Air pollution impacts

ENV-409

Air Pollution

Part 1 – health impacts (focus on particulate matter)

“Pollution”

pollution /pəˈluːʃ(ə)n/ *noun*.

“the presence in or introduction into the environment of a substance which has harmful or poisonous effects”

–Oxford English Dictionary

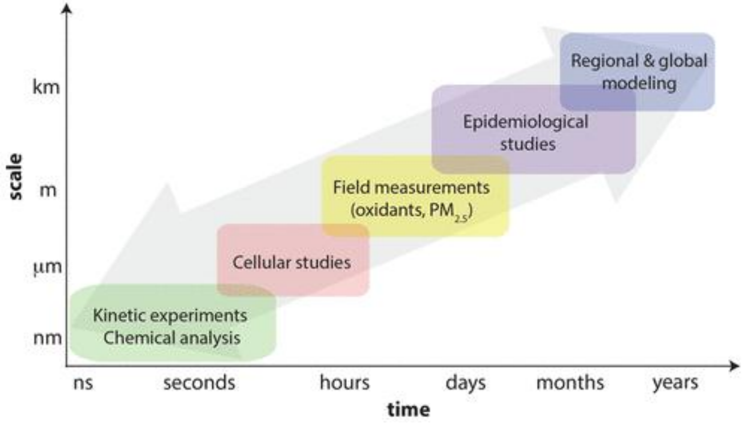
Types of pollutants

- Responsible for toxic/adverse health effects:
  - damaging to biological function
  - acute / chronic
  - morbidity / mortality
  - carcinogens, mutagens, teratogens
  - radiation
- Species contributing to “endangerment” of health
- Negative impacts on ecosystem welfare

1987

Guideline levels for each pollutant ($\mu g/m^3$):		
$PM_{2.5}$	1 year	~~10~~ **5** (reduced in 2021)
	24 h (99th percentile)	25
PM_{10}	1 year	20
	24 h (99th percentile)	50
Ozone, O_3	8 h, daily maximum	100
Nitrogen dioxide, NO_2	1 yr	40
	1 h	200
Sulfur dioxide, SO_2	24 h	20
	10 min	500

Study designs



Shiraiwa et al., *ES&T*, 2017

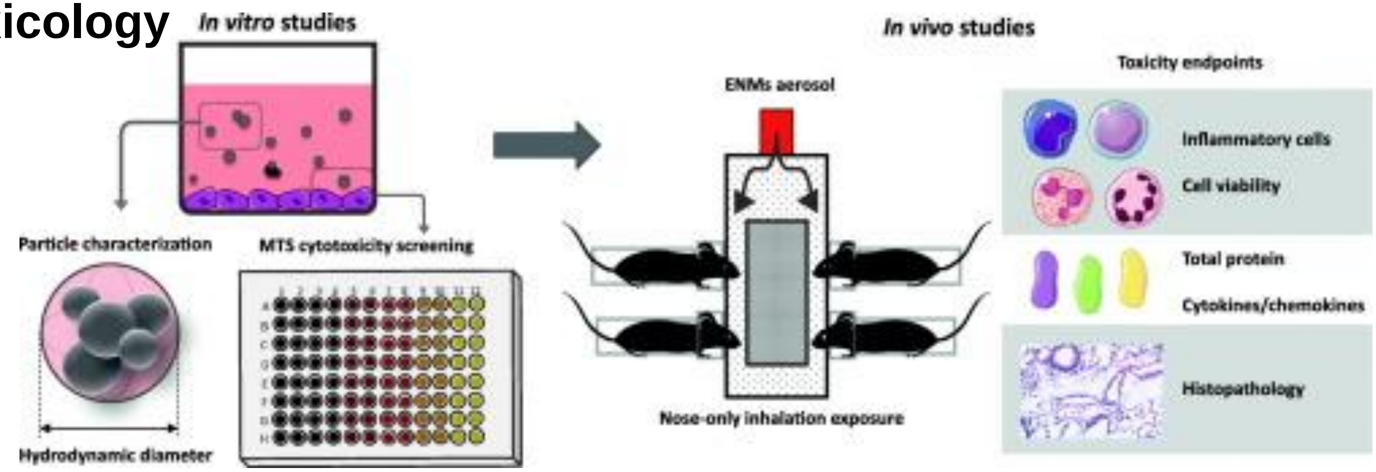
Epidemiology

Type	Description
Cohort	associate long-term cumulative exposure with health outcomes
Time series	associate daily exposure levels with population-averaged health outcomes
Case-crossover	study acute exposure and health outcomes in individuals selected after event
Panel	Follow preselected individuals in detail and investigate changes in repeated outcome measures

Peng and Dominici, *Statistical Methods for Environmental Epidemiology with R: A Case Study in Air Pollution and Health*, 2008

also:
- *cross-sectional*

Toxicology



Areecheewakul et al., *Nanoimpact*, 2020

in vitro
acellular / chemical assays
cellular / biological assays

in vivo
human subjects
other animal subjects

also:
- *ex vivo*
- *in silico*

Nanotoxicology: An Emerging Discipline Evolving from Studies of Ultrafine Particles

Günter Oberdörster,[1] Eva Oberdörster,[2] and Jan Oberdörster[3]

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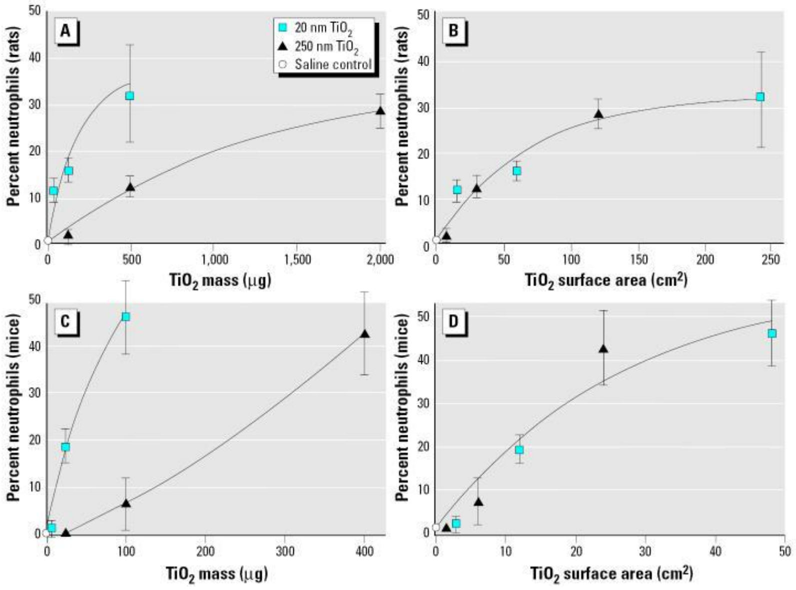
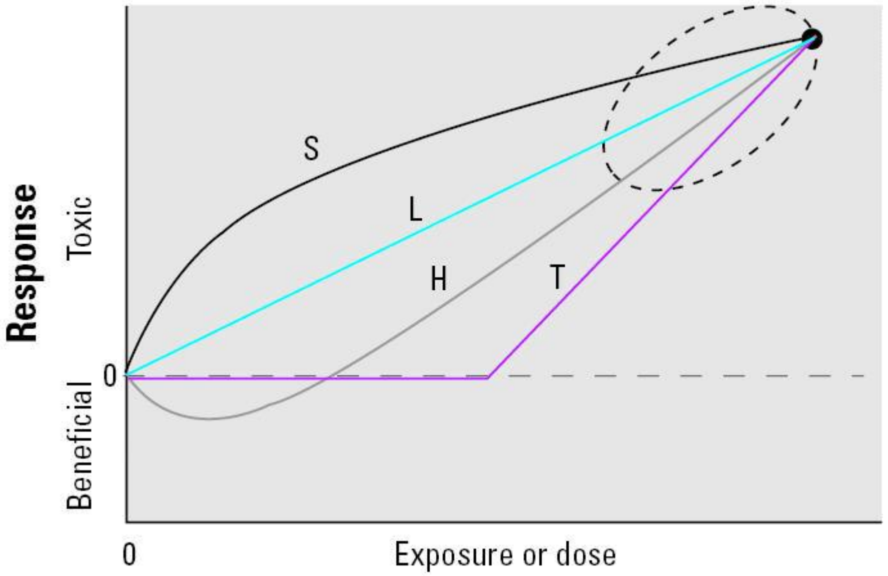


In vivo toxicology studies

- High dose and exposure concentrations
- Short timescale of experiments
- Interpolation to low concentrations



Atmos. Chem. Phys., 18, 15003–15016, 2018
https://doi.org/10.5194/acp-18-15003-2018

Atmospheric Chemistry and Physics
Open Access
EGU

Long-term trends in the ambient $PM_{2.5}$- and O_3-related mortality burdens in the United States under emission reductions from 1990 to 2010

Yuqiang Zhang[1,a], J. Jason West[2], Rohit Mathur[3], Jia Xing[4], Christian Hogrefe[3], Shawn J. Roselle[3], Jesse O. Bash[3], Jonathan E. Pleim[3], Chuen-Meei Gan[5], and David C. Wong[3]

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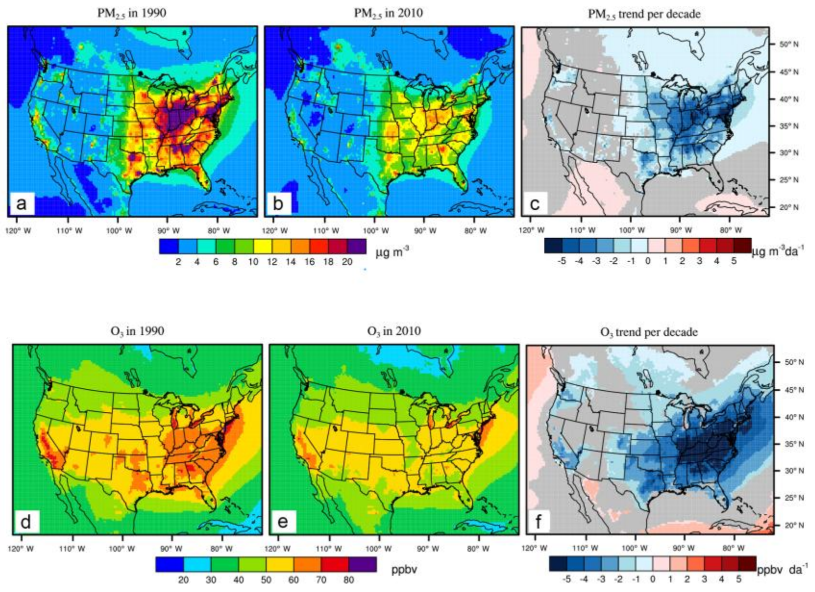
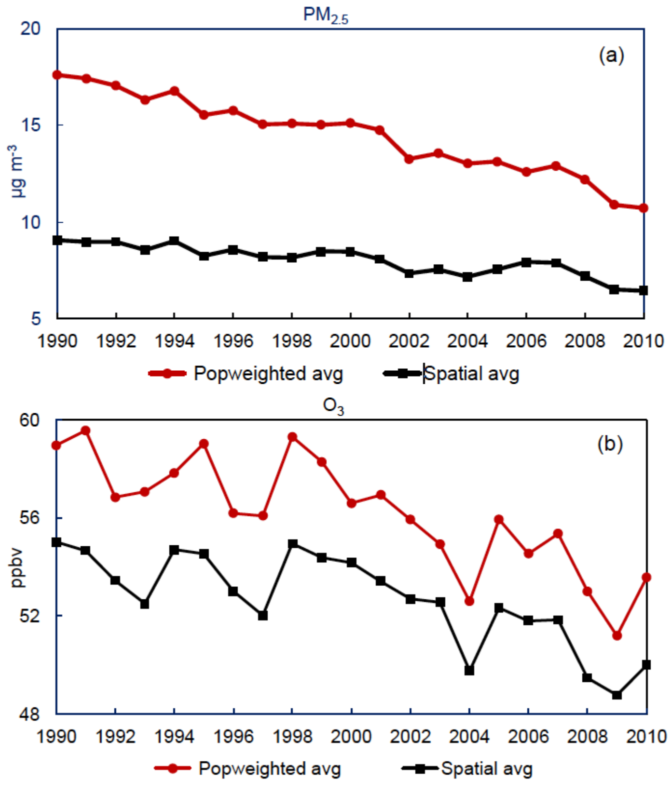
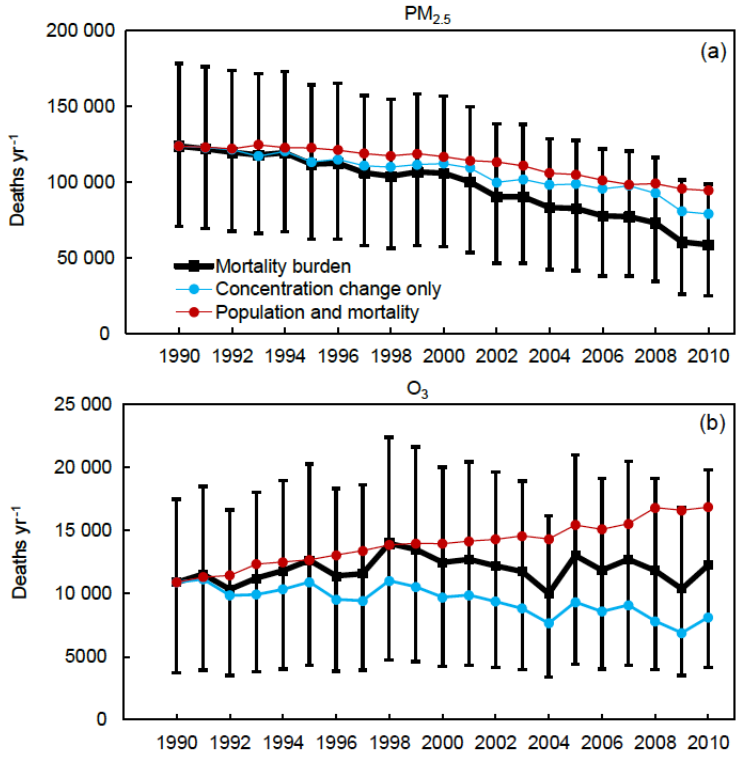
[a]now at: Nicholas School of the Environment, Duke University, Durham, NC 27710, USA

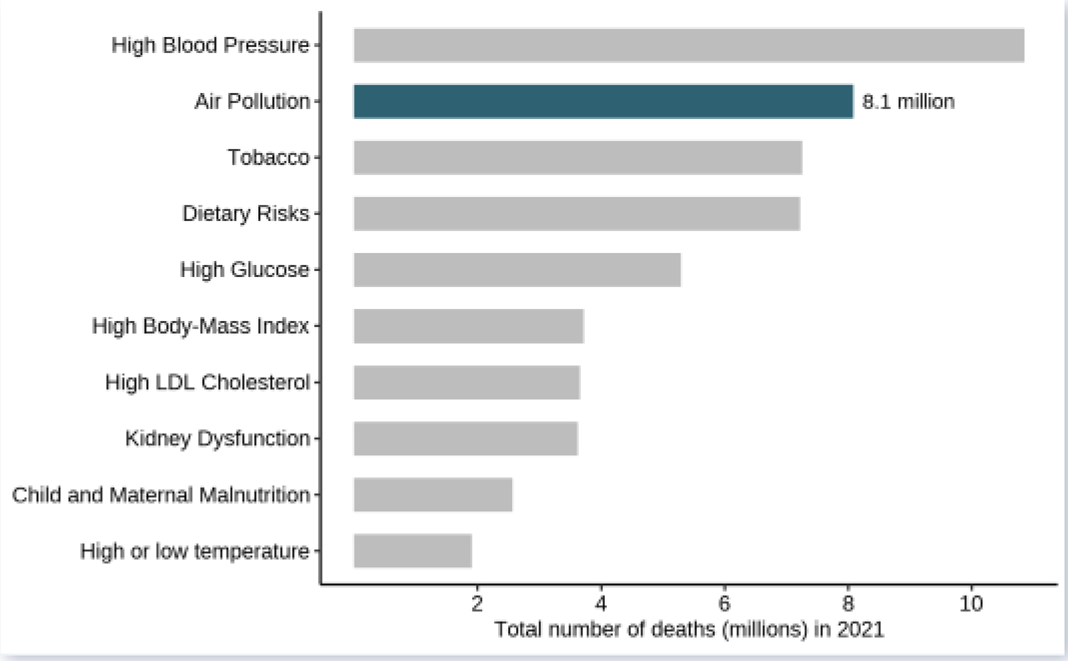






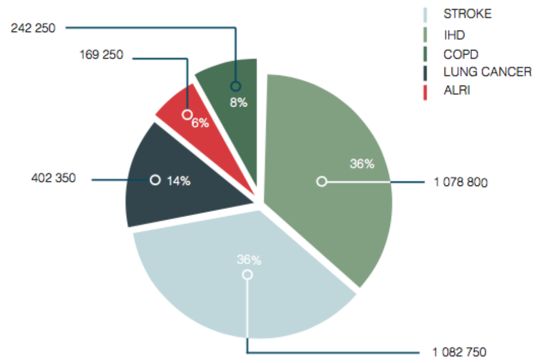
Particulate matter and health

- Mortality
- Respiratory illnesses
- Cardiovascular effects
- Neurogenerative diseases



https://vizhub.healthdata.org/gbd-compare/
State of Global Air 2024

Figure 20: Deaths attributable to AAP in 2012, by disease



Percentage represents percentage of total AAP burden. AAP: ambient air pollution; ALRI: acute lower respiratory disease; COPD: chronic obstructive pulmonary disease; IHD: ischaemic heart disease.

source: WHO

The New England
Journal of Medicine

Volume 329 DECEMBER 9, 1993 Number 24

AN ASSOCIATION BETWEEN AIR POLLUTION AND MORTALITY IN SIX U.S. CITIES

Douglas W. Dockery, Sc.D., C. Arden Pope III, Ph.D., Xiping Xu, M.D., Ph.D.,
John D. Spengler, Ph.D., James H. Ware, Ph.D., Martha E. Fay, M.P.H.,
Benjamin G. Ferris, Jr., M.D., and Frank E. Speizer, M.D.

Cohort study of 8111 Americans

Medical history and lifestyle examined over 14-16 years

Association found between excess mortality and fine particulate matter pollution

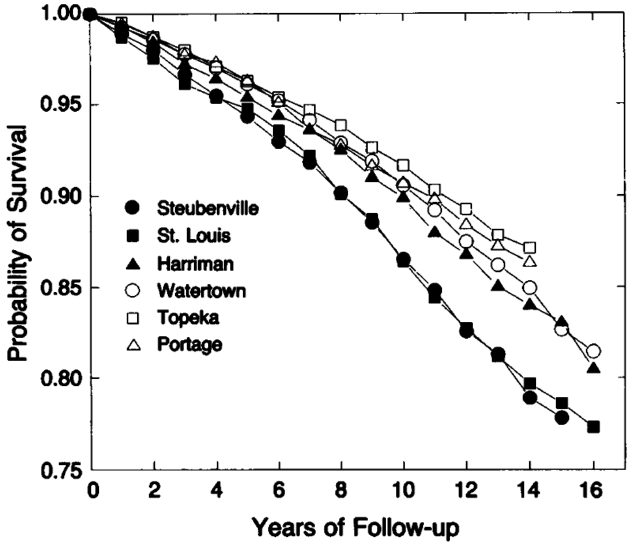


Figure 2. Crude Probability of Survival in the Six Cities, According to Years of Follow-up.

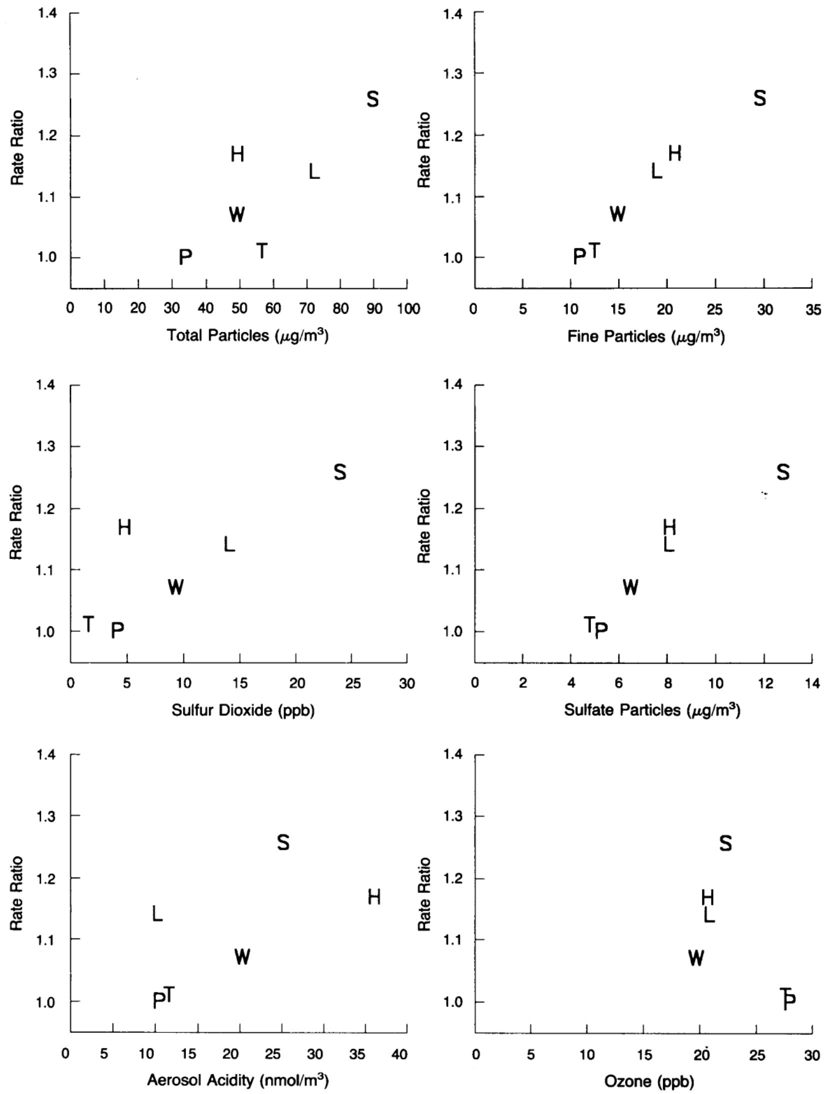


Figure 3. Estimated Adjusted Mortality-Rate Ratios and Pollution Levels in the Six Cities.
re shown for the measures of air pollution. P denotes Portage, Wisconsin; T Topeka, Kansas; W Watertown, Massachusetts; L St. Louis; H Harriman, Tennessee; and S Steubenville, Ohio.

Survival analysis

Cox proportional hazards model

$$\lambda_{\mathrm{A}}(t) = -\frac{d}{dt}\ln S(t)$$

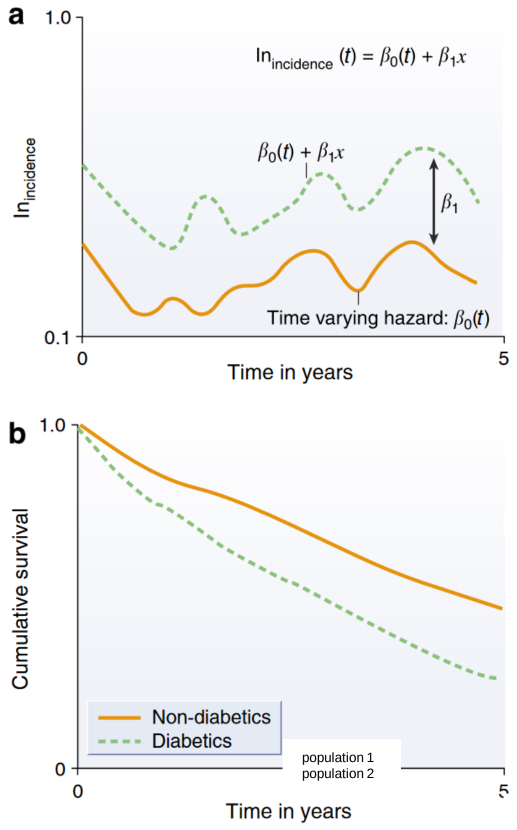
survival probability

hazard function | baseline hazard | confounders | exposure

$$\lambda_A(t) = \lambda_B(t) \times \exp\left(\sum_{i=1}^{k} \beta_i X_i + \gamma E\right)$$

log-linear relation to exposure

$$\ln \lambda_A(t) = \beta_0(t) + \sum_{i=1}^{k} \beta_i X_i + \gamma E$$



adapted from van Dijk et al., 2008

Confounders

- Stratified by age group and sex

- Smoking
- Education level
- BMI
- Exposure to local sources (occupational exposure)

Improvements in estimates

- Larger cohorts
- Better exposure estimate
  - combine ground-based measurements, satellite remote sensing, and air quality model simulations
  - high resolution
  - capture microenvironments
- More confounding variables
  - environmental variables
  - behavioral, social, and economic variables
  - demographic variables
- Specific chemical constituents

nature COMMUNICATIONS

ARTICLE

https://doi.org/10.1038/s41467-021-27484-1 OPEN

Check for updates

Secondary organic aerosol association with cardiorespiratory disease mortality in the United States

Havala O. T. Pye[1✉], Cavin K. Ward-Caviness[2], Ben N. Murphy[1], K. Wyat Appel[1] & Karl M. Seltzer[3]

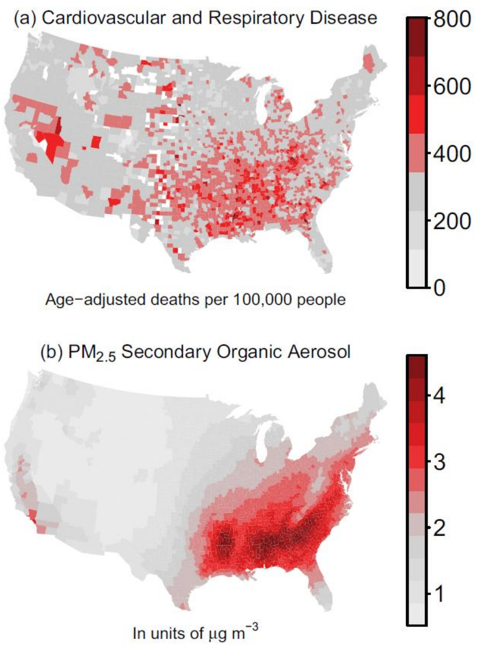


Fig. 1 Cardiorespiratory disease mortality rates and secondary organic aerosol concentrations. County-level, year 2016 (**a**) cardiovascular and respiratory disease age-adjusted death rates (per 100,000 in population) are from CDC and (**b**) $PM_{2.5}$ secondary organic aerosol concentrations are predicted by CMAQ. White in (**a**) indicates no death rate data while light gray indicates low reported rates.

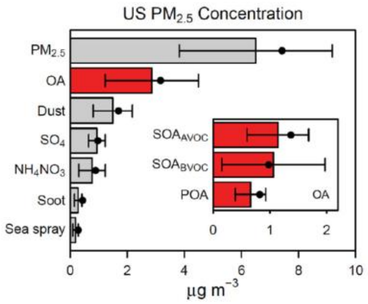


Fig. 2 Contiguous U.S. county-level average predicted concentration of $PM_{2.5}$ and its major components (bars) for 2016 (*n* = 2708 counties). Major components include organic aerosol (OA), a calcium-iron-silicon-aluminum rich aerosol (dust), sulfate (SO_4), ammonium and nitrate (NH_4NO_3), an elemental carbon and potassium rich aerosol (soot), and a chloride-sodium-magnesium rich aerosol (sea spray). Inset in red are the subcomponents of OA: SOA from anthropogenic VOCs (SOA_{AVOC}), SOA from biogenic VOCs (SOA_{BVOC}), and primary organic aerosol (POA). Error bars represent ±1 IQR variation in the pollutant from the county-level average. Points represent population-weighted concentrations.

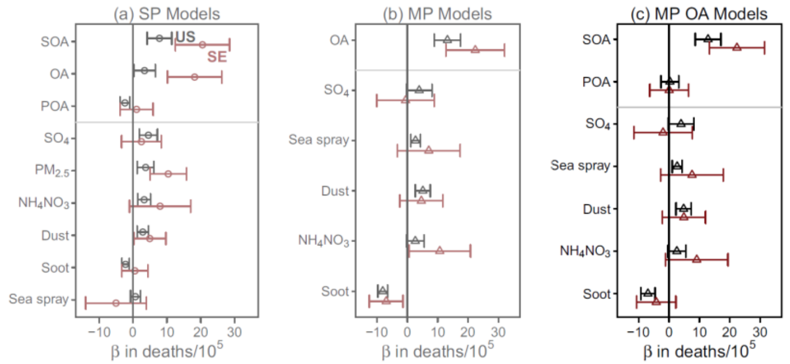


Fig. 3 Association of $PM_{2.5}$ and its components with death rates across the contiguous U.S. (*n* = 2708 counties) in black and southeastern (SE) U.S. (*n* = 646 counties) in red (open symbol) determined via regressed coefficients (β) from multiple linear regression and their 95% confidence intervals (whiskers). Models forms (see Methods, Table 2) are **a** single pollutant (SP, circles) or multipollutant (triangles) (**b**) for $PM_{2.5}$ components (MP) and **c** with refinement of OA subcomponents (MP OA). Regressed coefficients correspond to IQR-normalized species concentrations (Supplementary Table 1) in units of deaths per 100,000 in population. Horizontal gray lines are used to visually separate results for OA and its subcomponents (primary organic aerosol, POA, and secondary organic aerosol, SOA) from the other components.

On a per mass basis, SOA is associated with a 6.5× higher rate of mortality than $PM_{2.5}$, and biogenic and anthropogenic carbon sources both play a role in the overall SOA association with mortality.

PNAS

Check for updates

Global estimates of mortality associated with long-term exposure to outdoor fine particulate matter

Richard Burnett[a], Hong Chen[a,b], Mieczysław Szyszkowicz[a,1], Neal Fann[c], Bryan Hubbell[d], C. Arden Pope III[e], Joshua S. Apte[f], Michael Brauer[g], Aaron Cohen[h], Scott Weichenthal[i,j], Jay Coggins[k], Qian Di[l], Bert Brunekreef[m], Joseph Frostad[n], Stephen S. Lim[n], Haidong Kan[o], Katherine D. Walker[h], George D. Thurston[p], Richard B. Hayes[q], Chris C. Lim[r], Michelle C. Turner[s], Michael Jerrett[t], Daniel Krewski[u], Susan M. Gapstur[v], W. Ryan Diver[v], Bart Ostro[w], Debbie Goldberg[x], Daniel L. Crouse[y], Randall V. Martin[z], Paul Peters[aa,bb,cc], Lauren Pinault[dd], Michael Tjepkema[dd], Aaron van Donkelaar[z], Paul J. Villeneuve[aa], Anthony B. Miller[ee], Peng Yin[ff], Maigeng Zhou[ff], Lijun Wang[ff], Nicole A. H. Janssen[gg], Marten Marra[gg], Richard W. Atkinson[hh,ii], Hilda Tsang[jj], Thuan Quoc Thach[jj], John B. Cannon[e], Ryan T. Allen[e], Jaime E. Hart[kk], Francine Laden[kk], Giulia Cesaroni[ll], Francesco Forastiere[ll], Gudrun Weinmayr[mm], Andrea Jaensch[mm], Gabriele Nagel[mm], Hans Concin[nn], and Joseph V. Spadaro[oo]

Hazard ratios quantify risk per unit of PM

$$\mathrm{HR} = \exp(\gamma)$$

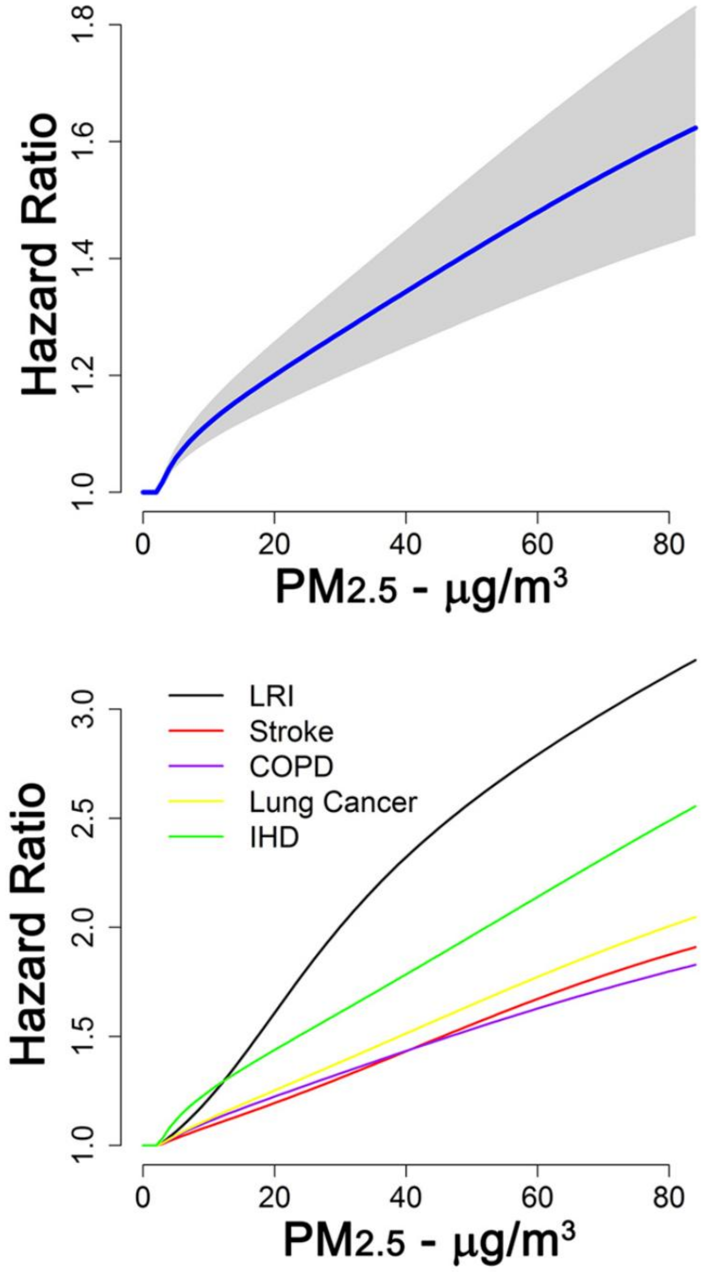


Fig. 1. GEMM hazard ratio predictions over $PM_{2.5}$ exposure range for noncommunicable diseases plus LRIs (NCD+LRI). (*Top*) With 95% confidence interval (gray shaded area). (*Bottom*) GEMM predictions for each of the five causes of death displayed. GEMM NCD+LRI, GEMM IHD, and GEMM stroke were based on the 60- to 64-y-old age group.

Harrell, Jr., *Regression Modeling Strategies*, 2015
Armitage et al., *Statistical methods in medical research*, 2002

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

Lancet Planet Health 2022; 6: e139–46

Published Online
January 5, 2022
https://doi.org/10.1016/S2542-5196(21)00350-8

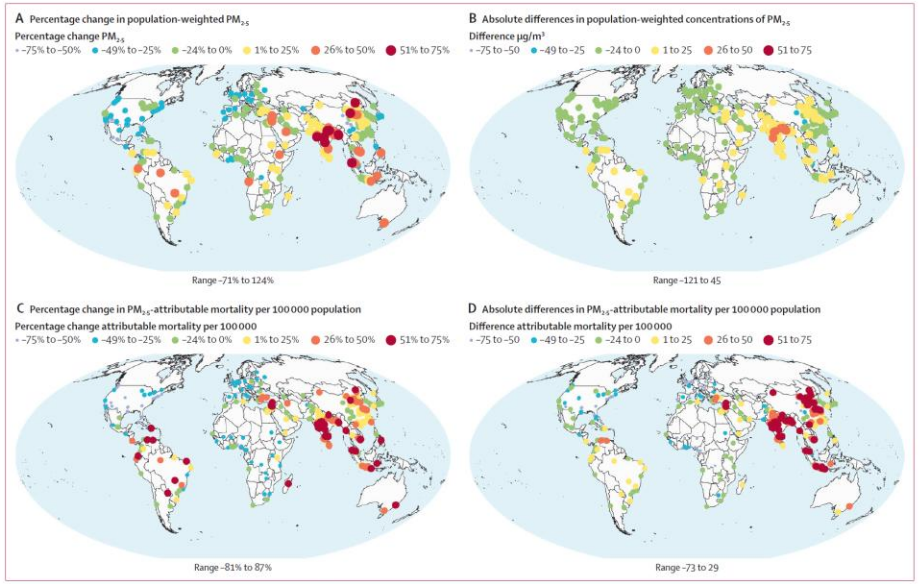


Figure 3: Change in population-weighted $PM_{2·5}$ concentrations and $PM_{2·5}$-attributable mortality rates between 2000 and 2019 for the top 250 most populated urban areas based on 2019 WorldPop estimates
(A) Percentage change in population-weighted $PM_{2·5}$ concentrations. (B) Absolute differences in population-weighted concentrations of $PM_{2·5}$. (C) Percentage change in $PM_{2·5}$-attributable mortality per 100000 population. (D) Absolute differences in $PM_{2·5}$-attributable mortality per 100 000 population.

Summary

Background With much of the world's population residing in urban areas, an understanding of air pollution exposures at the city level can inform mitigation approaches. Previous studies of global urban air pollution have not considered trends in air pollutant concentrations nor corresponding attributable mortality burdens. We aimed to estimate trends in fine particulate matter ($PM_{2·5}$) concentrations and associated mortality for cities globally.

Methods We use high-resolution annual average $PM_{2·5}$ concentrations, epidemiologically derived concentration response functions, and country-level baseline disease rates to estimate population-weighted $PM_{2·5}$ concentrations and attributable cause-specific mortality in 13 160 urban centres between the years 2000 and 2019.

Findings Although regional averages of urban $PM_{2·5}$ concentrations decreased between the years 2000 and 2019, we found considerable heterogeneity in trends of $PM_{2·5}$ concentrations between urban areas. Approximately 86% (2·5 billion inhabitants) of urban inhabitants lived in urban areas that exceeded WHO's 2005 guideline annual average $PM_{2·5}$ (10 μg/m³), resulting in an excess of 1·8 million (95% CI 1·34 million–2·3 million) deaths in 2019. Regional averages of $PM_{2·5}$-attributable deaths increased in all regions except for Europe and the Americas, driven by changes in population numbers, age structures, and disease rates. In some cities, $PM_{2·5}$-attributable mortality increased despite decreases in $PM_{2·5}$ concentrations, resulting from shifting age distributions and rates of non-communicable disease.

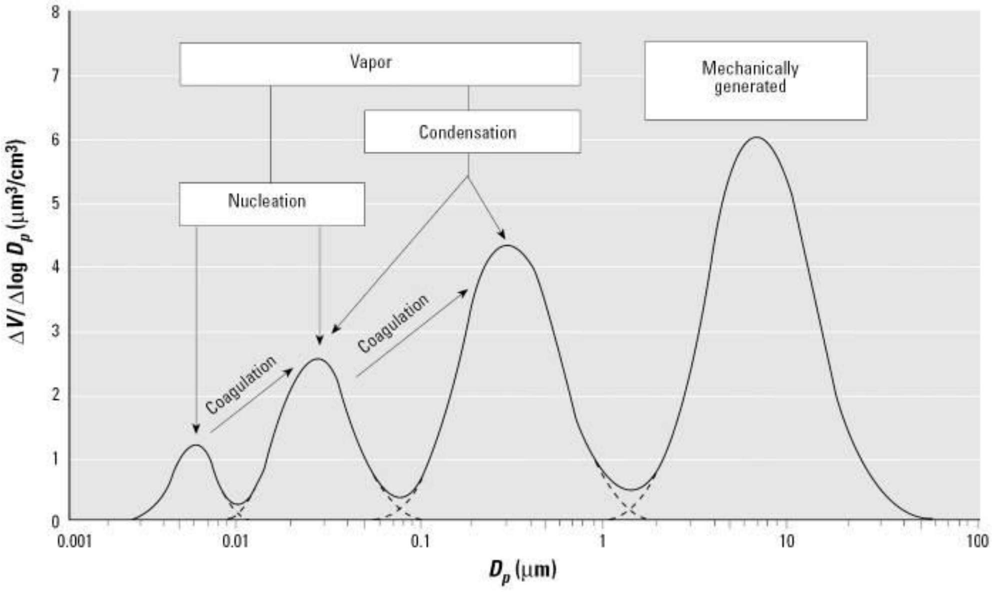
Interpretation Our study showed that, between the years 2000 and 2019, most of the world's urban population lived in areas with unhealthy levels of $PM_{2·5}$, leading to substantial contributions to non-communicable disease burdens. Our results highlight that avoiding the large public health burden from urban $PM_{2·5}$ will require strategies that reduce exposure through emissions mitigation, as well as strategies that reduce vulnerability to $PM_{2·5}$ by improving overall public health.

Mechanisms

Nanotoxicology: An Emerging Discipline Evolving from Studies of Ultrafine Particles

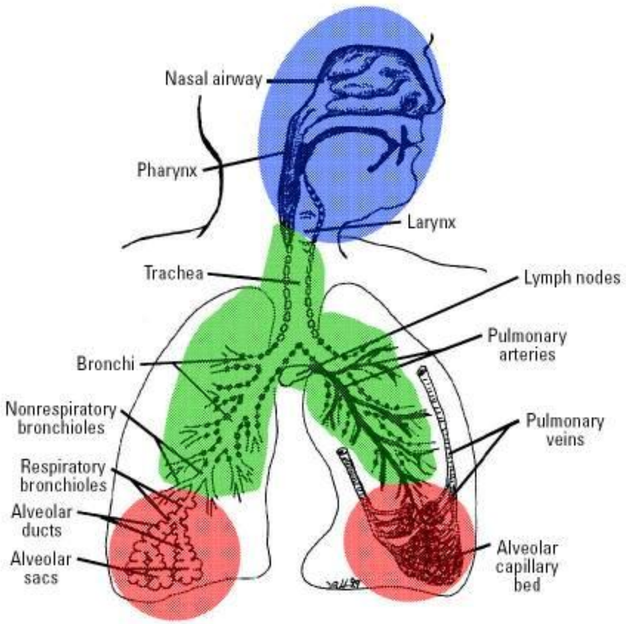
Günter Oberdörster,[1] Eva Oberdörster,[2] and Jan Oberdörster[3]

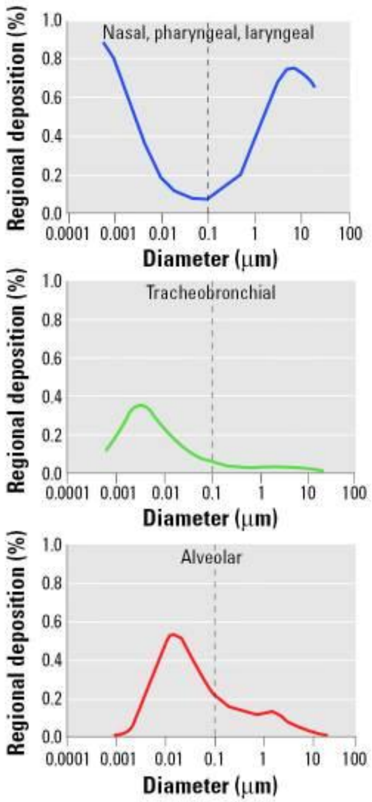
[1]Department of Environmental Medicine, University of Rochester, Rochester, New York, USA; [2]Department of Biology, Southern Methodist University, Dallas, Texas, USA; [3]Toxicology Department, Bayer CropScience, Research Triangle Park, North Carolina, USA



Deposited particles

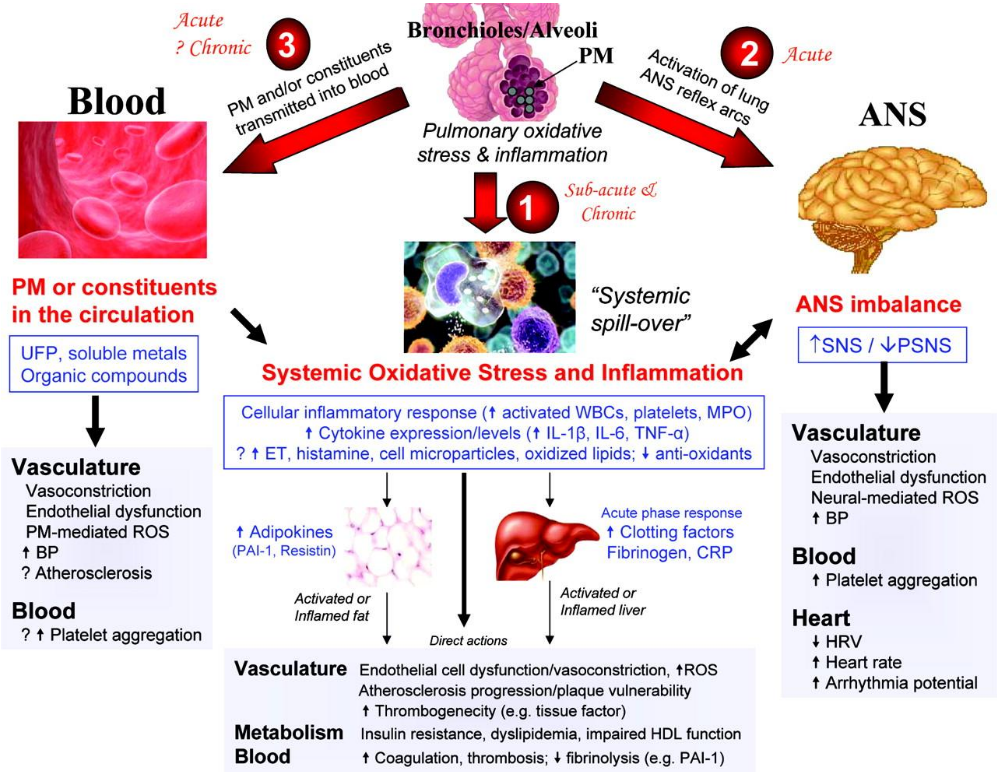
- mucocilliary clearance
- dissolution and blood stream
- translocation





Some hypotheses

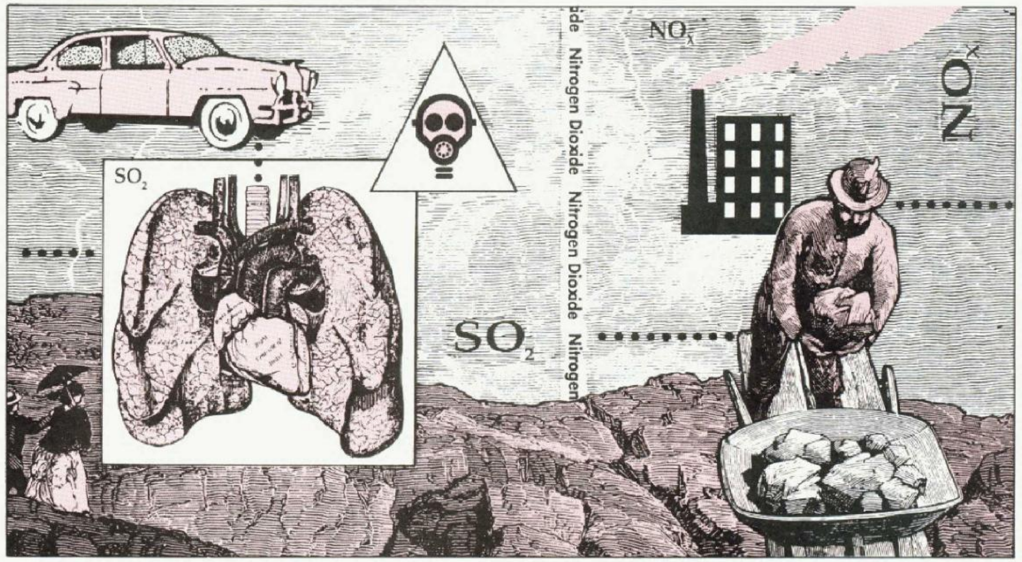
- mass concentrations
- ultrafine particles
- particle acidity
- transition metals
- oxidative stress



Brooks et al., *Circulation*, 2010

Acidity hypothesis

Acid air and health



John D. Spengler
Michael Brauer
Petros Koutrakis
Harvard School of Public Health
Boston, MA 02115

Environ. Sci. Technol., Vol. 24, No. 7, 1990

Toxicological effects

irritation

alteration of physiological function
- epithelial thickness
- alveolar clearance
- mucociliary clearance
- activation of macrophages
- secretory cells

tissue damage

(Lippman et al.)

Mass concentration hypothesis

ELSEVIER

The Science of the Total Environment 249 (2000) 85–101

the Science of the Total Environment

An International Journal for Scientific Research into the Environment and its Relationship with Man

www.elsevier.com/locate/scitotenv

Particulate matter in the atmosphere: which particle properties are important for its effects on health?

Roy M. Harrison*, Jianxin Yin

Division of Environmental Health and Risk Management, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK

- Consistent association between PM and health effects found across studies where chemical composition varied widely
- Maybe no smoking gun (chemically)
- Effect of size not available at the time
- Bioavailable species concentrations also not widely available

Panel study

- 1759 children in 12 Southern California communities
- Eight year study (10% attrition rate)
- Proportion of children with decreased lung function associated with $PM_{2.5}$ and other pollutants

The NEW ENGLAND JOURNAL of MEDICINE

ESTABLISHED IN 1812 SEPTEMBER 9, 2004 VOL. 351 NO. 11

The Effect of Air Pollution on Lung Development from 10 to 18 Years of Age

W. James Gauderman, Ph.D., Edward Avol, M.S., Frank Gilliland, M.D., Ph.D., Hita Vora, M.S., Duncan Thomas, Ph.D., Kiros Berhane, Ph.D., Rob McConnell, M.D., Nino Kuenzli, M.D., Fred Lurmann, M.S., Edward Rappaport, M.S., Helene Margolis, Ph.D., David Bates, M.D., and John Peters, M.D.

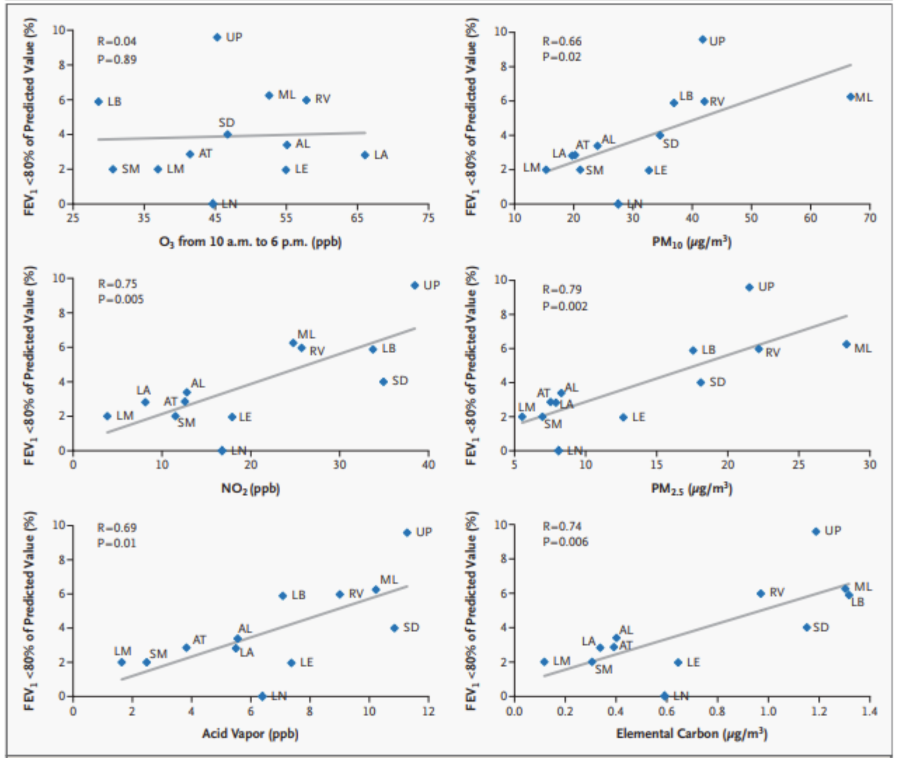


Figure 3. Community-Specific Proportion of 18-Year-Olds with a FEV_1 below 80 Percent of the Predicted Value Plotted against the Average Levels of Pollutants from 1994 through 2000.

The correlation coefficient (R) and P value are shown for each comparison. AL denotes Alpine, AT Atascadero, LE Lake Elsinore, LA Lake Arrowhead, LN Lancaster, LM Lompoc, LB Long Beach, ML Mira Loma, RV Riverside, SD San Dimas, SM Santa Maria, and UP Upland. O_3 denotes ozone, NO_2 nitrogen dioxide, and PM_{10} and $PM_{2.5}$ particulate matter with an aerodynamic diameter of less than 10 μm and less than 2.5 μm, respectively.

Time-series study

- National Morbidity, Mortality, and Air Pollution Study (NMMAPS)
- 90 cities
- 14 years 1987-2000
- Consider lagged relationships (1-day lag)
- 0.21-0.27% change in overall mortality with 10 µg/m increase in PM_{10}

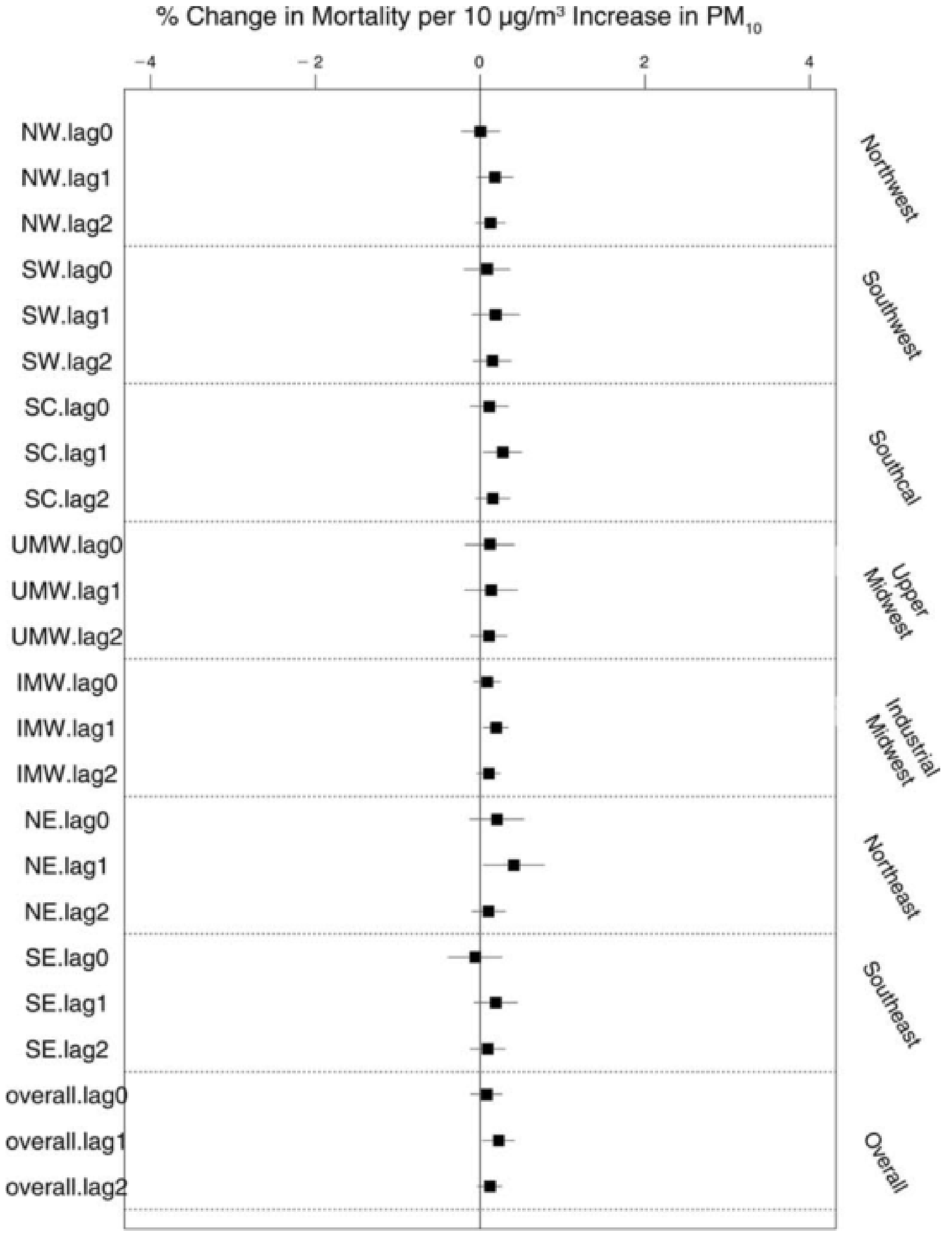
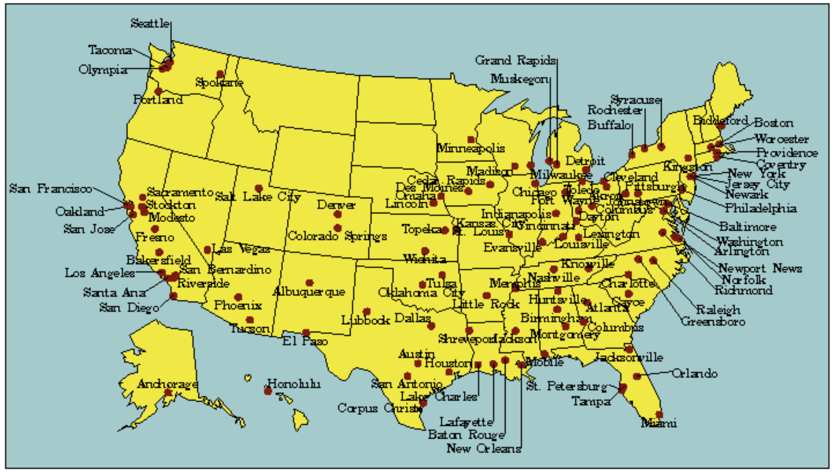


FIGURE 8. Posterior means and 95% posterior intervals of regional effects of PM_{10} on total mortality from nonexternal causes at lags 0, 1, and 2 for the 88 U.S. cities.



www.ihapss.jhsph.edu
Dominici et al., *J. Env. Tox. Health*, 2005

Ultrafine particle (UFP) hypothesis

HEI Perspectives 3

January 2013

Insights from HEI's research

Understanding the Health Effects of Ambient Ultrafine Particles

HEI Review Panel on Ultrafine Particles

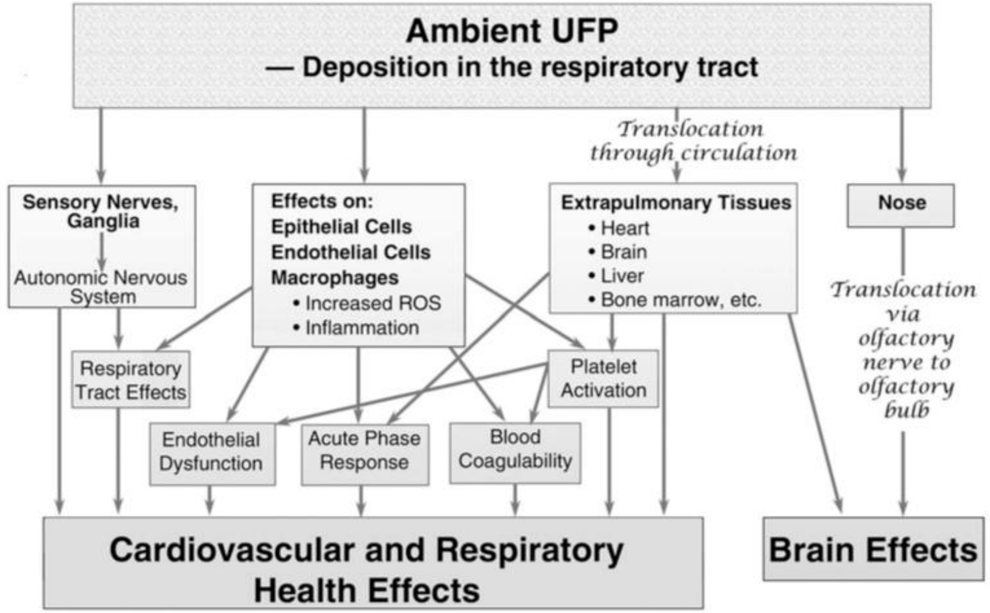


Figure 17. Hypothesized pathways via which inhalation of UFPs may lead to effects on cardiovascular and respiratory systems and on the brain.

Proceedings of the National Academy of Sciences of the United States of America

Magnetite pollution nanoparticles in the human brain

Barbara A. Maher[a,1], Imad A. M. Ahmed[b], Vassil Karloukovski[a], Donald A. MacLaren[c], Penelope G. Foulds[d], David Allsop[d], David M. A. Mann[e], Ricardo Torres-Jardón[f], and Lilian Calderon-Garciduenas[g,h]

Science AAAS

Power plants, like this one in Tyumen, Russia, let off air pollution that contains many nanoparticles, including magnetite. A new study finds this magnetite can make its way into human brains.

Sergei Butorin/iStockphoto

Industrial air pollution leaves magnetic waste in the brain

By Michael Price | Sep. 5, 2016 , 3:00 PM

Metals hypothesis

- PM samples from three emission sources (two oil and one coal fly ash) and four ambient airsheds (St. Louis, MO; Washington; Dusseldorf, Germany; and Ottawa, Canada)
- PM administered to rats by intratracheal instillation
- “lung dose of bioavailable transition metal, not instilled PM mass, was the primary determinant of the acute inflammatory response for both the combustion source and ambient PM samples”

Bioavailable Transition Metals in Particulate Matter Mediate Cardiopulmonary Injury in Healthy and Compromised Animal Models

Daniel L. Costa and Kevin L. Dreher

Pulmonary Toxicology Branch, Experimental Toxicology Division, National Health and Environmental Effects Research Laboratory, Research Triangle Park, North Carolina

Environmental Health Perspectives • Vol 105, Supplement 5 • September 1997

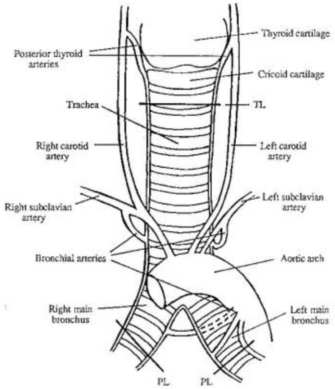


illustration:
Hyytinen, *Scand. Cardiovas. J.*, 1998

Water-soluble metals

Research

A Section 508–conformant HTML version of this article
is available at https://doi.org/10.1289/EHP2182.

Estimating Acute Cardiovascular Effects of Ambient $PM_{2.5}$ Metals

Dongni Ye,[1] Mitchel Klein,[1,2] James A. Mulholland,[3] Armistead G. Russell,[3] Rodney Weber,[3] Eric S. Edgerton,[4] Howard H. Chang,[5] Jeremy A. Sarnat,[1] Paige E. Tolbert,[1,2] and Stefanie Ebelt Sarnat[1]

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Atlanta, GA 1998-2013

Risk ratio for cardiovascular emergency department visits more strongly associated with water-soluble Fe than $PM_{2.5}$ (and other pollutants.)

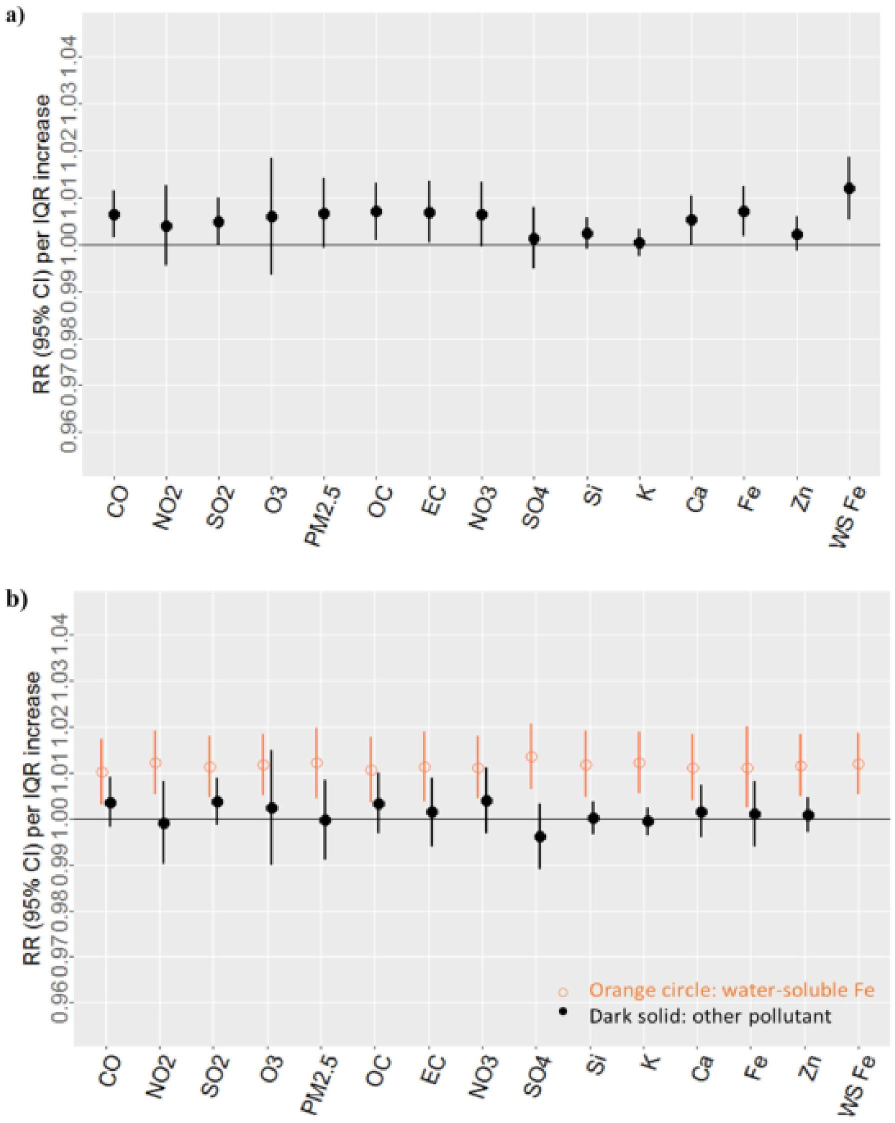

Figure 1. Estimated associations between cardiovascular emergency department visits and pollutants available during 1998–2013, year-round analysis (3,303 d), Atlanta, Georgia. Results from single-pollutant models (*a*); results from two-pollutant models: water-soluble Fe controlling for each of the other pollutants (*b*). Note: Ca, calcium; CO, carbon monoxide; EC, elemental carbon; Fe, iron; IQR, interquartile range; K, potassium; NO_2, nitrogen dioxide; NO_3, nitrate; O_3, ozone; OC, organic carbon; $PM_{2.5}$, particulate matter with aerodynamic diameter ≤ 2.5 μm; RR, rate ratio; Si, silicon; SO_2, sulfur dioxide; SO_4, sulfate; WS, water soluble; Zn, zinc.

Oxidative potential hypothesis

Critical Review
Cite This: Environ. Sci. Technol. 2017, 51, 13545−13567
pubs.acs.org/est

Aerosol Health Effects from Molecular to Global Scales

Manabu Shiraiwa,[*,†,‡] Kayo Ueda,[‖] Andrea Pozzer,[§] Gerhard Lammel,[‡,⊥] Christopher J. Kampf,[‡,#] Akihiro Fushimi,[¶] Shinichi Enami,[¶] Andrea M. Arangio,[‡,⊗] Janine Fröhlich-Nowoisky,[‡] Yuji Fujitani,[¶] Akiko Furuyama,[¶] Pascale S. J. Lakey,[†,‡] Jos Lelieveld,[§] Kurt Lucas,[‡] Yu Morino,[¶] Ulrich Pöschl,[‡] Satoshi Takahama,[⊗] Akinori Takami,[¶] Haijie Tong,[‡] Bettina Weber,[‡] Ayako Yoshino,[¶] and Kei Sato[¶]

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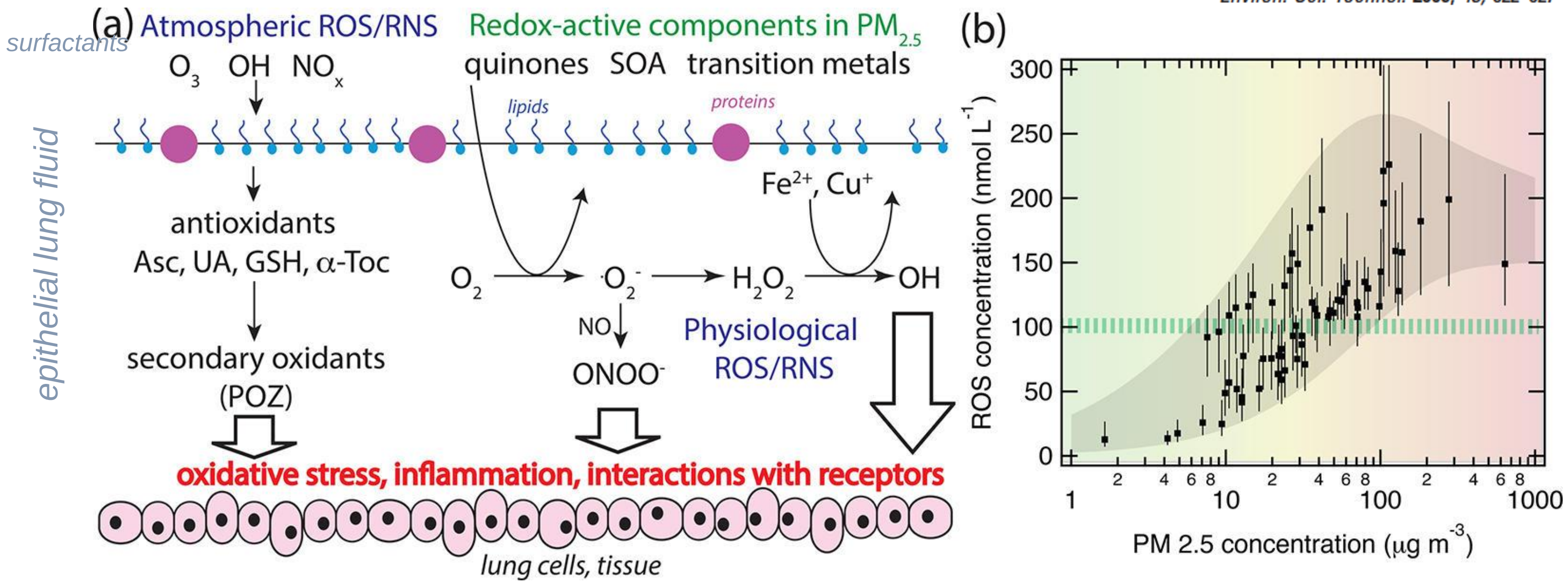
Generation of Hydroxyl Radicals from Ambient Fine Particles in a Surrogate Lung Fluid Solution

EDGAR VIDRIO,[†,‡] CHIN H. PHUAH,[§,‖] ANN M. DILLNER,[‖] AND CORT ANASTASIO*,[†,‡]

Graduate Group in Agricultural and Environmental Chemistry, Department of Land, Air and Water Resources, Department of Civil and Environmental Engineering, and Crocker Nuclear Laboratory, University of California—Davis, 1 Shields Avenue, Davis, California 95616

Environ. Sci. Technol. 2009, 43, 922–927



Mechanistic link for oxidative stress and inflammation

Naphthalene (simplest polycyclic aromatic hydrocarbon) secondary organic aerosol generated and aged in laboratory

human bronchial epithelial cell line (BEAS-2B) exposed

measure up-/down-regulation of proteins

unsaturated carbonyls implicated in toxicity

Proteome-wide effects of naphthalene-derived secondary organic aerosol in BEAS-2B cells are caused by short-lived unsaturated carbonyls

Jiajun Han[a,1], Shunyao Wang[b,1], Kirsten Yeung[a], Diwen Yang[a], Wen Gu[c], Zhiyuan Ma[d], Jianxian Sun[a], Xiaomin Wang[e], Chung-Wai Chow[e], Arthur W. H. Chan[a,b,f,2], and Hui Peng[a,f,2]

PNAS

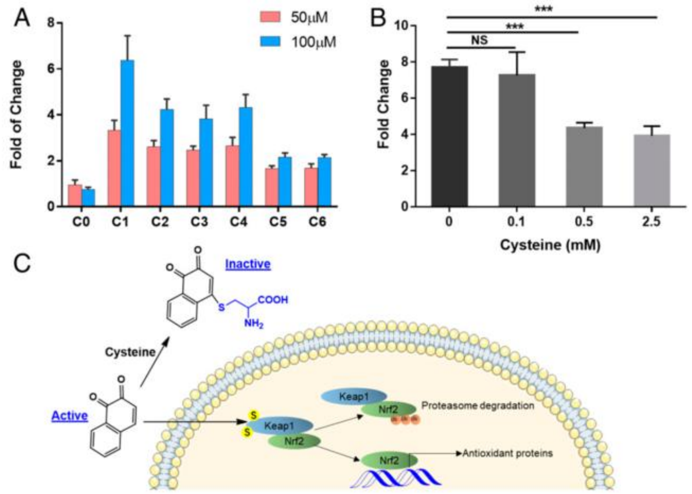


Fig. 5. Activation of Nrf2 reporter cells by NSOA is supplemented by cysteine preincubation. (*A*) Induction of Nrf2 responses by NSOA in Nrf2 Luciferase reporter MCF7 stable cell line. Results are presented as fold relative to vehicle control group ($n = 12$). *P* values are <0.001 for all treatments. (*B*) The induction of Nrf2 responses by NSOA were supplemented by preincubation with free cysteine. Results are presented as fold relative to vehicle control group ($n = 6$). $***P < 0.001$. (*C*) The schematic figure demonstrates that electrophilic NSOA chemicals (e.g., 1,2-naphthoquinone) are sequestered by free cysteine during preincubation, and hence reduce the activation of Nrf2 pathways inside the Nrf2 reporter cells.

Metals, acidity, and size

- acidic aerosols, which are smaller, solubilize metals to make them water-soluble

- study in Atlanta, GA – more metals from non-exhaust emissions can be solubilized near road

Environmental Science & Technology
Article
pubs.acs.org/est

Highly Acidic Ambient Particles, Soluble Metals, and Oxidative Potential: A Link between Sulfate and Aerosol Toxicity

Ting Fang,[†] Hongyu Guo,[†] Linghan Zeng,[†] Vishal Verma,[‡] Athanasios Nenes,[†,§,∥,⊥] and Rodney J. Weber[*,†]

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[‡]Department of Civil and Environmental Engineering, University of Illinois Urbana−Champaign, Champaign, Illinois 61801, United States
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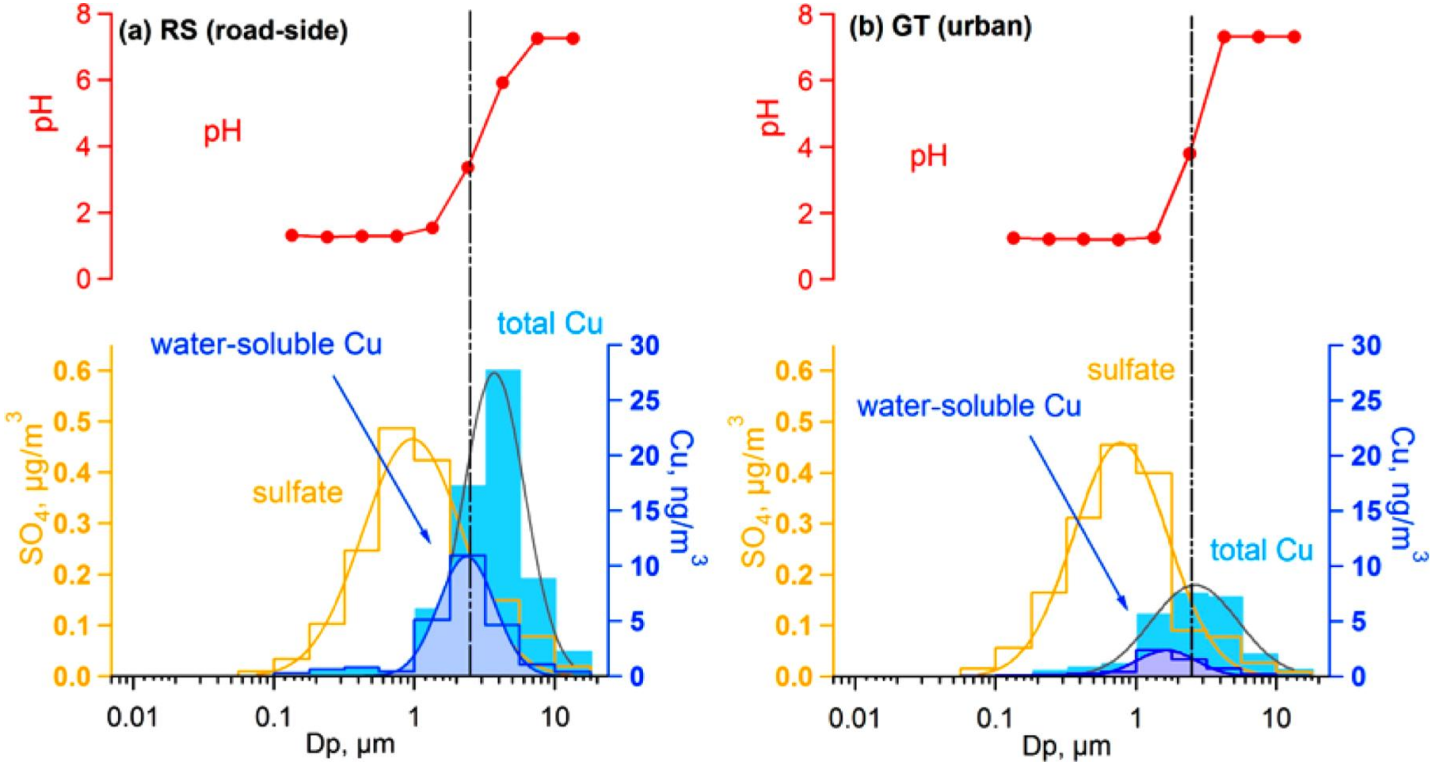

Sources of oxidative potential

Article

nature

Sources of particulate-matter air pollution and its oxidative potential in Europe

https://doi.org/10.1038/s41586-020-2902-8

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Kaspar R. Daellenbach[1,2,3], Gaëlle Uzu[4], Jianhui Jiang[1✉], Laure-Estelle Cassagnes[1], Zaira Leni[5], Athanasia Vlachou[1], Giulia Stefenelli[1], Francesco Canonaco[1,6], Samuël Weber[4], Arjo Segers[7], Jeroen J. P. Kuenen[7], Martijn Schaap[7,8], Olivier Favez[9], Alexandre Albinet[9], Sebnem Aksoyoglu[1], Josef Dommen[1], Urs Baltensperger[1], Marianne Geiser[5], Imad El Haddad[1✉], Jean-Luc Jaffrezo[4] & André S. H. Prévôt[1✉]

Europe (estimated for 2011):

Greatest mass from soil and biogenic organic aerosols

Greatest oxidative potential from anthropogenic sources - (wood burning and non-exhaust emissions)

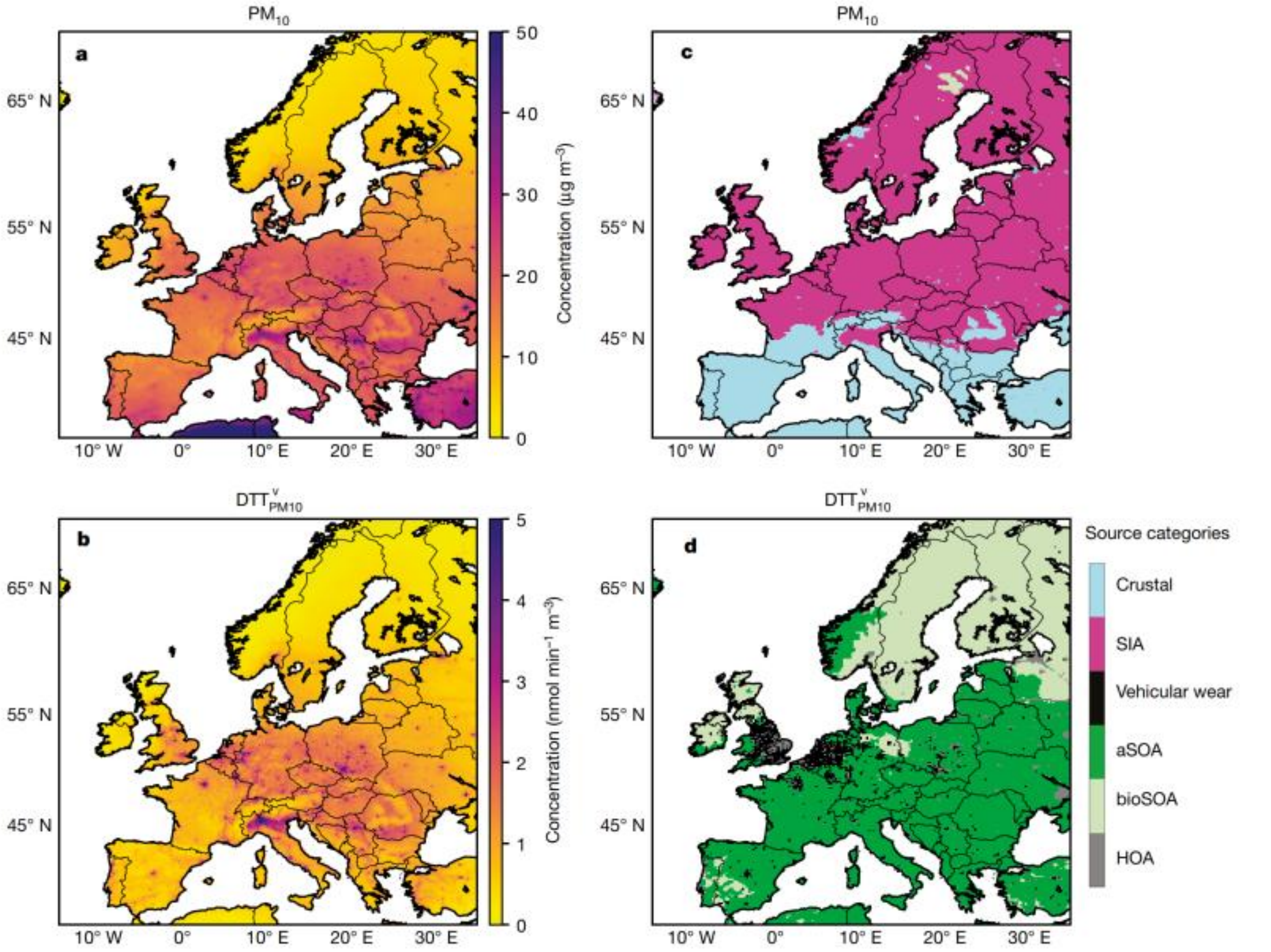


Fig. 2 | Levels and sources of PM10 and DTT$^{v}_{PM10}$ in Europe. OP^{v} and PM sources in Europe (only land surface displayed, spatial resolution: 0.25° × 0.125°) for the year 2011. **a**–**d**, Concentrations of PM_{10} (**a**) and DTT$^{v}_{PM10}$ (**b**) are shown, as are sources dominating PM_{10} mass concentrations (**c**) and DTT$^{v}_{PM10}$ (**d**), including crustal material (crustal), SIA (comprising $NH_4^+ + NO_3^- + SO_4^{2-}$), vehicular wear, anthropogenic SOA (aSOA), biogenic SOA (bioSOA), vehicular exhaust POA (HOA) (for other assays and $PM_{2.5}$, see Extended Data Fig. 5 and 7).

Progress continues

Better characterization of biological response

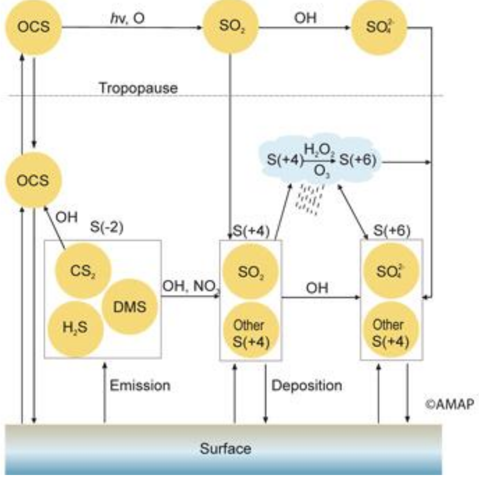
- Instrumentation / analytical techniques / cell lines for measuring biological response
- Models of biological response

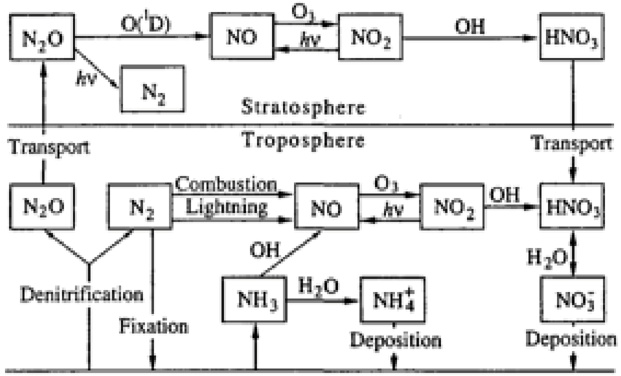
Better characterization of exposure estimates

- Instrumentation for chemical composition
- Hierarchical strategy for monitoring (high spatial and temporal coverage)
    - satellite
    - low cost sensors
    - conventional monitoring networks
    - Supersites
- Models of chemical transport

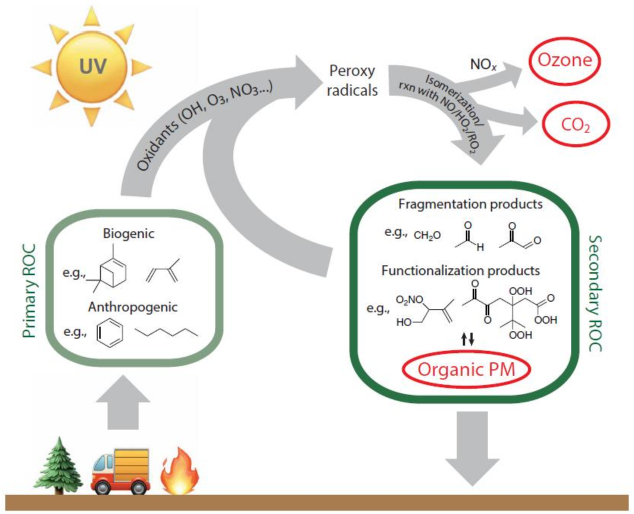
Part 2 – atmospheric chemistry and global energy balance

Emission and transformations





source: Seinfeld and Pandis 2006



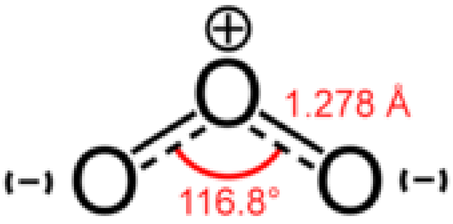
source: Heald and Kroll, *Sci. Adv.*, 2020

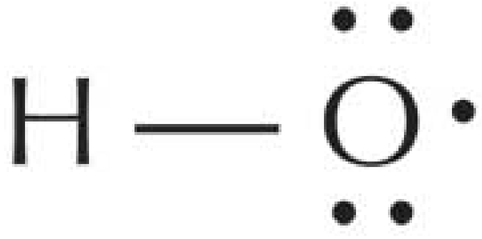
Atmospheric oxidation

Earth's atmosphere is an oxidizing environment.

Main oxidants:

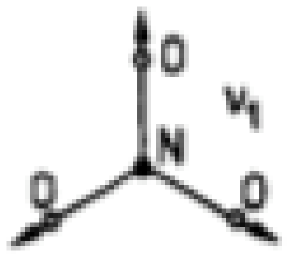
- Ozone
- Hydroxyl radical
- Nitrate radical





Example of reactivity with β-pinene
(Fry et al., *Atmos. Chem. Phys.*, 2009)

Oxidant	$k_{Ox+\beta-pinene}$ (cm^3 $molecules^{-1}$ s^{-1})	Average [Ox] (molecules cm^{-3})	τ_{Ox}
O_3	1.5×10^{-17}	7×10^{11} (30 ppb) (24 h average)	26.5 hr
OH	7.89×10^{-11}	1×10^{6} (0.04 ppt) (12 h daytime average)	3.5 hr
NO_3	2.51×10^{-12}	2.4×10^{8} (10 ppt) (12 h nighttime average)	0.5 hr



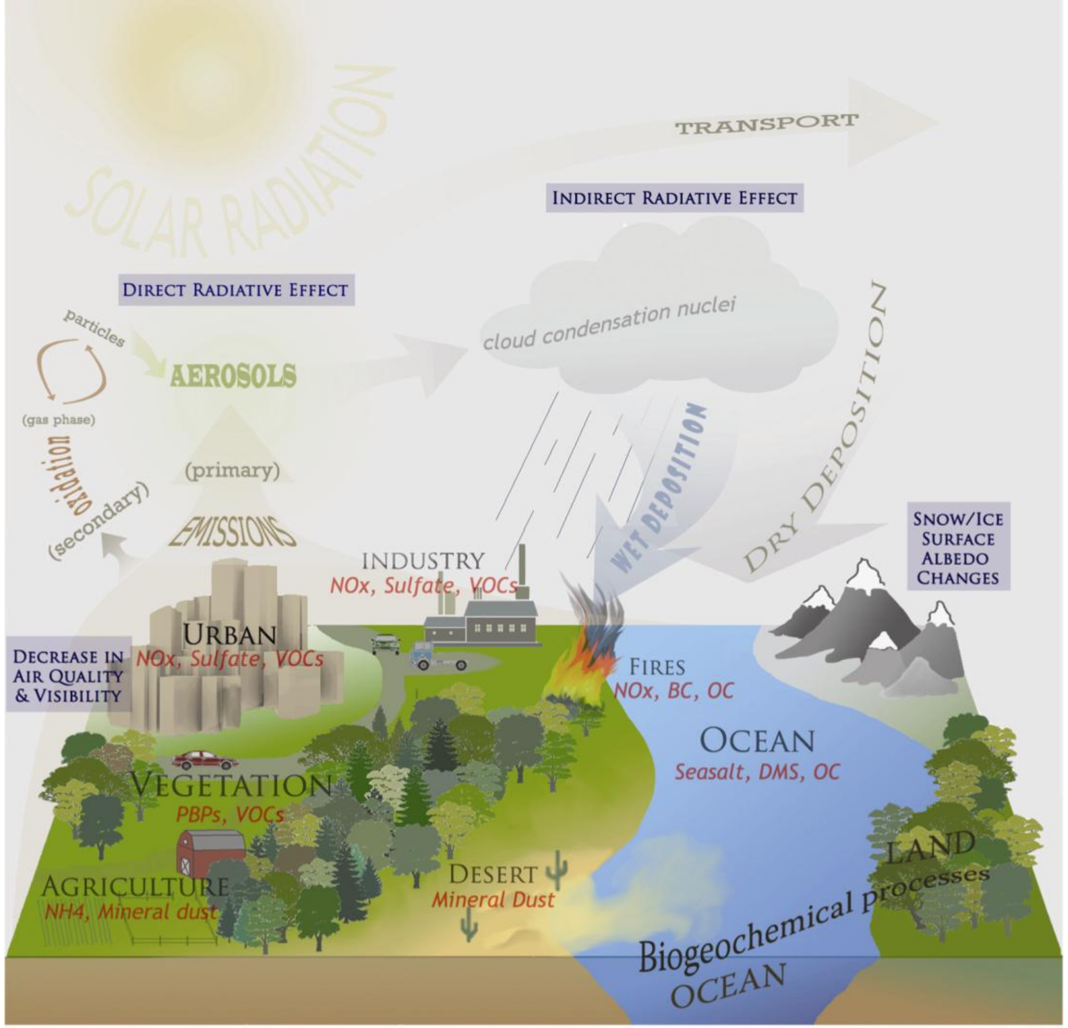
Wayne et al., *Atmos. Environ.*, 1991

Examples of oxidation reactions

	Gas-phase	Aqueous-phase
Nitrogen	$NO_{2(g)} + OH\cdot_{(g)} \rightarrow HNO_{3(g)}$	Dominant during nighttime $NO_{2(g)} + O_{3(g)} \rightarrow NO_{3(g)} + O_{2(g)}$ $NO_{3(g)} + NO_{2(g)} \rightarrow N_2O_{5(g)}$ $N_2O_{5(g)} + H_2O_{(l)} \rightarrow 2HNO_{3(l)}$
Sulfur	$SO_2 + OH\cdot \overset{M}{\rightarrow} HOSO_2\cdot$ $HOSO_2\cdot + OH\cdot \rightarrow HO_2\cdot + SO_3$ $SO_3 + H_2O \overset{M}{\rightarrow} H_2SO_4$	Important in clouds $SO_{2(g)} + H_2O \rightleftharpoons SO_2\cdot H_2O$ Hydration $SO_2\cdot H_2O \rightleftharpoons HSO_3^- \rightleftharpoons SO_3{}^{2-}$ Conversion among S(IV) forms $S(IV) \overset{O_3, H_2O_2, ...}{\rightarrow} S(VI)$ Conversion to sulfate S(VI)
Carbon	A reactive organic gas ROG can react with an oxidant to form n products P which can partition between the gas and particle phase $ROG \overset{\text{oxidant}}{\rightarrow} a_1P_1 + a_2P_2 + ... + a_nP_n$	Oxidation also occurs in the aqueous phase

Atmospheric reactions can happen in the gas-phase or condensed-phase (aerosols and clouds)

Air pollution effects on ecosystems



Mahowald N, et al. 2011.
Annu Rev. Environ. Resour. 36:45–74

- Nutrient transport
- Acid precipitation
- Precipitation patterns
- Energy balance

Acid deposition

Mechanisms

- dry deposition (20-70%)
- wet deposition

Impacts

- (aquatic) loss of fish populations
- (terrestrial) leaching of nutrients

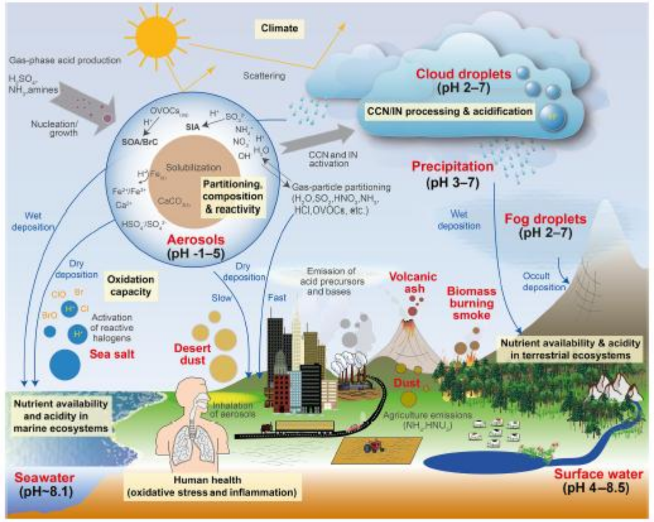


Figure 1. Sources and receptors of aerosol and cloud droplet acidity. Major primary sources and occurrence in the atmosphere are identified in bold red text: sea salt, dust, and biomass burning (sources); and aerosols, fog droplets, cloud droplets, and precipitation (occurrence). Key aerosol processes are indicated by arrows and gray text: nucleation/growth, light scattering, cloud condensation nuclei (CCN) and ice nuclei (IN) activation, and gas–particle partitioning. Sinks (wet, dry, and occult deposition) are indicated by blue lines and text. The effects that aerosols have in the atmosphere, and on terrestrial and marine ecosystems and human health, are highlighted in pale yellow boxes. Approximate pH ranges of aqueous aerosols and droplets, seawater, and terrestrial surface waters are also given.

Pye et al., *Atmos. Chem. Phys.*, 2020

Likens and Butler, 2020

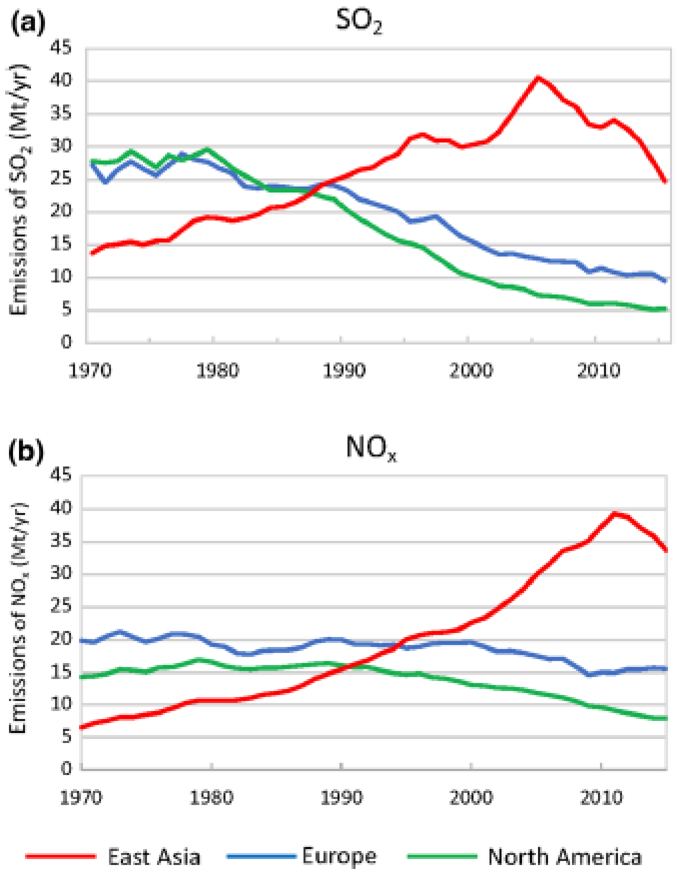


Fig. 1 Historical emissions of **a** SO_2 and **b** NO_x in East Asia compared with those in Europe and North America (Based on EDGAR v.5 for Europe and North America and on REAS v.3 for East Asia)

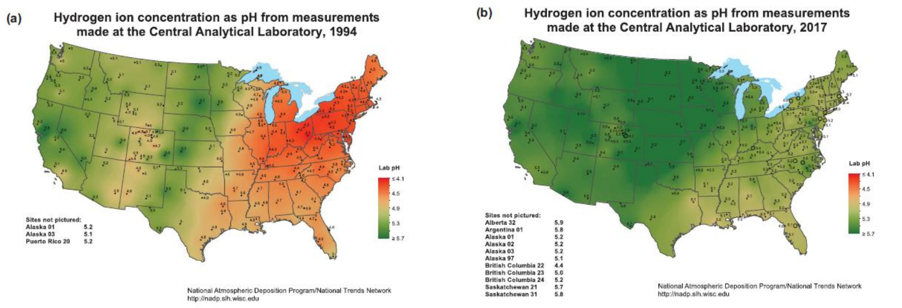
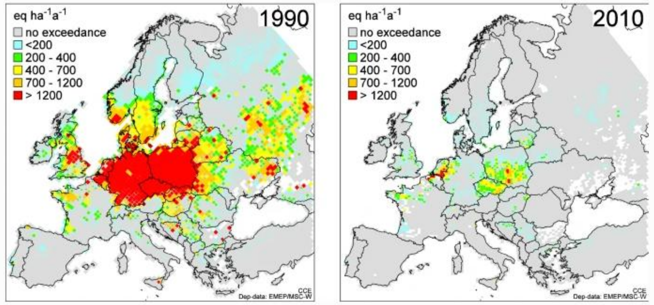


FIGURE 7.5 (See color insert.) National levels of pH in precipitation for (a) 1994 and (b) 2017. (Adapted from NADP[31].)



The outcome of emission control of SO2, NOx, and NH3 between 1990 and 2010 presented as maps on exceedance of critical loads of acidity. Such maps have played an important role for illustrating outcomes of future policies as well as of actions taken (from Maas and Grennfelt 2016)

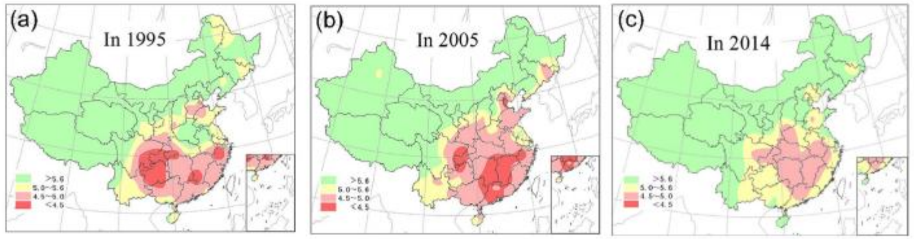
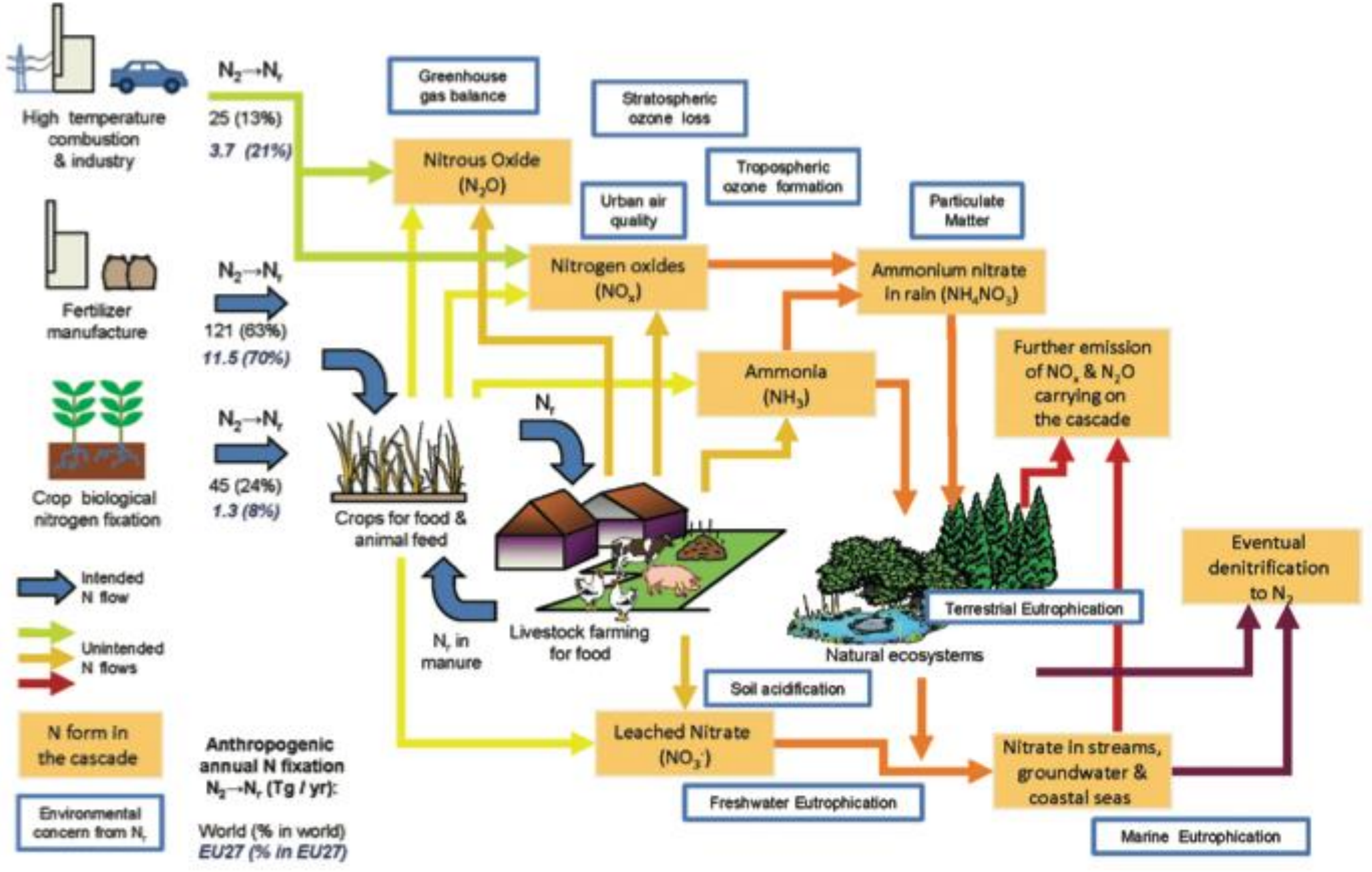


Fig. 4 Spatial distribution of annual average precipitation pH in China in **a** 1995, **b** 2005 and **c** 2014 (adapted from Duan et al. 2016)

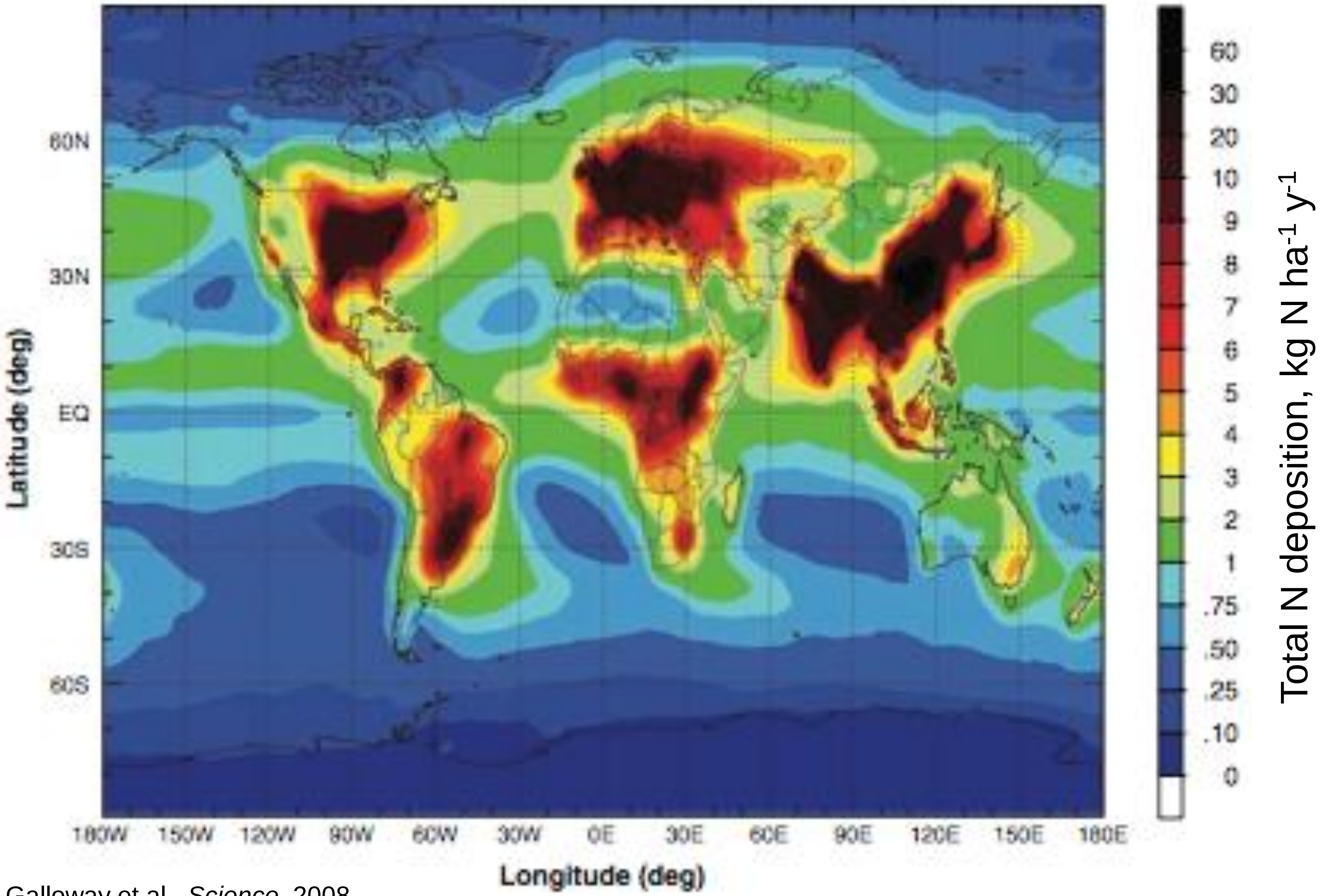
Akimoto et al., *Ambio*, 2022
Grennfelt et al., *Ambio*, 2020
Likens and Butler, 2020

The nitrogen cascade

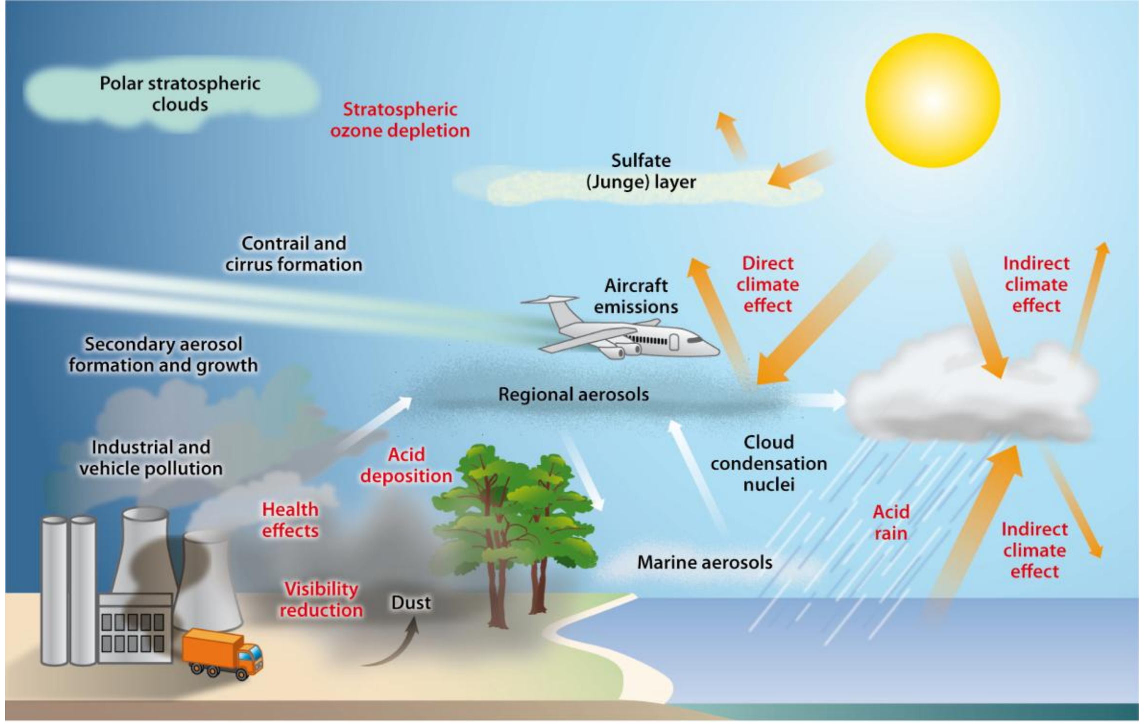


source: European Nitrogen Assessment, 2011

Nitrogen deposition



Galloway et al., *Science*, 2008



Kolb CE, Worsnop DR. 2012.
Annu. Rev. Phys. Chem. 63:471–91

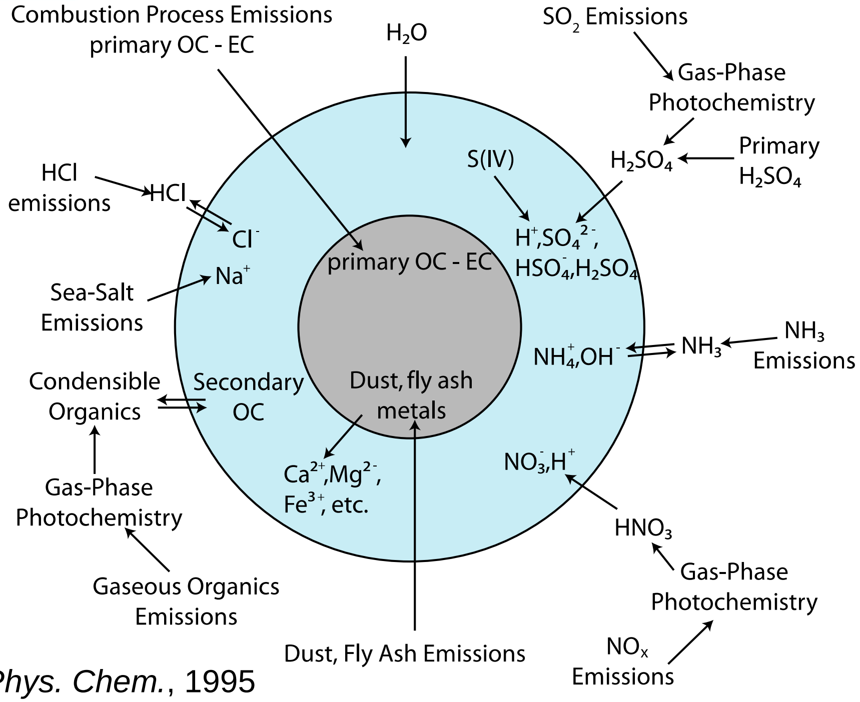
There are many sources of aerosols:

- Biogenic (terrestrial vegetation, marine, dust)
- Anthropogenic (industrial, transportation)

Impacts:

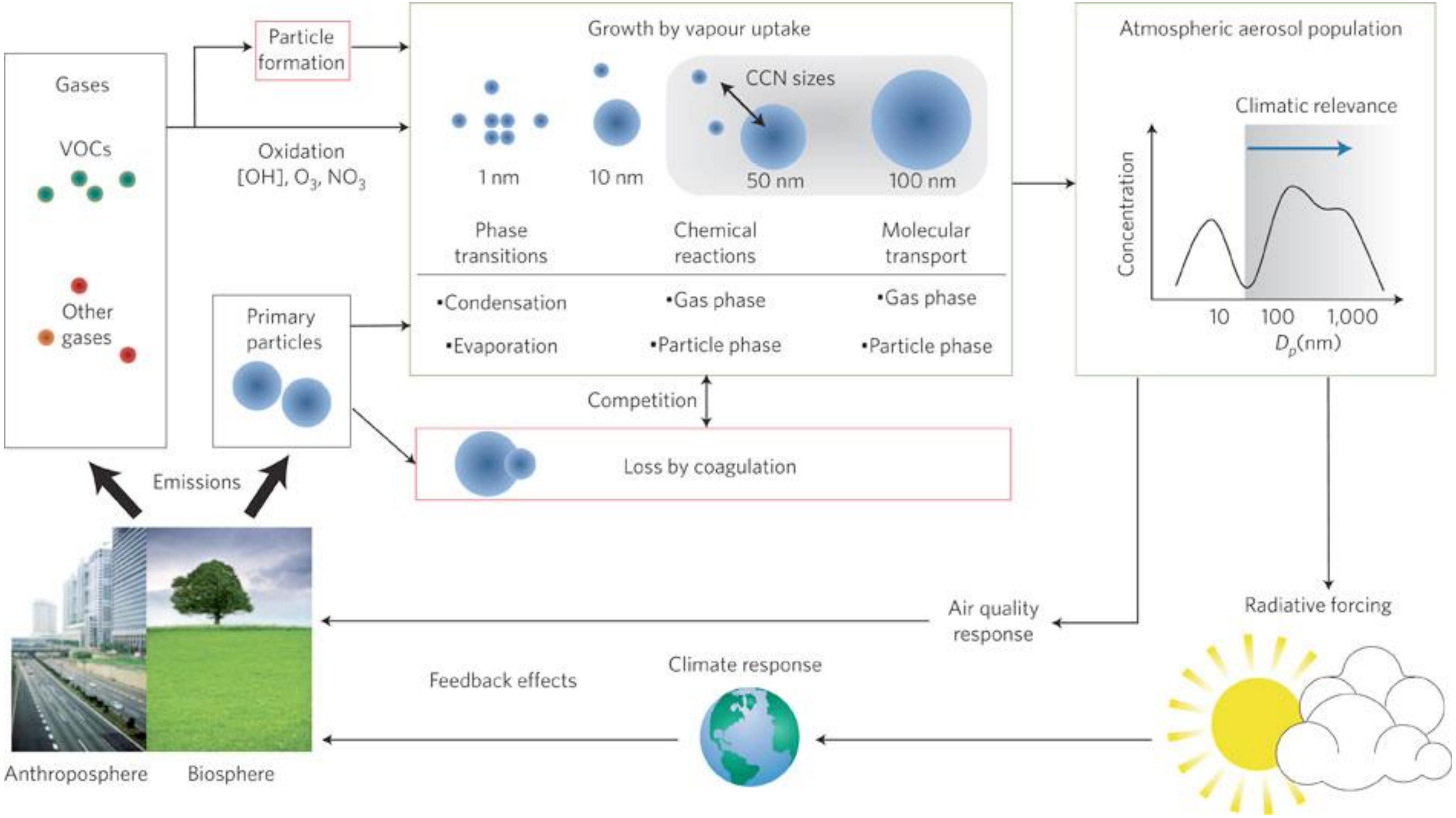
- Health
- Visibility
- Nutrient transport
- Climate

- Atmospheric PM is a complex mixture of a large number of molecules (to be contrasted with other pollutants which are single atoms one or two molecules)
- “A pollutant for all seasons”



adapted from Pandis et al., *J. Phys. Chem.*, 1995

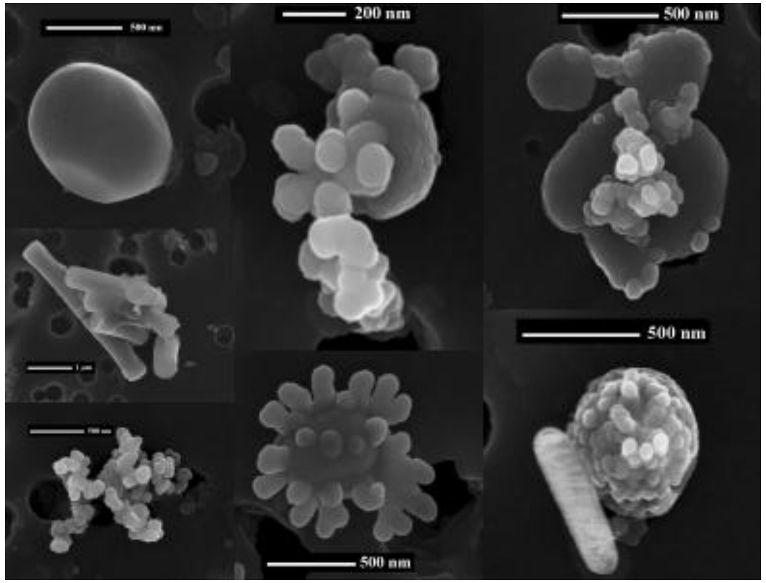
Connections between volatile organic compound (VOC) emissions, nanoparticle growth, climate, and air quality.



Riipinen, *Nature Geosci.*, 2012

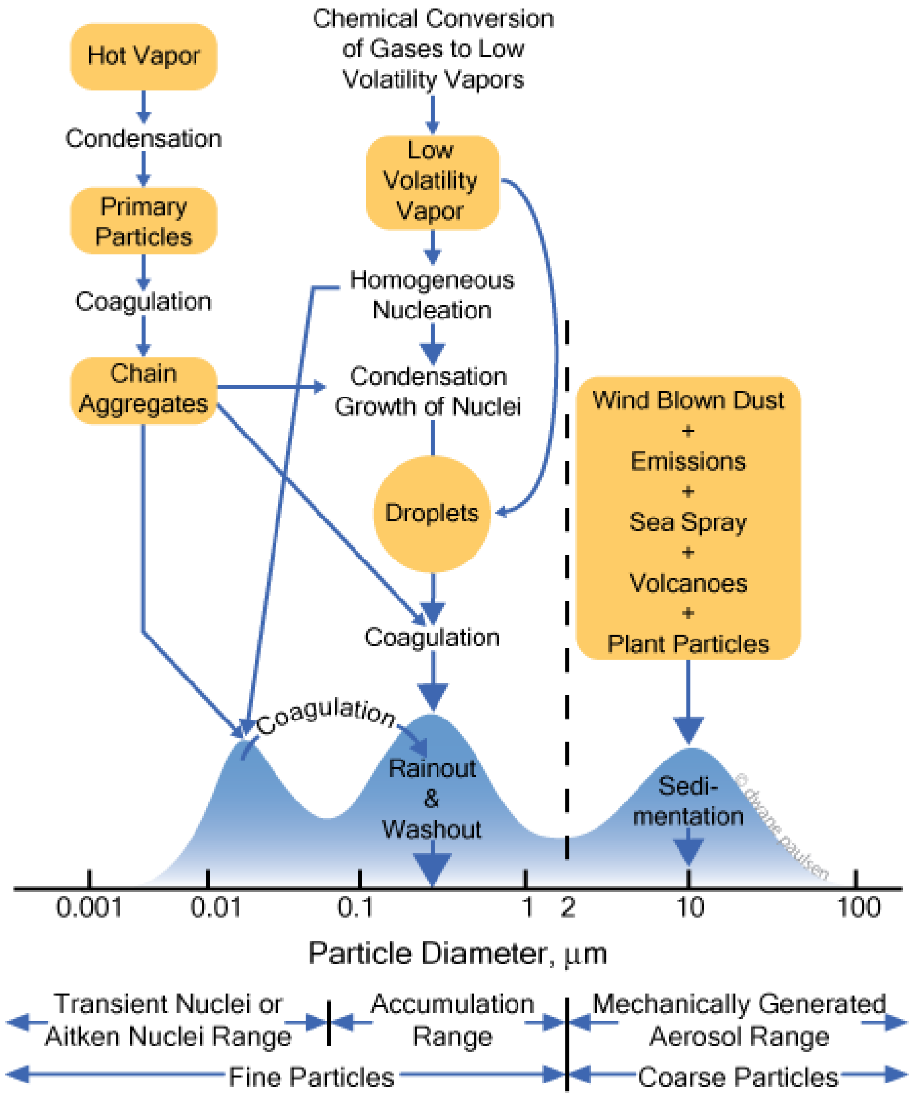
Atmospheric aerosols vary in size in shape

Scanning electron microscopy images



Coz et al., *Aerosol Sci. Tech.*, 2008

- Sizes (before atmospheric processing) are indicative of emission or production mechanism
- Size determines atmospheric lifetimes and impacts
- Shape (morphology) determines surface area; gas-particle interactions



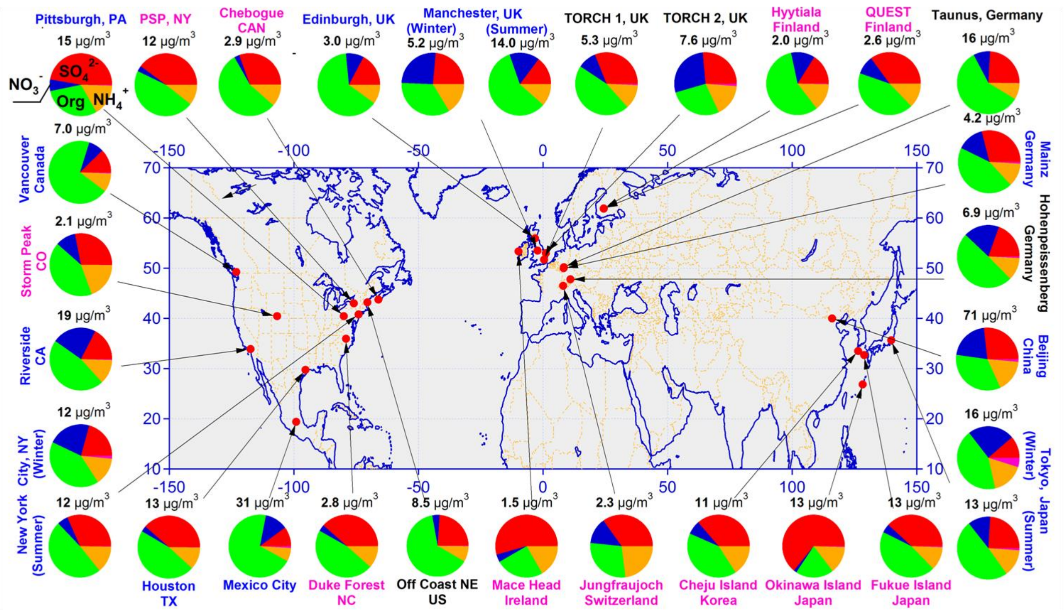
source: http://www.dwanepaulsen.net

Average chemical composition

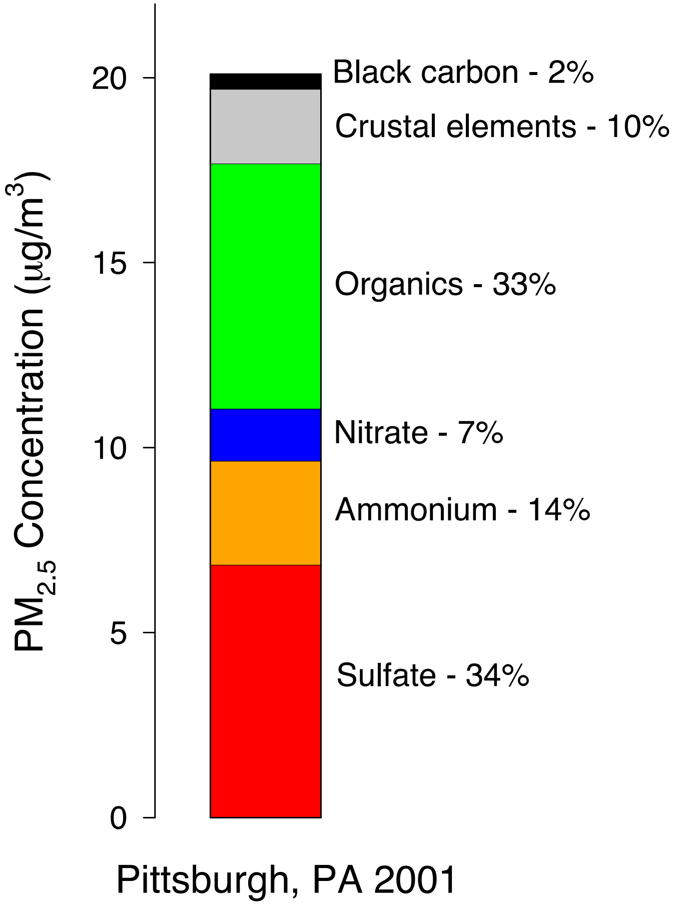
Major components:

- Inorganic salts/ions
- Organic compounds (10,000+)
- Black carbon/soot
- Crustal elements (dust)

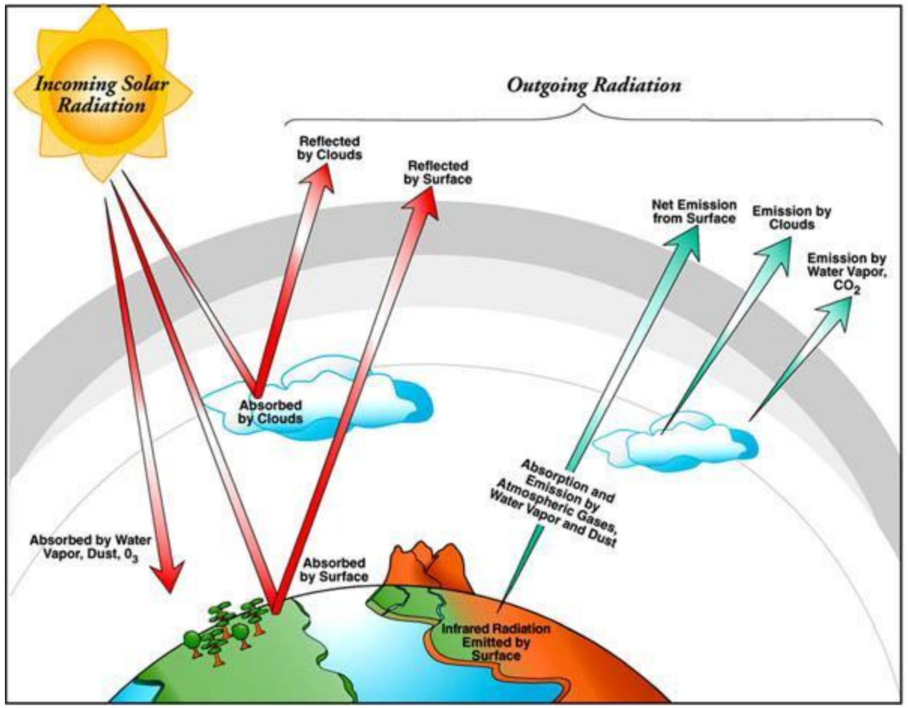
Occur in different proportions throughout the world



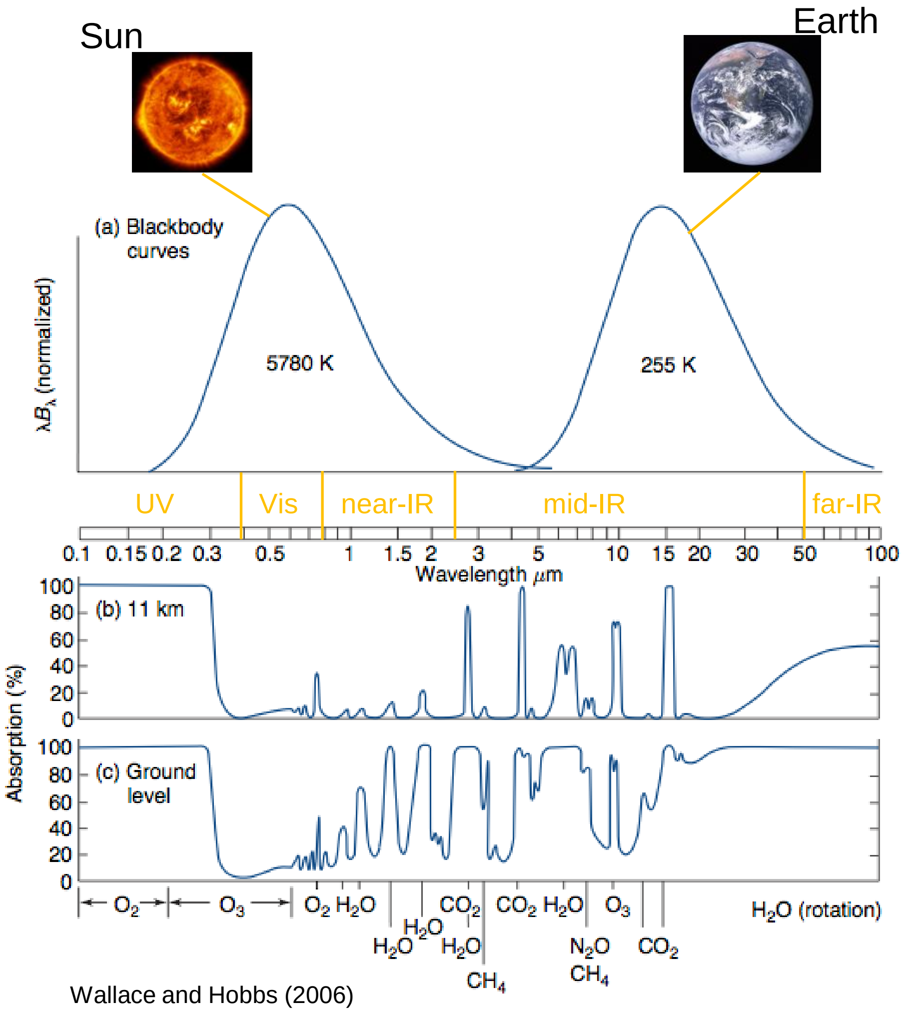
NR-PM$_1$: Zhang et al., *Geophys. Res. Lett.*, 2007



Earth’s energy balance

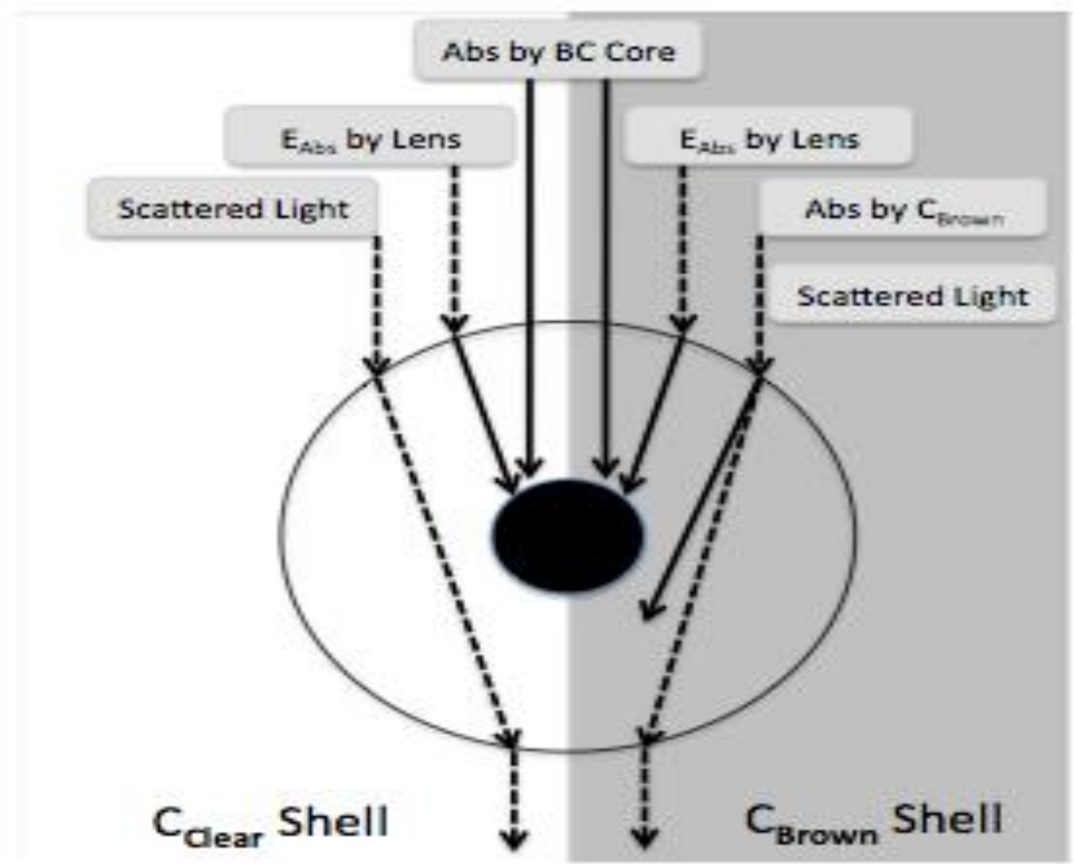


US Department of Energy



Wallace and Hobbs (2006)

Aerosol direct effect



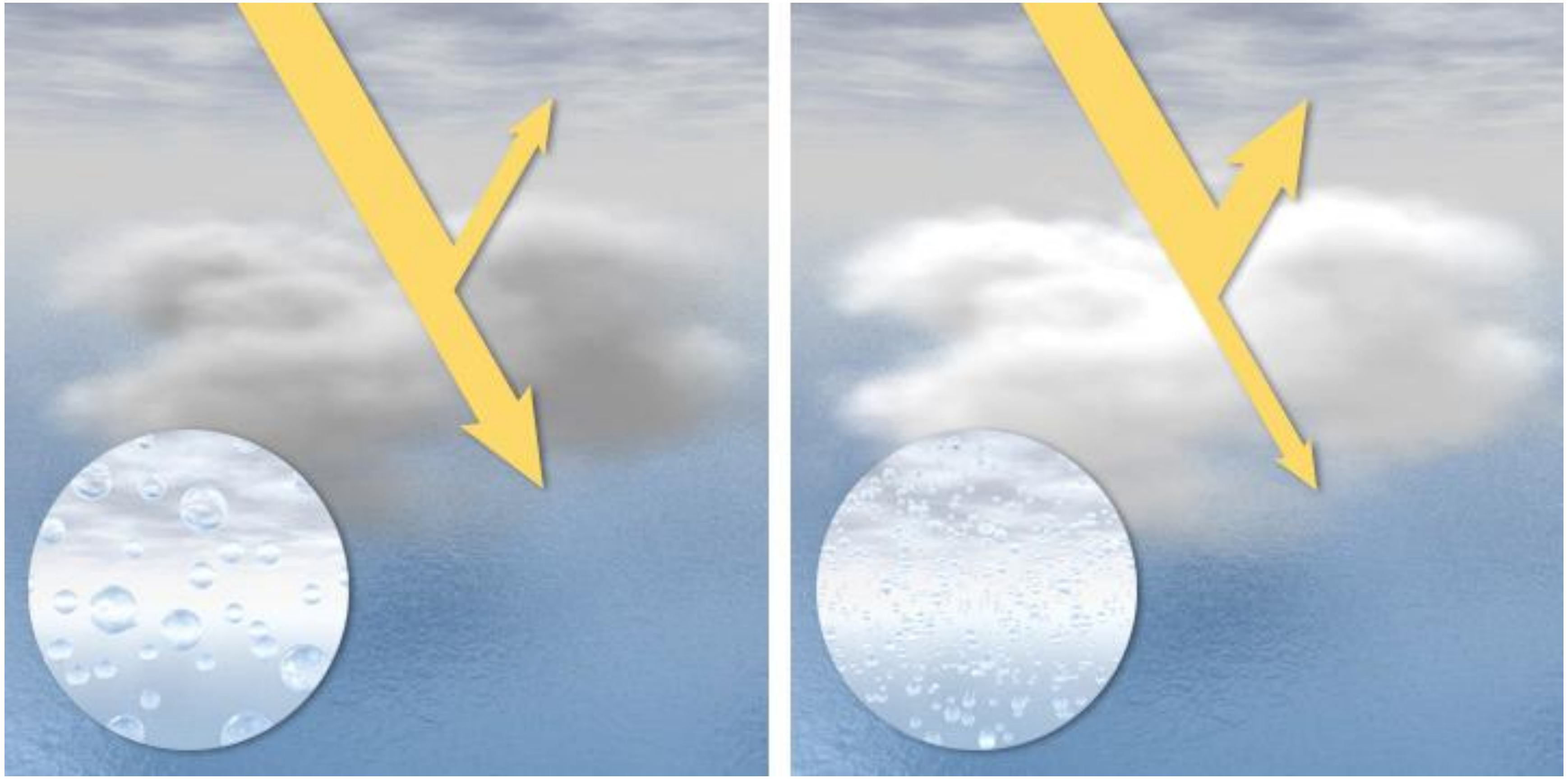
Lack and Cappa, *Atmos. Chem. Phys.*, 2010

Aerosols can scatter or absorb solar radiation.

Pittsburgh, PA, 2001-2002

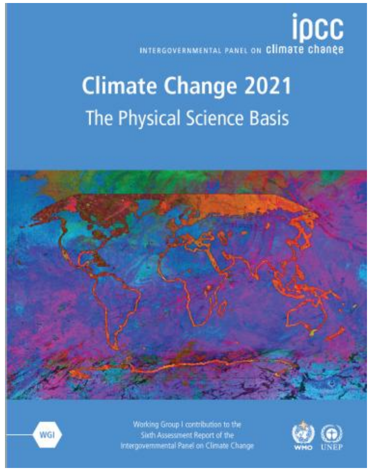
Aerosol indirect effect

Size and abundance of aerosols affect lifetime of clouds

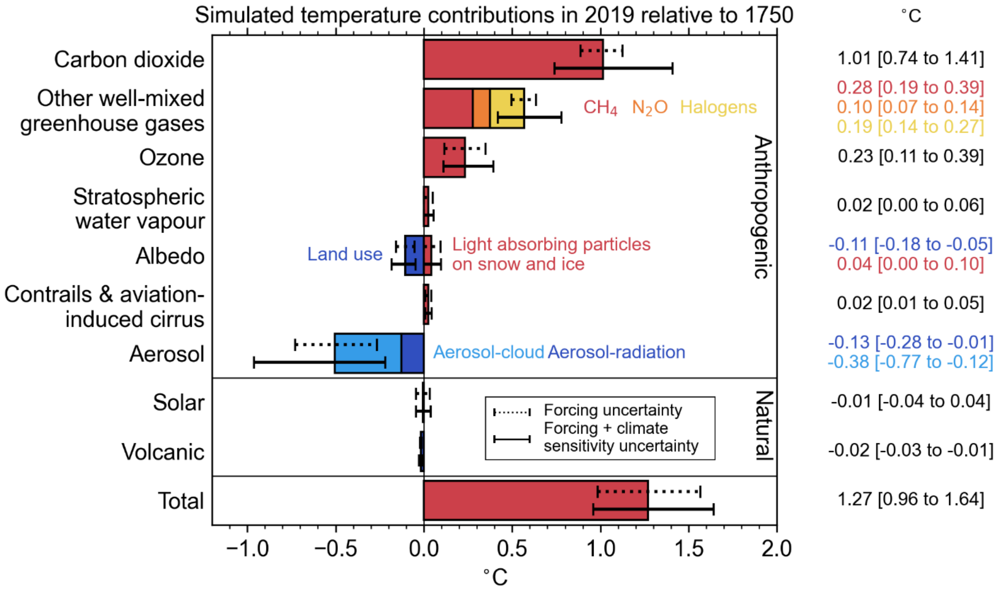


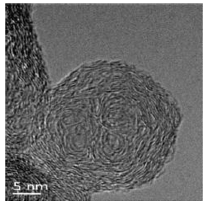
source: NASA

Aerosol forcings

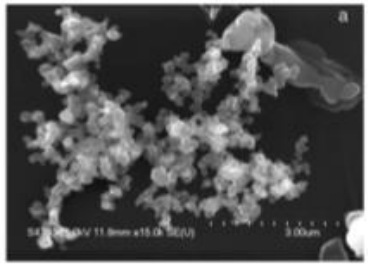


IPCC, 2021





Vander Wal et al. (2007)

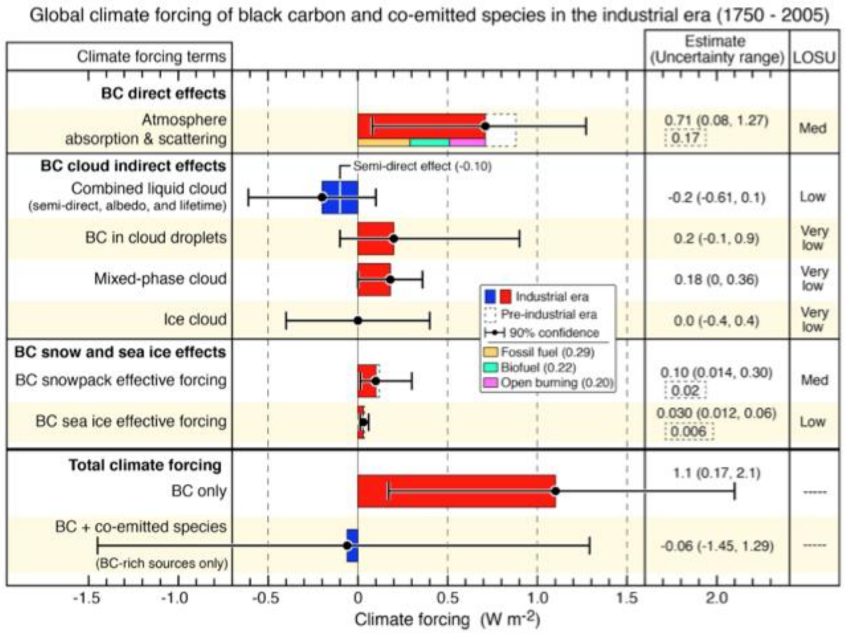


Depending on the measurement technique/ community, black carbon is also called soot or elemental carbon.

JOURNAL OF GEOPHYSICAL RESEARCH: ATMOSPHERES, VOL. 118, 5380–5552, doi:10.1002/jgrd.50171, 2013

Bounding the role of black carbon in the climate system: A scientific assessment

T. C. Bond,[1] S. J. Doherty,[2] D. W. Fahey,[3] P. M. Forster,[4] T. Berntsen,[5] B. J. DeAngelo,[6] M. G. Flanner,[7] S. Ghan,[8] B. Kärcher,[9] D. Koch,[10] S. Kinne,[11] Y. Kondo,[12] P. K. Quinn,[13] M. C. Sarofim,[6] M. G. Schultz,[14] M. Schulz,[15] C. Venkataraman,[16] H. Zhang,[17] S. Zhang,[18] N. Bellouin,[19] S. K. Guttikunda,[20] P. K. Hopke,[21] M. Z. Jacobson,[22] J. W. Kaiser,[23] Z. Klimont,[24] U. Lohmann,[25] J. P. Schwarz,[3] D. Shindell,[26] T. Storelvmo,[27] S. G. Warren,[28] and C. S. Zender[29]



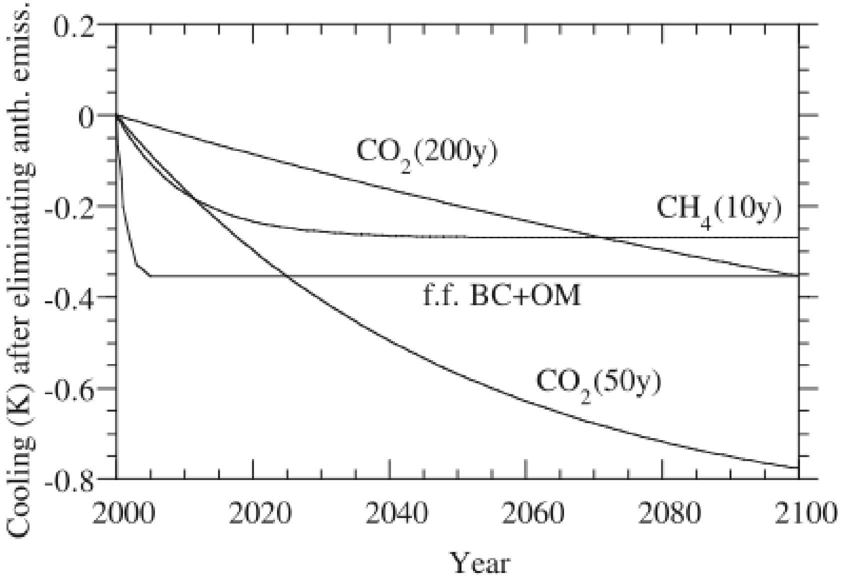
Black carbon impacts on climate

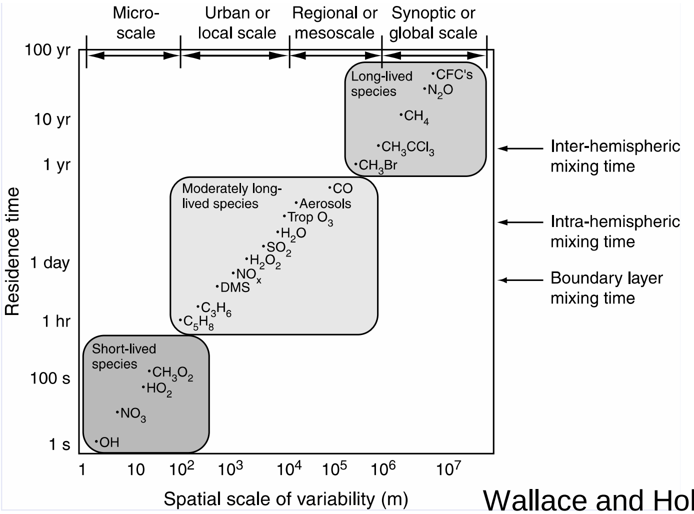
JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 107, NO. D19, 4410, doi:10.1029/2001JD001376, 2002

Control of fossil-fuel particulate black carbon and organic matter, possibly the most effective method of slowing global warming

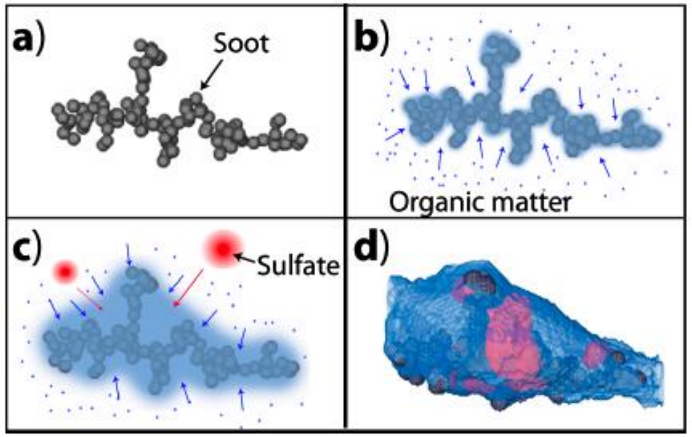
Mark Z. Jacobson
Department of Civil and Environmental Engineering, Stanford University, Stanford, California, USA

Received 9 October 2001; revised 5 February 2002; accepted 12 April 2002; published 15 October 2002.

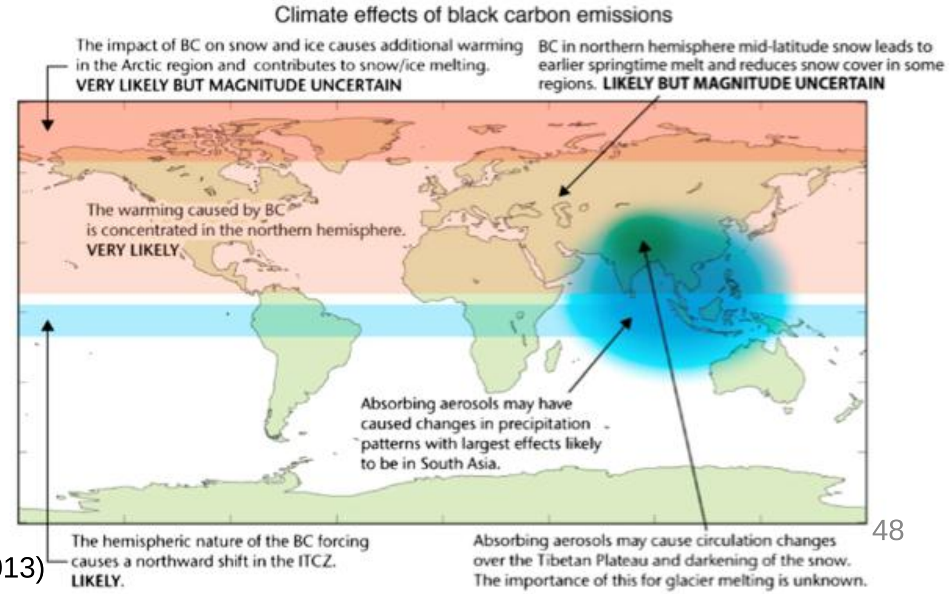




Wallace and Hobbs (2006)



Adachi et al. (2010)



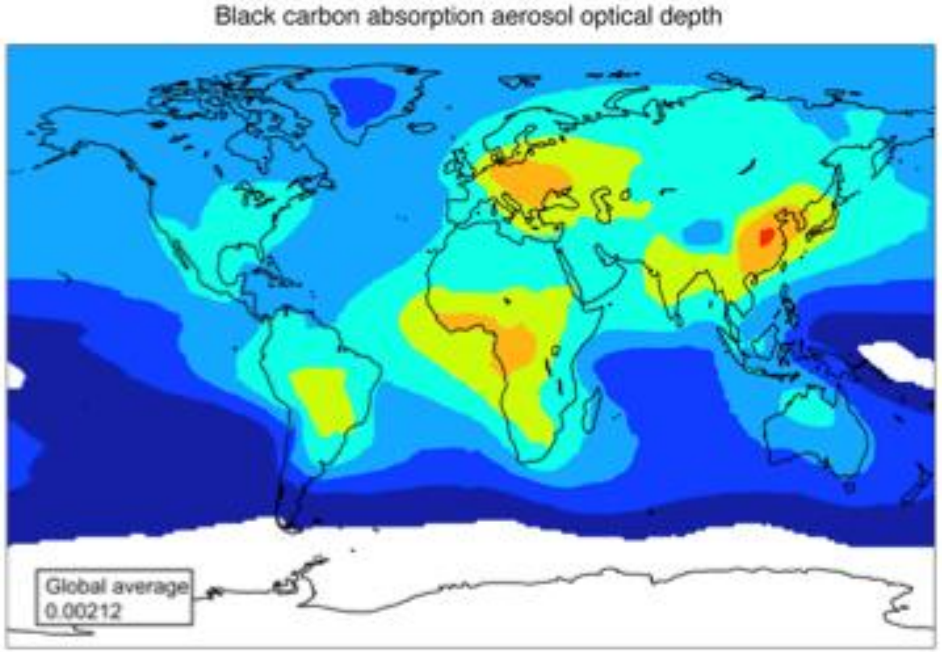
Bond et al. (2013)

Environ. Sci. Technol. **2005,** *39,* 5921–5926

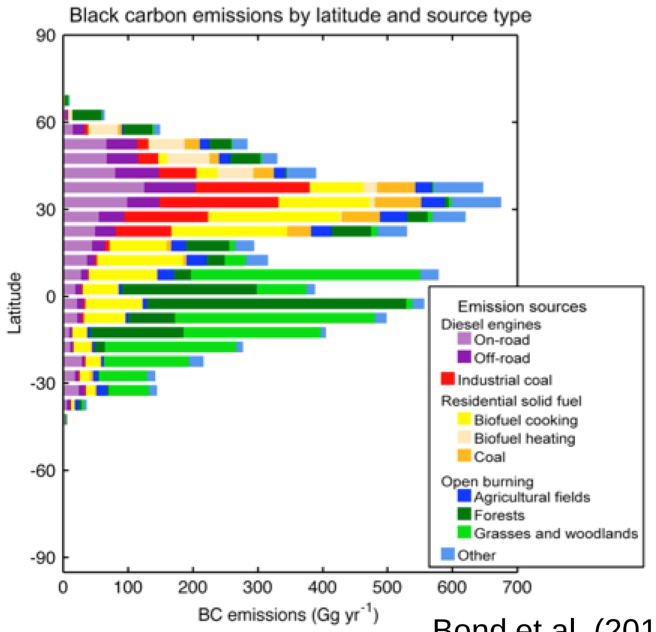
Can Reducing Black Carbon Emissions Counteract Global Warming?

TAMI C. BOND* AND HAOLIN SUN

Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801

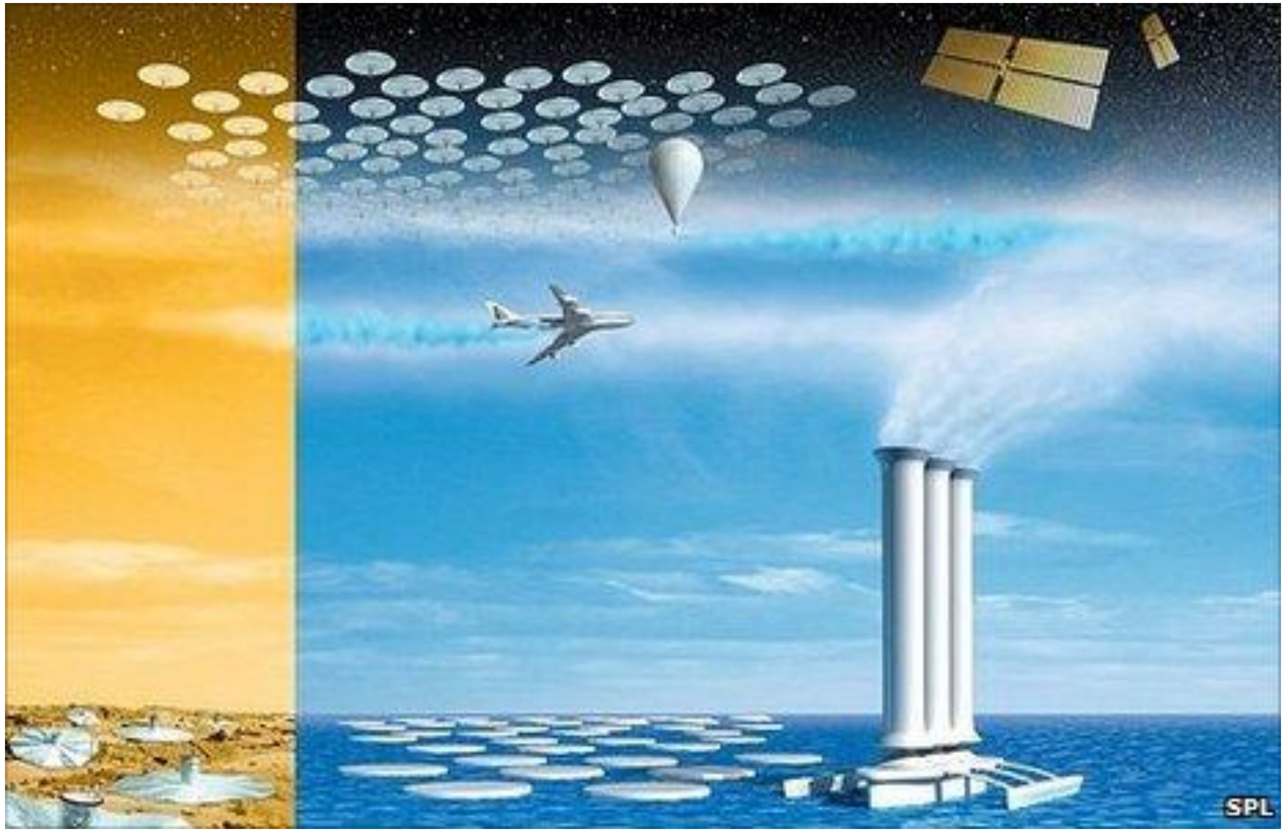


Bond et al. (2013)



Bond et al. (2013)

Geoengineering

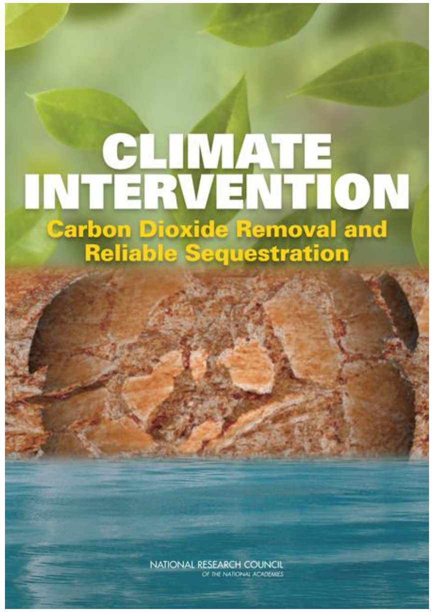


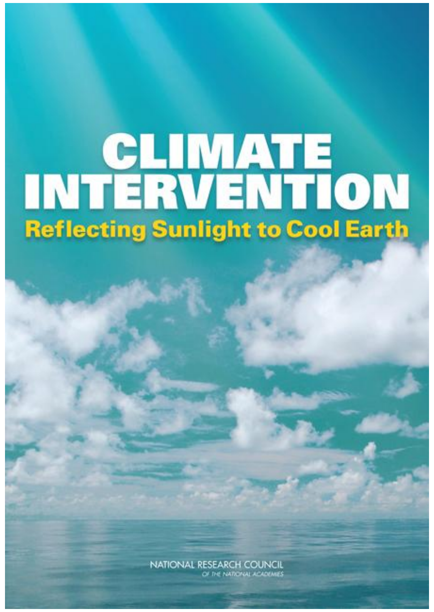
source: BBC

MIT Technology Review

A Cheap and Easy Plan to Stop Global Warming

Intentionally engineering Earth's atmosphere to offset rising temperatures could be far more doable than you imagine, says David Keith. But is it a good idea?



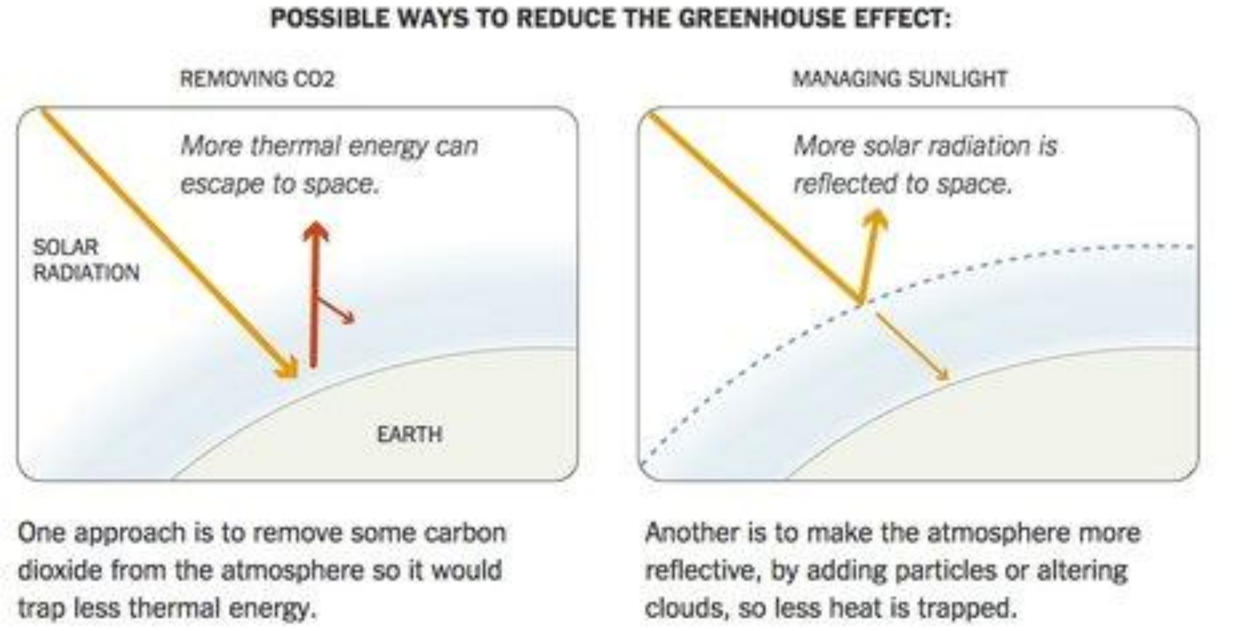


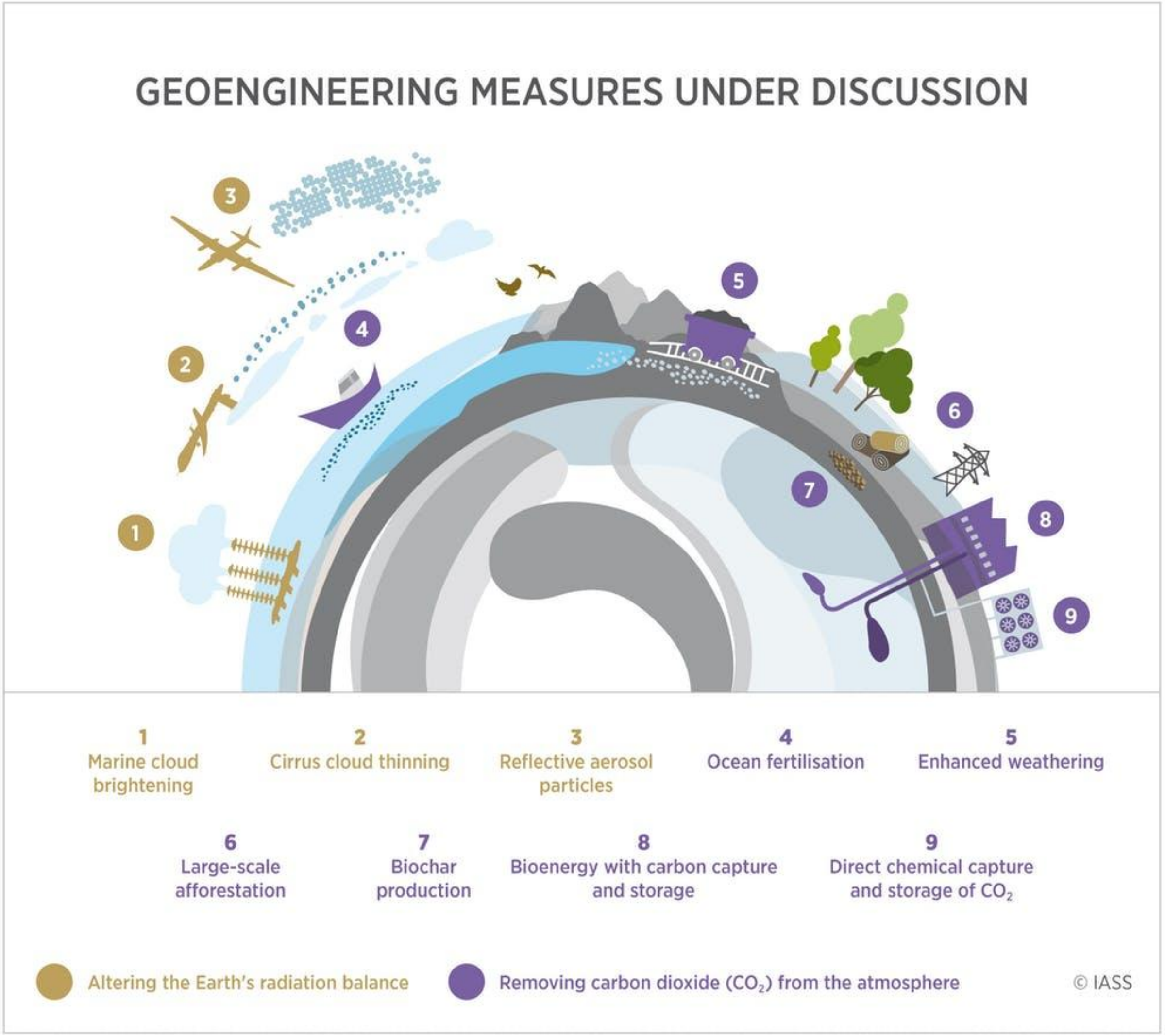
The New York Times

CLIMATE CHANGE

In Geoengineering Study, Science Academy Sees Merit in CO2 Removal, Risk in Reflecting Sunlight

By ANDREW C. REVKIN FEBRUARY 10, 2015 11:00 AM



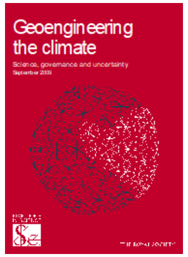


Technologies:

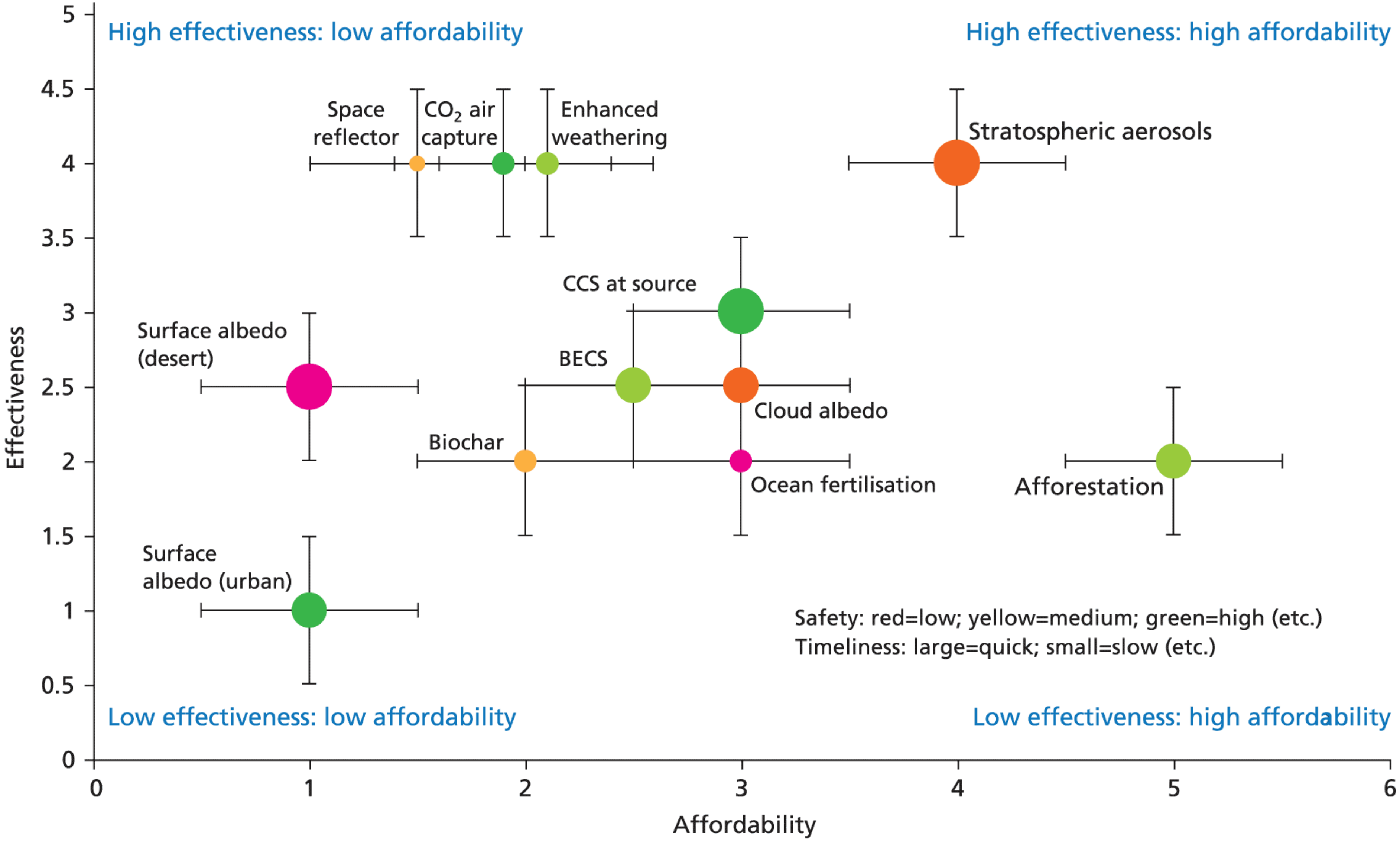
- Solar Radiation Management (SRM)
- Cirrus cloud thinning (CCT)
- Negative Emissions Technologies (NETs)

Governance:

- Impact assessment
- Economic analysis
- Policy analysis
- Transparency



UK Royal Society, *Geoengineering the climate: Science, governance and uncertainty*, 2009



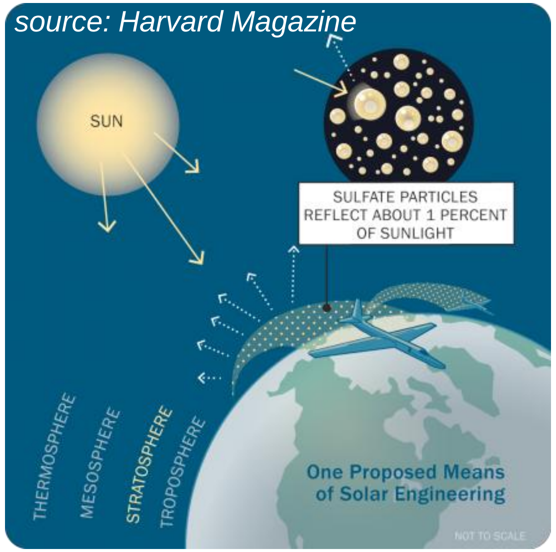
Stratospheric sulfate injection

ALBEDO ENHANCEMENT BY STRATOSPHERIC SULFUR INJECTIONS: A CONTRIBUTION TO RESOLVE A POLICY DILEMMA?

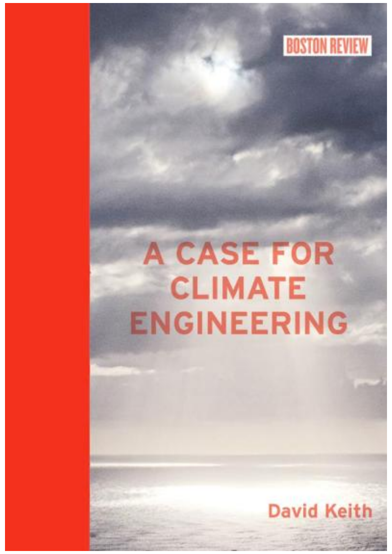
An Editorial Essay

P. J. CRUTZEN

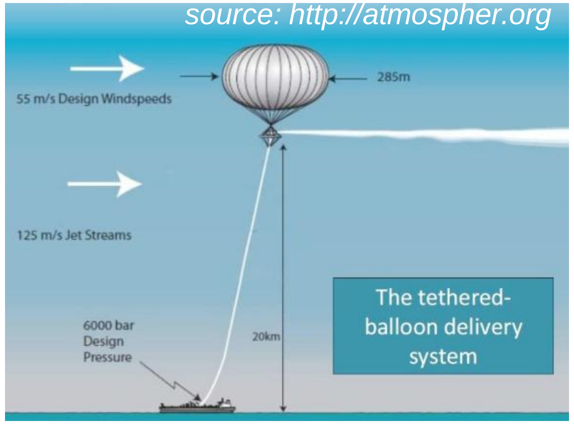
Climatic Change (2006) 77: 211–219
DOI: 10.1007/s10584-006-9101-y



source: Harvard Magazine



source: New Scientist



source: http://atmospher.org

Stratospheric solar geoengineering without ozone loss

David W. Keith[a,b,1], Debra K. Weisenstein[a], John A. Dykema[a], and Frank N. Keutsch[a,c]

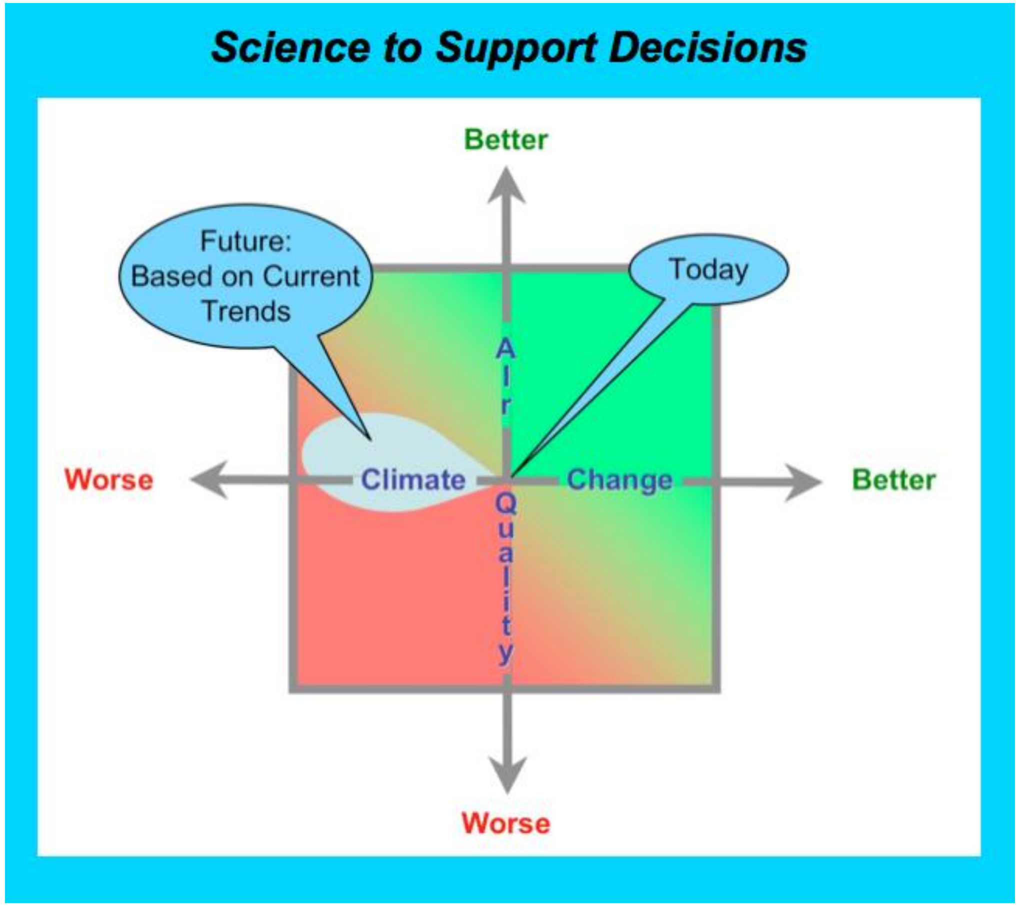
[a]John A. Paulson School of Engineering and Applied Sciences, Harvard University, Cambridge, MA 02138; [b]John F. Kennedy School of Government, Harvard University, Cambridge, MA 02138; and [c]Department of Chemistry and Chemical Biology, Harvard University, Cambridge, MA 02138

14910–14914 | PNAS | December 27, 2016 | vol. 113 | no. 52

- Injection of SO_2 leads to hygroscopic sulfate particles that facilitate release of catalysts for ozone destruction (NO_x, ClO_x, BrO_x radical families) through heterogeneous chemistry

- Instead use calcium carbonate (limestone)

Air quality and climate change



from CalNex 2010 White Paper
Research at the Nexus of Air Quality and Climate Change

ESTIMATED RELATIVE BENEFITS OF INTERVENTIONS

BASED ON CASE STUDIES AND EXPERT JUDGMENT

INTERVENTIONS BY SECTOR
Listed alphabetically

Energy
1. Coal-fired TPP replaced by gas
2. Coal-fired TPP replaced by renewables

Transport
3. Cleaner buses
4. Electric buses
5. Eliminate uncontrolled diesel emissions
6. Electric vehicles
7. EURO 4/IV standards
8. Expand mass transit
9. Further upgrade to EURO 6/VI standards
10. Reduce very high sulfur in diesel
11. Upgrade motorcycles
12. Vehicle inspection and testing

Industry
13. Emission controls on all industry
14. Emission controls on large plants
15. Energy efficiency for industry
16. Upgrade brick kilns

Household
17. Cleaner household fuels
18. Control open waste burning
19. Improved biomass cookstoves
20. Upgrade small boilers

Agriculture & Rural
21. Prevent crop residue burning
22. Prevent forest fires

Other
23. Dust control in urban areas

DIFFICULTY LOW — HIGH

COST EFFECTIVENESS LESS — MORE

How to Read the Chart
Using No. 10 as an example, we can see that reducing very high sulfur content in diesel fuel is not difficult, (blue) and is very cost effective, (a large circle). Lower sulfur fuels result in less PM2.5 and other toxic emissions, so are less dangerous to breath (high health benefits), but because the fuel is still carbon-based, there are not significant CO_2 reductions relative to other interventions, hence its position in the upper left quadrant of the chart.