Sleuthing Emergent Air Pollution:

From fast-growing tropical cities to the nascent space tourism industry

Harvard Seminar

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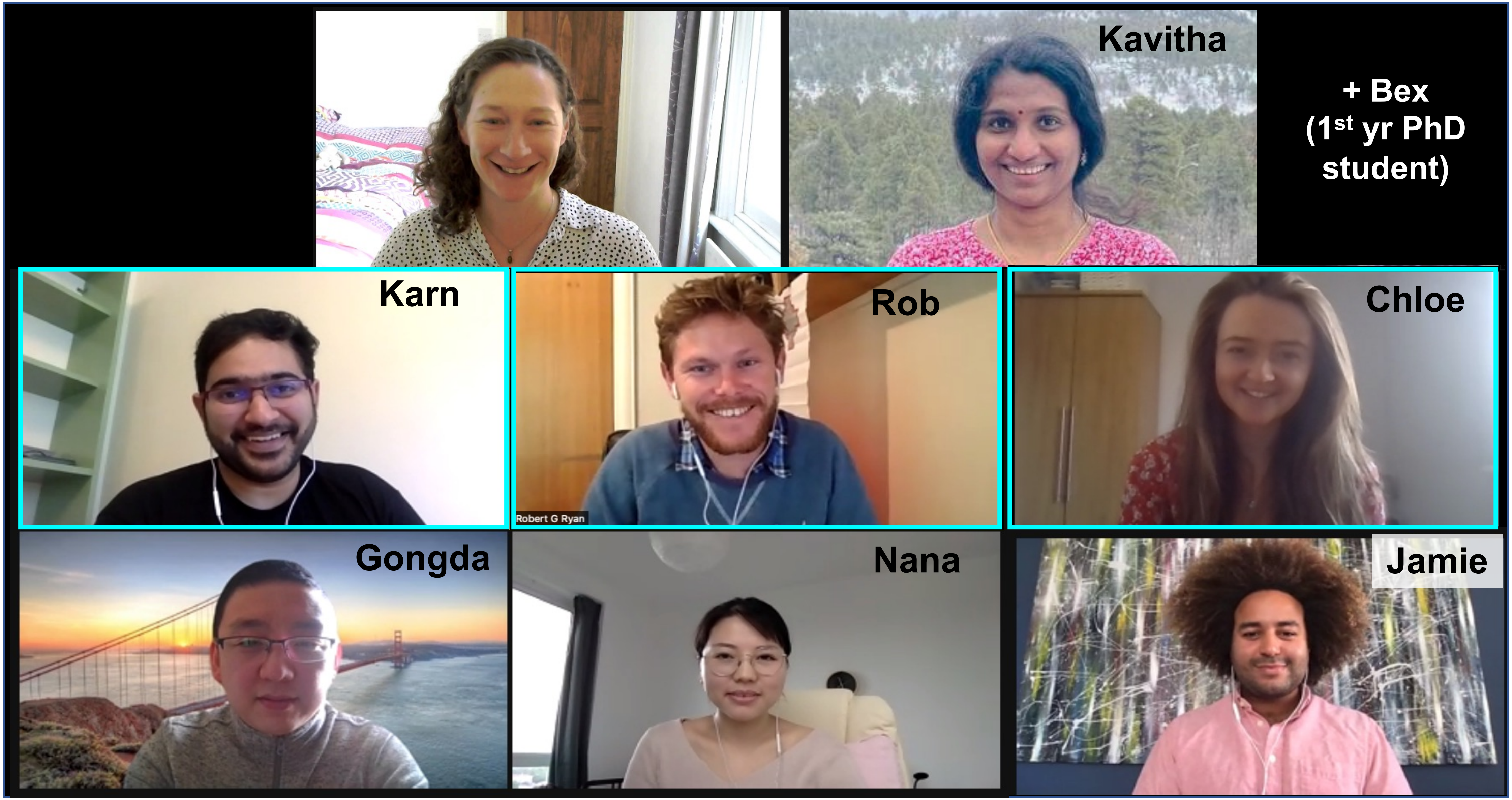
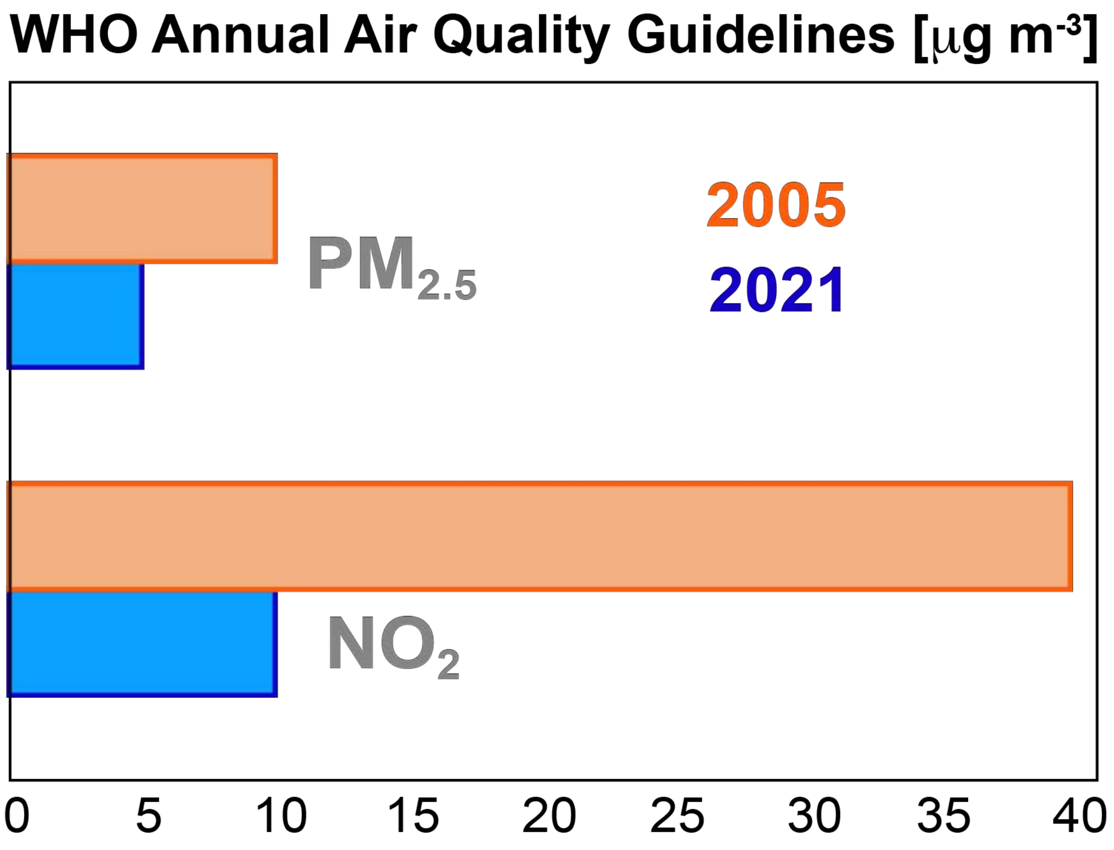
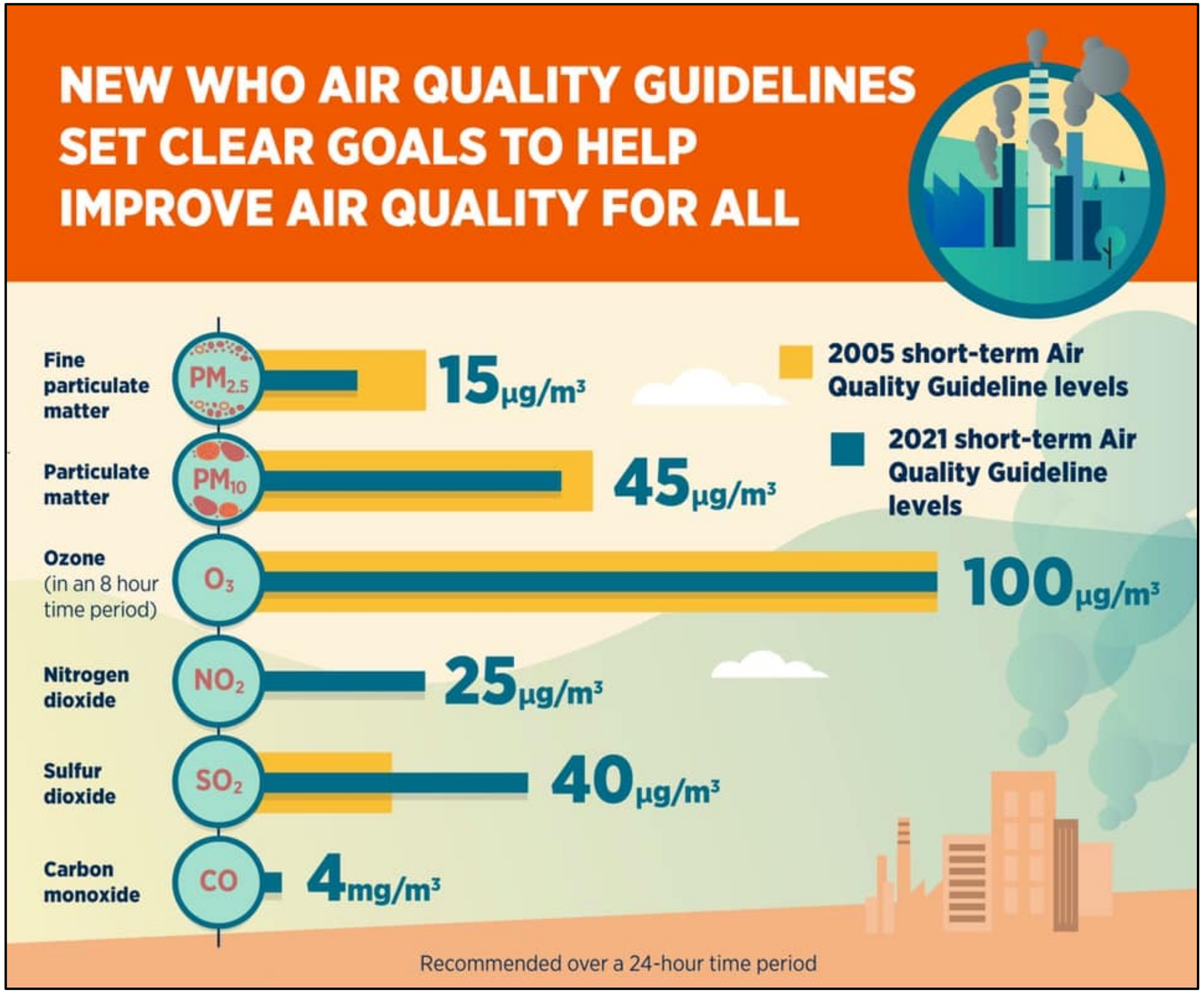


Stricter World Health Organization (WHO) guidelines

(https://apps.who.int/iris/handle/10665/345329)



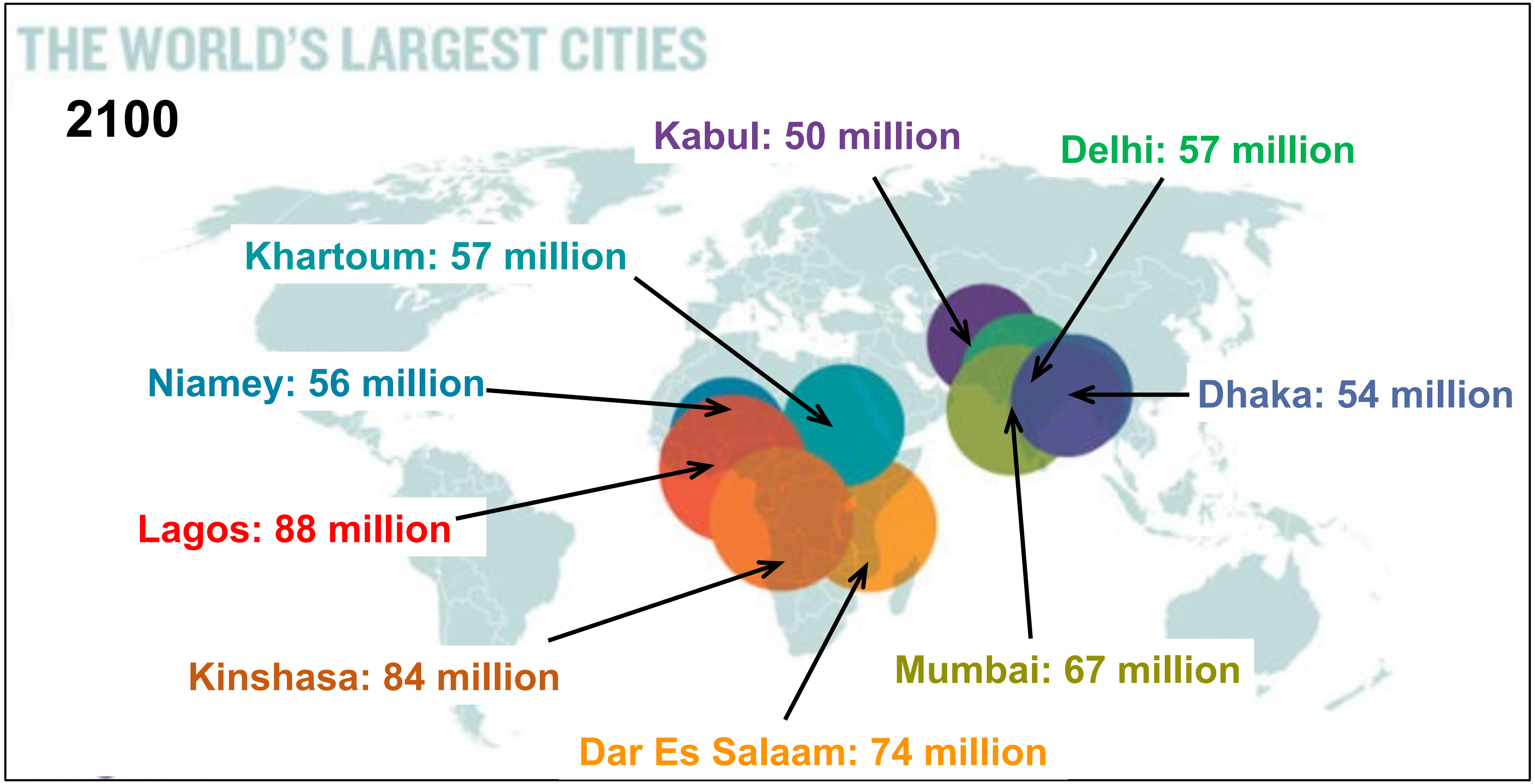


Source: WHO Facebook page

Megacities of the future

By 2100, most of the largest cities will be in tropical Africa and Asia

Greatest air quality knowledge gaps are in African megacities (WHO, 2021)



Largest cities in 2020 (population in millions):

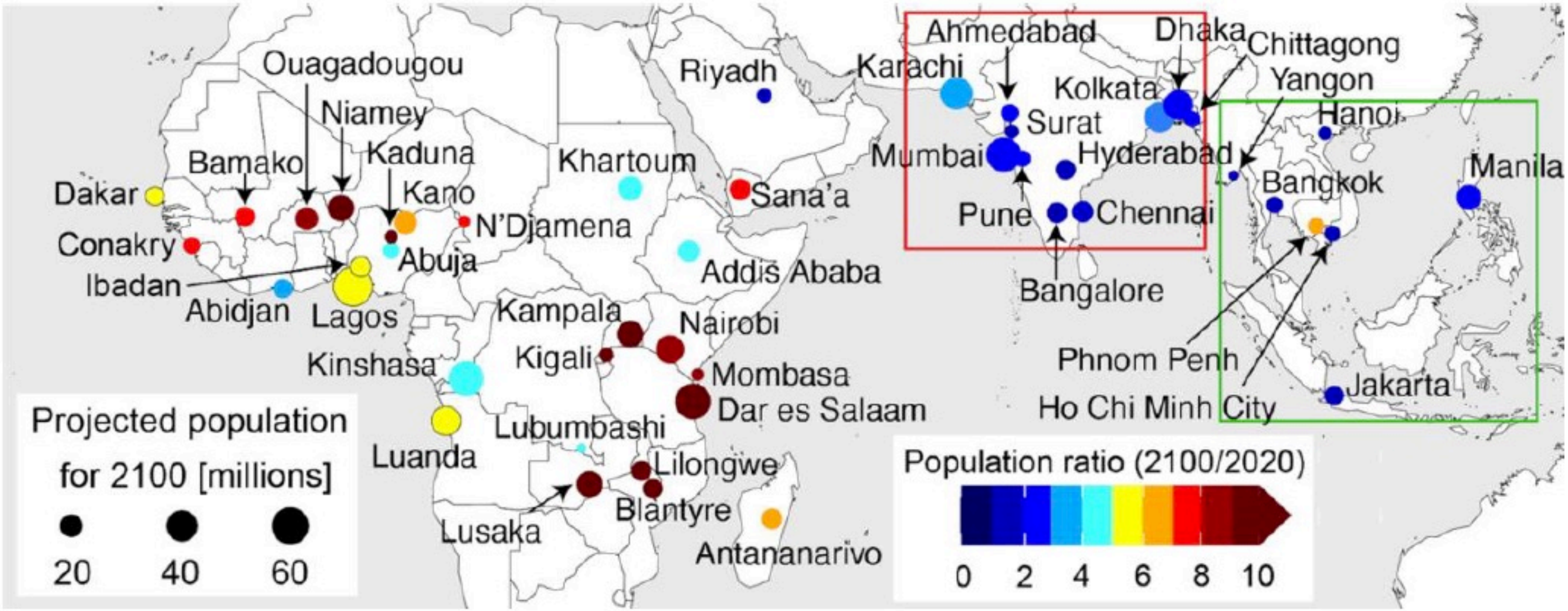
1. Tokyo (38)
2. Delhi (29)
3. Shanghai (26)
4. Sao Paulo (22)
5. Mexico City (22)
6. Cairo (20)
7. Mumbai (20)
8. Beijing (20)
9. Dhaka (20)
10. Osaka (19)

Adapted image: https://medium.com/ensia/here-come-the-megacities-1b0f8a2287f2

Projections: https://journals.sagepub.com/doi/full/10.1177/0956247816663557

Fastest-growing cities are in the tropics

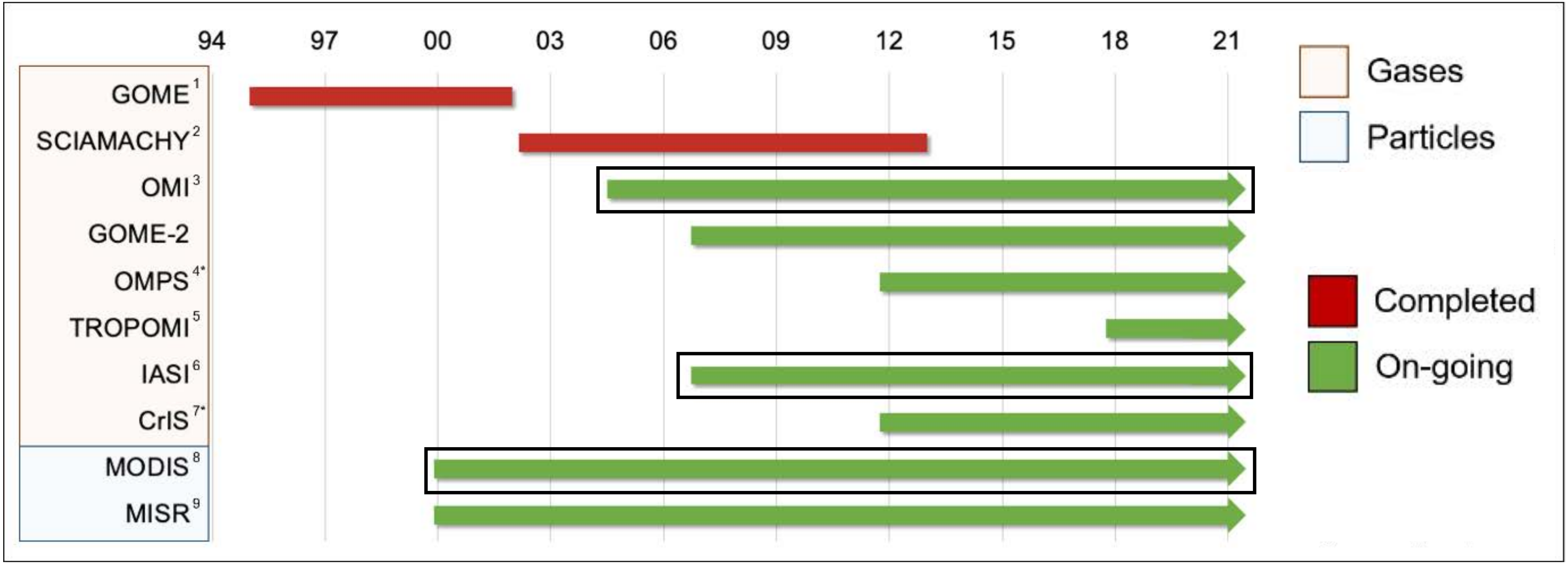
Air quality trends in the 46 fastest-growing cities in tropical Africa, Asia and the Middle East



Regional annual projected population growth rates for 2020-2100 [Hoornweg & Pope, 2017]:

3-31% for Africa, 0.8-3% for **South Asia**, 0.5-7% for **Southeast Asia**

Long and consistent record of air pollution from space



<u>Space-based constraints on air pollution:</u>

OMI: NO_2 (**NO_x**), HCHO (**NMVOCs**)

IASI: **NH_3**

MODIS: AOD (**$PM_{2.5}$**)

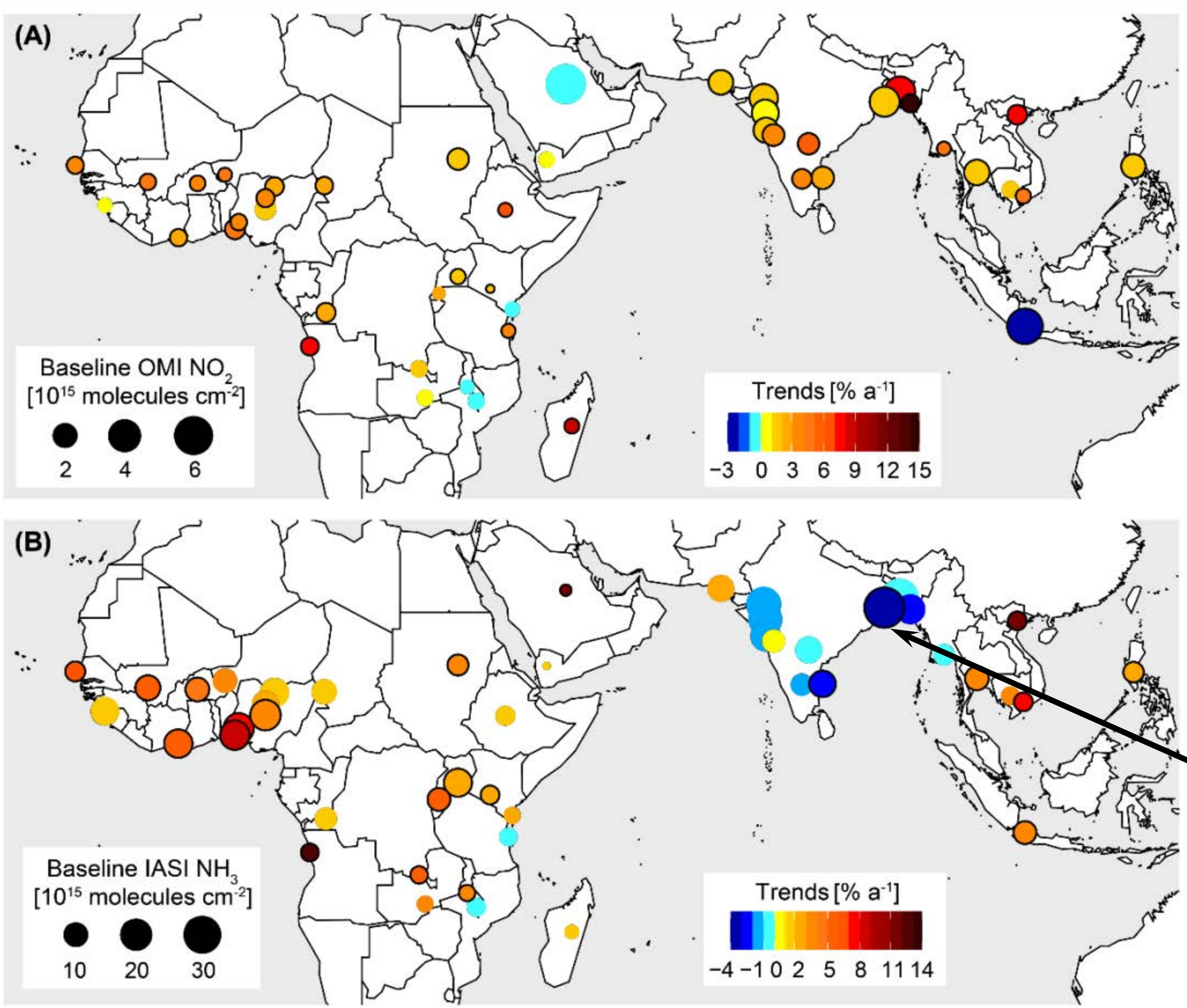
Steep annual increases in NO_x and NH_3

Circle size: starting point

Circle color: trend

Circle outline: significant

NO_2 trends
(proxy for **NO_x**)
[2005-2018]



NH_3 trends
(depends on acidic aerosol abundance)
[2008-2018]

NO_x increase:
up to 14% a^{-1}

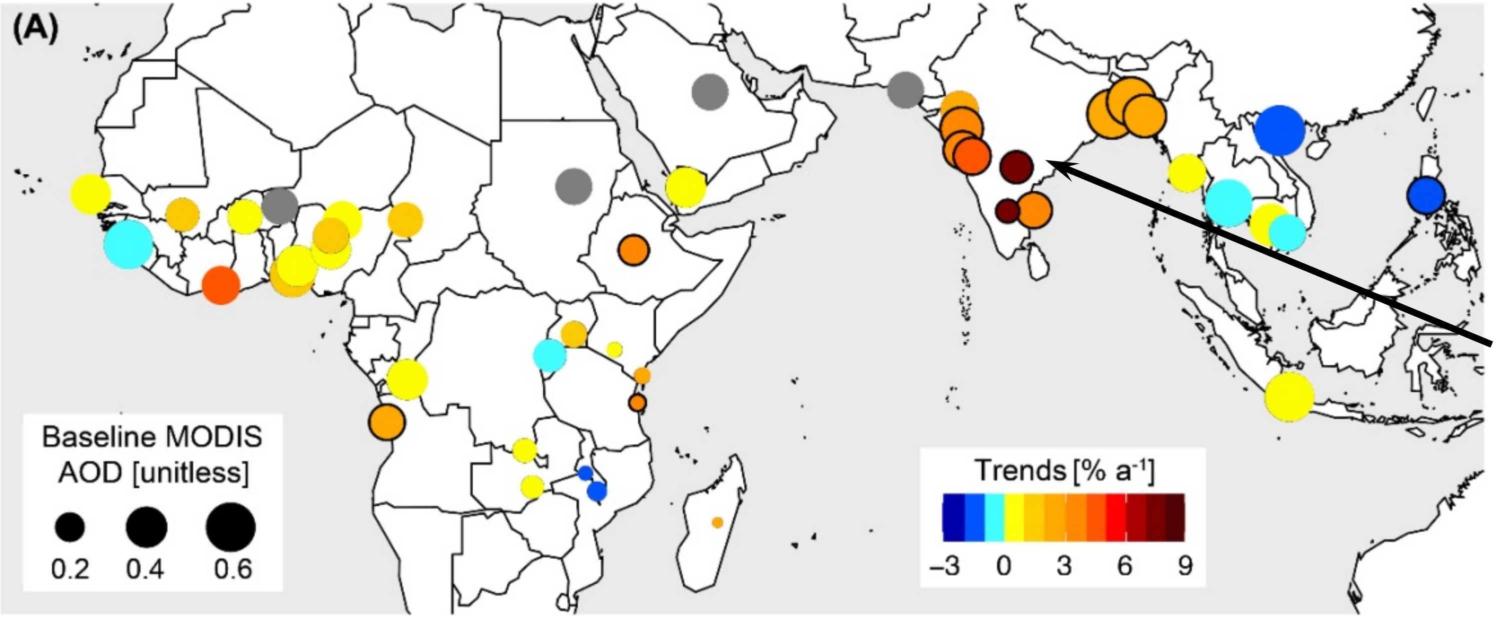
NH_3 increase:
up to 12% a^{-1}

Decline over Indian subcontinent due to increase in uptake to acidic aerosols

NH_3 data provided by M. Van Damme, L. Clarisse, P.-F. Coheur, ULB

Annual changes in $PM_{2.5}$ and ozone production regimes

AOD trends
(proxy for $\mathbf{PM_{2.5}}$)
[2005-2018]



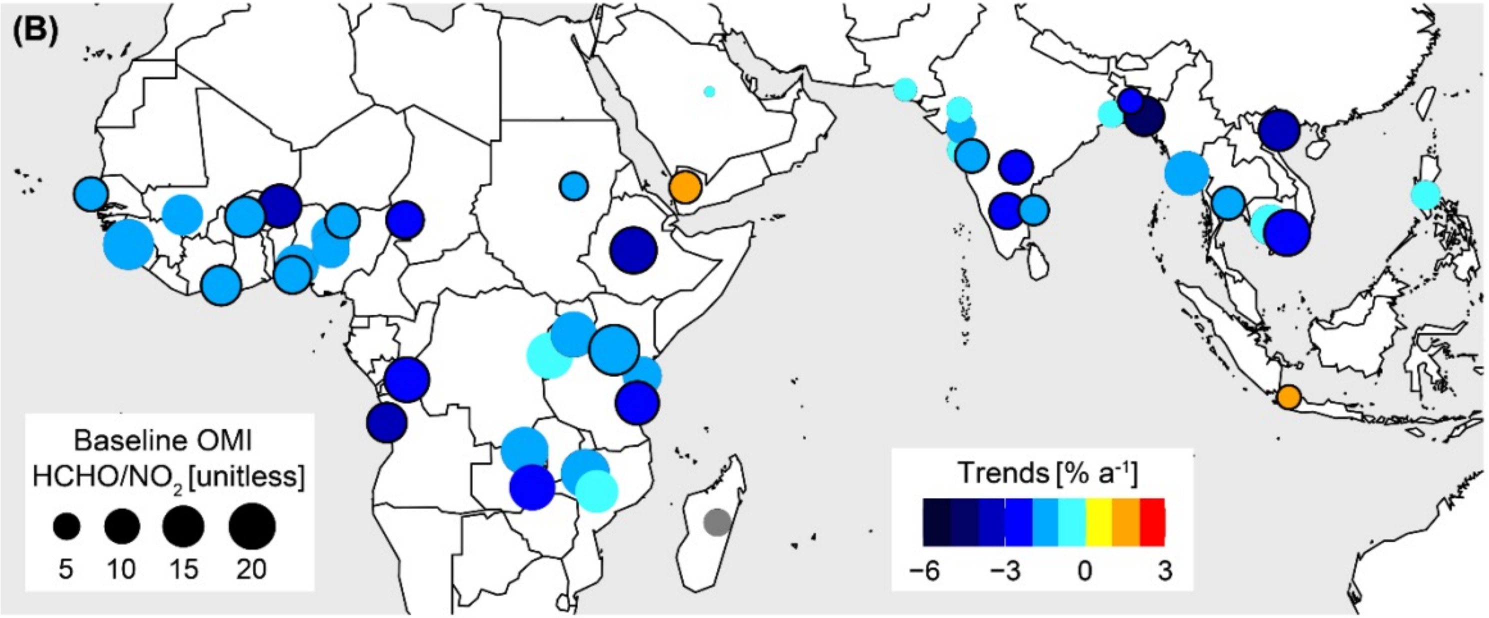
Size: starting point

Color: trend

Outline: significant

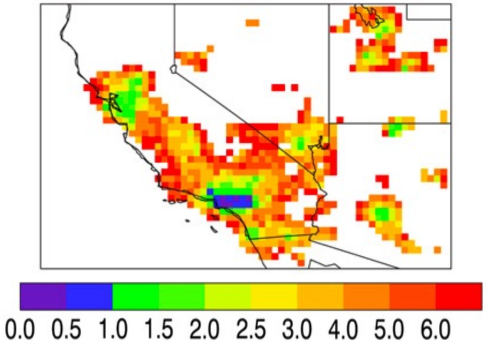
Increases in $PM_{2.5}$ precursors SO_2, NH_3, NO_x

$\mathbf{HCHO/NO_2}$ trends
(proxy for ozone production regime)
[2005-2018]



O_3 production sensitive to NO_x, but transitioning

JJA 2005-2007

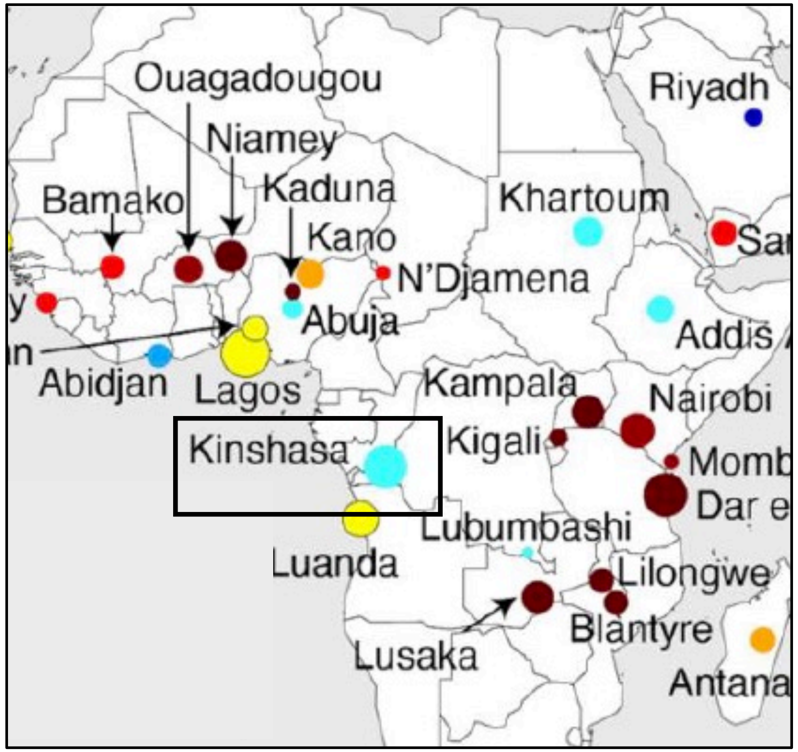


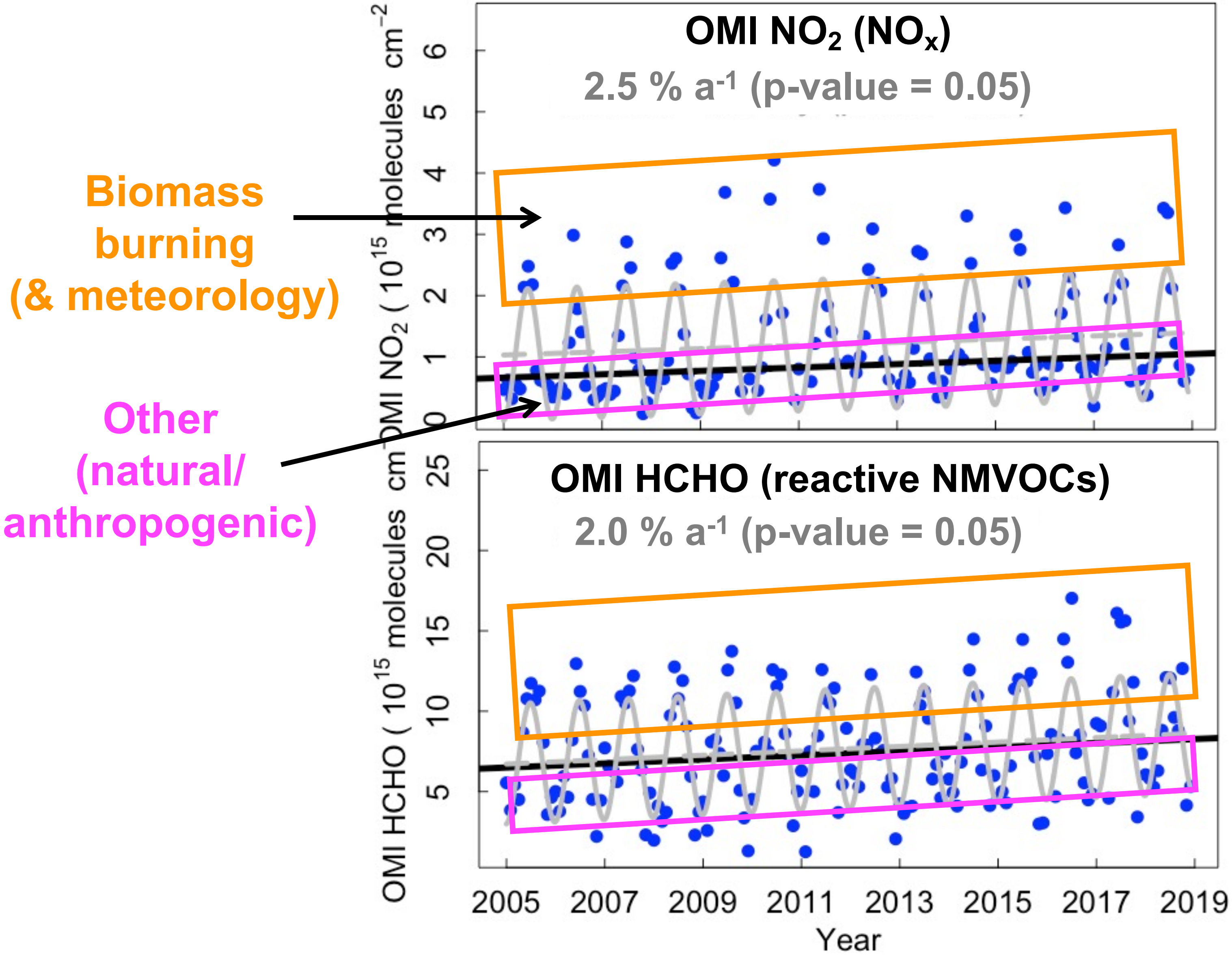
[Duncan et al. 2010]

What's driving the observed trends?

Challenging to answer with limited/no surface observations and questionable emission inventories

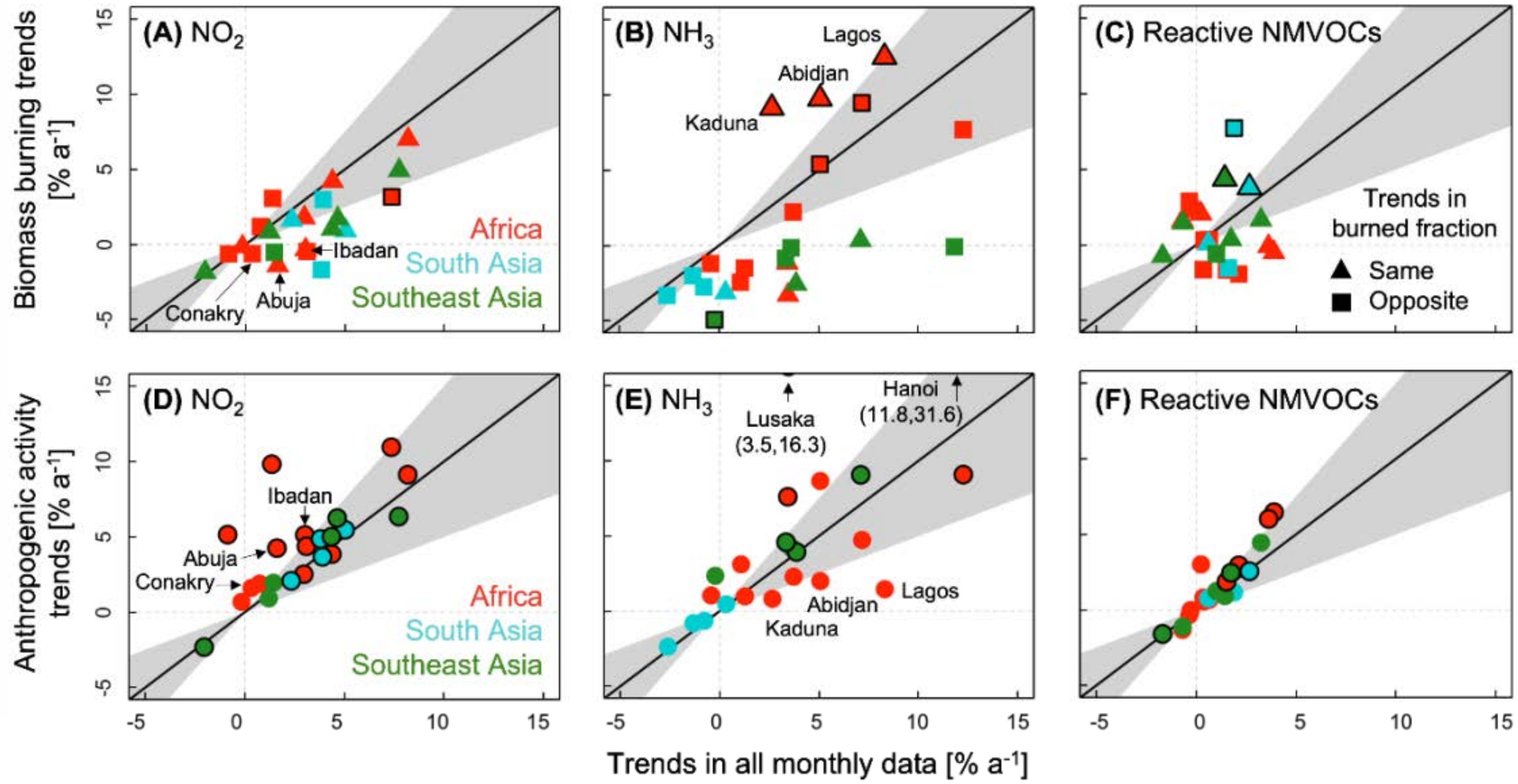
Air quality in tropics influenced by seasonal biomass burning





What's driving the observed trends?

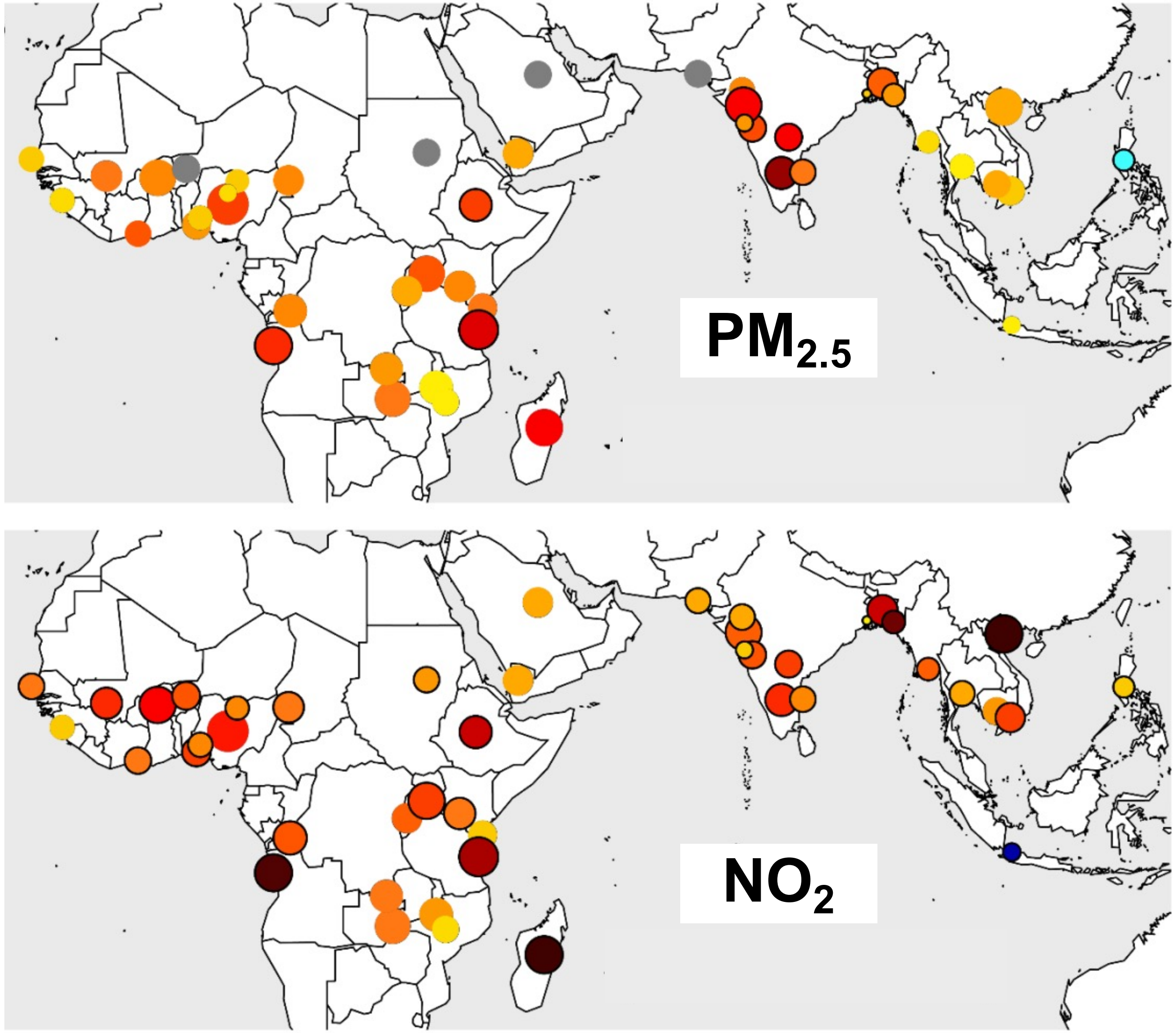
We use a statistical approach and knowledge of seasonality of emissions to assess the relative role of anthropogenic and biomass burning emission



Consistency in trends for anthropogenic influenced months and all data months supports anthropogenic emissions as air pollution trend drivers with some offsetting from decline in agricultural activity

Unprecedented air pollution exposure trends

Effect of combined rise in air pollution and population on urban exposure to air pollution

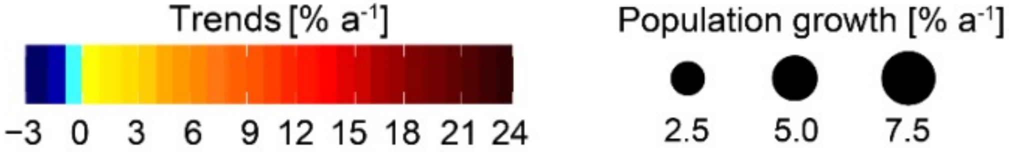


Steep increases in $PM_{2.5}$ in India
(up to **18 % a^{-1}**)

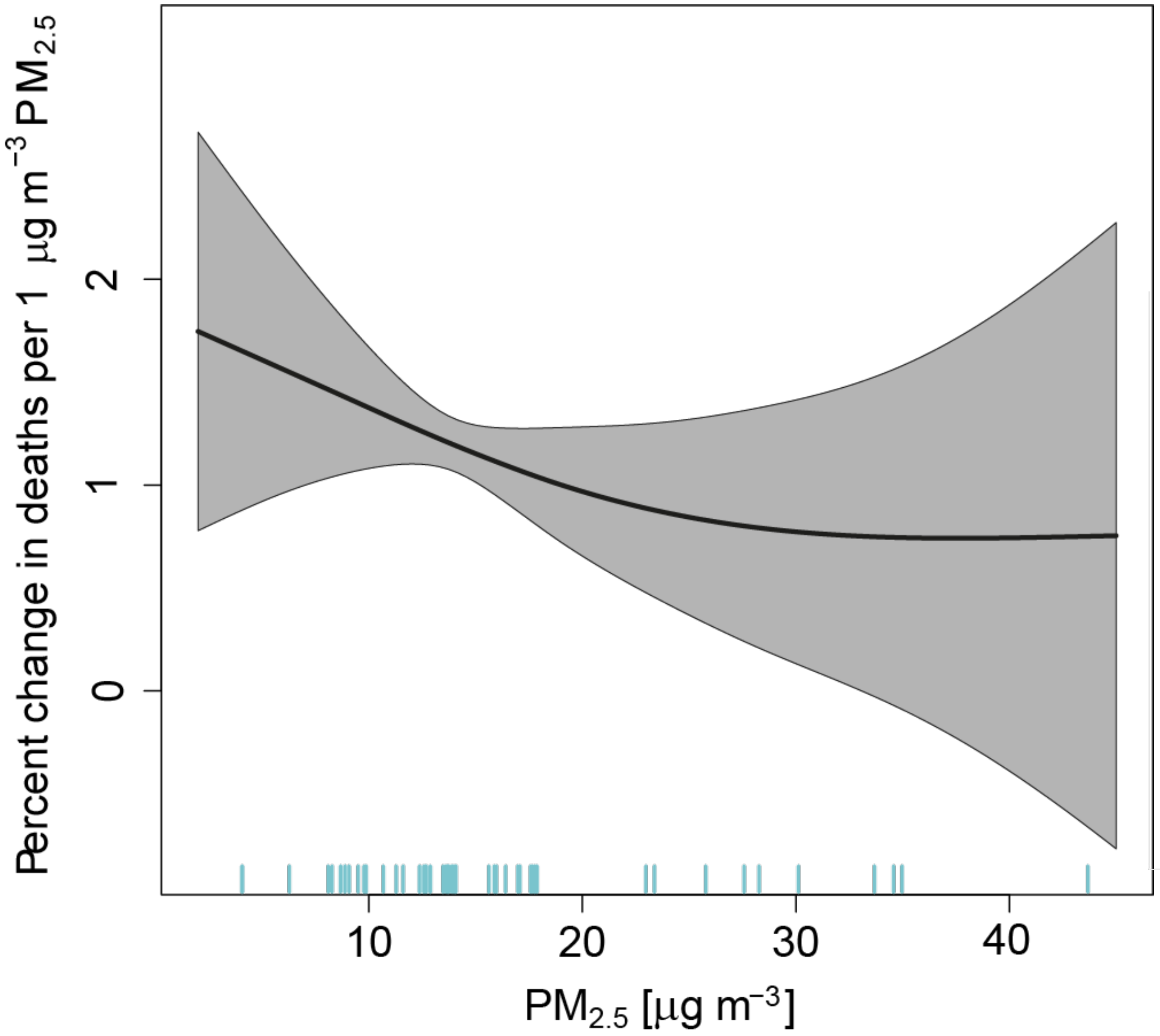
Steep increases in NO_2 everywhere
(up to **23% a^{-1}**)

Many adverse health outcomes from exposure to $PM_{2.5}$ and NO_2

Incidence of premature mortality most severe for $PM_{2.5}$

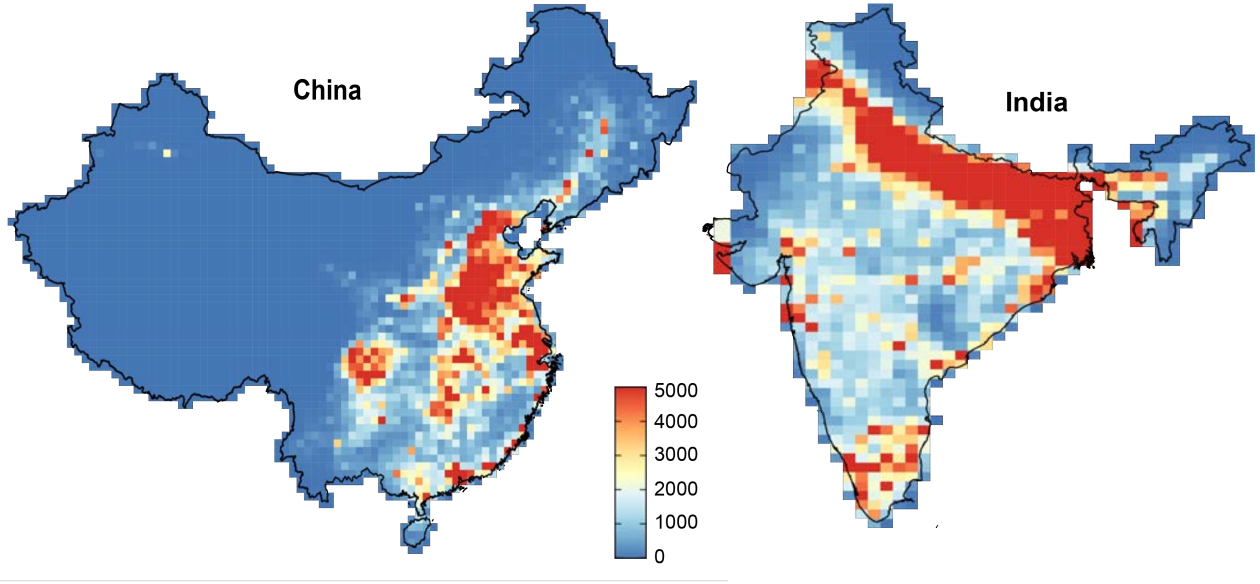


Determine premature mortality attributable to $PM_{2.5}$ exposure



More cohorts, greater $PM_{2.5}$ range, more health endpoints than previous approaches.

Led to very large premature mortality estimate from fossil fuel combustion:

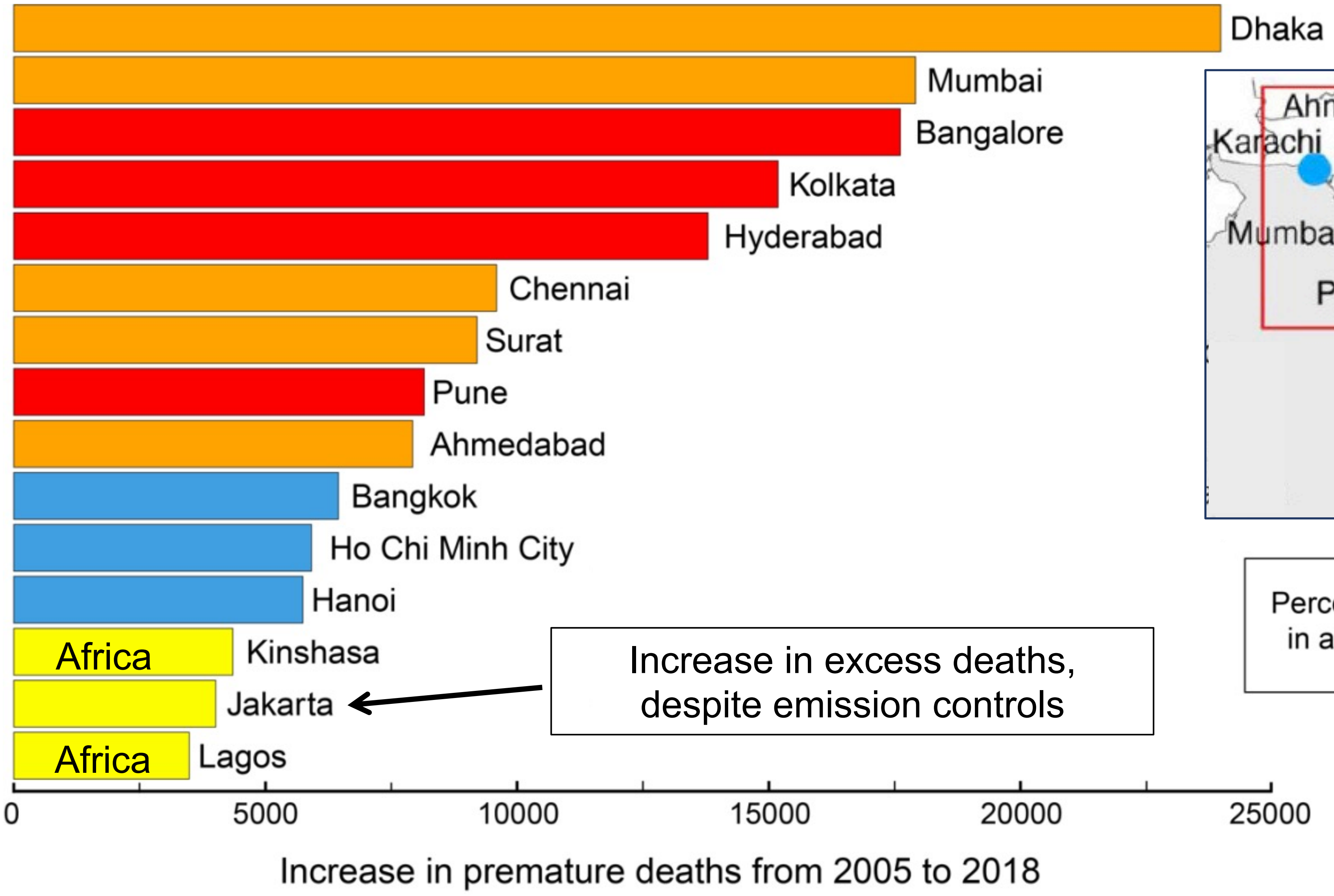


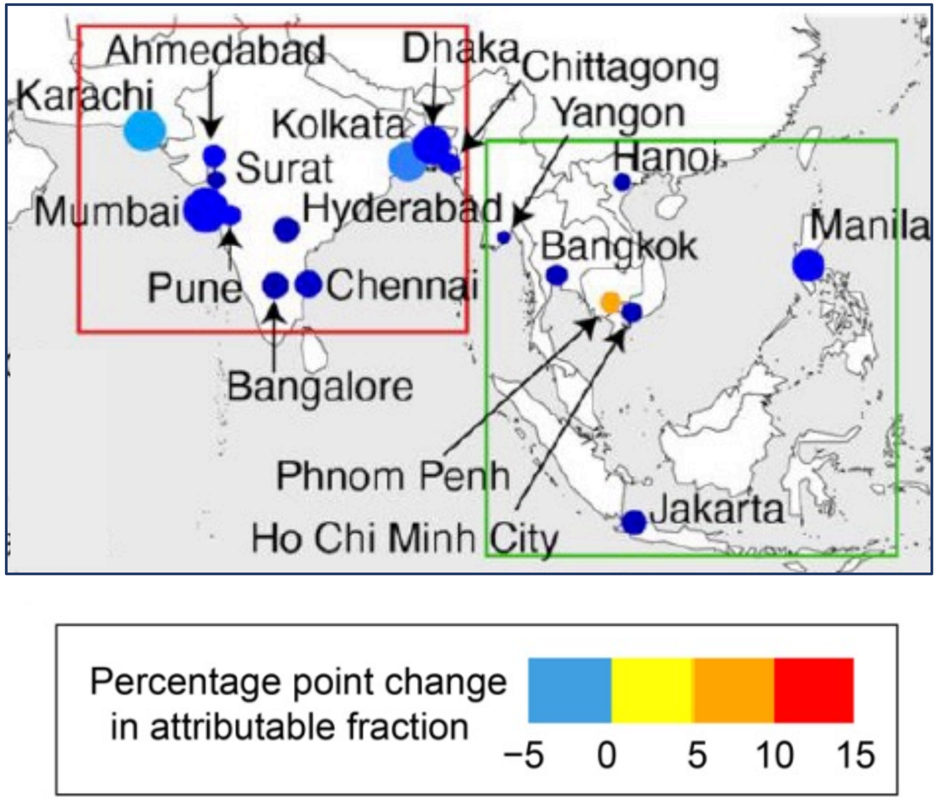
10 million premature deaths (63% in India and China)
[Vohra et al., 2021]

Relate ambient $PM_{2.5}$ to premature mortality using concentration-response curve from Joel Schwartz's group

Use GEOS-Chem 2012 $PM_{2.5}$ and AOD trends to calculate $PM_{2.5}$ at in 2005 (start) and 2018 (end) of the record

Premature mortality attributable to rise in $PM_{2.5}$ exposure





Total: 179,550
[95% CI: -227,131 to 586,231]

Highest ranked are almost all in Asia.

Africa likely to be ranked higher for adverse health effects of increases in exposure to NO_2

Conclusions

- Steep increases in air pollution, precursors, and urban exposure driven by anthropogenic activity (policies need to be developed to target these!)
- Total premature mortality of 180,000 from 2005 to 2018 over cities where we can derive $PM_{2.5}$ trends
- Worst health burden for cities in Asia, but steep increases in air pollution and forecast population growth suggest African cities are poised for a health crisis
- Routine, reliable, publicly accessible ground-based measurements of air quality are crucial

Reference:

Karn Vohra, E. A. Marais, W. J. Bloss, J. Schwartz, L. J. Mickley, M. Van Damme, L. Clarisse, P.-F. Coheur, *Severe health burden in tropical future megacities from rapid rise in anthropogenic air pollution and population*, in review, Science Advances.

An emerging source: Power barges (powerships)

Natural gas operated powerships

Generating capacity has increased 13-fold in a decade

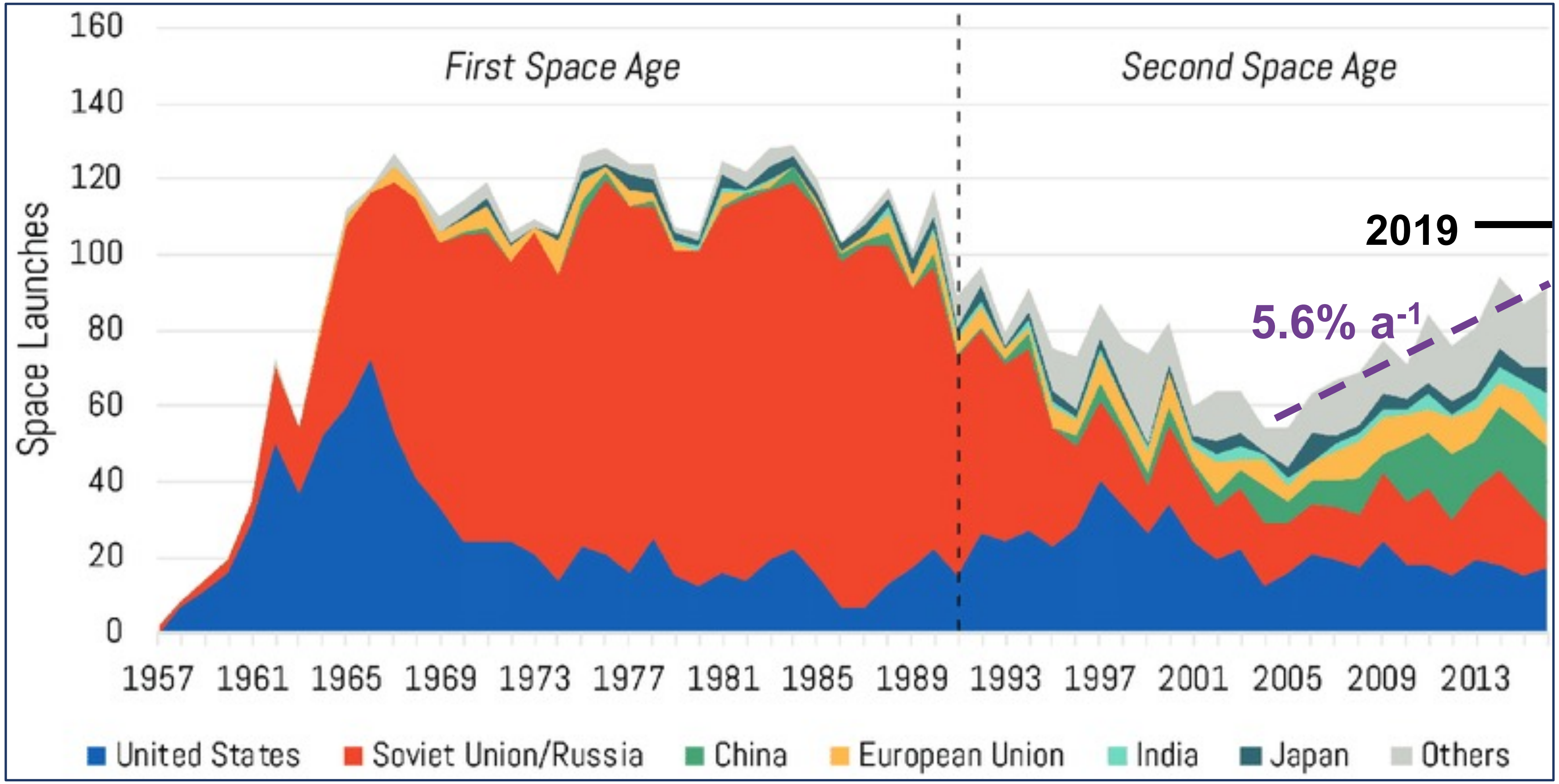
A popular quick to install gas-to-electricity option in Africa, Asia, the Middle East and the Caribbean.

Emission factor and local air pollution and methane leakage measurements are needed to assess influence on air quality and climate

Impact of the rocket launches on the atmosphere

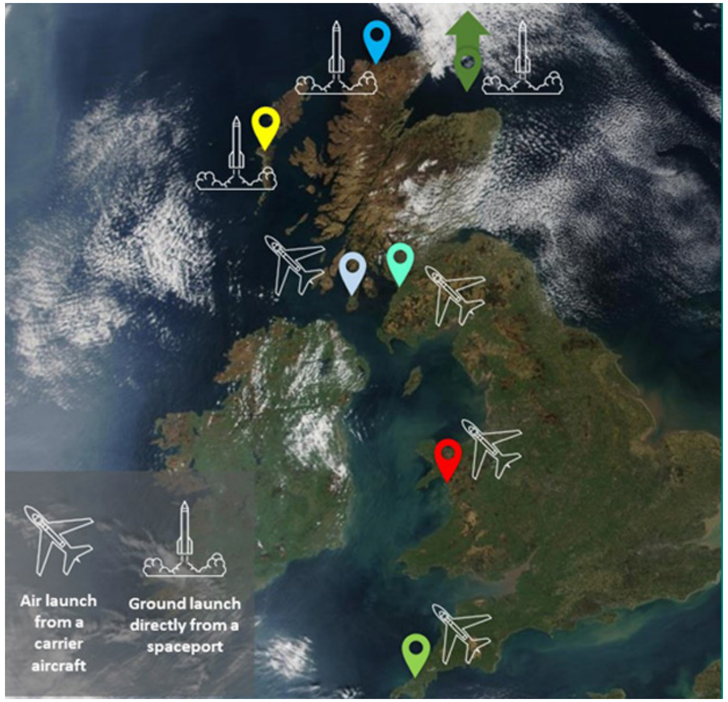
Space industry no longer dominated by Russia and the US. Even the UK has joined the race!

Space launches by country since dawn of space race



Source: http://dx.doi.org/10.13140/RG.2.2.15240.11525

UK vertical and horizontal spaceports



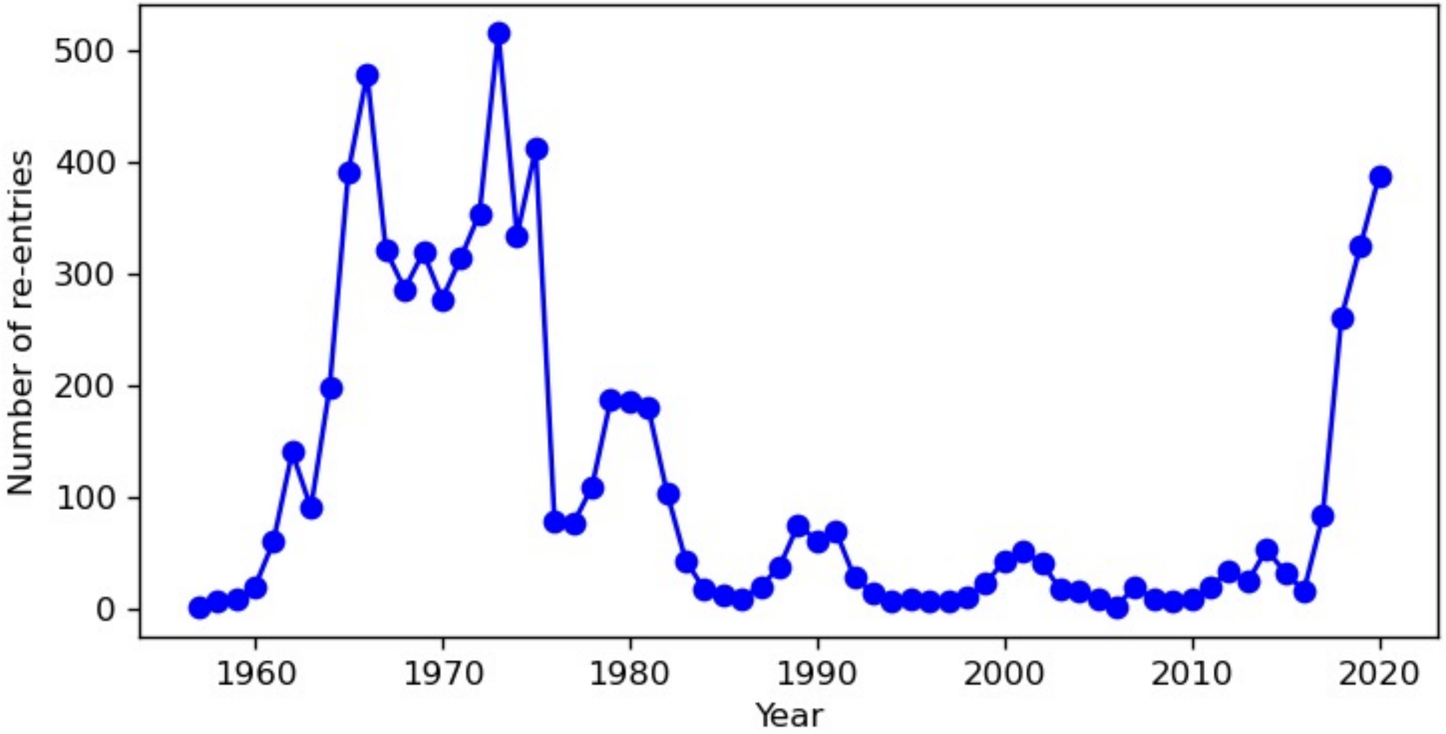
Source: UK Space Agency

Space industry anticipated to grow from £350 million industry in 2019 to > £1 trillion by 2040

Surge in returning space junk and reusable rockets

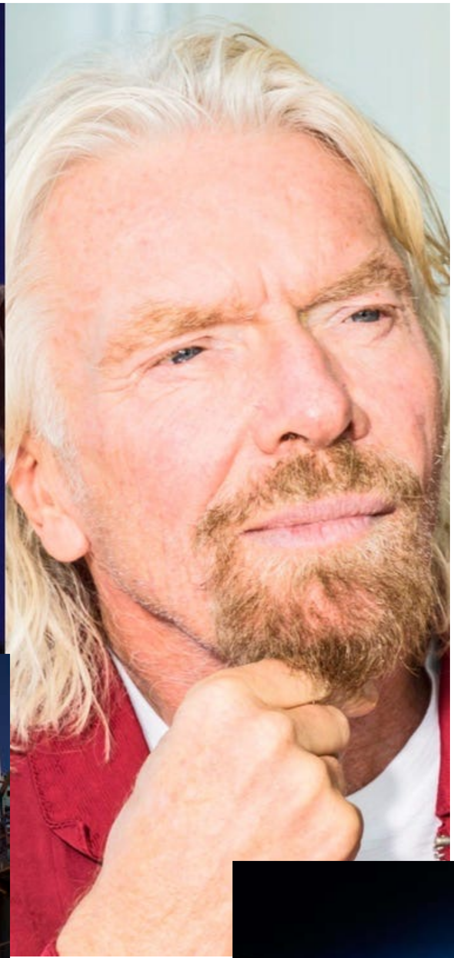
Re-entry burn produces ~17.5 mass % NO_x for heat shields of reusable components and 100% for complete burn-up

Spent satellites and space debris (as old as the space race), discarded boosters and rocket stages, reusable rockets stages, space capsules/shuttles/pods/planes



Data Source: ESA (https://discosweb.esoc.esa.int/)

The nascent (exclusive) space tourism industry

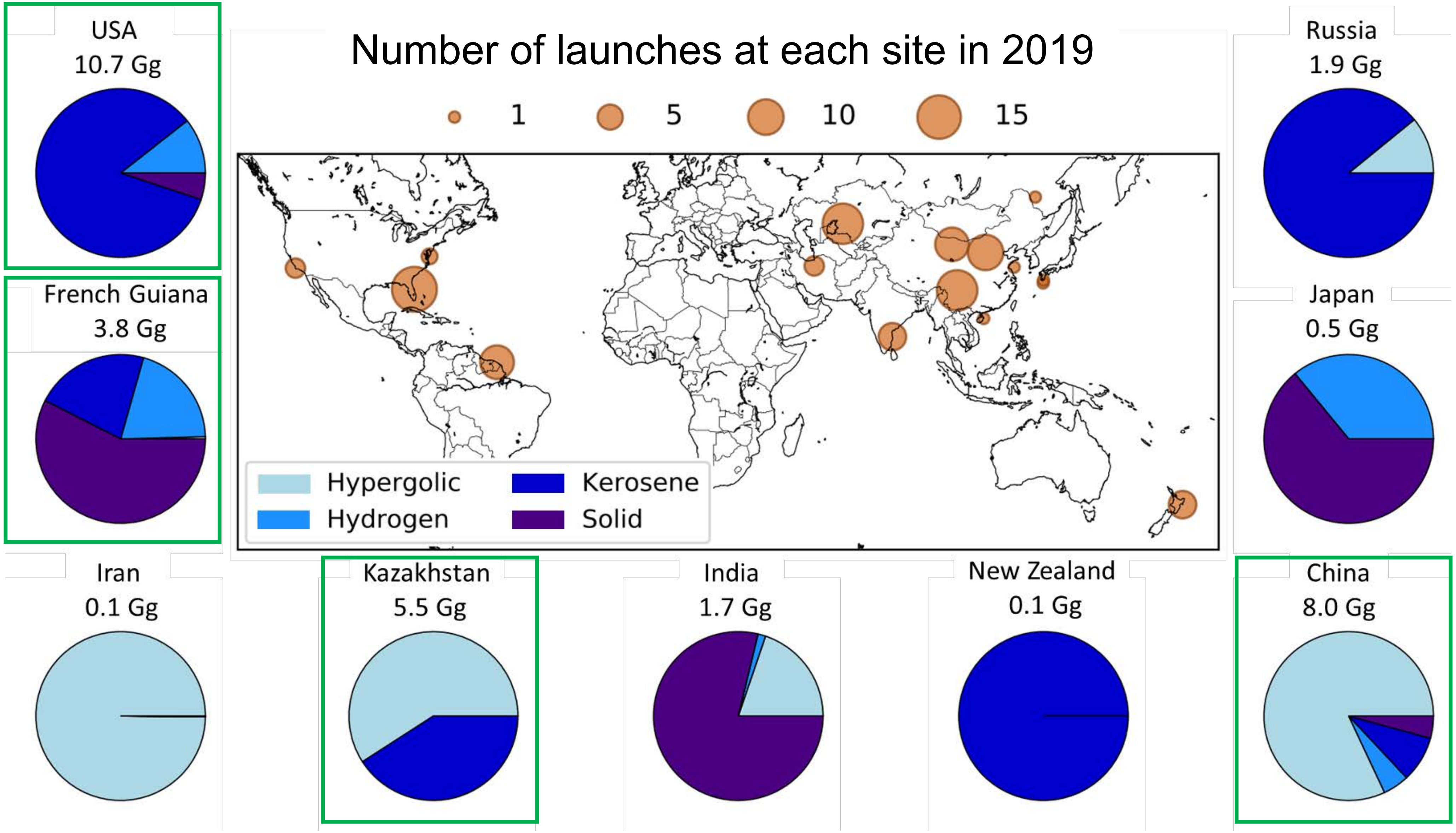


SpaceX

Blue Origin

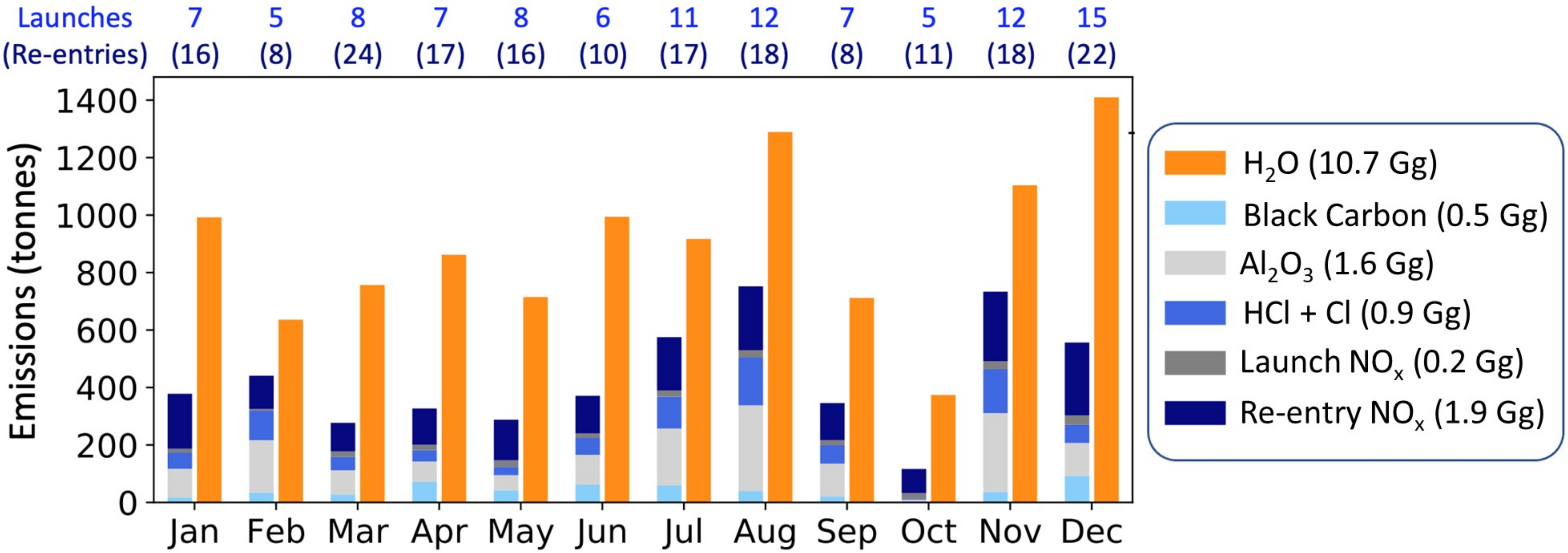
Virgin Galactic

Geographic distribution of launch sites and fuels used



Space tourism: solid (rubber) [Virgin Galactic], hydrogen [Blue Origin], kerosene [SpaceX]

Total emissions from purposeful rocket launches



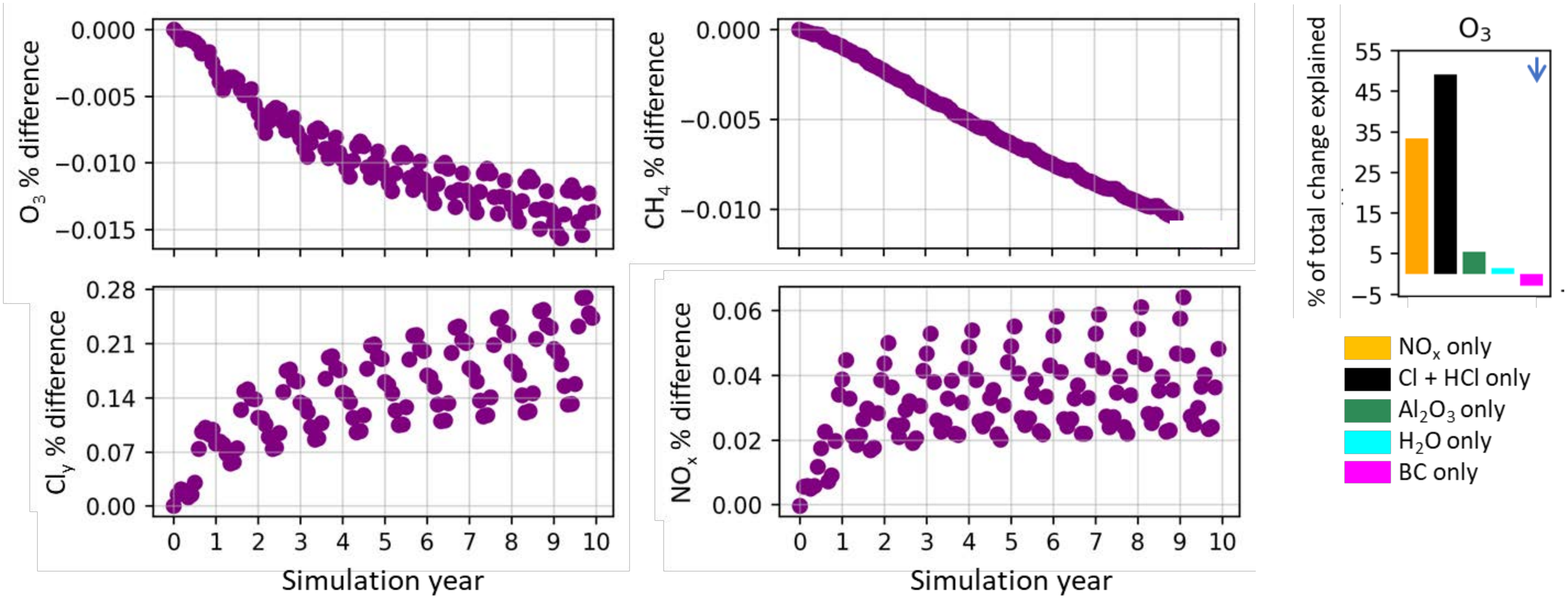
All emissions are relatively small, but most released directly released to the upper atmosphere

Most NO_x from re-entry burn

Conduct decade-long simulation with 5.6% a^{-1} increase in emissions.

Effect of purposeful rocket launches on stratospheric ozone

Difference between simulation with and without rocket emissions averaged from 200 to 1 hPa

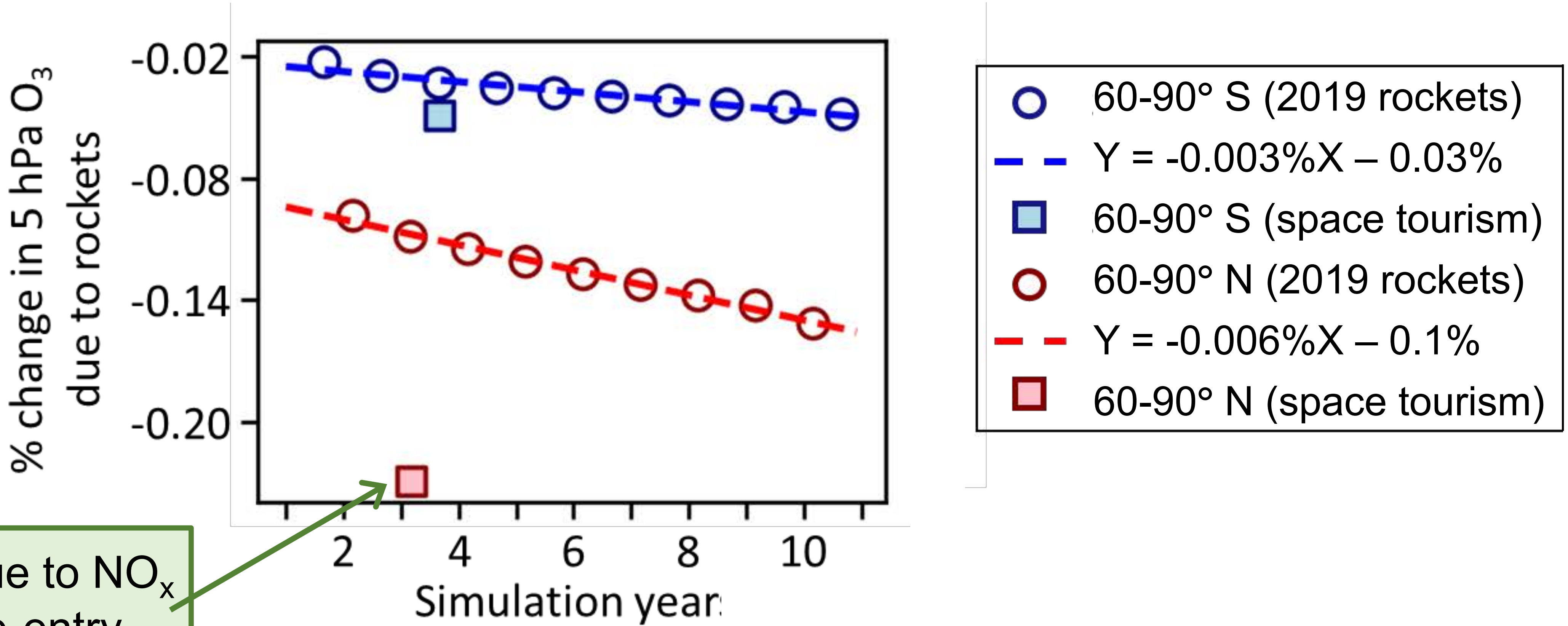


O_3 and Cl_y take ~4 years to establish, NO_x ~2 years, CH_4 continues to decay

Greatest ozone loss occurs in the upper stratosphere (~5 hPa)

Effect of space tourism on stratospheric ozone

Change in upper stratospheric ozone in the upper latitudes (60-90° N/S)



Mostly due to NO_x from re-entry

Space tourism simulation suggests ozone depletion of **~0.3% decade^{-1}**
This is ~20% of the upper stratospheric ozone recovery in northern hemisphere of 1.6% decade^{-1}

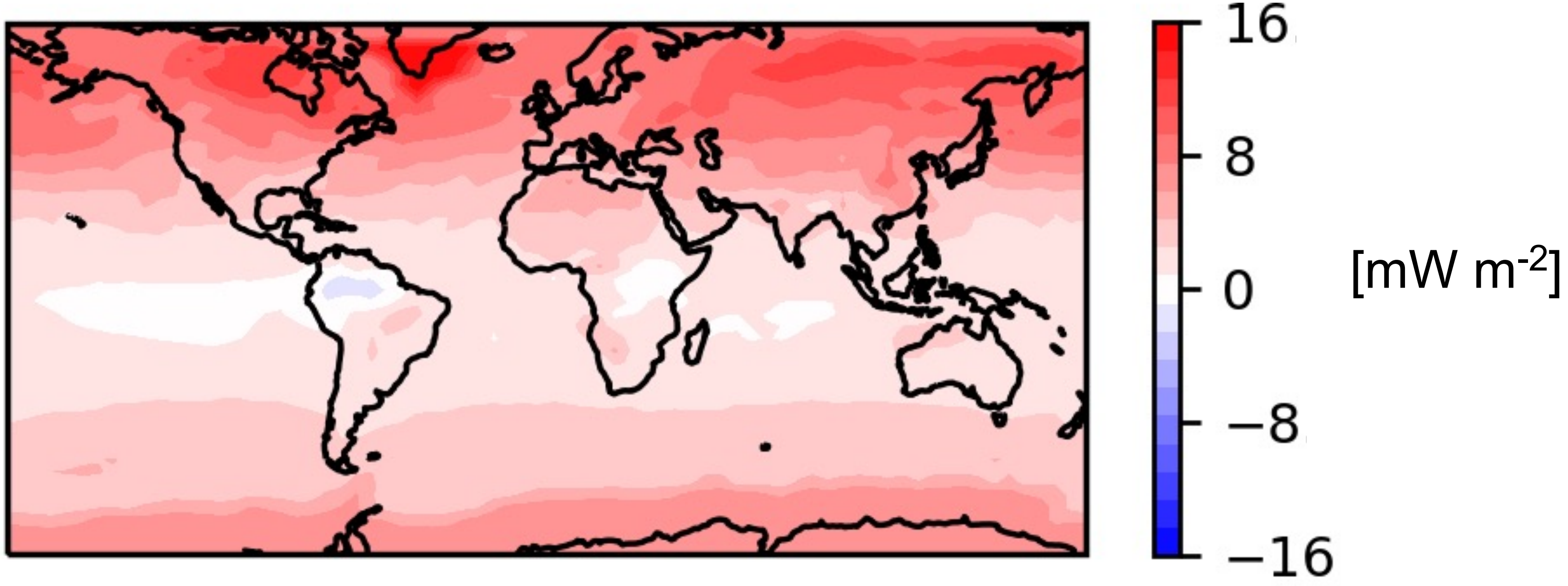
Value for southern hemisphere conservative, as 2019 was anomalously warm over Antarctica

Effect of space tourism on climate

PRELIMINARY

All-sky top-of-atmosphere radiative forcing due to purposeful rocket launches

Global annual mean:
4.7 mW m^{-2}



Biggest impact is from BC (warming) offset slightly by decline in CH_4 and stratospheric ozone

~0.01 % of global BC emissions, 2% of BC radiative forcing.

12 mW m^{-2} (Gg BC)$^{-1}$ suggests space tourism (0.8 Gg BC) scenario is ~10 mW m^{-2}
(4% of global radiative forcing due to BC and a third of radiative forcing of aviation industry emissions)

Conclusions

- Impact of purposeful rockets on stratospheric ozone quite small, assuming no dramatic increase in launches.
- Large relative influence of BC emissions on radiative forcing
- Space tourism scenario has potential to undermine Montreal Protocol progress in repairing the ozone layer and contribute substantial warming from BC emissions
- Lots of caveats: radiative forcing excludes alumina particles, lots of other chemicals produced from rocket fuel and re-entry burn, re-entry burn NO_x emissions uncertain
- Regardless, no international regulation imposed on "tail-pipe" rocket emissions, so nothing to stop the use of the most hazardous fuel types.

Reference:

Robert G. Ryan, E. A. Marais, C. J. Balhatchet, S. D. Eastham, *Impact of rocket launch and space debris air pollutant emissions on stratospheric ozone and global climate*, to submit to Earth's Future.