Current and future burden of disease from major air pollution sources in China and India

Michael Brauer

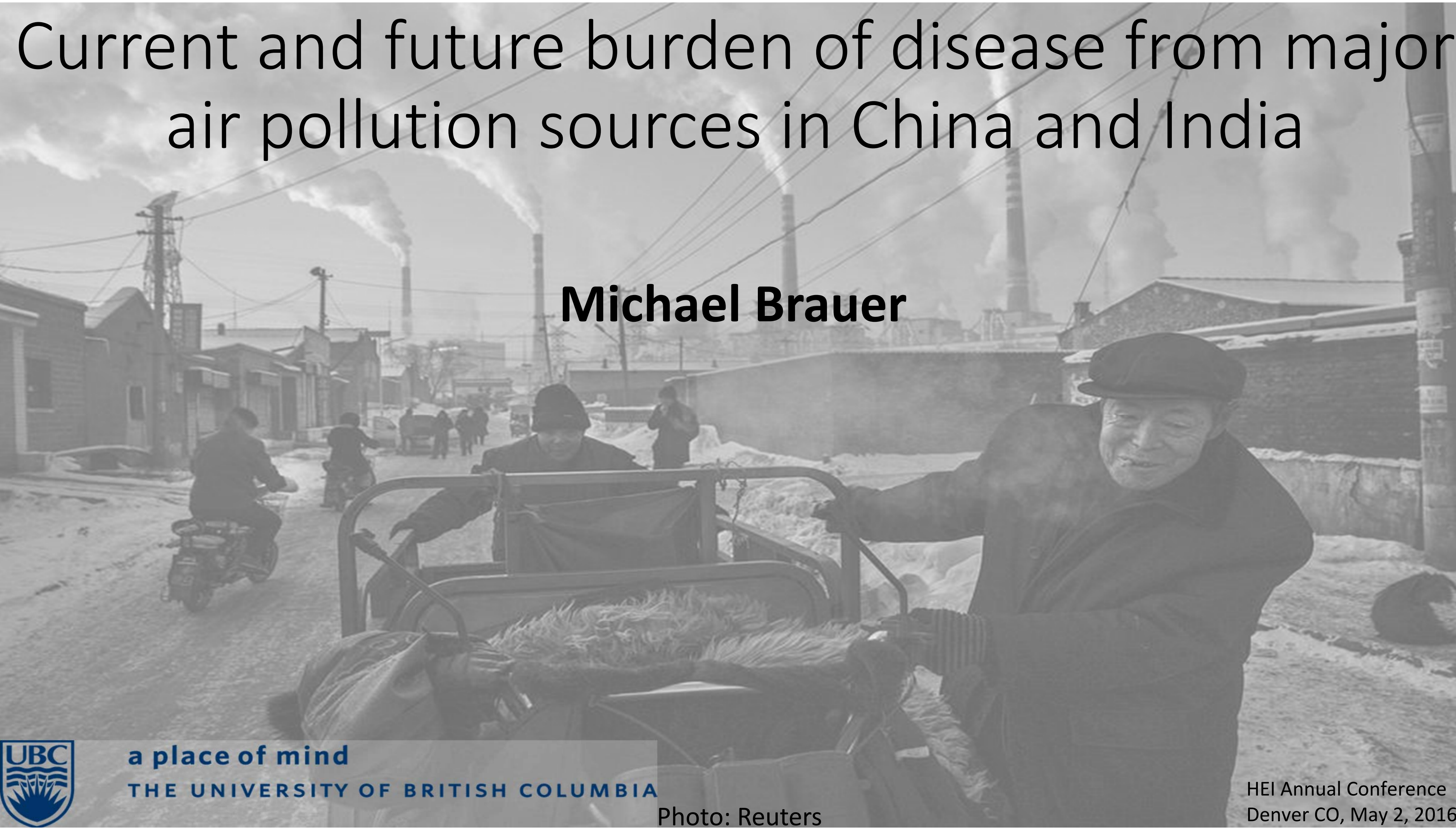
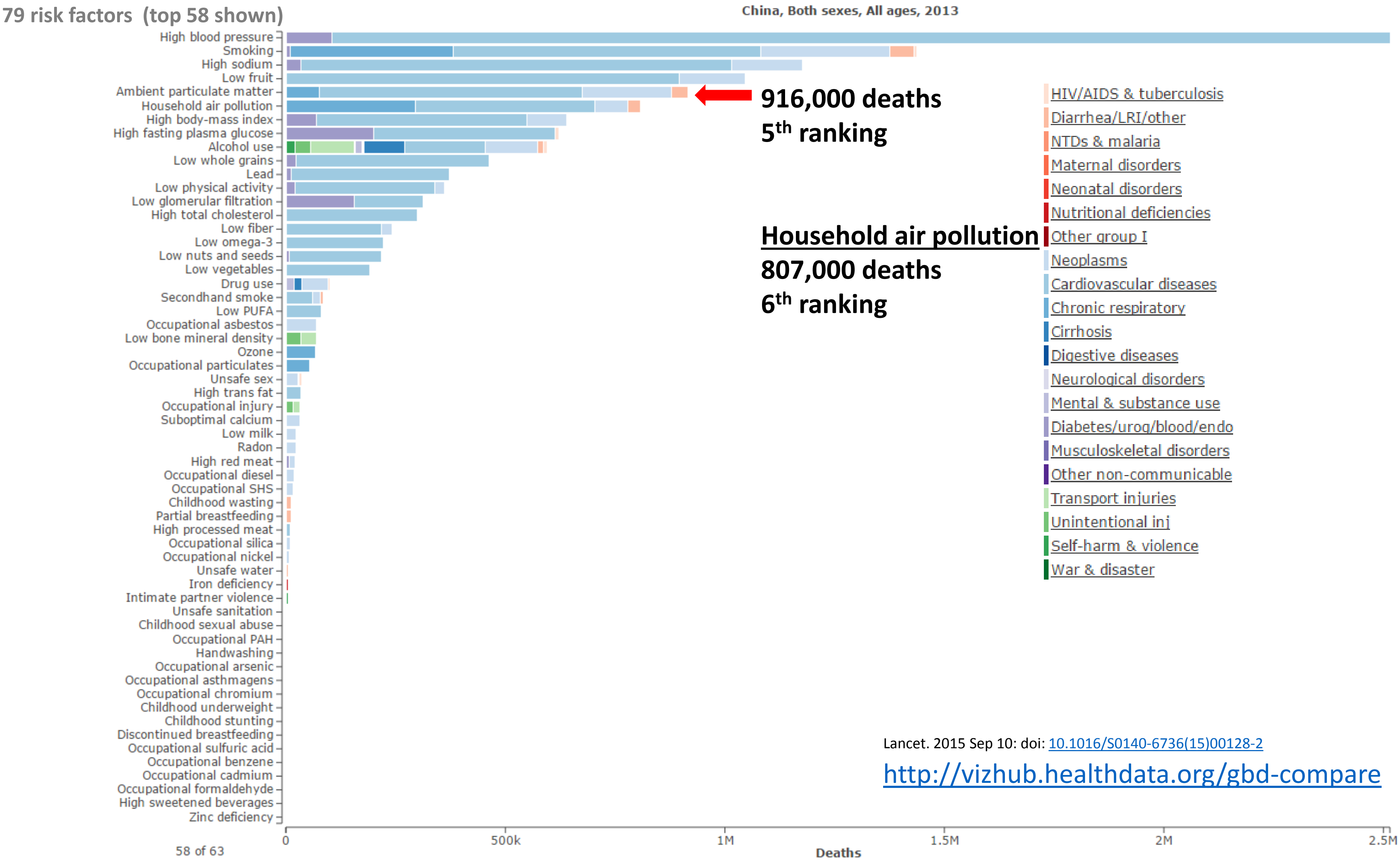


Photo: Reuters

a place of mind
THE UNIVERSITY OF BRITISH COLUMBIA

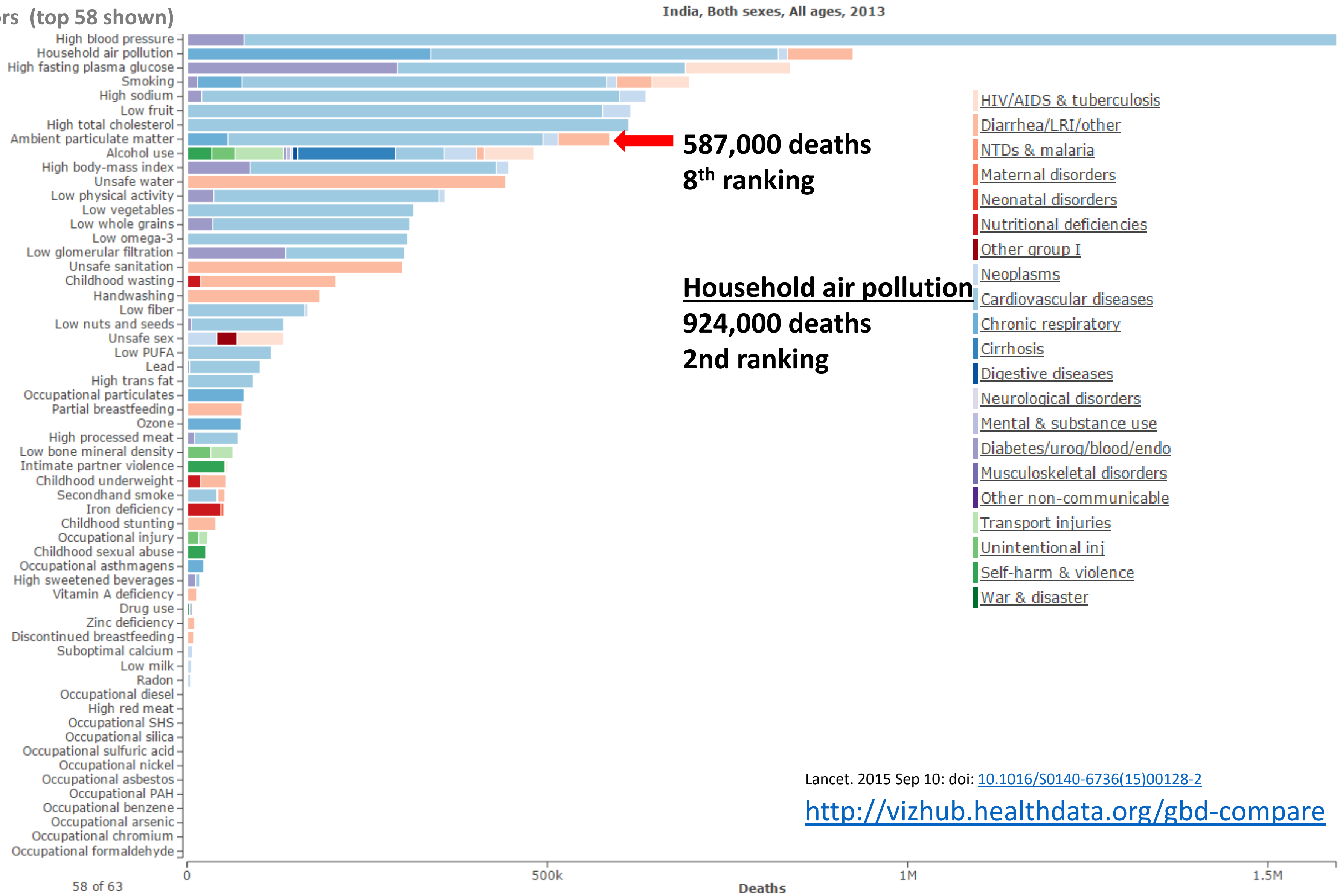
HEI Annual Conference
Denver CO, May 2, 2016



Lancet. 2015 Sep 10: doi: 10.1016/S0140-6736(15)00128-2

http://vizhub.healthdata.org/gbd-compare

79 risk factors (top 58 shown)



587,000 deaths
8th ranking

Household air pollution
924,000 deaths
2nd ranking

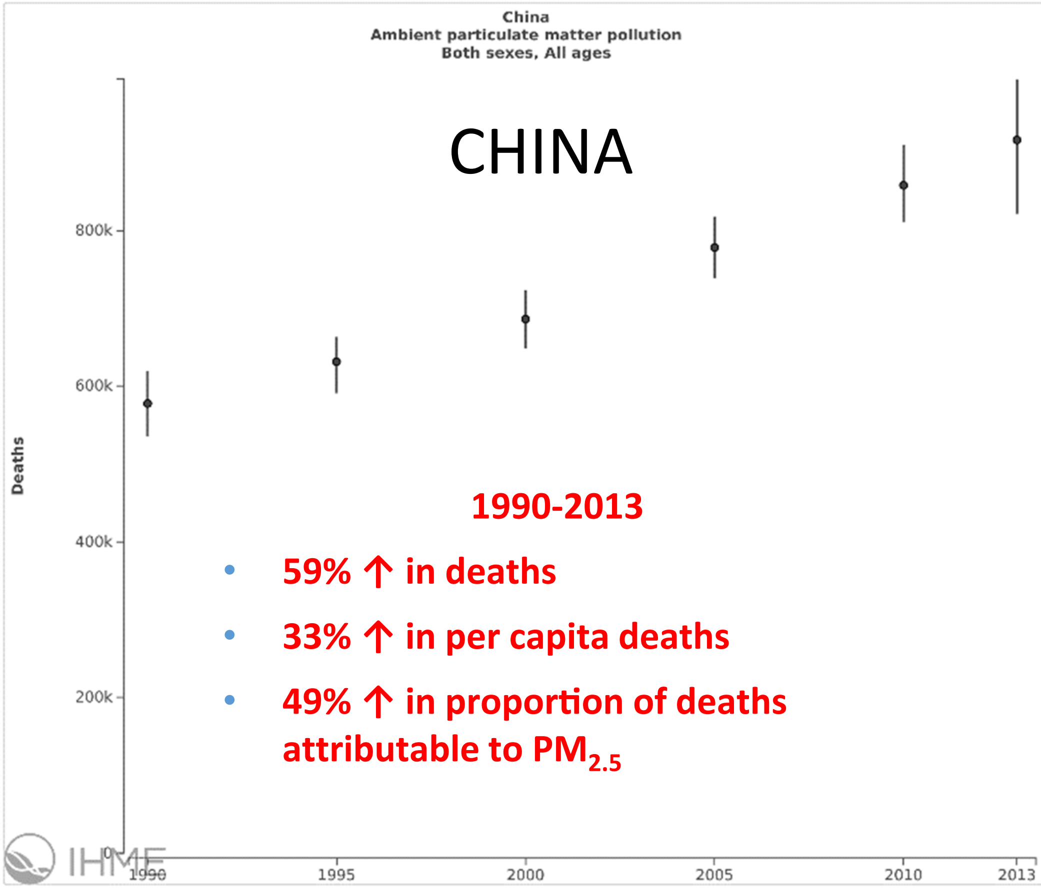
Lancet. 2015 Sep 10: doi: 10.1016/S0140-6736(15)00128-2

http://vizhub.healthdata.org/gbd-compare

	CHINA OUTDOOR PM	CHINA HOUSEHOLD	INDIA OUTDOOR PM	INDIA HOUSEHOLD	USA OUTDOOR PM
IHD	**236,926** **17%**	**151,722** **11%**	**296,489** **19%**	**315,039** **20%**	**43,160** **7.9%**
Stroke	**363,494** **19%**	**256,674** **13%**	**139,941** **20%**	**166,871** **23%**	**10,881** **6.6%**
COPD	**75,761** **8%**	**295,786** **32%**	**56,665** **7%**	**338,491** **45%**	**1,710** **1.1%** Ozone: 12,366
Lung Cancer	**201,864** **37%**	**75,050** **14%**	**21,432** **35%**	**12,882** **21%**	**17,363** **9.8%**
ALRI	**38,064** **18%**	**28,041** **13%**	**72,041** **18%**	**90,878** **22%**	**5,718** **6.7%**
	916,102	**807,238**	**586,788**	**924,550**	**78,814**

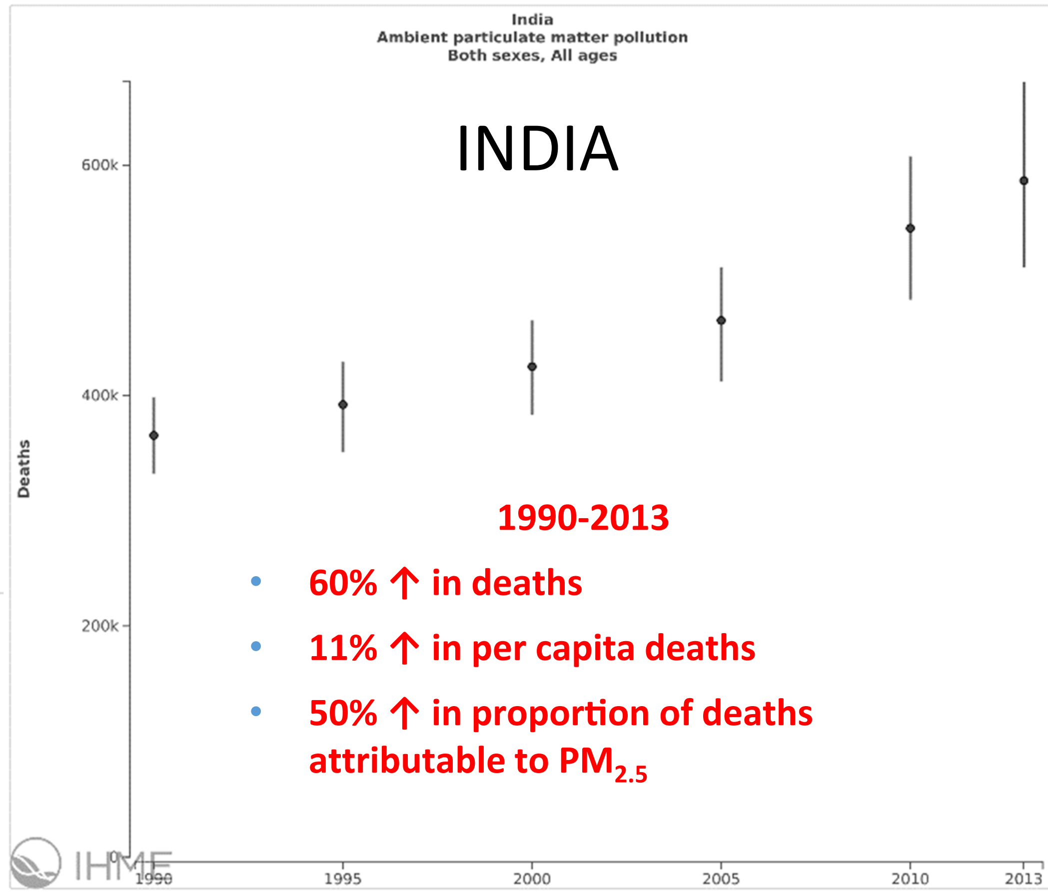
http://vizhub.healthdata.org/gbd-compare

Mortality attributable to ambient $PM_{2.5}$



1990-2013

- **59% ↑ in deaths**
- **33% ↑ in per capita deaths**
- **49% ↑ in proportion of deaths attributable to $PM_{2.5}$**



1990-2013

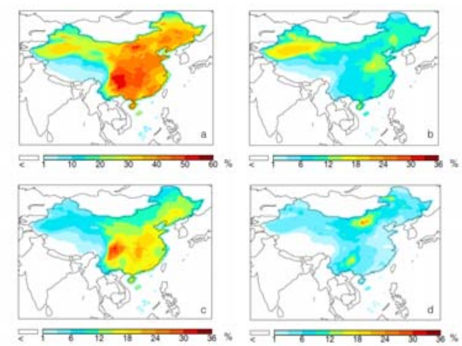
- **60% ↑ in deaths**
- **11% ↑ in per capita deaths**
- **50% ↑ in proportion of deaths attributable to $PM_{2.5}$**

http://vizhub.healthdata.org/gbd-compare

GBD-MAPS general methodology

f_{source}

- Estimate major source contribution to ambient $PM_{2.5}$
- Calculate fraction ambient $PM_{2.5}$ attributable to each source

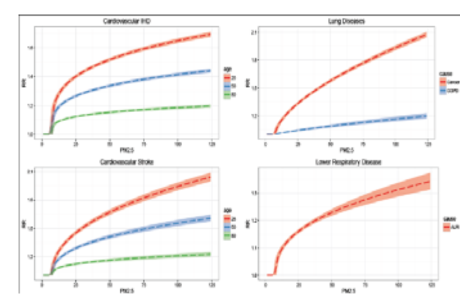


$PM_{2.5\ source}$

- $f_{source\ i}$ x ambient $PM_{2.5}$ → ambient $PM_{2.5}$ attributable to each source

Disease Burden

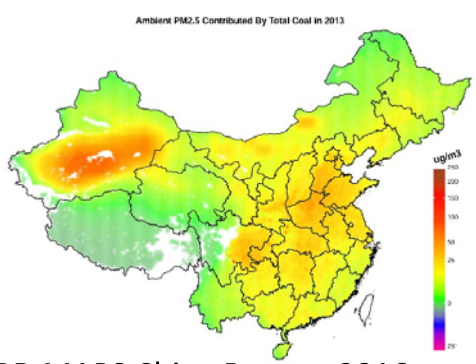
- Use integrated exposure response functions and cause-specific mortality estimates in combination with $\mathbf{PM_{2.5\ source\ i}}$ → source contribution to disease burden

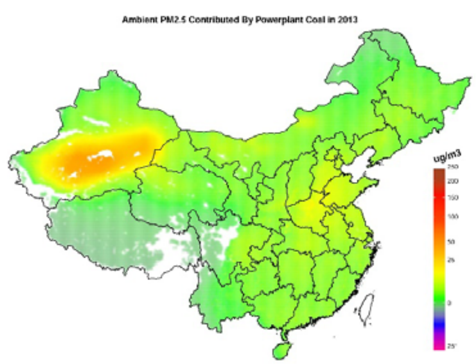


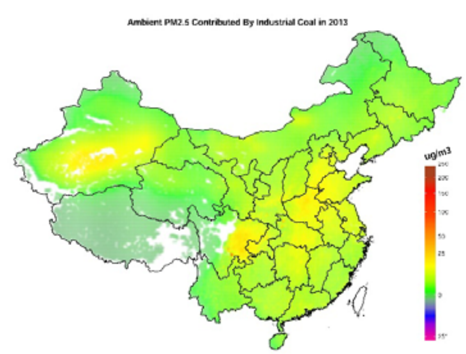
Population-weighted proportions of ambient $PM_{2.5}$ by source, China

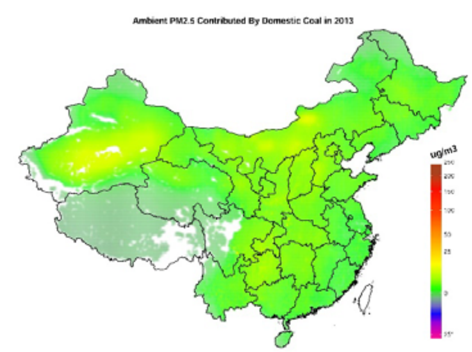
Total Coal	Industrial	Power Plant	Domestic
40.3%	**17.4%**	**9.5%**	**4.3%**

Non-coal Industrial	Transport	Biomass	Open Burning
10.3%	**15.1%**	**14.8%**	**7.6%**









GBD MAPS China Report, 2016

Estimated disease burden in 2013, China

Subsector	Mean $PM_{2.5}$	Deaths
All Ambient PM2.5	54.3	916,000
Total Coal	21.9	366,000
Powerplant Coal	5.2	86,500
Industrial Coal	9.4	155,500
Non Coal Industial	5.6	95,000
Domestic Coal	2.4	41,000
Domestic Biomass	8.0	136,500
Traffic	8.2	137,500
Open Burning	4.1	70,000

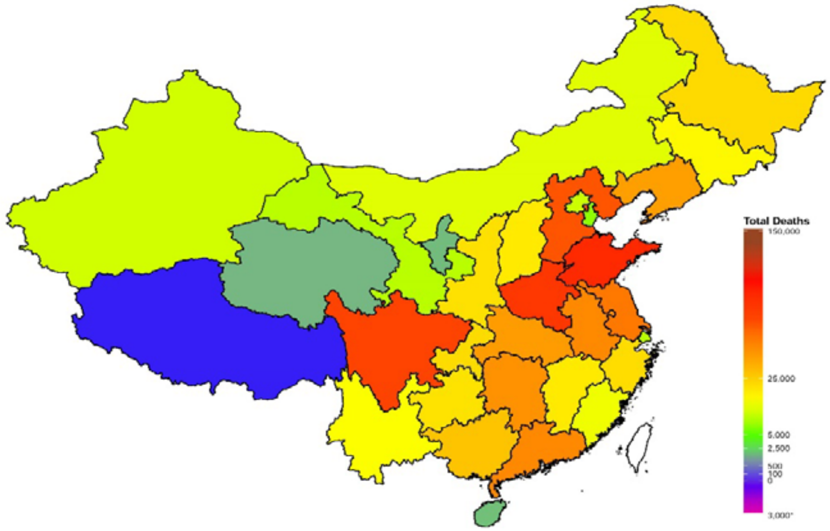
Industrial Coal + Non Coal Industial: 250,500

Domestic Coal + Domestic Biomass: 177,500

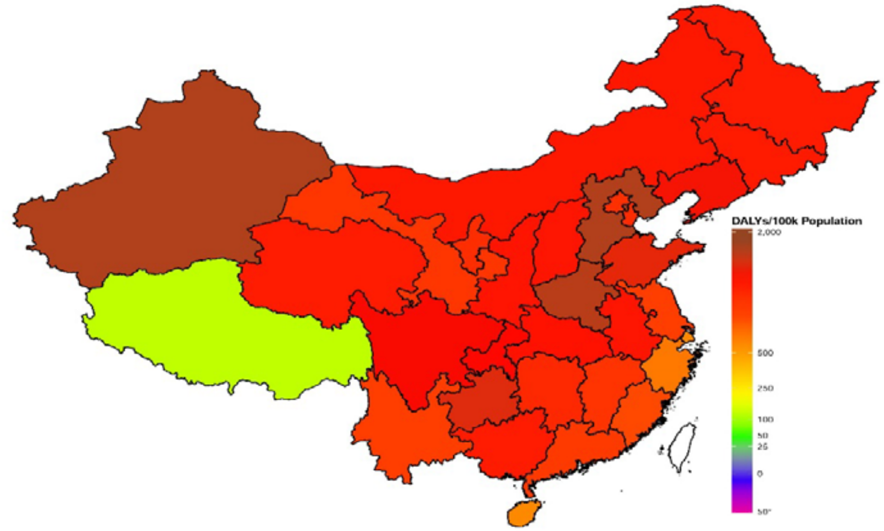
Source sector contributions to mean population-weighted ambient $PM_{2.5}$ and $PM_{2.5}$ - attributable deaths in China, 2013.

GBD MAPS China Report, 2016

Total Deaths – All Ambient Pm2.5 in 2013, Scenario: STD (2013)

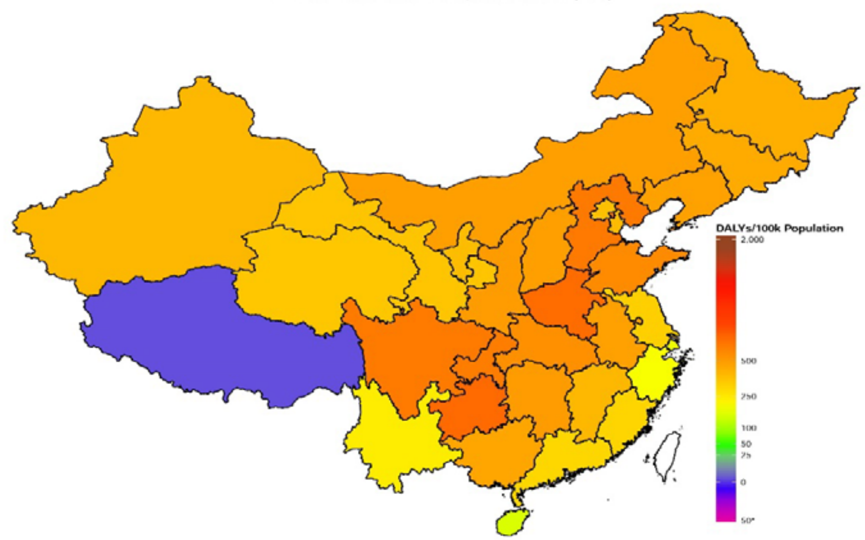


DALY Rate – All Ambient Pm2.5 in 2013, Scenario: STD (2013)



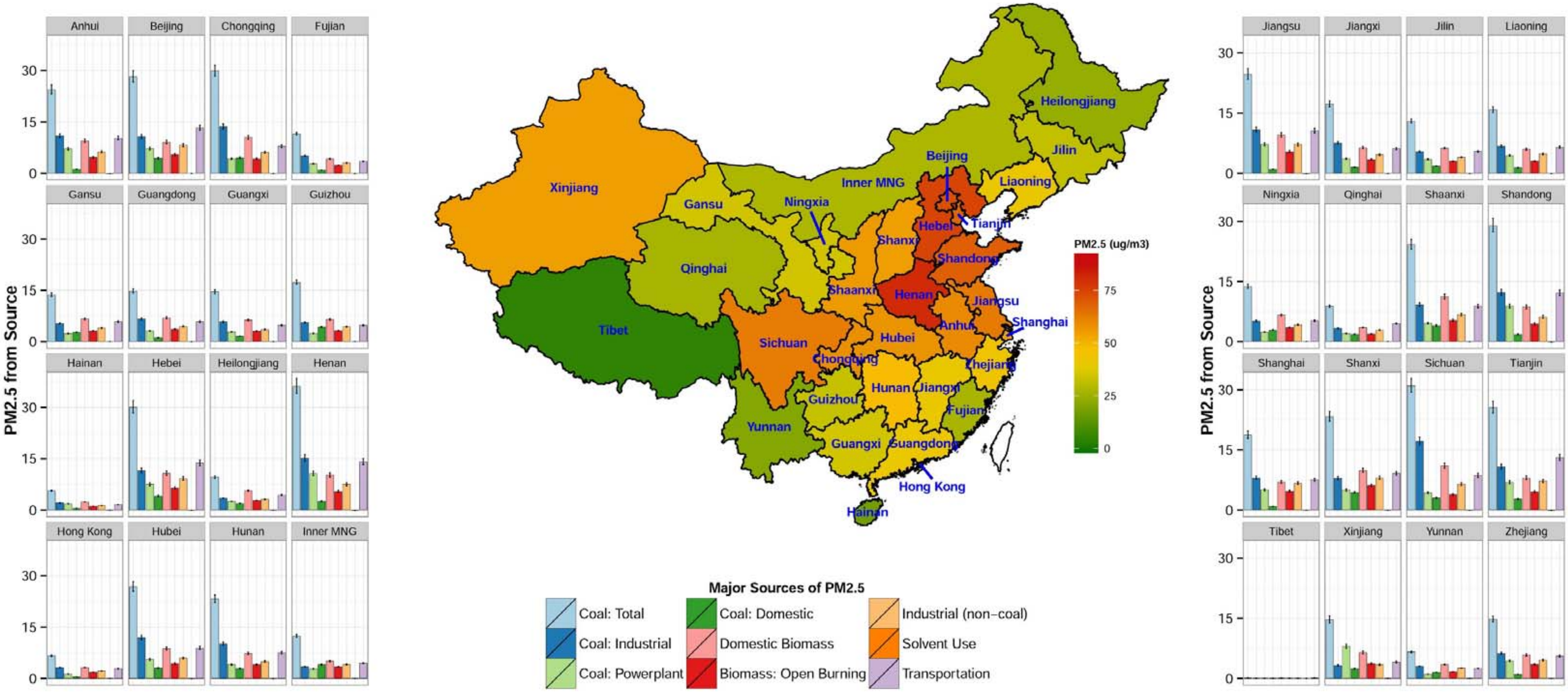
Total Deaths – Coal: Total in 2013, Scenario: STD (2013)

DALY Rate – Coal: Total in 2013, Scenario: STD (2013)



GBD MAPS China Report, 2016

Total PM2.5 by Province & Breakdown of Major Sources – 2013

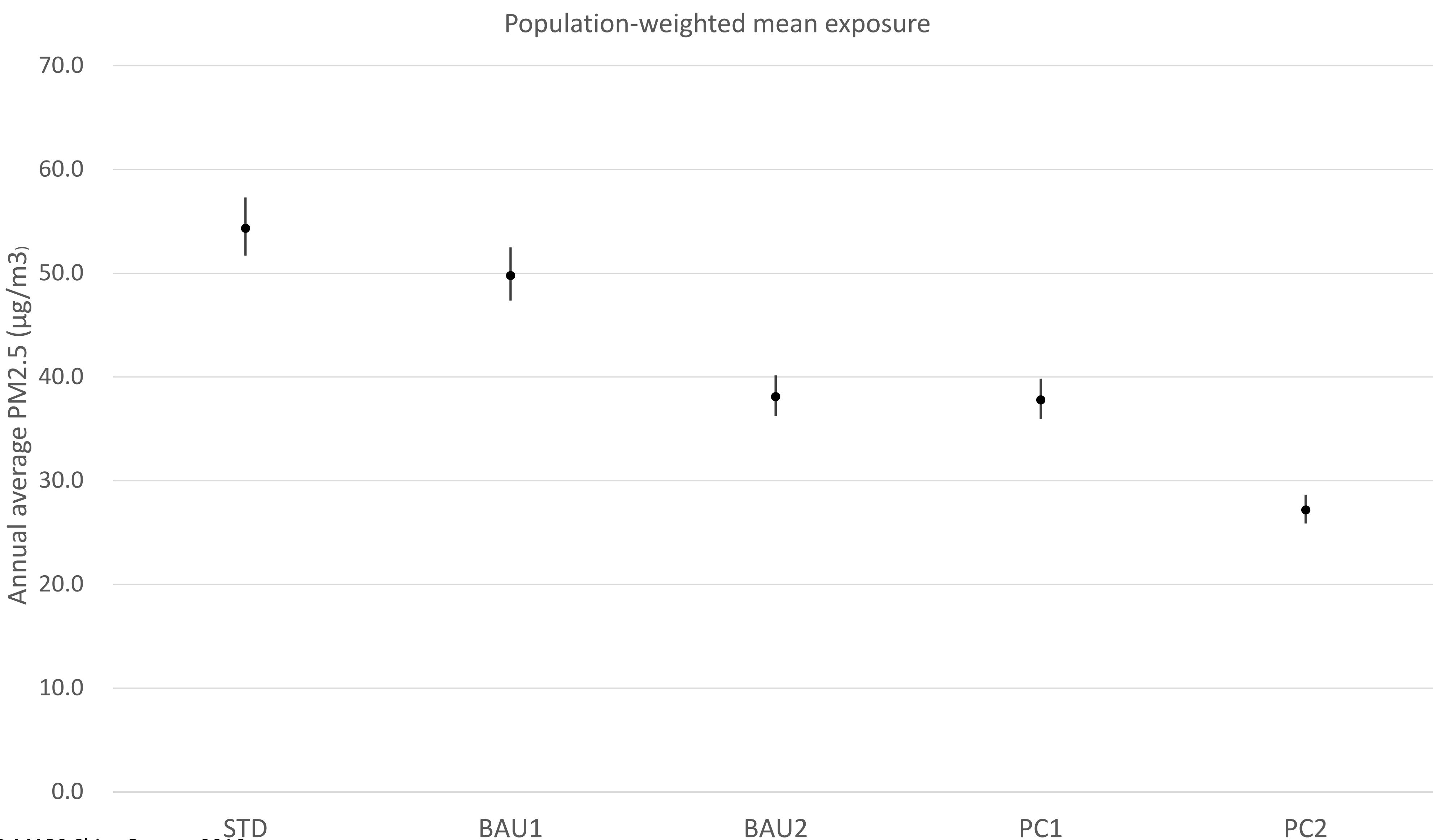


GBD MAPS China Report, 2016

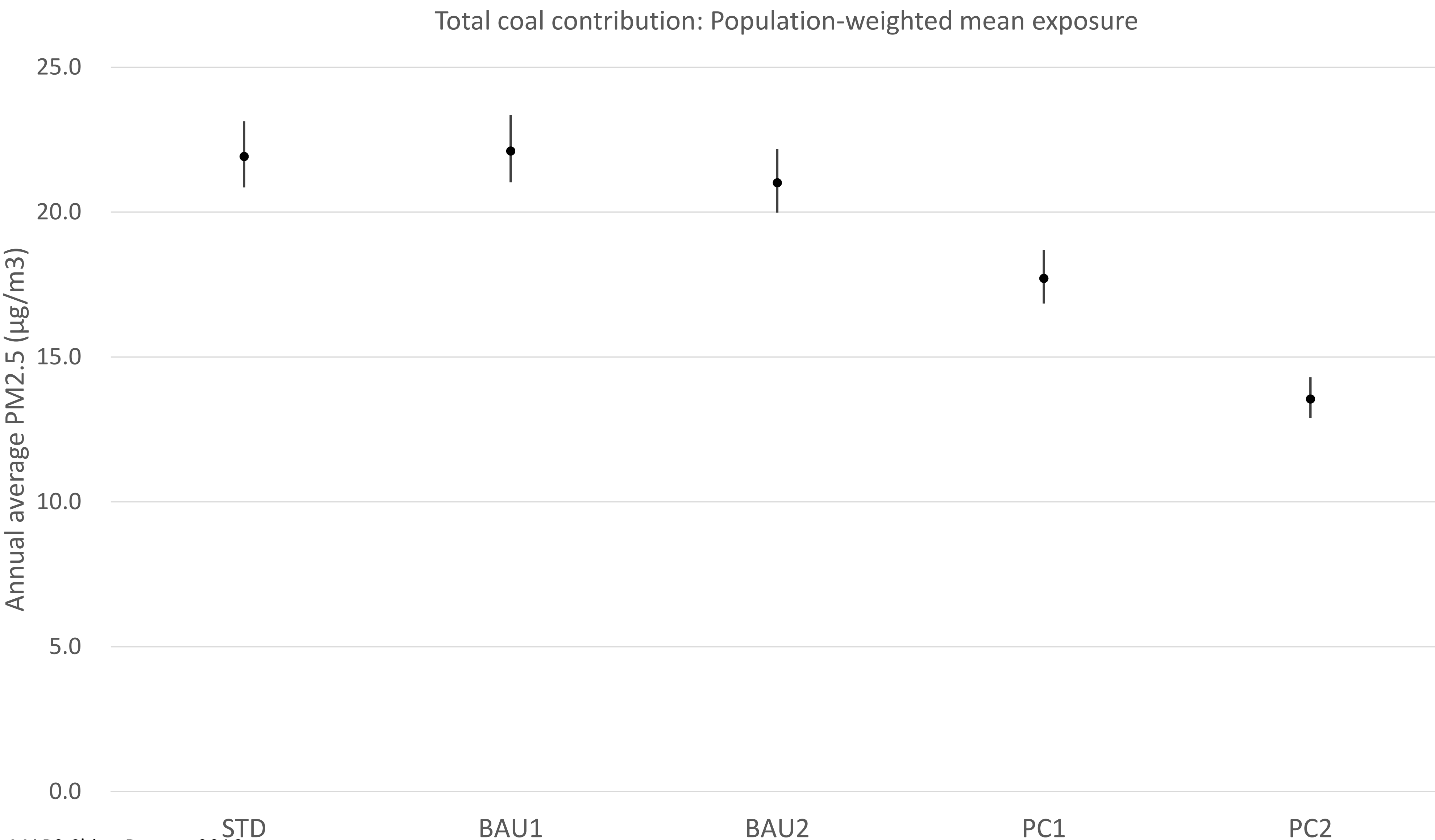
Future scenarios

	End of Pipe Emission Control Policy	
Energy policy	**[1] Twelfth Five-Year Plan for Environmental Protection**	**[2] Maximum Feasible Emission Controls Regardless of Cost**
BAU: Current Legislation and Implementation Status (at end of 2012)	BAU[1]	BAU[2]
PC: Additional energy-saving policies implemented (life style changes, structural adjustments, energy efficiency improvements).	PC[1]	PC[2]

GBD MAPS China Report, 2016



GBD MAPS China Report, 2016



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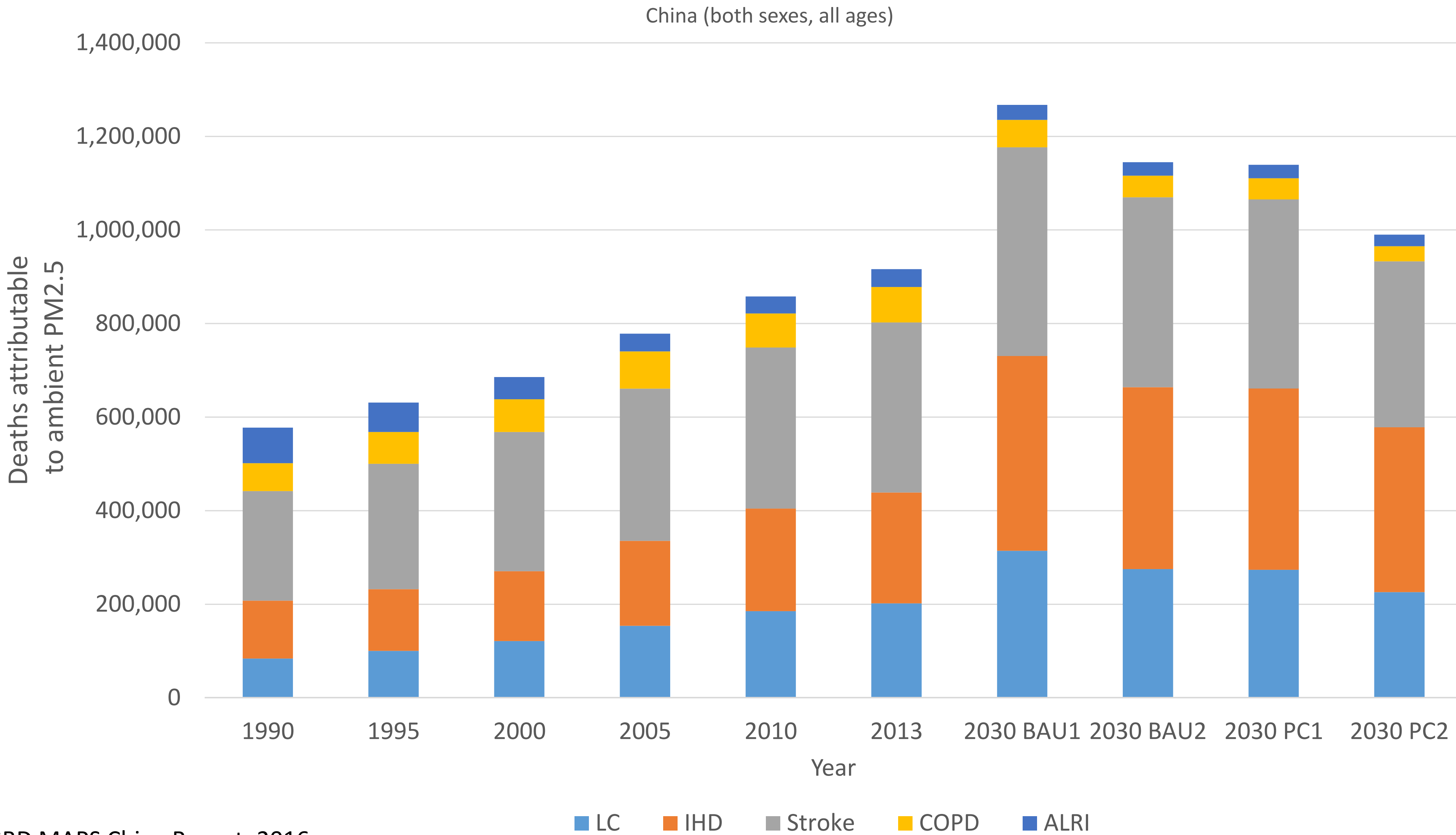

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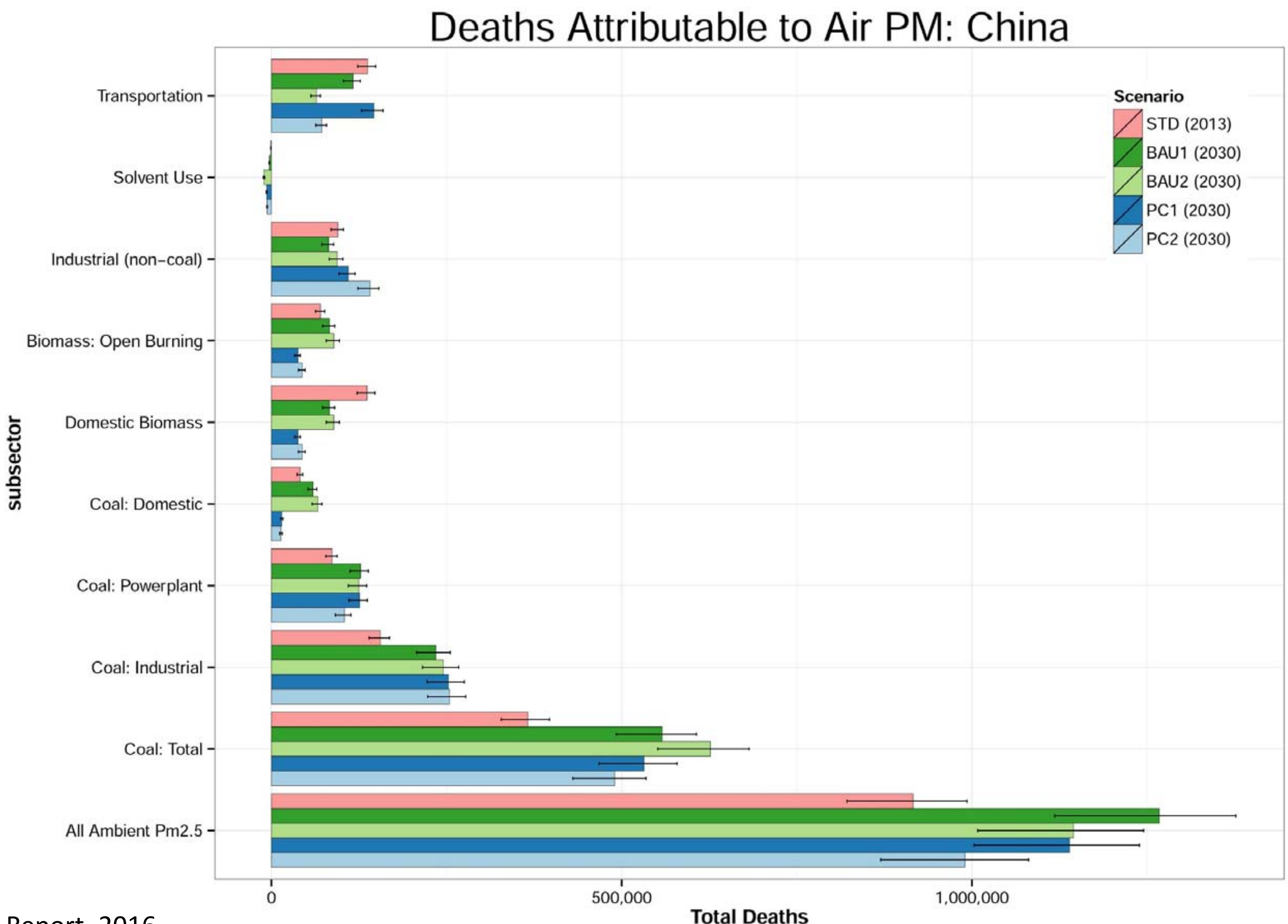

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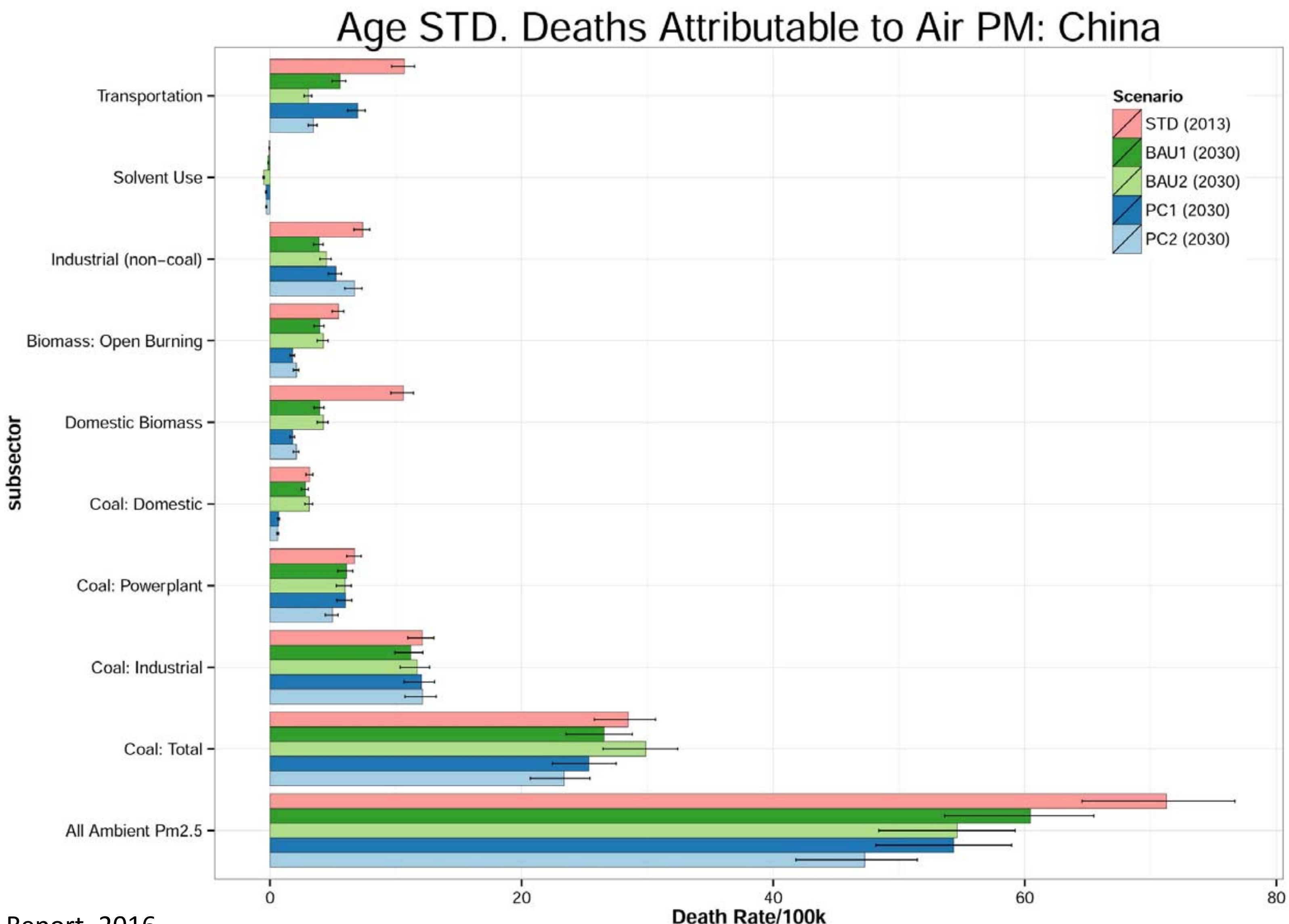
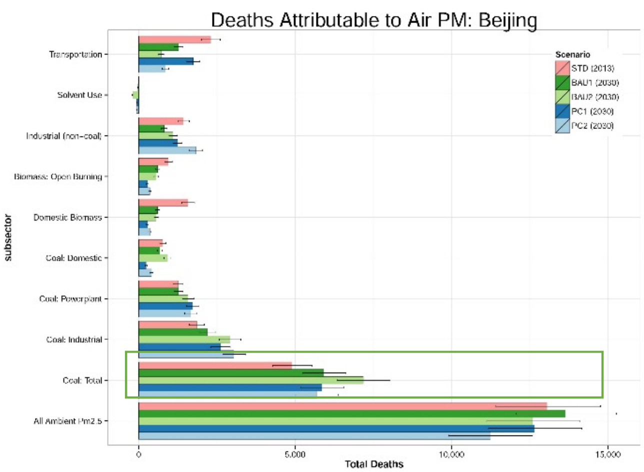
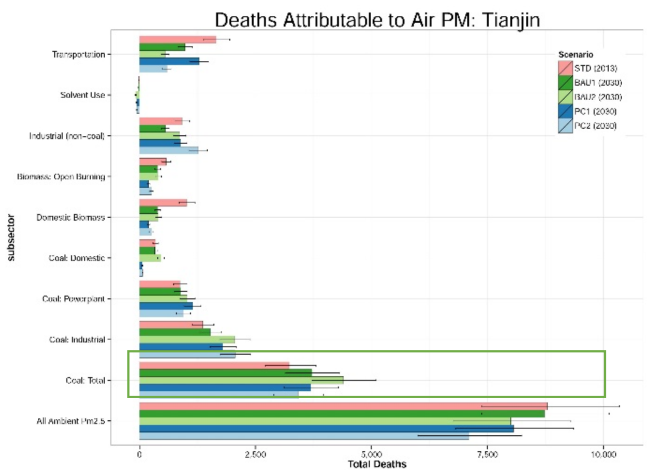


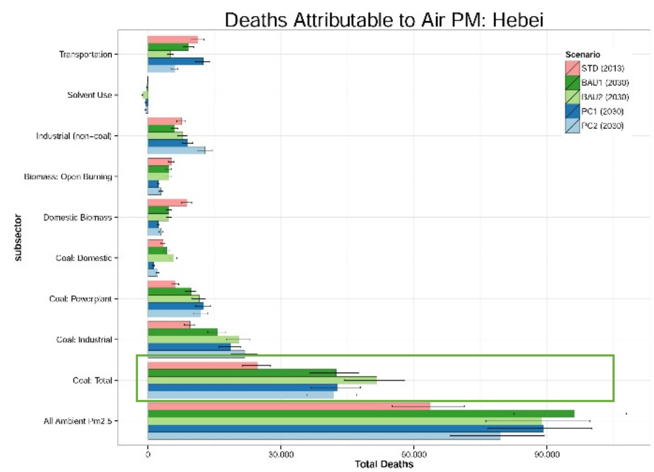
GBD MAPS China Report, 2016

Provincial level results: Jing-Jin-Ji region

- Deaths attributable to $PM_{2.5}$ in 2013: Beijing 4900 due to coal (total 13,000), Hebei 3200 (8800), Tianjin 24,600 (63,700)
- Deaths in Beijing & Tianjin for most future scenarios decrease; patterns in Hebei follow national projections
- Decreases projected in Beijing and Tianjin mainly due to decreases in non-coal source sectors such as transportation, domestic (coal and biomass) and open biomass burning.







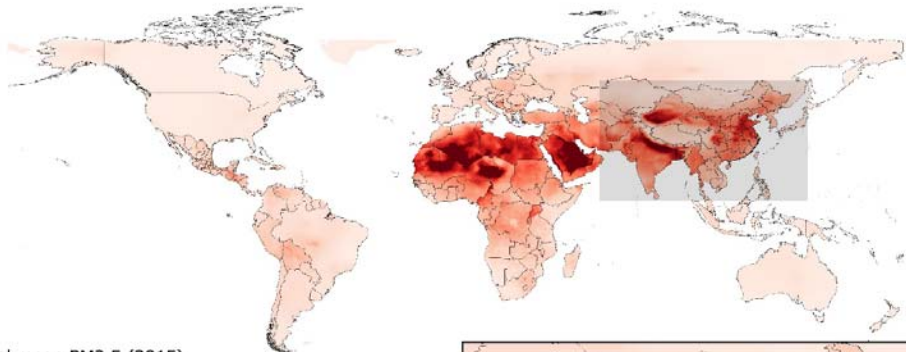
GBD MAPS China Report, 2016

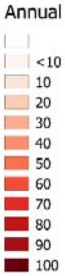
India

GBD2015 improvements to better capture regional differences & incorporate ground measurements

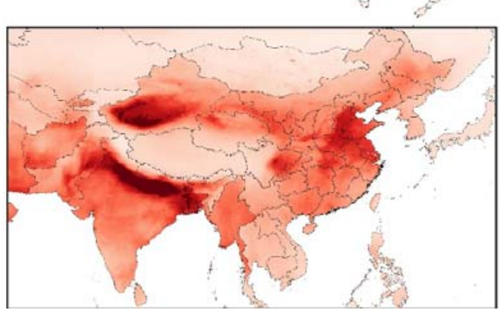
$$\log(PM_{2.5}) = \beta_0 + \beta_1 \log(SAT_i) + \beta_{3..n} + \varepsilon_i$$

Bayesian Hierarchical Model





Median R^2 = 0.81
Median RMSE = 10 μg/m^3
Median MAE = 5.6 μg/m^3



G. Shaddick, M. Thomas, 2016

van Donkelaar A, Martin RV, Brauer M, Hsu NC, Kahn RA, Levy RC, Lyapustin A, Sayer AM, Winker DM. Global Estimates of Fine Particulate Matter using a Combined Geophysical-Statistical Method with Information from Satellites, Models, and Monitors. Environ Sci Technol. 2016. **DOI:** 10.1021/acs.est.5b05833

Variables:
Population
Σ(SO_4^{2-}, NO_3^-, NH_4^+ OC) (relative species contribution)
Mineral dust (relative contribution)
Inverse distance to nearest urban land surface

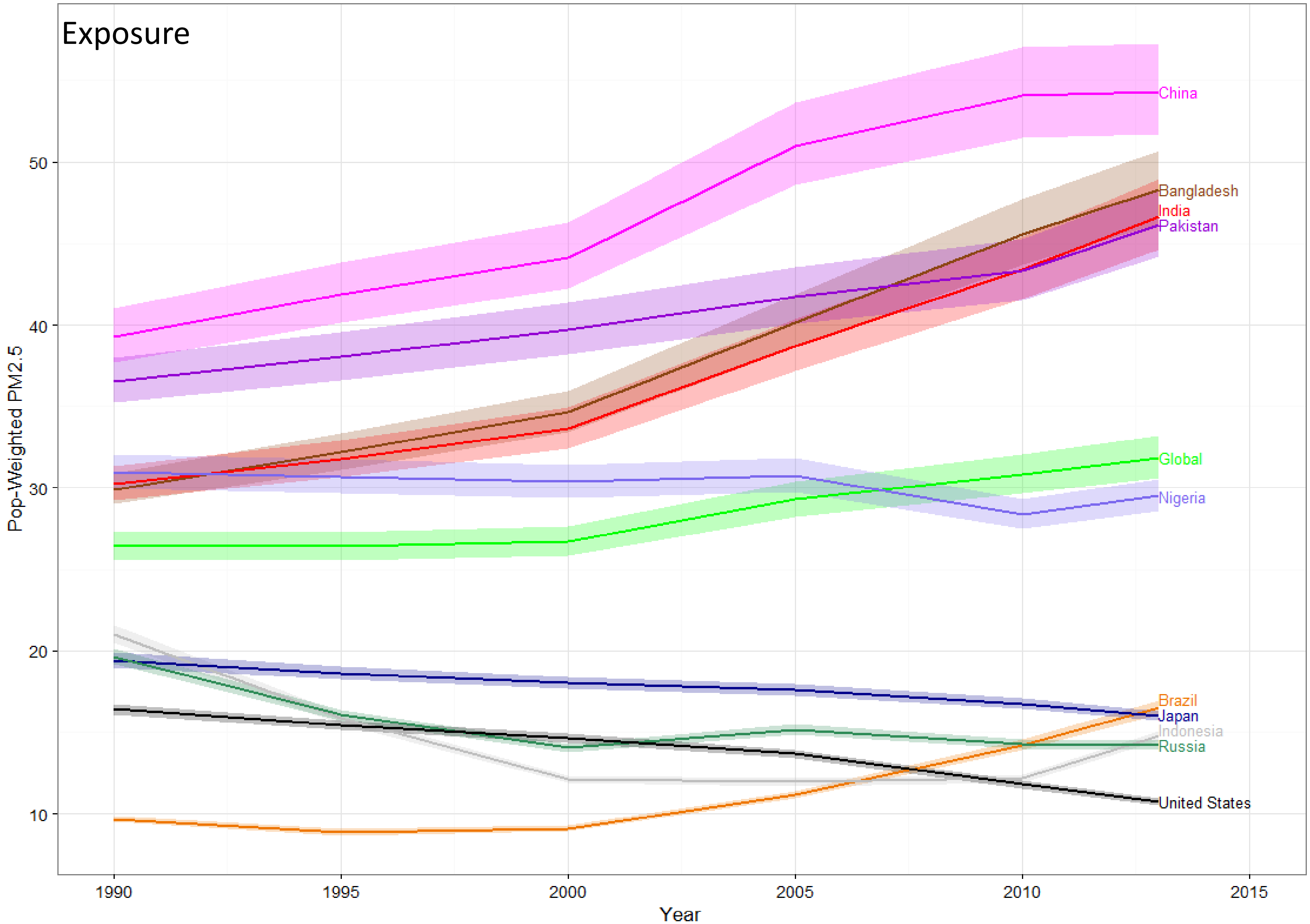
Binary variables related to measurements (N ~ 6000) :
Exact location
Site monitor
$PM_{2.5}$ direct measure or from $PM_{2.5}$:PM_{10} ratio.

Interactions between binary variables satellite estimates.

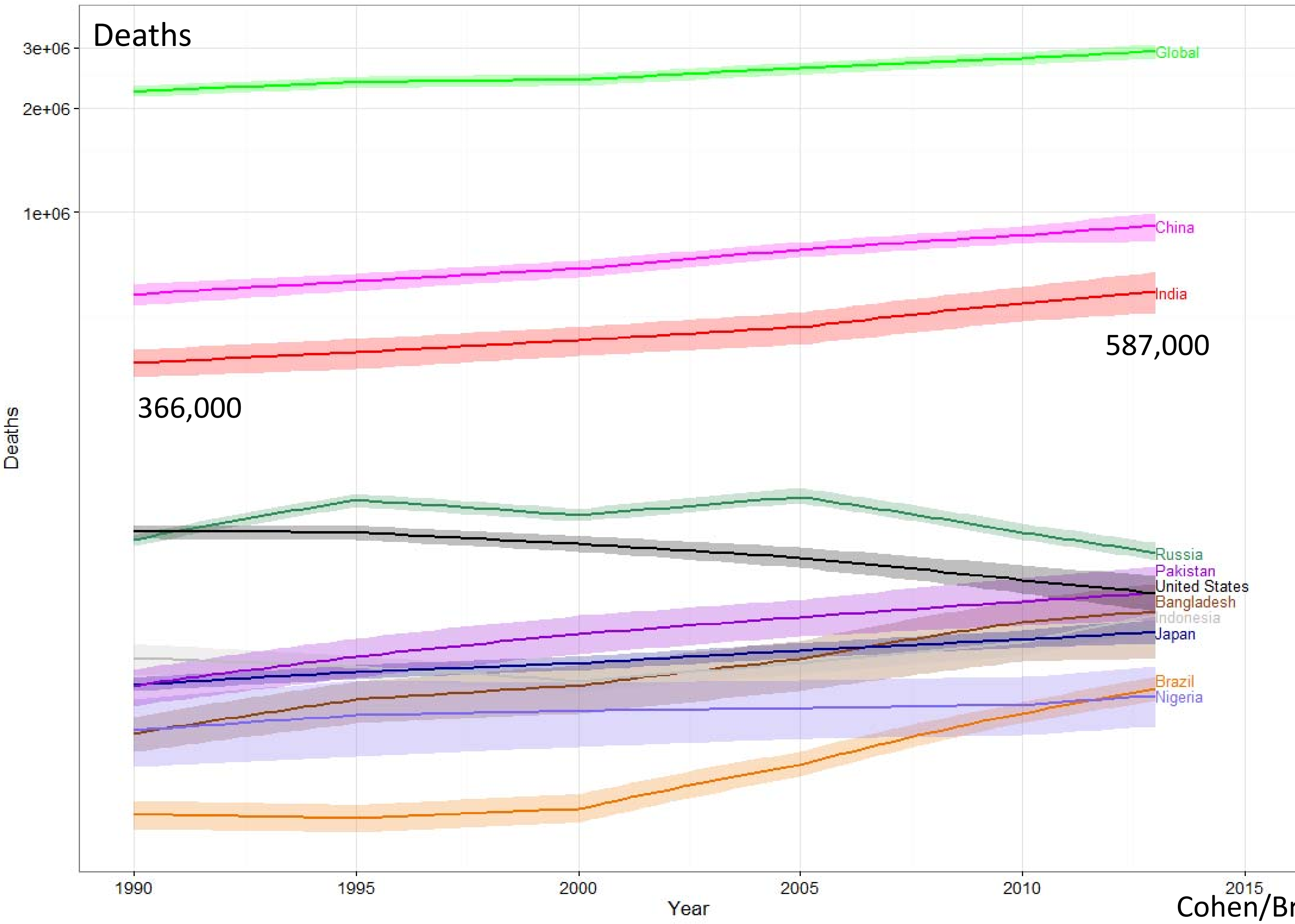
Grid cell random effects on the intercept (multiple ground monitors in a grid cell).

Country-region-super-region hierarchical random effects for intercepts, satellite and population terms.

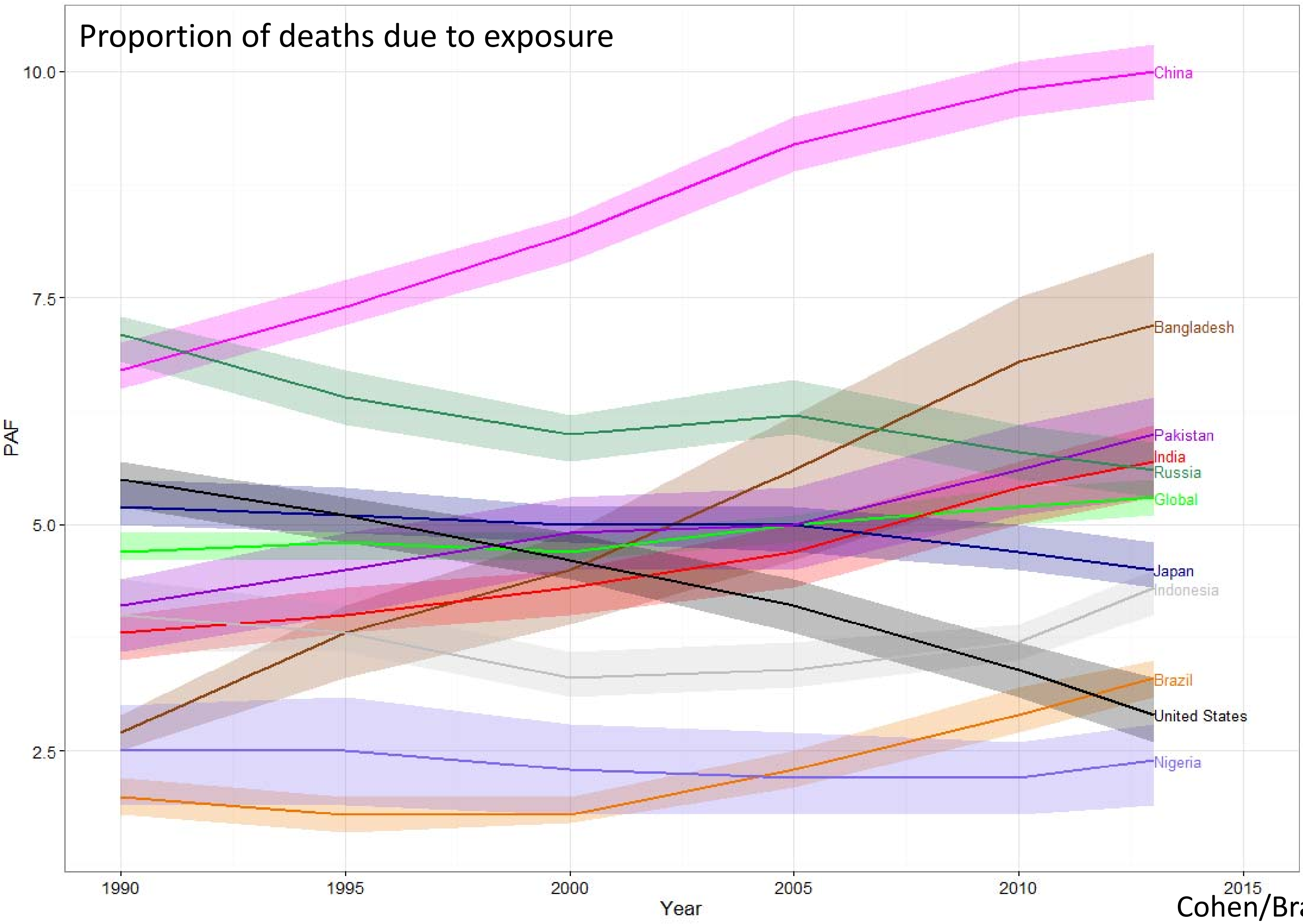
Country level random effects for population using a neighbourhood structure allowing specific borrowing of information from neighbouring countries.



Brauer et al., 2016

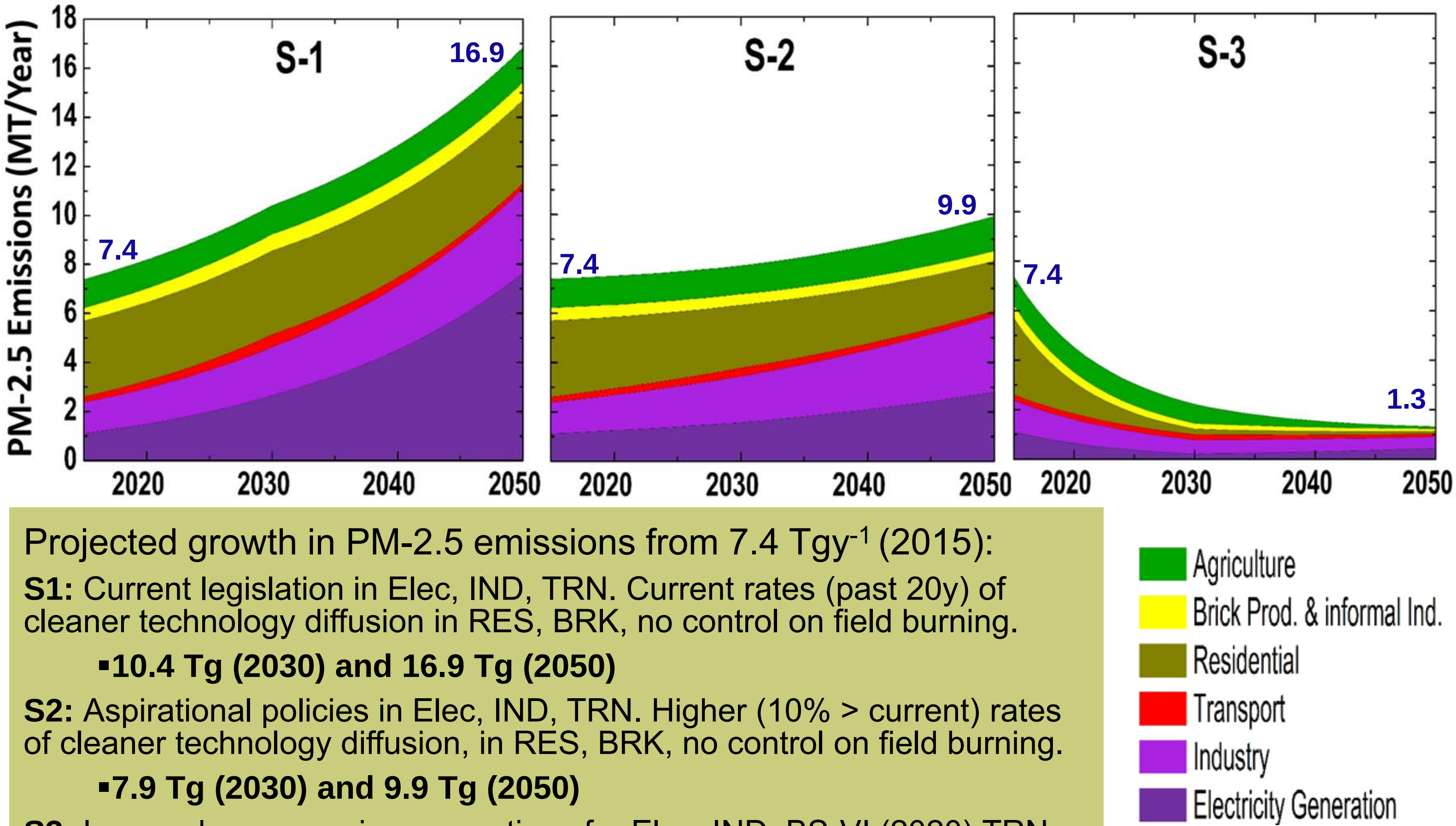


Cohen/Brauer et al., Submitted 2016



Cohen/Brauer et al., Submitted 2016

Projected evolution of Indian PM-2.5 emissions



Projected growth in PM-2.5 emissions from 7.4 Tgy^{-1} (2015):

S1: Current legislation in Elec, IND, TRN. Current rates (past 20y) of cleaner technology diffusion in RES, BRK, no control on field burning.

- **10.4 Tg (2030) and 16.9 Tg (2050)**

S2: Aspirational policies in Elec, IND, TRN. Higher (10% > current) rates of cleaner technology diffusion, in RES, BRK, no control on field burning.

- **7.9 Tg (2030) and 9.9 Tg (2050)**

S3: Low-carbon scenario assumptions for Elec, IND; BS-VI (2020) TRN; complete phase out of traditional technologies in residential, bricks and informal industry, field burning controlled by 2030.

- **2.2 Tg (2030) and 1.3 Tg (2050)**

C. Venkataraman et al.
IIT-Bombay. Draft, 2016

Conclusions

CHINA

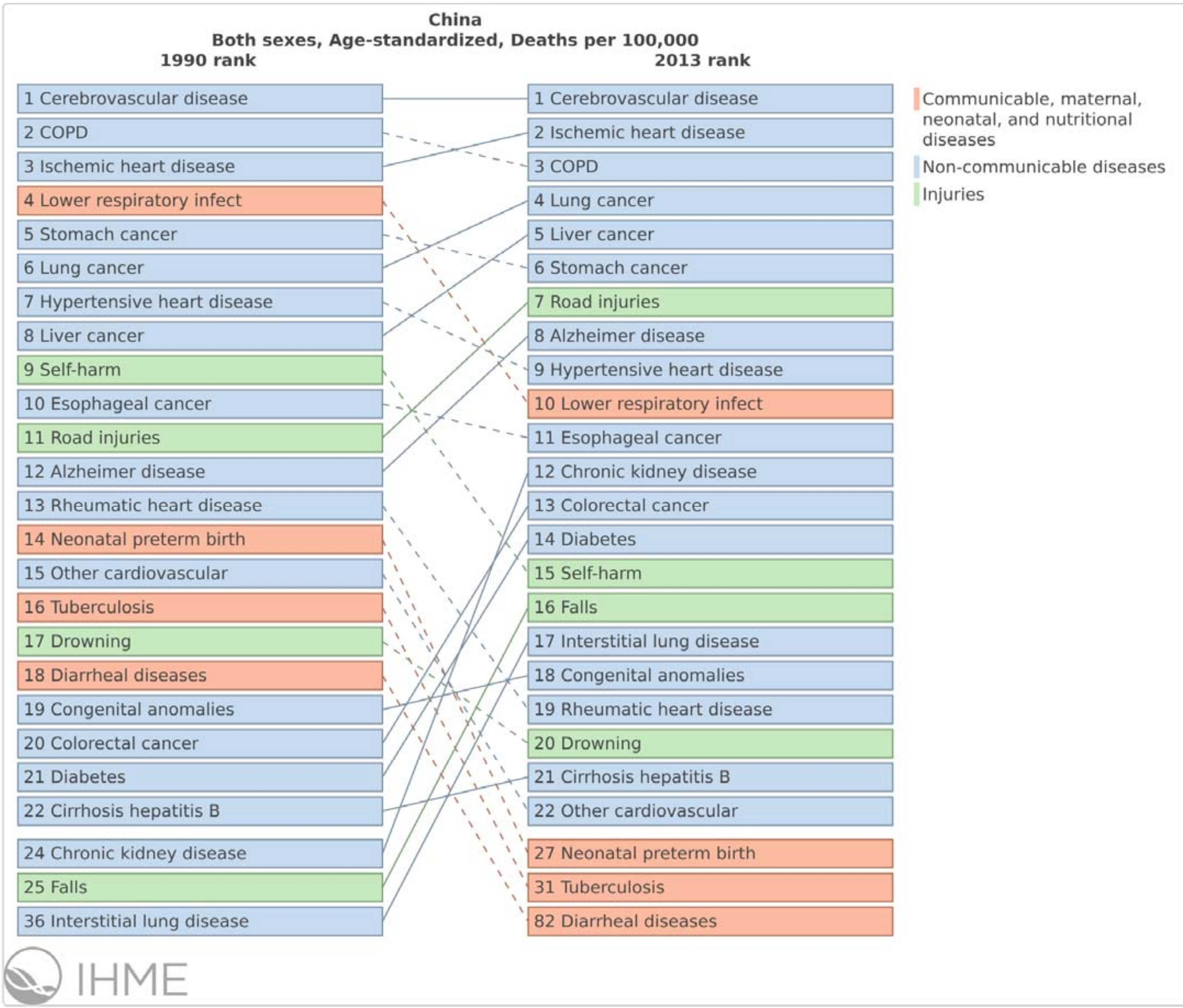
- Coal combustion $PM_{2.5}$ in China (2013):
  - 40% of exposure to ambient $PM_{2.5}$
  - 366,000 deaths
  - 12th leading mortality risk factor > high cholesterol, drug use or secondhand smoking.
- Industrial coal, domestic (biomass and coal) combustion: largest contributors to ambient $PM_{2.5}$ attributable mortality in 2013.
  - Domestic combustion (177,000 deaths) > industrial coal (155,000) > transportation (137,000) > power plant coal combustion (86,500)
- Despite decreased ambient $PM_{2.5}$, increases in future attributable deaths for all (2030) scenarios
  - 0.99 - 1.3 million deaths
  - aging population, increased prevalence of diseases impacted by $PM_{2.5}$.
- Urgent need for even more aggressive strategies to reduce emissions from coal combustion (and other sectors)

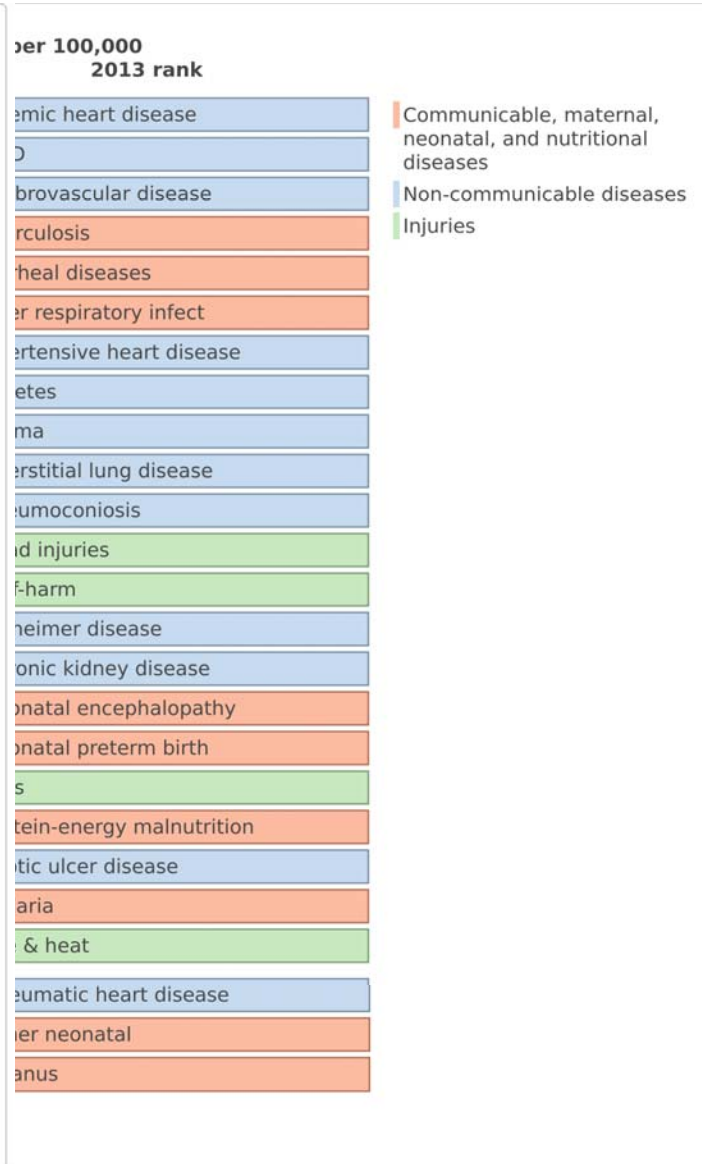
INDIA

- Past trends indicate increasing burden of disease attributable to ambient $PM_{2.5}$
- Scenarios based on current and aspirational policies indicate increase in emissions without stabilizing through 2050
  - Emissions from industrial sources and power generation to dominate in future

Photo: Ecobrick.in

EXTRA SLIDES


China
Both sexes, Age-standardized, Deaths per 100,000
1990 rank
2013 rank
1 Cerebrovascular disease
2 COPD
3 Ischemic heart disease
4 Lower respiratory infect
5 Stomach cancer
6 Lung cancer
7 Hypertensive heart disease
8 Liver cancer
9 Self-harm
10 Esophageal cancer
11 Road injuries
12 Alzheimer disease
13 Rheumatic heart disease
14 Neonatal preterm birth
15 Other cardiovascular
16 Tuberculosis
17 Drowning
18 Diarrheal diseases
19 Congenital anomalies
20 Colorectal cancer
21 Diabetes
22 Cirrhosis hepatitis B
24 Chronic kidney disease
25 Falls
36 Interstitial lung disease
1 Cerebrovascular disease
2 Ischemic heart disease
3 COPD
4 Lung cancer
5 Liver cancer
6 Stomach cancer
7 Road injuries
8 Alzheimer disease
9 Hypertensive heart disease
10 Lower respiratory infect
11 Esophageal cancer
12 Chronic kidney disease
13 Colorectal cancer
14 Diabetes
15 Self-harm
16 Falls
17 Interstitial lung disease
18 Congenital anomalies
19 Rheumatic heart disease
20 Drowning
21 Cirrhosis hepatitis B
22 Other cardiovascular
27 Neonatal preterm birth
31 Tuberculosis
82 Diarrheal diseases
Communicable, maternal, neonatal, and nutritional diseases
Non-communicable diseases
Injuries
IHME


2013 rank
Communicable, maternal, neonatal, and nutritional diseases
Non-communicable diseases
Injuries

GBD MAPS Working Group

Michael Brauer (co-chair)	University of British Columbia
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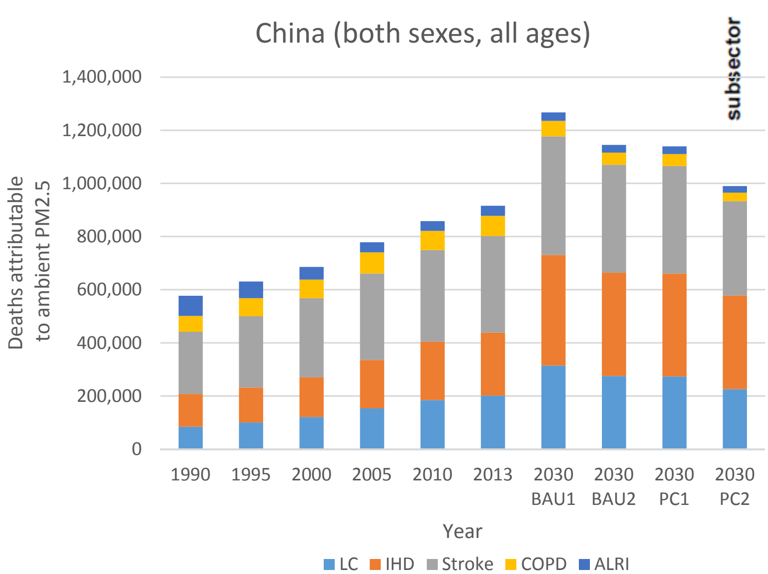
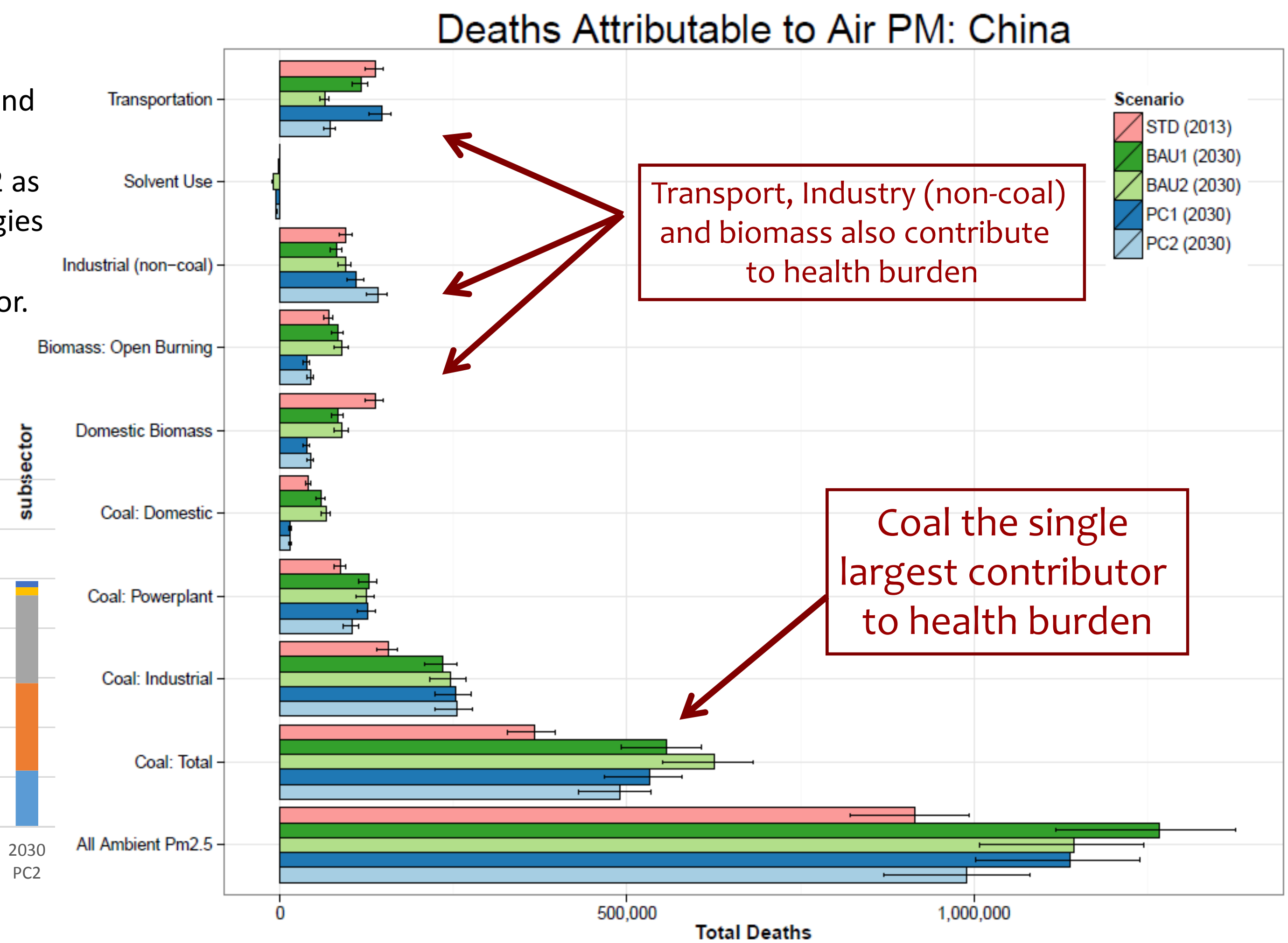
Ma Qiao	Tsinghua University
Zhou Maigeng	China CDC
Yin Peng	China CDC
Chandra Venkataraman	IIT Bombay
Pankaj Sadavarte	IIT Bombay
Sarath Guttikunda	IIT Bombay
Alok Jhaldiyal	IIT Bombay
Wang Yuxuan	University of Texas, Galveston
Kan Haidong	Fudan University
Randall Martin	Dalhousie University
Aaron van Donkelaar	Dalhousie University
Richard Burnett	Health Canada
Mohammad Forouzanfar	IHME
Joseph Frostad	IHME

Disease burden in 2013 and 2030: Coal and other major sources

- Predicted mortality increases in all future scenarios, mainly due to population aging and increase of disease in Chinese population;
- Disease burden decrease from BAU1 to PC2 as energy policies and emission control strategies is applied;
- Coal remains as the single largest contributor.





GBD-MAPS

1. Estimate coal combustion/major source sector contribution to ambient $PM_{2.5}$ →
   e.g fraction ambient $PM_{2.5}$ attributable to coal combustion (**f_{coal}**)
2. f_{coal} x ambient $PM_{2.5}$ → ambient $PM_{2.5}$ attributable to coal combustion ($PM_{2.5\ coal}$)
3. Use integrated exposure response functions and cause-specific mortality estimates in combination with **$PM_{2.5\ coal}$** → coal combustion contribution to disease burden

- **China**
- India
- Eastern Europe

Estimating $PM_{2.5}$

Environmental Science & Technology

Article

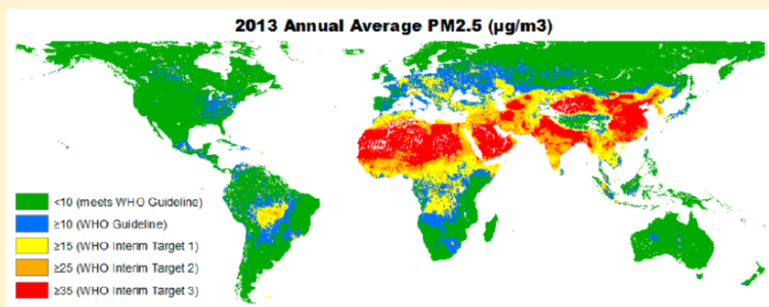
pubs.acs.org/est

Ambient Air Pollution Exposure Estimation for the Global Burden of Disease 2013

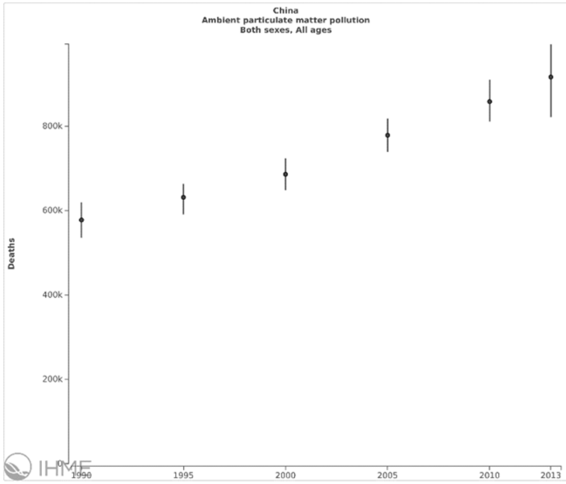
Michael Brauer,[*,†] Greg Freedman,[‡] Joseph Frostad,[‡] Aaron van Donkelaar,[§] Randall V. Martin,[§] Frank Dentener,[||] Rita van Dingenen,[||] Kara Estep,[‡] Heresh Amini,[⊥] Joshua S. Apte,[#] Kalpana Balakrishnan,[▽] Lars Barregard,[h] David Broday,[○] Valery Feigin,[◆] Santu Ghosh,[▽] Philip K. Hopke,[¶] Luke D. Knibbs,[▲] Yoshihiro Kokubo,[∞] Yang Liu,[☆] Stefan Ma,[⊗] Lidia Morawska,[⋈] José Luis Texcalac Sangrador,[◎] Gavin Shaddick,[r] H. Ross Anderson,[∠] Theo Vos,[‡] Mohammad H. Forouzanfar,[‡] Richard T. Burnett,[⧖] and Aaron Cohen[∂]

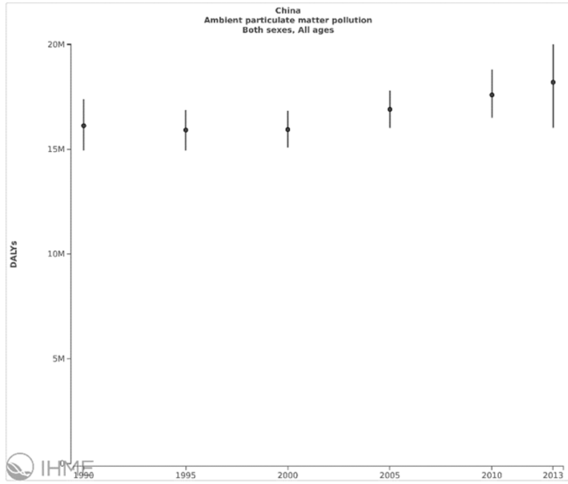
ABSTRACT: Exposure to ambient air pollution is a major risk factor for global disease. Assessment of the impacts of air pollution on population health and evaluation of trends relative to other major risk factors requires regularly updated, accurate, spatially resolved exposure estimates. We combined satellite-based estimates, chemical transport model simulations, and ground measurements from 79 different countries to produce global estimates of annual average fine particle ($PM_{2.5}$) and ozone concentrations at 0.1° × 0.1° spatial resolution for

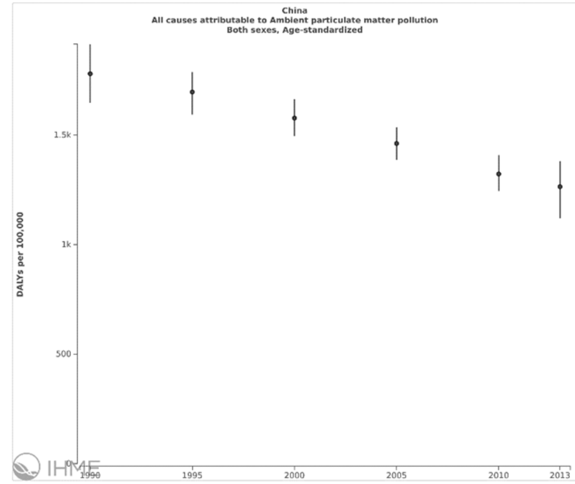
continued...

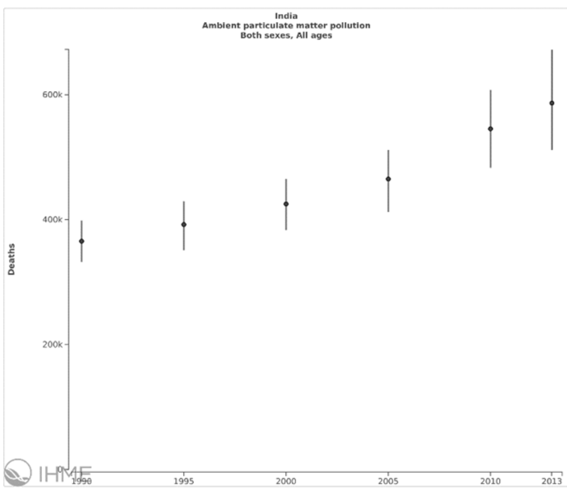


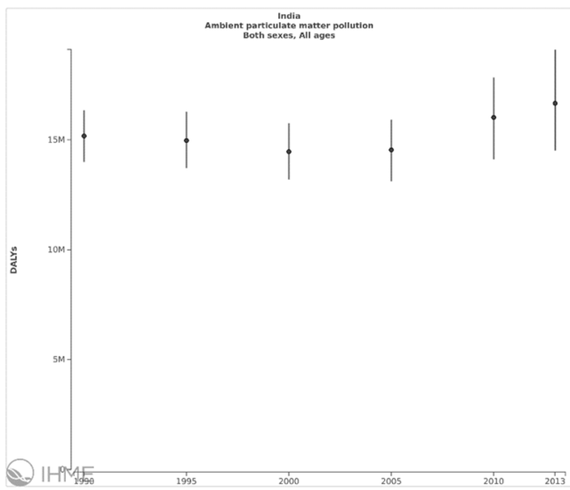
Brauer et al., 2015. doi: 10.1021/acs.est.5b03709

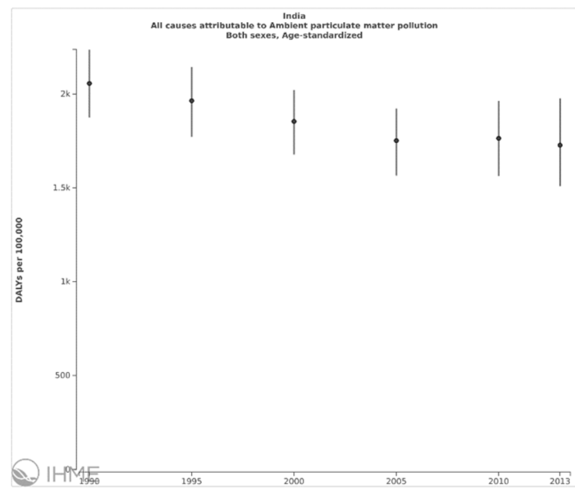

China
Ambient particulate matter pollution
Both sexes, All ages
Deaths
800k
600k
400k
200k
0
1990
1995
2000
2005
2010
2013

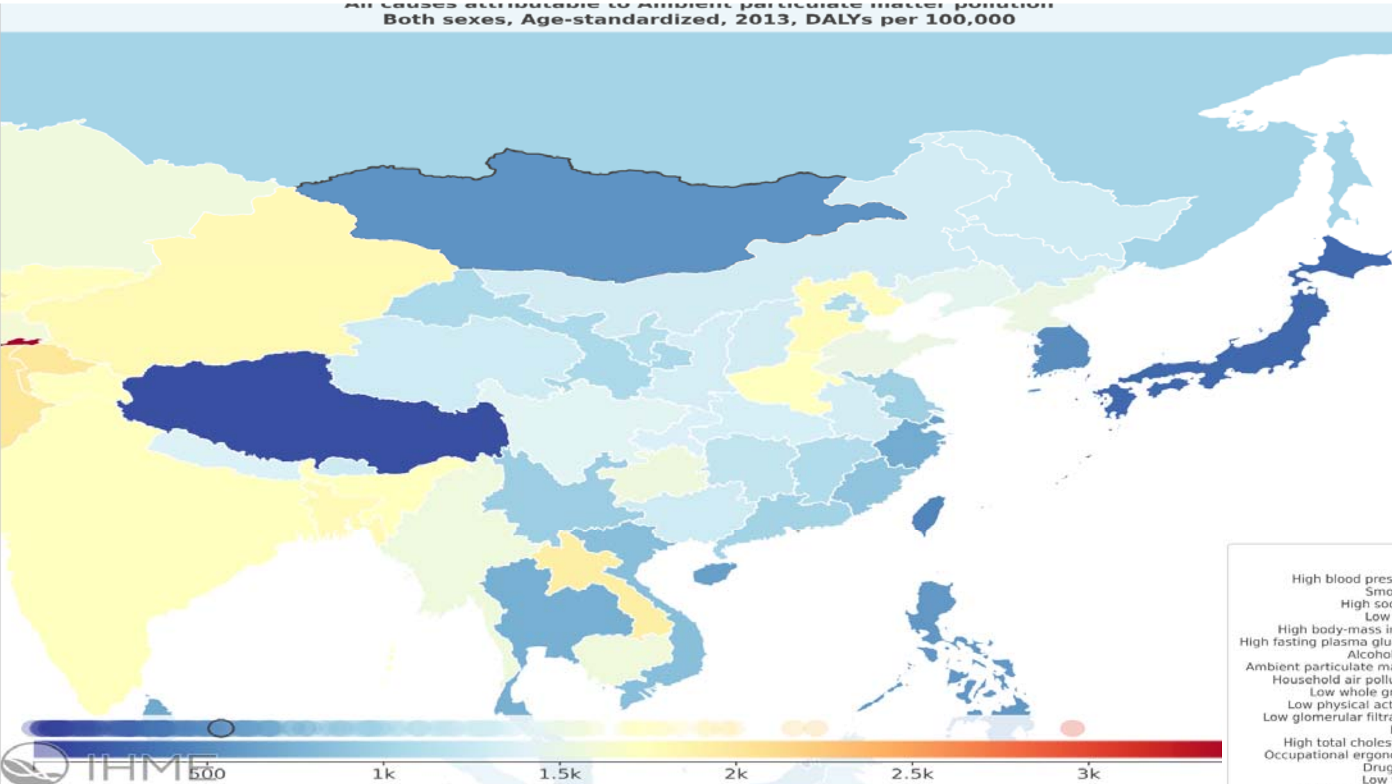

China
Ambient particulate matter pollution
Both sexes, All ages
DALYs
20M
15M
10M
5M
0
1990
1995
2000
2005
2010
2013

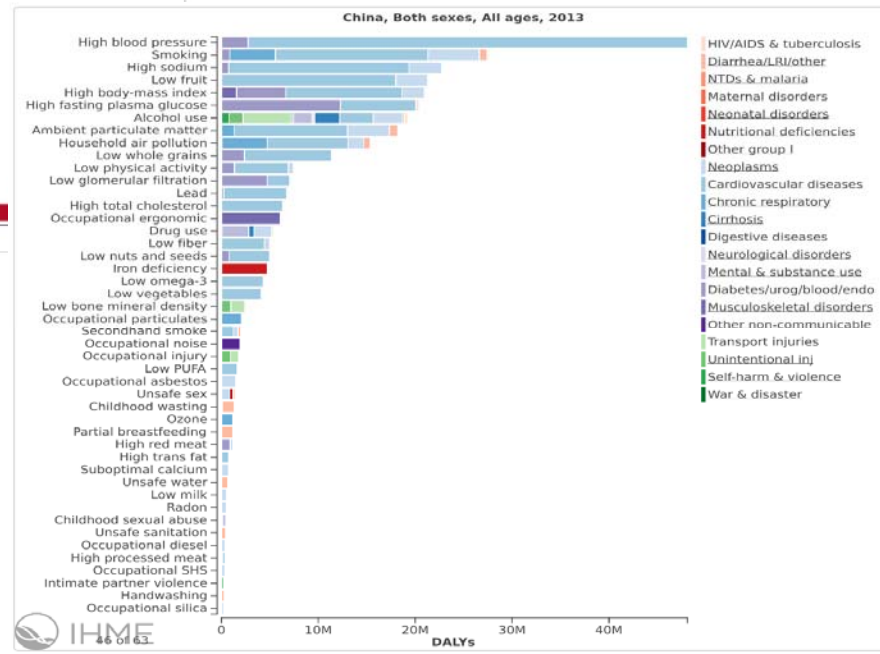

China
All causes attributable to Ambient particulate matter pollution
Both sexes, Age-standardized
DALYs per 100,000
1.5k
1k
500
0
1990
1995
2000
2005
2010
2013


India
Ambient particulate matter pollution
Both sexes, All ages
Deaths
600k
400k
200k
0
1990
1995
2000
2005
2010
2013

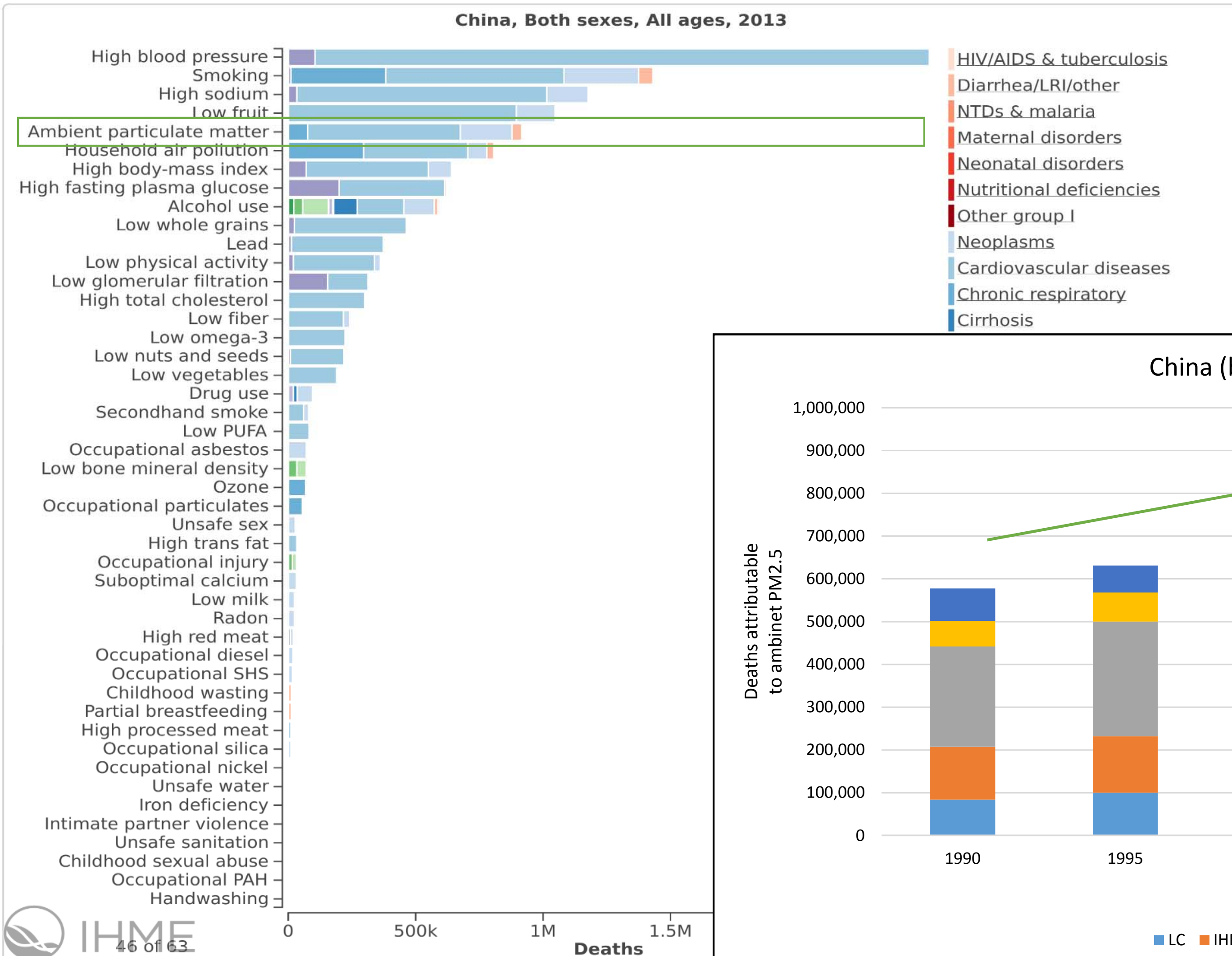

India
Ambient particulate matter pollution
Both sexes, All ages
DALYs
15M
10M
5M
0
1990
1995
2000
2005
2010
2013


India
All causes attributable to Ambient particulate matter pollution
Both sexes, Age-standardized
DALYs per 100,000
2k
1.5k
1k
500
0
1990
1995
2000
2005
2010
2013


Both sexes, Age-standardized, 2013, DALYs per 100,000
500
1k
1.5k
2k
2.5k
3k
IHME

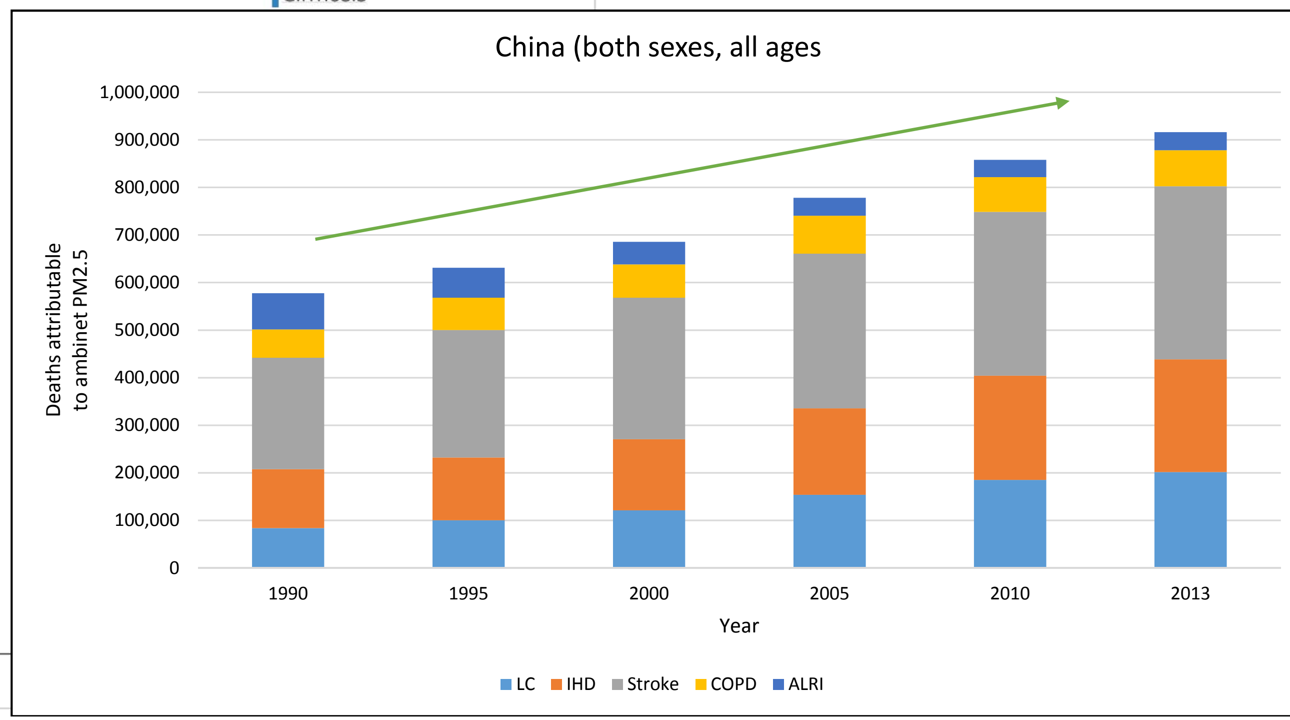

China, Both sexes, All ages, 2013
High blood pressure
Smoking
High sodium
Low fruit
High body-mass index
High fasting plasma glucose
Alcohol use
Ambient particulate matter
Household air pollution
Low whole grains
Low physical activity
Low glomerular filtration
Lead
High total cholesterol
Occupational ergonomic
Drug use
Low fiber
Low nuts and seeds
Iron deficiency
Low omega-3
Low vegetables
Low bone mineral density
Occupational particulates
Secondhand smoke
Occupational noise
Occupational injury
Low PUFA
Occupational asbestos
Unsafe sex
Childhood wasting
Ozone
Partial breastfeeding
High red meat
High trans fat
Suboptimal calcium
Unsafe water
Low milk
Radon
Childhood sexual abuse
Unsafe sanitation
Occupational diesel
High processed meat
Occupational SHS
Intimate partner violence
Handwashing
Occupational silica
0
10M
20M
30M
40M
DALYs
HIV/AIDS & tuberculosis
Diarrhea/LRI/other
NTDs & malaria
Maternal disorders
Neonatal disorders
Nutritional deficiencies
Other group I
Neoplasms
Cardiovascular diseases
Chronic respiratory
Cirrhosis
Digestive diseases
Neurological disorders
Mental & substance use
Diabetes/urog/blood/endo
Musculoskeletal disorders
Other non-communicable
Transport injuries
Unintentional inj
Self-harm & violence
War & disaster
IHME

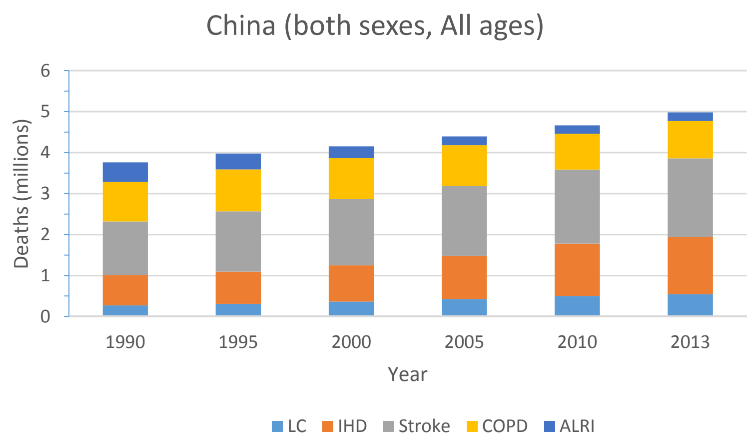
Air pollution is a major contributor to disease burden in China

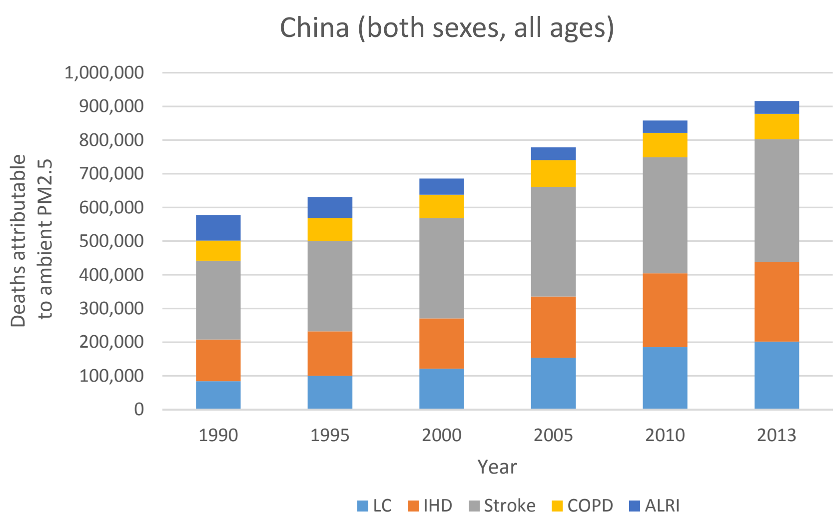


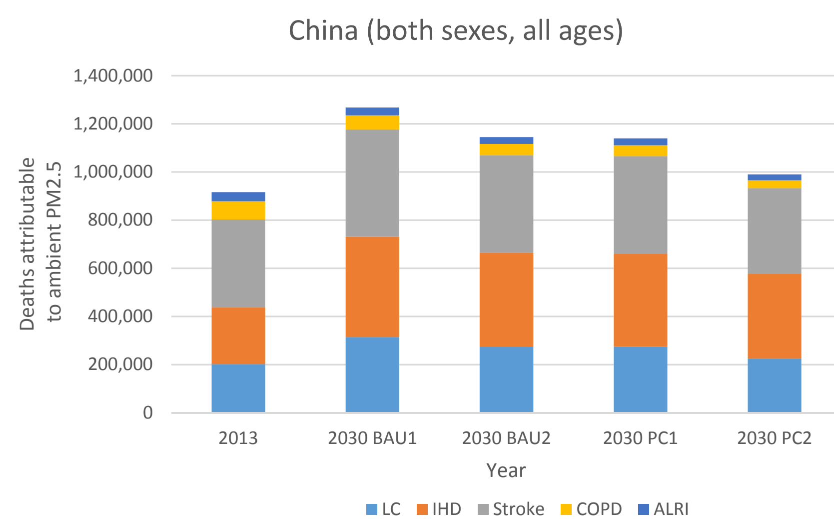
Deaths from air pollution 1990-2013

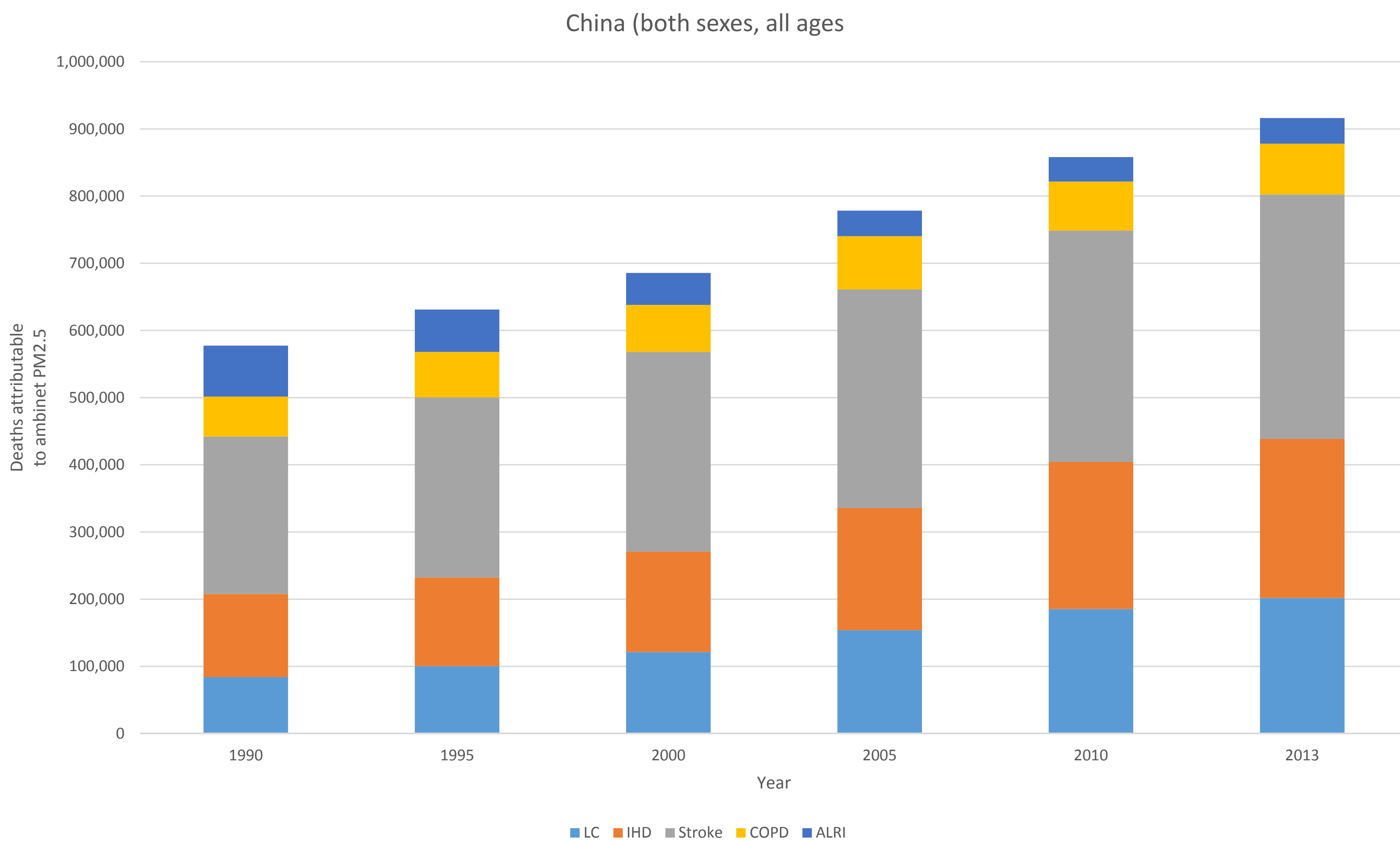
1. 59% ↑ in total deaths
2. 33% ↑ in per capita deaths
3. 49% ↑ in proportion of deaths attributable to $PM_{2.5}$




China (both sexes, All ages)
Deaths (millions)
6
5
4
3
2
1
0
1990
1995
2000
2005
2010
2013
Year
LC
IHD
Stroke
COPD
ALRI

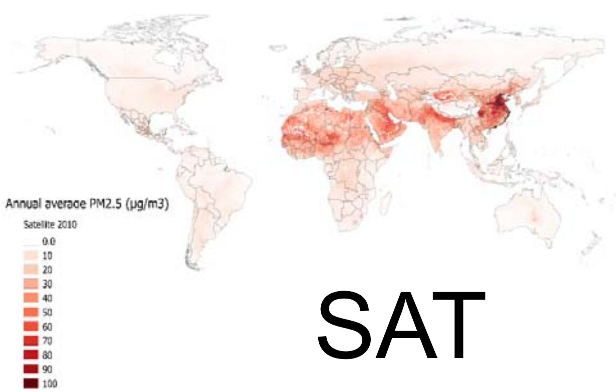

China (both sexes, all ages)
Deaths attributable to ambient PM2.5
1,000,000
900,000
800,000
700,000
600,000
500,000
400,000
300,000
200,000
100,000
0
1990
1995
2000
2005
2010
2013
Year
LC
IHD
Stroke
COPD
ALRI

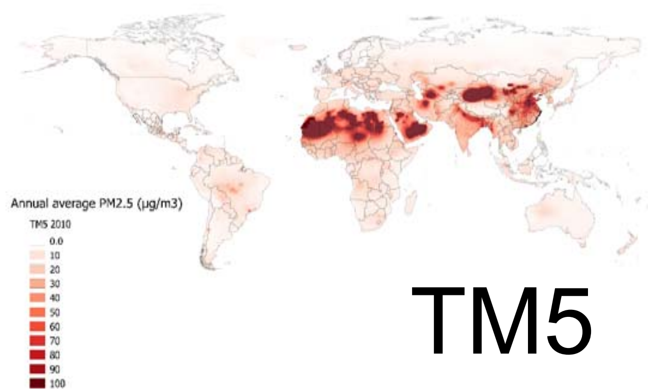

China (both sexes, all ages)
Deaths attributable to ambient PM2.5
1,400,000
1,200,000
1,000,000
800,000
600,000
400,000
200,000
0
2013
2030 BAU1
2030 BAU2
2030 PC1
2030 PC2
Year
LC
IHD
Stroke
COPD
ALRI

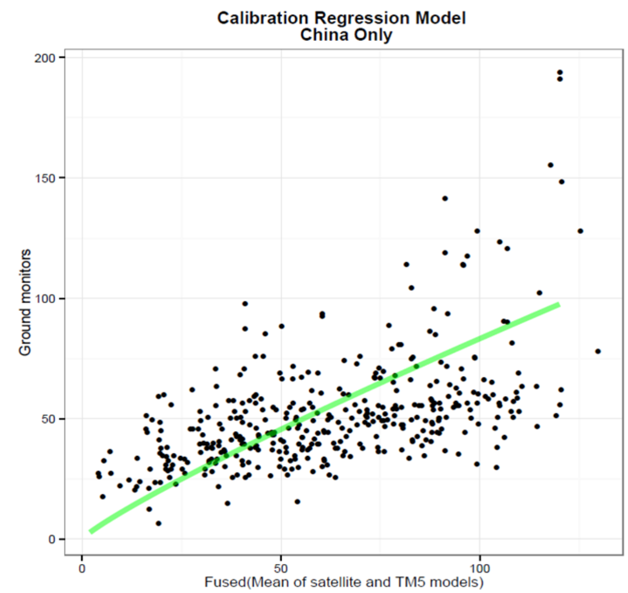

China (both sexes, all ages
1,000,000
900,000
800,000
700,000
600,000
500,000
400,000
300,000
200,000
100,000
0
Deaths attributable to ambinet PM2.5
1990
1995
2000
2005
2010
2013
Year
LC
IHD
Stroke
COPD
ALRI

2. Estimating ambient $PM_{2.5}$ attributable to coal combustion

- Final estimates based on average of (1.4 million) grid cell values (SAT, TM5) and calibrated (regression model) with measurements
  - 0.1° x 0.1° resolution
  - extrapolated to 2013 using 2010-2011 trend in SAT
- Incorporate variance between two estimates and measurements in uncertainty assessment
- Unique contributions from each approach



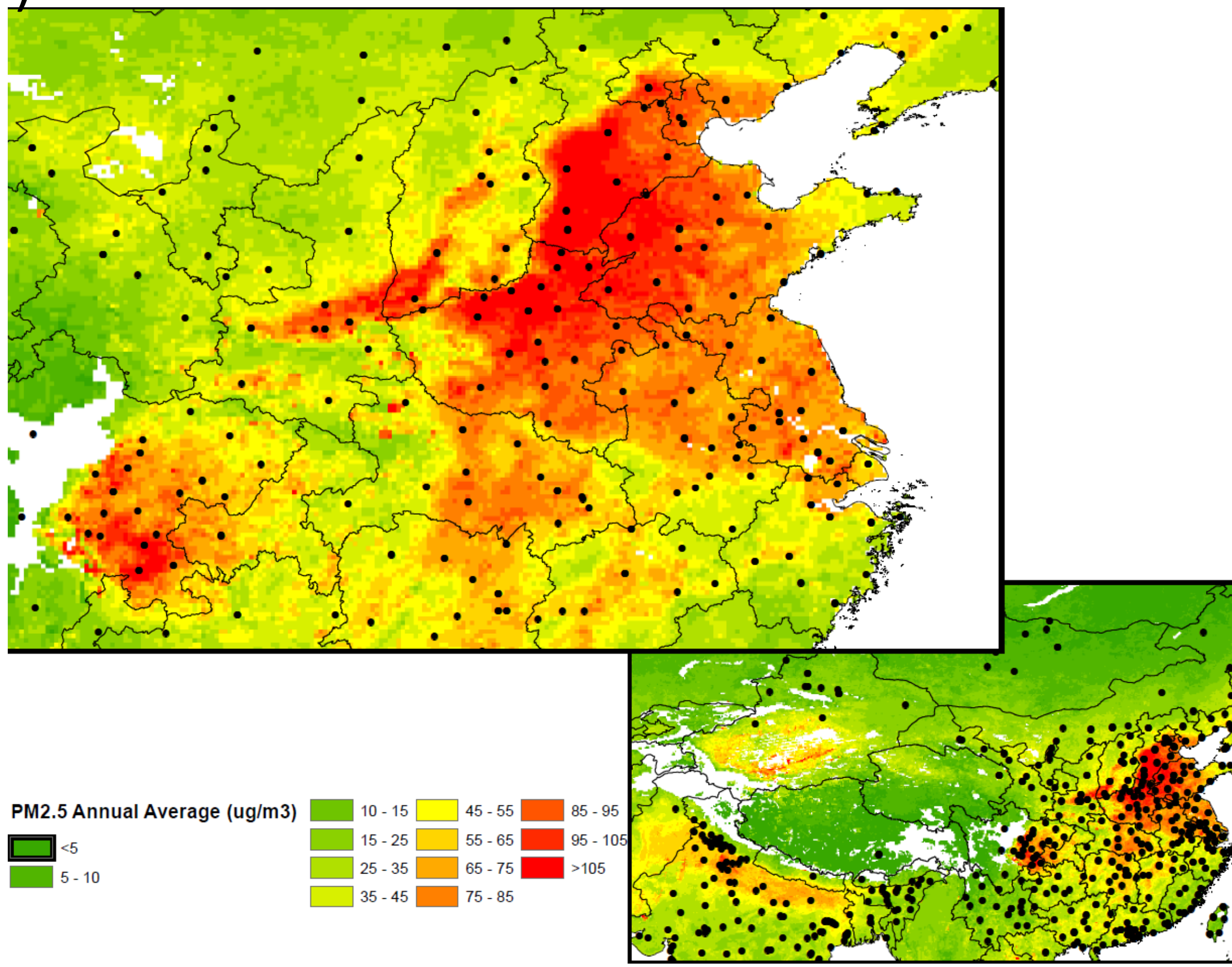




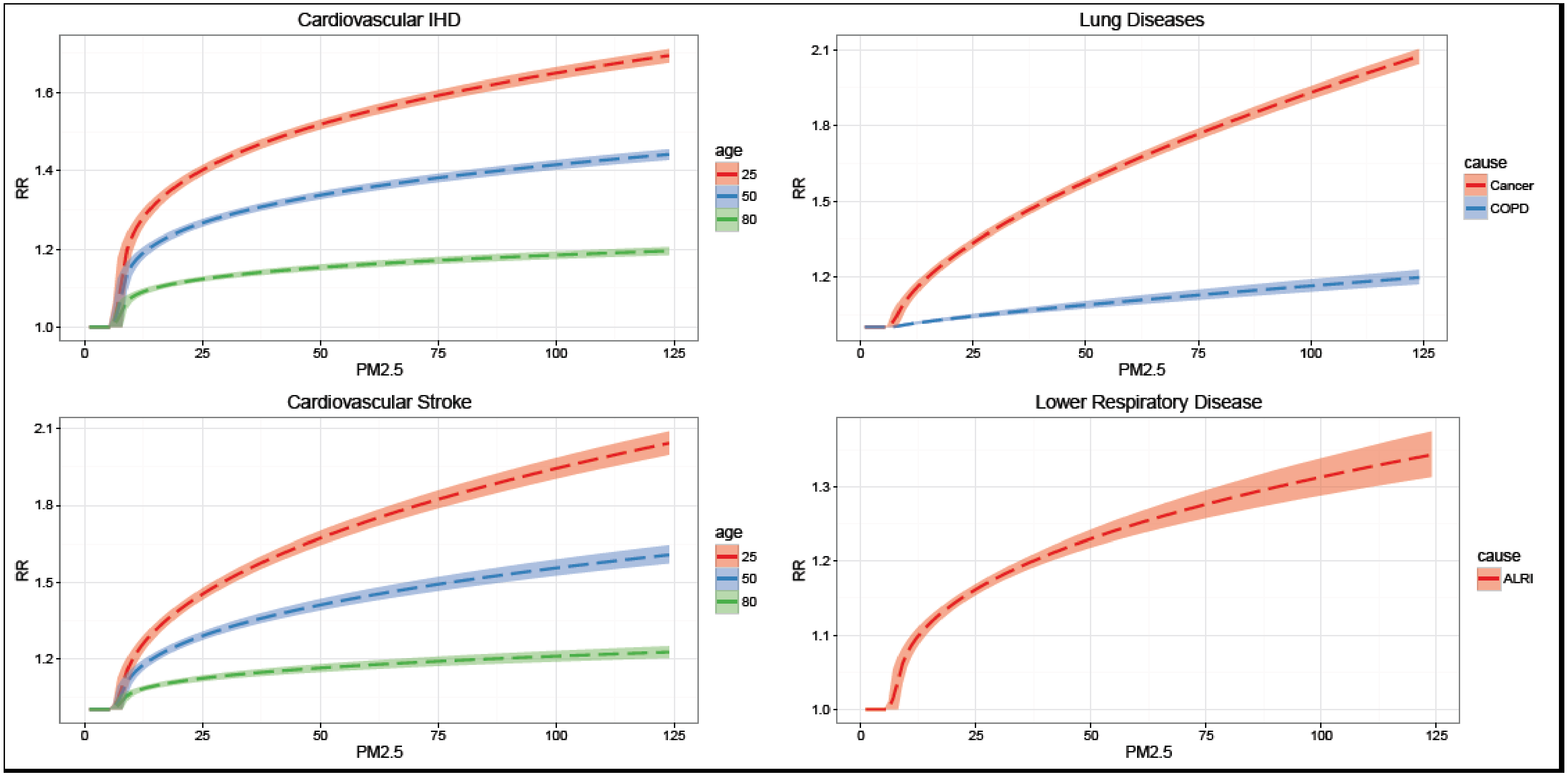
Brauer et al., 2015

Ground measurements – China (2013 annual average)

- 90 Locations $PM_{2.5}$ measurements
- 304 Locations $PM_{2.5}$ estimated from PM_{10} measurements



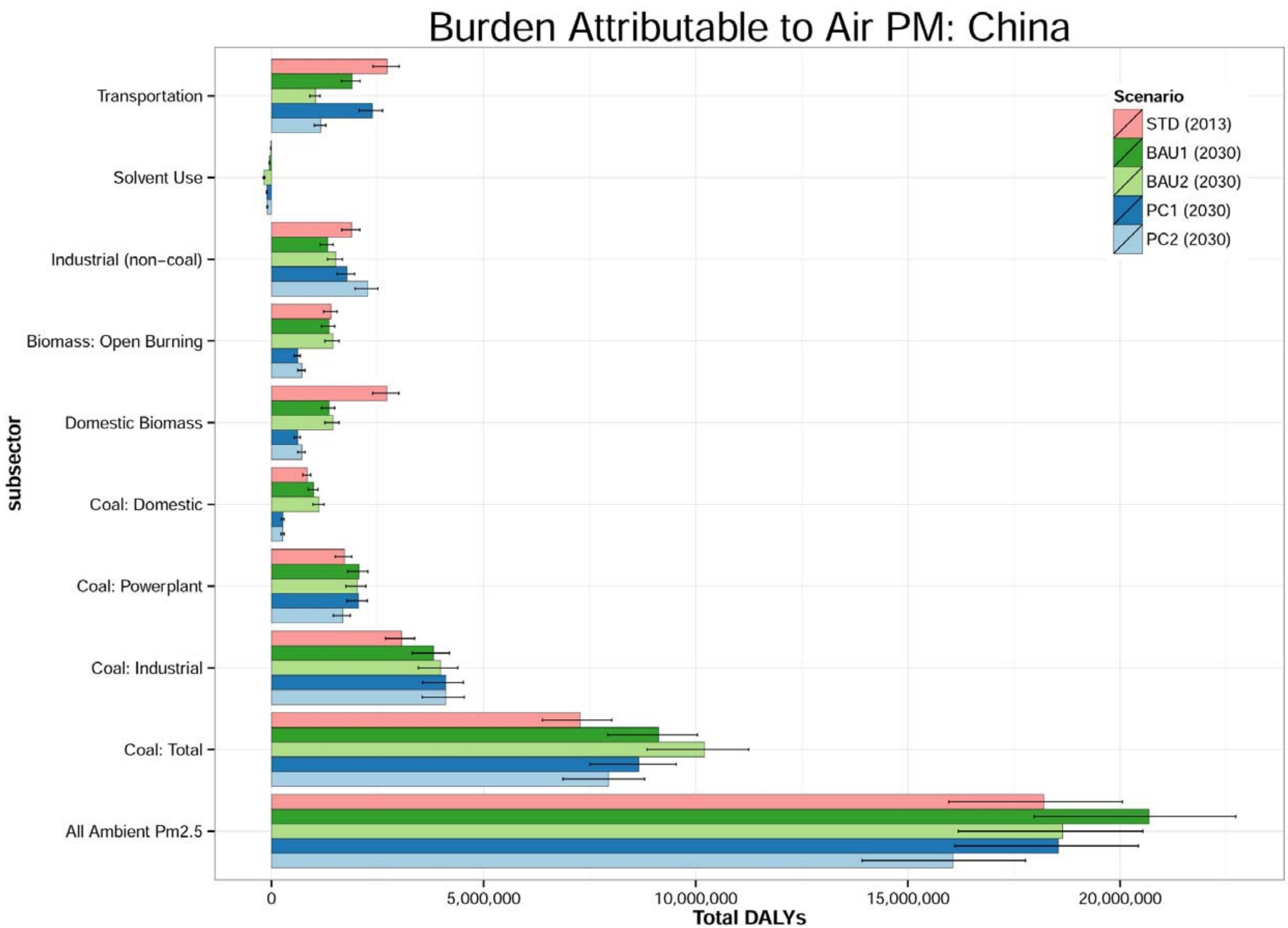
Brauer et al., 2015



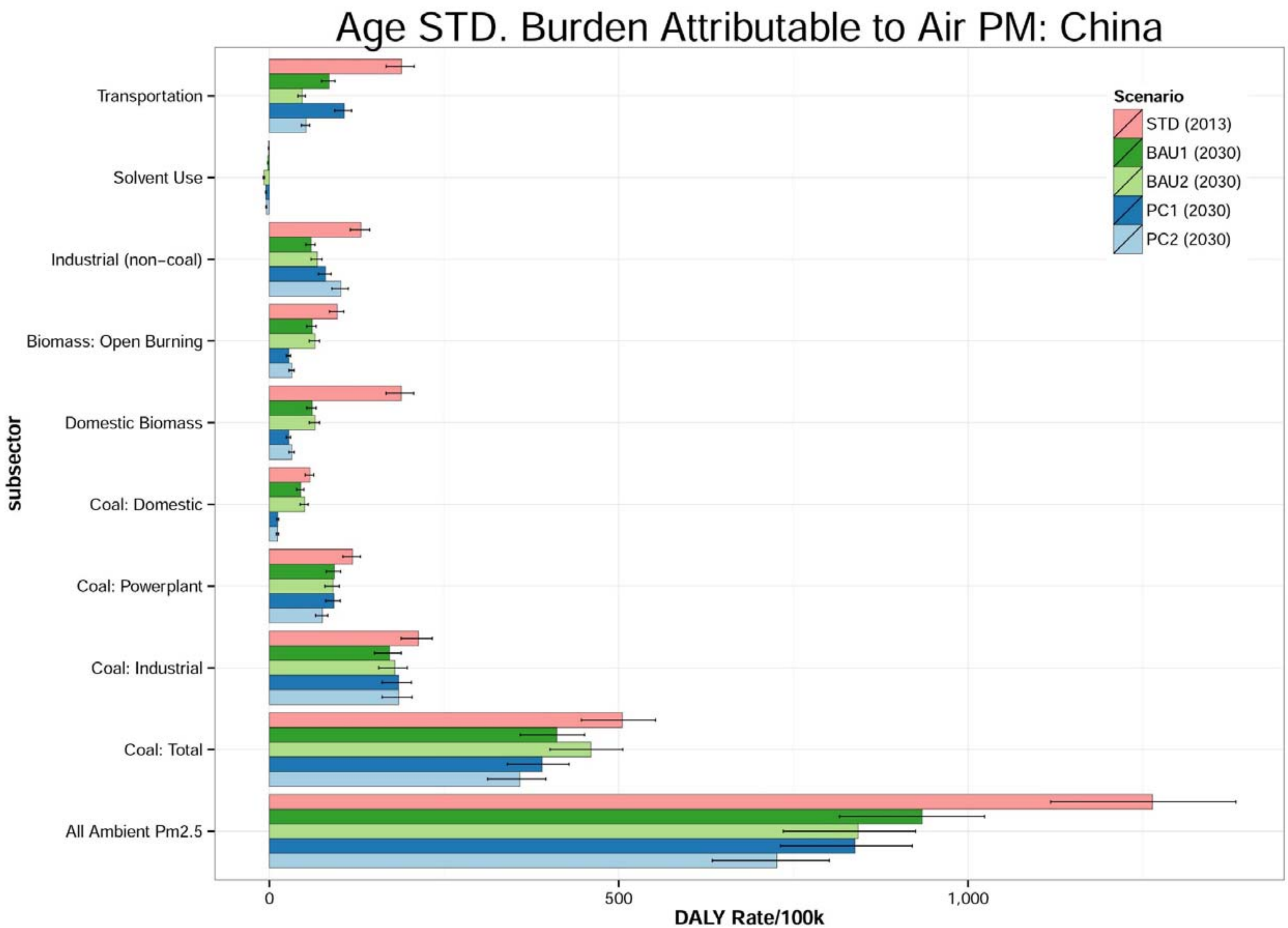
Forouzanfar et al. 2015; Burnett et al. 2014; Cohen/Brauer et al. 2016 Submitted

Future scenarios

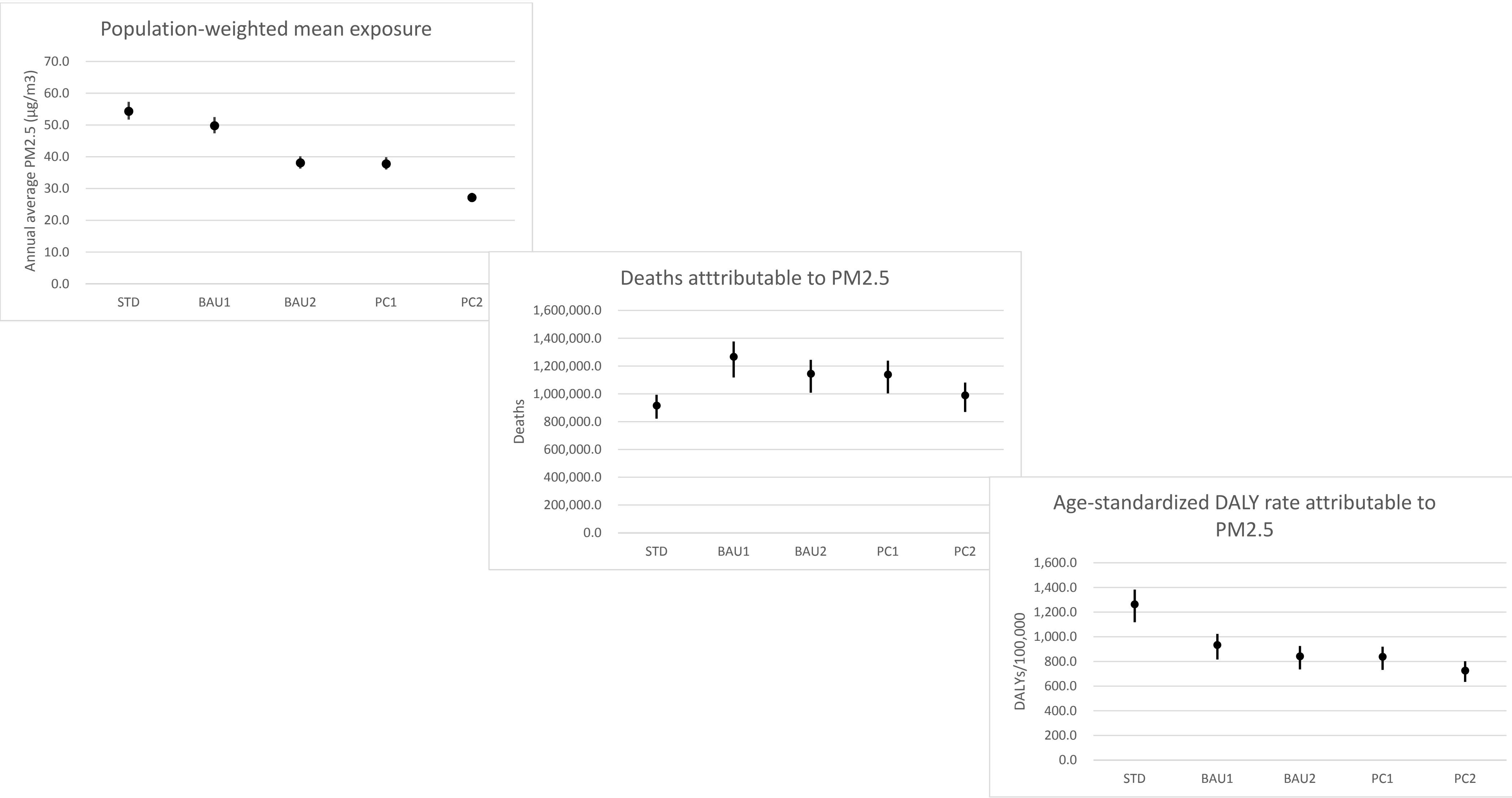
Energy scenario	Description	Emission scenario	Description
Business as usual (BAU)	Current legislation & implementation status (to end of 2013)	BAU[1]	BAU energy policy End-of-pipe control strategy: Based on “12th Five-Year Plan for Environmental Protection”; New emission standards released during 2011-2013; progressively strengthened control policies afterwards.
		BAU[2]	BAU energy policy End-of-pipe control strategy: full implementation of technically feasible control technologies by 2030, regardless of cost
Alternative policy (PC)	New stringently enforced energy-policies including life style changes, structural adjustment & efficiency improvements.	PC[1]	PC energy policy Same end-of-pipe control strategy as BAU[1]
		PC[2]	PC energy policy Same end-of-pipe control strategy as BAU[2] Maximum feasible reductions of emissions

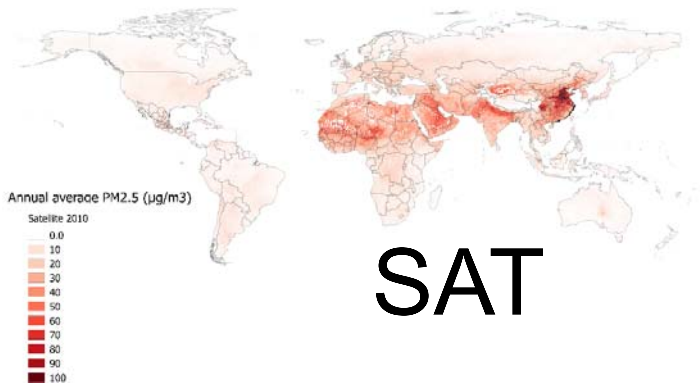


Burden Attributable to Air PM: China
Scenario
STD (2013)
BAU1 (2030)
BAU2 (2030)
PC1 (2030)
PC2 (2030)
subsector
Transportation
Solvent Use
Industrial (non-coal)
Biomass: Open Burning
Domestic Biomass
Coal: Domestic
Coal: Powerplant
Coal: Industrial
Coal: Total
All Ambient Pm2.5
0
5,000,000
10,000,000
15,000,000
20,000,000
Total DALYs

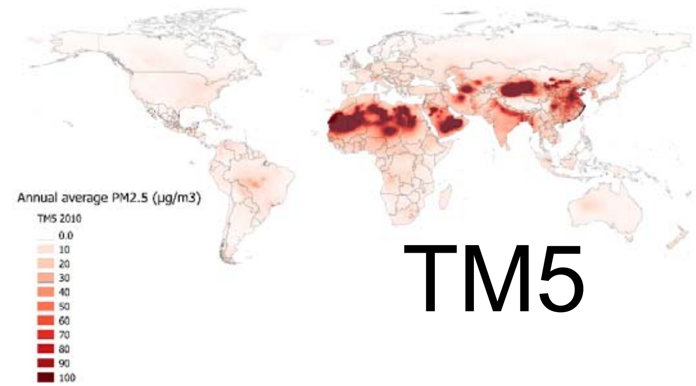


Age STD. Burden Attributable to Air PM: China
Scenario
STD (2013)
BAU1 (2030)
BAU2 (2030)
PC1 (2030)
PC2 (2030)
subsector
Transportation
Solvent Use
Industrial (non−coal)
Biomass: Open Burning
Domestic Biomass
Coal: Domestic
Coal: Powerplant
Coal: Industrial
Coal: Total
All Ambient Pm2.5
0
500
1,000
DALY Rate/100k


Population-weighted mean exposure
Annual average PM2.5 (µg/m3)
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
STD
BAU1
BAU2
PC1
PC2
Deaths atttributable to PM2.5
Deaths
1,600,000.0
1,400,000.0
1,200,000.0
1,000,000.0
800,000.0
600,000.0
400,000.0
200,000.0
0.0
STD
BAU1
BAU2
PC1
PC2
Age-standardized DALY rate attributable to PM2.5
DALYs/100,000
1,600.0
1,400.0
1,200.0
1,000.0
800.0
600.0
400.0
200.0
0.0
STD
BAU1
BAU2
PC1
PC2

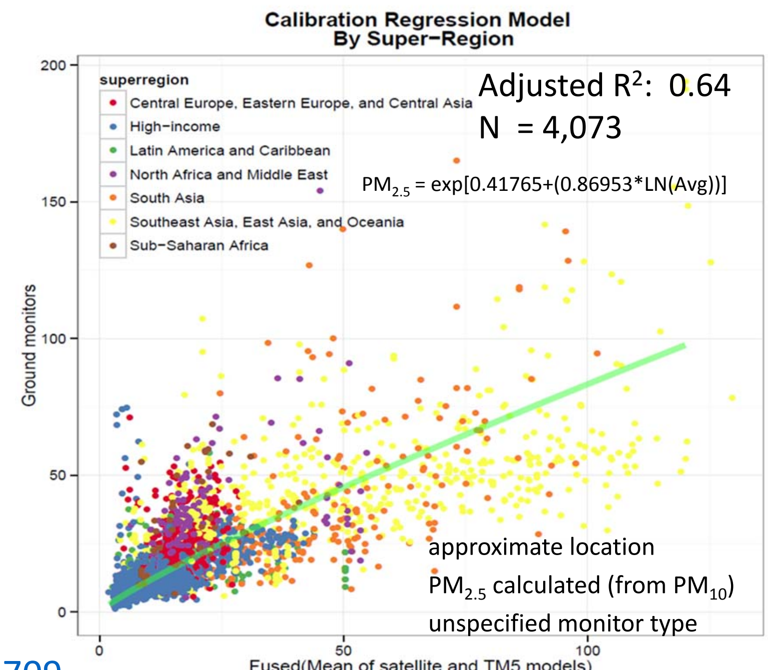


SAT



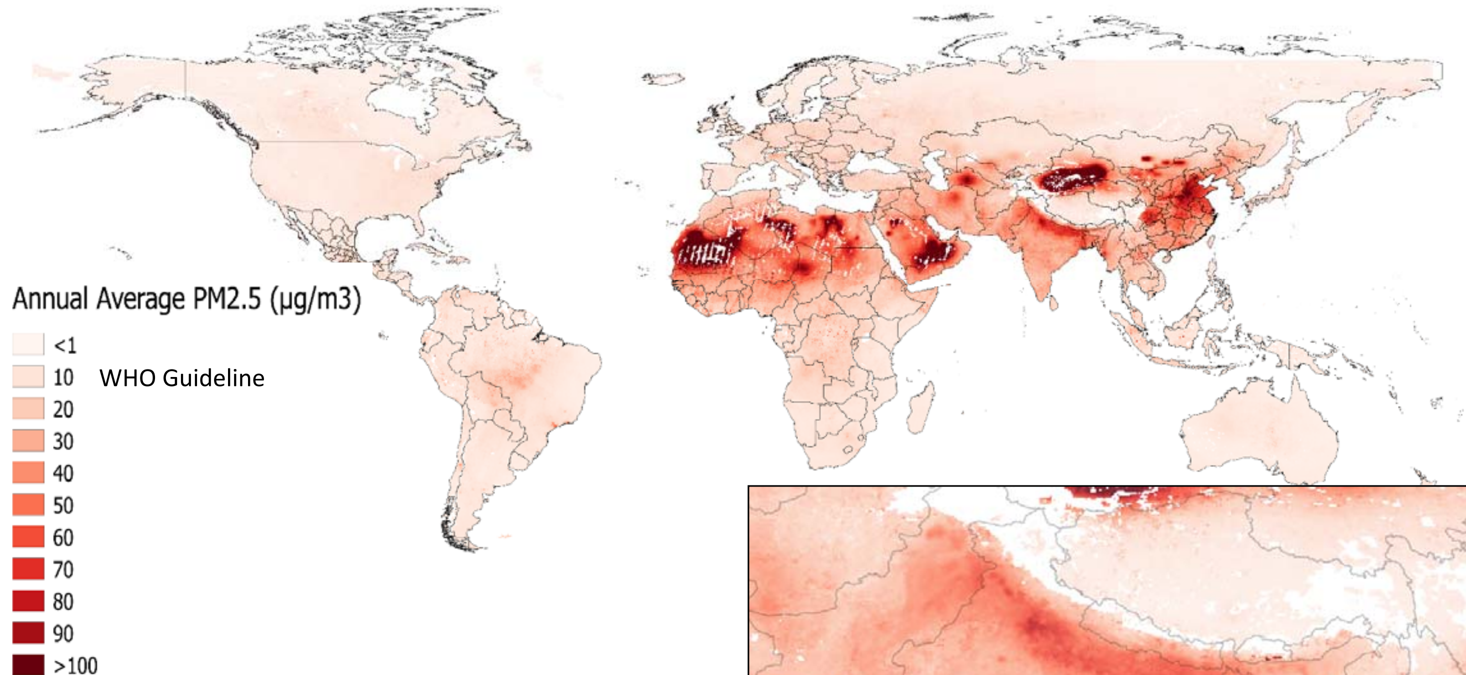
TM5

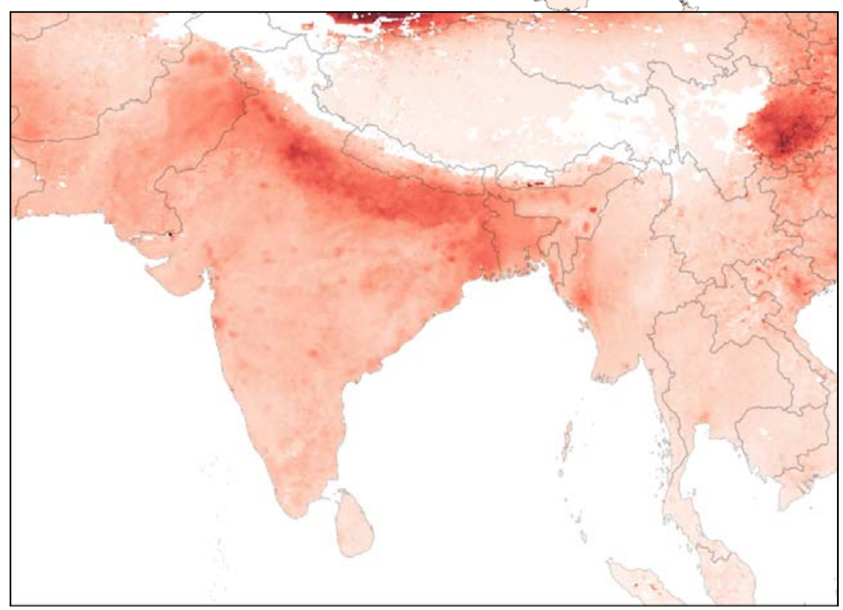
- Final estimates based on average of (1.4 million) grid cell values (SAT, TM5) and calibrated (regression model) with measurements
  - 0.1° x 0.1° resolution
  - extrapolated to 2013 using 2010-2011 trend in SAT
- Incorporate variance between two estimates and measurements in uncertainty assessment
- Unique contributions from each approach



Brauer et al.. 2015. doi: 10.1021/acs.est.5b03709

2013 Annual Average $PM_{2.5}$

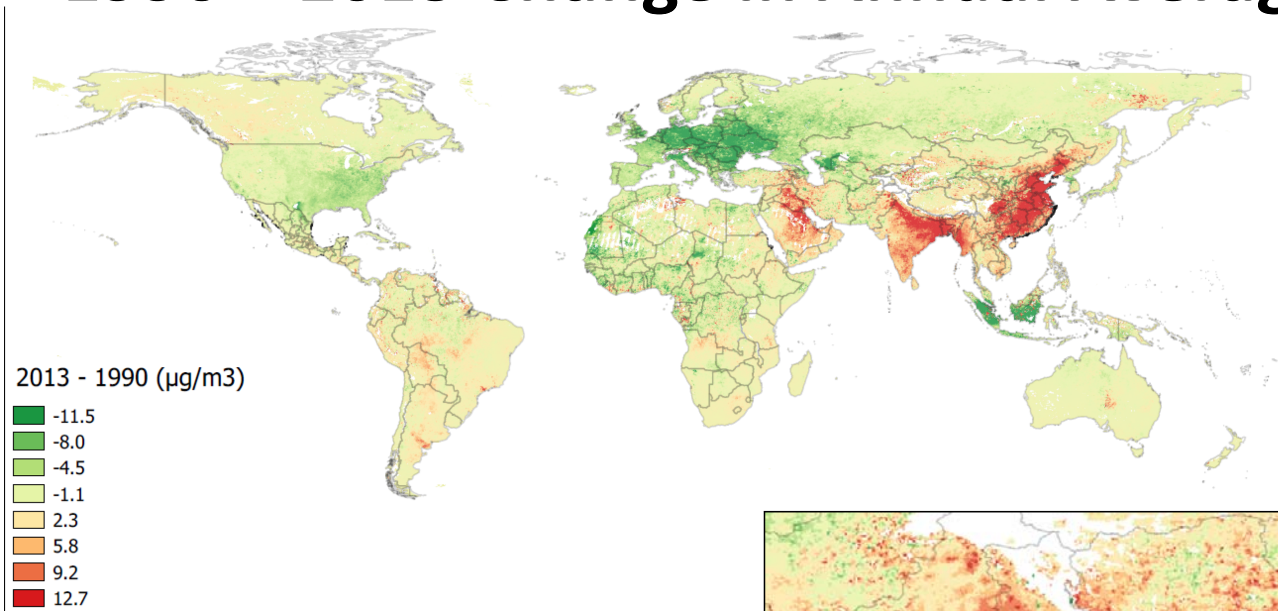


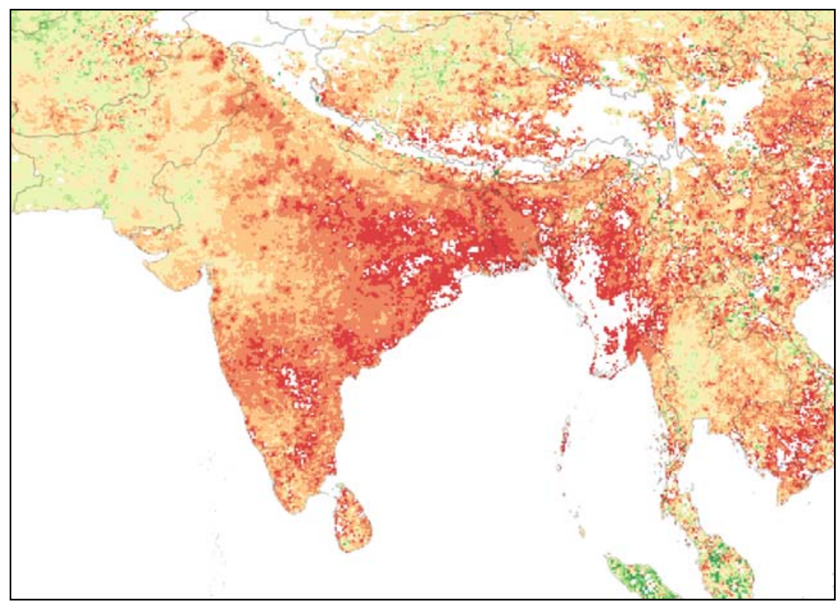


- Global coverage
- ~11 x 11 km resolution
- 1990 – 2013 trends – annually updated

Brauer et al. Environ Sci Technol. 2015

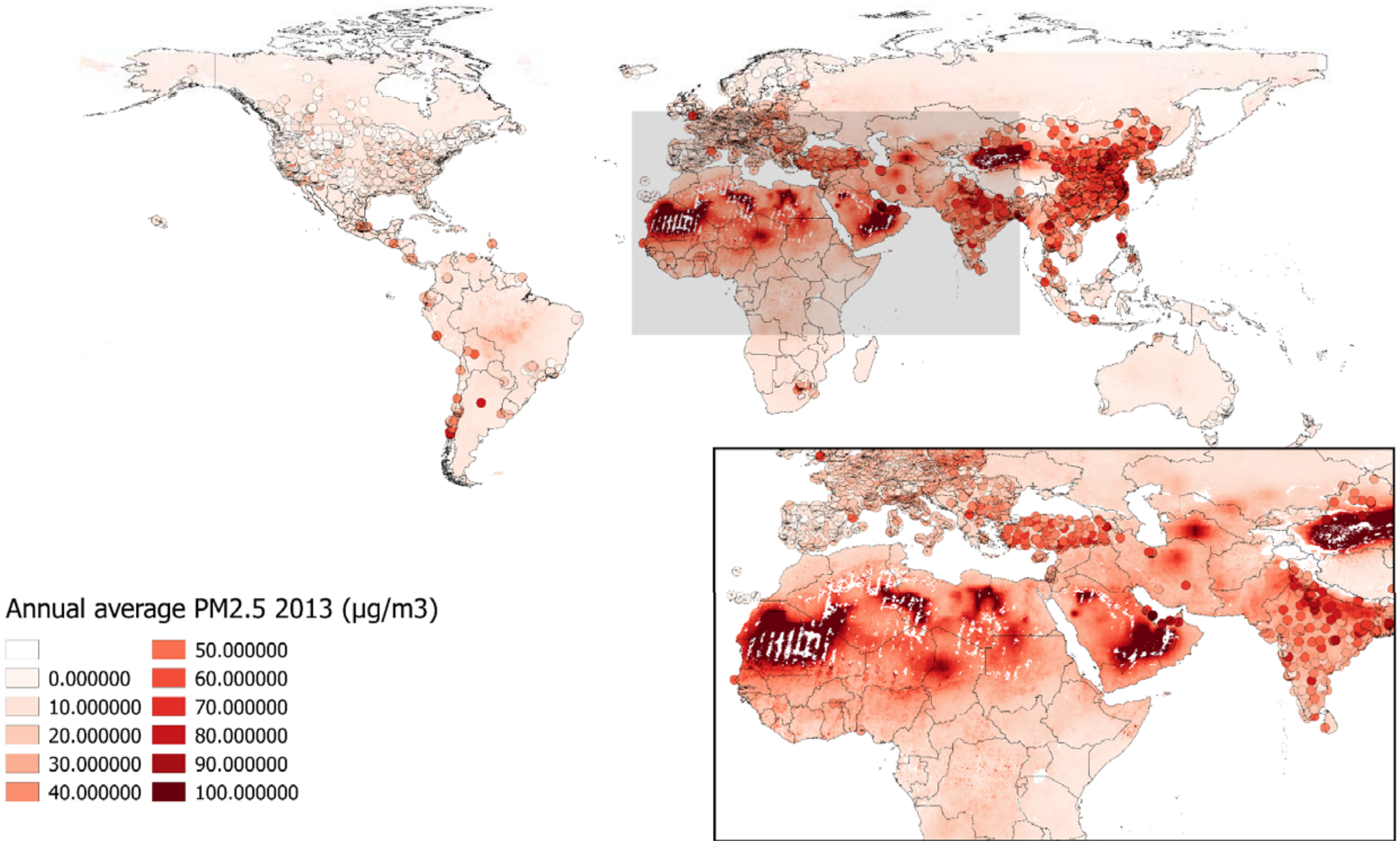
1990 – 2013 Change in Annual Average $PM_{2.5}$

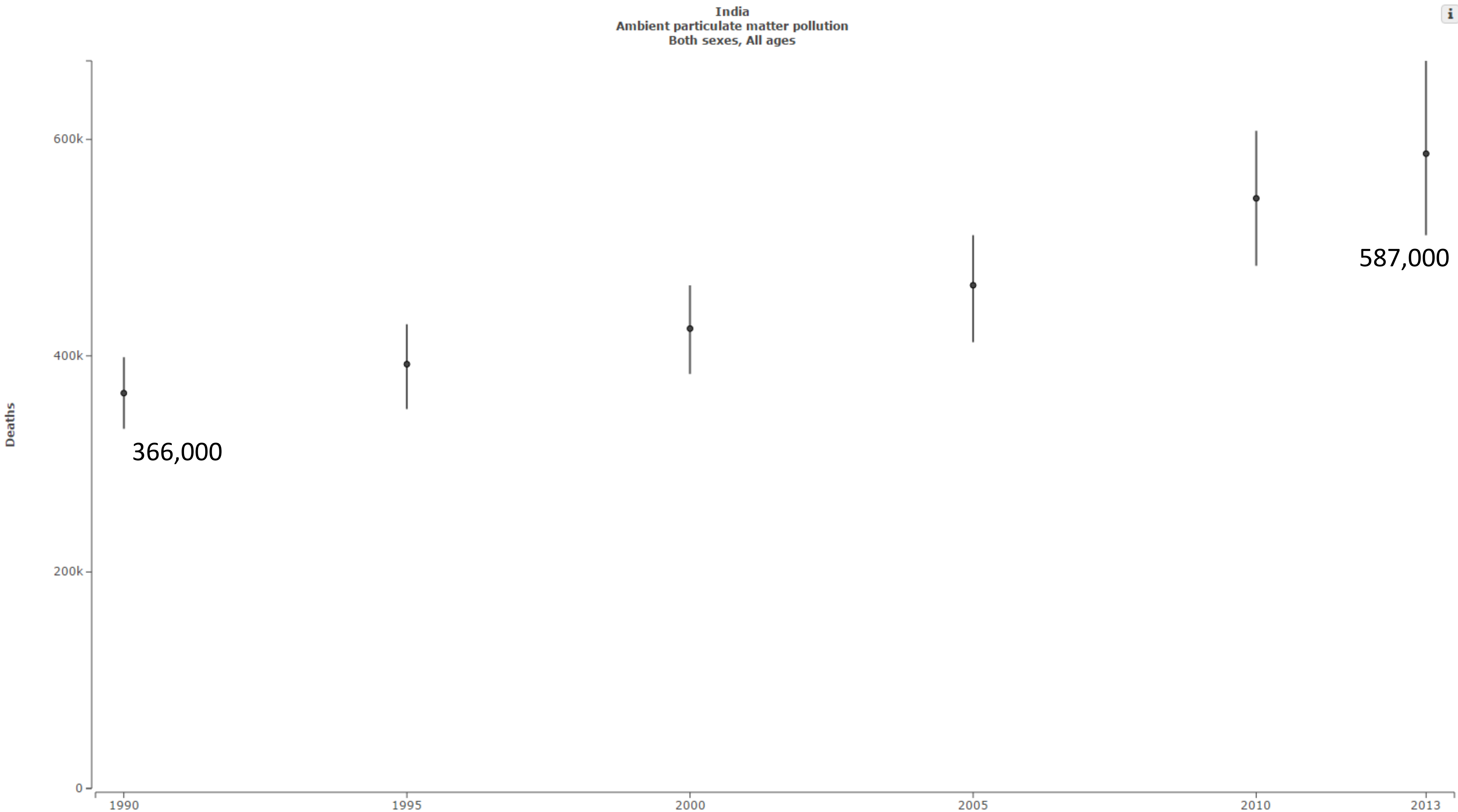


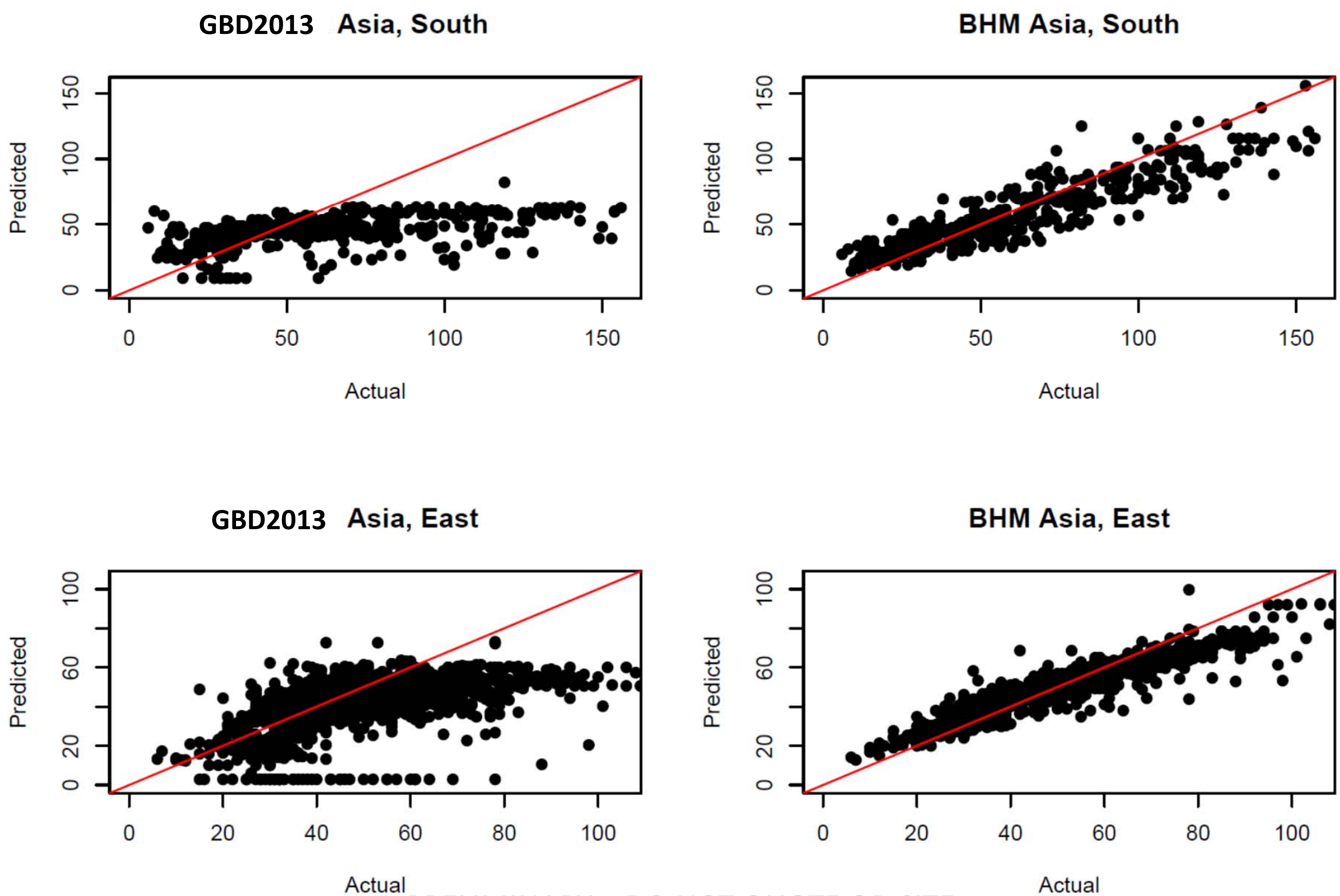


Brauer et al. Environ Sci Technol. 2015

2013 Annual Average $PM_{2.5}$




India
Ambient particulate matter pollution
Both sexes, All ages
Deaths
600k
400k
200k
0
1990
1995
2000
2005
2010
2013
366,000
587,000


GBD2013 Asia, South
BHM Asia, South
GBD2013 Asia, East
BHM Asia, East
Predicted
Actual
0
50
100
150
20
40
60
80