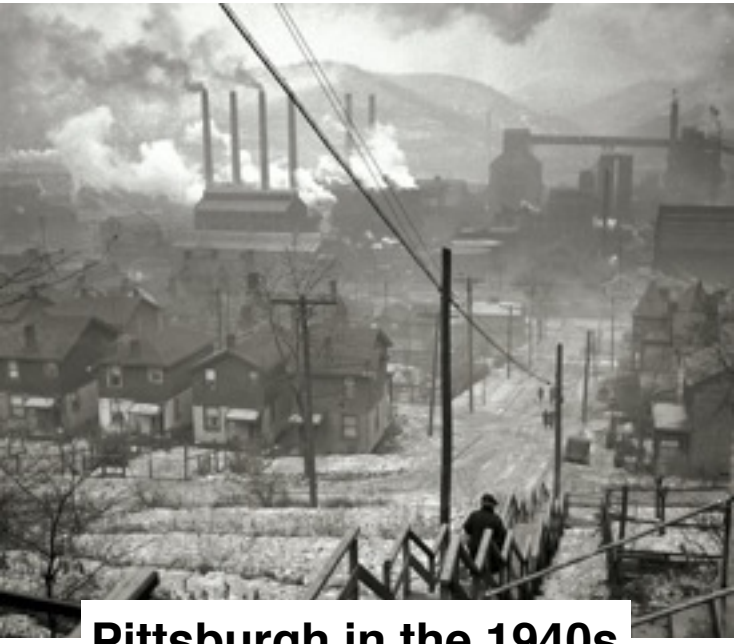
The industrial revolution and air pollution



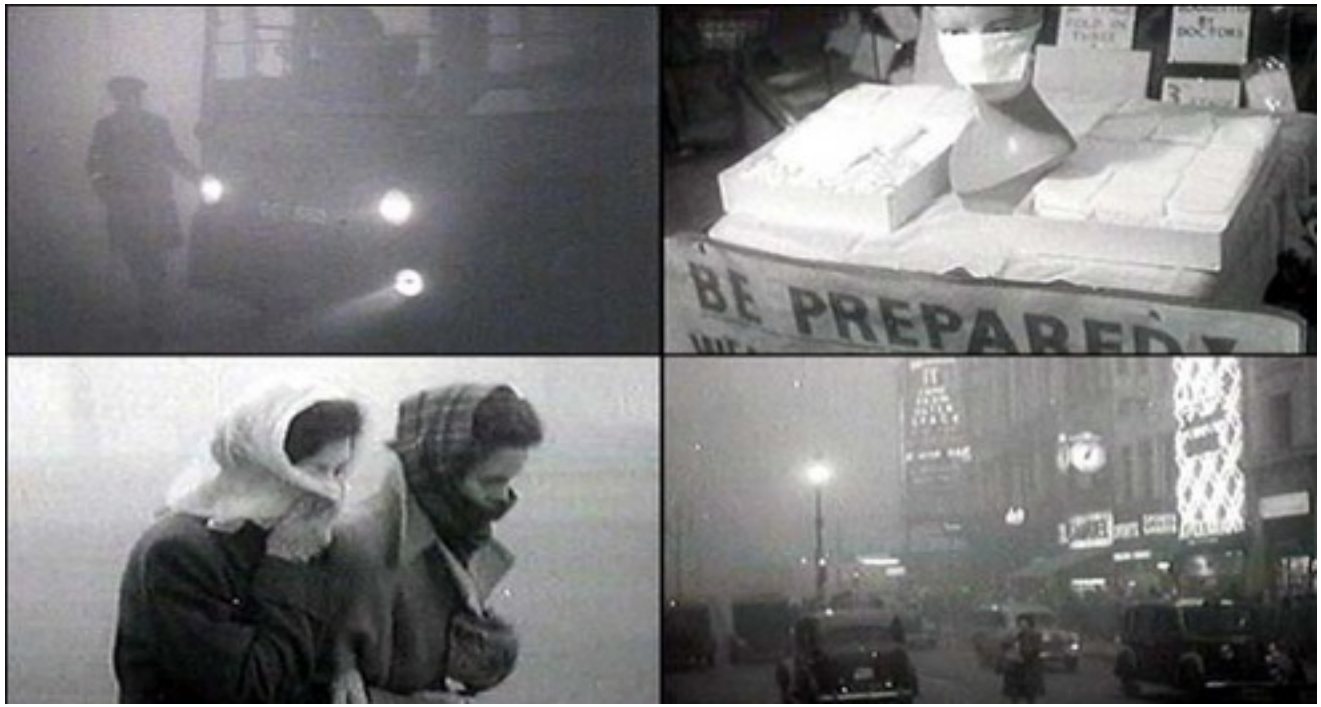
Pittsburgh in the 1940s

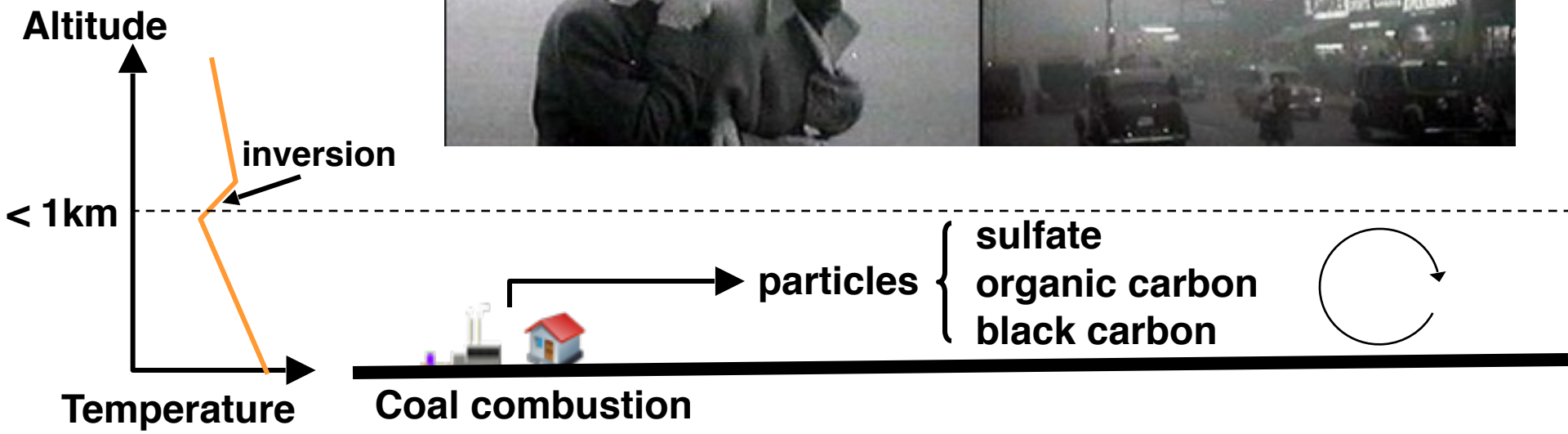
“Make great efforts to build China into a strong and prosperous industrialized country under the leadership of the Party and chairman Mao!”

LONDON FOG

Aerosols a.k.a.particulate matter (PM) from domestic+industrial coal combustion

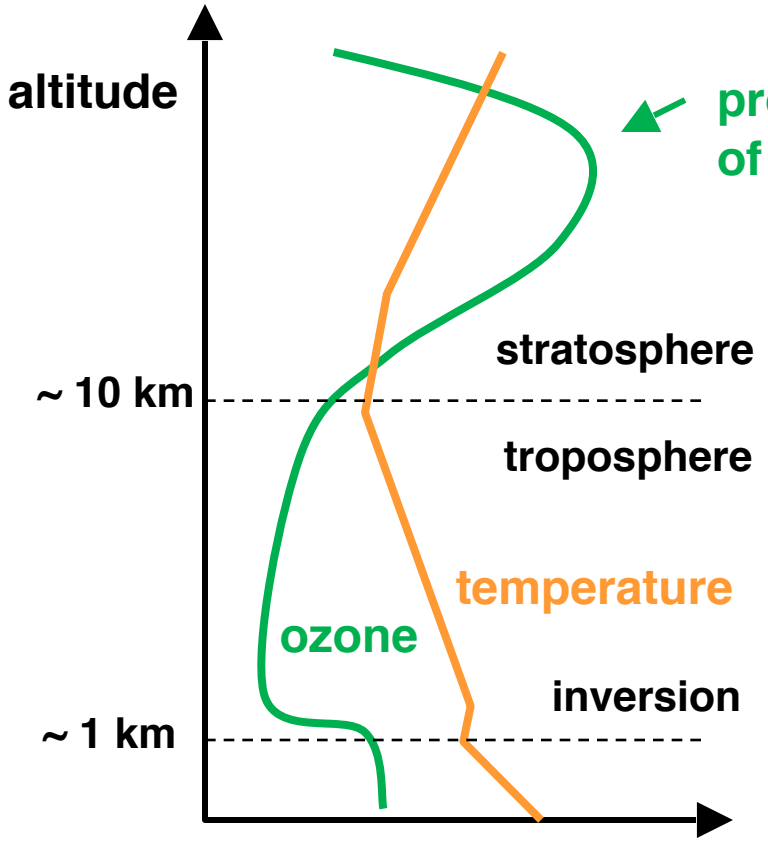
"Killer fog" of December 1952 resulted in 10,000 excess deaths



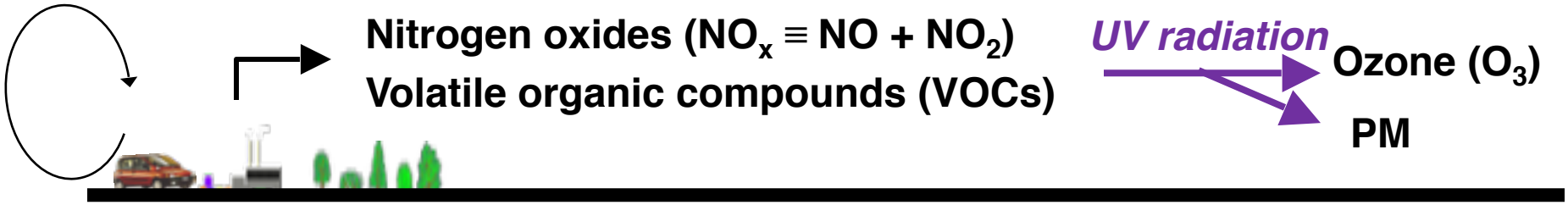


Los Angeles smog

Respiratory problems, vegetation damage due to high surface ozone



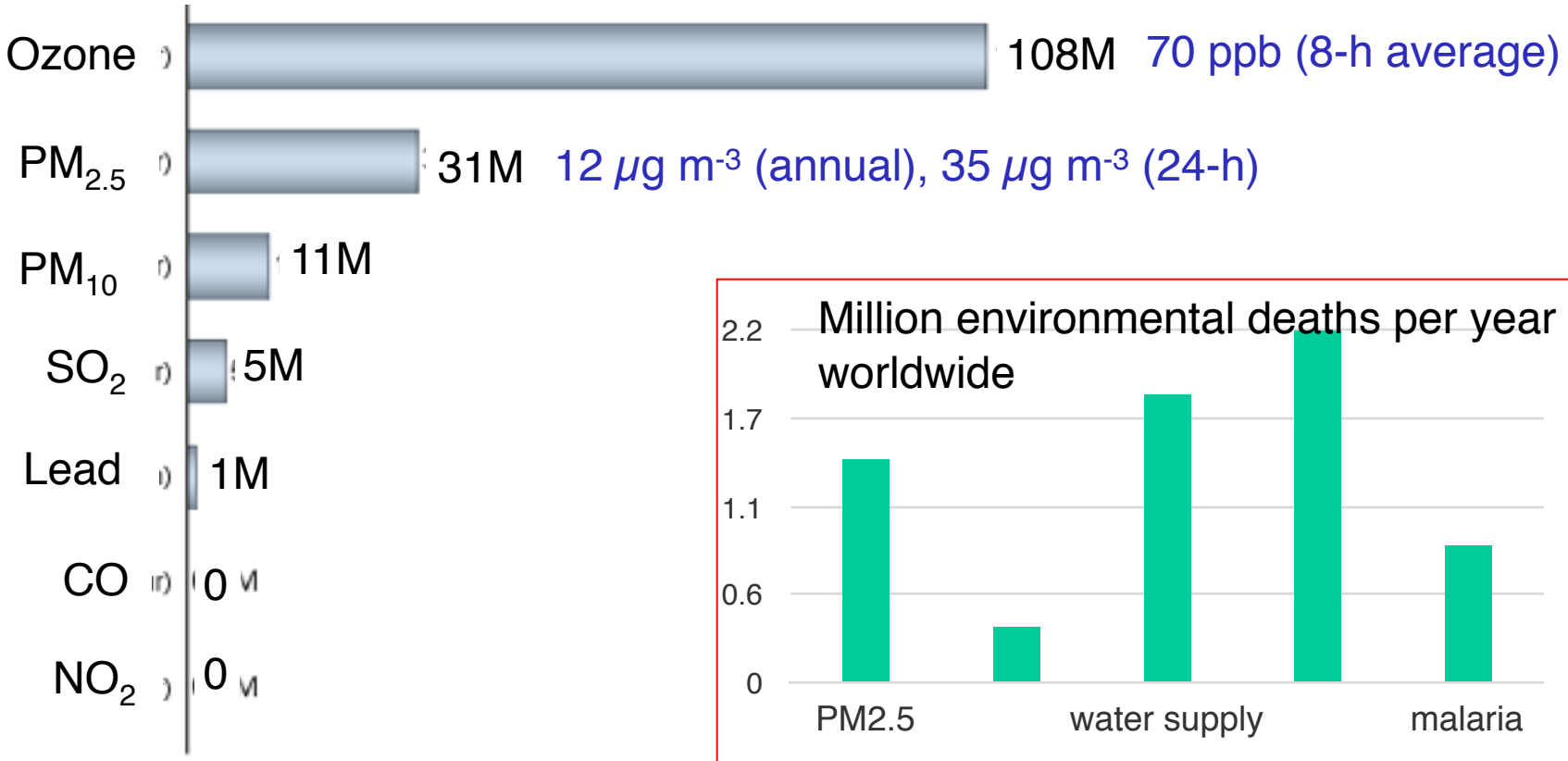
produced by photolysis of oxygen (O_2)



AIR POLLUTION TODAY:

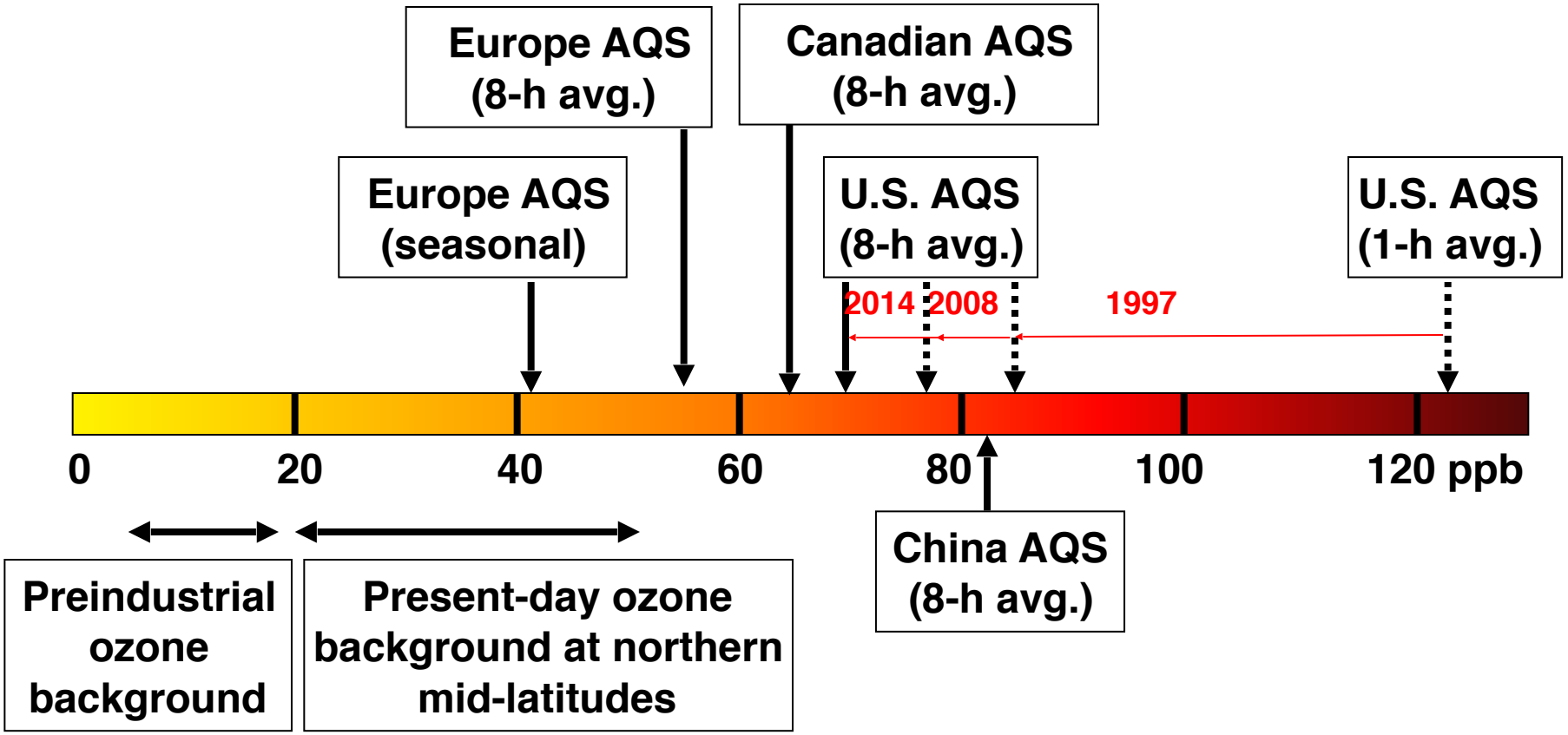
Ozone and fine particulate matter ($PM_{2.5}$) are the major pollutants

US population exposed to air pollutants
in excess of national ambient air quality standards (NAAQS), 2015

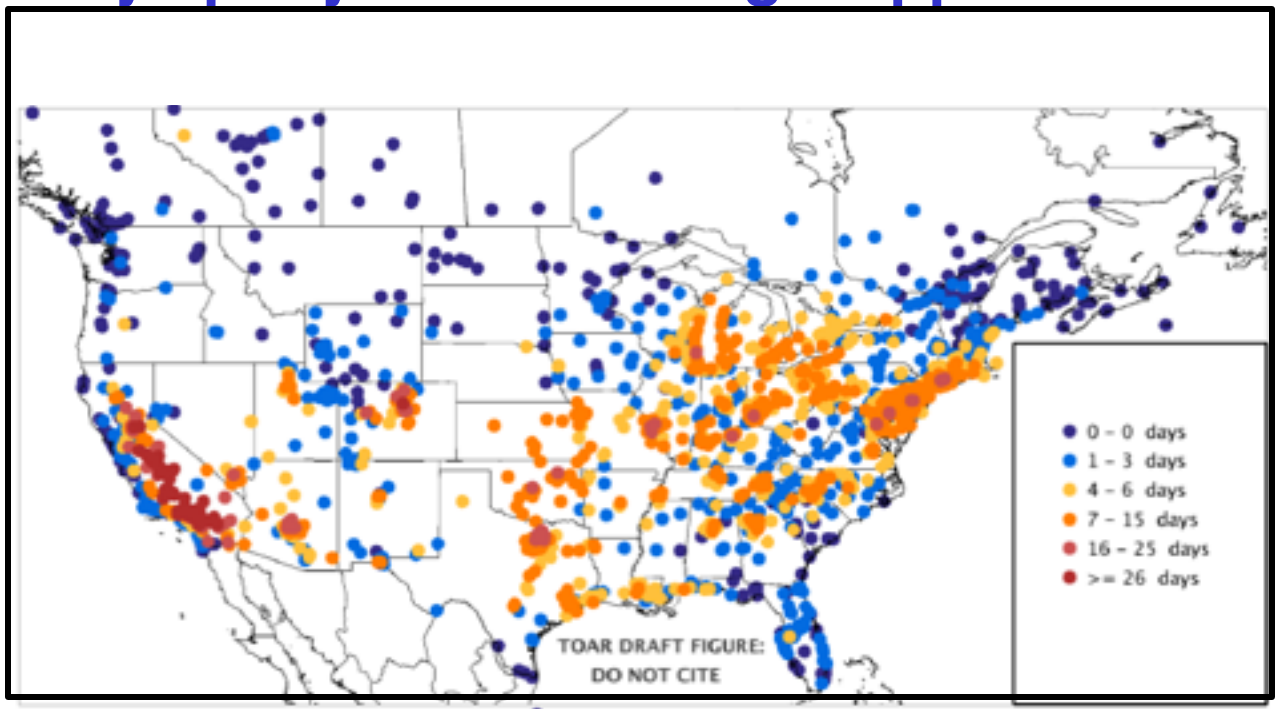


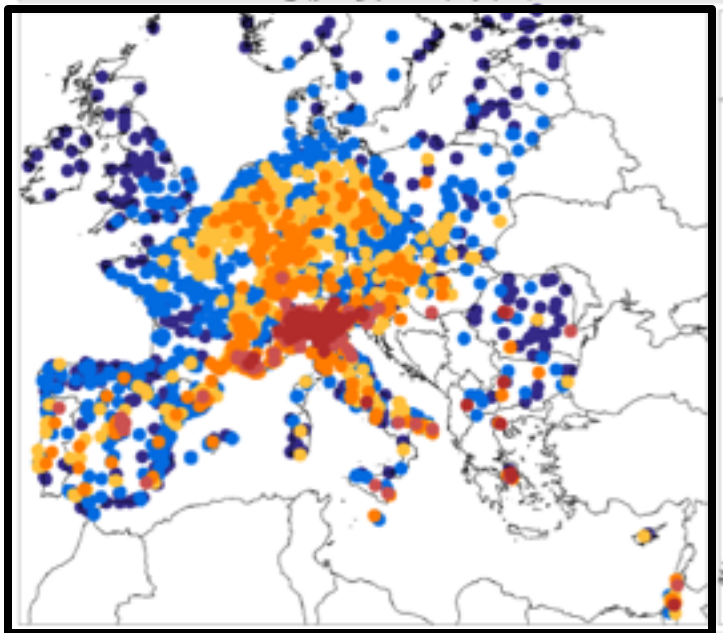
US EPA [2017], OECD [2012]

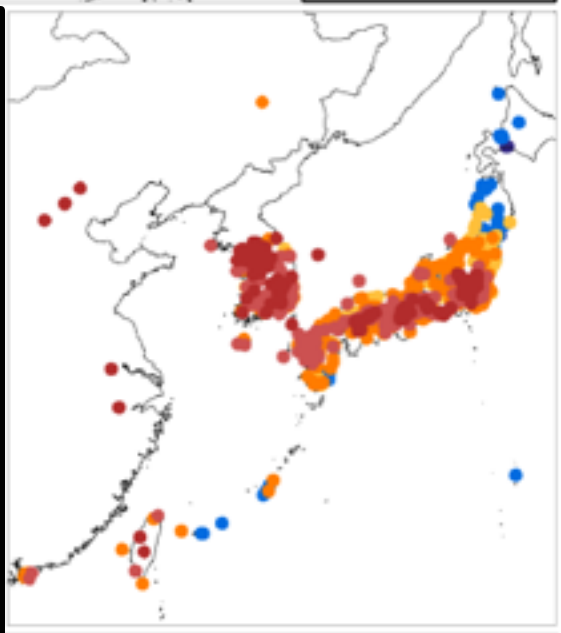
Ozone air quality standards in the US and in the world



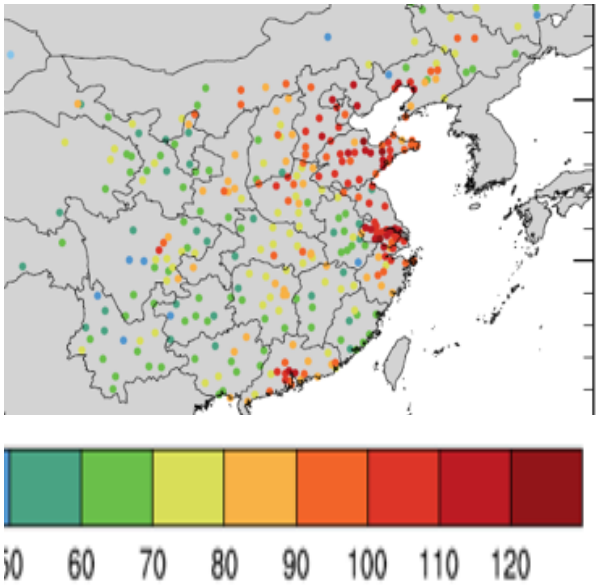
Days per year exceeding 70 ppb ozone standard, 2010-2014







4th highest MDA8 in China, 2014-2016



TOAR [2017];
Ke Li, Harvard

Questions

1. Diesel cars have a larger NO_2/NO emission ratio than gasoline cars. For a given NO_x emission amount, this makes diesel cars contribute more to ozone pollution. Why?

2. In Los Angeles in the 1980s, the proposal was seriously made that NO_x emission controls should be relaxed to fight the ozone pollution problem. Does that make any sense?

How to control ozone pollution?

Decrease emissions of nitrogen oxides ($NO_x \equiv NO + NO_2$)

and/or volatile organic compounds (VOCs)

NO_x: efficient combustion (power plants, vehicles)

VOCs: inefficient combustion (vehicles, fires), industry, vegetation

…but complicated by non-linear dependence

Ozone production mechanism:

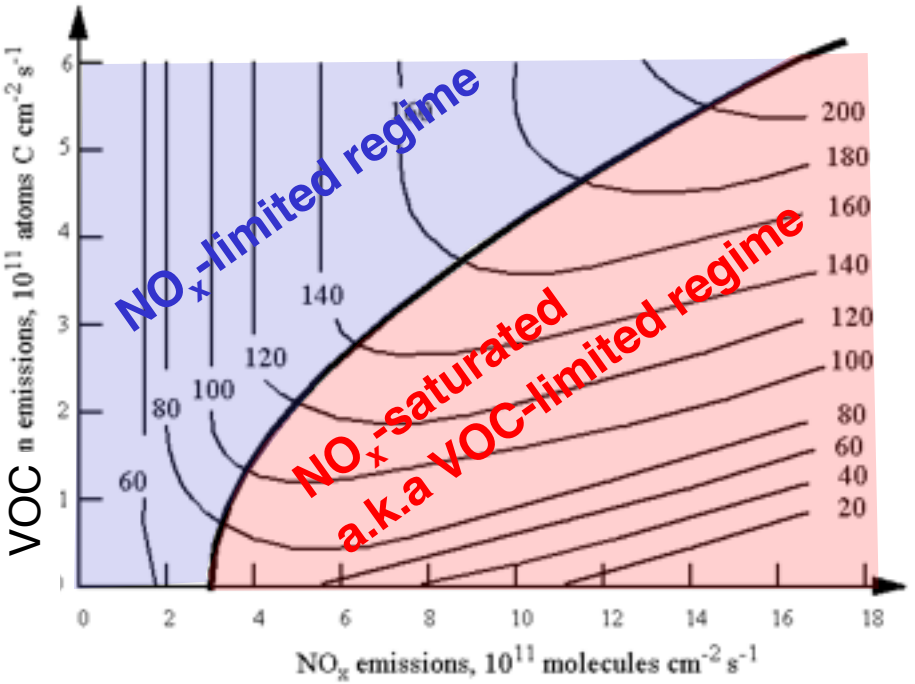
$$RH + OH \xrightarrow{O_2} RO_2 + H_2O \quad (1)$$

$$RO_2 + NO \longrightarrow RO + NO_2 \quad (2)$$

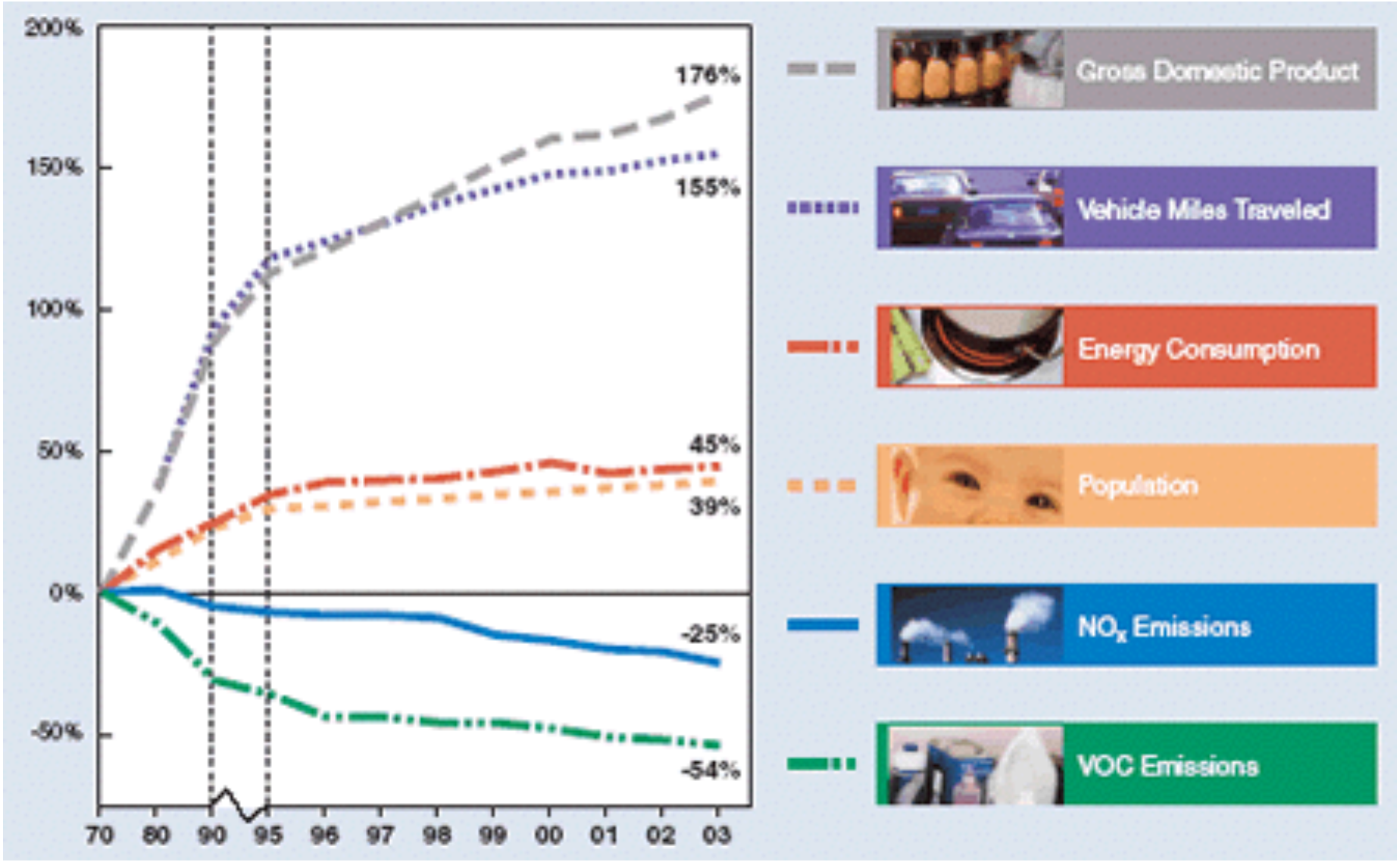
$$NO_2 + h\nu \xrightarrow{O_2} NO + O_3 \quad (3)$$

Ozone production can be limited by reaction (1) (VOC-limited regime) or reaction (2) (NO_x-limited regime)

Ozone (ppb) vs. NO_x and VOC emissions

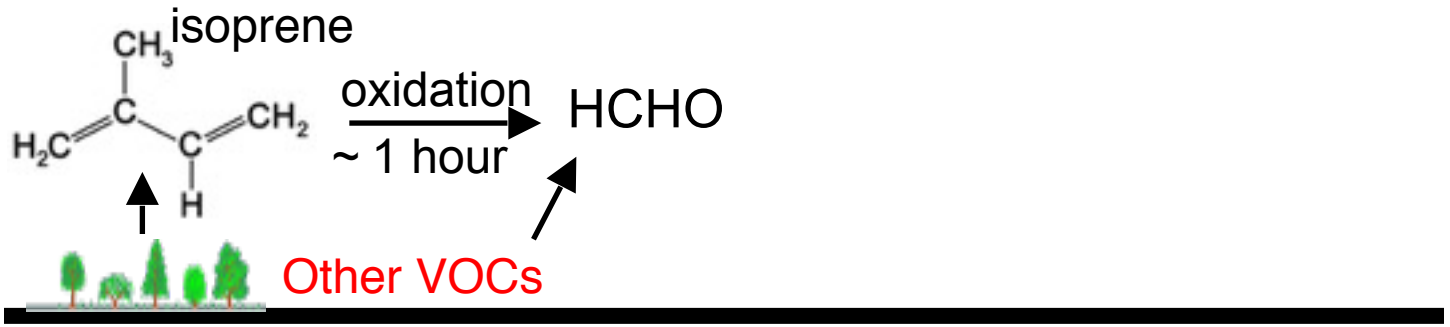


1970-2003 TREND OF U.S. EMISSIONS

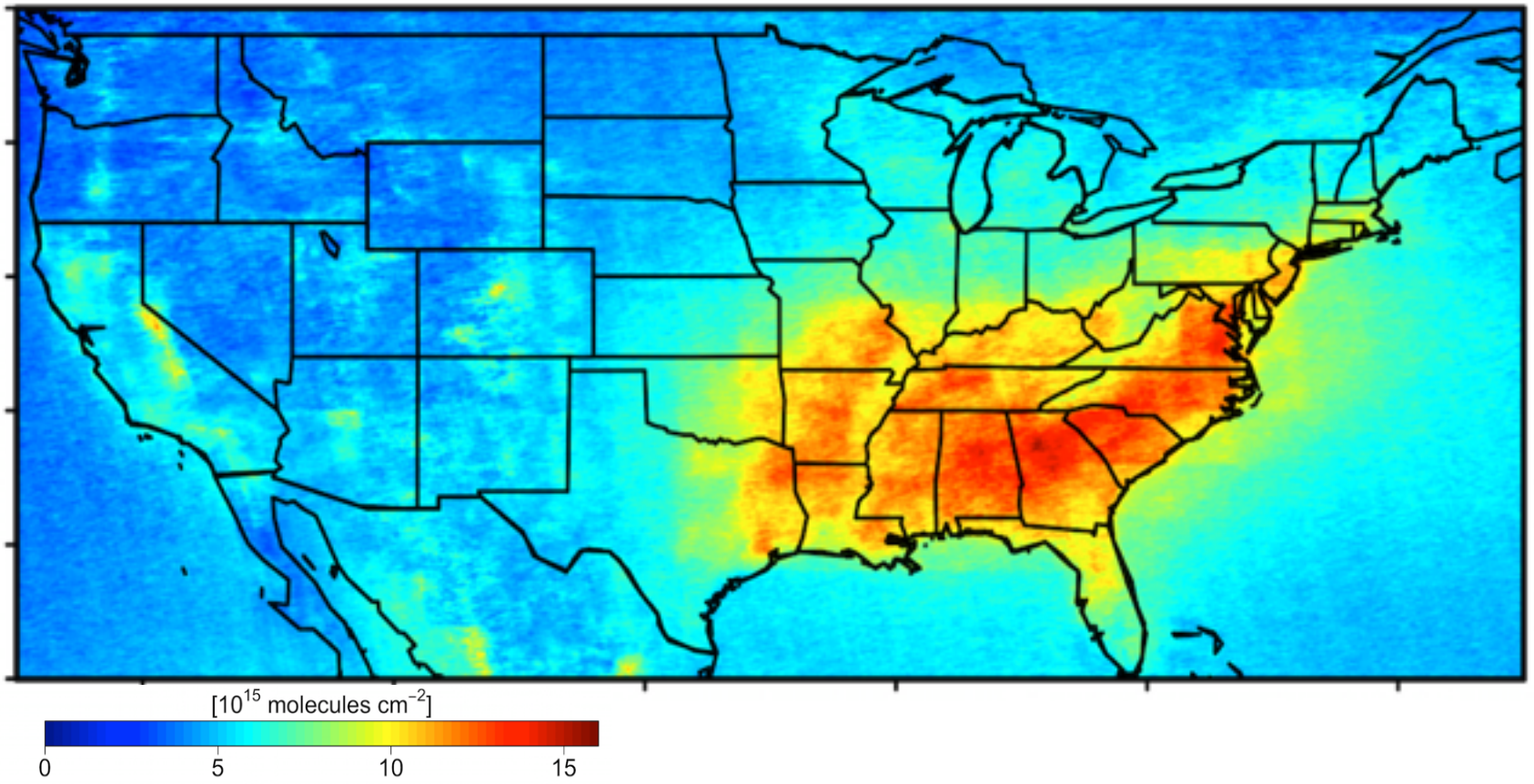


Focus until 2000s was on VOC emission controls

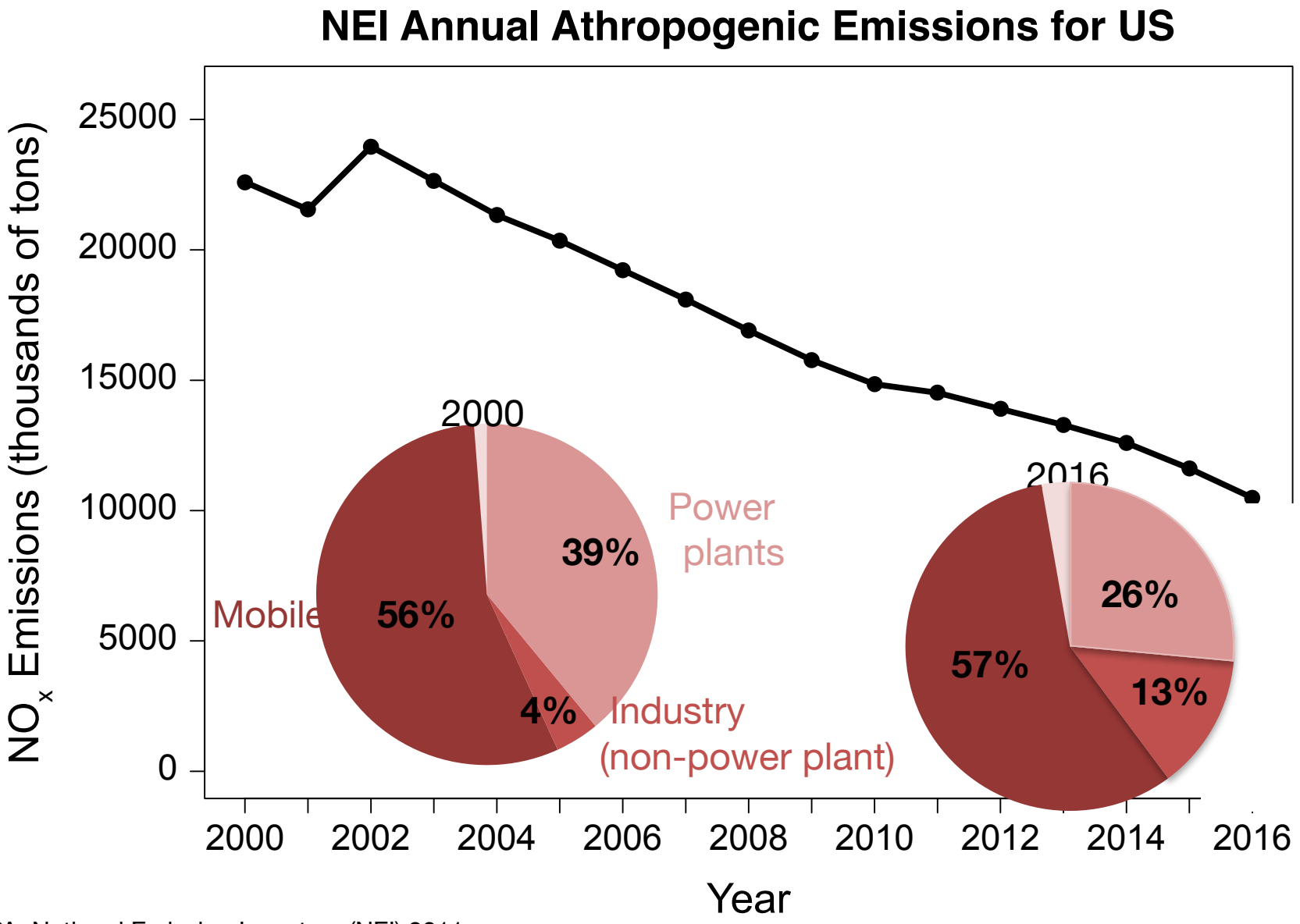
but biogenic emissions of VOCs dominate over anthropogenic



OMI satellite observations of formaldehyde (HCHO) columns, May-Aug 2005-2014



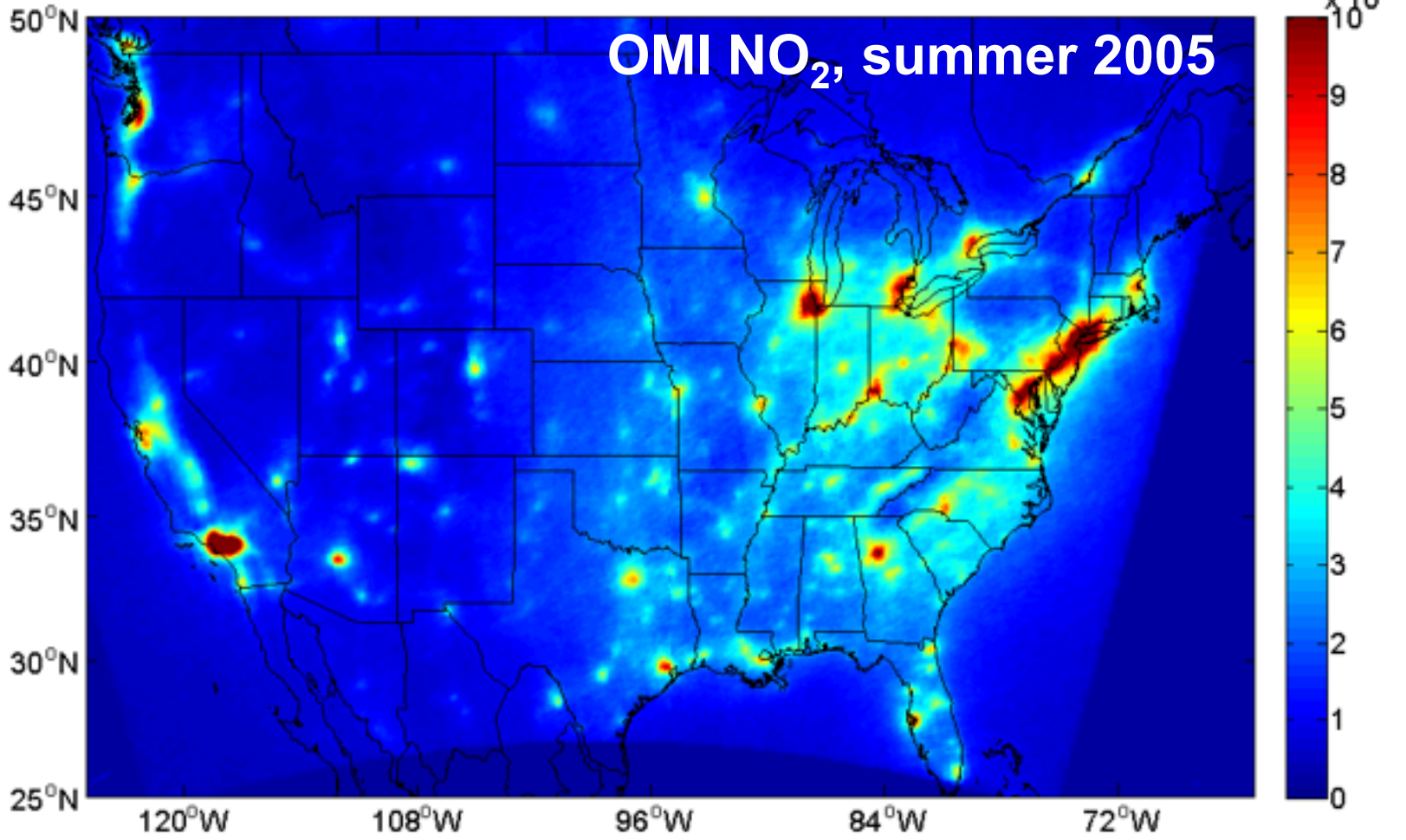
US NO_x emissions have decreased by 54% from 2000 to 2016



US EPA, National Emission Inventory (NEI) 2011

Post-2000 decline in US emissions of NO_x (≡ NO + NO_2)

as seen by OMI satellite observations of NO_2



Russell et al. [2012]

Post-2000 decline in US emissions of NO_x (≡ NO + NO_2)

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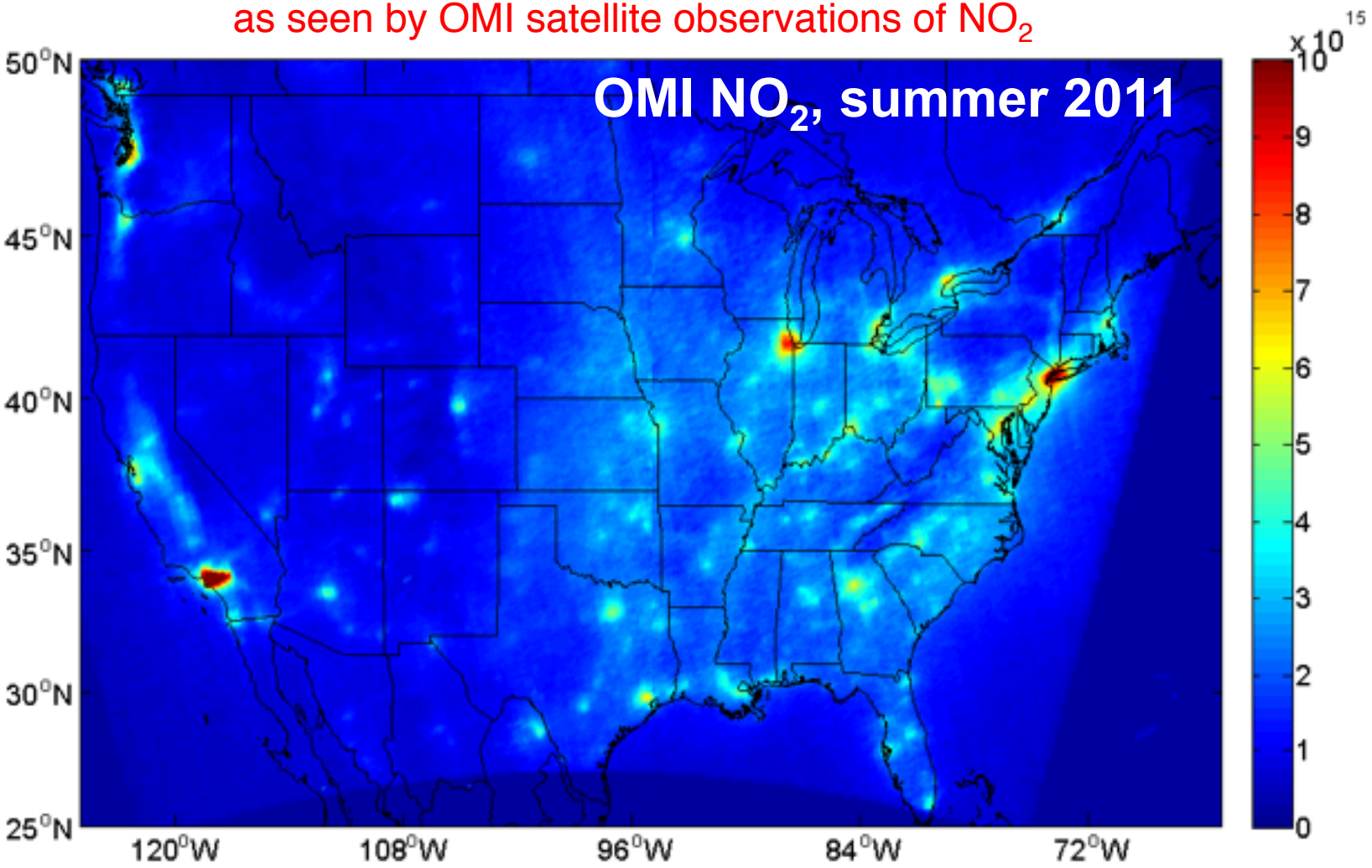
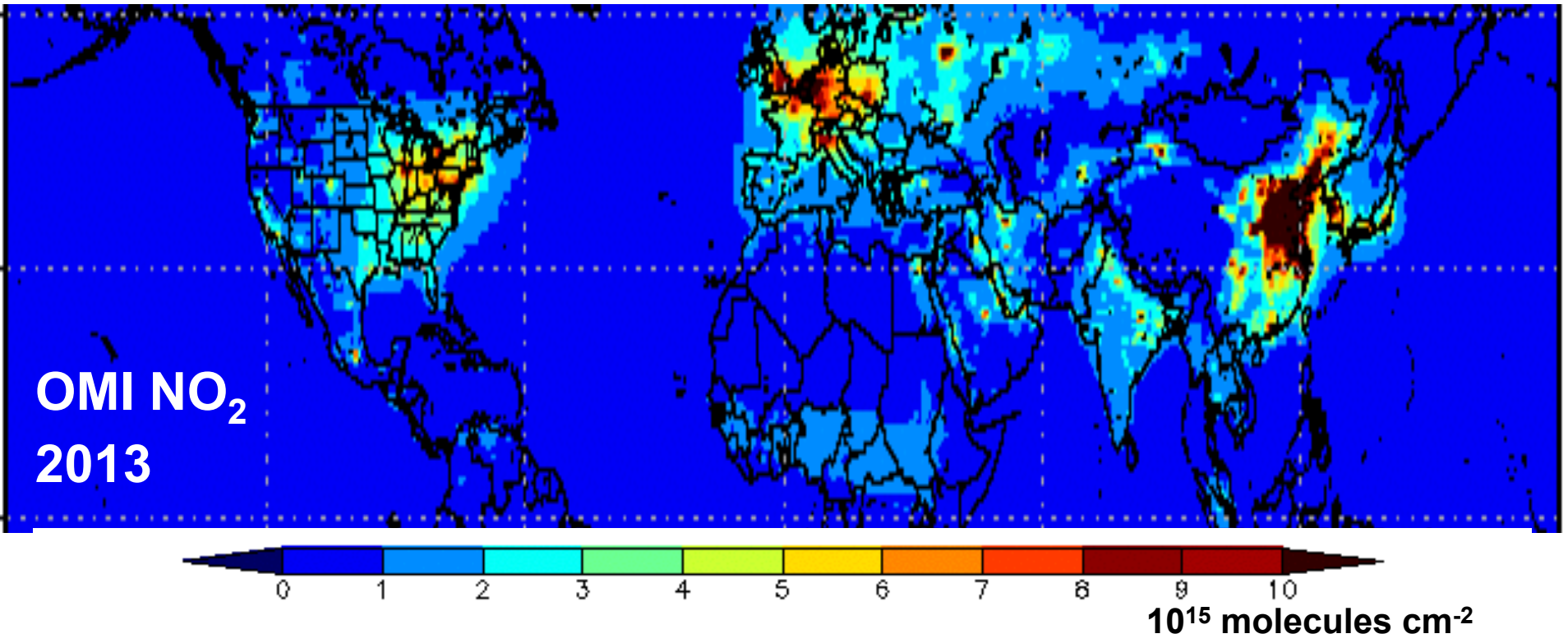


30% decrease in NO_x emissions from 2005 to 2011

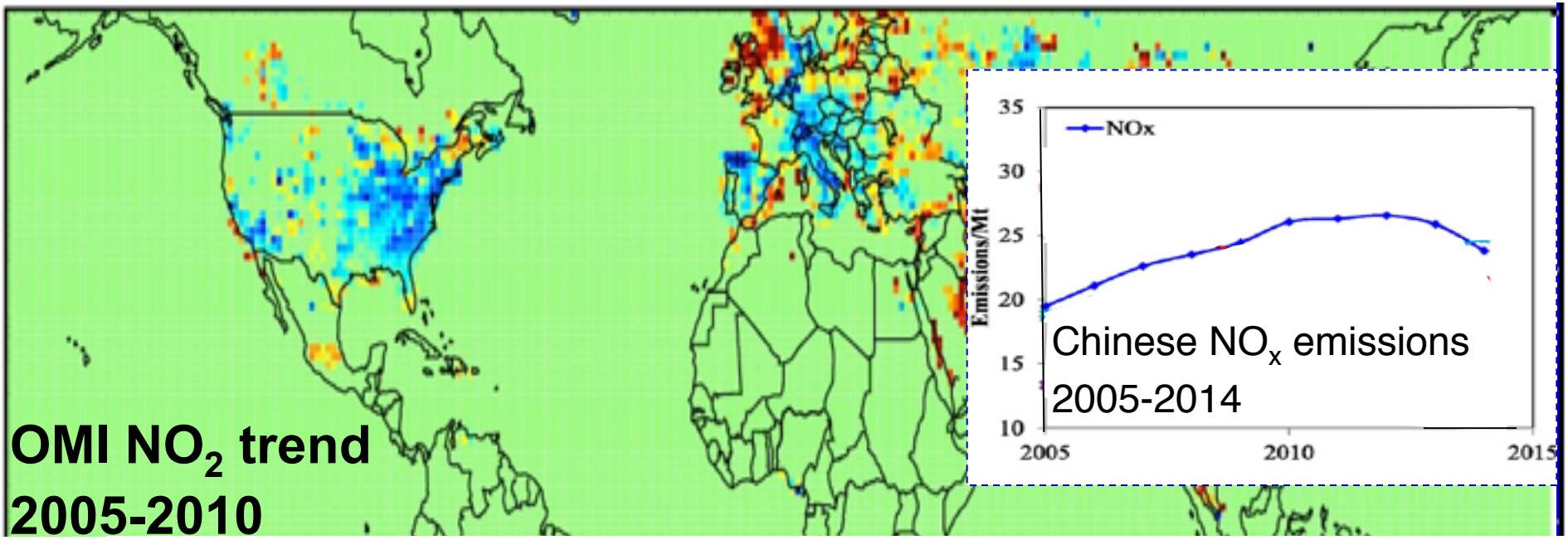
Russell et al. [2012]

NO_x emissions observed from space



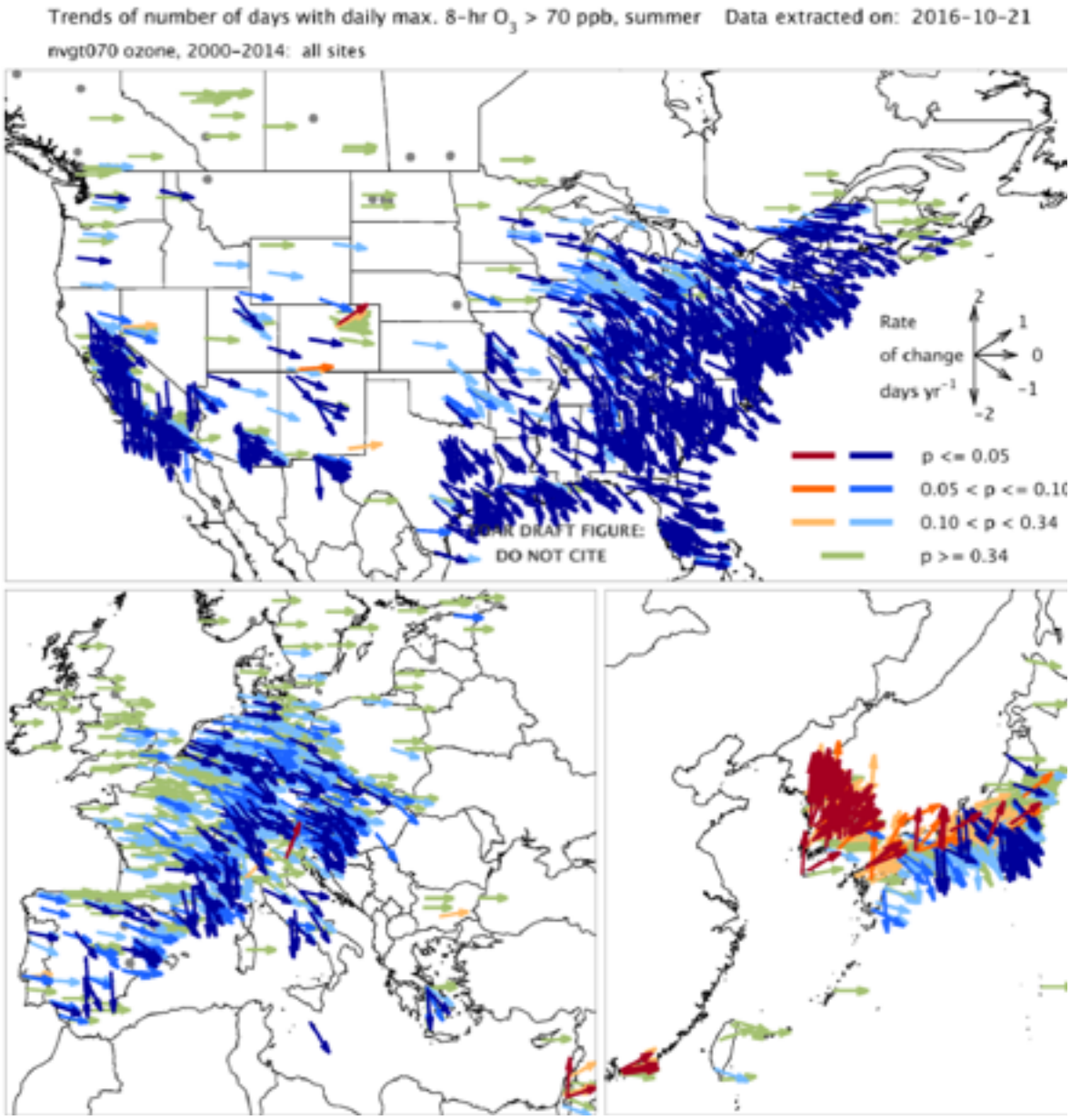
http://disc.sci.gsfc.nasa.gov/giovanni

NO_x emission trends observed from space



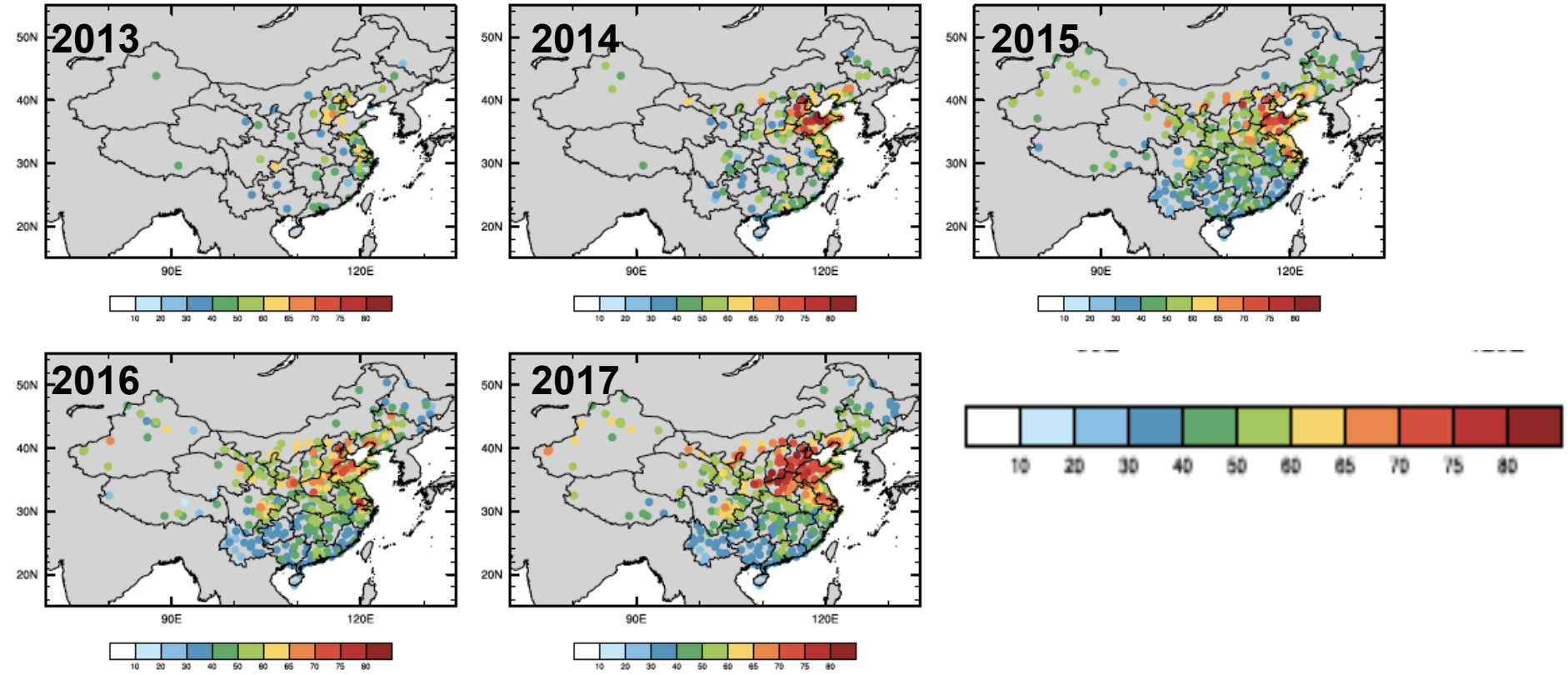
Verstraeten et al. [2014]

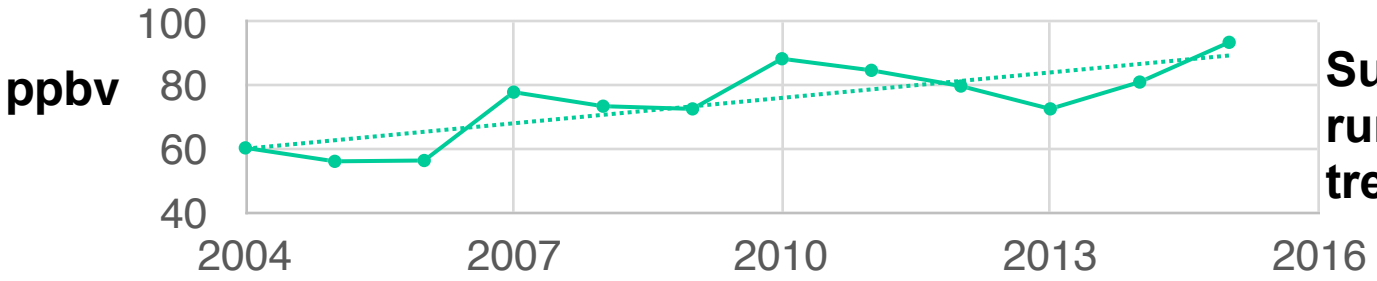
Trend in #days/year with ozone > 70 ppb, summer 2000-2014



TOAR [2017]

Surface summer ozone in China: increasing trend

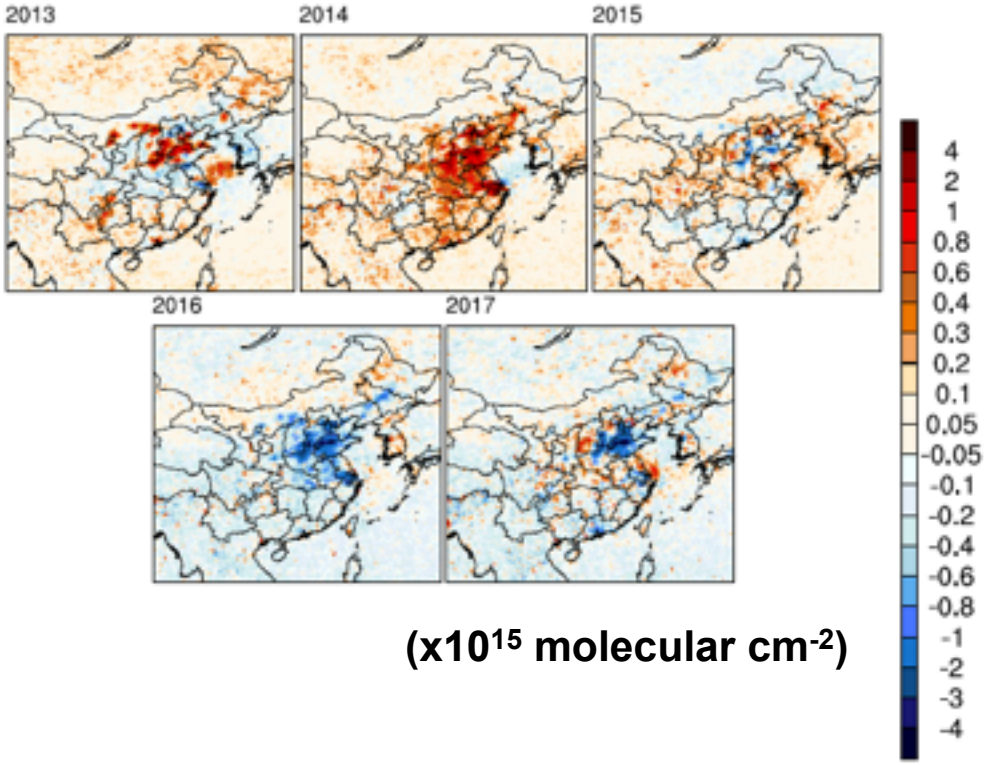




Summer MDA8 ozone at rural area of Beijing: trend= 2.67 ppbv yr^{-1}

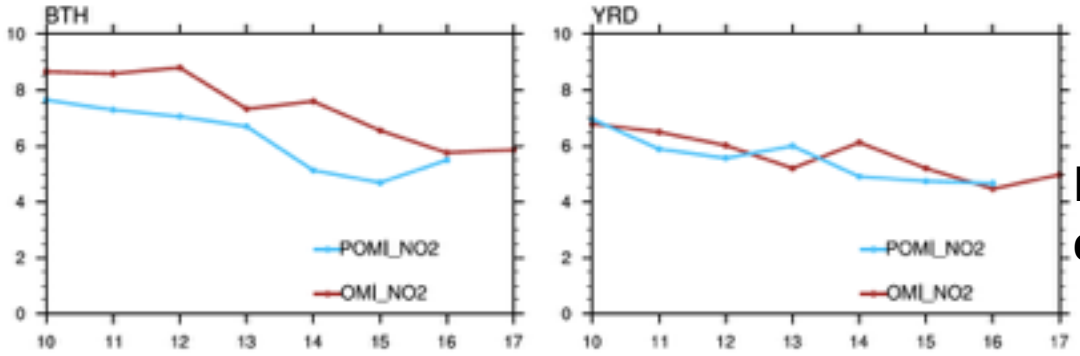
Ke Li, Harvard

OMI tropospheric NO_2 column in summer



(x10^{15} molecular cm^{-2})

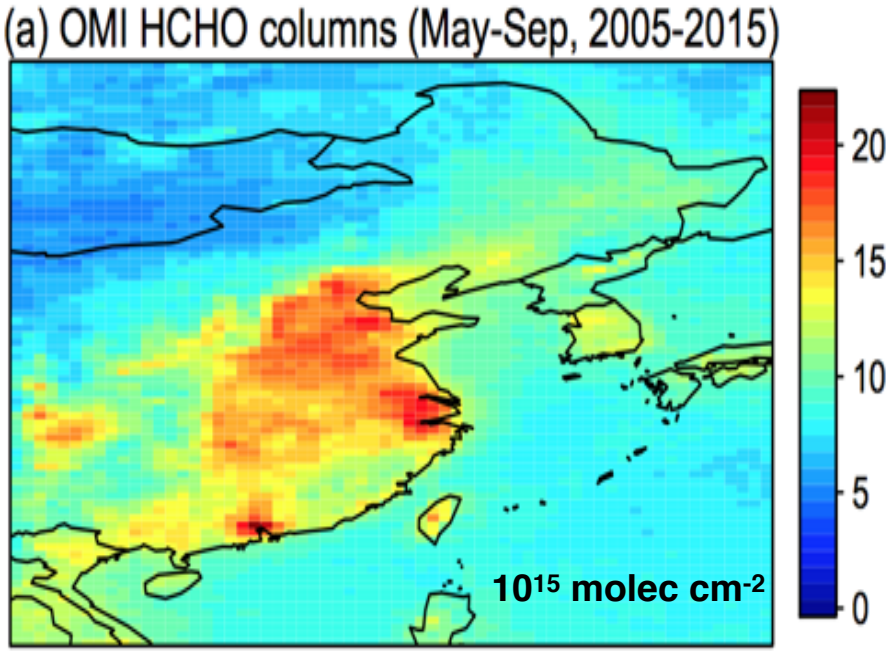
Ozone production in polluted China is in NO_x-saturated regime; decreasing NO_x causes increases in ozone

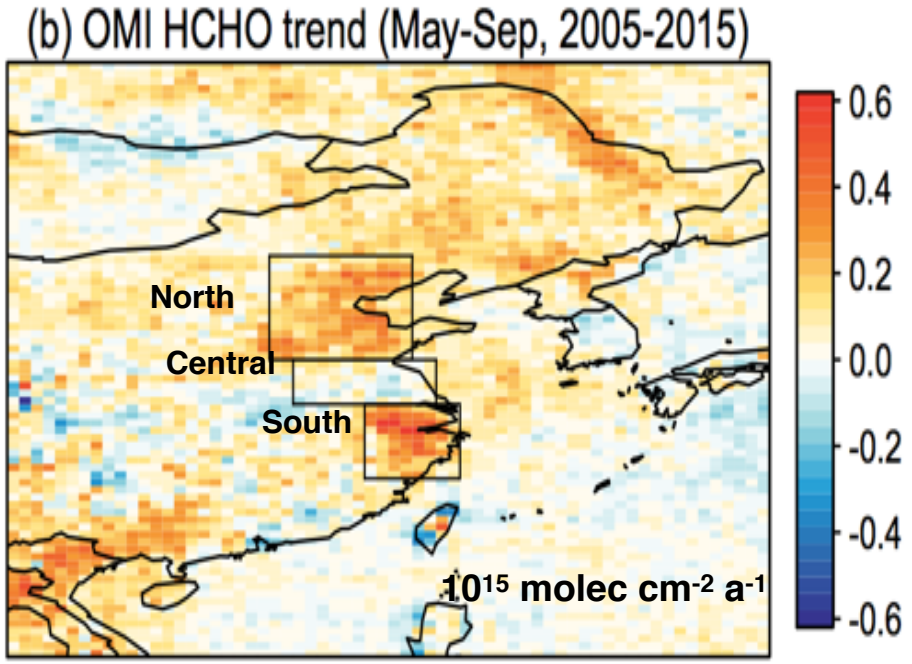


Regional averaged OMI NO2 column

Ke Li, Harvard

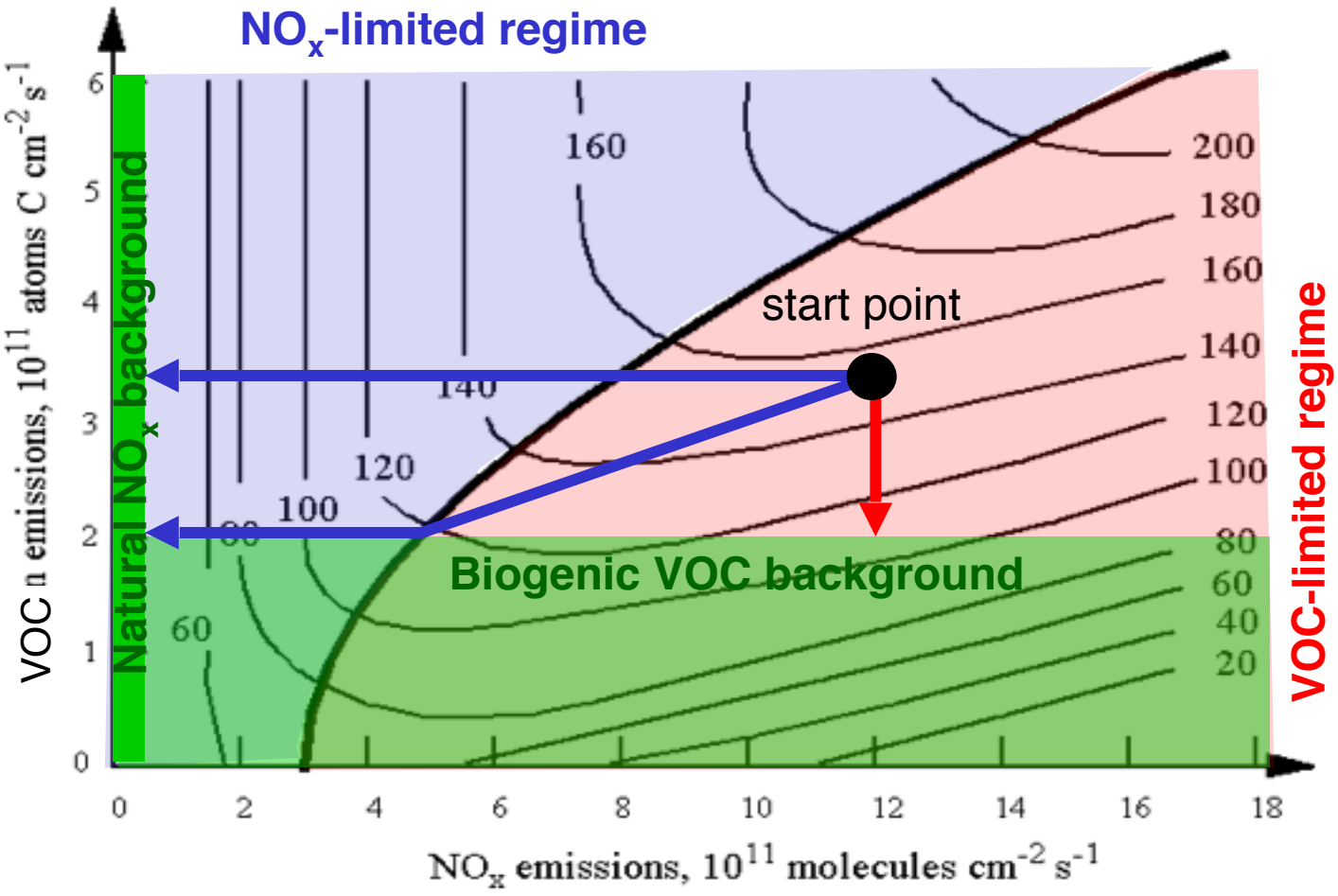
Formaldehyde from space shows increase in VOC emissions





Lu Shen, Harvard

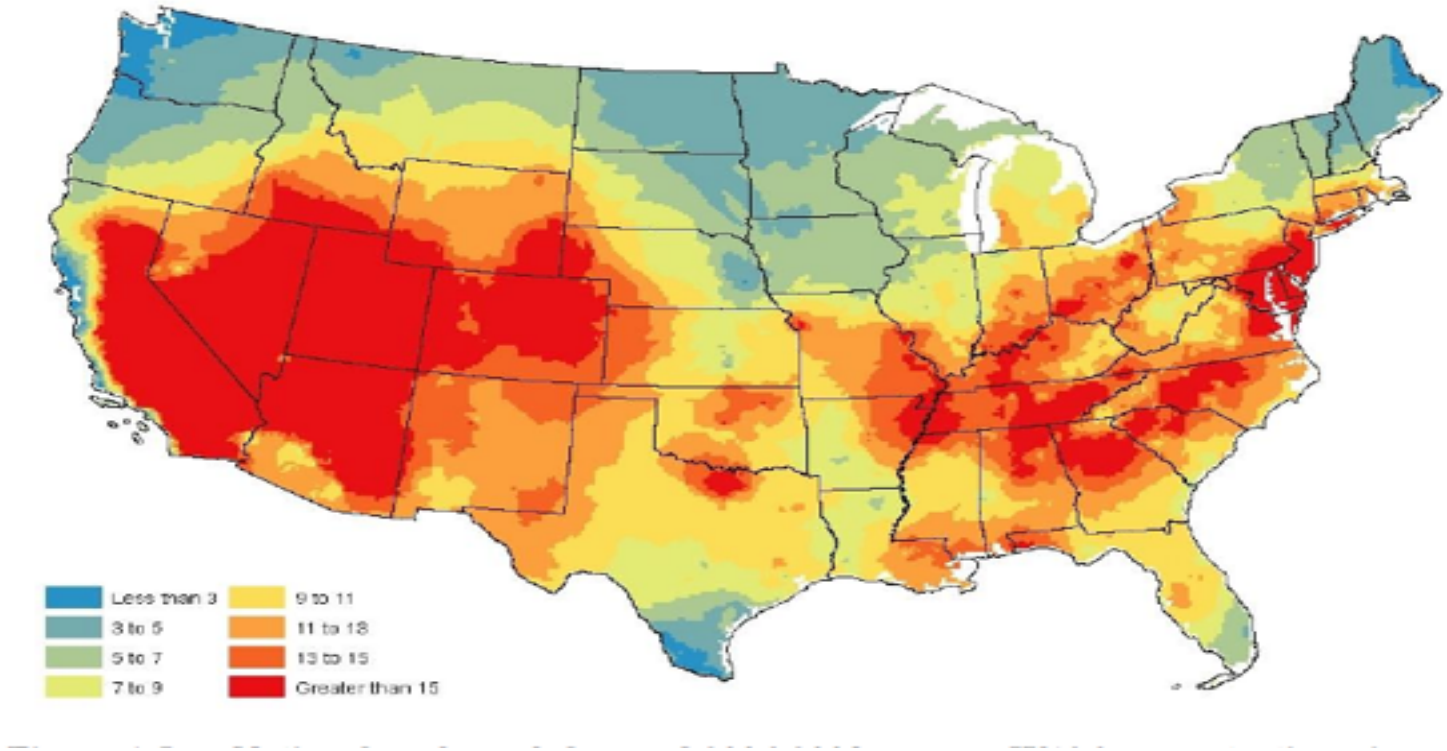
NO_x controls are needed to meet current ozone standards … even if production is NO_x-saturated



- VOC controls will only get you so far until you are limited by biogenic background
- NO_x controls are only way to get to current ozone standards and have side benefits (NO_2 air quality, nitrogen deposition)

As ozone standard tightens, the nature of the problem changes

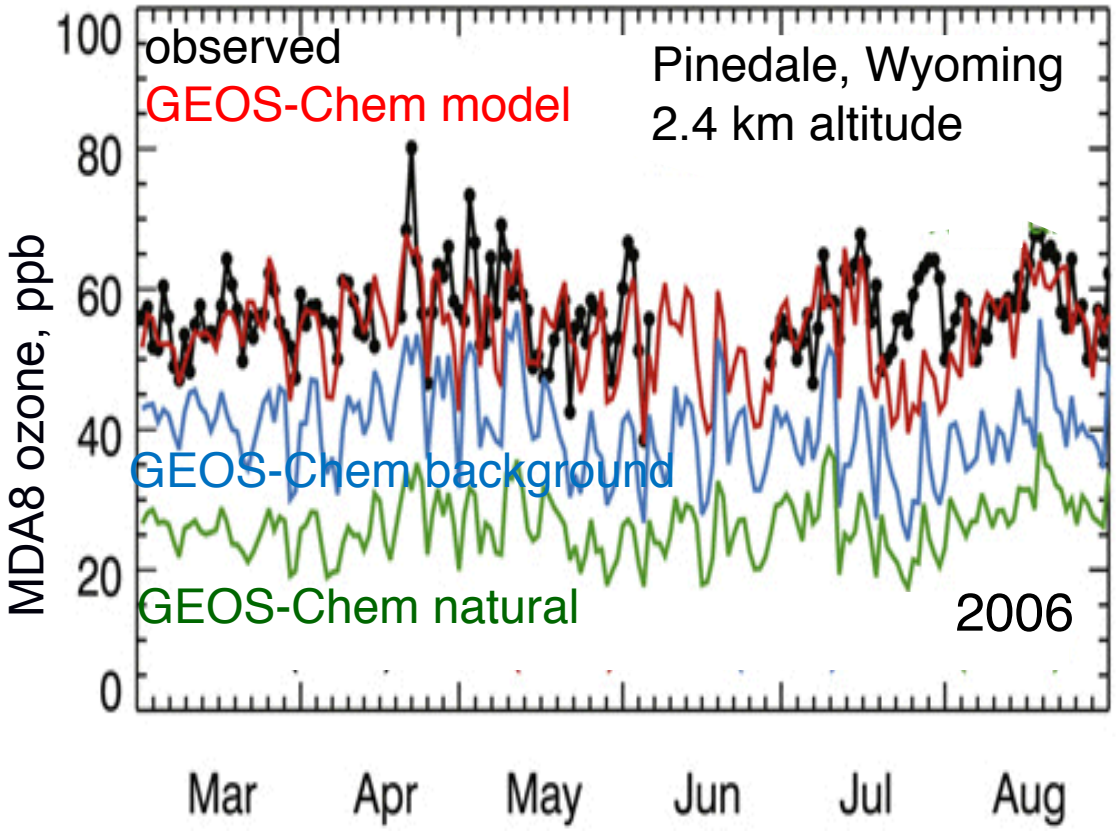
Seasonal dose in excess of 60 ppb [EPA, 2014]

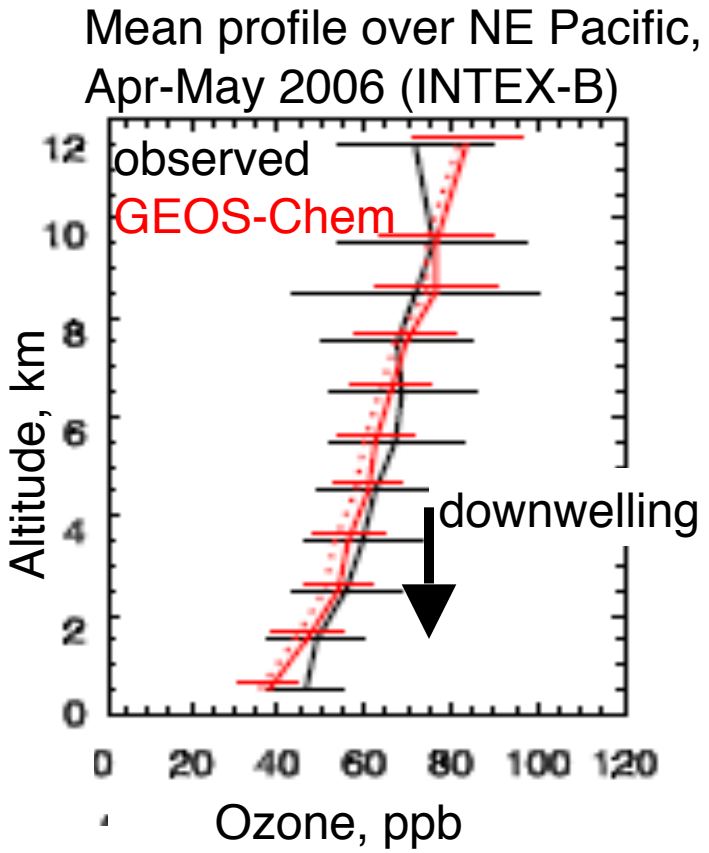


60 ppb exceedances are largest in Intermountain West

Ozone in Intermountain West originates out of N America

Background = ozone present in absence of anthropogenic sources in North America



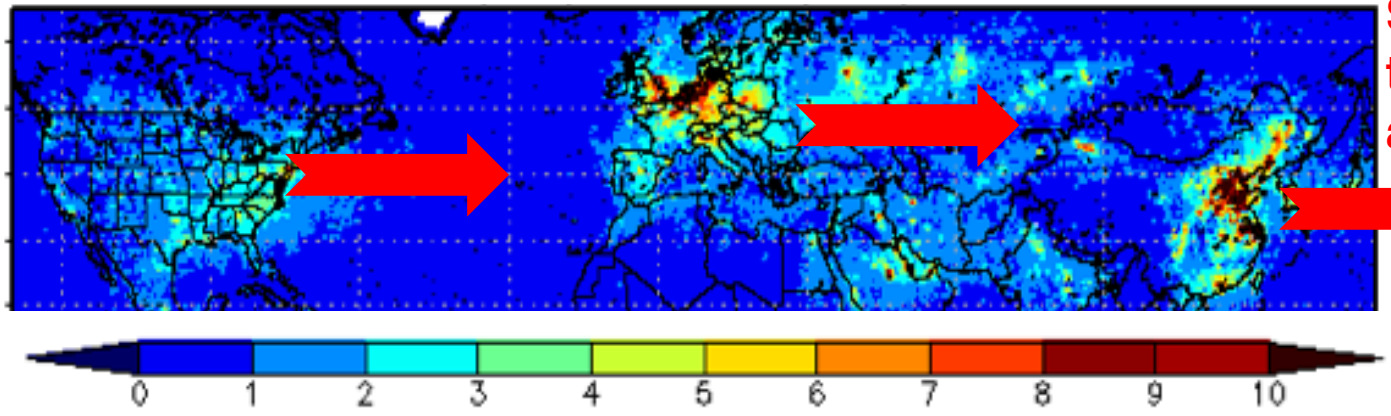


- Domestic emissions have little influence on intermountain west
- Anthropogenic background contributes ~15 ppb with little day-to-day variability

Zhang et al. [2014]

Intercontinental transport of ozone pollution

2012 OMI NO_2 column, 10^{15} molecules cm^{-2}



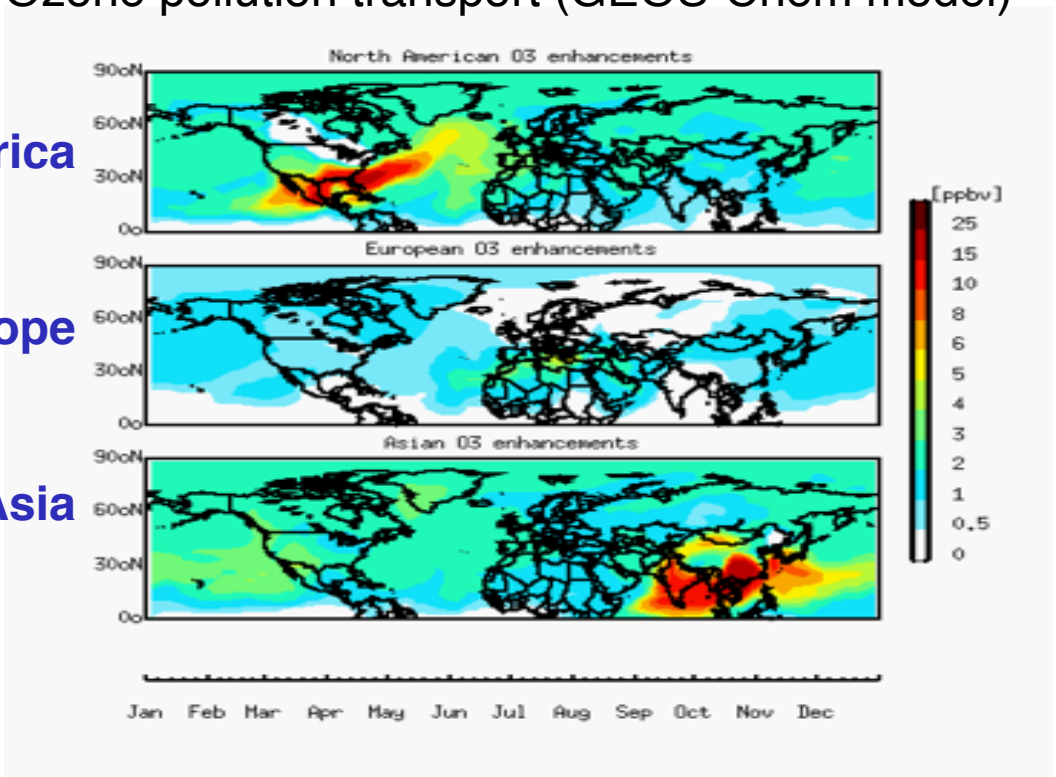
Strong westerlies transport ozone around mid-latitudes

Ozone pollution transport (GEOS-Chem model)

N America

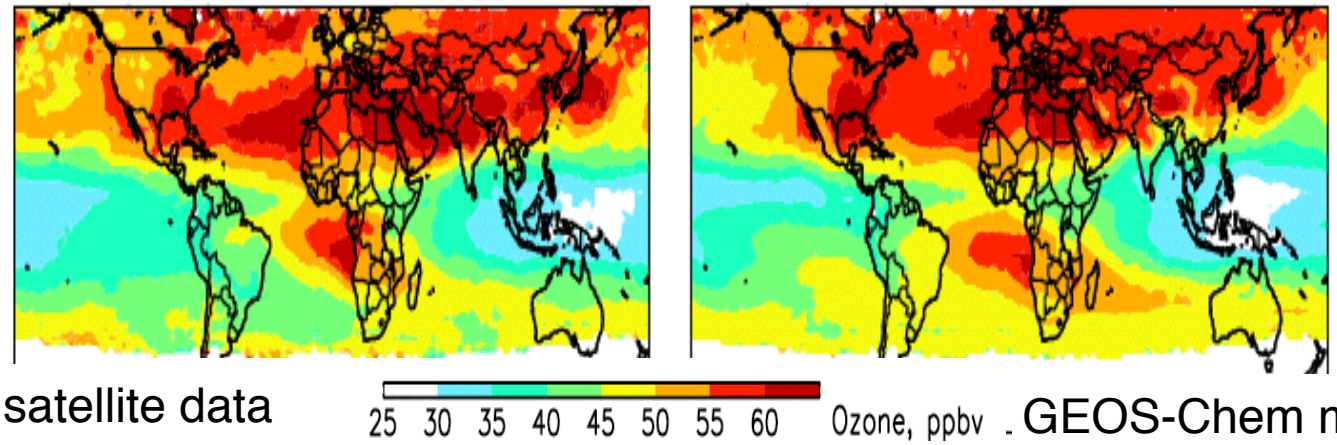
Europe

Asia



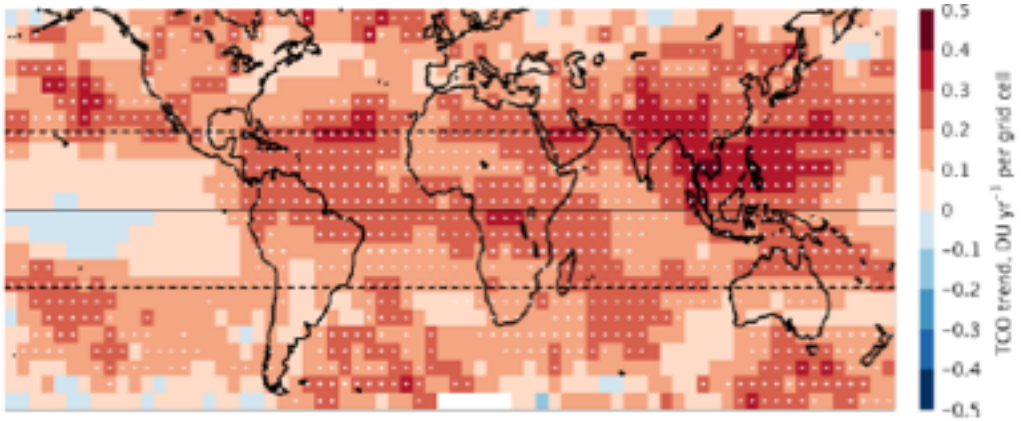
Global tropospheric ozone is rising…and we don't know why

Mean 500 hPa ozone in JJA 2013



- **Partly natural:** stratospheric influence, lightning, wildfires
- **Partly anthropogenic:** methane, intercontinental pollution, fires, ships, aircraft…

OMI tropospheric ozone column trend, 2005-2016:
increasing almost everywhere



Models can reproduce present-day levels but not long-term trends

Cause of increase is not clear. Asian emissions? Ships? Aircraft? Wildfires? Increasing transport from stratosphere?

Hu et al. [2017], TOAR [2017]