Using remote sensing and Earth system models to improve air quality and public health in megacities

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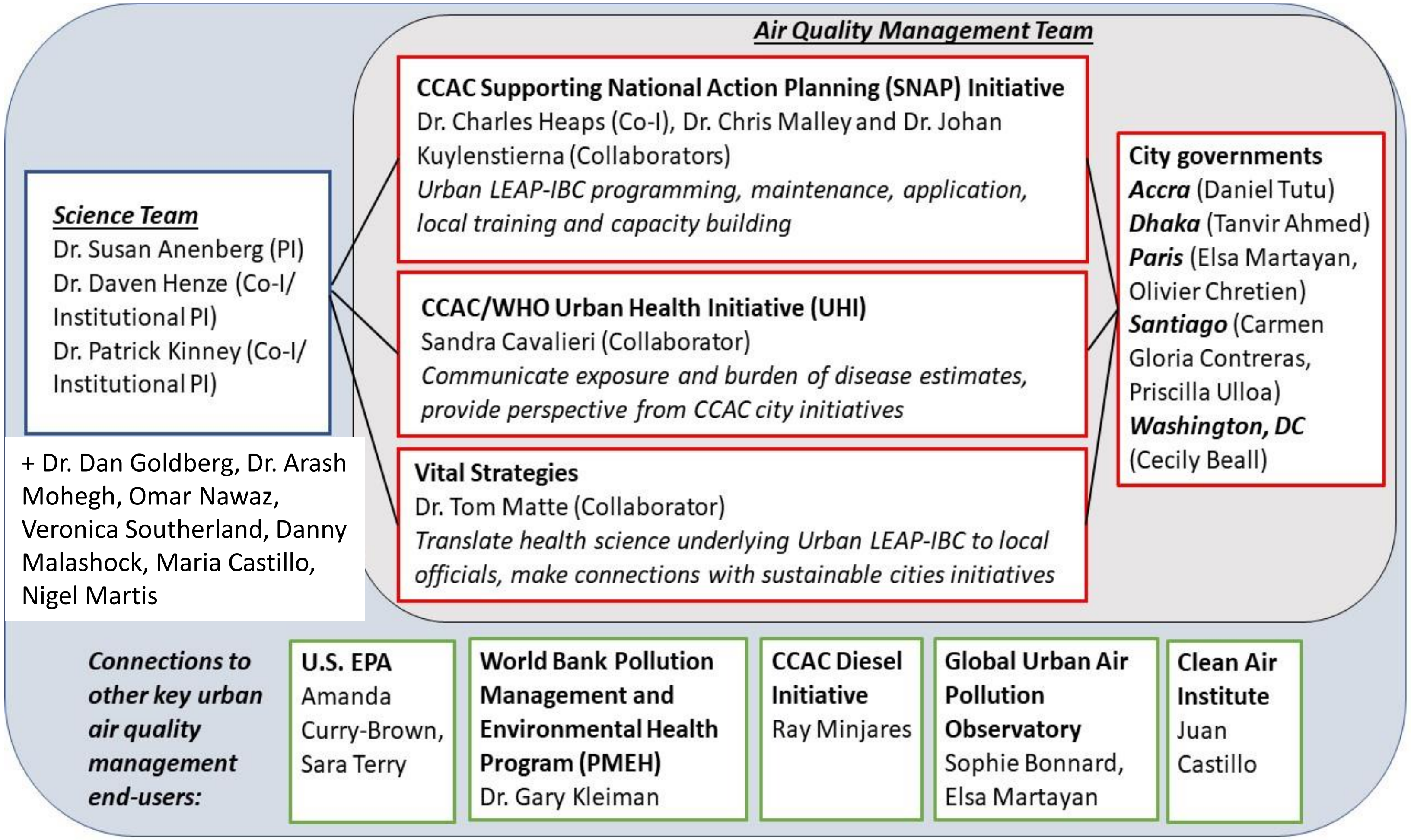
Objective and Team

Objective: Meet the needs of U.S. and international organizations to quantitatively assess air pollution health impacts and mitigation benefits in cities

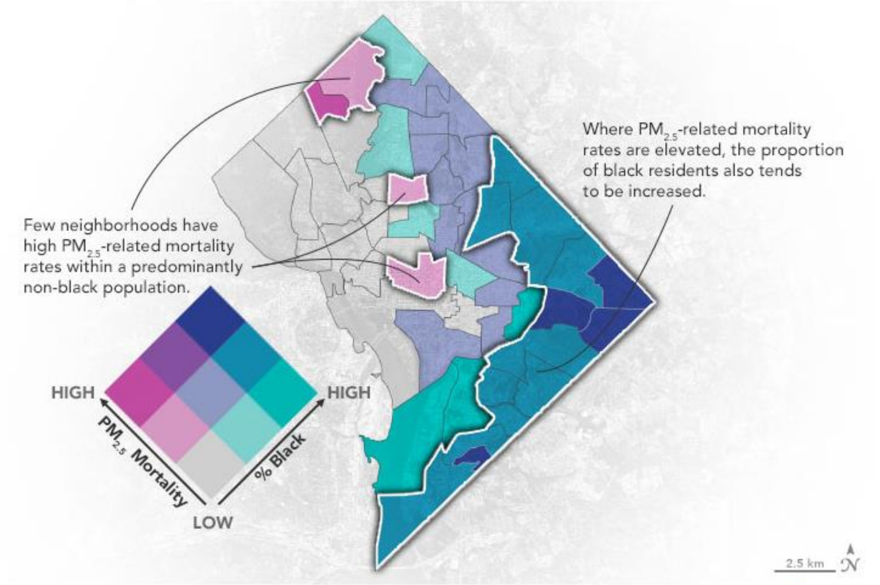
1. Improve and verify estimates of **urban $PM_{2.5}$, ozone, and NO_2 concentrations** and **NOx and SOx emissions** for 5 pilot cities using NASA satellite data from MODIS, MISR, CALIPSO, OMI, as well as TROPOMI and GEOS-Chem
2. Estimate **15-year trends** in $PM_{2.5}$, ozone, and NO_2 exposures and associated mortality and morbidity burdens in cities
3. Expand the national-scale **tool used by the Climate and Clean Air Coalition** to estimate health benefits of mitigation policies to the urban scale
4. In partnership with stakeholders, apply the new tools to **assess health benefits of air quality policy** options in these three pilot cities



Air pollution inequity in Washington, DC

Images | Global Maps | Articles | Blogs | NASA earth observatory | EO

An Extra Air Pollution Burden



2015

JPEG

Like many cities in the eastern United States, Washington, D.C., has seen major improvements in air quality in recent decades. Levels of fine particle pollution ($PM_{2.5}$) have declined by roughly 50 percent in the city since 2000 due to passage of a series of clean

View this area in EO Explorer

New research shows that neighborhoods in Washington, D.C., with more people of color are exposed to more air pollution and have higher rates of disease.

Image of the Day for November 9, 2021

Instruments:
In situ Measurement
Model
Photograph

Appears in this Collection:
Applied Sciences

AGU ADVANCING EARTH AND SPACE SCIENCE

GeoHealth

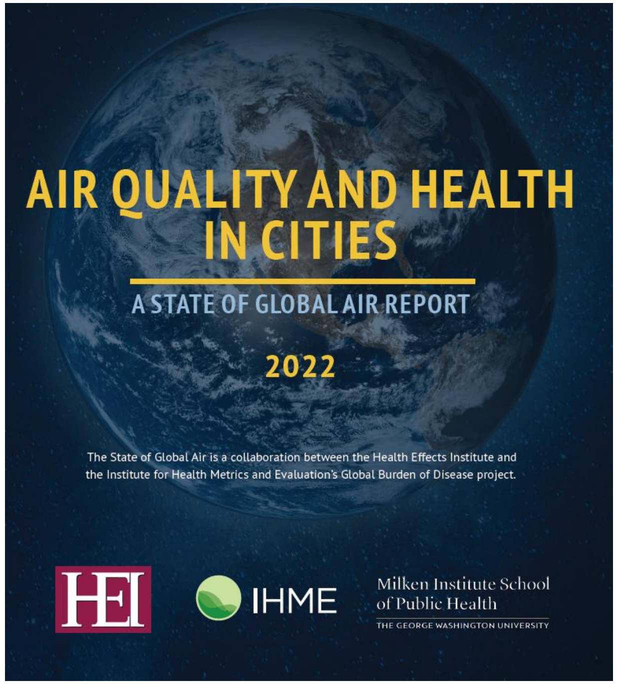
RESEARCH ARTICLE
10.1029/2021GH000431

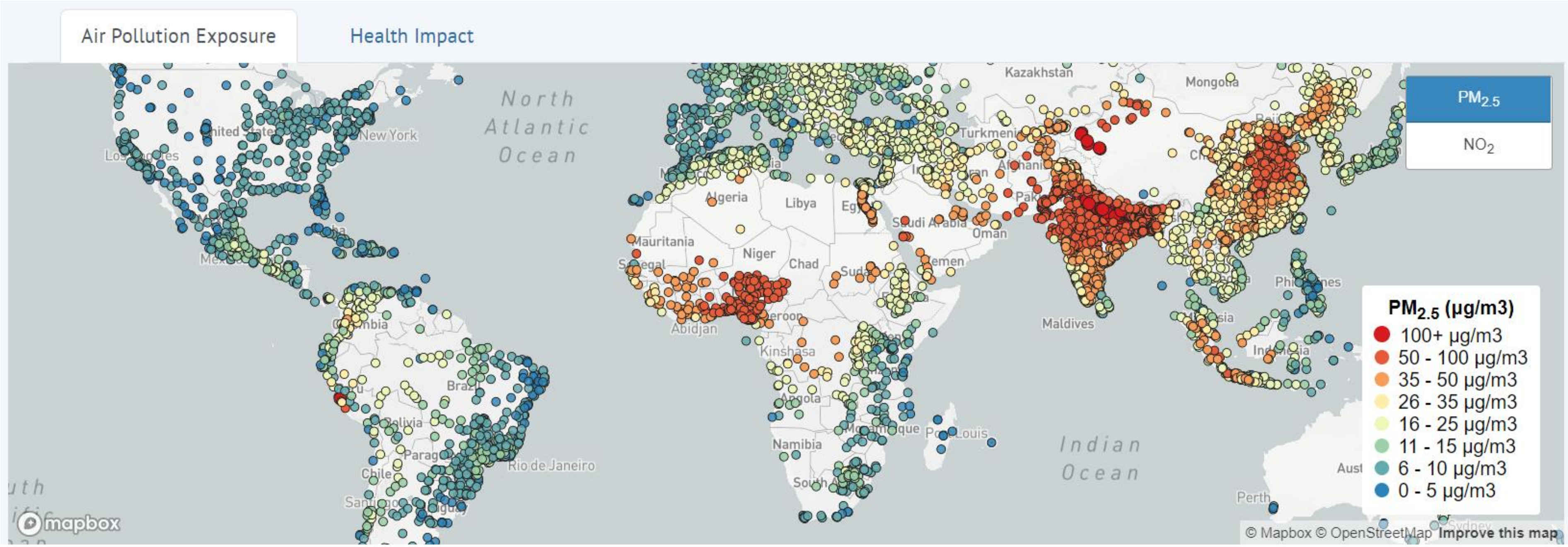
Key Points:
- Fine particulate matter-attributable health risks are unevenly and inequitably distributed across

Estimating Intra-Urban Inequities in $PM_{2.5}$-Attributable Health Impacts: A Case Study for Washington, DC

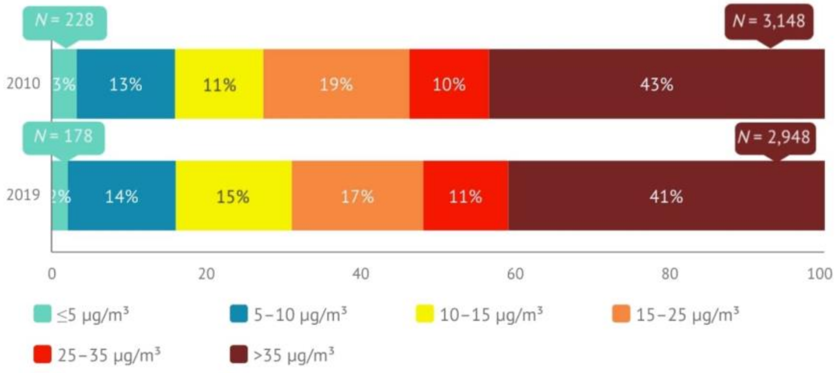
Maria D. Castillo[1], Patrick L. Kinney[2], Veronica Southerland[1], C. Anneta Arno[3], Kelly Crawford[4], Aaron van Donkelaar[5,6], Melanie Hammer[6], Randall V. Martin[6,5], and Susan C. Anenberg[1]

Partner highlight: Health Effects Institute





Percent of cities globally with $PM_{2.5}$ below WHO guideline



Methods/data from HAQ-supported papers

OPEN **Particulate matter-attributable mortality and relationships with carbon dioxide in 250 urban areas worldwide**

Susan C. Anenberg, Pattanun Achakulwisut, Michael Brauer, Daniel Moran, Joshua S. Apte & Daven K. Henze

Global urban temporal trends in fine particulate matter ($PM_{2.5}$) and attributable health burdens: estimates from global datasets

Veronica A Southerland, Michael Brauer, Arash Mohegh, Melanie S Hammer, Aaron van Donkelaar, Randall V Martin, Joshua S Apte, Susan C Anenberg

Long-term trends in urban NO_2 concentrations and associated paediatric asthma incidence: estimates from global datasets

Susan C Anenberg*, Arash Mohegh*, Daniel L Goldberg, Gaige H Kerr, Michael Brauer, Katrin Burkart, Perry Hystad, Andrew Larkin, Sarah Wozniak, Lok Lamsal

Global, national, and urban burdens of paediatric asthma incidence attributable to ambient NO_2 pollution: estimates from global datasets

Pattanun Achakulwisut, Michael Brauer, Perry Hystad, Susan C Anenberg

Partner highlight: Vital Strategies

Brief on satellite data for air quality and health

Audience: policymakers and other stakeholders

Goal: briefly introduce satellite AQ data as an available data source in addition to surface monitoring.

Using Satellite Data for Air Quality and Health Applications

Key characteristics of satellite data: [BOX]

- Critical source of spatially resolved, publicly available data since the 1990s
- Routinely used to characterize exposures for estimates of global burden of disease from air pollution
- Provide estimates of regional and local air quality estimates in the absence of data from ground monitoring

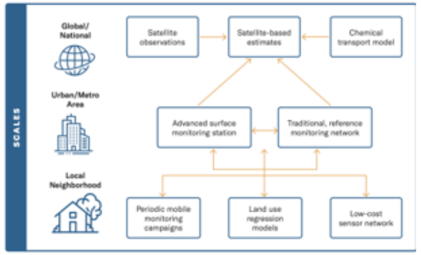


Figure 1 Integrated air quality monitoring system

Innovations in monitoring technology, remote sensing and modelling can provide actionable air pollution data more rapidly and at lower cost than solely relying on conventional monitoring approaches. Satellites orbiting around Earth have been capturing global air quality data for more than two decades and have become critical source global air quality trends. Satellites "see" the atmospheric column that is converted to surface estimates using mathematical models. **These satellite-derived estimates can fill data gaps for regions with little or no ground monitoring.**

Integrated Air Quality Monitoring System

For low- and middle-income countries with limited monitoring capacity, there is no one solution for air quality management. Instead, a hybrid approach that combines conventional solutions with innovative approaches at different scales is more cost effective (Figure 1). Depending on the existing monitoring capacity, satellite data can be used to inform different air quality questions. For regions with no ground monitoring, satellite data can help identify areas that likely have pollutant concentrations well above health action levels[1]. In countries with sufficient ground monitoring capacity, satellite data can be part of an integrated air quality management framework to inform long-term spatiotemporal trends. This brief lays out the basics of satellite data along with some use cases for air quality and health applications.

Global Burden of Disease (GBD) [BOX]

Many cities lack ground monitoring data needed to track air pollutants that impact public health. GBD calculations utilize satellite-derived estimates to fill the critical gaps in exposure data over space and time. Annual averages concentrations are calculated across the entire globe at 1x1 km grid resolution and linked to population size to estimate how many people are exposed. The population level exposures are then linked to underlying disease rates in cities and countries to estimate the disease burden of air pollution. Most recent estimates include disease global burden from $PM_{2.5}$, O_3 and NO_2.[2]

Satellites and sensors

Satellites are platforms on which instruments or sensors are placed. One satellite may have multiple sensors on board, and the same sensor can be on board multiple satellites. Each sensor can capture information on multiple parameters. For example, the MODIS[3] sensor is on board both Aqua and Terra satellites and is a critical source of global $PM_{2.5}$ estimates. TROPOMI, short for Tropospheric Monitoring Instrument, is on board Sentinel 5 - Precursor satellite and measures gases like Ozone, NO_2, SO_2, CO, and aerosols like dust, smoke and black carbon. $PM_{2.5}$ and NO_2 are the most widely used satellite data products for air quality and health applications.

How do satellites measure pollutants?

Each constituent of earth's atmosphere - particles, aerosols, gases have their own spectral signature i.e., the amount of electromagnetic radiation they can absorb, scatter and reflect. Sensors like MODIS and TROPOMI are designed to capture this information which is then converted to geophysical characteristics using mathematical models and computer algorithms.

Satellites vs ground monitors

An important distinction between data from satellites and ground monitors is the quantity they measure. While ground monitors measure surface concentrations, satellites capture information in a vertical atmospheric column (Figure 2). These column measurements are then converted to surface estimates using statistical models or full meteorology-chemical transport models to provide spatially resolved estimates of air quality. The raw satellite

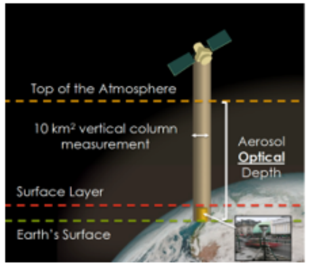


Figure 2 Satellite vs Ground-based measurements [4]

data undergoes several processing and validation steps before it is publicly released for practical applications. Ground measurements are used to validate satellite estimates where feasible. Gridded data sometimes known as Level 3 data [5] in the form of daily estimates and monthly averages is most commonly used for large studies. Non-gridded native or level 2 data is more suitable for advanced users and is available within a day or two of measurements.

$PM_{2.5}$ Measurements

Satellites do not measure pollutants directly. Rather, they measure Aerosol Optical Depth or AOD, which can be considered a proxy for $PM_{2.5}$. AOD is a unitless quantity that represents the amount of aerosols in a column of the atmosphere. Satellite AOD data is extensively used to determine $PM_{2.5}$ concentrations (Figure 3).

NO_2 Measurements

Satellites are now able to also capture spatial patterns in NO_2 at high resolution, at fine enough resolution to estimate concentrations in major cities and from individual sources like power plants and industries. Long term trends are available from OMI[6] and TROPOMI measurements of columnar NO_2.

Spatial and temporal resolution

Depending on the satellite technology and retrieval algorithm, spatial resolution can vary from anywhere between 1km to ~100 km grids. For example, level 2 MODIS AOD data is available at 1km, 3 km and 10 km-grid resolutions while the gridded level 3 data is available at a coarser resolution of ~110 km-grid. The 1 km product has relatively high spatial resolution but more instrument "noise", while the 10 km product has less instrument "noise", but is at coarser spatial resolution.

Temporal resolution largely depends on the orbit that satellites follow. There are two broad types - one that have sun-synchronous polar orbits - so they "see" the same place on earth once or twice a day at the same time which translates to one or two measurements per day. For example - MODIS sensors aboard the Aqua and Terra satellites make daily morning and afternoon measurements respectively. The second type of satellite stays

[1] Vital Strategies 2020, Accelerating City Progress on Clean Air, Technical Guide.

[2] Health Effects Institute 2022. Air Quality and Health In Cities: A State of Global Air Report.

[3] MODerate resolution Imaging Spectro-radiometer

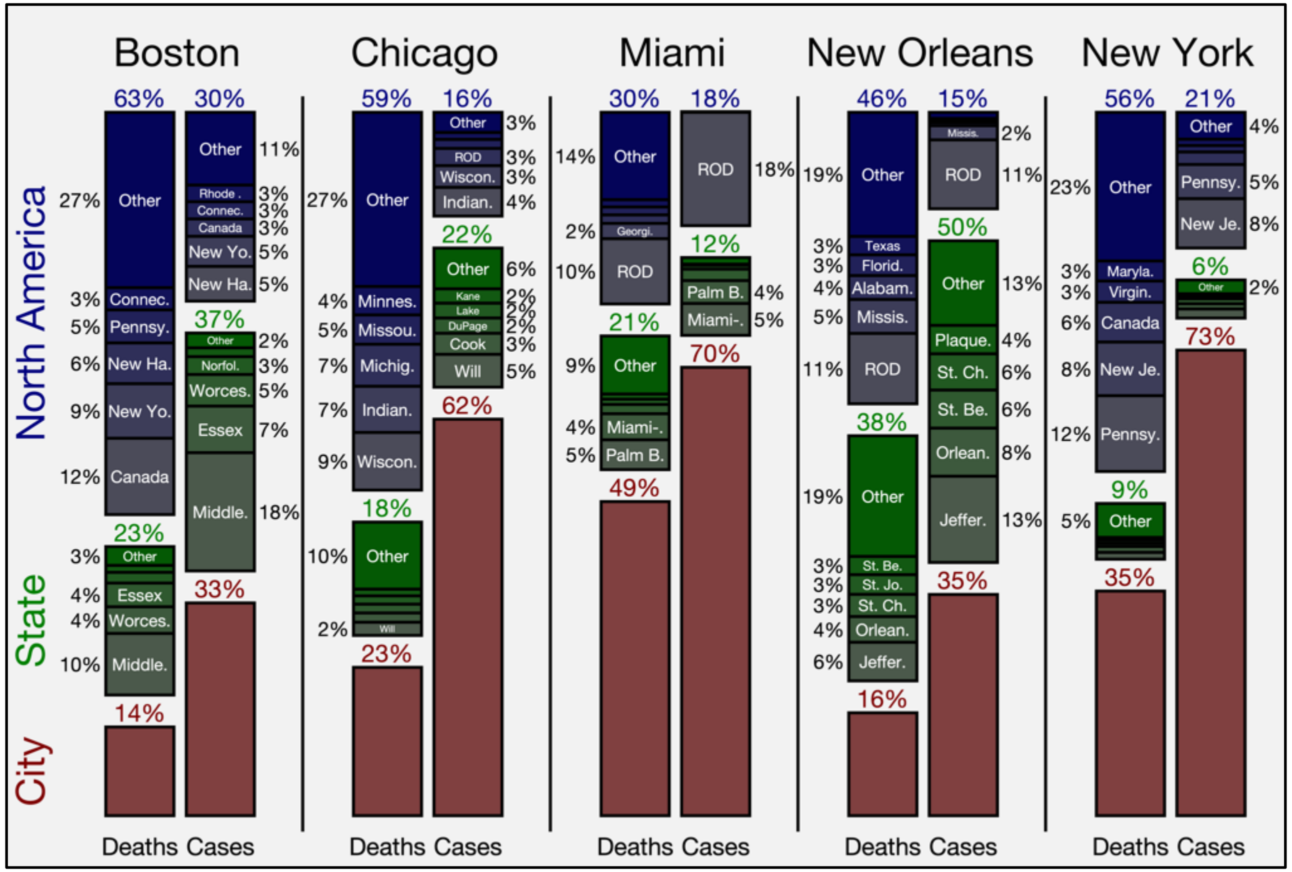
[4] NASA's Applied Remote Sensing Training Program

[5] NASA nomenclature

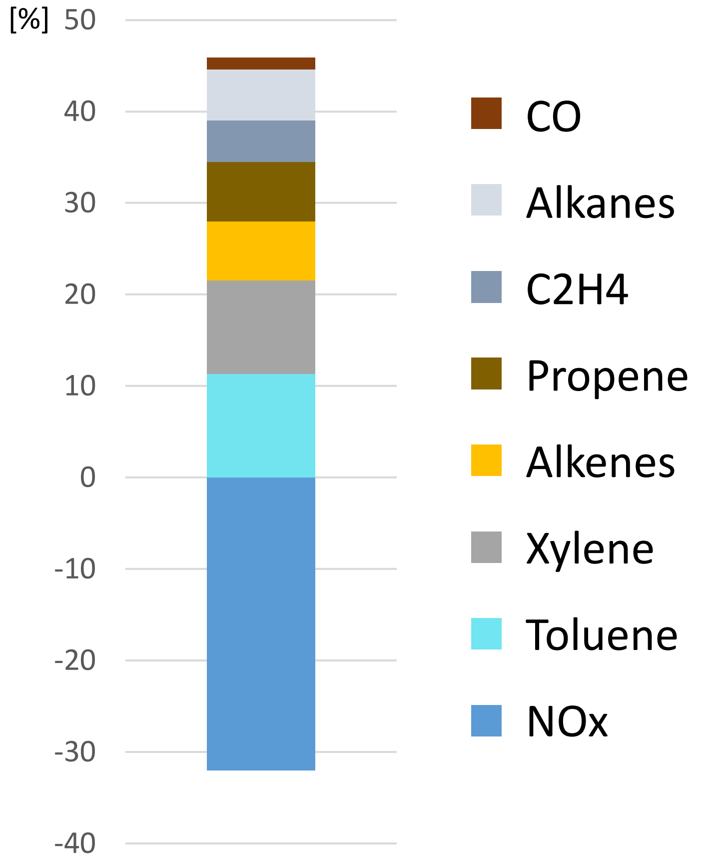
Source attribution of air pollution health impacts using satellite data and model simulations (partners: C40 and SEI)

M. Omar Nawaz, Jinkyul Choi, Daven Henze, University of Colorado Boulder

Municipal vs **county** vs **state** contributions to premature deaths associated with long-term exposure to $PM_{2.5}$ and O_3 (left), as well as NO_2-attributable asthma cases (right) in 14 C40 cities in the US (Nawaz et al., in prep).

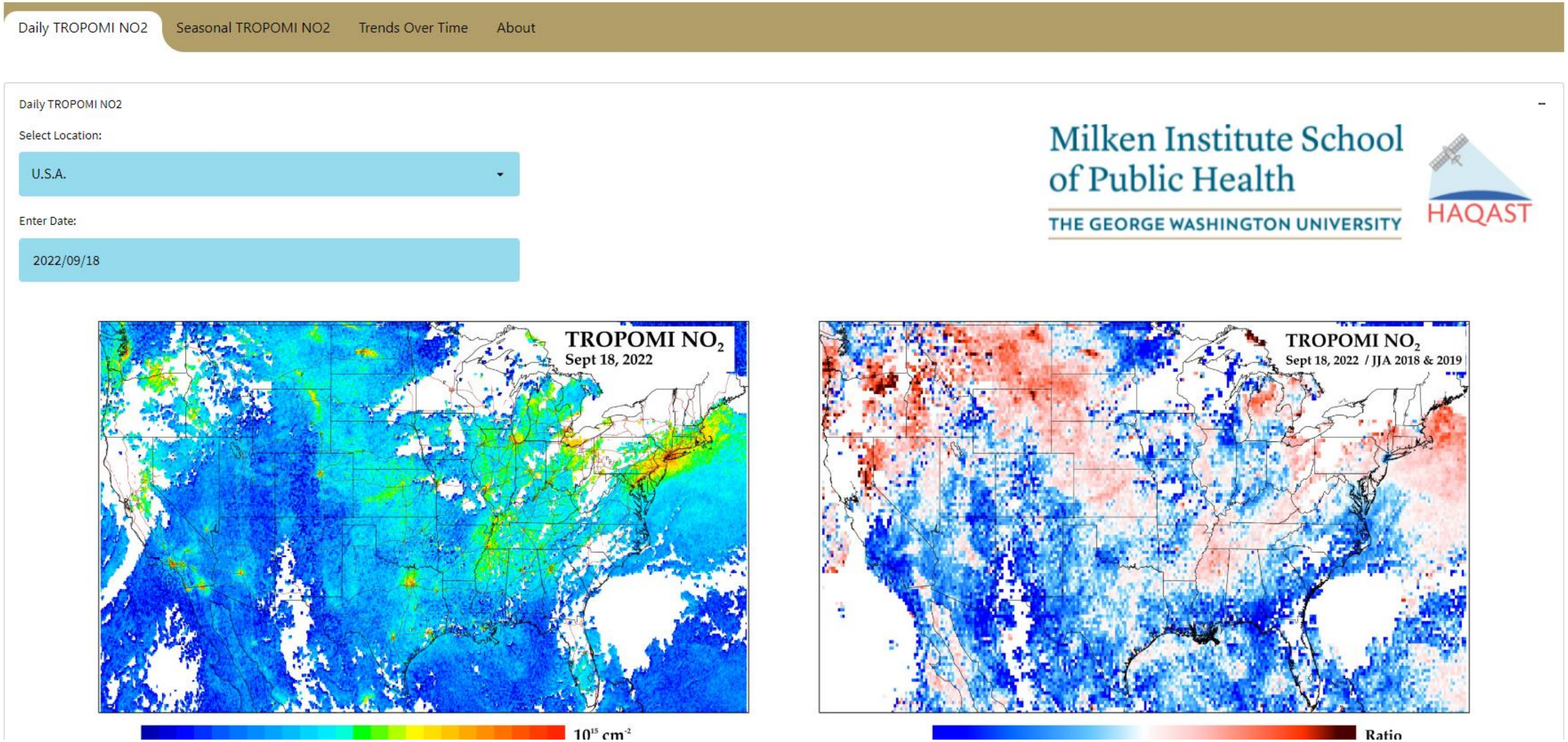


Domestic anthropogenic contributions to premature deaths from long-term O_3 exposure in South Korea, in collaboration with UNEP and SEI (Choi et al., in prep).



Making it easier to see satellite NO_2 data

https://tropomino2.us/



Thanks to Dan Goldberg

Successes and challenges

- Started at ARL 6 (Nov. 2018), now at ARL 9 (Feb. 2022).
  - ***Health Effects Institute*** is using our estimates of PM2.5, ozone, and NO2 concentrations and health impacts in ~13,000 cities in its new State of Global Air – Cities project.
  - ***C40 Cities*** is using our PM2.5 estimates in multiple ways:
    - As the basis for the C40 Cities Clean Air Declaration in October 2019.
    - As an indicator to track progress on air quality among all member cities.
    - As a baseline concentration from which to estimate the air quality benefits of urban climate action plans.
    - In presentations to cities, funders, and external audiences to compare cities' experiences with and progress on air quality.
  - ***Stockholm Environment Institute's*** Urban LEAP-IBC model has been released, used in multiple cities, and described in a journal article.
  - ***DC Department of Energy and Environment*** is using our PM2.5 disparity study to direct emission-reducing resources.
  - ***Environmental Defense Fund*** is using our urban air quality estimates to publicly communicate about air pollution health risks within U.S. cities (e.g. for Boston, https://www.globalcleanair.org/traffic-pollution-harms-childrens-lungs/).
  - ***Vital Strategies*** developed a brief on satellite data for air quality and health aimed at policymakers.
  - Webpages with interactive AQ estimates in 13,000 cities (https://urbanairquality.online/) and TROPOMI NO2 maps (https://tropomino2.us/) are live and getting positive feedback from end users.

Manuscript/Publications

In preparation:
•Rao, S., S. Anenberg, A. Diz Lois Palomares, Z. Klimont, A. Mohegh, S. Tsyro. Global scenarios of pediatric asthma incidence due to NO2 in 2050. In preparation.

Under review:
•Apte, J.S., S Seraj, S.E. Chambliss, M. Hammer, S.C. Anenberg, A. van Donkelaar, R.V. Martin, M. Brauer Air inequality: Global divergence in urban fine particulate matter.
•Kerr, G., R.V. Martin, A. van Donkelaar, M. Brauer, K. Burkart, S. Wozniak, D.L. Goldberg, S.C. Anenberg. Increasing disparities in air pollution health burdens in the United States. Under review.
•Malashock, D., M.N. DeLang, J.S. Becker, M.L. Serre, J.J. West, K.-L. Chang, O.R. Cooper, S.C. Anenberg. Trends in ozone concentration and attributable mortality for urban, peri-urban, and rural areas worldwide between 2000 and 2019: Estimates from global datasets. Under review.
•Pozzer, A., S.C. Anenberg, R. Burnett, S. Dey, A. Haines, J. Lelieveld, S. Chowdhury. Mortality attributable to outdoor air pollution: a review of global estimates. In preparation.
•Larkin, A., A. Mohegh, D.L. Goldberg, M. Brauer, S.C. Anenberg, P. Hystad. A global spatial-temporal land use regression model for nitrogen dioxide air pollution. Under review.

Published:
1. Goldberg, D., Harkey, M., Foy, B. de, Judd, L., Johnson, J., Yarwood, G., & Holloway, T. Evaluating NOx emissions and their effect on O3 production in Texas using TROPOMI NO2 and HCHO. https://doi.org/10.5194/acp-2022-299
2.von Salzen, K., C.Hl Whaley, S.C. Anenberg, R. van Dingenen, Z. Klimont, R. Mahmood, S.R. Arnold, S. Beagley, R.-Y-Chien, J. Christensen, S. Eckhardt, A.M.L. Ekman, N. Evangeliou, G. Faluvegi, M.G. Flanner, J.S. Fu, M. Gauss, W. Gong, J.L. Hjorth, U. Im, S. Krishnan, K. Kupiainen, T. Kuhn, J. Langner, K.S. Law, L. Marelle, D. Olivie, T. Onishi, N. Oshima, A. D.-L. Palomares, V.-V. Paunu, Y. Peng, D. Plummer, L. Pozzoli, S. Rao-Skirbekk, J.-C. Raut, M. Sand, J. Schmale, M. Sigmond, M.A. Thomas, K. Tsigaridis, S.G. Tsyro, S.T. Turnock, M. Wang, B. Winter (2022) Policies to limit air pollution are key for successfully mitigating Arctic warming. Communications Earth and Environment, in press.
3.O'Dell, K., B. Ford, J. Burkhardt, S. Magzamen, S. Anenberg, J. Bayham, E.V. Fischer, J.R. Pierce (2022) Influence of wildfire smoke on indoor air quality in several western US cities. *Environmental Research: Health*, In press.
4.Kerr, G.H., D.L. Goldberg, K.E. Knowland, C.A. Keller, D. Oladini, I. Kheirbek, L. Mahoney, Z. Lu, S.C. Anenberg* (2022) Diesel passenger vehicle shares influenced COVID-19 changes in urban nitrogen dioxide air pollution. *Environmental Research Letters*, in press.
5.Arctic Monitoring and Assessment Program (AMAP), 2021 (chapter lead author). "Health and Ecosystem Impacts" Chapter 8 in: AMAP 2021 Assessment: Arctic climate, air quality, and health impacts from short-lived climate forcers (SLCFs). Tromsø, Norway. (Anenberg was Chapter Lead Author)
6. Malashock, D. A., DeLang, M. N., Becker, J. S., Serre, M. L., West, J. J., Chang, K.-L., et al. (2022). Estimates of ozone concentrations and attributable mortality in urban, peri-urban and rural areas worldwide in 2019. Environmental Research Letters, 17(5), 054023. https://doi.org/10.1088/1748-9326/AC66F3
7. Southerland, V.A., S.C. Anenberg, M. Brauer, A. Mohegh, M. Hammer, R. Martin, A. van Donkelaar, J. Apte (2022) Global urban temporal trends in fine particulate matter (PM2.5) and attributable health burdens: estimates from global datasets. Lancet Planetary Health, https://doi.org/10.1016/S2542-5196(21)00350-8.
8. Anenberg, S.C., A. Mohegh, D.L. Goldberg, G.H. Kerr, M. Brauer, K. Burkart, P. Hystad, A. Larkin, S. Wozniak, L. Lamsal (2022) Long-term trends in urban NO2 concentrations and associated pediatric asthma cases: estimates from global datasets. Lancet Planetary Health, 6(1): E49-E58, https://doi.org/10.1016/S2542-5196(21)00255-2.
9. Nawaz, O., S, Anenberg, D. Goldberg, D. Jo, B. Nault, J. Jimenez, H. Cao, C. Harkins, Z. Qu (2021) Impacts of sectoral, regional, species and day-specific emissions on air pollution and public health in Washington DC. Elementa, https://doi.org/10.1525/elementa.2021.00043.
10. Castillo, M.D., P.L. Kinney, V. Southerland, A. Arno, K. Crawford, A. van Donkelaar, M. Hammer, R.V. Martin, S.C. Anenberg (2021) Estimating intra-urban inequities in PM2.5-attributable health impacts: A case study for Washington, DC. GeoHealth, 5, 11, e2021GH000431, https://doi.org/10.1029/2021GH000431.
11. Goldberg, D.L., S.C. Anenberg, L.N. Lamsal, Z. Lu, E.E. McDuffie, S.J. Smith, D.G. Streets (2021) Urban NOx emissions around the world declined faster than anticipated between 2005 and 2019. Environmental Research Letters, 16, 11, https://doi.org/10.1088/1748-9326/ac2c34.
12. Anenberg, S.C., G.H. Kerr, D.G. Goldberg (2021) Leveraging satellite data to address air pollution inequities. EM Magazine, https://blogs.gwu.edu/sanenberg/files/2021/10/Anenberg_EM.pdf.
13. Goldberg, D.G., S.C. Anenberg, G.H. Kerr, Z. Lu, D.G. Streets (2021) TROPOMI: A revolutionary new satellite instrument measuring NOx air pollution. EM Magazine, https://blogs.gwu.edu/sanenberg/files/2021/10/Goldberg_EM.pdf.
14. Holloway, T., D. Miller, S. Anenberg, M. Diao, B. Duncan, A. Fiore, D. Henze, J. Hess, P. Kinney, Y. Liu, J. Neu, S. O'Neill, R.B. Pierce, A. Russell, D. Tong, J.J. West, M. Zondlo (2021) Satellite monitoring for air quality and health. Annual Review of Biomedical Data Science, In press.
15. Malley, C.S., W.K. Hicks, J.C.I. Kuylenstierna, E. Michaelopoulou, A. Molotoks, J. Slater, C.G. Heaps, S. Ulloa, J. Veysey, D.T. Shindell, D.K. Henze, O. Nawaz, S.C. Anenberg, B. Mantlana, T.P. Robinson (2021) Integrated assessment of global climate, air pollution, and dietary, malnutrition and obesity health impacts of food production and consumption between 2014 and 2018. *Environmental Research Communications*, in press.
16. Goldberg, D., S. Anenberg, G.H. Kerr, A. Mohegh, Z. Lu, D.G. Streets (2021) TROPOMI NO2 in the United States: A detailed look at the annual averages, weekly cycle, effects of temperature, and correlation with surface NO2 concentrations. Earth's Future, https://doi.org/10.1029/2020EF001665.
17. Southerland, V.A., S.C. Anenberg, M. Harris, J. Apte, Hystad, A. van Donkelaar, R. Martin, M. Beyers, A. Roy (2021) Assessing the distribution of air pollution health risks within cities: a neighborhood-scale analysis leveraging high resolution datasets in the Bay Area, California. Environmental Health Perspectives, https://doi.org/10.1289/EHP7679.
18. Kuylenstierna, J.C.I., C.G. Heaps, T. Ahmed, H.W. Vallack, W.K. Hicks, M.R. Ashmore, C.S. Malley, G. Wang, E.N. Lefevre, S.C. Anenberg, F. Lacey, D.T. Shindell, U. Bhattacharjee, D.K. Henze (2020) Using the LEAP-IBC tool to assess air quality and climate co-benefits of emission reduction strategies: A case study for Bangladesh. Environment International, 145, 106155, doi:10.1016/j.envint.2020.106155.
19. Goldberg, D.L., S.C. Anenberg, Z. Lu, D.G. Streets, D. Griffin, C.A. McLinden (2020) Disentangling the impact of the COVID-19 lockdowns on urban NO2 from natural variability. Geophysical Research Letters, doi:10.1029/2020GL089269.
20. Nawaz, M. O., and D. K. Henze (2020) Premature deaths in Brazil associated with long-term exposure to PM2.5 from Amazon fires between 2016-2019, GeoHealth, doi: 10.1029/2020GH000268.

Thanks!

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