Recent advances in top-down estimates of emissions from human activities, soils, and fires

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Colloquium

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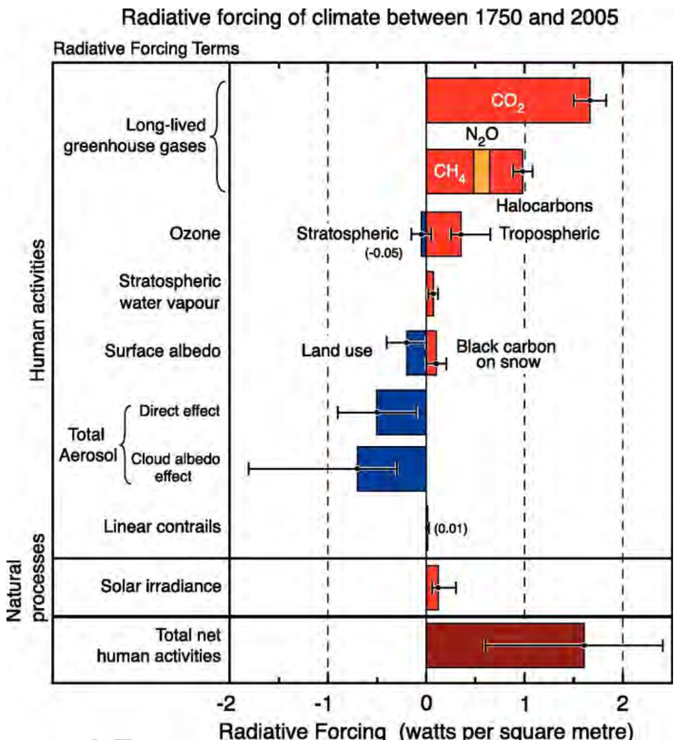
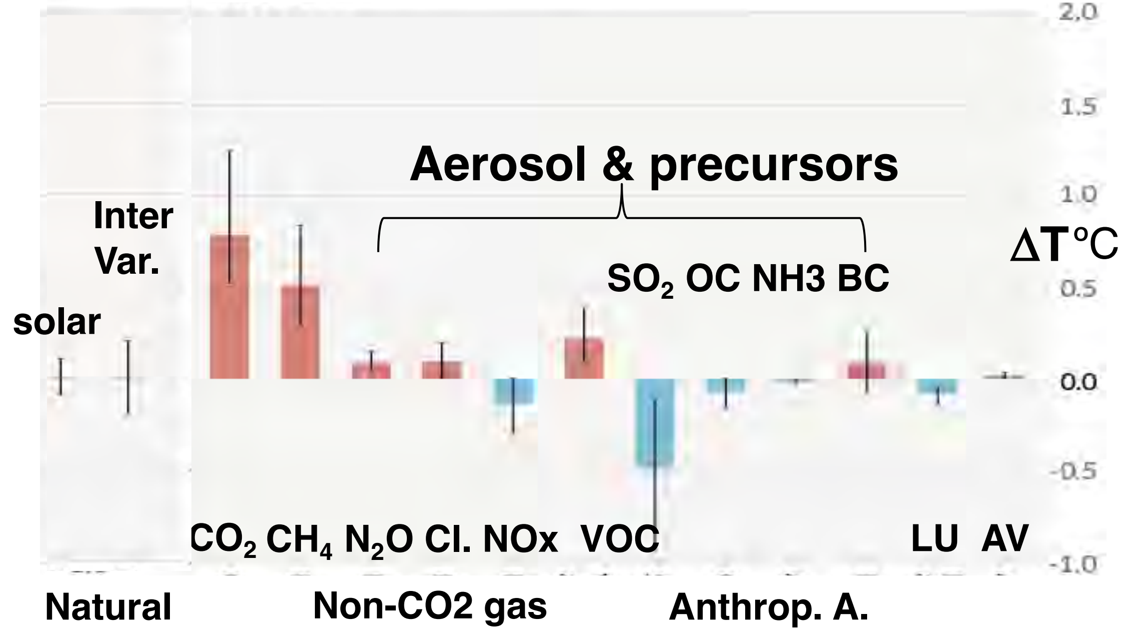
IPCC AR6: "Observed warming is driven by emissions from human activities, with greenhouse gas warming partly masked by aerosol cooling"

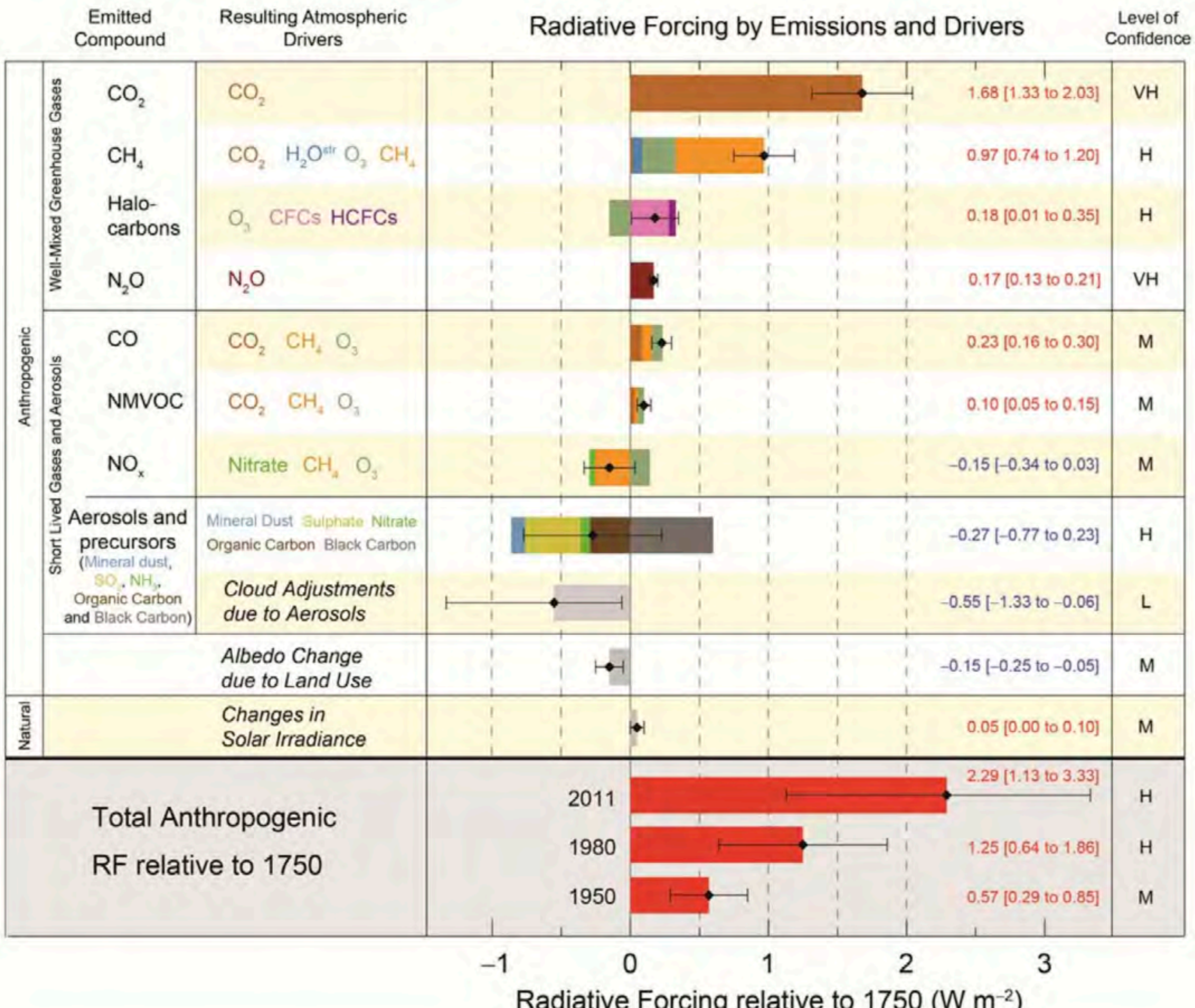


AR-5



AR-6

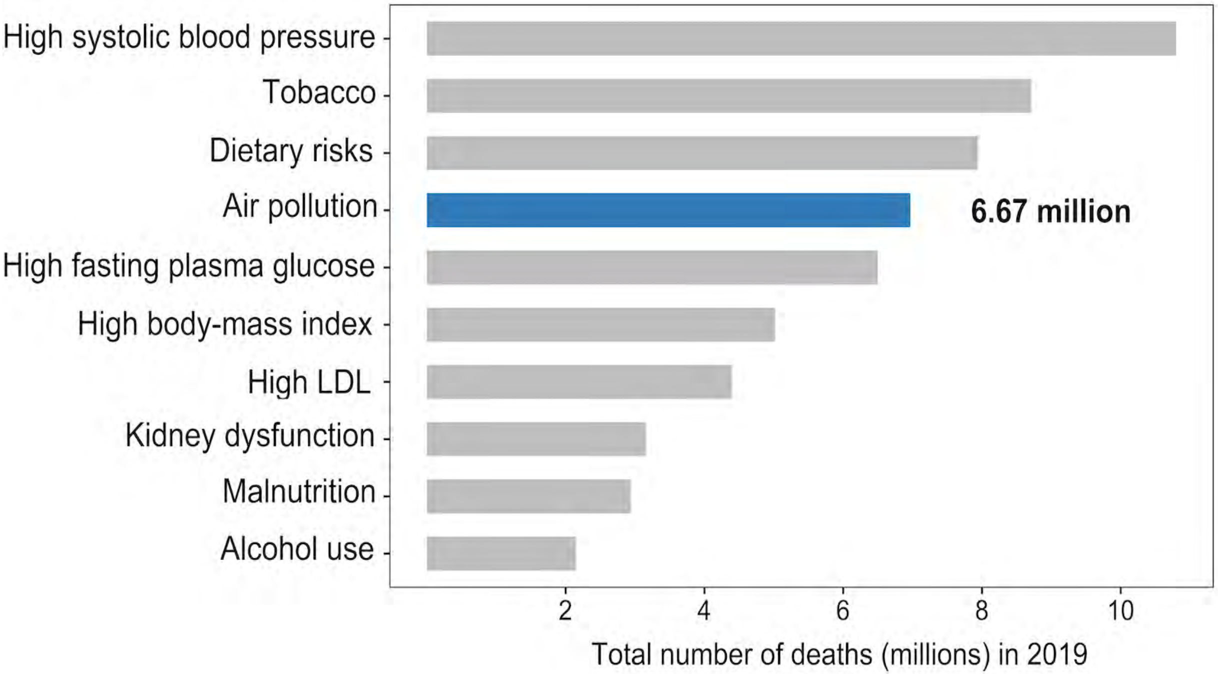
- Prior to AR6, IPCC's summary for policy makers has centered around the climate forcing by forcing agent.
- In AR6, a new paradigm has emerged, in which the climate forcing must be attributed to the sources of these agents, i.e., the emissions.



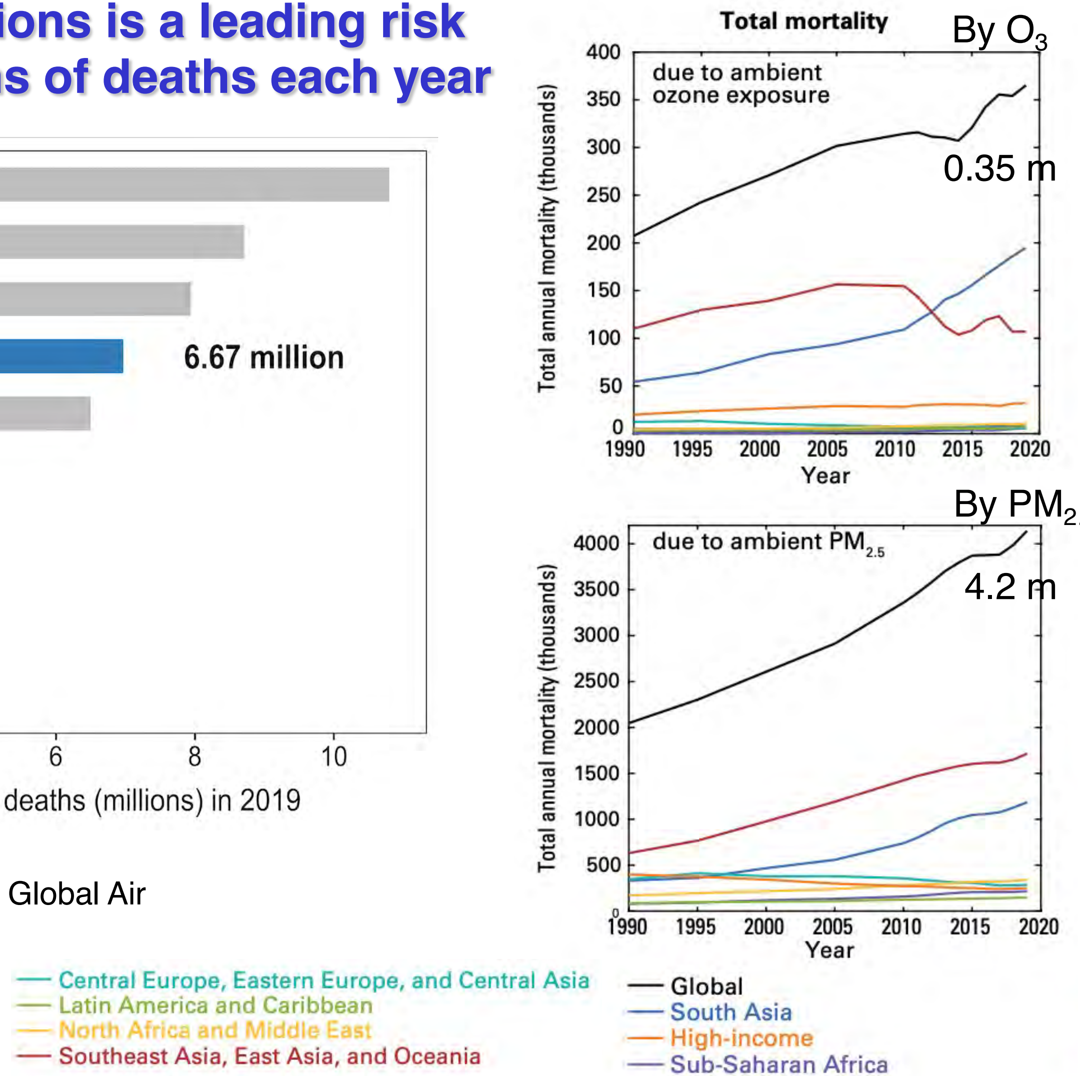
Emitted Compound
Resulting Atmospheric Drivers
Radiative Forcing by Emissions and Drivers
Level of Confidence
Anthropogenic
Well-Mixed Greenhouse Gases
Short Lived Gases and Aerosols
Natural
CO2
CH4
Halo-carbons
N2O
CO
NMVOC
NOx
Aerosols and precursors (Mineral dust, SO2, NH3, Organic Carbon and Black Carbon)
CO2
CO2 H2Ostr O3 CH4
O3 CFCs HCFCs
N2O
CO2 CH4 O3
CO2 CH4 O3
Nitrate CH4 O3
Mineral Dust Sulphate Nitrate Organic Carbon Black Carbon
Cloud Adjustments due to Aerosols
Albedo Change due to Land Use
Changes in Solar Irradiance
1.68 [1.33 to 2.03] VH
0.97 [0.74 to 1.20] H
0.18 [0.01 to 0.35] H
0.17 [0.13 to 0.21] VH
0.23 [0.16 to 0.30] M
0.10 [0.05 to 0.15] M
−0.15 [−0.34 to 0.03] M
−0.27 [−0.77 to 0.23] H
−0.55 [−1.33 to −0.06] L
−0.15 [−0.25 to −0.05] M
0.05 [0.00 to 0.10] M
Total Anthropogenic RF relative to 1750
2011 2.29 [1.13 to 3.33] H
1980 1.25 [0.64 to 1.86] H
1950 0.57 [0.29 to 0.85] M
−1 0 1 2 3
Radiative Forcing relative to 1750 (W m−2)

AR6

Air pollution affected by emissions is a leading risk factor that contributes to millions of deaths each year



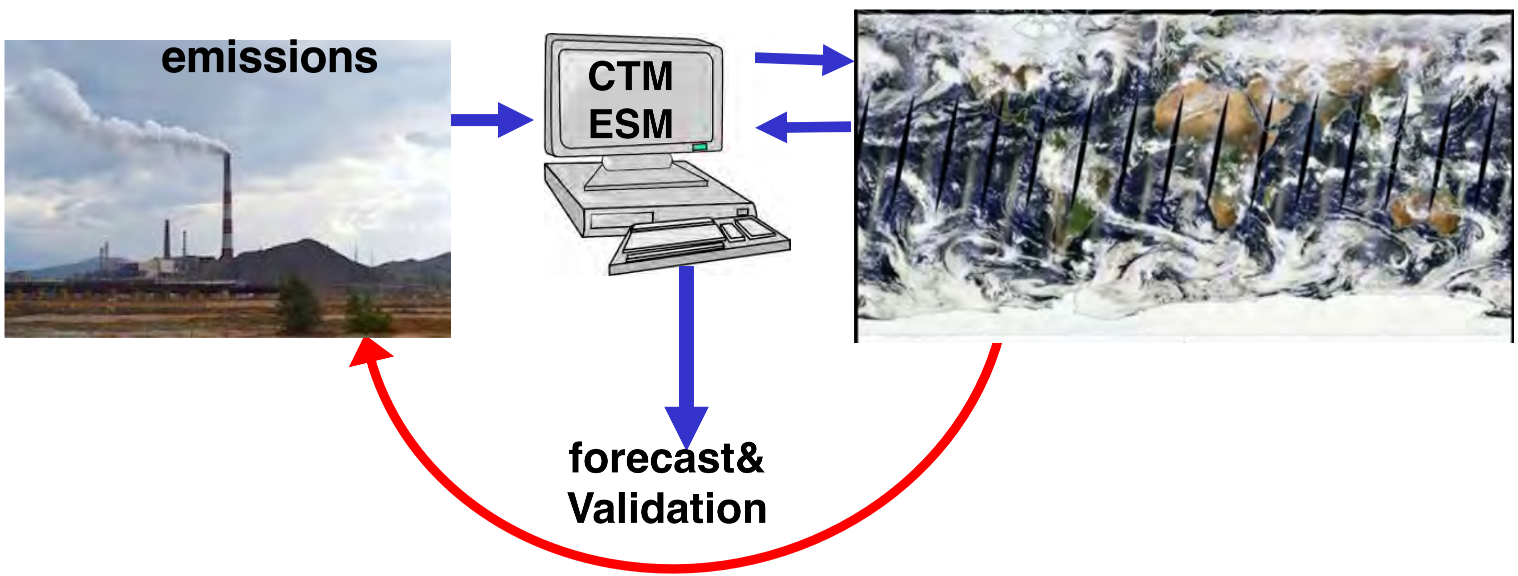
Source: WHO & Health Effect Institute & State of Global Air



Source: WMO, Air Quality and Climate Bulletin

Importance of emissions: a modeling perspective

- **CTM and climate model simulations can only be as good as the emissions.**
- **Data assimilation (without constraints of emissions) for CTM and ESM:**
  - suffers from emission errors that are persistent.
  - may improve forecast when observations of state parameters are available, but such improvement decay quickly with time once obs. are not available.
- **For both climate studies and air quality forecast, there is a need to have a holistic interpretation from emissions to observations, and vice versa.**



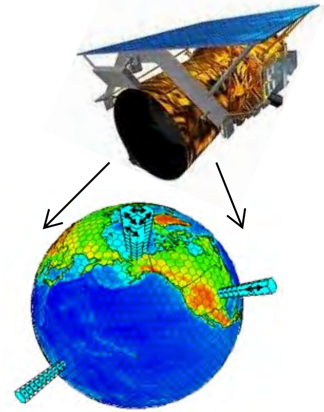
Top-Down vs. Bottom-Up estimates of emissions

Bottom-up emission estimate

Ground-based network/data

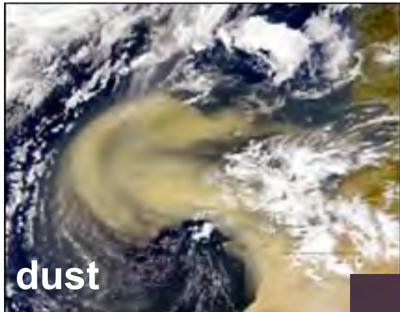
- Usually has a 2~3 yr lag
- Seasonal/ monthly
- Point or area average
- Chemically speciated
- Lack of constraint on emission above the surface

Top-down emission estimate

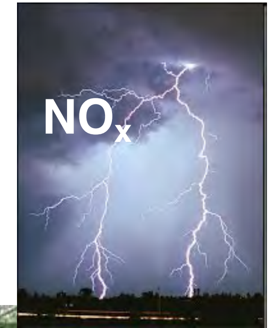


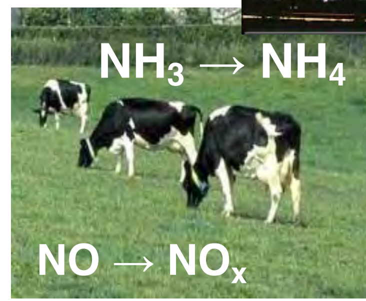
- Has the potential for near real time
- Daily (polar-orbiting) or higher (geo..)
- Globally with high spatial resolution
- Trace gases & optical thickness
- Reflecting the columnar mass, and thus 1st order of emission

Emission Sources



Primary sources for aerosols:
directly from surface





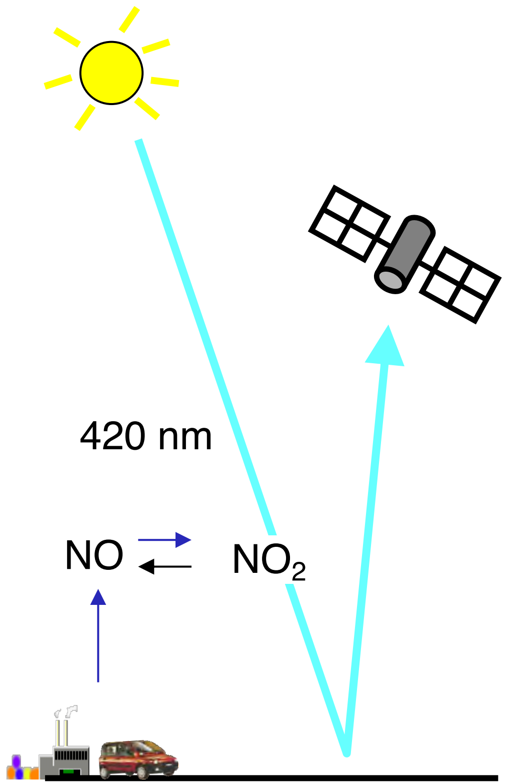
Secondary sources:
Atmospheric chemistry

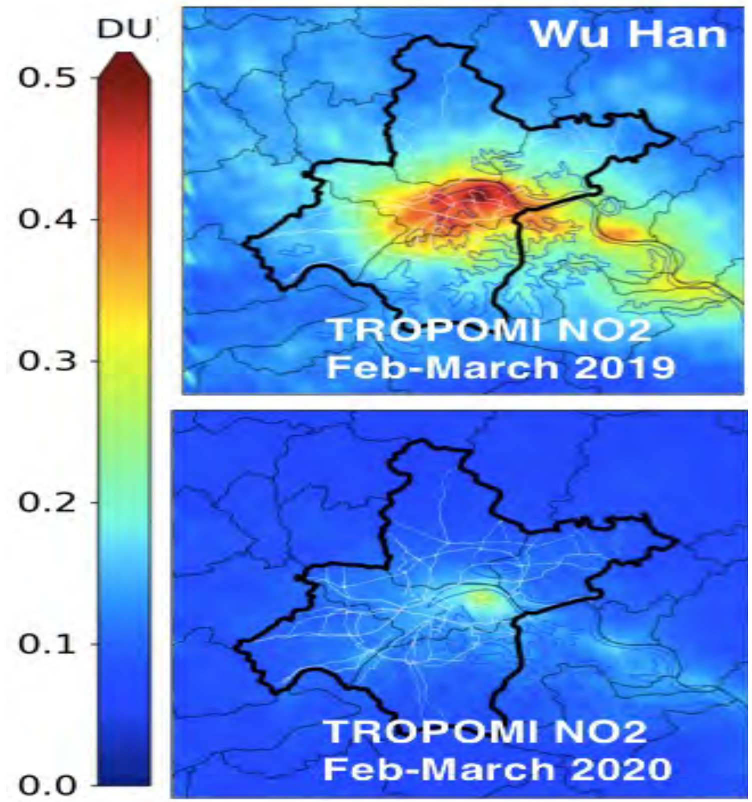
Emission sources have large spatial and temporal variations (minutes-hours, meters to kilometers).

Outline

- Satellite constraints of SO_2 & NO_2
- Efficacy of top-down emissions
- Satellite constraints of emission processes
  - Soil NOx
  - Fire emissions
- Summary and outlook

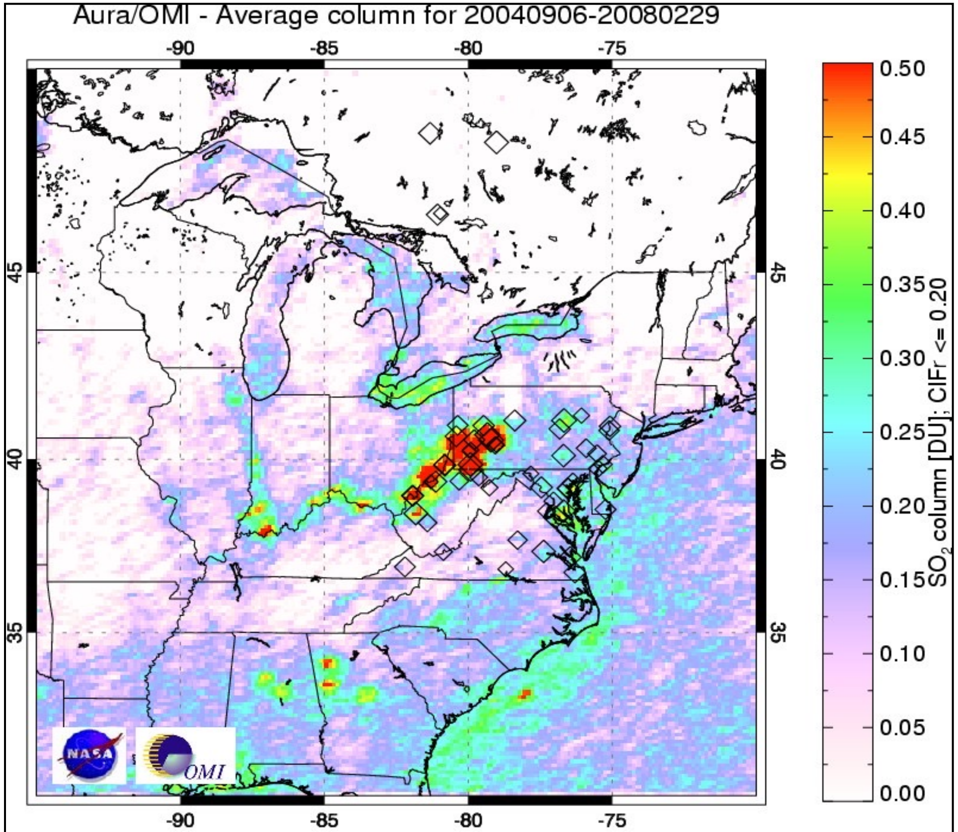
View NO_2 from space





NO_x is mainly from fossil fuel combustion; limiting precursor for ozone formation

Average OMI SO_2 burdens over eastern USA



◊ - major power plants

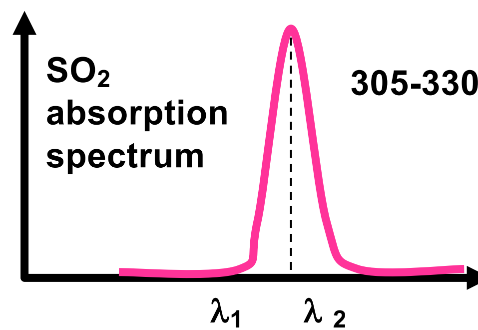
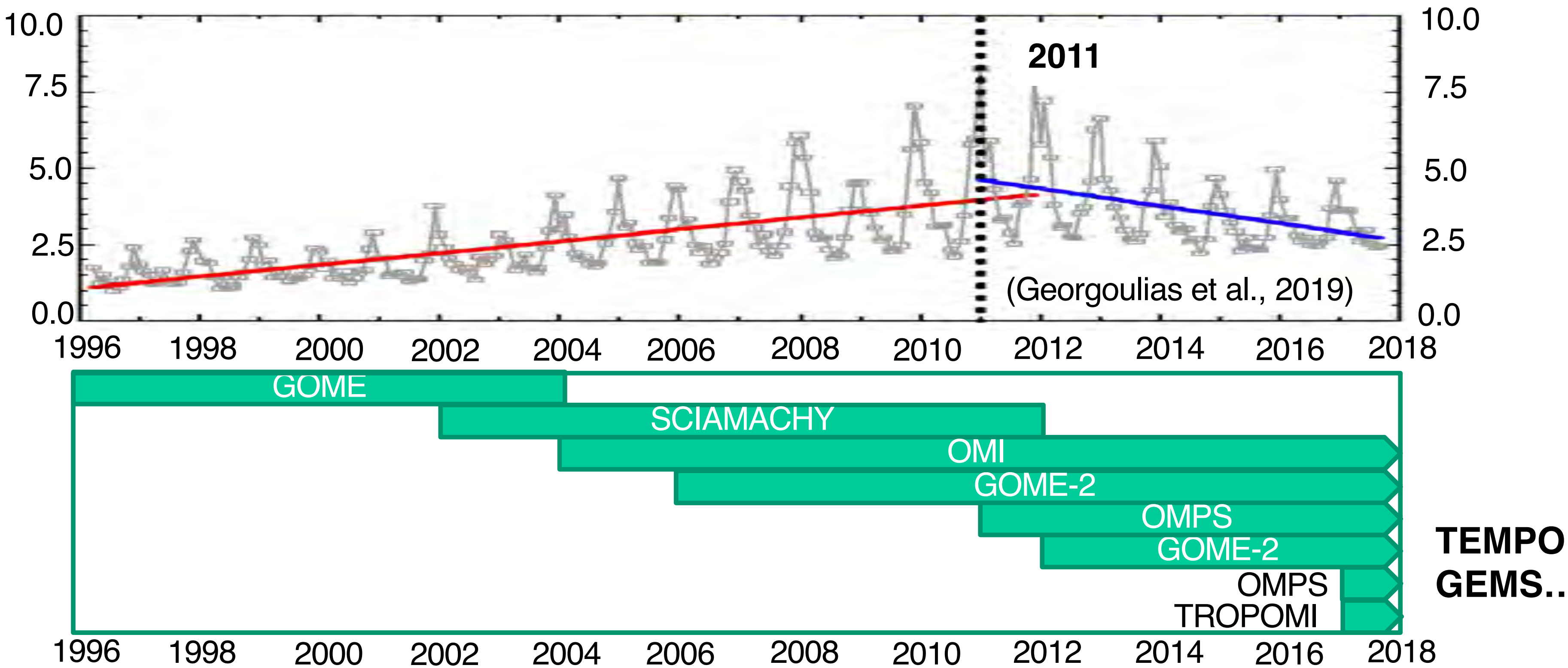


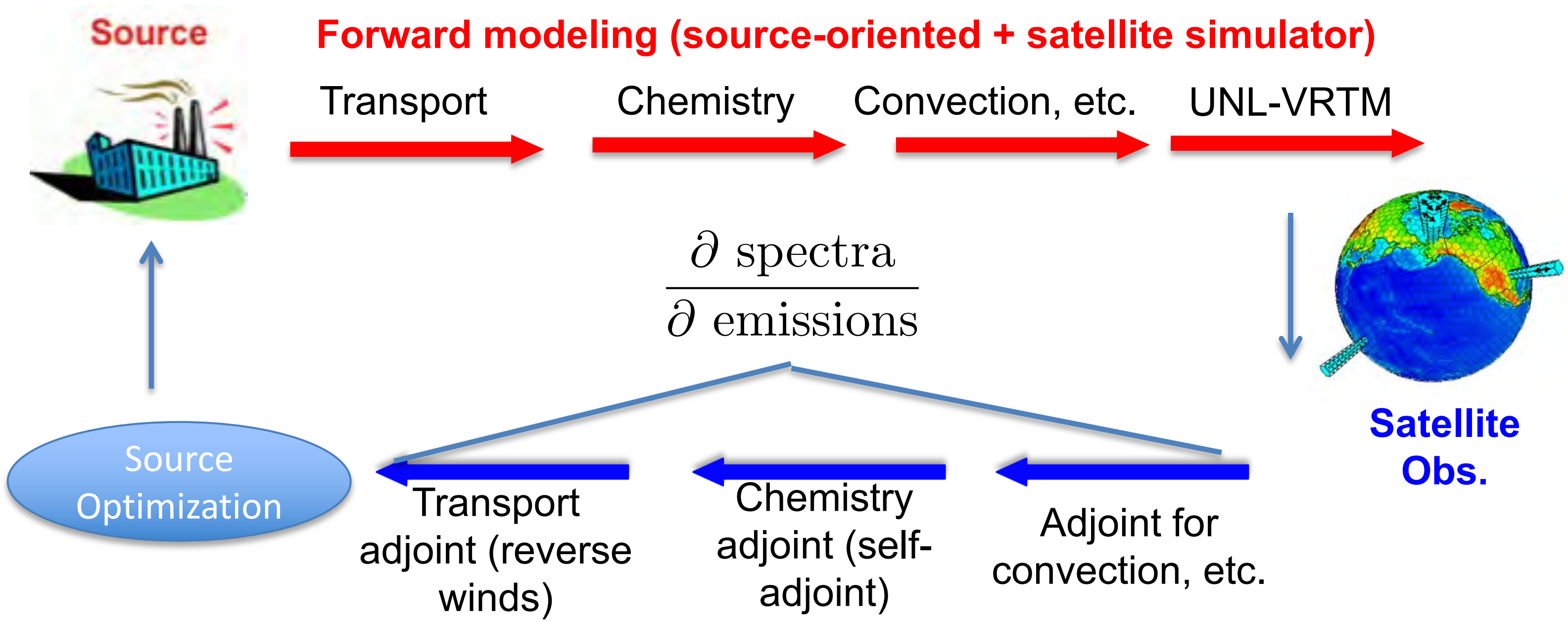
Image courtesy: Nickolay Krotkov, NASA

Questions to be addressed:

- **Separate vs. joint DA of SO_2 and NO_2 from satellite observations**
- **Implication for AQ forecast at urban scale**



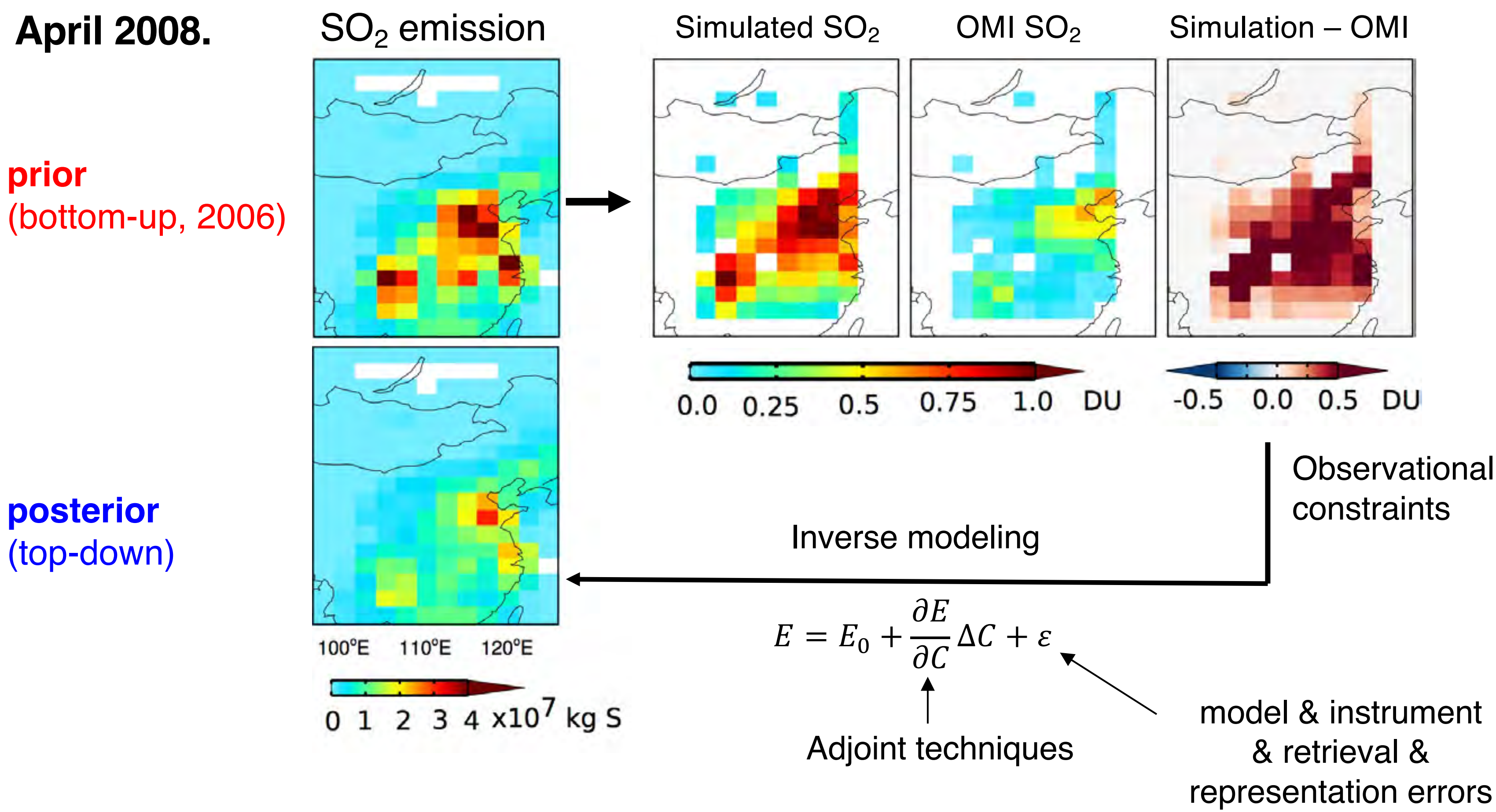
GEOS-Chem adjoint modeling



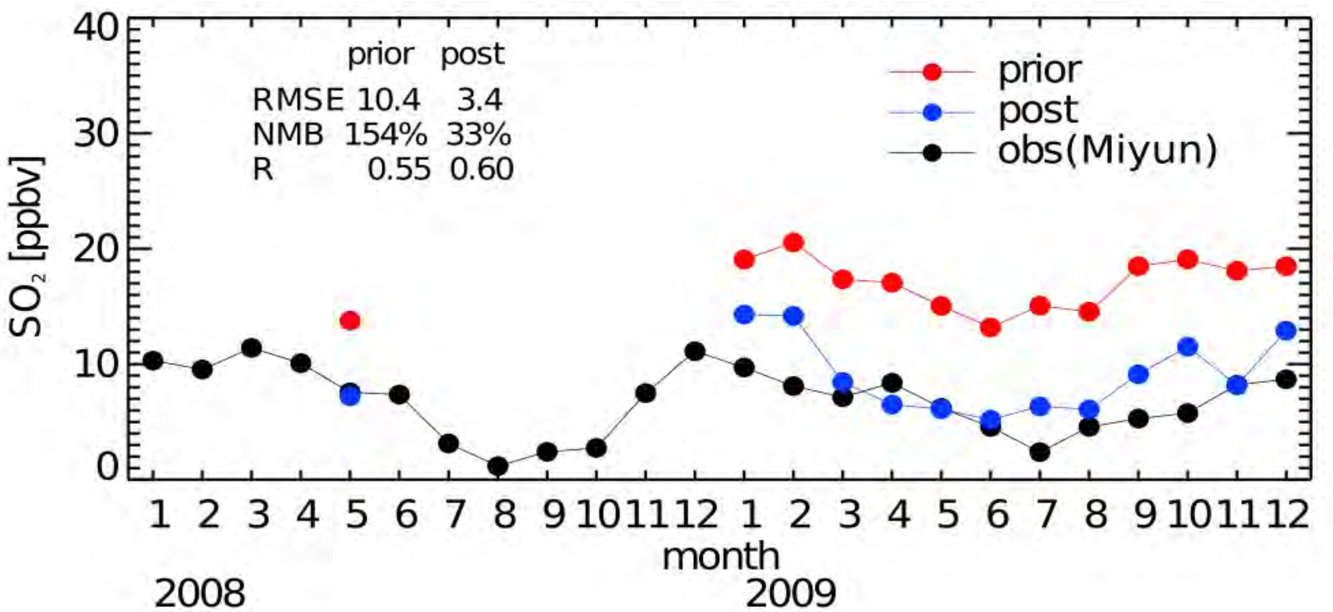
Optimize the emissions by iteratively minimizing the cost function that depends on the model error, observation error, and the difference between model and observation.

$$J(\boldsymbol{\sigma}) = \frac{1}{2}\sum_{\Omega}\left[H\big(M(\boldsymbol{\sigma})\big) - \mathbf{c}_{obs}\right]^T \mathbf{S}_{obs}^{-1}\left[H\big(M(\boldsymbol{\sigma})\big) - \mathbf{c}_{obs}\right] + \gamma\frac{1}{2}[\boldsymbol{\sigma} - \boldsymbol{\sigma}_a]^T \mathbf{S}_a^{-1}[\boldsymbol{\sigma} - \boldsymbol{\sigma}_a]$$

Using OMI SO_2 to constrain SO_2 emissions



Implication for air quality forecast: applying posterior emission from last month to forecast AQ in this month

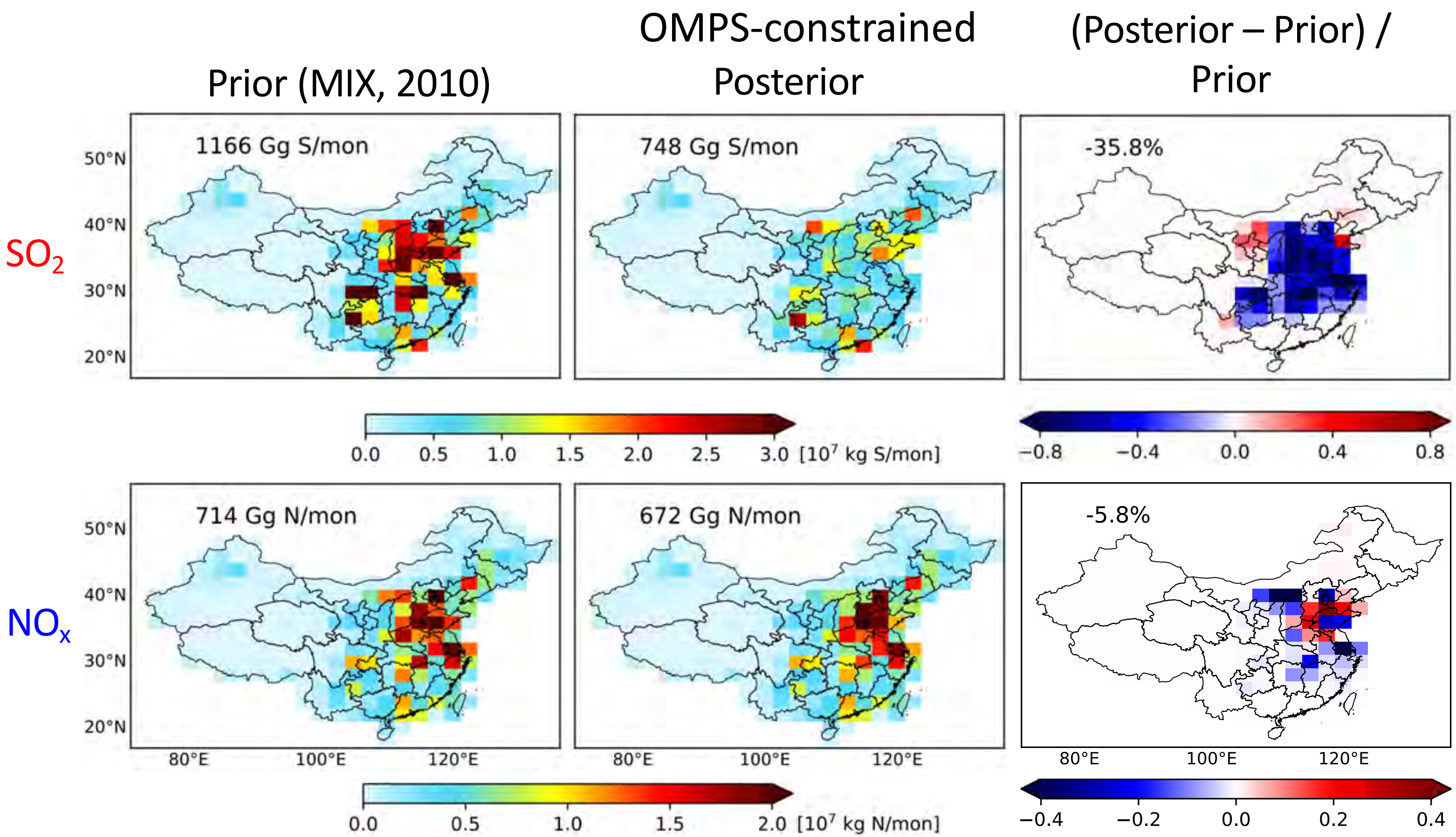


Wang, Y.

A new approach for monthly updates of anthropogenic sulfur dioxide emissions from space: Application to China and implications for air quality forecasts,

Wang, Y., et al., Geophys. Res. Lett., 2016

Joint inversion of anthropogenic SO_2 and NO_x emissions

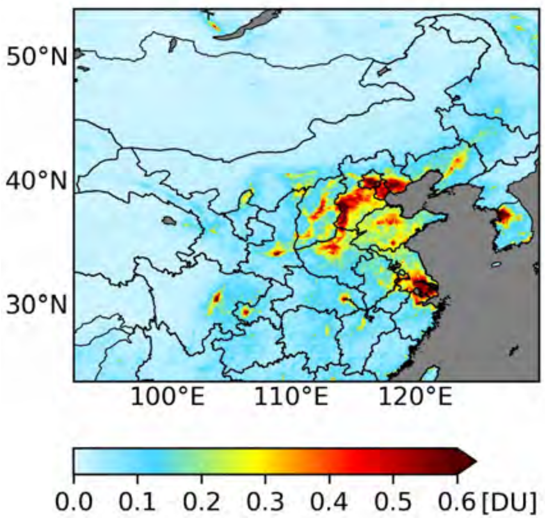


Results using GEOS-chem adjoint (V.8) at 2° x 2.5° resolution, Oct. 2013

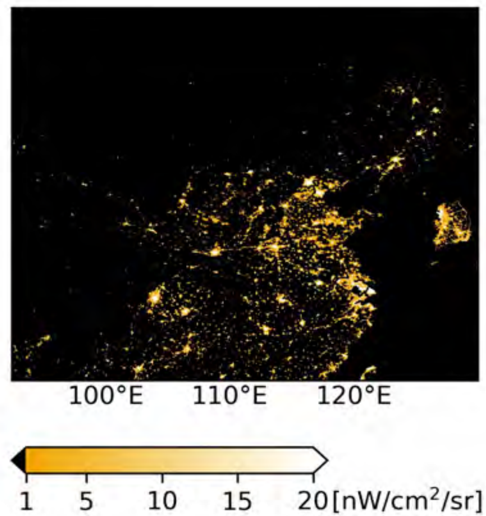
Y. Wang et al., ACP, 2020a.

The relationship between TROPOMI NO_2 and VIIRS nighttime light

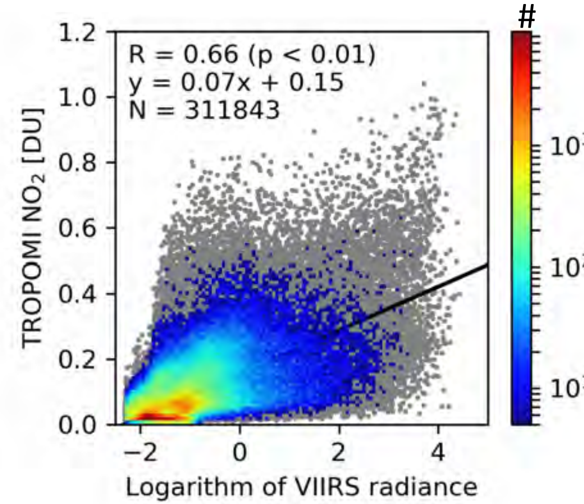
TROPOMI NO_2



VIIRS nighttime light



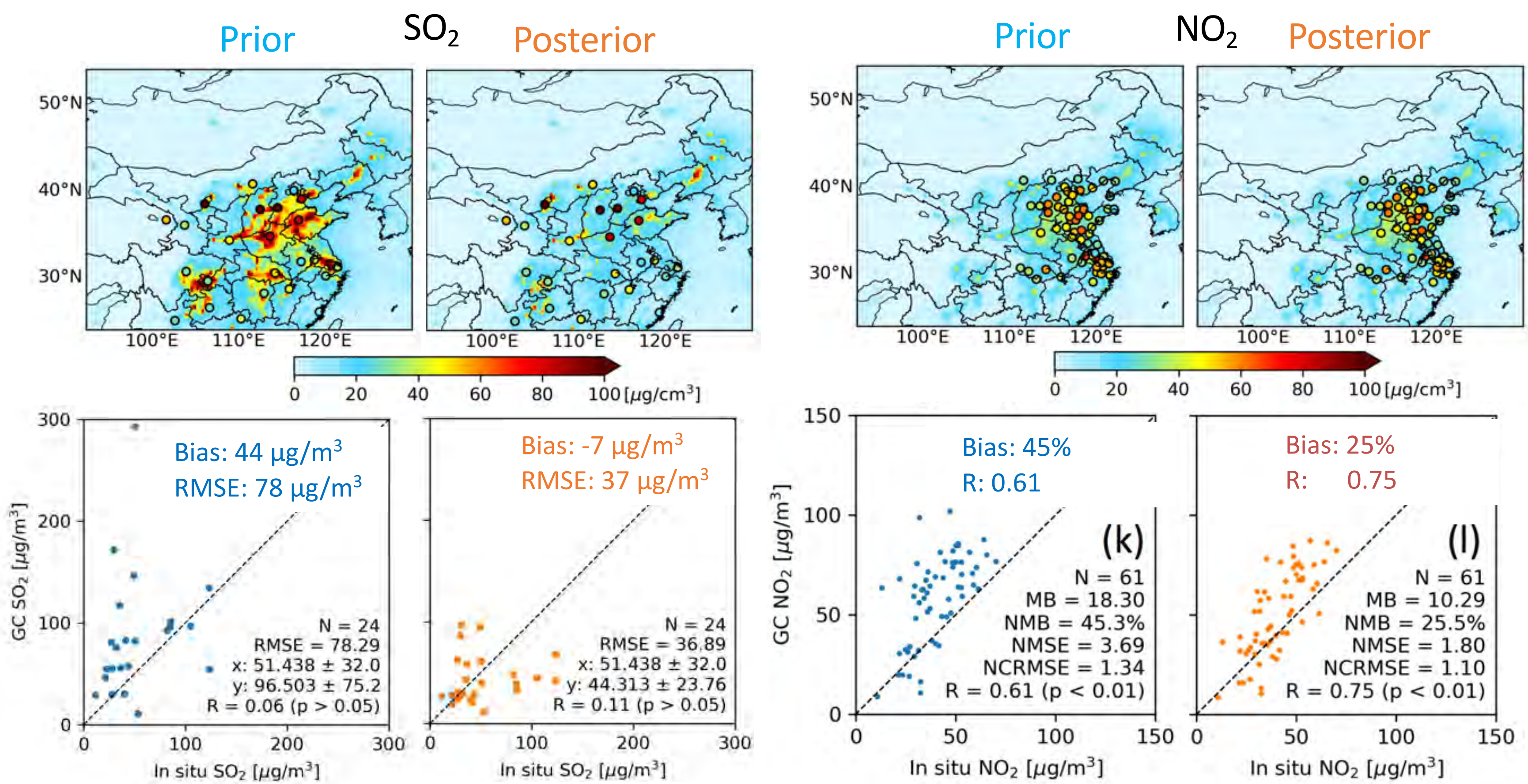
NO_2 VS nighttime light



There is good correlation between TROPOMI NO_2 vertical column density and VIIRS nighttime light, thus VIIRS nighttime light intensity should be good proxy for downscaling NO_x emissions.

Y. Wang et al., ACP, 2020b

Apply top-down constraints in present month to improve forecasts in next month



All results are for Nov. 2013 at 0.25x0.3125 degree resolution by using GEOS-chem nested model.

Efficacy of the top-down emissions

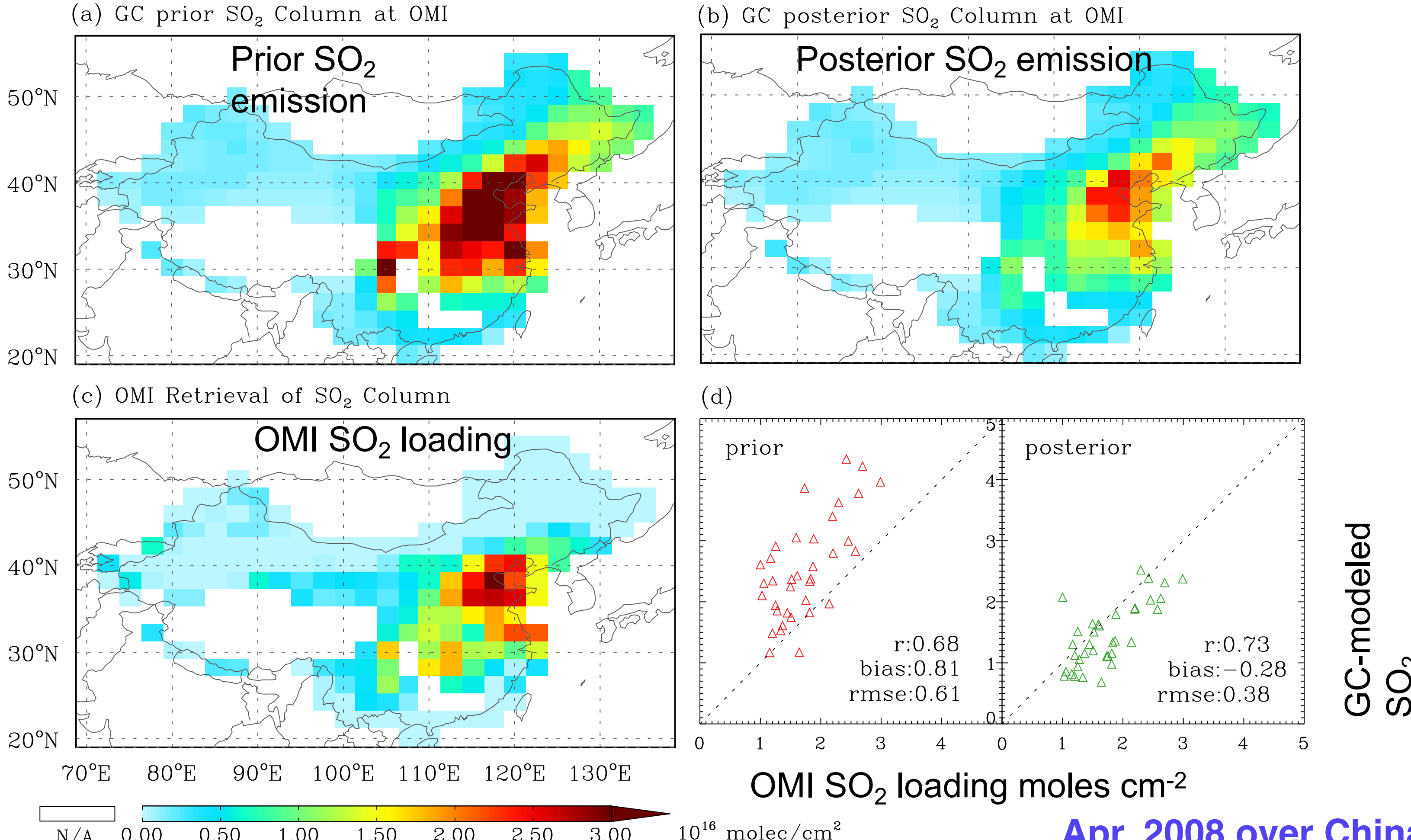
Two methods to test it:

1) Compare with the emissions inverted from satellite-based aerosol observations.

2) Use these emissions for the models that are different from the host model that is used in the top-down estimates.

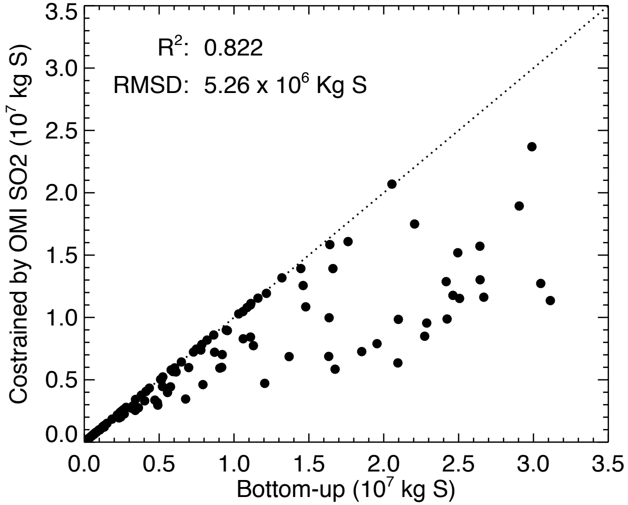
Use MODIS AOD/Radiance to constrain aerosol primary & secondary emissions

Xu et al., JGR, 2013

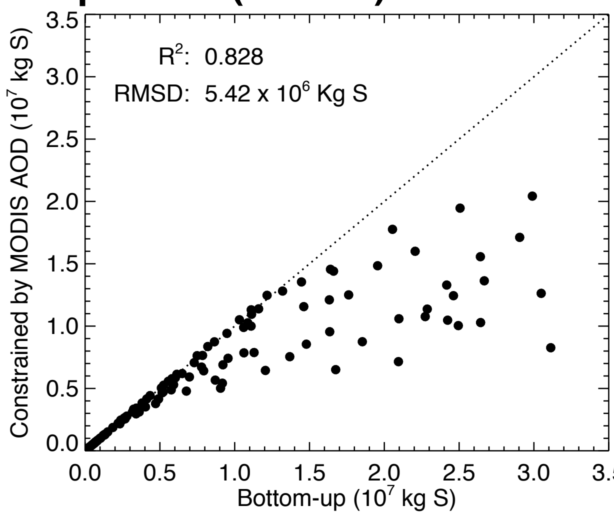


Apr. 2008 over China

Top-down (OMI) vs. bottom-up

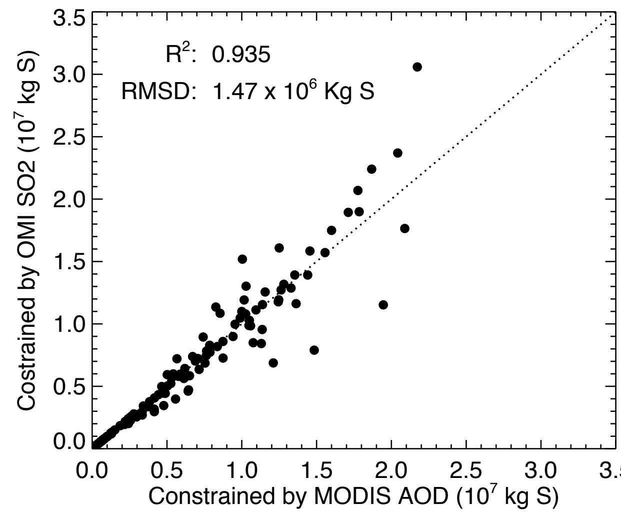


Top-down (MODIS) vs. bottom-up

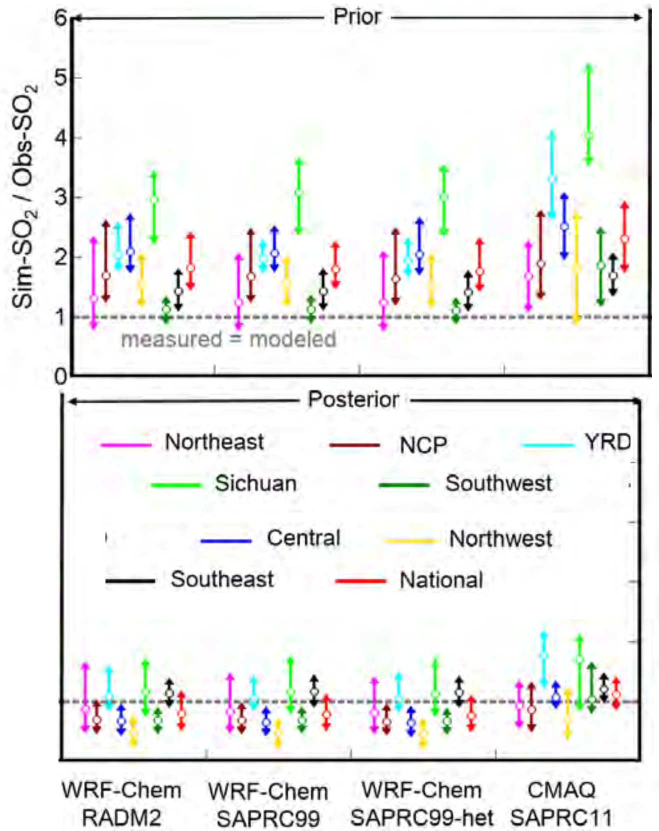


Two different sensors (one for gas and one for aerosols) telling nearly the same results about SO_2 emissions!

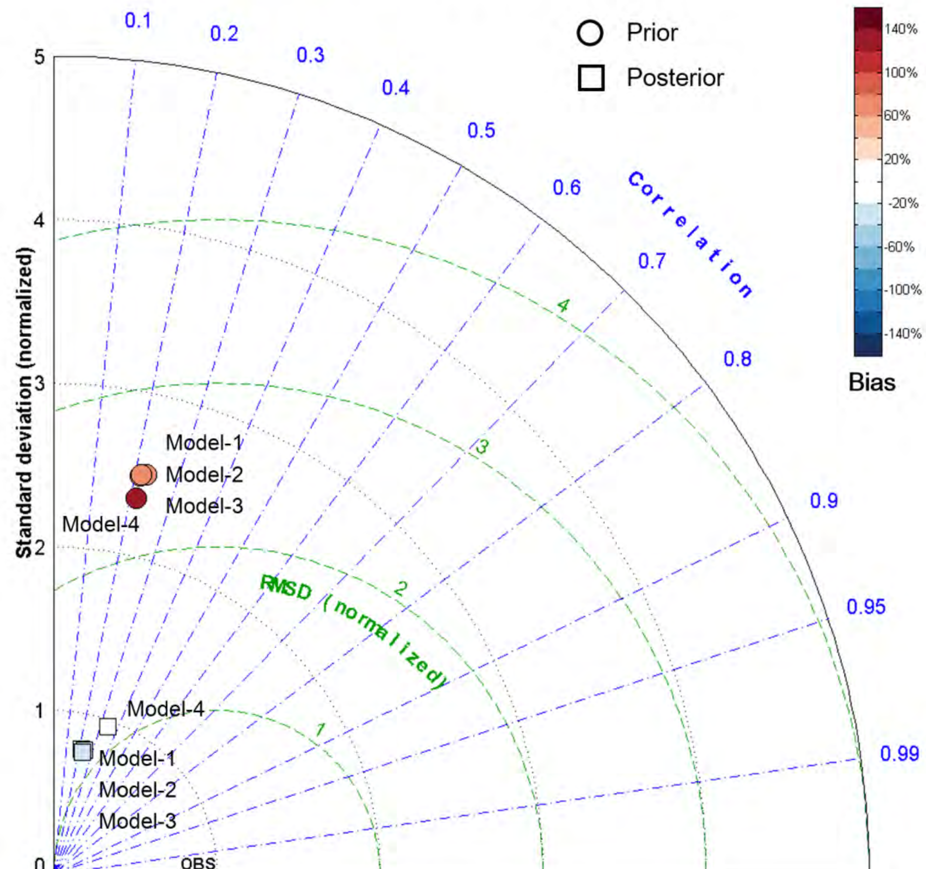
Top-Down from MODIS vs. Top-down from OMI



The top-down approach using OMI SO_2 and global GEOS-Chem adjoint modeling can timely update anthropogenic SO_2 emission for **regional AQ modeling**.



Efficacy is shown to be robust for four different AQ models (chemistry schemes)

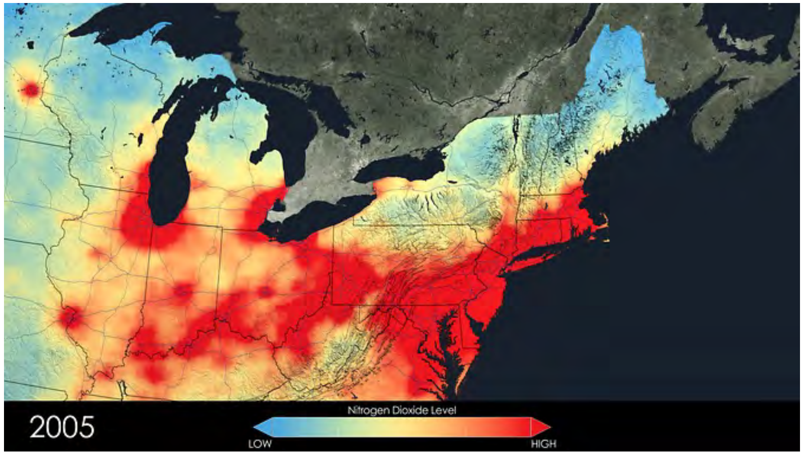


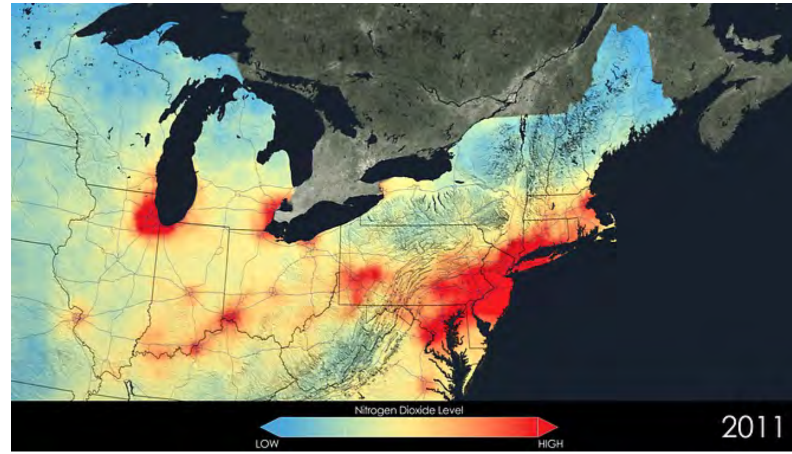
Surface SO_2

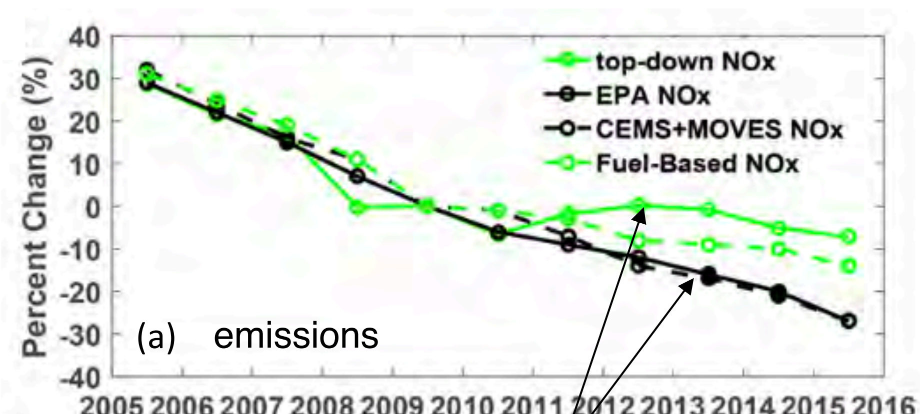
Li et al., 2021. ERL

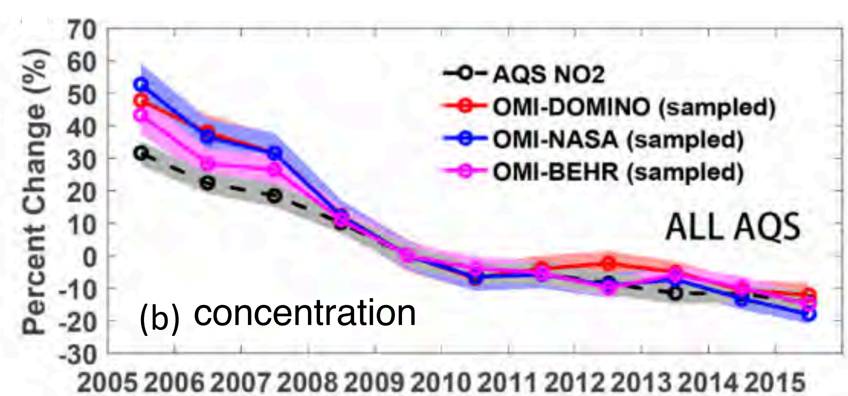
Here in U.S.

Has the NOx emission reduction been slow down since 2009?







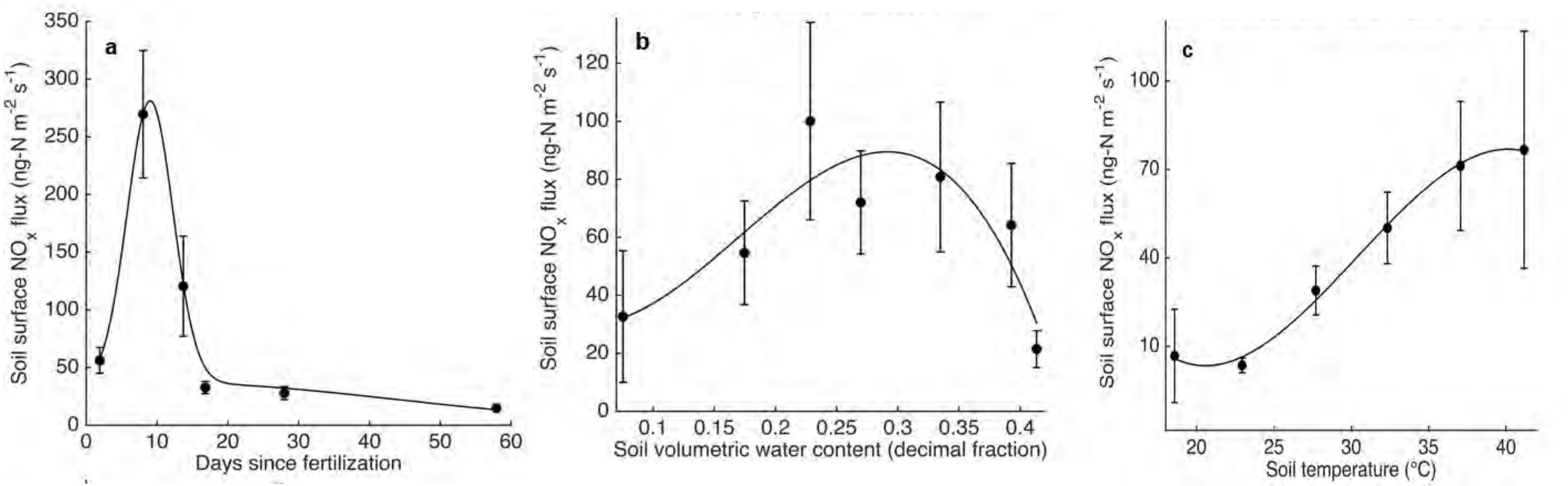


Does NOx emission reduction slow down?

Jiang et al., 2016

Soil NOx emissions

- ~1/4 of global NOx production is derived from soils, mostly from fertilized agriculture; however, estimates of global soil NOx emissions vary widely (9–27Tg per year).
- Fertilization and N deposition are known to increase soil NOx emissions; however, the majority of studies are conducted at temperatures below 35C.
- Strong pulse NOx emission responses to rewetting of soils in high-temperature regions are important, yet understudied in managed systems.

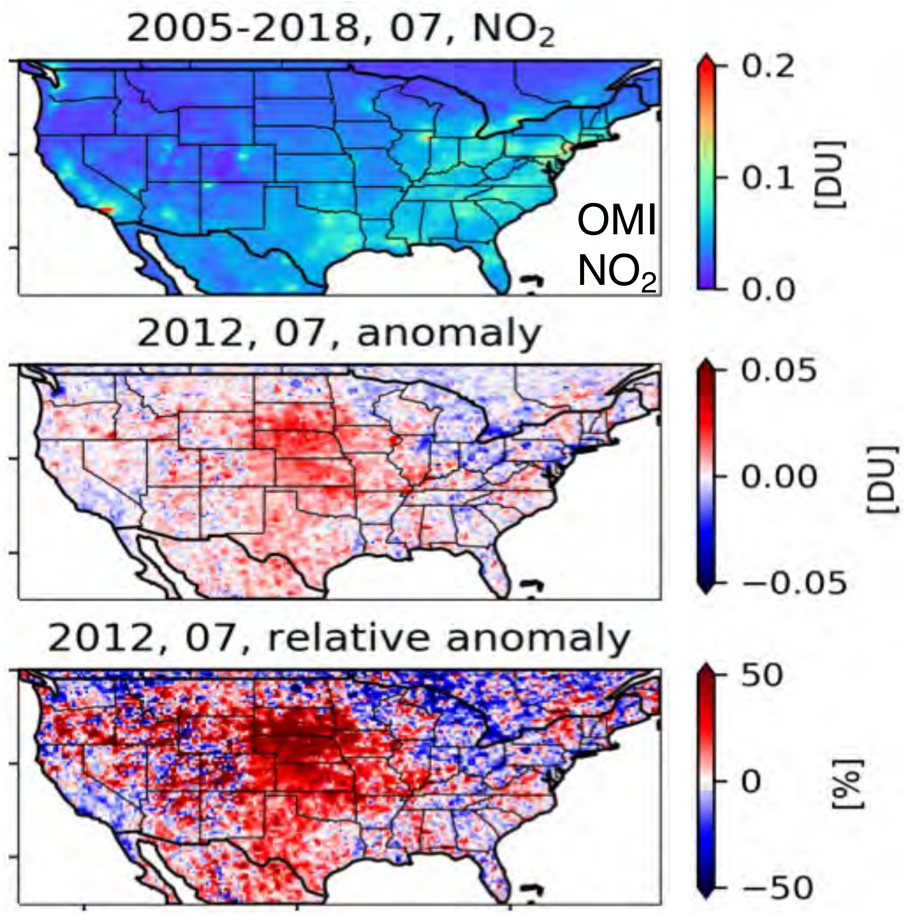


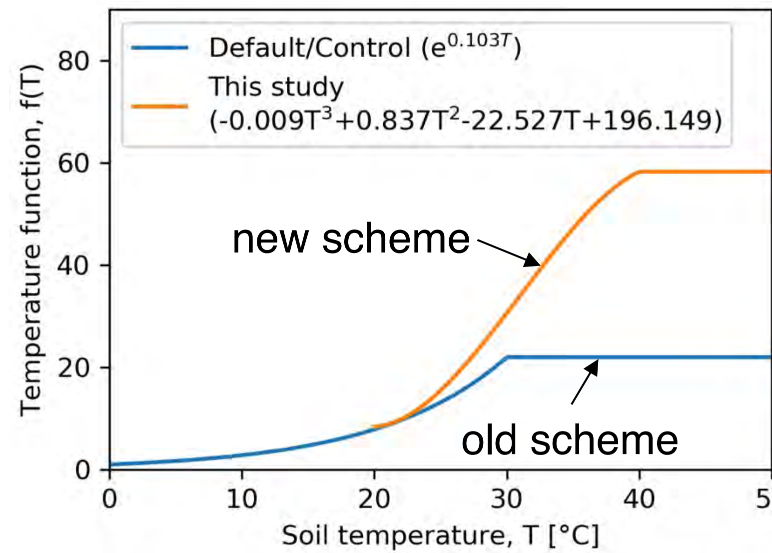
Days after fertilization **Soil moisture v/v** **Soil temperature v/v**

Oikawa et al., 2015, Nature Comm.

Observation-based insights of emission process

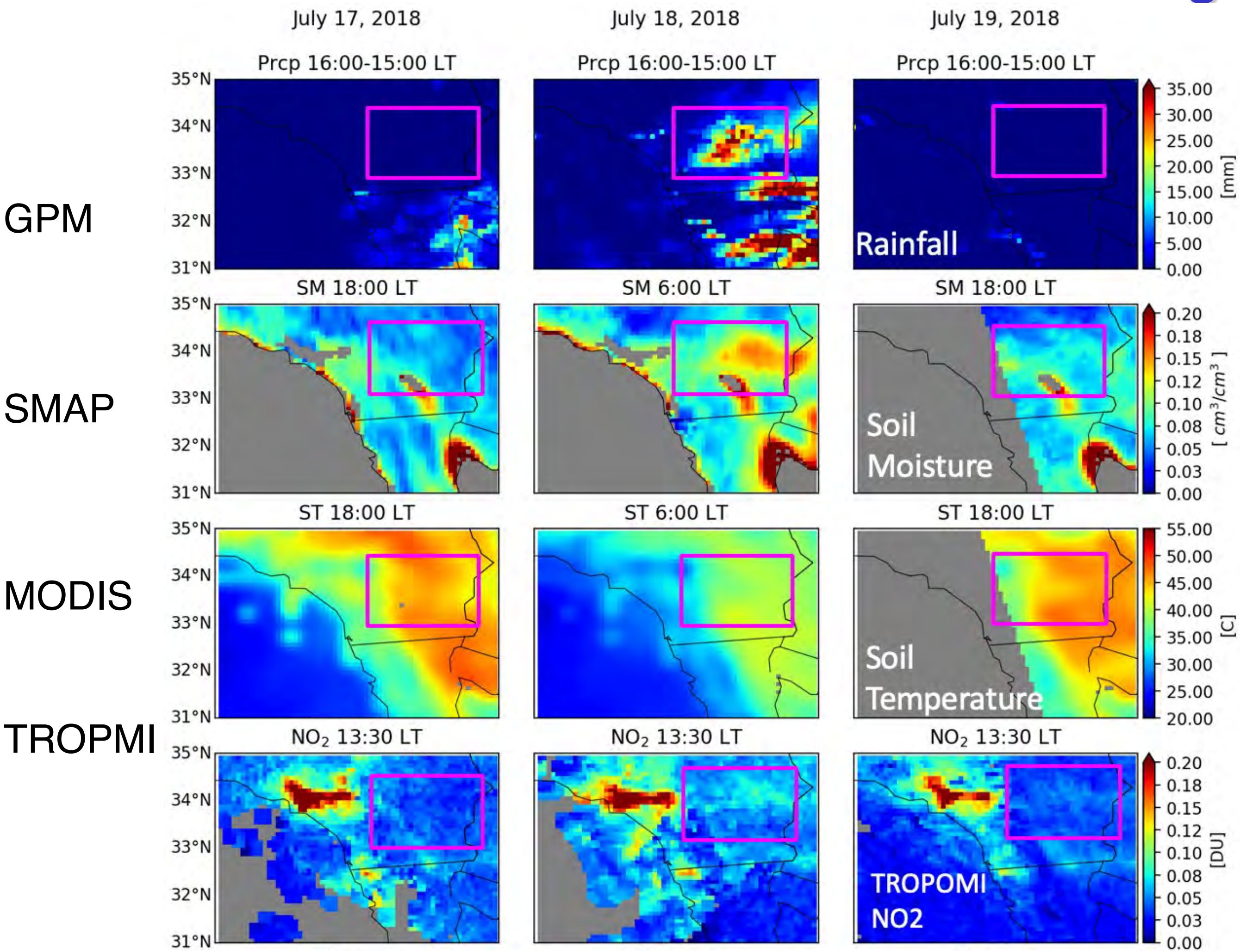
dependence of soil NOx emission on temperature





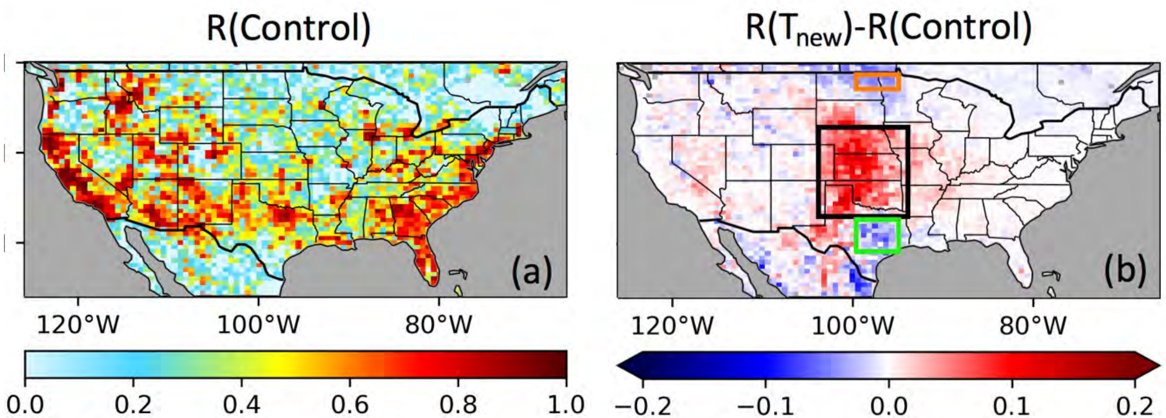
Wang et al., 2021
Environ. Res. Lett.

Pulse of NOx emission after re-wetting

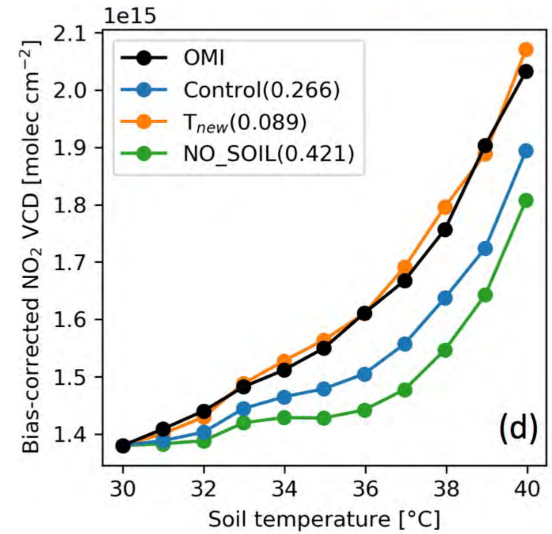


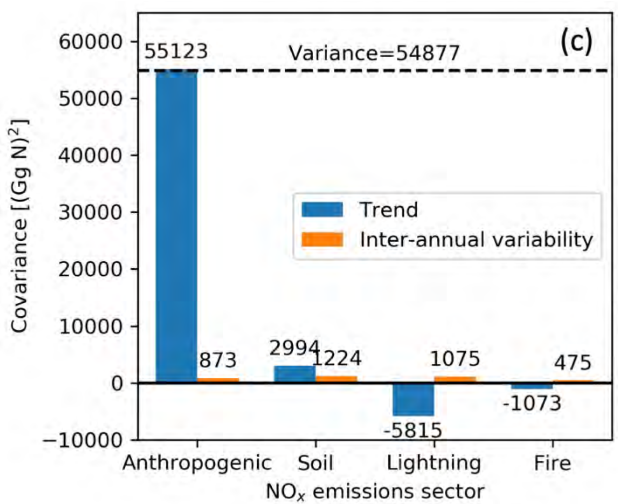
Tong et al., 2021, *Environ. Sci. & Tech.*

Improved simulation of soil NOx emission



Based on data in 2005–2019 data





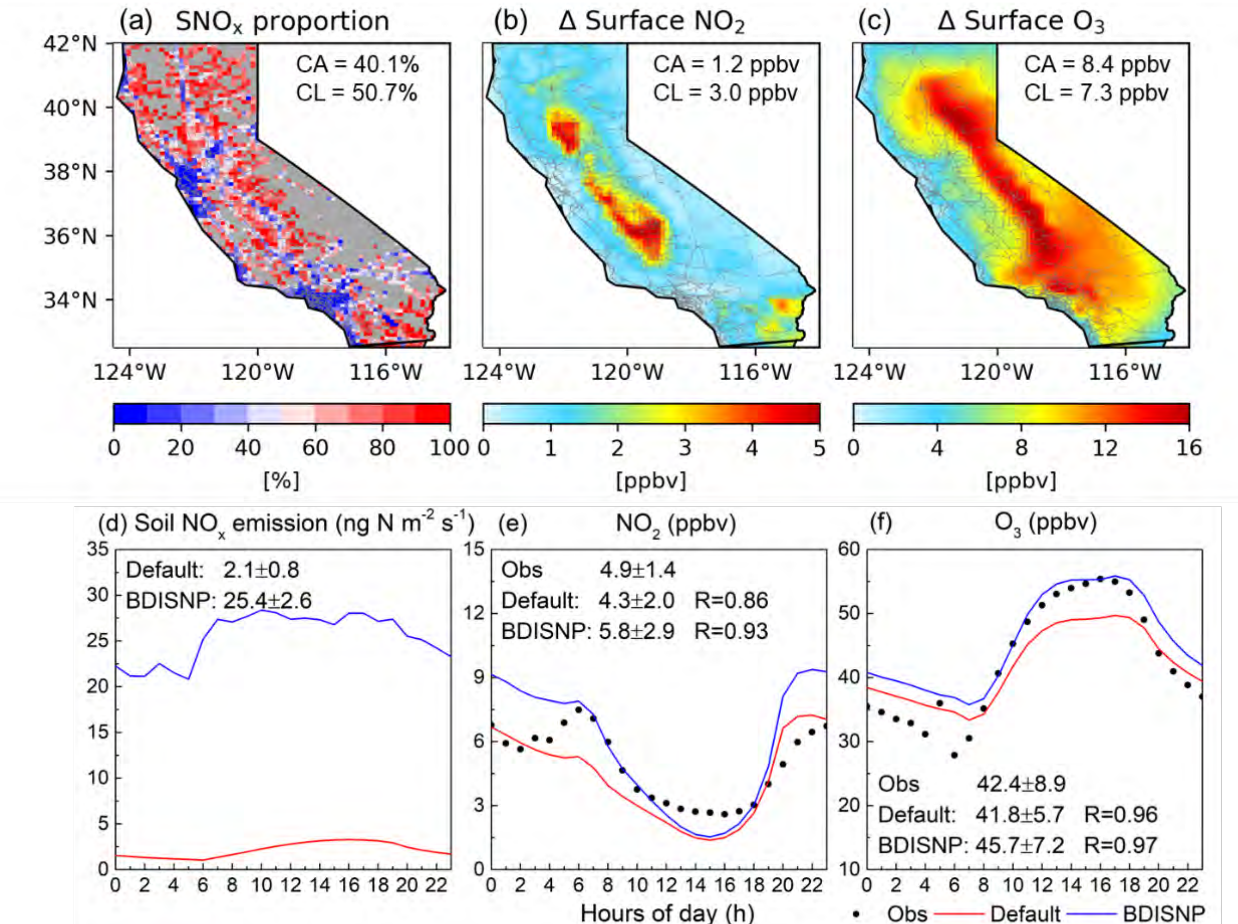
- Soil and lightning NO*x* combined emissions trends change from –3.95% a^{-1} during 2005–2009 to 0.60% a^{-1} from 2009 to 2019, thereby rendering the abrupt slowdown of total NO*x* emissions reduction.

- Non-linear inter-annual variations explain 6.6% of the variance of total NO*x* emissions.

- Inter-annual variations of either soil or lightning are comparable (slightly larger than anthropogenic sources.

Wang et al., 2021, ERL

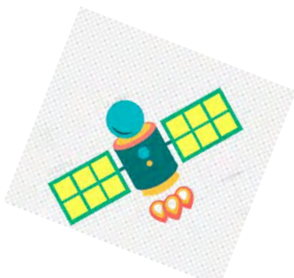
At regional scale



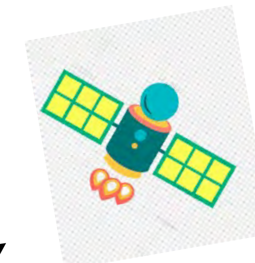
- SNO_x exceed anthropogenic sources over croplands which accounts for 50.7% of NO_x emissions
- Such considerable SNO_x enhance the monthly mean NO_2 columns by 34.7% (53.3%) and surface NO_2 concentrations by 176.5% (114.0%), leading to an additional 23.0% (23.2%) of surface O_3 concentration in California (cropland).

Tong et al., 2021. EST

Next frontier in remote sensing of fires

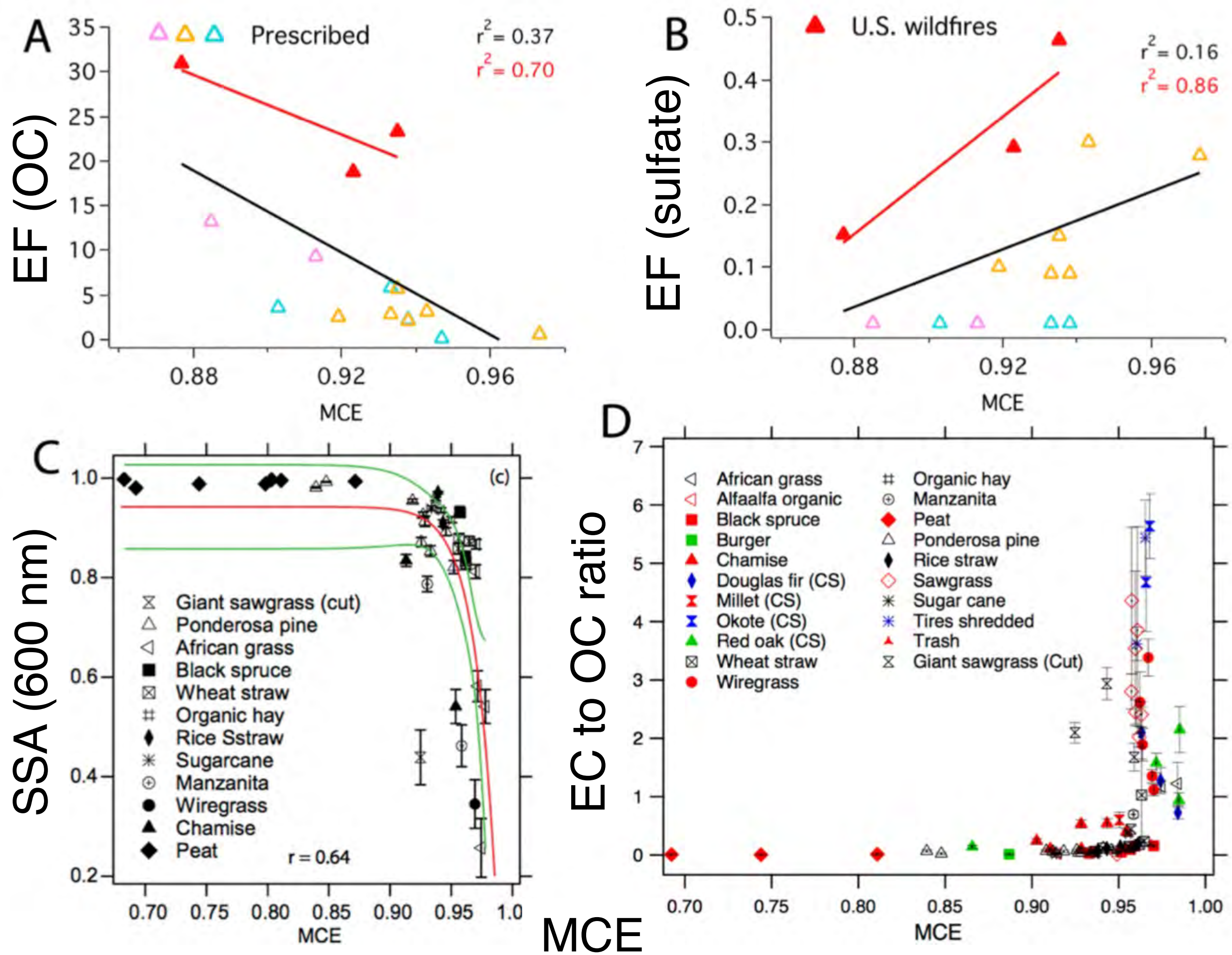


Fire
combustion
efficiency?



FRP
T, fire area

Fire Phase often described as Modified Combustion Efficiency, CO_2 / ($CO+CO_2$) → Emission Factor



Liu et al., [2017]

Pokhrel et al., [2016]

How emission factor is treated in fire emission estimates?

- Static for the same type; no consideration of wind speed, relative humidity, ..
- Schemes for surface/biome types are oversimplified and vary in different emission algorithms

GFED4s

Specie	Savanna	Boreal forest	Temperate forest	Tropical forest	Peat	Agriculture
CO_2	1686	1489	1647	1643	1703	1585
CO	63	127	88	93	210	102
CH_4	1.94	5.96	3.36	5.07	20.8	5.82
NMHC	3.4	8.4	8.4	1.7	1.7	9.9
H_2	1.7	2.03	2.03	3.36	3.36	2.59
NO_x (as NO)	3.90	0.90	1.92	2.55	1.00	3.11
N_2O	0.20	0.41	0.16	0.20	0.20	0.10
PM2.5	7.2	15.3	12.9	9.1	9.1	6.3

6 biome types

van der Werf et al., 2017.

FLAMBE

Reid et al., 2010

Light Grasses/tundra
Grasslands/Savannah
Cerrado/Woody Shrub
Crops
Temperate/Boreal-Low
Temperate-High
Tropical Forest
Wetland
Boundary regions

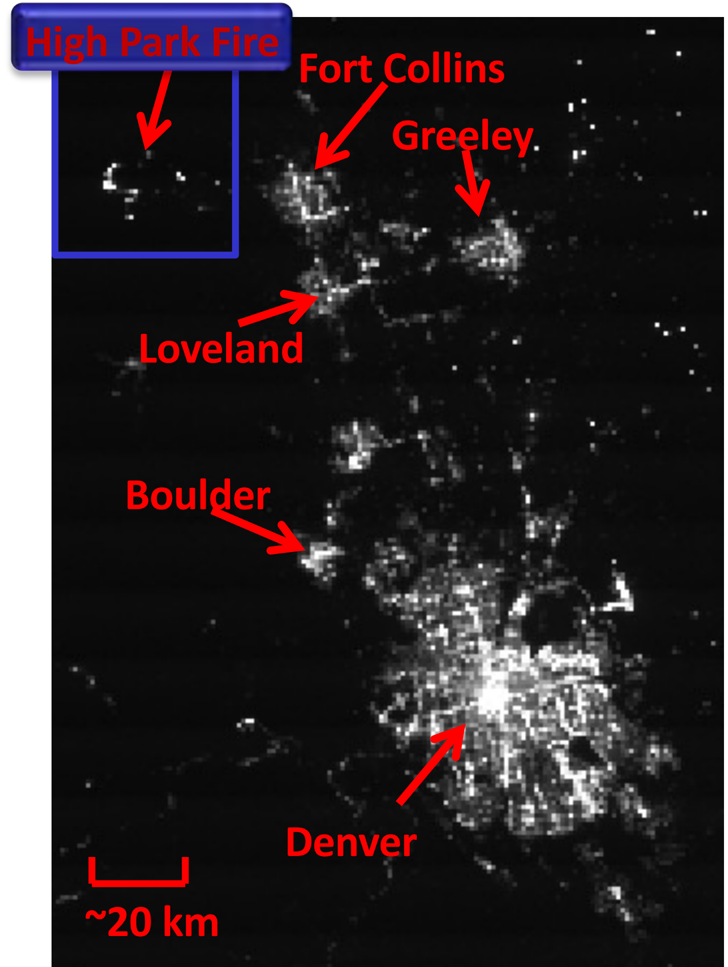
9 biome types

Smoldering, Flaming, and Light

Flaming, visible **Smoldering, no visible radiation**

- If the combustion happens heterogeneously at the surface of solid fuels (vegetation and wood), the combustion is smoldering producing incomplete-oxidized products
- If oxidation happens homogeneously between oxygen in the air and the gas pyrolysate, combustion products are soot and complete-oxidized gases. These products absorb enough energy during the combustion process leading them to emit visible radiation as a flame (Rein 2009; Sato et al. 1969).
- While fire emits radiation at all wavelengths, it is the visible intensity that indicates the strength of flaming.

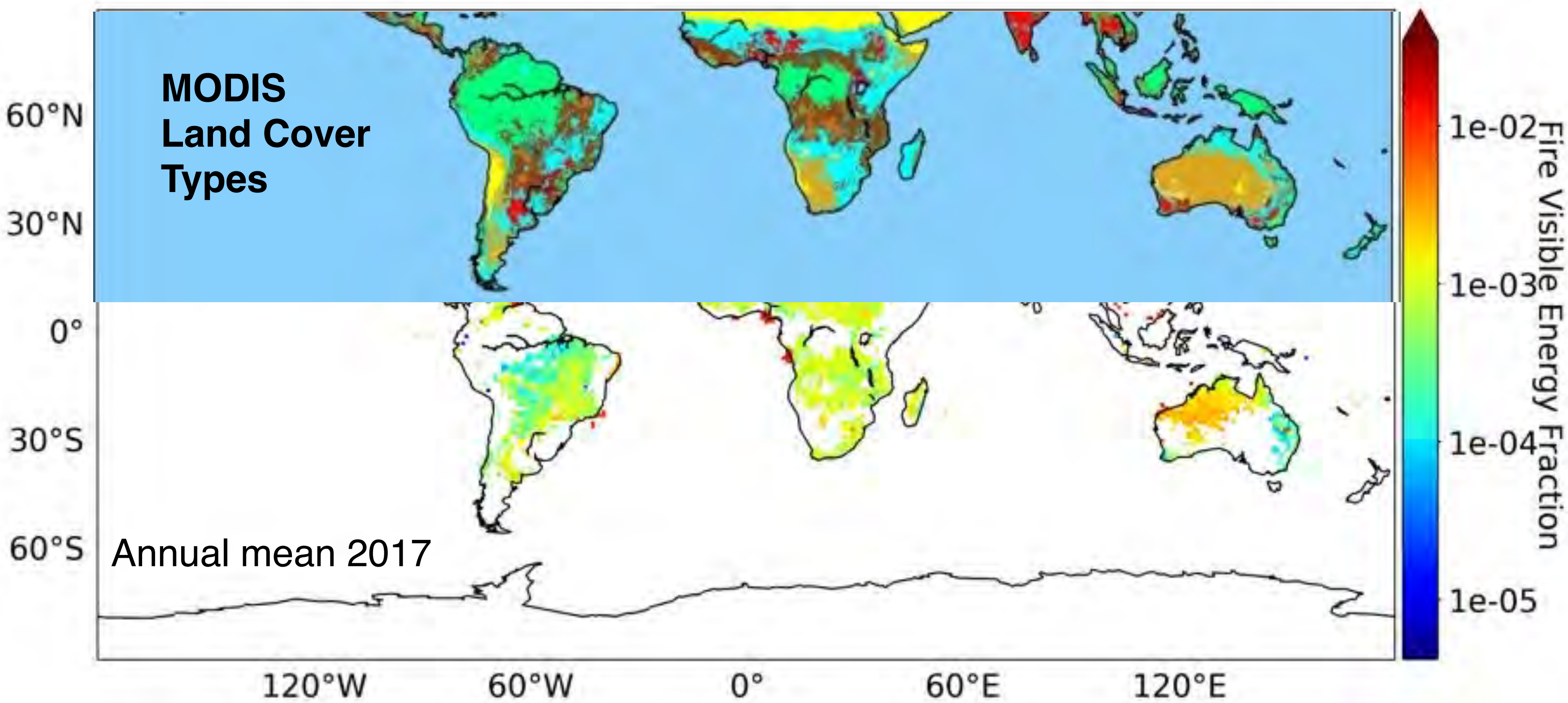
Fire Light seen by VIIRS



12 June 2012

Insights for Fire MCE Climatology as revealed by Visible Energy Fraction (VEF)

$$VEF = \frac{VLP \times \Delta t}{FRP \times \Delta t} = \frac{VLP}{FRP}$$

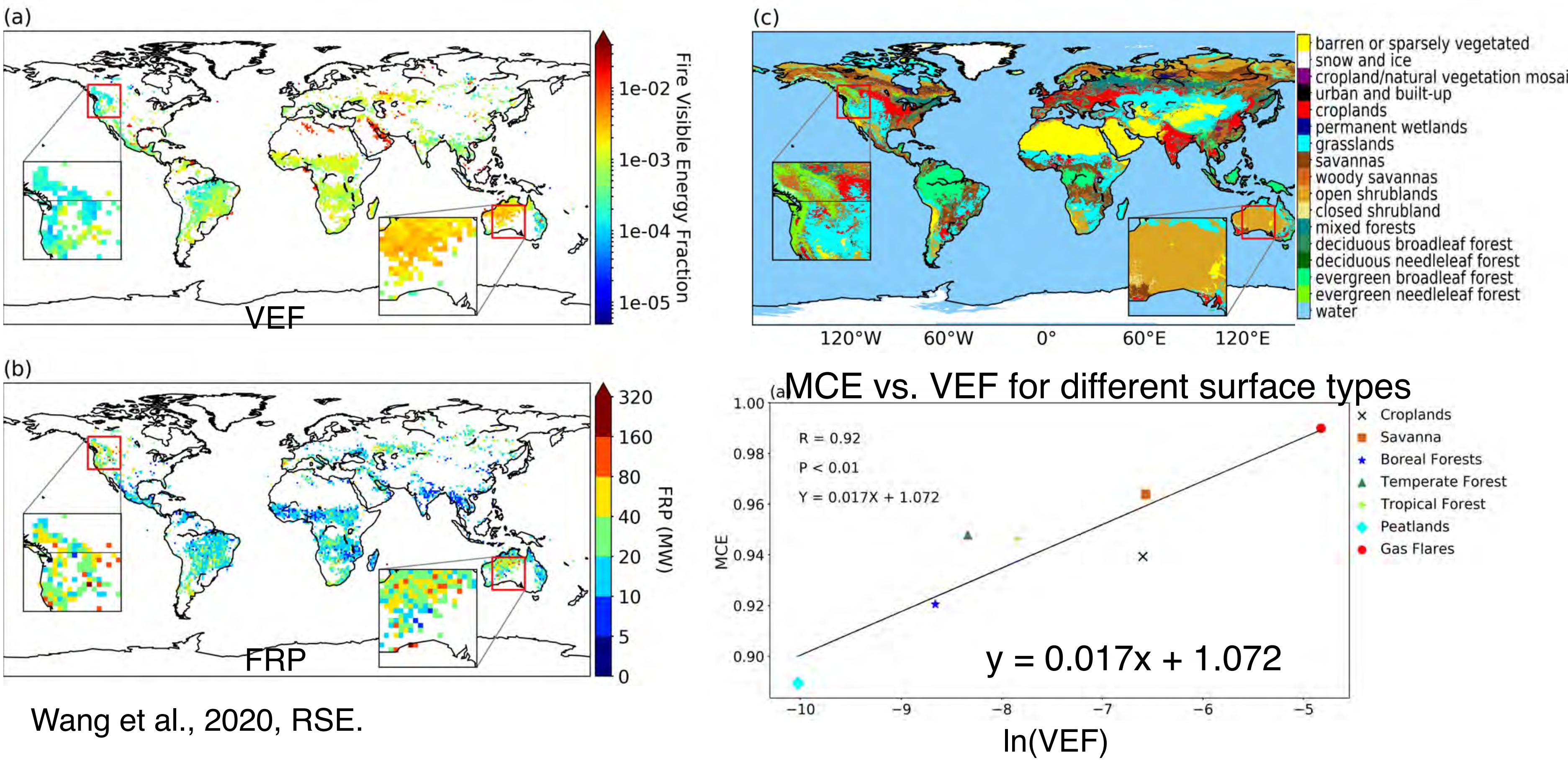


Our research algorithm: Firelight Detection Algorithm (FILDA)

Wang et al., 2020
Rem.. Sen. Environ.

VEF is indicative of MCE

- VEF spatial distribution clearly shows the impact of biome types on fire MCE
- FRP has difficulty to describe MCE variation, such as shrubland vs. evergreen forests

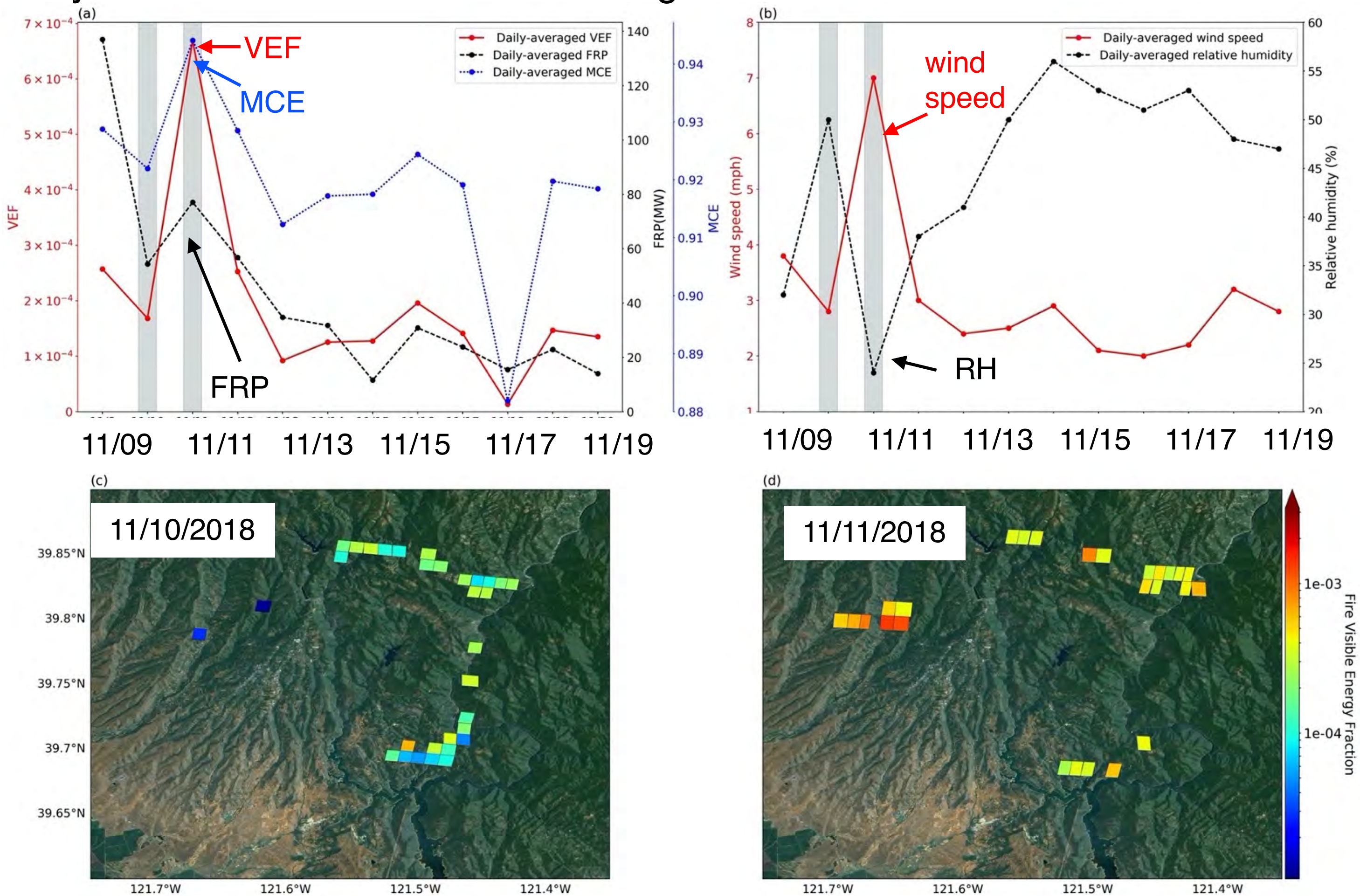


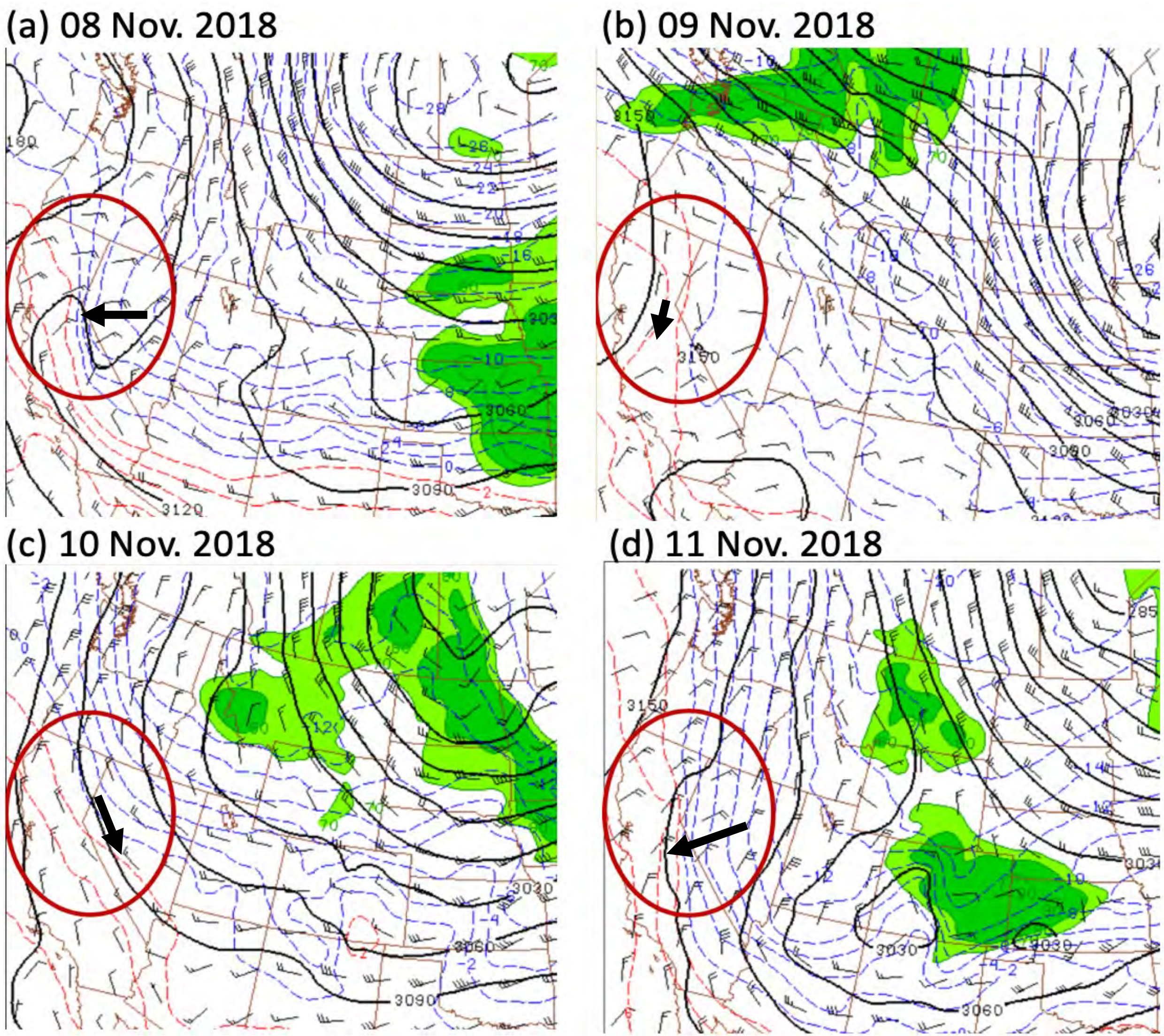
Wang et al., 2020, RSE.

VEF & MCE variations show meteorological impact on combustion

High & dry winds lead to increase of flaming on 11 Nov. 2018.

Camp Fire





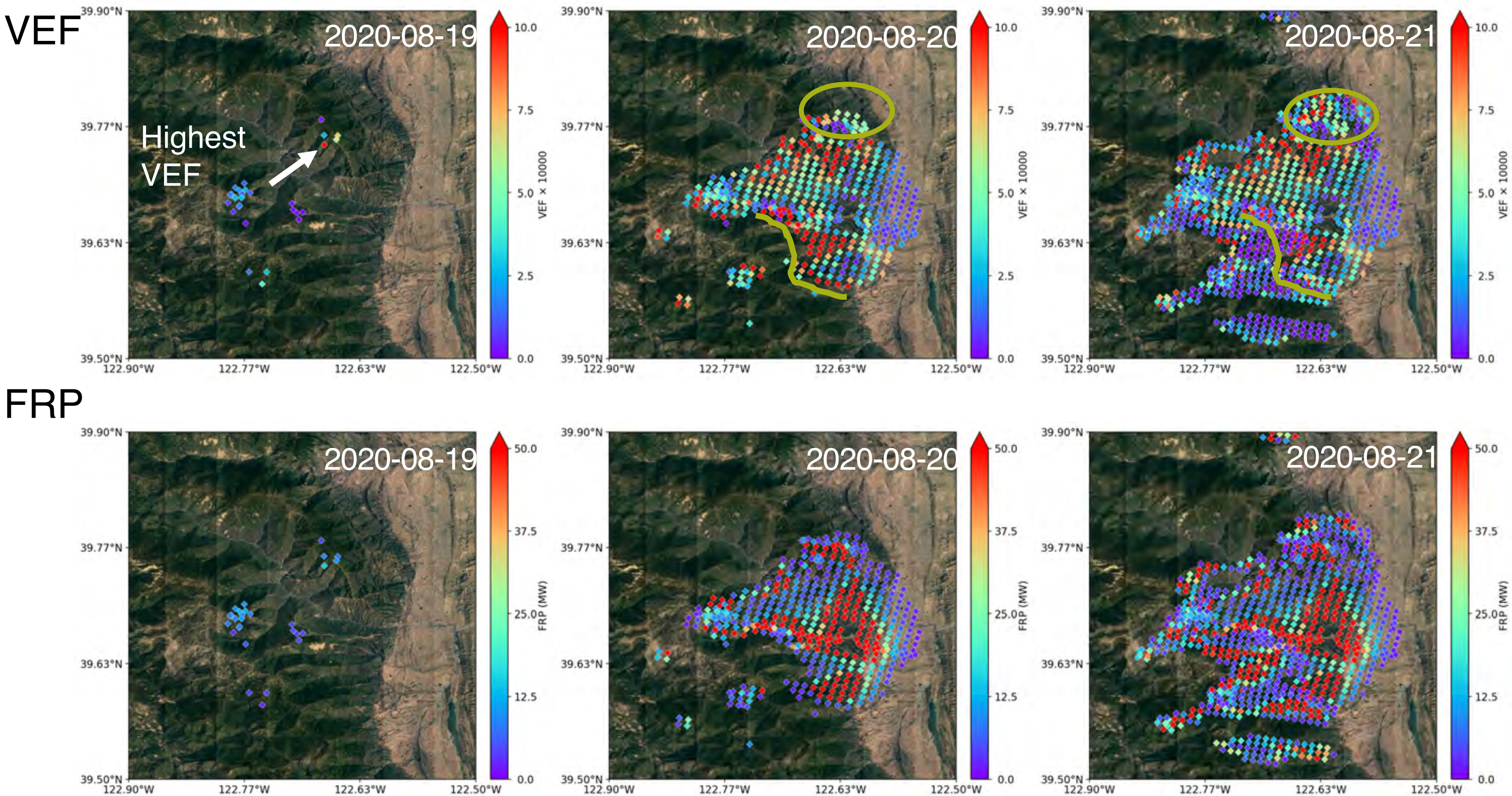
Synoptic map at 700 mb.

10 am local each day

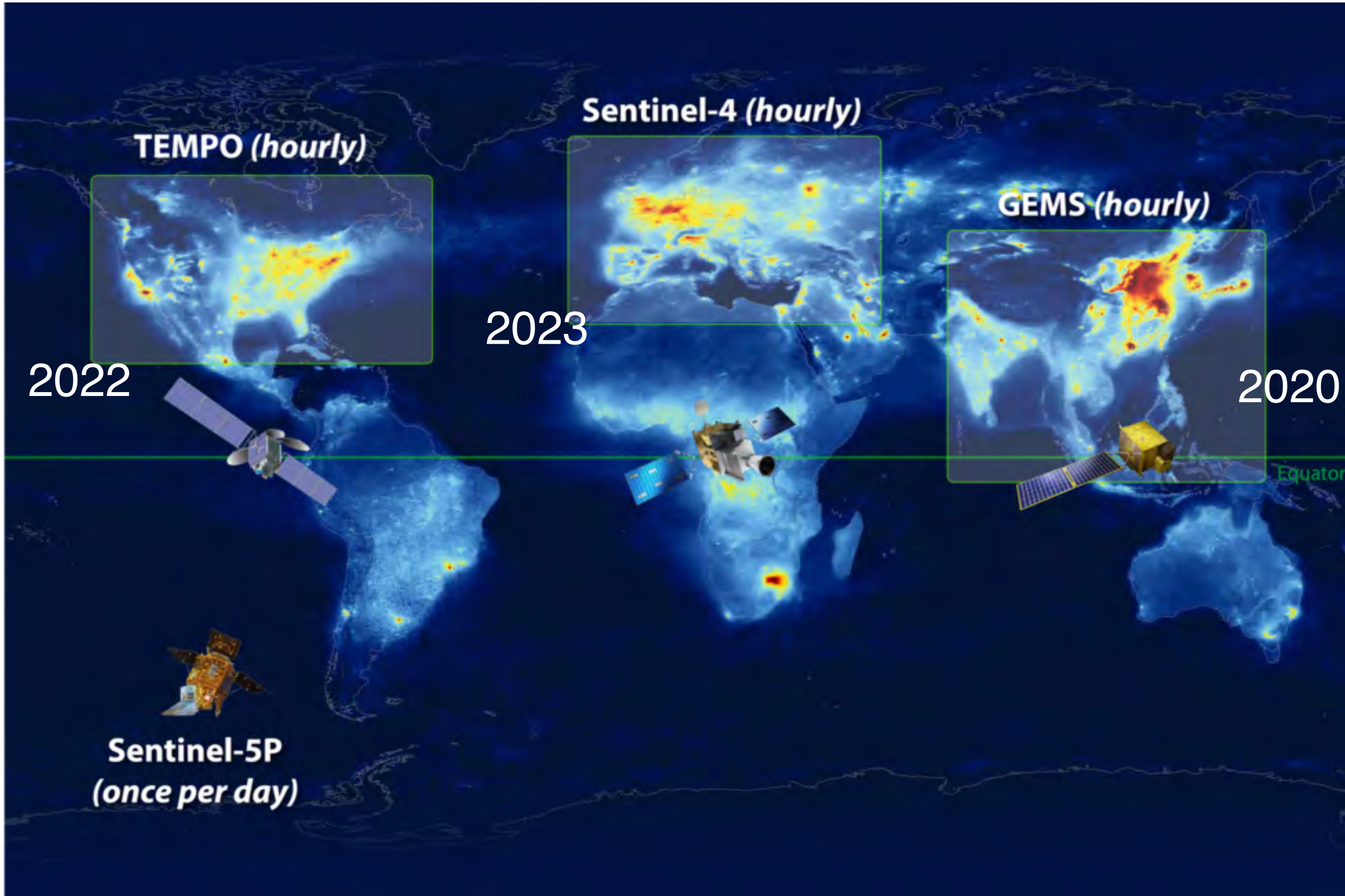
Diablo Winds

VEF has a potential to better predict fire growth

High VEF -> flaming → predicting movement of fire lines



GEO constellation mapping AQ in the coming decade



All the three future GEO satellite will provide hourly retrievals of SO_2 and NO_2.

Geostationary and Extended Orbits (GEO-XO)

https://www.nesdis.noaa.gov/GEO-XO

Now in formulation

Summary

- Satellite data can provide timely insights on the change of emissions from different sources and in some cases, reveal process-level of understanding of emissions.
- Top-down method offers unique opportunity to improve the regional AQ forecast via data assimilation (with timely update of emissions, e.g., 4D-VAR).
- In U.S., as anthropogenic emissions decrease, the background emissions (including those from agricultural activities, soils, and fires) are increasingly important for the air quality prediction.
- Climate predictions and mitigation of climate change requires accurate knowledge of the emissions from different sectors. Future use of TEMPO, GEMS, and others multi-sensor data toward rapid update of emissions for improving urban scale air quality forecast and mitigation of climate change all look promising!

Thank you!

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