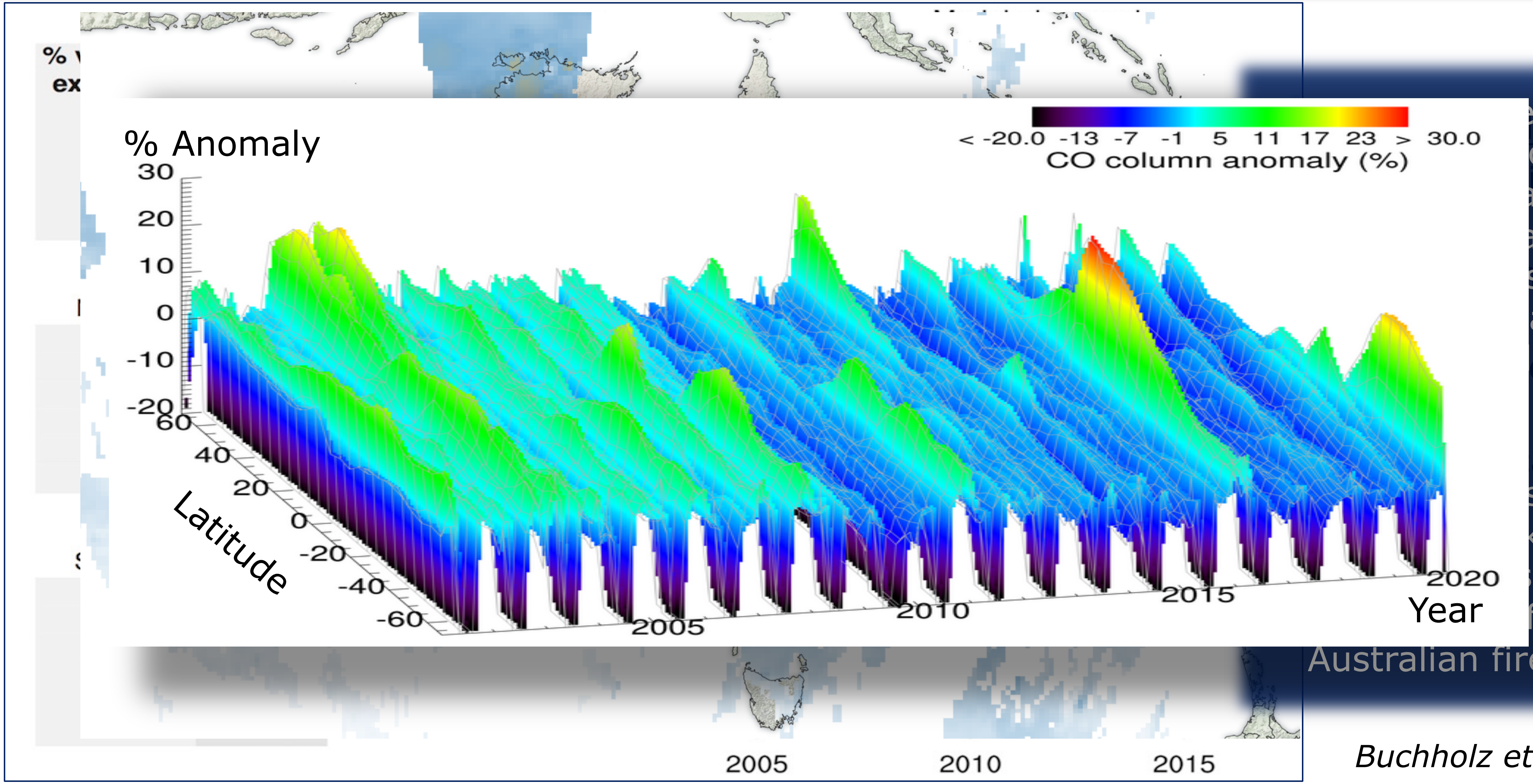

NASA Terra/MOPITT observations of extreme carbon monoxide pollution from large fires driven by El Nino conditions, September, 2015



Predicting CO interannual variability for fire regions



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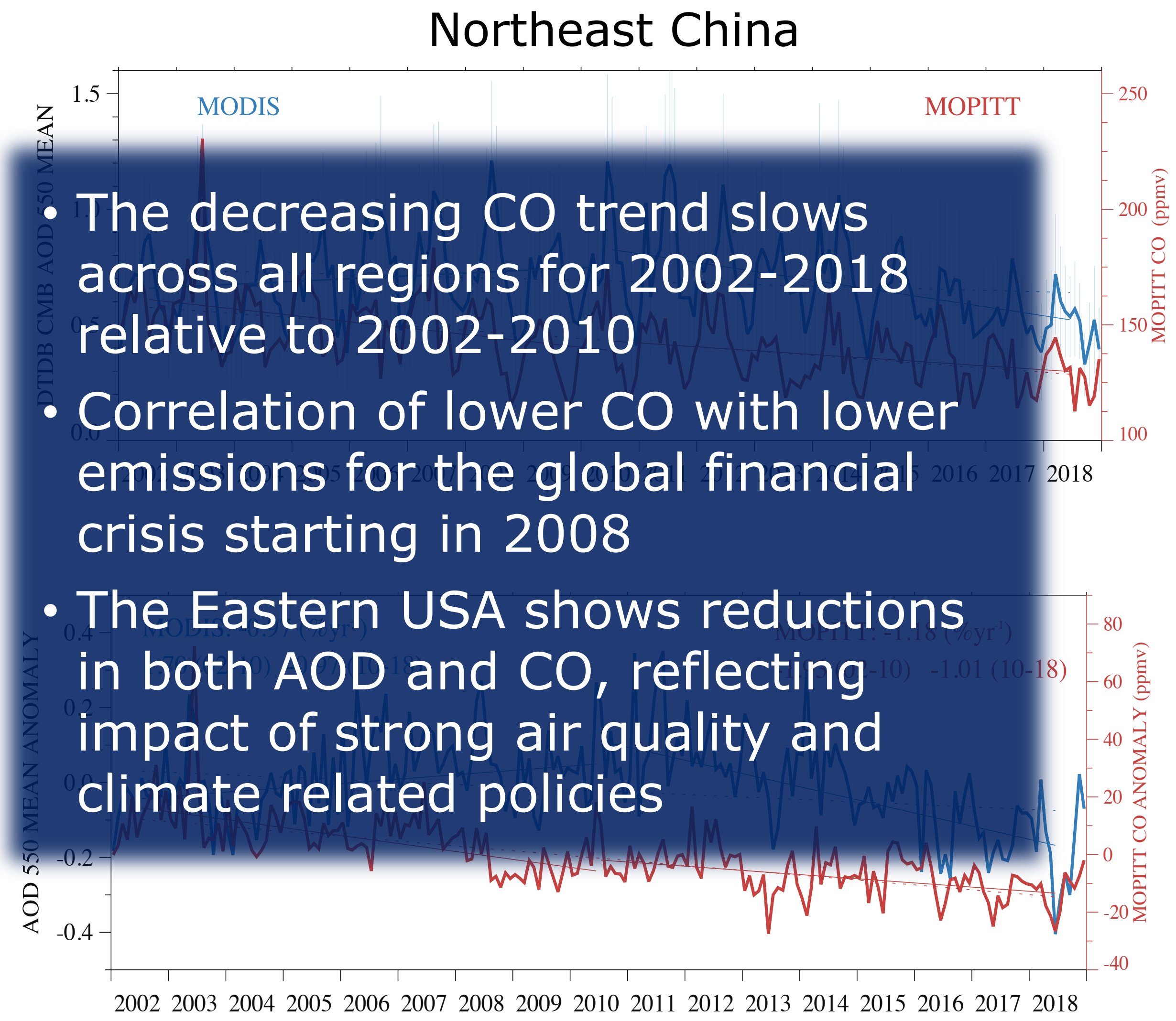
from the
Australian fires

Buchholz et al., JGR 2018

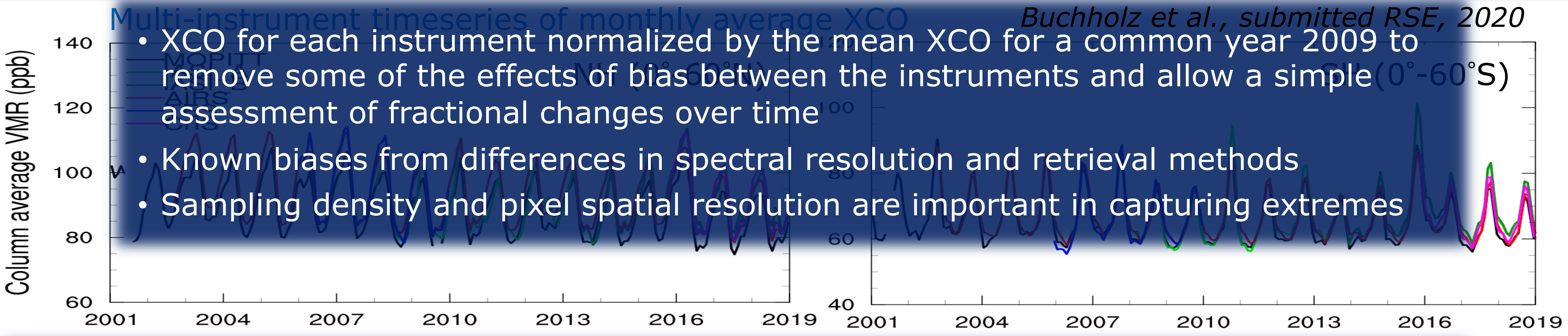
Regional CO and aerosol optical depth (AOD) trends

- Northeast China has the strongest CO trend across all time periods
- Peak AOD continues longer than peak CO due to the impact of dust aerosols during the dry summer months
- Initial CO decline in China was not accompanied by an AOD decline
- Reflects move to a centralized energy production that improved combustion efficiency but not particulate pollution
- In 2010, China implemented Clean Air Policies *(Zheng et al., 2018)*, and AOD started decreasing along with the continued decrease in CO

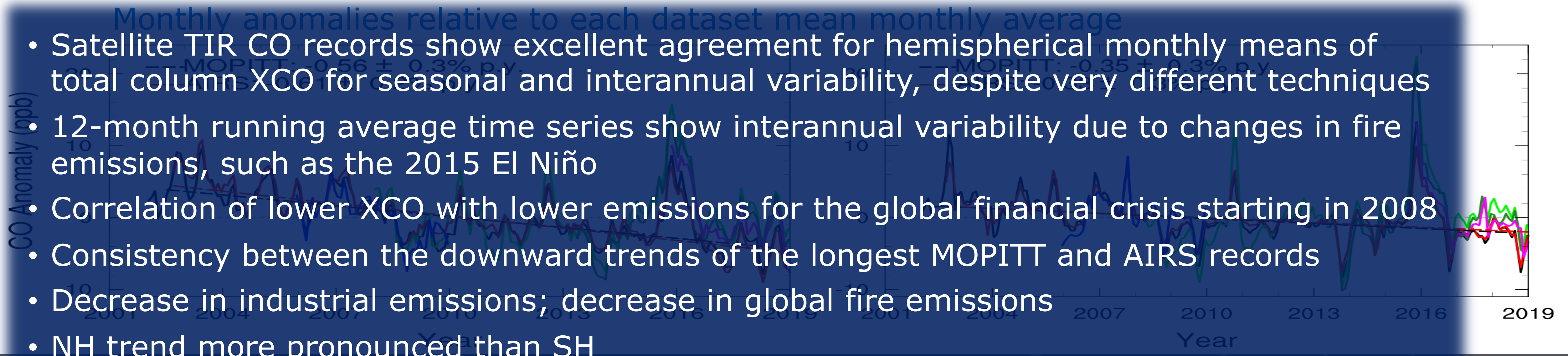


- The decreasing CO trend slows across all regions for 2002-2018 relative to 2002-2010
- Correlation of lower CO with lower emissions for the global financial crisis starting in 2008
- The Eastern USA shows reductions in both AOD and CO, reflecting impact of strong air quality and climate related policies

CO trends across different satellite instruments



- XCO for each instrument normalized by the mean XCO for a common year 2009 to remove some of the effects of bias between the instruments and allow a simple assessment of fractional changes over time
- Known biases from differences in spectral resolution and retrieval methods
- Sampling density and pixel spatial resolution are important in capturing extremes



- Satellite TIR CO records show excellent agreement for hemispherical monthly means of total column XCO for seasonal and interannual variability, despite very different techniques
- 12-month running average time series show interannual variability due to changes in fire emissions, such as the 2015 El Niño
- Correlation of lower XCO with lower emissions for the global financial crisis starting in 2008
- Consistency between the downward trends of the longest MOPITT and AIRS records
- Decrease in industrial emissions; decrease in global fire emissions
- NH trend more pronounced than SH

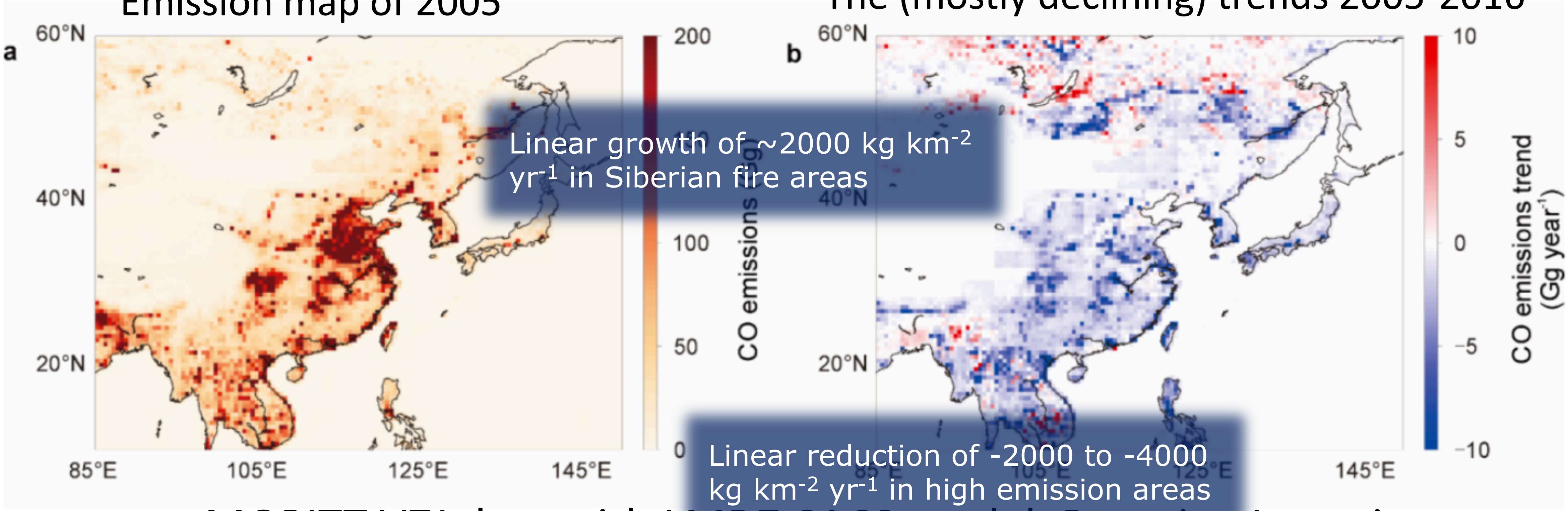
Trends in Asian CO emissions using top-down estimates constrained by MOPITT

“Rapid decline in carbon monoxide emissions and export from East Asia between years 2005 and 2016”

Zheng et al., ERL, 2018

Emission map of 2005

The (mostly declining) trends 2005-2016

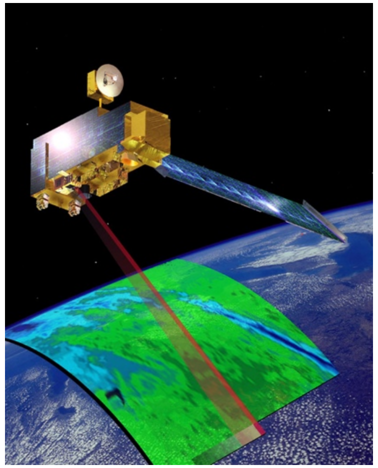


Linear growth of ~2000 kg km^{-2} yr^{-1} in Siberian fire areas

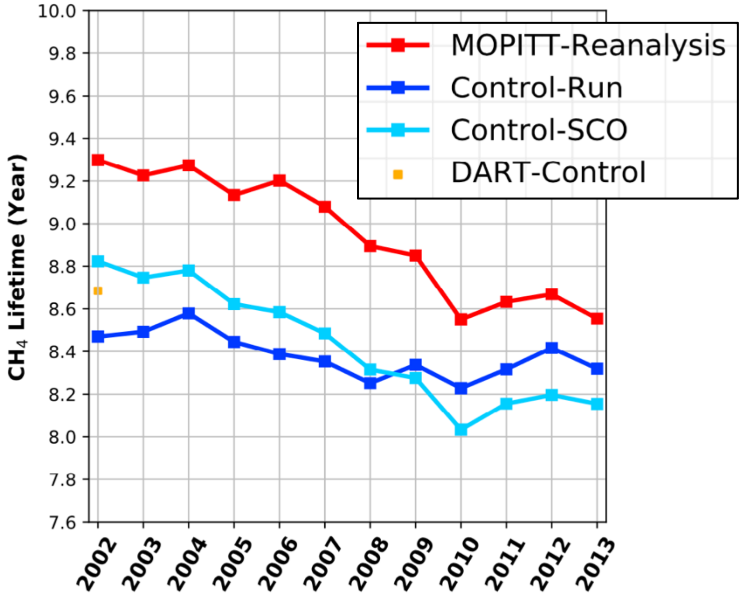
Linear reduction of -2000 to -4000 kg km^{-2} yr^{-1} in high emission areas

MOPITT V7J data with LMDZ-SACS model; Bayesian Inversion

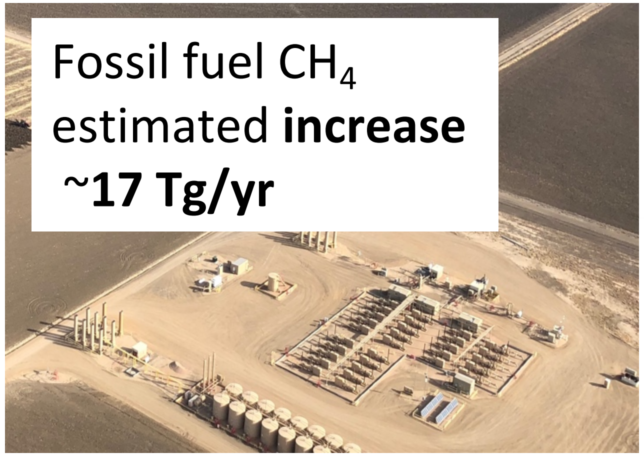
MOPITT CO data used to estimate changes in methane lifetime and explain conflicting methane trend observations



After assimilating MOPITT data, CAM-Chem model results show that decreasing concentrations of CO over the last decade (from decreases in both anthropogenic and biomass burning emissions) correspond to an 8% (9 months) decrease in methane lifetime through interactions with OH (*Gaubert et al., GRL, 2017*)



Methane emissions from fires, identified using MOPITT carbon monoxide measurements, have been decreasing since the early 2000s due to a global decrease in tropical fires (*Worden et al., Nature Comm., 2018*)

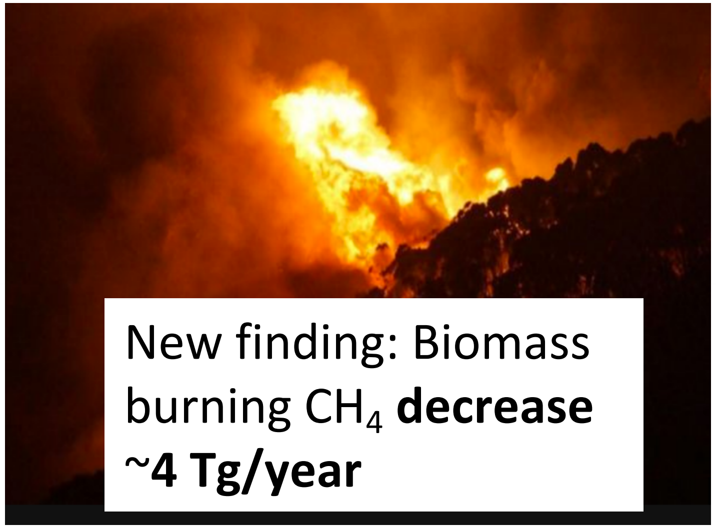


Fossil fuel CH_4 estimated **increase** **~17 Tg/yr**

+

Wetlands CH_4 **increase** **~12 Tg/yr**

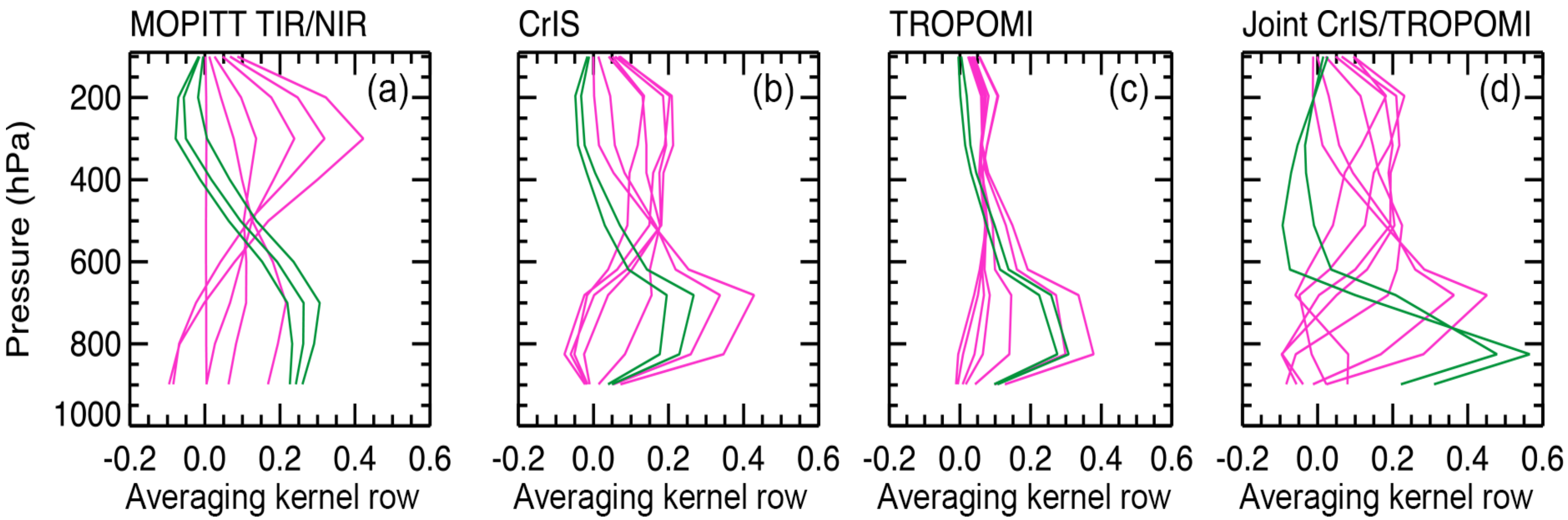
= 29 Tg/yr
…which is greater than the observed **25 Tg/yr** CH_4 increase



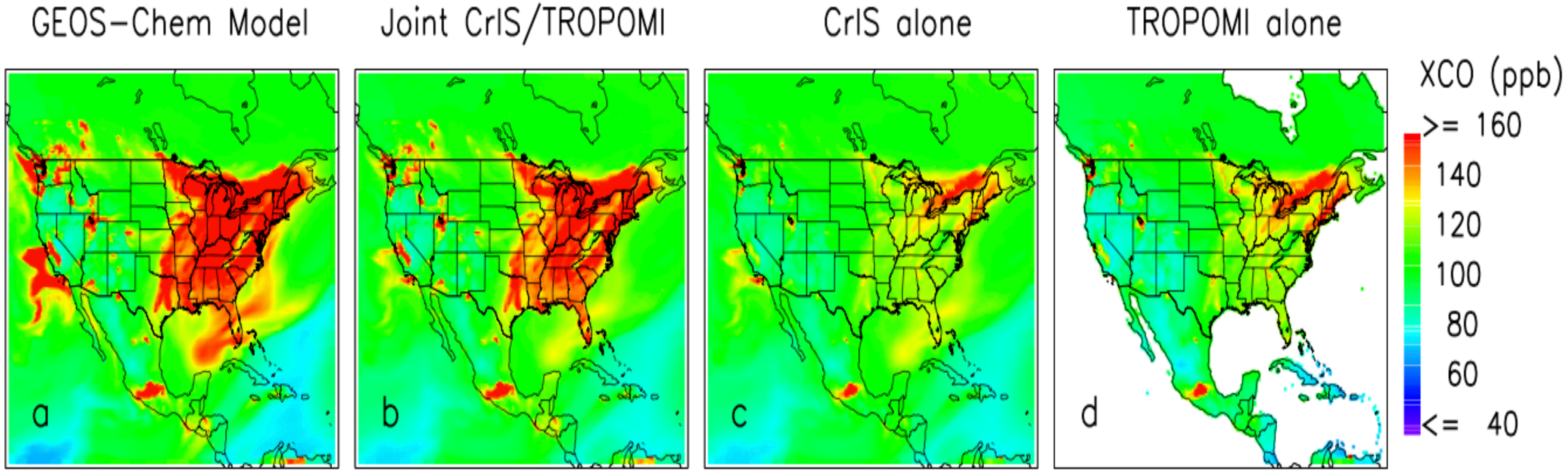
New finding: Biomass burning CH_4 **decrease** **~4 Tg/year**

Extending the TIR+SWIR MOPITT CO record with SNPP/CrIS and S5P/TROPOMI

Averaging Kernels From Dejian Fu et al., *AMT*, 2016 – Using MUSES Algorithm for single pixel, OE retrievals



Simulated retrievals of surface layer CO (0-2km)



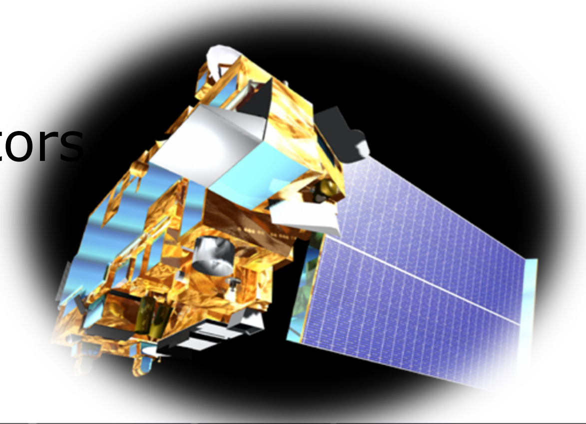
20 years of MOPITT carbon monoxide observations

ances:

- Demonstrate interannual variability and long-term trends with the longest satellite record of global CO observations (2000-2020)
- Allow sensitivity to near-surface CO concentrations using multi-spectral observations and a unique height-resolved tropospheric CO retrieval
- Help determine aerosol sources and plume height information through correlations
- Observe pollution transport to show how emissions from fires and cities influence atmospheric chemistry on the global scale
- Improve understanding of carbon fluxes from fires
- Estimate chemical emissions for fossil fuel use, fire and biogenic sectors

Applications advances:

- Helped standardize and promoted understanding of tropospheric trace gas retrievals … especially use of Averaging Kernels
- Established satellite validation practices
- Provided first-stop validation for other satellite CO sensors
- Enabled prediction of pollution using data assimilation for air quality forecasts and field campaign flight planning
- Pioneered chemical data assimilation
- Evaluated and improved global pollution transport and chemistry in models



IASI : what’s up

IASI contributes the most to **weather forecast**

15 330

Earth orbits
per year for [Metop-A, Metop-B and Metop-C]

>500

Publications
using IASI data

Detection of volcanic plumes, large fires, pollution peaks, etc.

2012 Launch of
Metop-B

2006 Launch of
Metop-A

Launch of
Metop-C 2018

~17

Terabytes of data
per year

33

Gases
mesuread:
4 times
more than
anticipated

8461

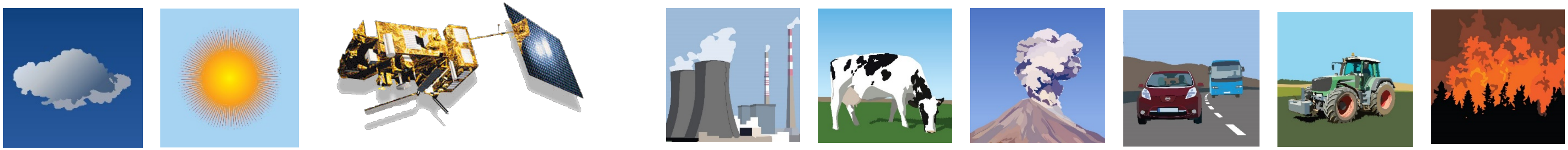
Spectral channels
measured at
high resolution

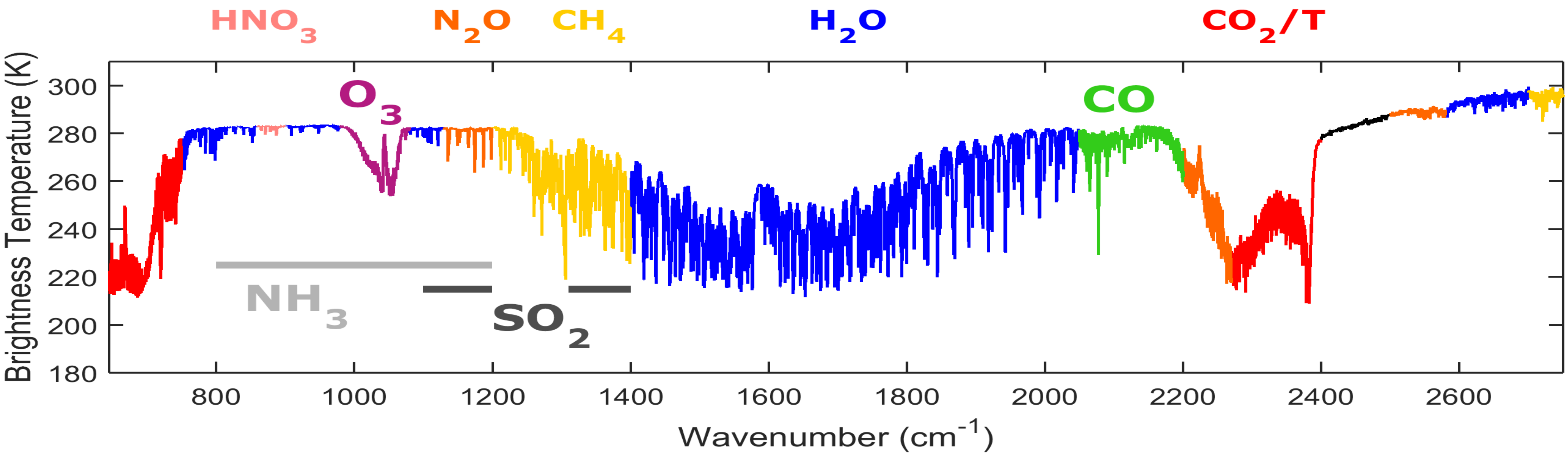
First space mission to study atmospheric composition for at least **18 years**

The IASI instrument studies the evolution of atmospheric composition

VIDEO

VIDEO

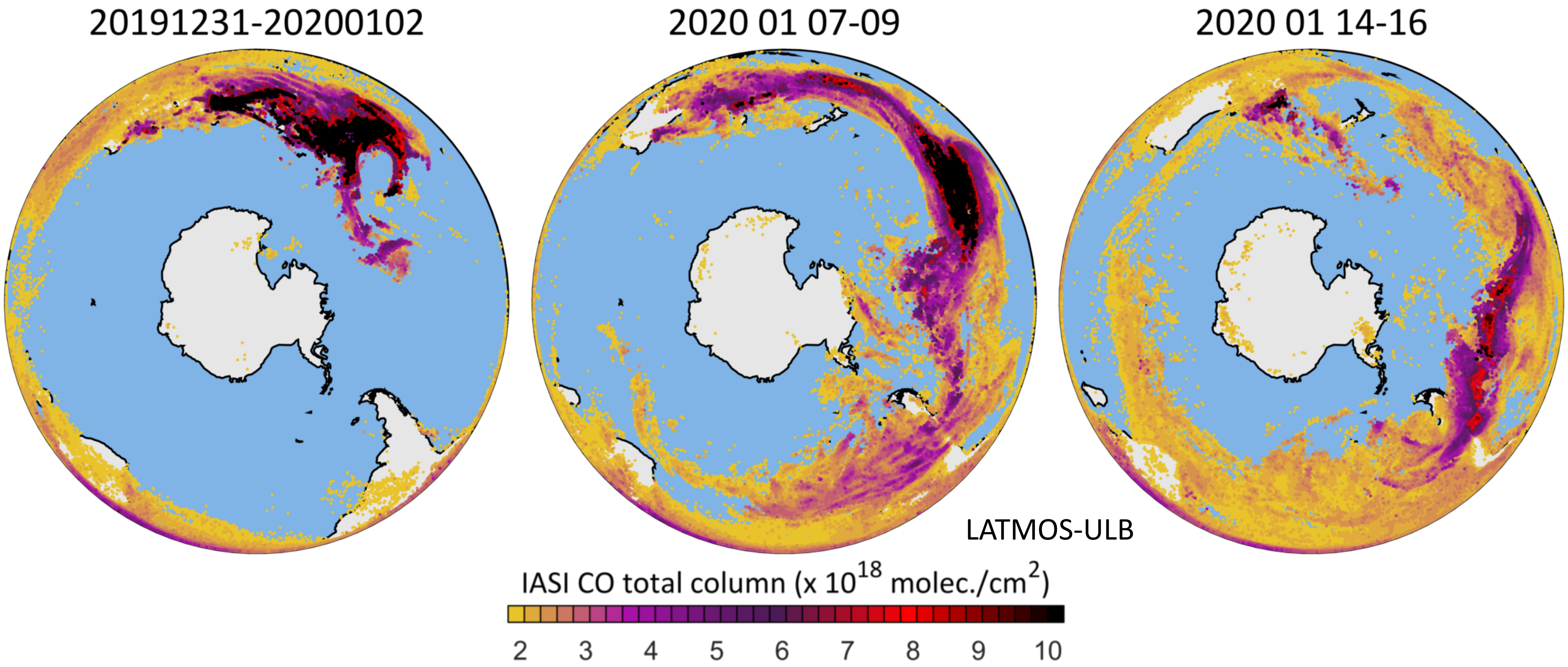




Now 31 species
measured or *detected* by IASI

Greenhouse gases and ozone-related substances (13)	H_2O, CO_2, CH_4, N_2O, O_3, HNO_3, CFC-11, CFC-12, HCFC-22, CF_4, *SF_6*, *CCl_4*, *HFC-134a*
Air quality and VOCs (12)	CO, CH_3OH, HCOOH, CH_3COOH, CH_3COCH_3, C_2H_2, C_2H_4, NH_3, HCN, PAN, SO_2, OCS
Concentrated plumes (6)	HCl, H_2S, C_3H_6, C_4H_4O, HONO, *HCHO*

Carbon monoxide (CO), Australian fires



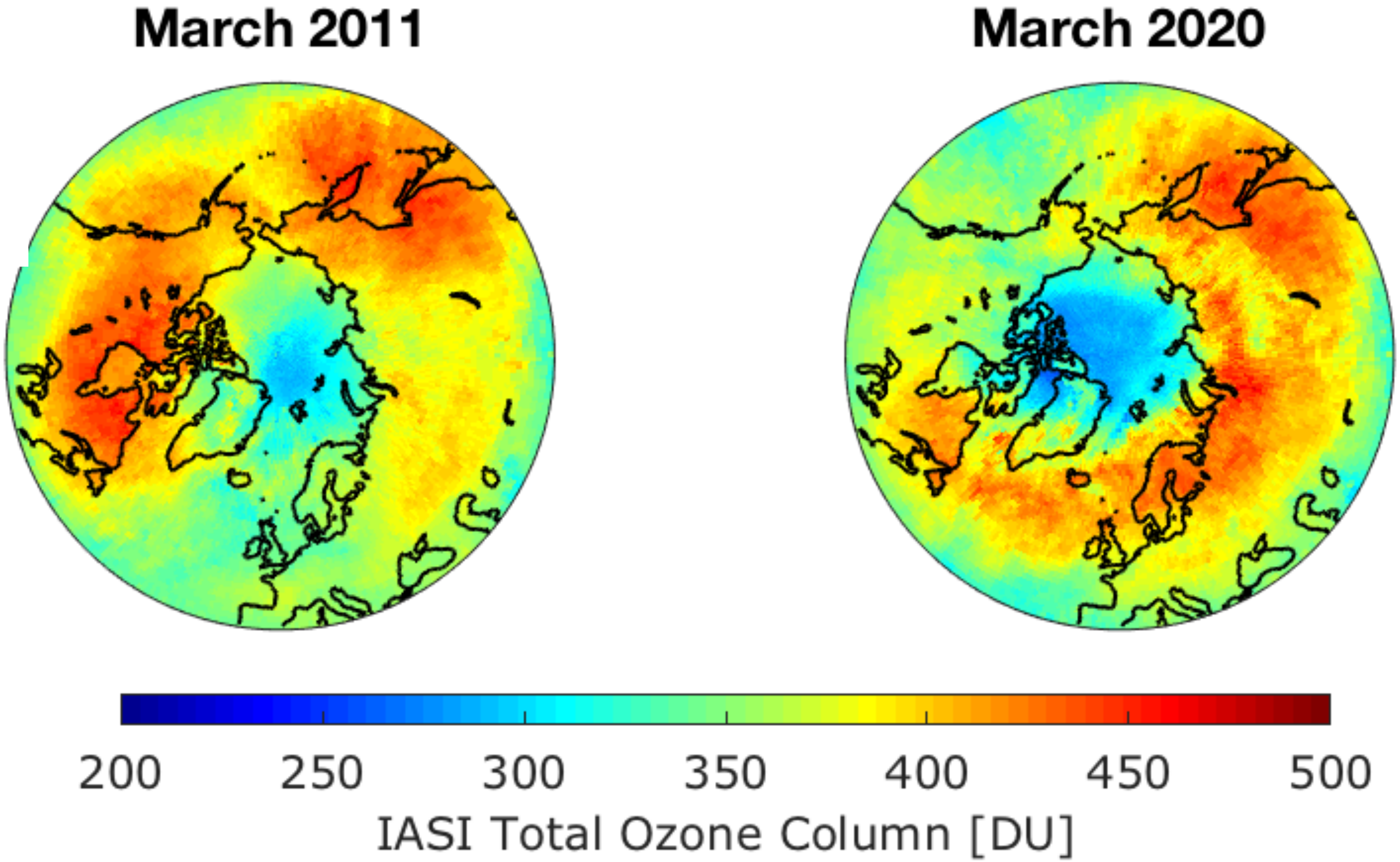
20191231-20200102

2020 01 07-09

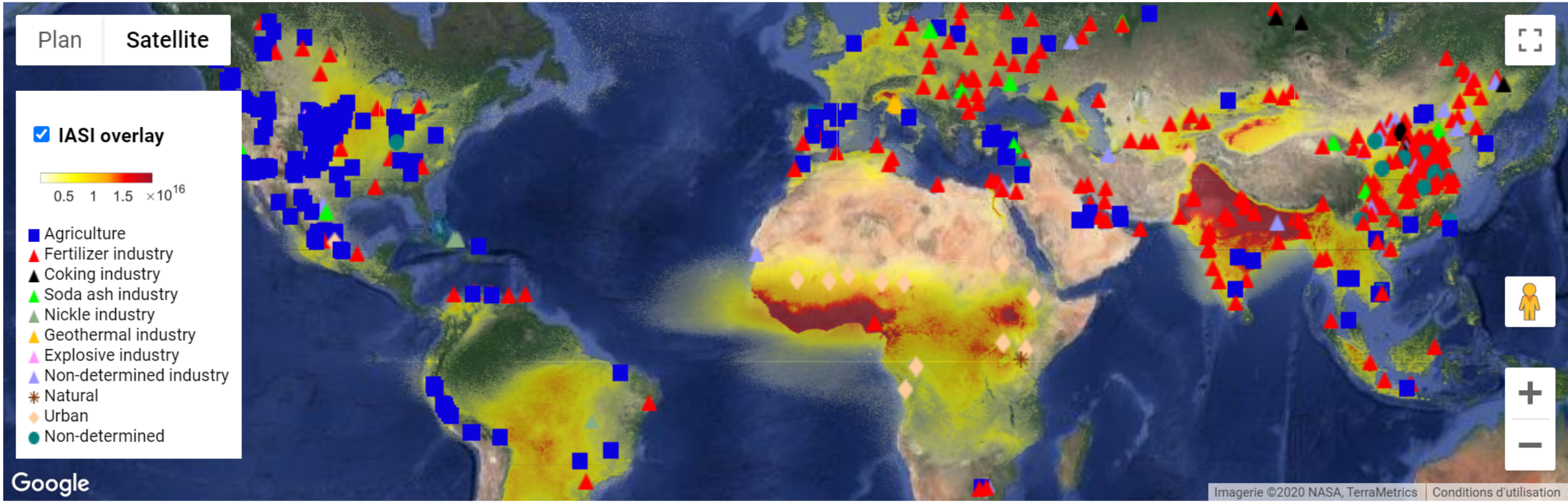
2020 01 14-16

LATMOS-ULB

Ozone @ North Pole



Safieddine et al (LATMOS), GRL 2020



Global ammonia point sources as seen by IASI satellite instruments

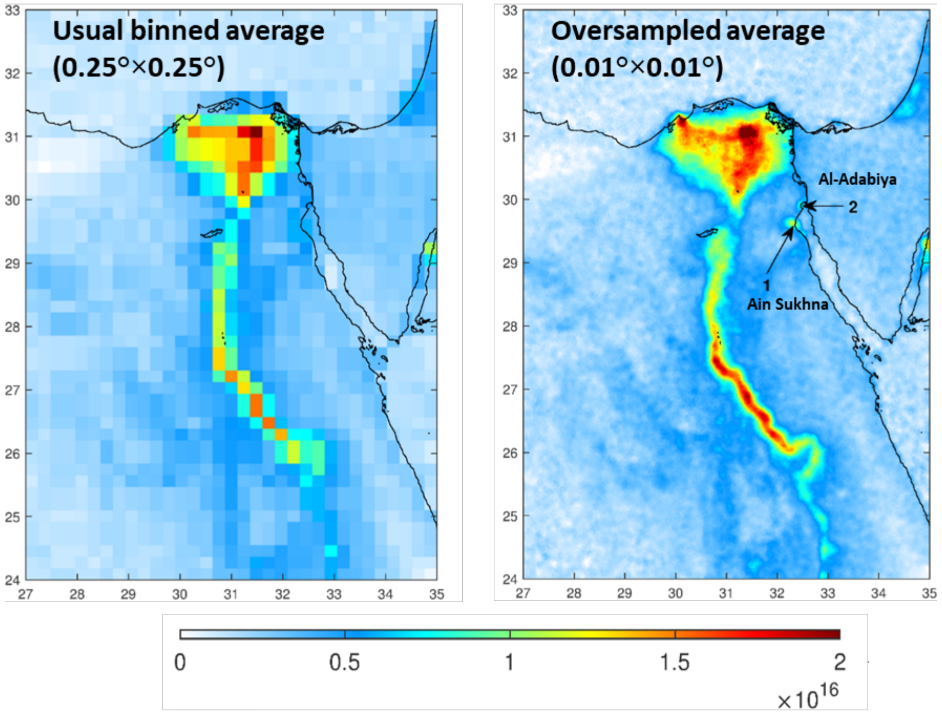
https://www2.ulb.ac.be/cpm/NH3-IASI.html

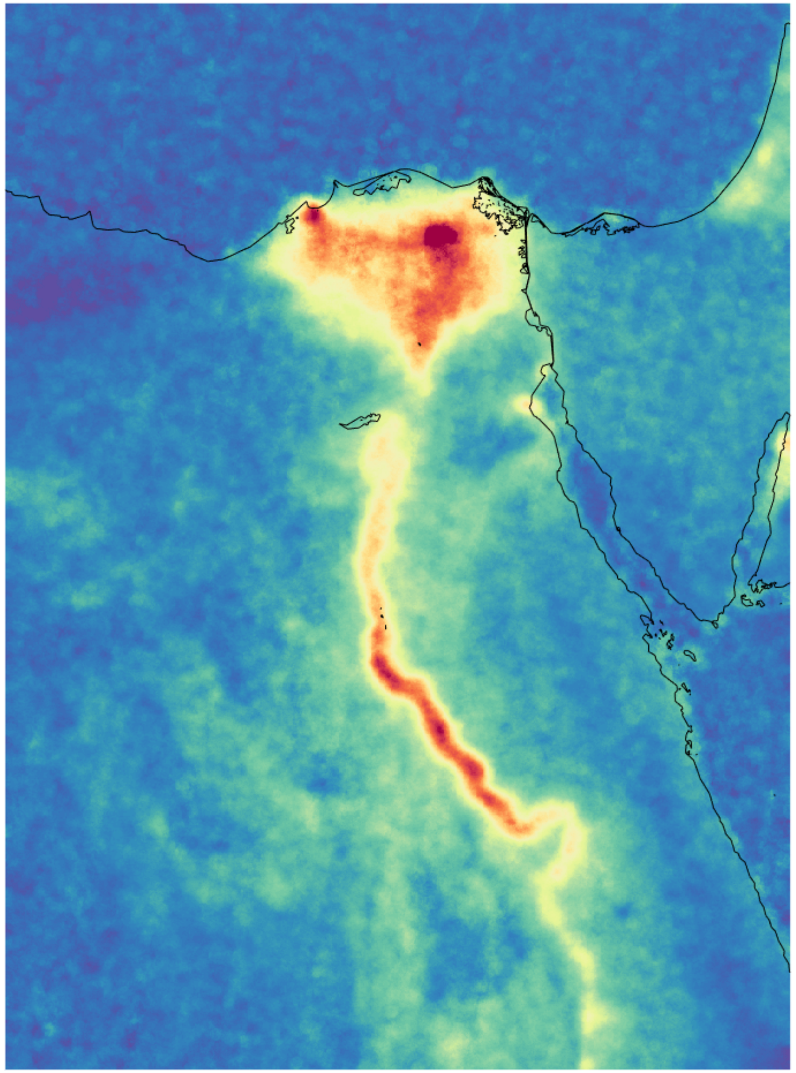
Van Damme, M., Clarisse, L., Whitburn, S., Hadji-Lazaro, J., Hurtmans, D., Clerbaux, C., Coheur, P.-F. **Industrial and agricultural ammonia point sources exposed**. *Nature* **564**, 99-103, doi: [10.1038/s41586-018-0747-1](https://doi.org/10.1038/s41586-018-0747-1), 2018

Point sources and hotspots from 10-year; regular oversampled **average**

Van Damme et al., Nature, 2018

The elliptical footprints of IASI are averaged on a **0.01° × 0.01°** high-resolution grid and weighted by the inverse of their footprint area

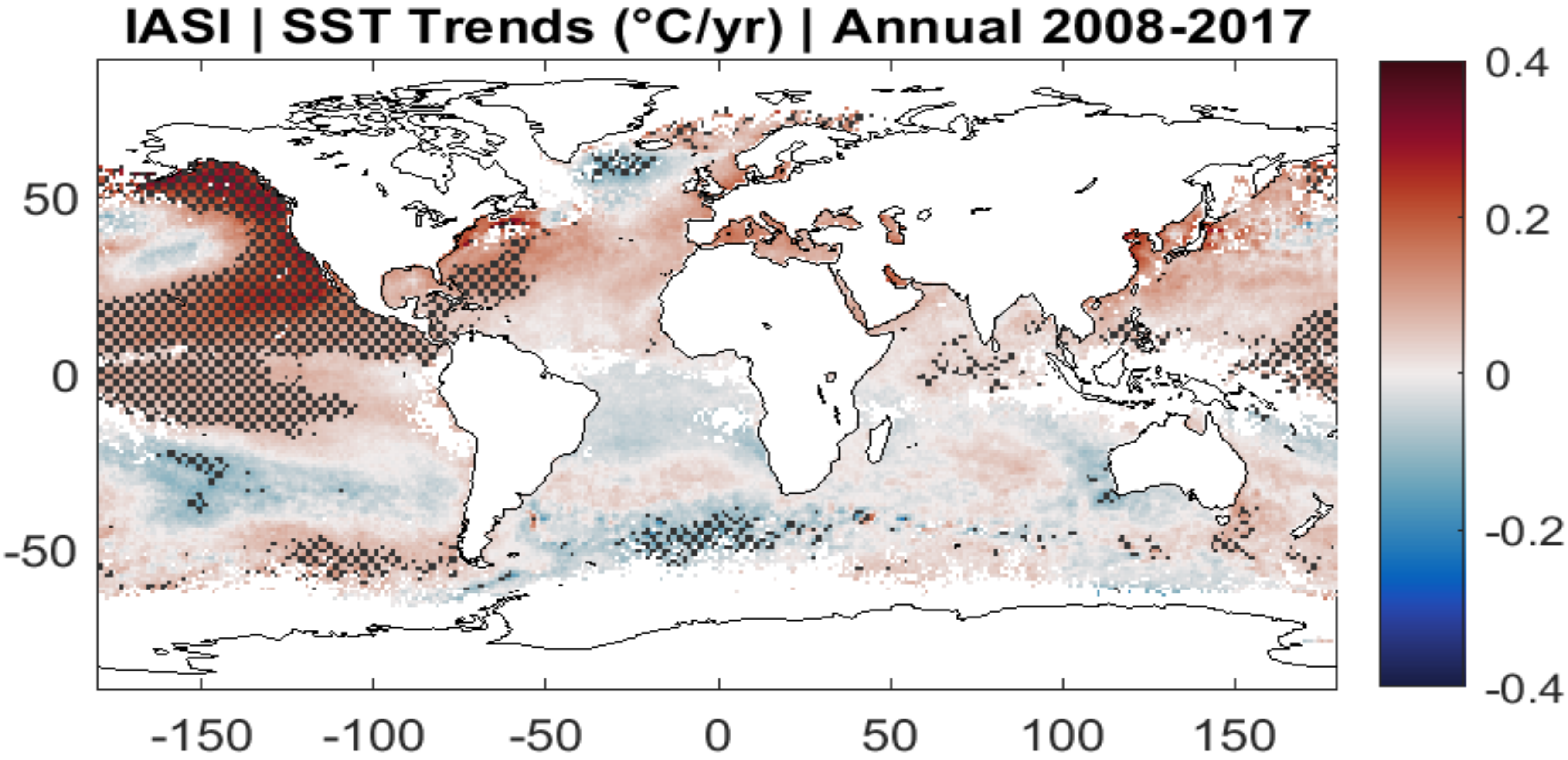




10 years

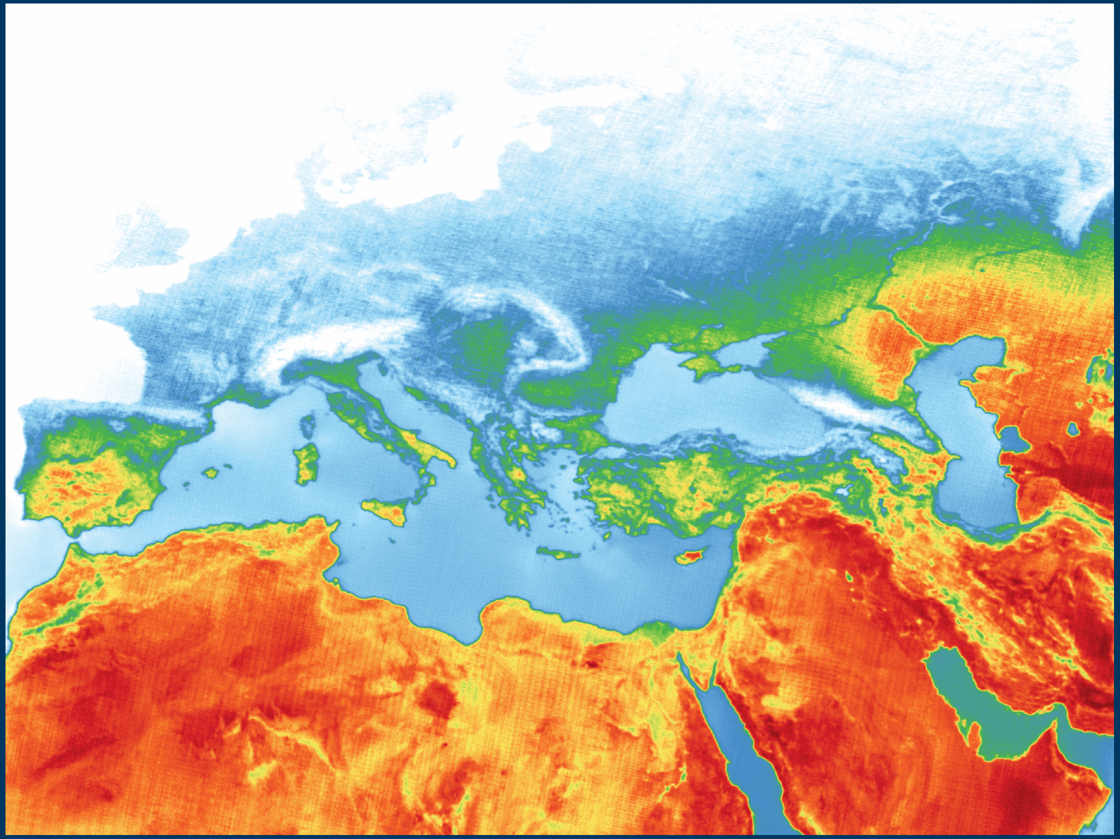
Van Damme et al., 2014
Van Damme et al., 2018
Sun et al., 2018

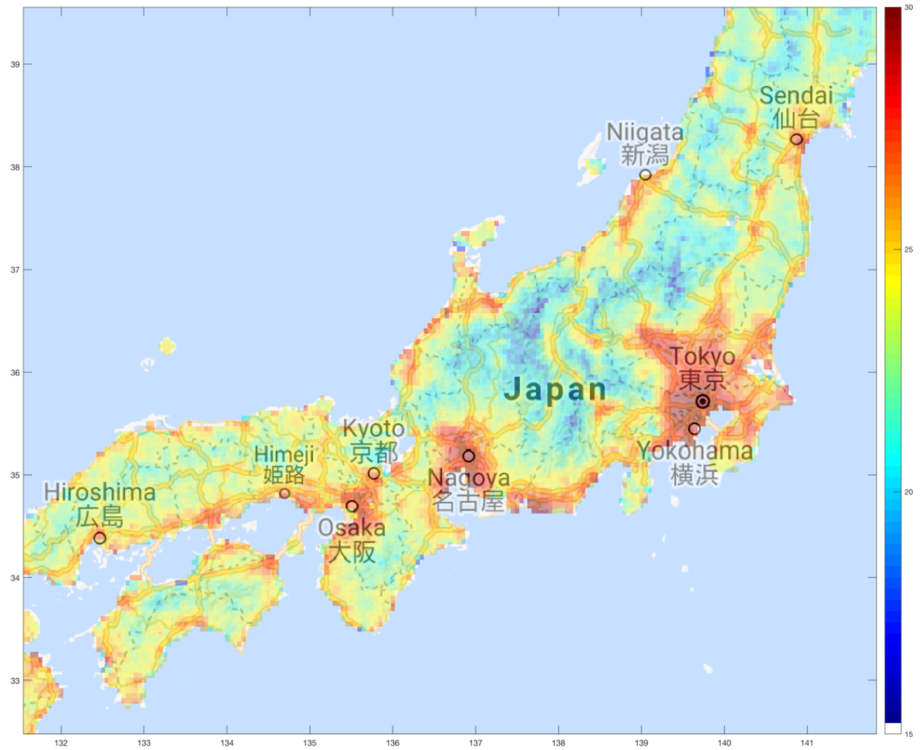
Surface (skin) temperatures from IASI measurements



Parracho et al (LATMOS), 2020

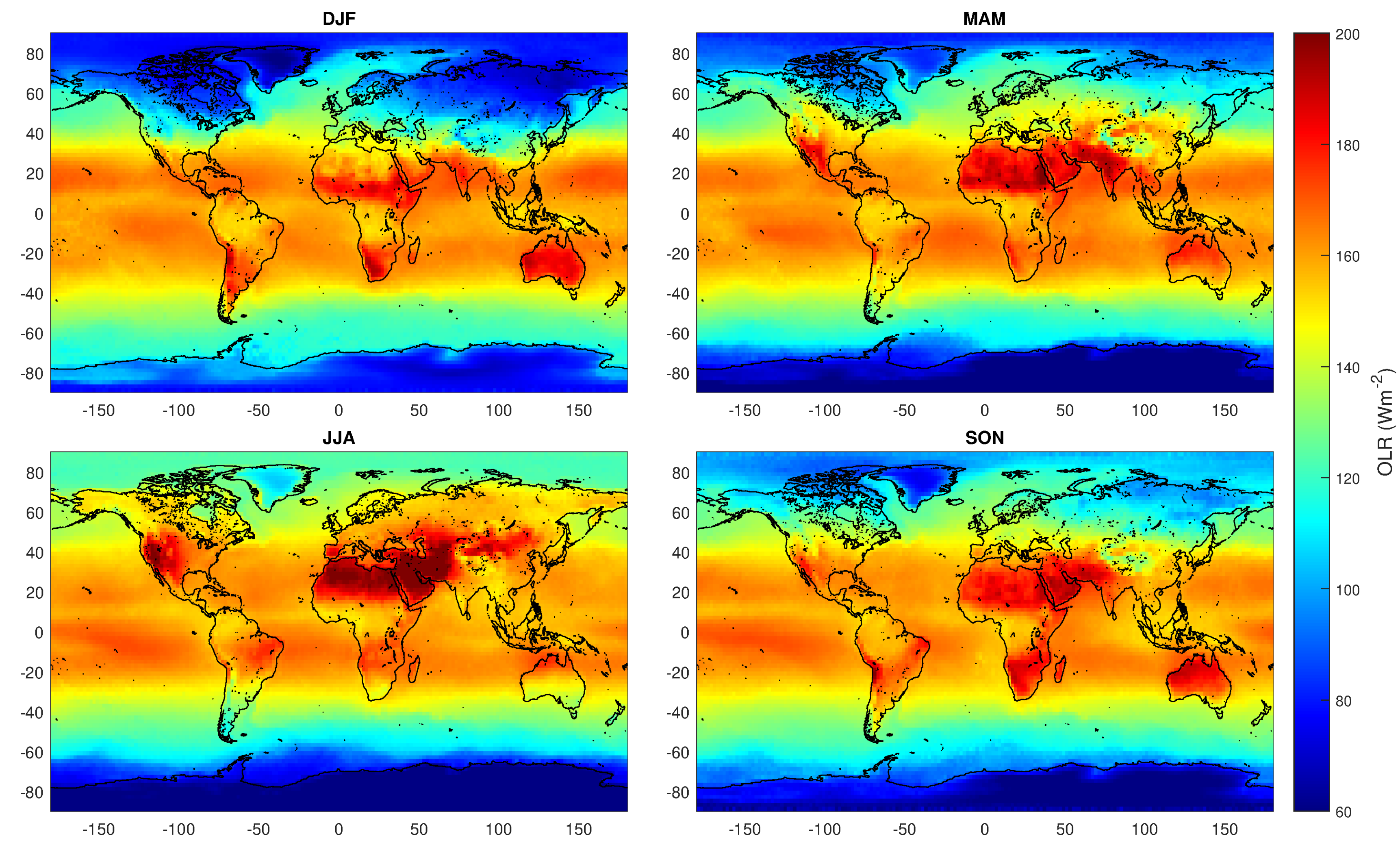
Surface (skin) temperatures from IASI measurements



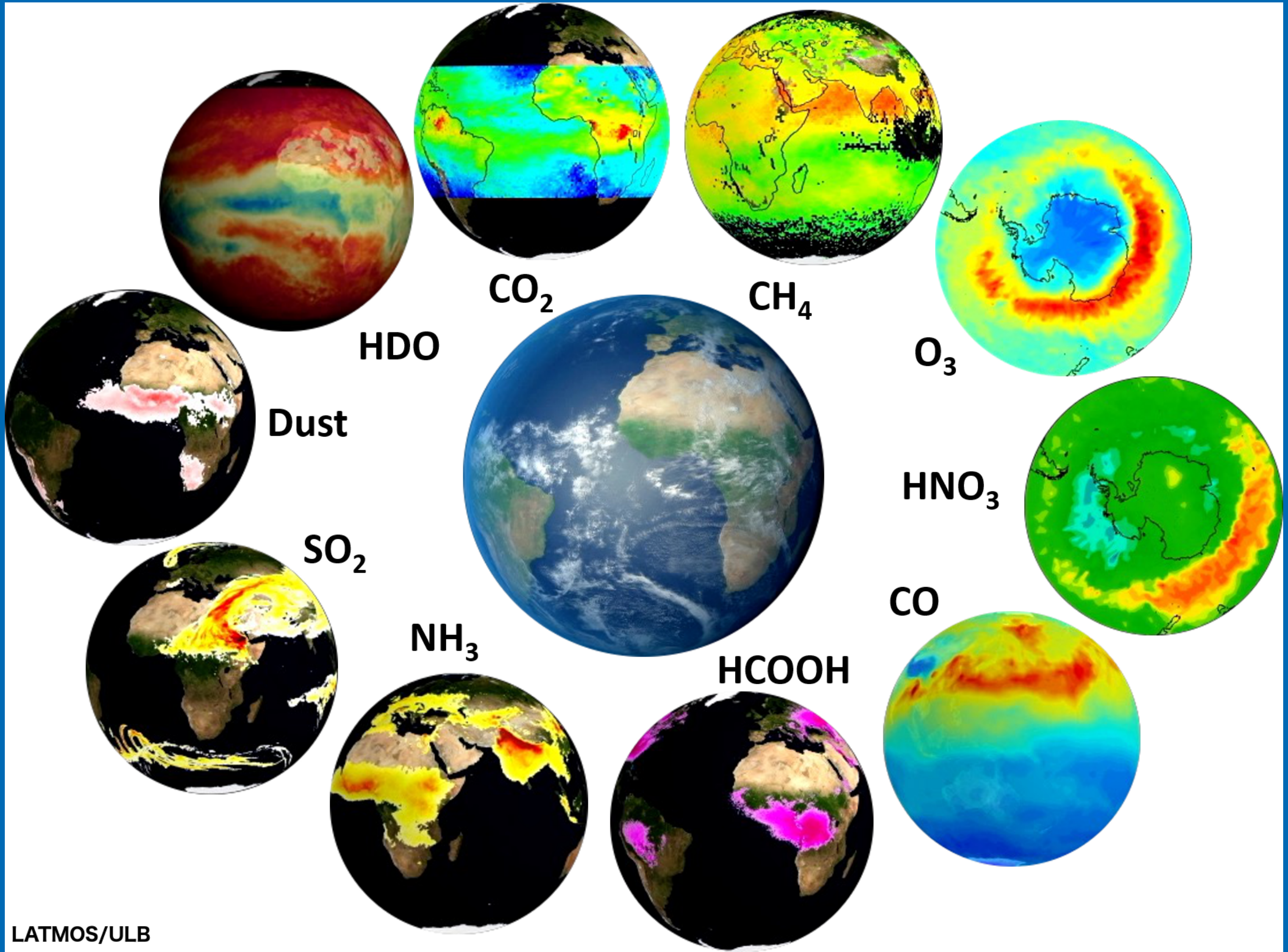


IASI FT – LATMOS / ULB 2020

IASI Seasonal integrated OLR



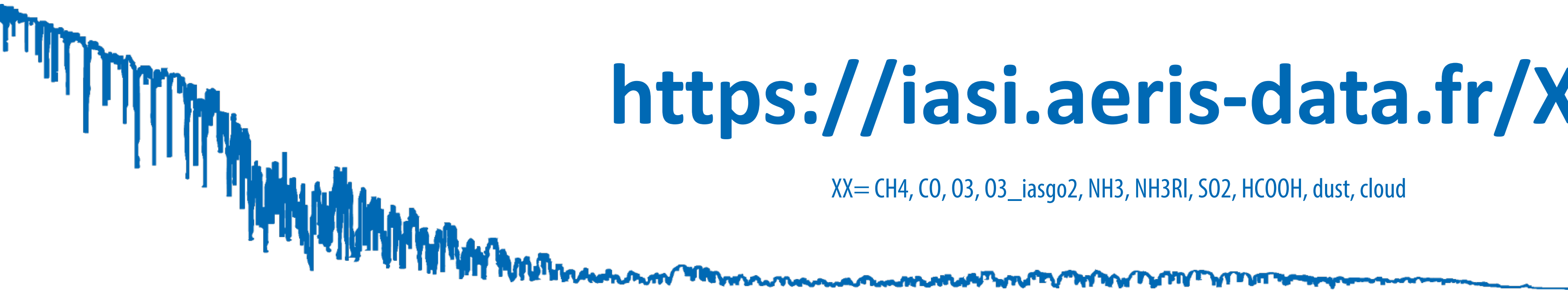
S. Whitburn (ULB) J. of Climate 2020



LATMOS/ULB

https://iasi.aeris-data.fr/XX

XX= CH4, CO, O3, O3_iasgo2, NH3, NH3RI, SO2, HCOOH, dust, cloud



IASI B & C/Metop (IASI-A is starting to drift)

IASI-New Generation : **more vertical information + better sensitivity at the surface**

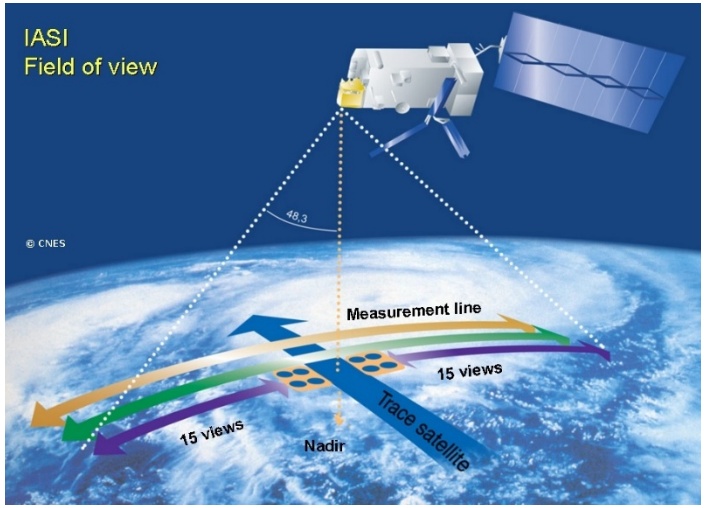
Same spectral range/pixel size as IASI (12 km)

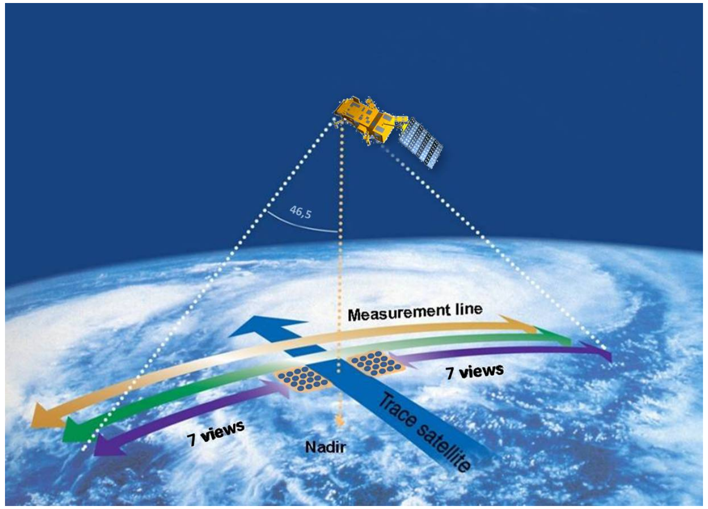
Improved S/N + spectral resolution,

9 pixels in footprint (instead of 4)

Different instrument (Mertz interferometer vs FTS)

Different industrial than for IASI





IASI and IASI-NG spectrum

0.5 cm^{-1}
0.25 cm^{-1}