Global Change Impacts on Air Quality and Health

Arlene M. Fiore
amfiore @ mit.edu | teampaccc.mit.edu

GLOBAL CHANGE IMPACTS

CLIMATE SYSTEM CHANGES
- temperature
- precipitation
- weather patterns
- cryosphere

RADIATIVE FORCING
- absorption
- scattering
- albedo changes

ATMOSPHERIC COMPOSITION
- atmospheric chemistry and physics

AIR POLLUTION

ANTHROPOGENIC EMISSIONS
- emissions from natural systems

Figure 6.1
IPCC AR6 Ch6 (Szopa et al., 2021)
Exposure to air pollution is a leading risk factor for premature mortality.

Figure 1: Global ranking of risk factors by total number of deaths from all causes in 2019.

- High systolic blood pressure
- Tobacco
- Dietary risks
- Air pollution (6.67 million deaths)
- High fasting plasma glucose
- High body-mass index
- High LDL
- Kidney dysfunction
- Malnutrition
- Alcohol use

Top air pollutants are fine particulate matter (aerosols) and tropospheric ozone.

Figure 1 of 2020 report (2019 data): https://www.stateofglobalair.org/resources
Key Challenge #1: Uncertainties in quantifying exposure to the two top air pollutants (ozone and fine particles)

"Ground-truth" state and local air monitoring

ground-level ozone

c/o M. Tao

Satellite products
tropospheric column NO₂

Goldberg et al., 2021

Models

Young et al., 2018

http://www.tropomi.eu/

TROPOMI Satellite products
The view from space: Declining sources of fine particles in recent decades over some world regions (e.g., sulfur dioxide (SO$_2$) over eastern U.S.A.)

OMI/Aura product, https://airquality.gsfc.nasa.gov/
Air pollutant (PM$_{2.5}$) concentrations are needed to implement air quality standards & for use in health impact studies, but uncertain

Consistent decrease observed in seven PM$_{2.5}$ products despite discrepancies (by 4.2-4.6 µg m$^{-3}$; 25-36%) despite 6 µg m$^{-3}$ range in population-weighted mean PM$_{2.5}$ in 2002

Robust finding across all PM$_{2.5}$ datasets: Lower PM$_{2.5}$ in 2012 vs. 2002 saves lives in New York State (annual mortality burden decreased by >60% from 2002 to 2012).

Excess mortality burden attributed to PM$_{2.5}$ exposure* =
Baseline Mortality \times \text{Attributable Fraction (Relative Risk, function of PM$_{2.5}$)} \times \text{Population}

*Uses GBD 2010 methods; integrated exposure-response model of Burnett et al (2014) developed from a meta-analysis; Ischemic Heart Disease (IHD) is the leading cause

Robust finding across all PM$_{2.5}$ datasets: Lower PM$_{2.5}$ in 2012 vs. 2002 saves lives in New York State (annual mortality burden decreased by >60% from 2002 to 2012)

Excess mortality burden attributed to PM$_{2.5}$ exposure* = Baseline Mortality $\times$ Attributable Fraction (Relative Risk, function of PM$_{2.5}$) $\times$ Population

*Uses GBD 2010 methods; integrated exposure-response model of Burnett et al (2014) developed from a meta-analysis; Ischemic Heart Disease (IHD) is the leading cause

Uncertain exposure also affects relative risk!
Publicly available datasets of daily mean surface PM$_{2.5}$ over New York State: Which one should be selected for health studies?

- Atmospheric chemistry models with chemical data assimilation (WRF-CMAQ 12 km; CAMS Reanalysis ~75 km)
- Machine-learning + satellite + land-use variables + monitors (Bi et al., 2018, 1km) + atmospheric chemistry models (Di et al., 2019 1km)
- Air quality model without chemical data assimilation (U.S. EPA EQUATES 12 km)

Carlos Carrillo-Gallegos
A new statistical approach (Bayesian Non-parametric Ensemble, BNE) to generate a best estimate + uncertainty by combining multiple exposure products

Daily mean PM$_{2.5}$ averaged over New York State, summer 2010

PRELIMINARY RESULTS

→ To be used in epidemiological studies (with NYS DOH)
Ozone and particulate matter events sometimes co-occur with heat waves, modulated by synoptic-scale weather.

Warmer climate:
→ more heat waves
→ more pollution?

e.g., Kirtman et al. 2013 (IPCC AR5 WG1 Ch 11)

Figure 7 of Fiore, Naik, Leibensperger, JAWMA, 2015
Key Challenge #2: Uncertain responses of air pollution to global change

Change in summertime 2m Temp simulated by two global chemistry-climate models

GFDL-CM3 (n=3; $T_{\text{max}}$)  
CESM1 (n=12; $T_{\text{mean}}$)

2006 → 2100  Climate change scenario “RCP8.5_WMGG”

- PM (& ozone in GFDL CM3) precursor emissions held at 2005 levels
- Greenhouse gas pathways prescribed following RCP8.5
- Sea salt, dust, DMS, lightning NO$_x$ tied to model meteorology
- Biogenic & wildfires emissions held constant
- Aerosols (& ozone in GFDL CM3) affect simulated meteorology

Fiore et al., JGR, 2022
Approach: Diagnose changes in frequency & duration of pollution (and heat) events in two chemistry-climate (climate-aerosol only for NCAR) models

- Daily fields archived from GFDL CM3 chemistry-climate & NCAR climate-aerosol models

- EOF analysis on daily PM$_{2.5}$, O$_3$, Temp.
  - Identify regions that vary coherently
  - Reduces size of dataset for analysis

- Select periods (year, decade) for: downscaling (dynamical, statistical); investigate processes; bias correction; extreme value theory methods…

- Time series analysis: Identify changes in frequency and duration of regional-scale events

- Information for air quality (and climate?) management

Goal: tap spatial coverage and statistical power of initial condition ensembles in global (chemistry-) climate models to investigate air quality-climate linkages

---

Fiore et al., JGR, 2022
The Northeast principal component shows more PM$_{2.5}$ excursions into the upper quartile later in the 21$^{\text{st}}$ century.

Occurs in GFDL CM3 RCP8.5_WMGG ensemble members #1, #2, and #3, implying a forced climate signal.

Fiore et al., JGR, 2022
Two models simulate increasing duration of longer upper quartile summertime PM$_{2.5}$ events over the Northeast U.S.A. under rising greenhouse gases.

**NUMBER OF UPPER QUARTILE “EVENTS”**
(Totaled over each decade; then averaged over all ensemble members)

- **GFDL-CM3 (N=3)**
- **NCAR-CESM1 (N=12)**

![Graph showing number of upper quartile events over time for GFDL-CM3 and NCAR-CESM1 models.](image)

G. Milly

*Fiore et al., JGR, 2022*
Climate change will hamper efforts to improve U.S. air quality – Key Message 1 from the Air Quality Chapter of the Fifth National Climate Assessment (2023)

Figure 14.1. Climate change will have varying effects on ozone and fine particulate matter (PM$_{2.5}$) concentrations over the United States, including through impacts on weather-sensitive emissions.

- **Wildfires**
  - Ozone: +
  - PM$_{2.5}$: +
  - Increasing wildfires will degrade air quality.

- **Heatwaves**
  - Ozone: +
  - PM$_{2.5}$: +
  - High temperatures and clear skies can increase pollution.

- **Temperatures**
  - Ozone: +
  - PM$_{2.5}$: +
  - Overall, pollution concentrations will increase as temperatures rise.

- **Drought**
  - Ozone: +
  - PM$_{2.5}$: +
  - Drought will decrease uptake of ozone by vegetation and increase dust PM$_{2.5}$.

- **Biogenic emissions**
  - Ozone: +
  - PM$_{2.5}$: +
  - Warmer temperatures will increase pollutant sources from vegetation and soil.

- **Precipitation**
  - Ozone: Little change
  - PM$_{2.5}$: –
  - Higher precipitation may wash out PM$_{2.5}$.

- **Regional transport**
  - Ozone: ?
  - PM$_{2.5}$: ?
  - Transport of pollution may change, but the trends are unclear.

- **Humidity**
  - Ozone: –
  - PM$_{2.5}$: +
  - Higher humidity will reduce ozone but increase PM$_{2.5}$.

- **Stagnation**
  - Ozone: ?
  - PM$_{2.5}$: ?
  - Pollutants accumulate during stagnant periods, but trends in stagnation are uncertain.

*Feedbacks (mostly) neglected in our prior work.*
Key challenge #3: Uncertainty in precursor emissions and formation chemistry matters for designing effective ground-level ozone abatement strategies.

Volatile Organic Compounds (VOCs)
E.g., Isoprene (C$_5$H$_8$), methane (CH$_4$)

Nitrogen Oxides (NO$_x$)
= NO + NO$_2$

What can we learn about ozone-forming chemistry and its changes in space and time from instruments aboard satellites?

Data source: U.S. EPA 2014 National Emissions Inventory

Slide c/o M. Tao, Columbia
Satellite and airborne datasets imply enhanced sensitivity of local ozone smog formation to NO\textsubscript{x} emission controls over NYC area on the highest-ozone days.

Madankui Tao
(Grad student, Columbia)

Tao et al., ES&T 2022

Summer 2018
Looking forward... new ‘eyes in the sky’ to observe air pollutants throughout daylight hours

We seek to identify new applications of satellite data for understanding local-to-regional ozone chemistry and co-exposure to multiple pollutants & heat

[e.g., Tao et al., submitted; Tao et al., ES&T 2022; Jin et al., ES&T 2020]
Current HAQAST ‘Tiger Team’ on Analysis to support air quality and health TEMPO applications for surface ozone
10 HAQAST Pis/Co-Is + their teams; 12+ AQ/health organizations; other scientific collaborators

www.haqast.org
Some closing thoughts on Key Challenges in understanding Global Change Impacts on Air Quality and Health

**#1: Uncertainty in air pollution (co-)exposures**

→ Opportunities with novel approaches to fuse datasets but fundamental constraint of insufficient independent data for validation

**#2: Uncertainty in air pollution response to climate (and other global) change**

→ Many processes in play, with net balance likely to vary in space and time; some processes missing from current Earth System models

**#3: Uncertainty in ozone precursors, formation chemistry and sinks**

→ Transformative new satellite data coming online next month but careful work needed to determine information content