University of Leeds

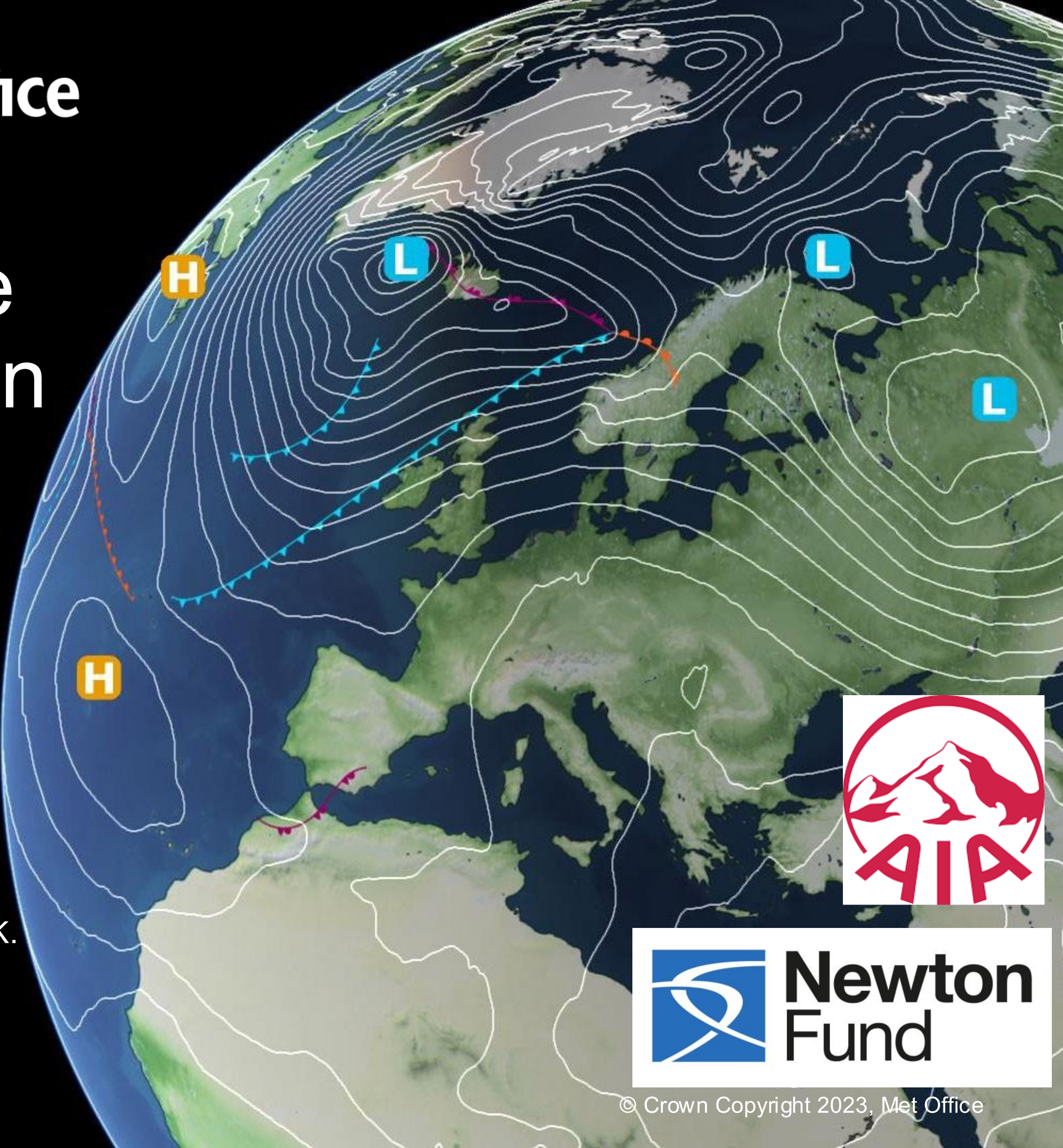
Met Office

Considerations for future projections of air pollution concentrations

Carly Reddington[1]
(c.l.s.reddington@leeds.ac.uk)

Steven Turnock[2,3], Luke Conibear[4],
Ben Silver[1], and many other co-authors

[1]Institute for Climate and Atmospheric Science, University of Leeds, UK.
[2]Met Office Hadley Centre, UK.
[3]University of Leeds Met Office Strategic Research Group, UK.
[4]Tomorrow.io, US.



AIA

Newton Fund

AIR POLLUTION EFFECTS ON HEALTH, VEGETATION & CLIMATE

Air Pollutants and Health

Long-term exposure to ambient (outdoor) air pollution was estimated to cause ~5.4 million premature deaths worldwide in 2023 (*State of Global Air, 2025*)

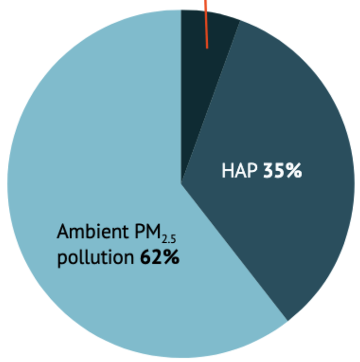
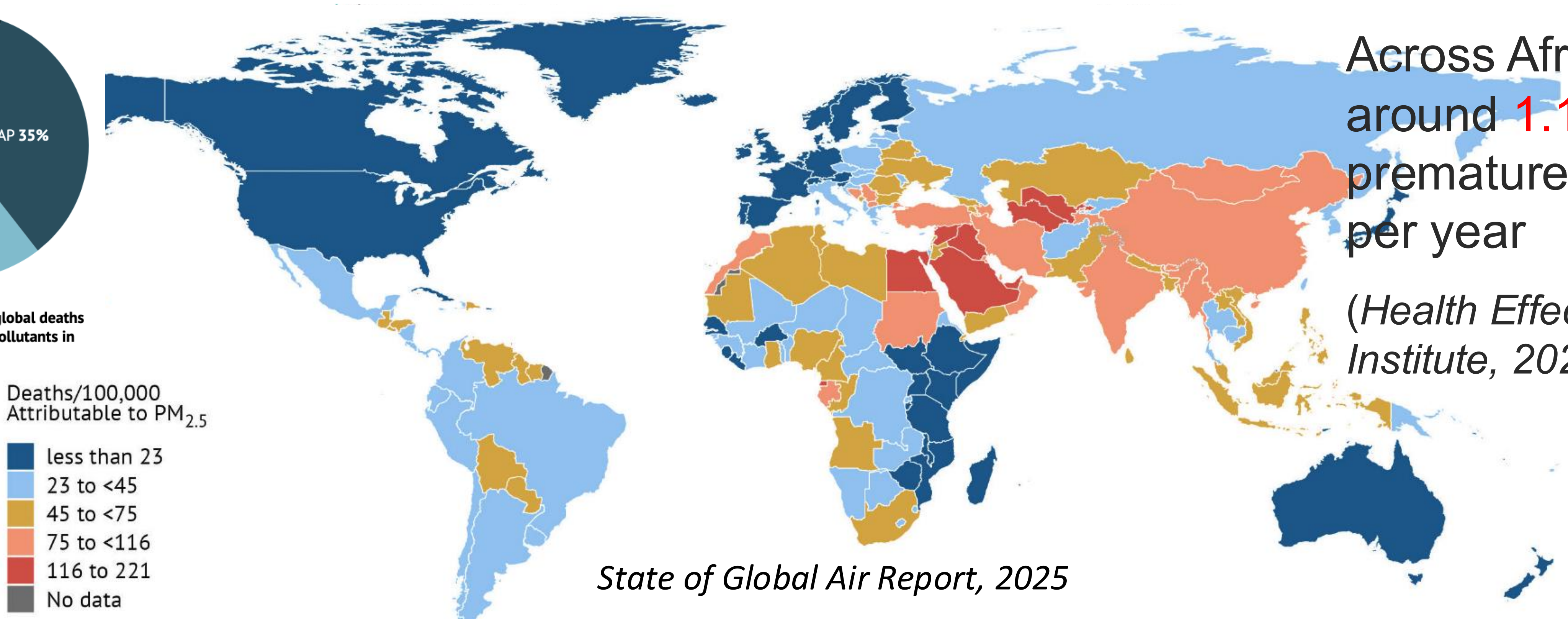


FIGURE 12: **Percentage of global deaths attributable to individual pollutants in 2023.**



State of Global Air Report, 2025

Across Africa around 1.1 million premature deaths per year

(*Health Effects Institute, 2022*)

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Air Pollutants and Vegetation

- Particulate Matter (PM), Ozone (O_3 - tropospheric)
- High concentrations of Air Pollutants in the lower atmosphere lead to poor air quality and impact vegetation/Ecosystems

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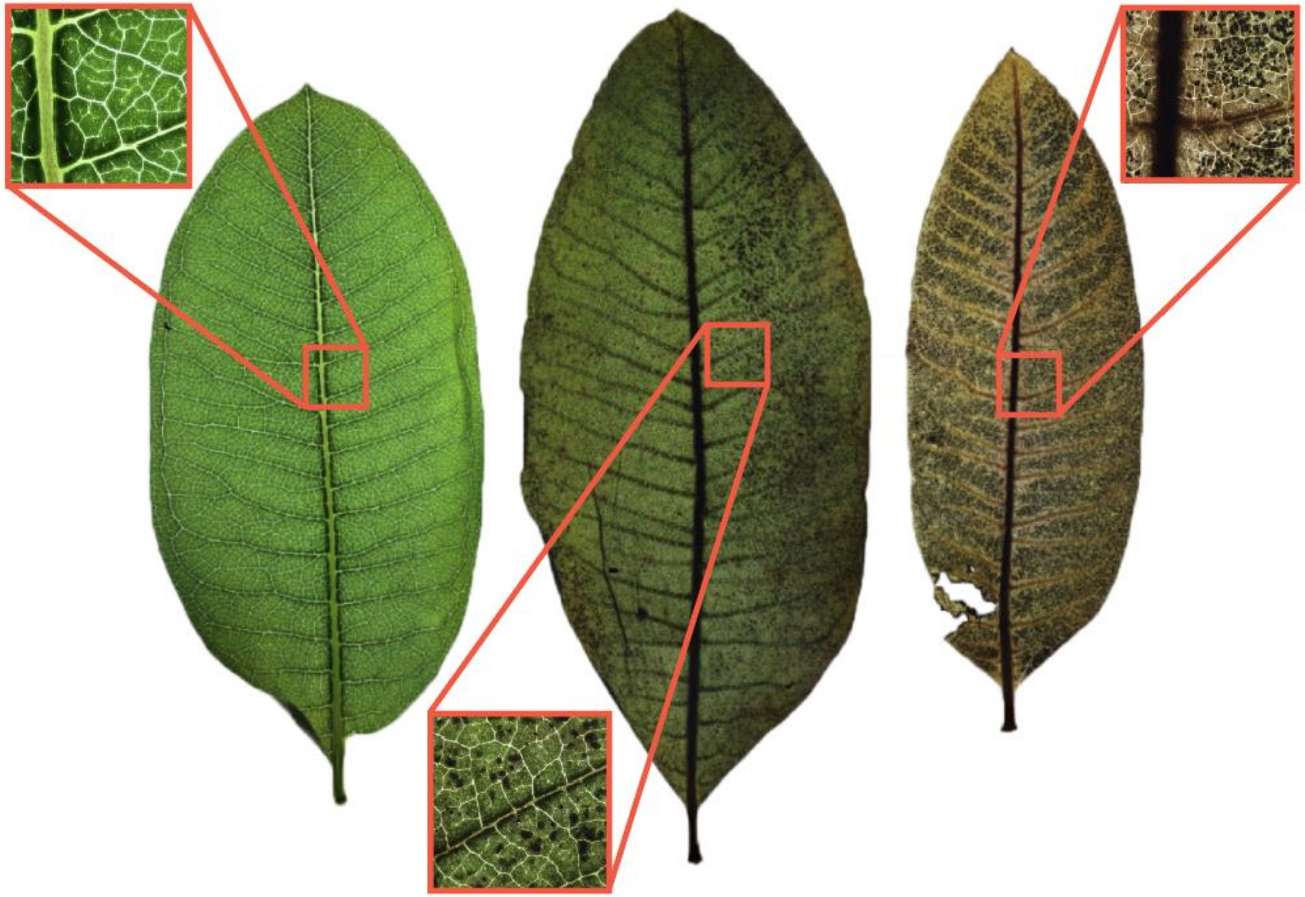
Ozone damage to vegetation



Three leaves from milkweed plants showing increasing levels of ozone damage from left to right.
Credit: Robin Rohrback, Adapted by American Geosciences Institute

Brown spots indicate damage to leaf cells from ozone pollution
Credit: Danica Lombardozzi/National Center for Atmospheric Research

Air Pollutants and Vegetation

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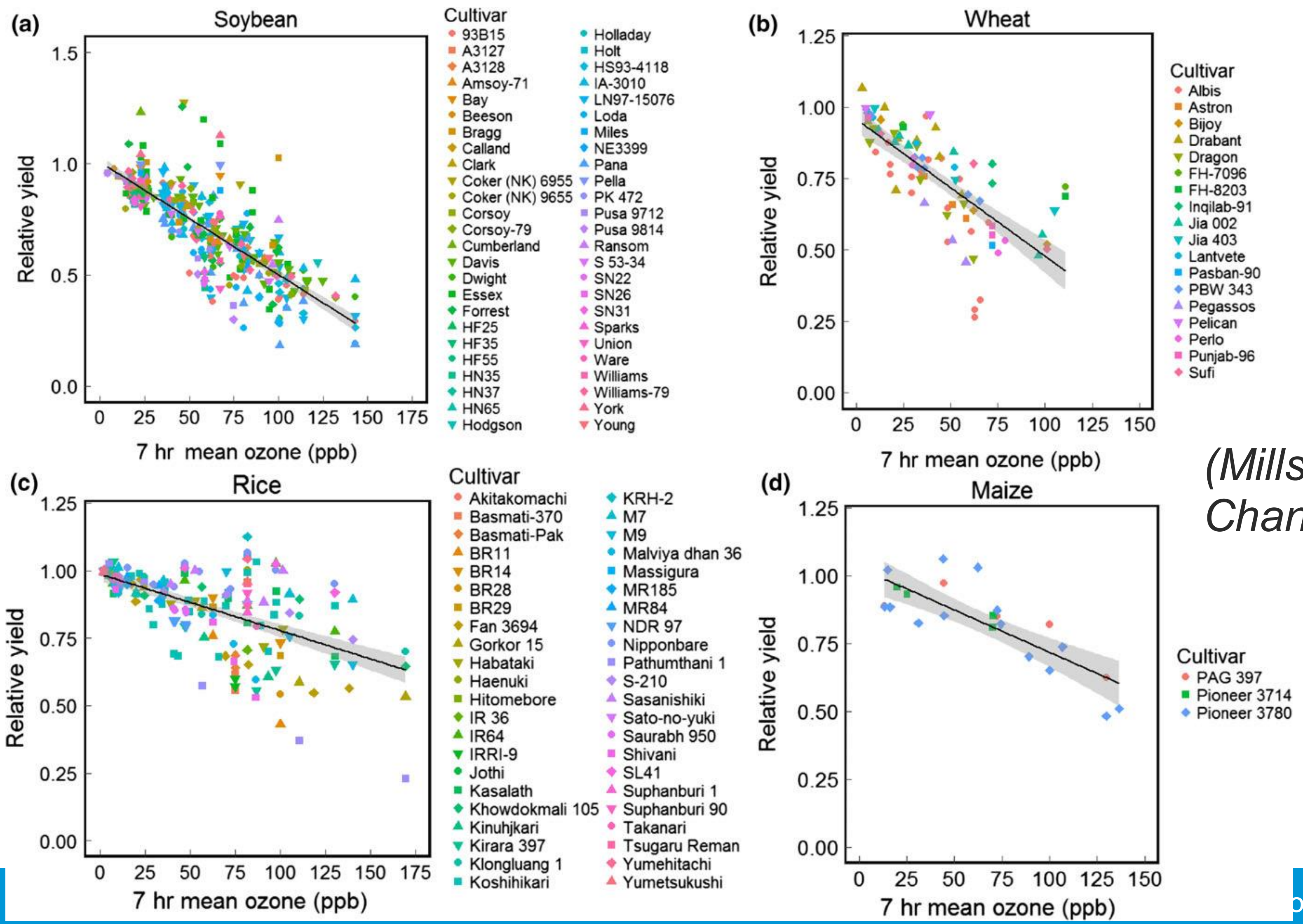
Ozone impacts on crop yields



(Mills et al., Glob Change Biol., 2018)

Air Pollutants and Climate

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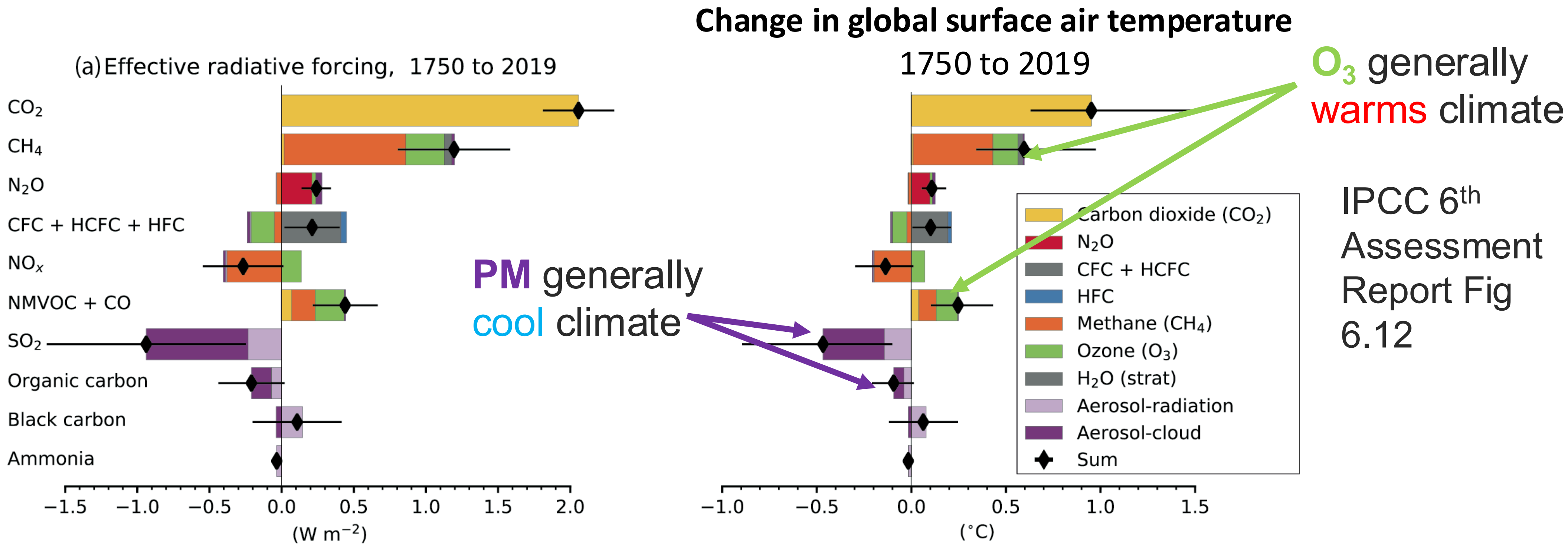
- Particulate Matter (PM), Ozone (O_3 - tropospheric), Nitrogen dioxide (NO_2), Sulphur Dioxide (SO_2), Carbon monoxide (CO), heavy metals
- Air pollutants can impact climate (O_3 has a warming effect and PM has a cooling effect on climate)



IPCC 6th Assessment Report Fig 6.12

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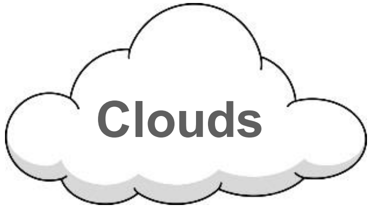
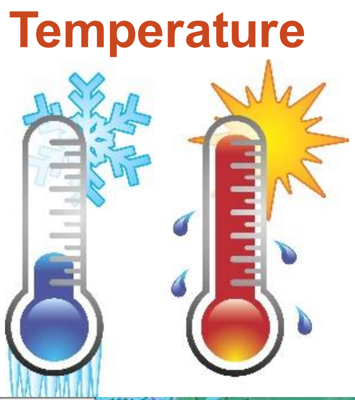
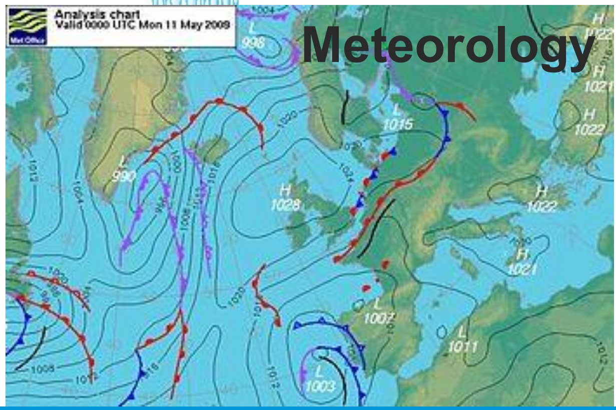
Air Pollutants and Climate

- Particulate Matter (PM), Ozone (O_3 - tropospheric)
- Air pollutants can impact climate.
- **Climate can also impact on air quality**
  - ❑ Background Ozone ↓ but peak ozone in episodes ↑
  - ❑ PM more uncertain (both ↑ and ↓)







(*Jacob and Winner, Atmos. Environ. 2009; Fiore et al., Chem. Soc. Rev. 2012; Allen et al., Nat. Clim. Change, 2016*)

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Air Pollutants and Climate

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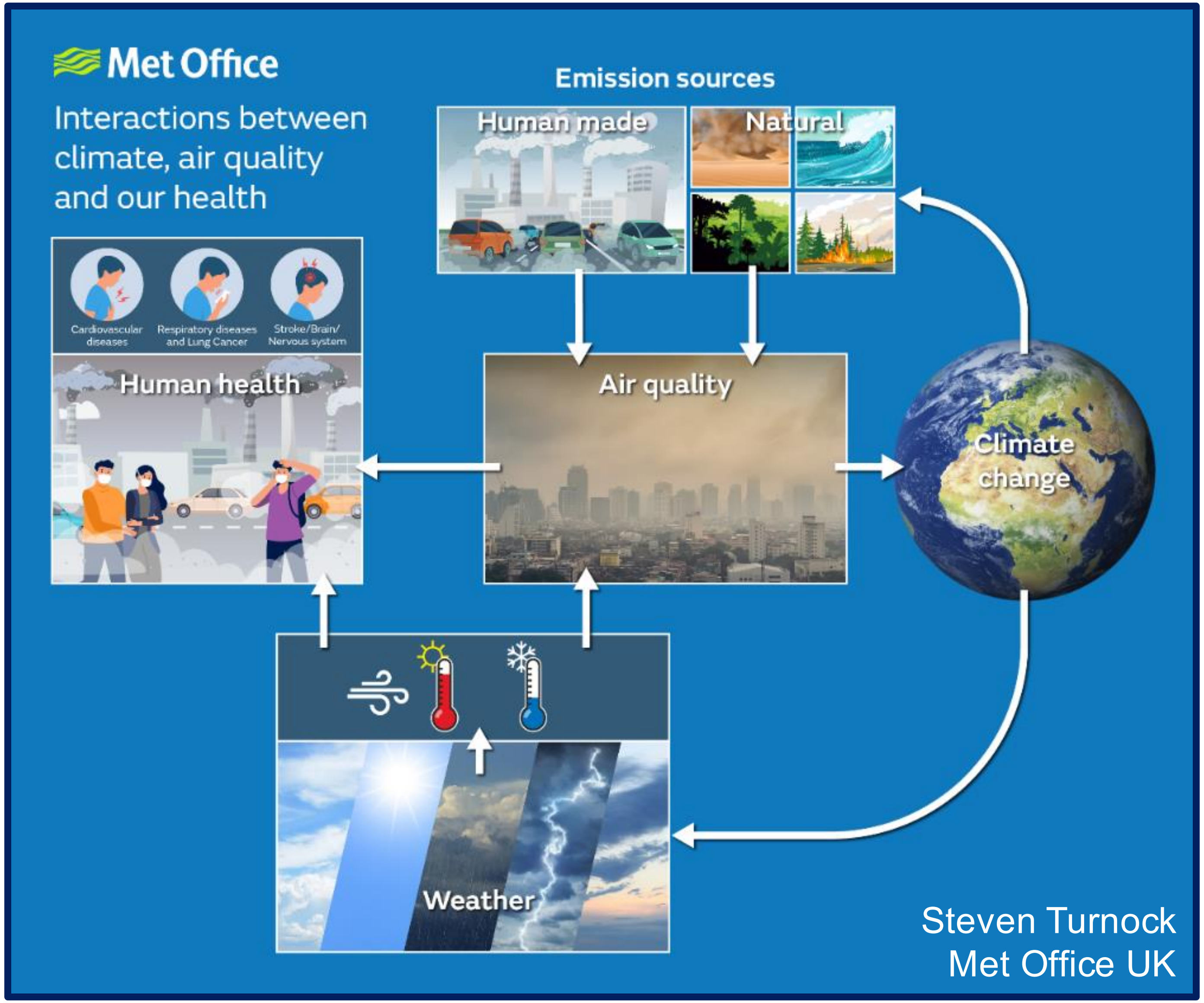

Air Pollutants and Climate Policy

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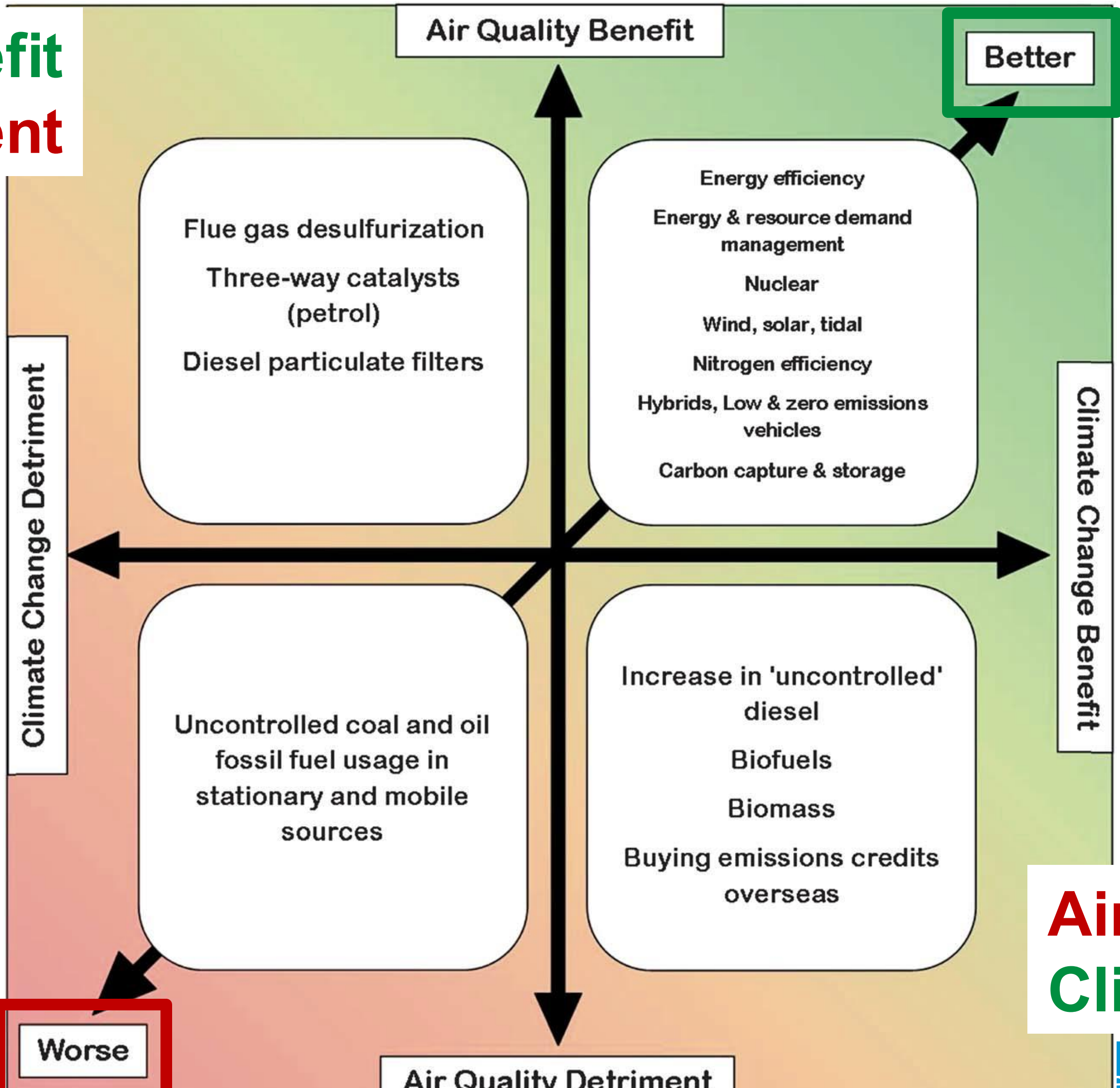
How do we seek to control air quality and climate change in the future?

☑ **Air Quality Benefit**
☒ **Climate Detriment**

In future it is important to consider both air quality and climate policy together to achieve maximum benefits



Air Quality and Climate Benefit (“co-benefits”) ☑

Fig. 1 from von Schneidemesser and Monks, (2013), adapted from Williams, (2012) and Monks et al., (2009)

☒ **Air Quality and Climate Detriment**

Air Quality Detriment ☒
Climate Benefit ☑

HISTORICAL CHANGES IN AIR POLLUTION

Historical Air Quality

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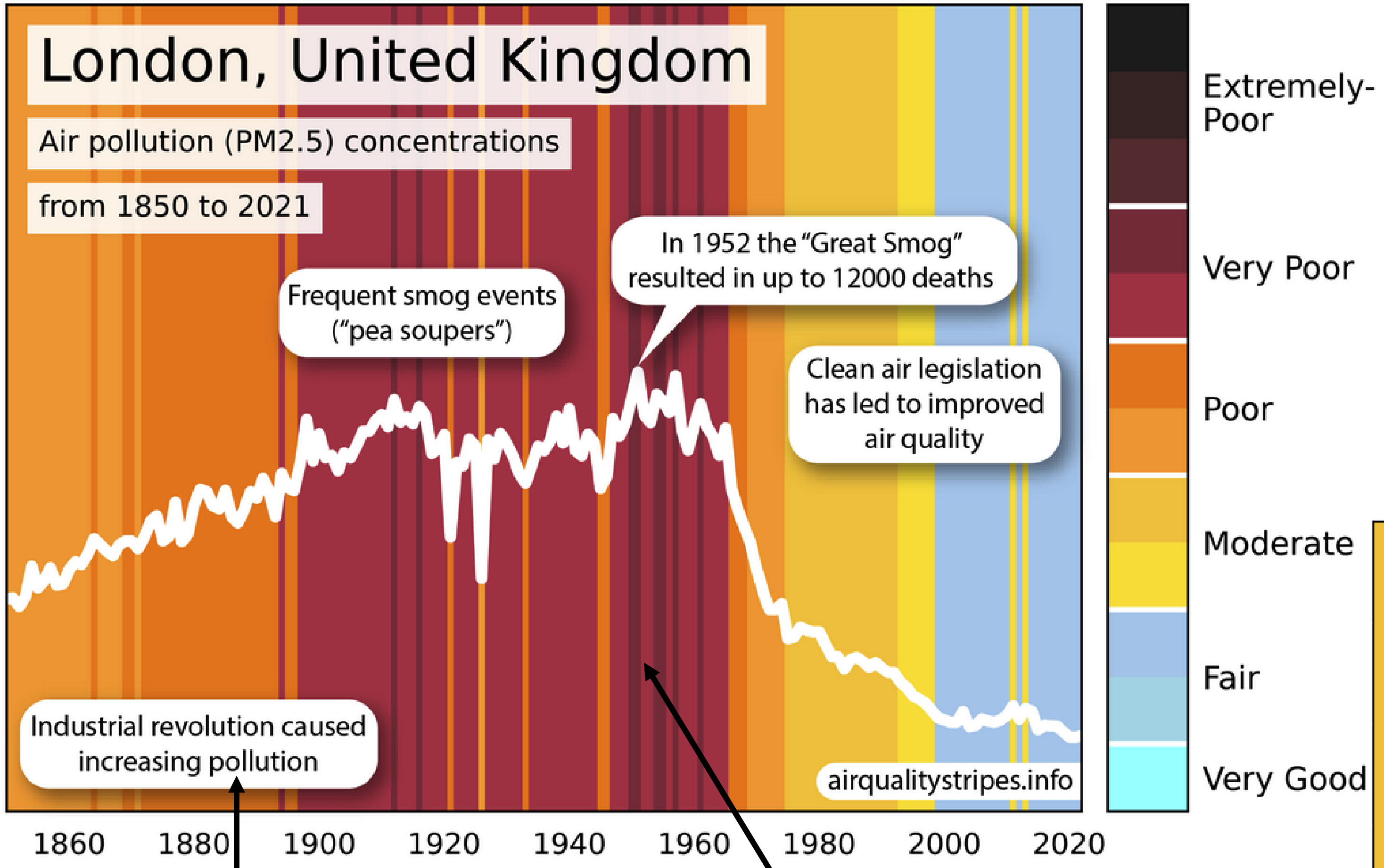
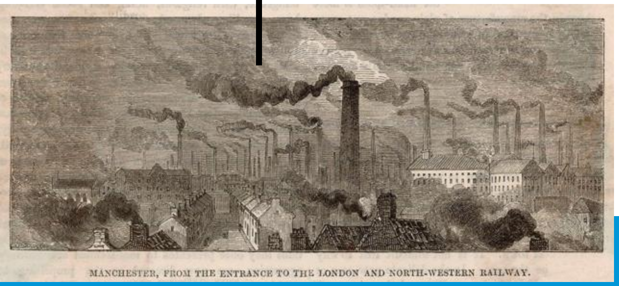
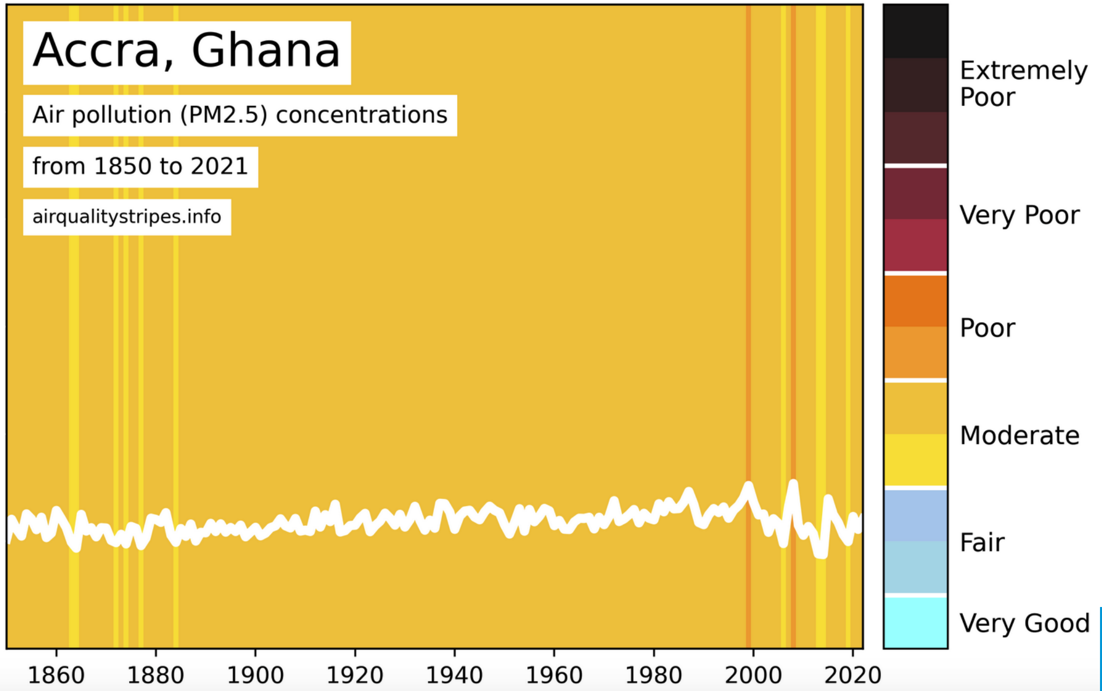
https://airqualitystripes.info/



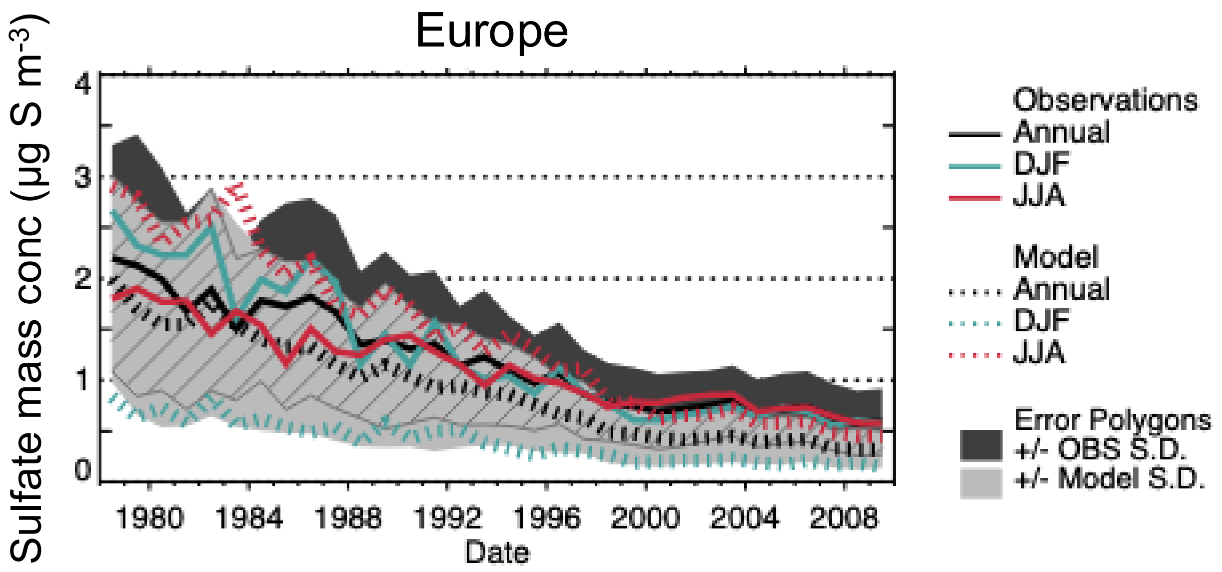
To project future changes in air pollution, it is important to understand changes in air pollution in the past



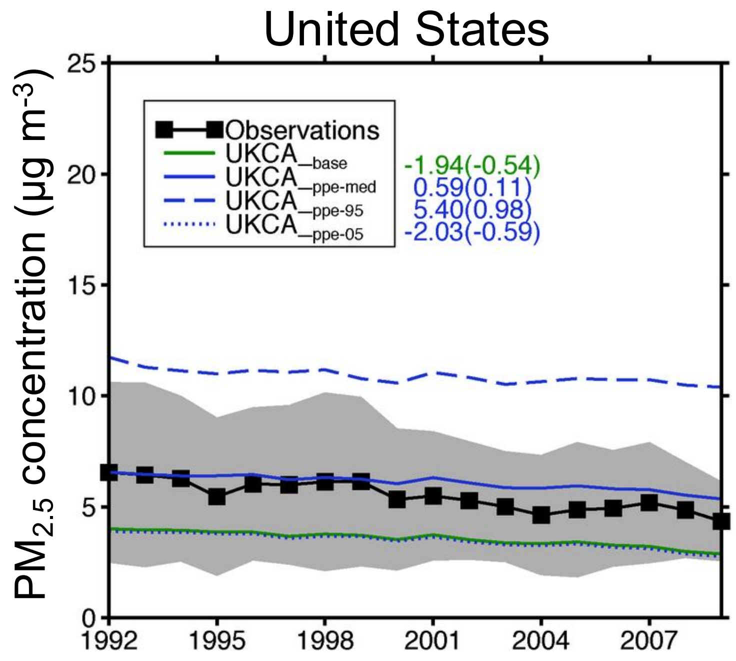


Changes in PM pollution over recent decades

Over recent decades, emission control efforts have delivered notable reductions in particulate matter (PM) concentrations across Europe and North America.



(Turnock et al., Atmos. Chem. Phys., 2016)



(Butt et al., Environ. Res. Lett., 2017)

Carly Reddington, c.l.s.reddington@leeds.ac.uk

Recent declines in $PM_{2.5}$ pollution in China

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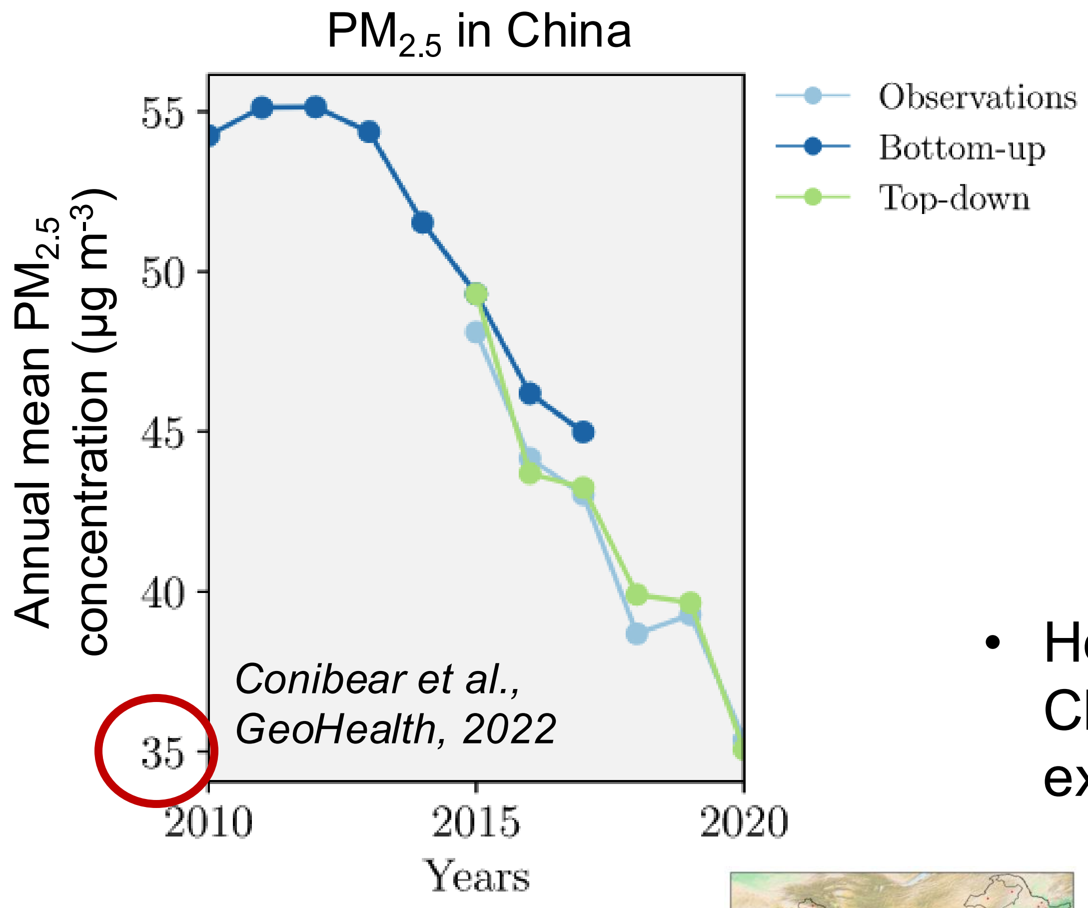
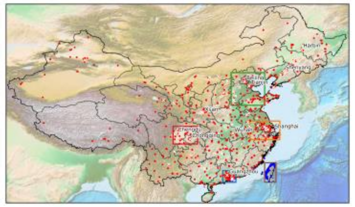


Concentrations averaged over 100's of measurement locations in China



- Measured ambient $PM_{2.5}$ concentrations **decreased by ~26%** over **2015−2020**.

⇒ provided large public health benefits

⇒ mainly been attributed to **decreasing anthropogenic emissions**

- However, **$PM_{2.5}$ exposure remains high** across China and the loss of healthy life from air pollution exposure remains substantial.

(Conibear et al., GeoHealth, 2022; Silver et al., Atmos. Chem. Phys., 2020; Silver et al., Environ. Res. Lett., 2020; Silver et al., Environ. Res. Lett., 2018)

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Recent increases in ozone pollution in China

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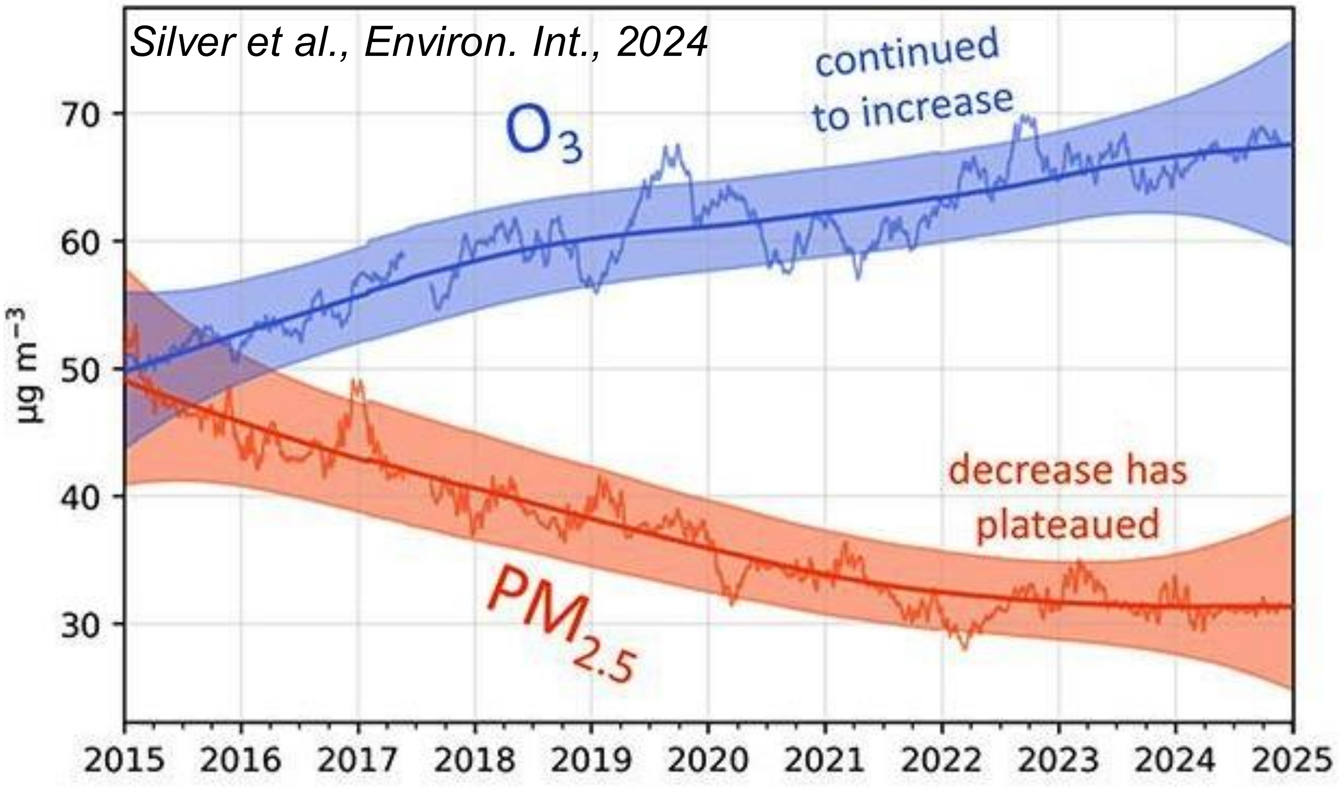
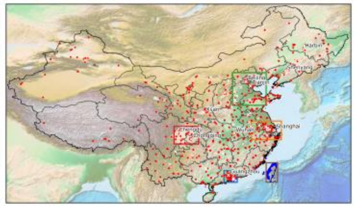


- In contrast to $PM_{2.5}$, **ground-level ozone concentrations have increased** over recent years.
- This is despite or partly due to emission control efforts in China.

(Silver et al., Environ. Int., 2024)

Changes averaged over 100's of measurement locations in China



Carly Reddington, c.l.s.reddington@leeds.ac.uk

Global $PM_{2.5}$ exposure remains high

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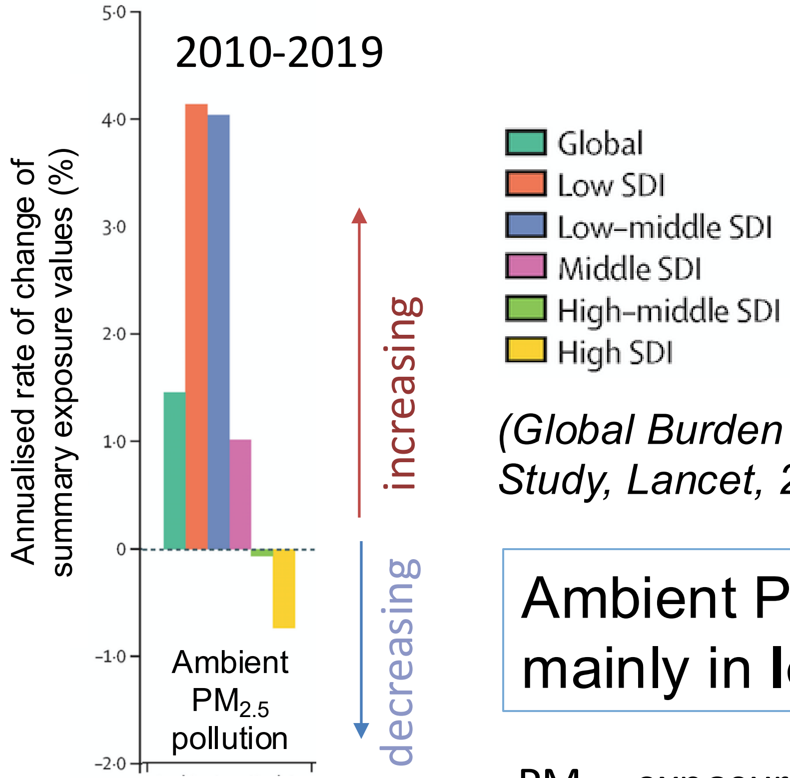
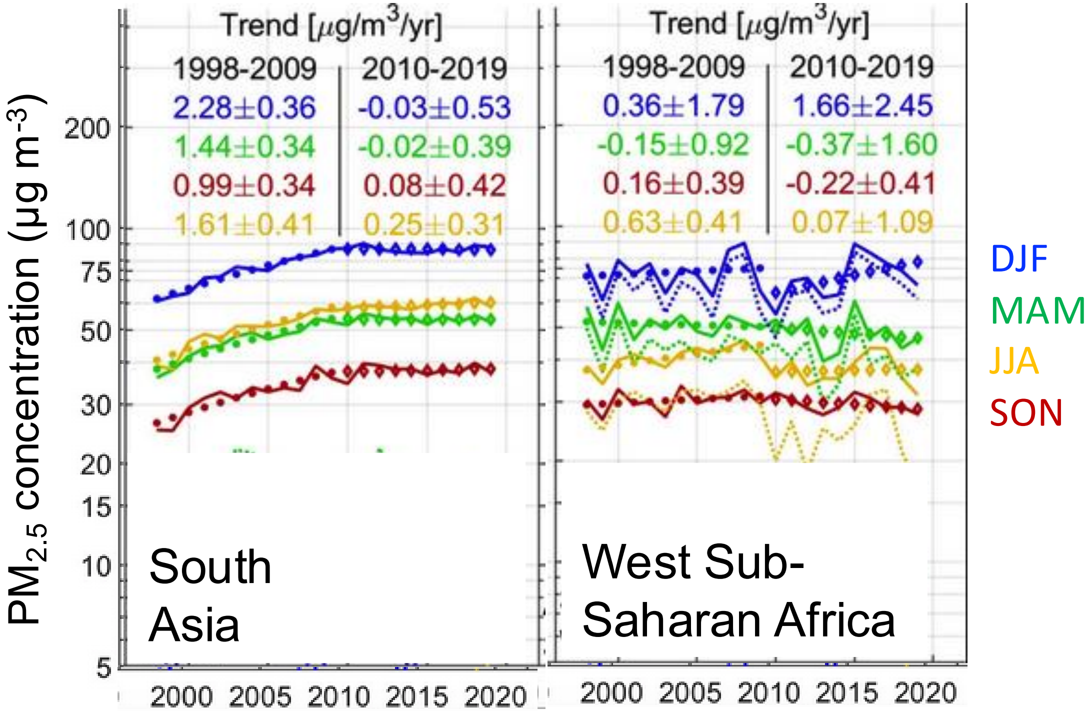
Ambient $PM_{2.5}$ concentrations remain relatively high across Asia and Africa, and are increasing in some regions.



(Global Burden of Disease Study, Lancet, 2020)



(van Donkelaar et al., Environ. Sci. Technol., 2021)

Ambient $PM_{2.5}$ exposure has increased globally, with increases mainly in **low to middle socioeconomic status countries**.

$PM_{2.5}$ exposure = population-weighted annual mean $PM_{2.5}$ concentration

Carly Reddington, c.l.s.reddington@leeds.ac.uk

INEQUALITIES IN $PM_{2.5}$ EXPOSURE

$PM_{2.5}$ exposure inequalities

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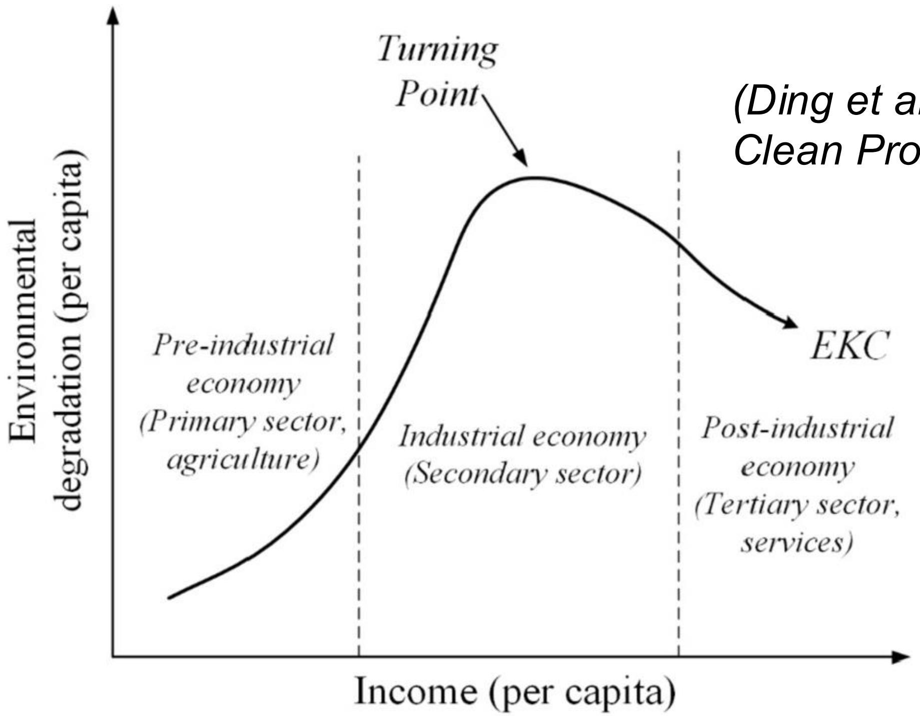
- Ambient $PM_{2.5}$ exposure is often greater in populations with a lower socioeconomic status compared to those with a high socioeconomic status (*Hajat et al., Curr. Environ. Health Rep., 2015*)

- Ambient $PM_{2.5}$ concentrations tend to be linked with economic development.

- 'Outsourcing' manufacturing to lower-income countries/regions can exacerbate disparities (*Nansai et al., Environ. Int., 2020*)

- Additional drivers of inequality arise from polluting activities predominantly undertaken by poorer communities (*Reddington et al., GeoHealth, 2021*)

An Environmental Kuznets Curve (EKC)



(*Ding et al., J. Clean Prod. 2019*)

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Demographics influence $PM_{2.5}$ health outcomes

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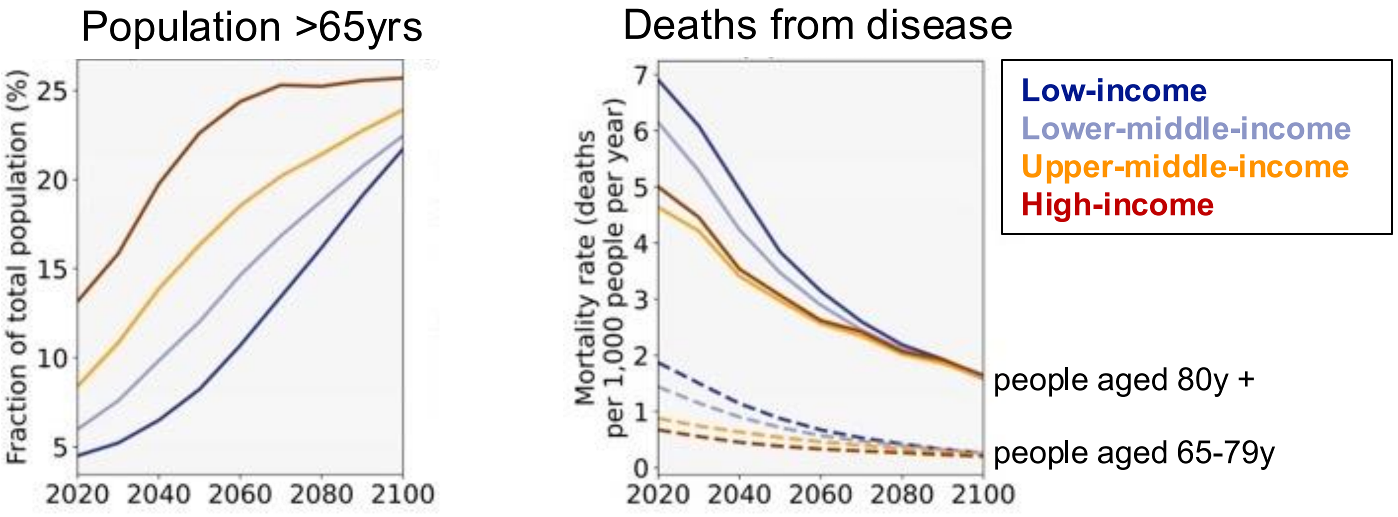
- Inequities in $PM_{2.5}$ exposure can be compounded by other socioeconomic factors that increase the vulnerability and disease susceptibility of a population.
- Lower-income countries or communities tend to suffer from reduced access to healthcare and poorer nutrition (*O'Neill et al., 2003*)
- High-income countries tend to have older (more vulnerable) populations than low- and middle-income countries (*United Nations, 2019*)

Frederick S. Pardee Center for International Futures



(*Reddington et al., Earth's Future, 2023*)

Carly Reddington, c.l.s.reddington@leeds.ac.uk

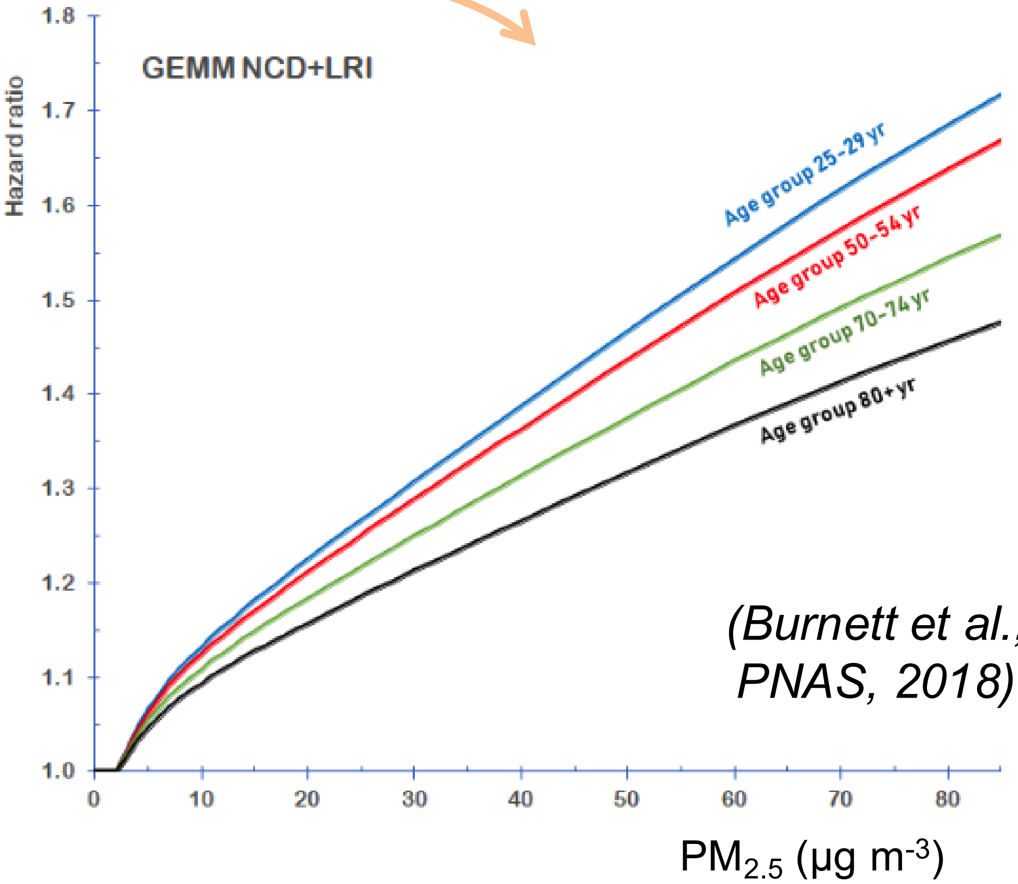
Estimating $PM_{2.5}$-attributable deaths

$$\Delta AD = pop \times mort \times PAF_{\beta}(PM_{2.5}, cf)$$

(Burnett & Cohen, Atmosphere, 2020)

Estimation of $PM_{2.5}$-attributable deaths depends on:

- $PM_{2.5}$ exposure
- Population count
- Population age
- Mortality rate



(Burnett et al., PNAS, 2018)

Carly Reddington, c.l.s.reddington@leeds.ac.uk

Demographics influence $PM_{2.5}$ health outcomes

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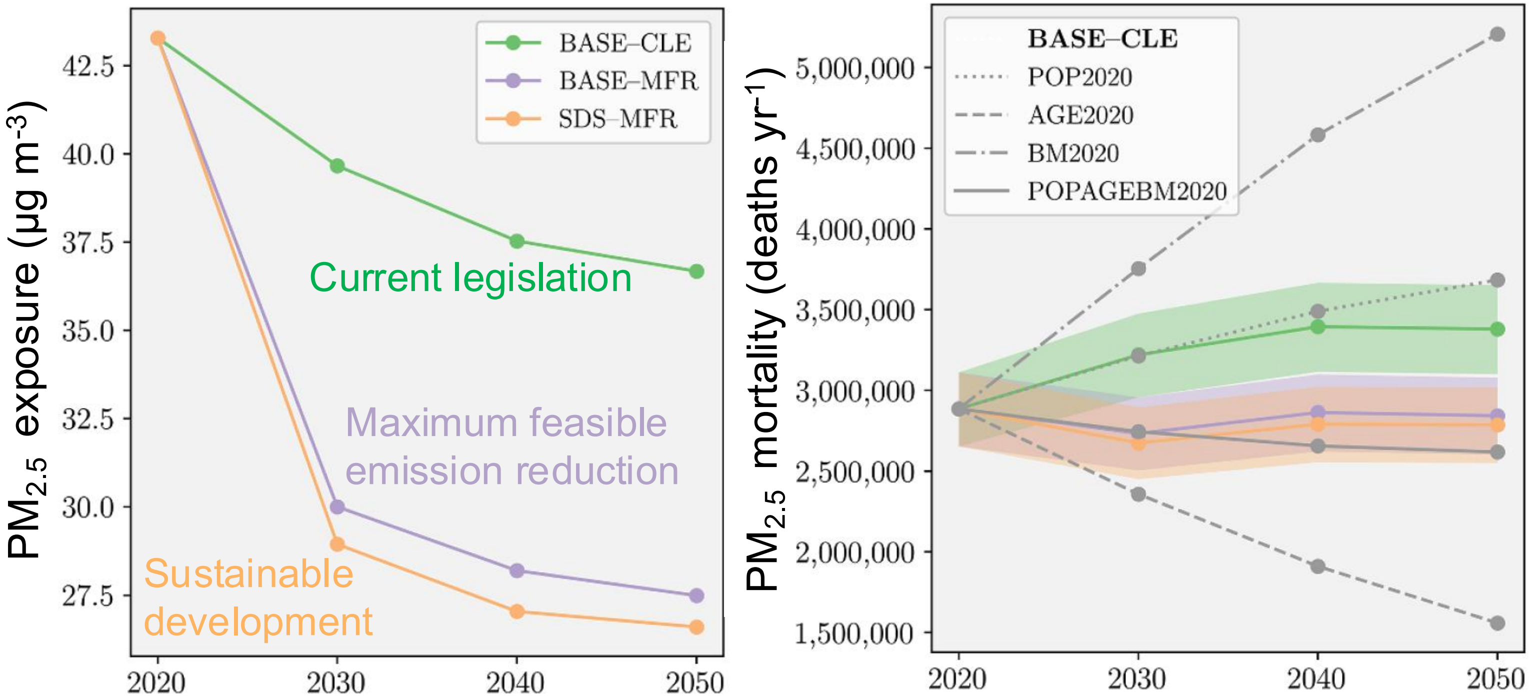
Future $PM_{2.5}$ exposure and health outcomes in China

2020 to 2050



Impact of fixing mortality at 2020 values

$PM_{2.5}$ deaths increase under CLE relative to 2020

Impact of fixing pop age at 2020 values

(Conibear et al., Environ. Res. Lett., 2022)

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FUTURE PROJECTIONS OF GREENHOUSE GAS AND AIR POLLUTANT EMISSIONS

Future climate and air pollution pathways

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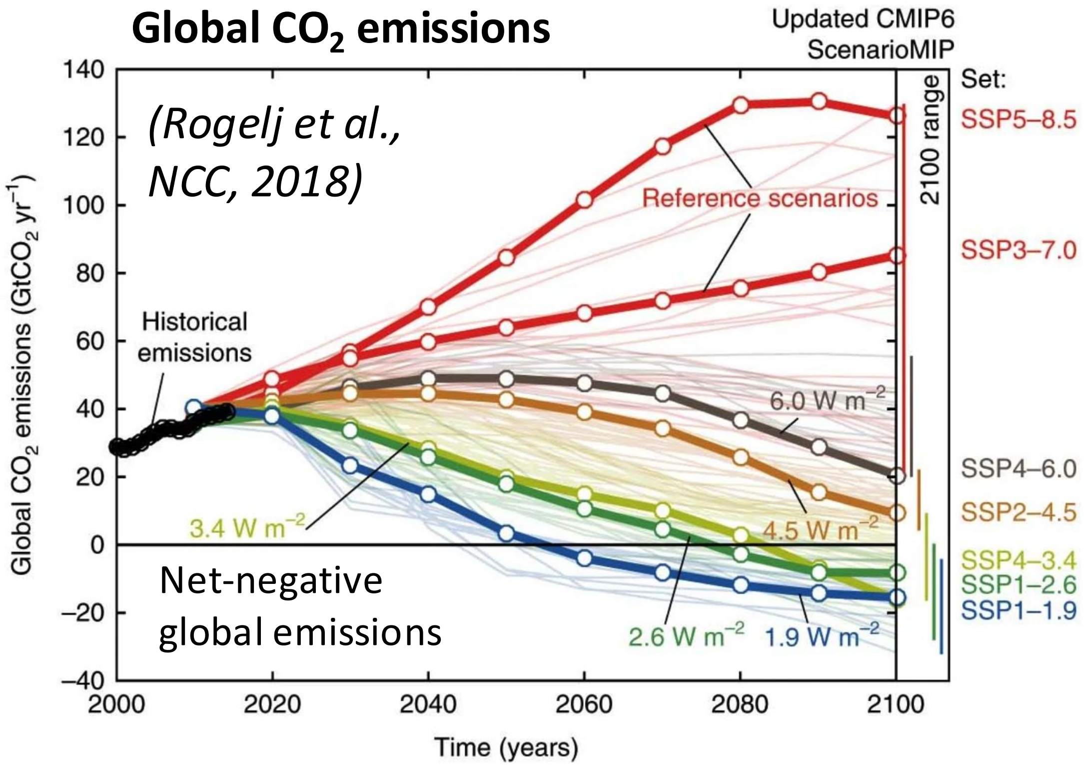
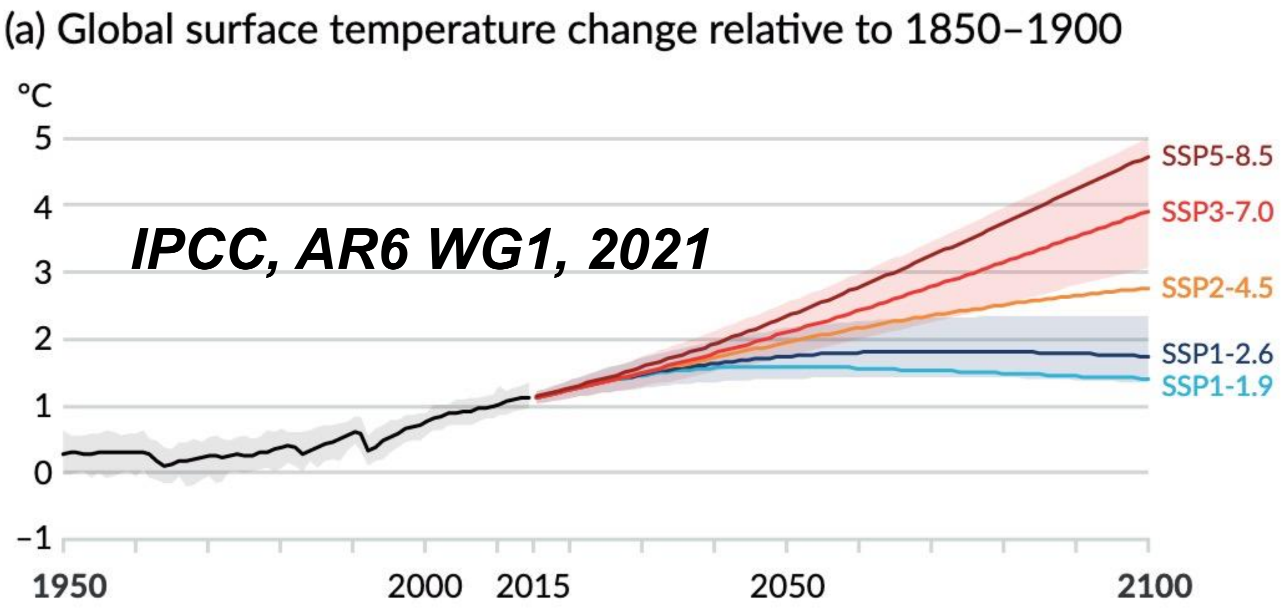
Scenarios for the IPCC 6th Assessment Report (2021)

SSP = **Shared Socioeconomic Pathway**





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Future climate and air pollution pathways

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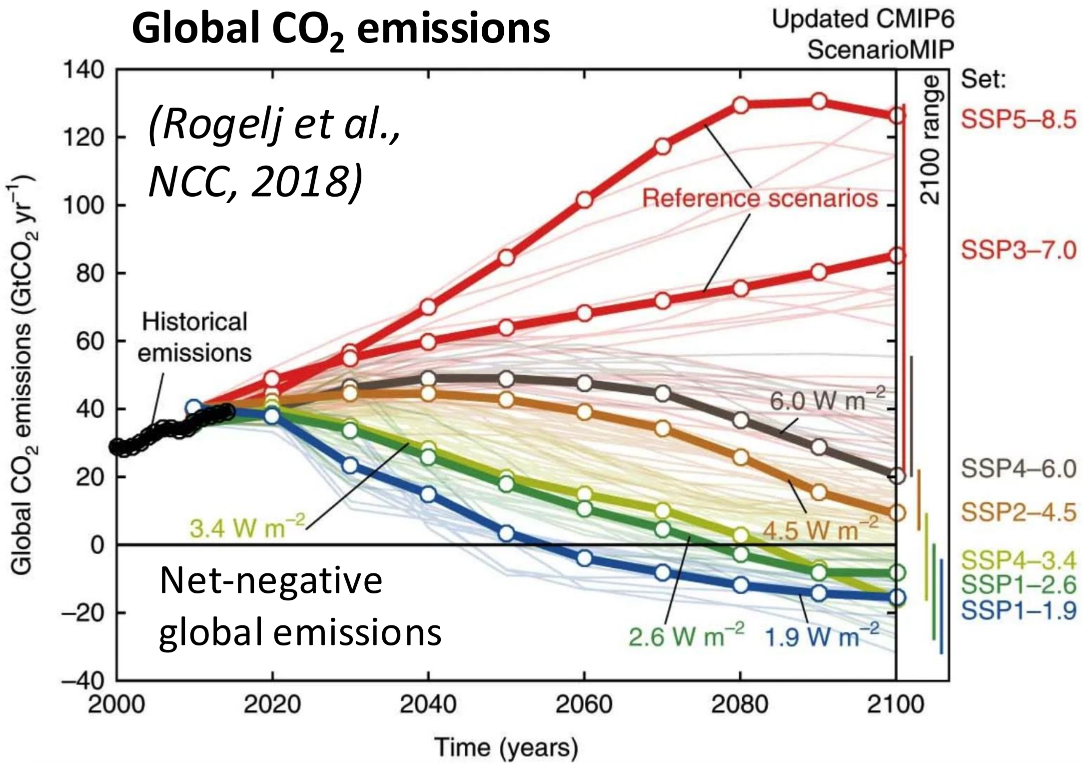
Scenarios for the IPCC 6th Assessment Report (2021)

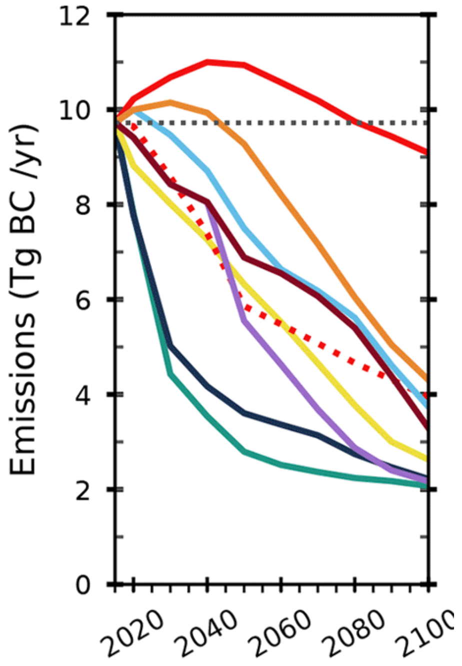
Global CO_2 emissions

(Rogelj et al., NCC, 2018)



SSP = **Shared Socioeconomic Pathway**

Global air pollutant emissions



(Turnock et al., Atmos. Chem. Phys., 2020)

Crucial to quantify co-benefits of climate change mitigation to motivate climate action.

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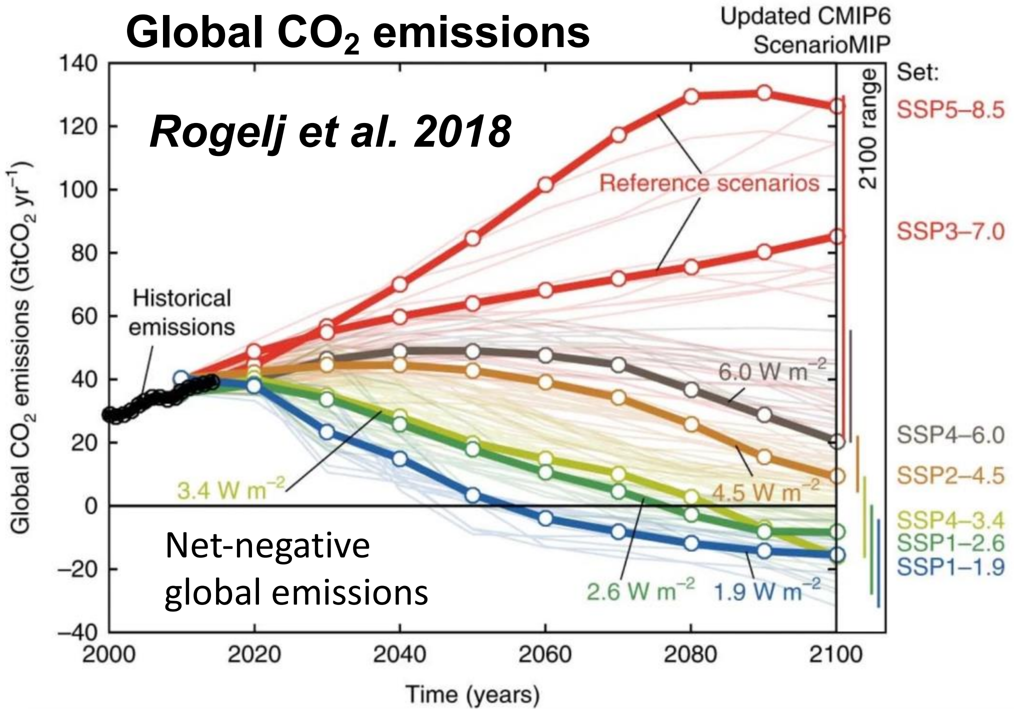
Shared Socioeconomic Pathway scenarios



Scenario	SSP narrative
SSP119	Decarbonisation
SSP126	Decarbonisation
SSP245	Middle of the road
SSP370	Regional Rivalry
SSP370-lowNTCF	Regional Rivalry
SSP434	Inequality
SSP460	Inequality
SSP534	Fossil-fuel development
SSP585	Fossil-fuel development

Carly Reddington, c.l.s.reddington@leeds.ac.uk

Shared Socioeconomic Pathway scenarios

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☑ Air Quality Benefit
☒ Climate Detriment

Air Quality and Climate Benefit ☑

SSP119

SSP126

SSP245

SSP370

SSP370-lowNTCF

SSP434

SSP460

SSP534

SSP585

Graphic by Steven Turnock

☒ Air Quality and Climate Detriment

Air Quality Detriment ☒
Climate Benefit ☑

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Projected population under the SSPs

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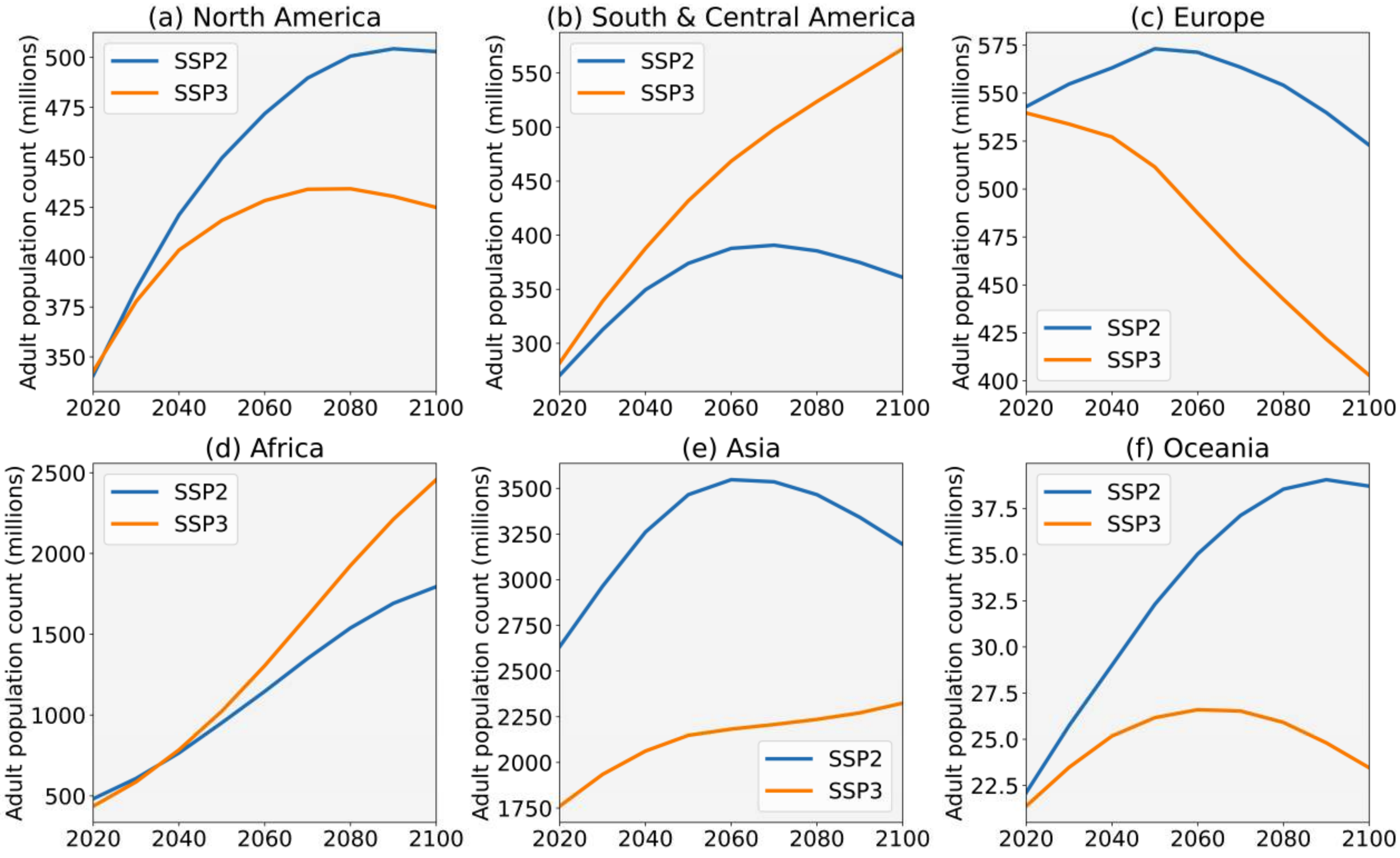

Gridded population for SSP2 and SSP3 *(Jones and O'Neill, Environ. Res. Lett., 2016)*

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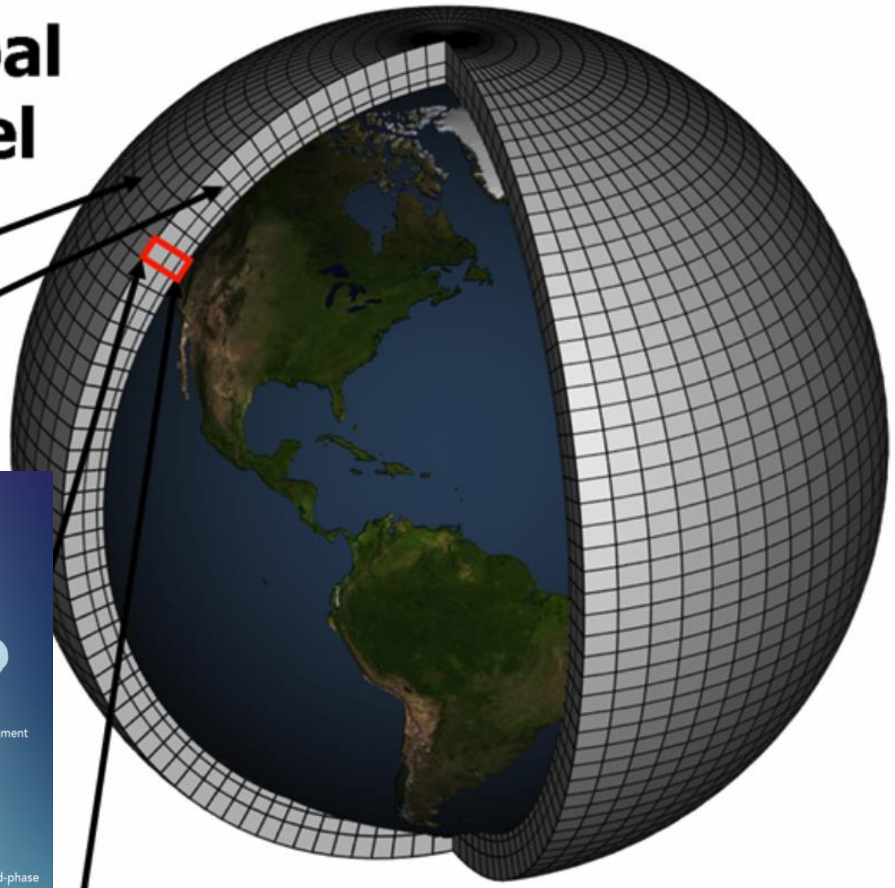
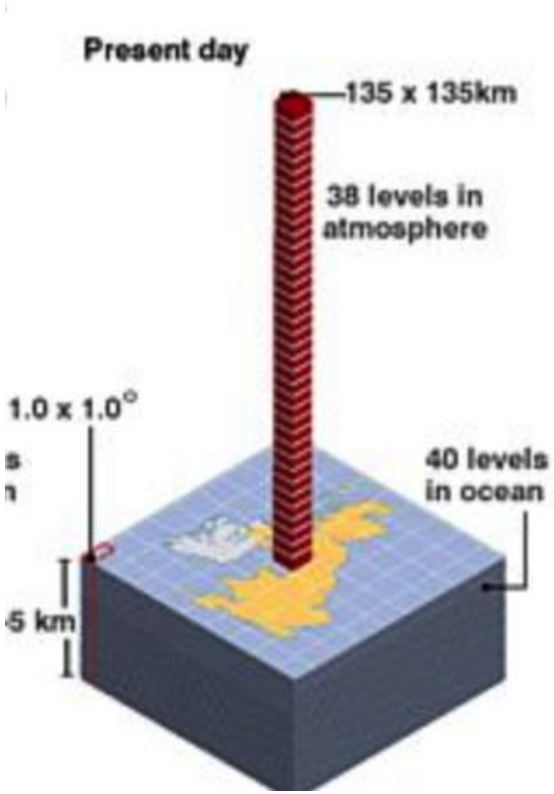
FUTURE PROJECTIONS OF AIR POLLUTION HEALTH IMPACTS UNDER DECARBONISATION

Climate models





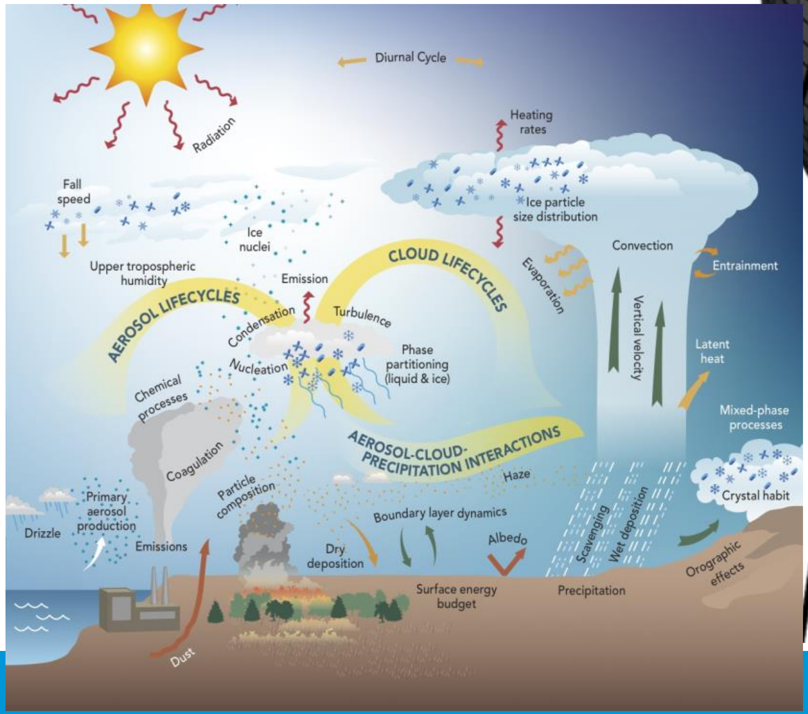


Image sources: https://asr.science.energy.gov/about, https://www.gfdl.noaa.gov/climate-modeling/

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Methodology

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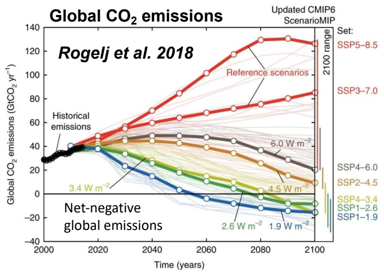
Air pollution health inequalities in a low-carbon future

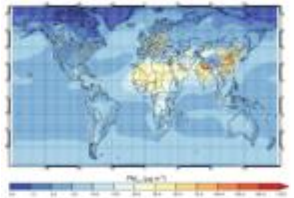
Population demographics

SSPs + climate policy

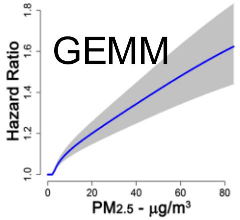


CMIP6 climate & earth system model simulations

5-yr mean $PM_{2.5}$ concentration 2015 - 2100

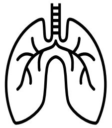


Exposure-outcome association



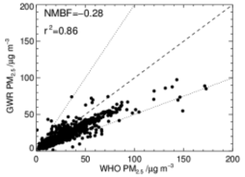
Burnett et al., PNAS, 2018

Premature mortality attributable to ambient $PM_{2.5}$ exposure



Baseline scenario: SSP245
Decarbonisation scenarios: SSP126 & SSP119

Evaluate & bias-correct model outputs using present-day measurements



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Shared Socioeconomic Pathway scenarios

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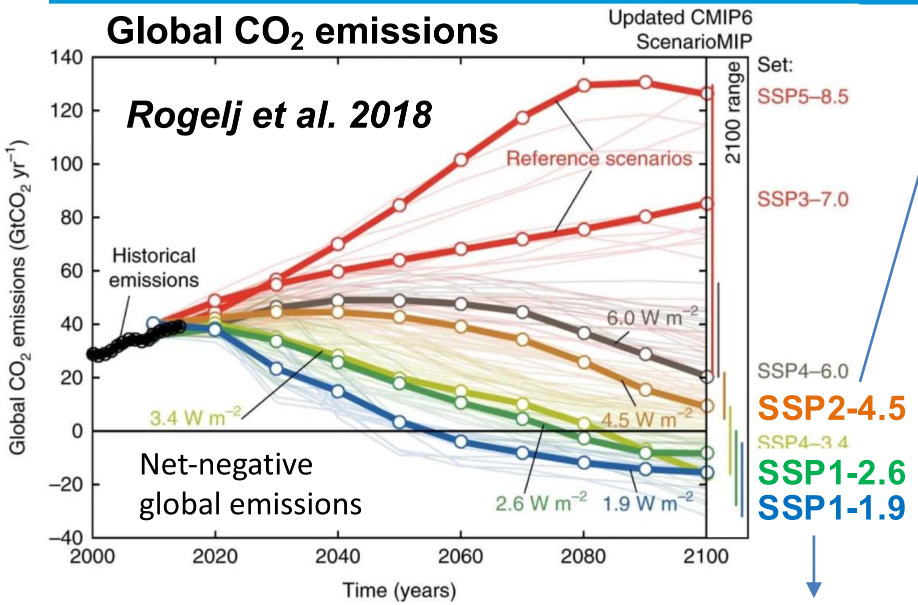

SSP2: "Middle-of-the-road" scenario

- Medium population
- Medium and uneven economic growth, human development, technological progress, and energy and food demand per capita;
- Resource-intensive lifestyles;
- Limited economic convergence and global cooperation;
- **Medium air pollution controls** (significant advancement, yet < SSP1)

SSP1: "Taking the Green Road" (decarbonisation) scenario

- Low population and energy & food demand per capita;
- Economic convergence and global cooperation;
- High economic growth per capita, human development, technological progress;
- Environmentally oriented technological behavioural change;
- Resource efficient lifestyles;
- Substantial land use change (e.g., increased global forest cover)
- **Strong air pollution controls** (fastest and widest implementation).

Selected future scenarios

Air Quality Benefit
Climate Detriment

Air Quality and Climate Benefit

SSP119

SSP126

("Decarbonisation" Scenarios)

SSP245

("Middle of the Road" Scenario)

Air Quality and Climate Detriment

Air Quality Detriment
Climate Benefit

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Future $PM_{2.5}$ exposure by income group

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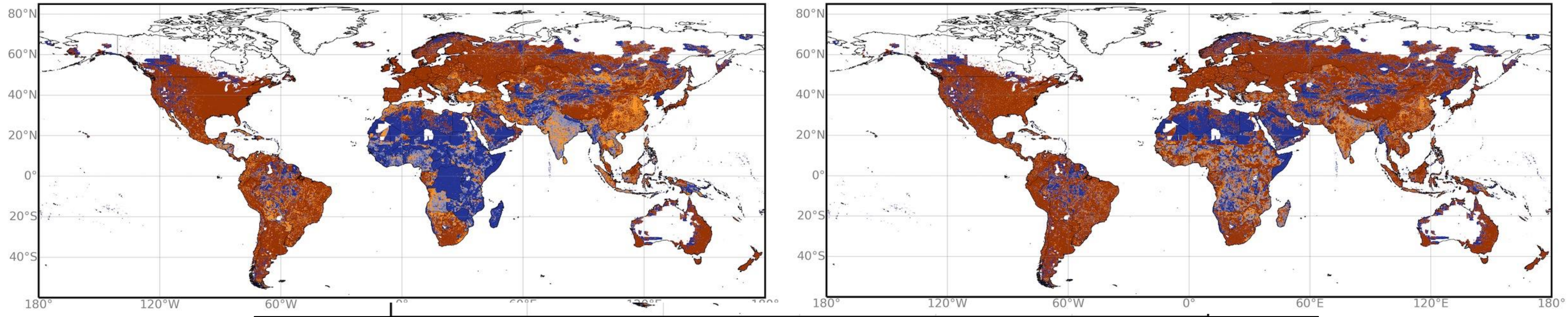
- Split global population into four socioeconomic groups (low-, lower-middle-, upper-middle-, and high-income).
- Used per-capita Gross Domestic Product (GDP) data for years 2020 to 2100.

2020 Global distribution of income regions **2100**



Low-income **Lower-middle-income** **Upper-middle-income** **High-income**

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Future global surface $PM_{2.5}$ concentrations

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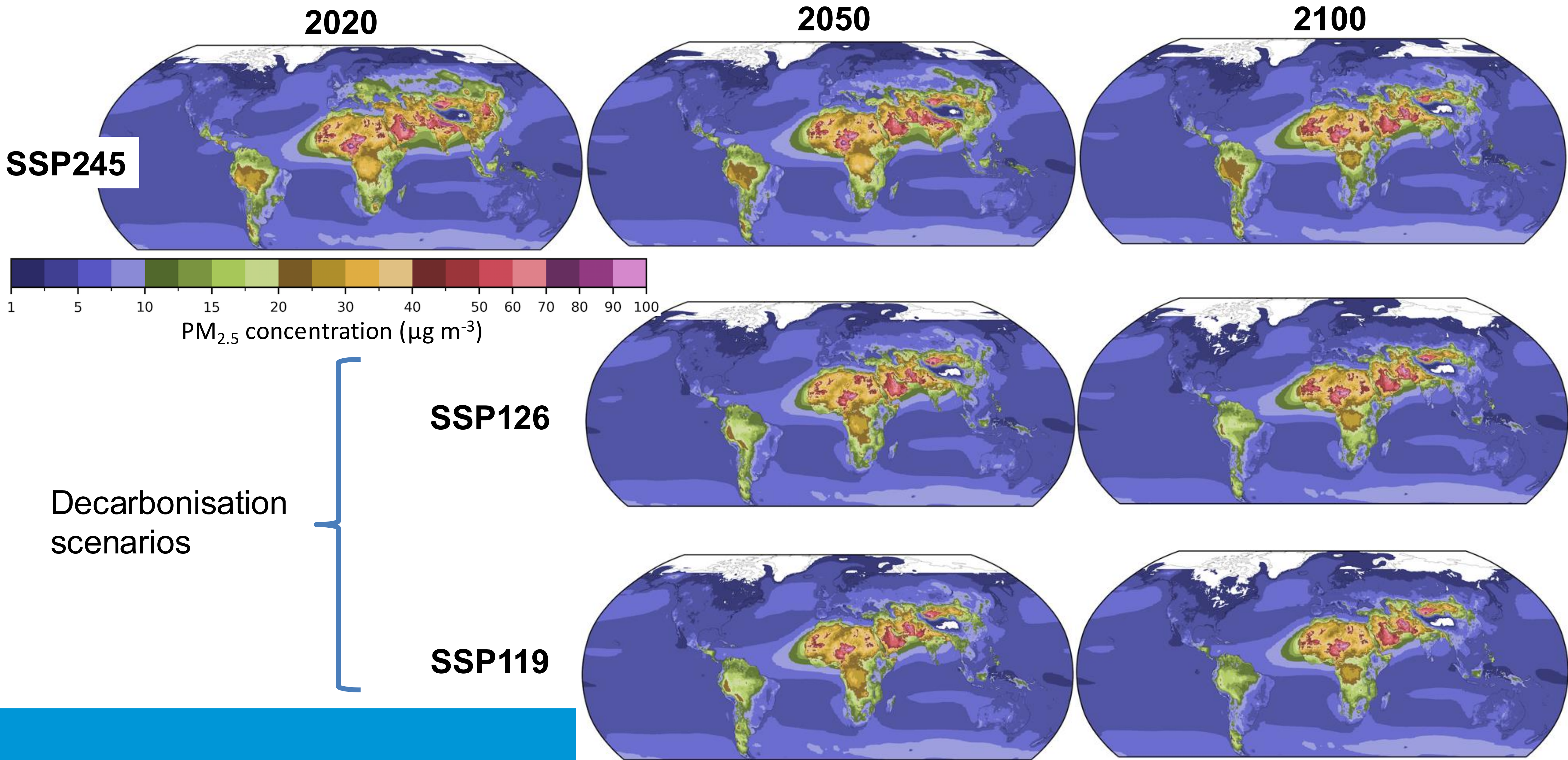
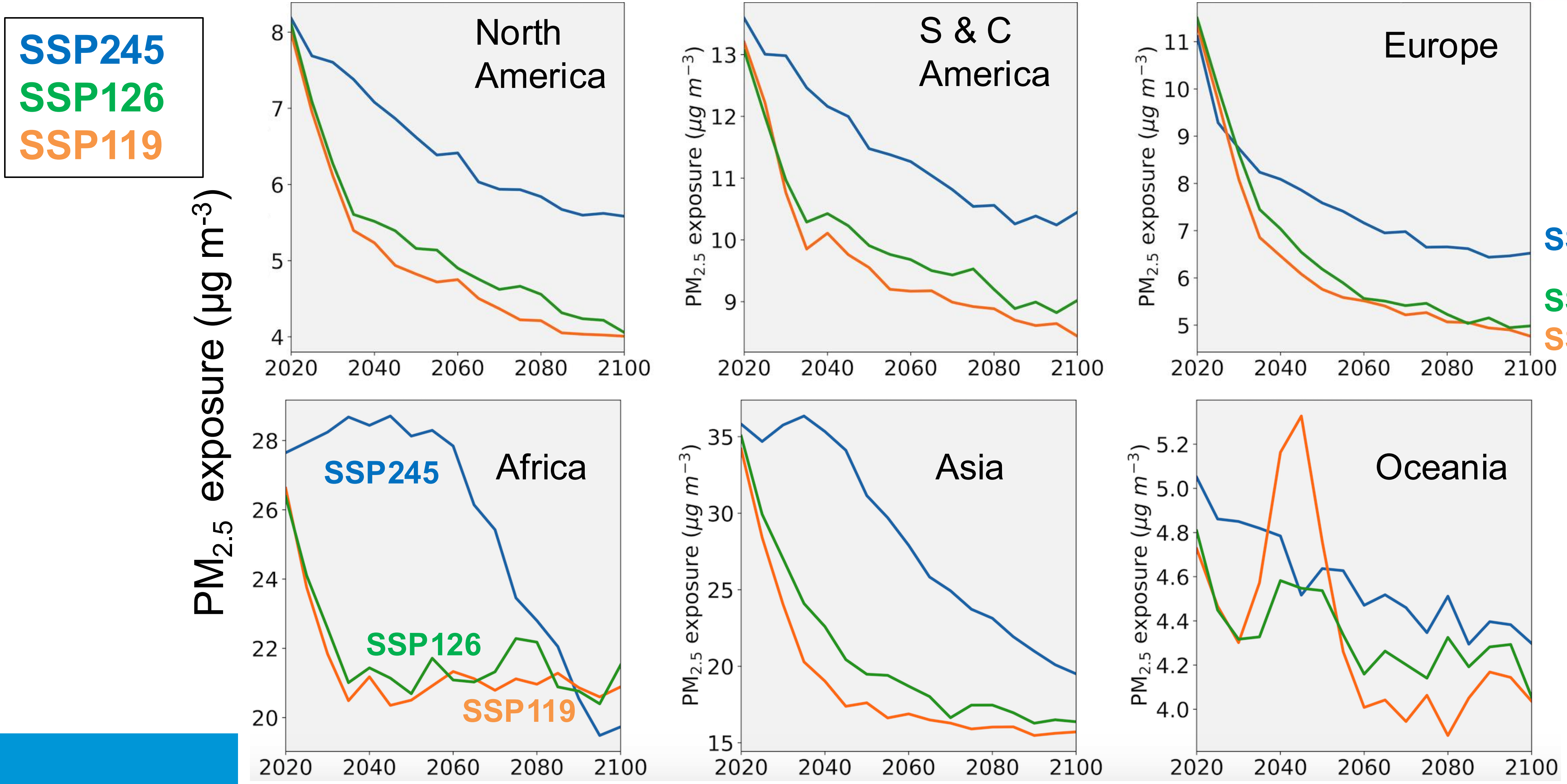


Future $PM_{2.5}$ exposure by world region

By the end of the 21st century, the decarbonisation scenarios predict substantial reductions in population exposure to $PM_{2.5}$ pollution globally.



Note: y-axes are different!

Future $PM_{2.5}$ exposure by income group

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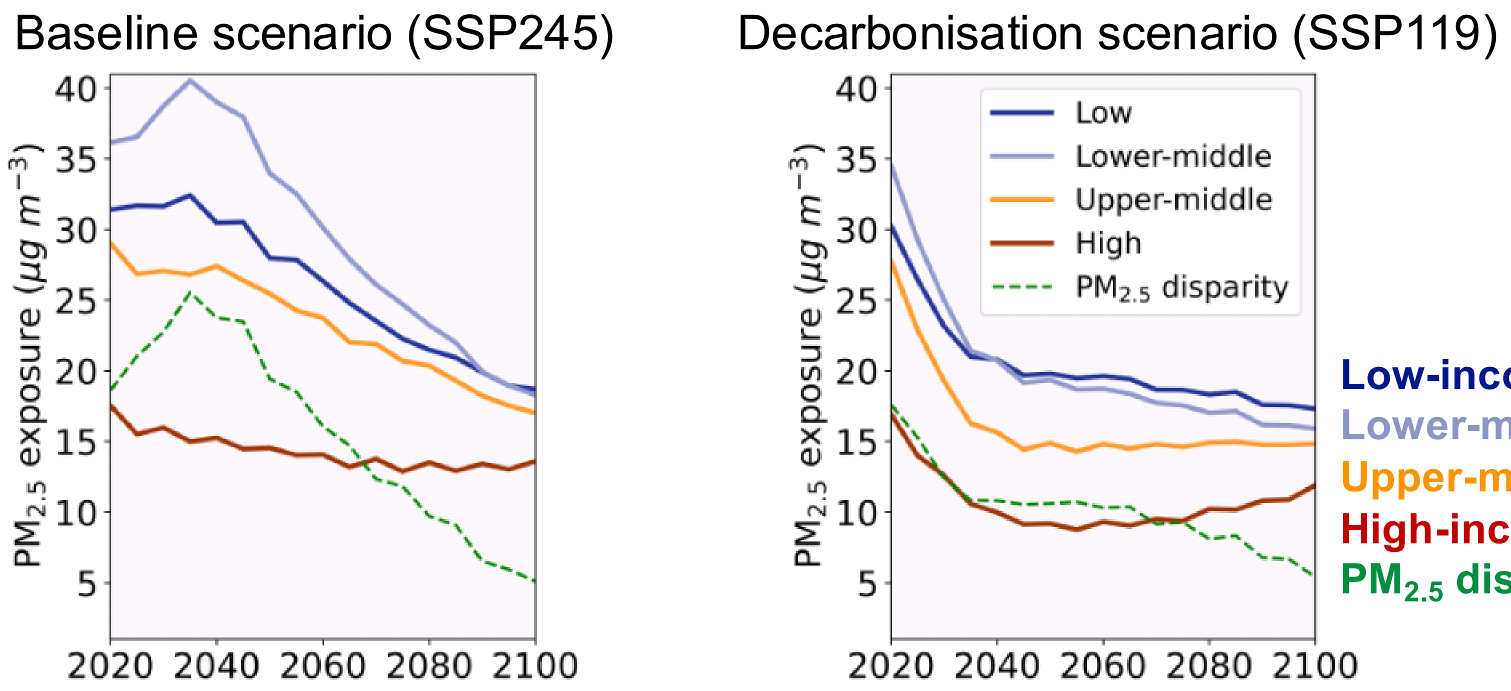
$PM_{2.5}$ disparity = difference in $PM_{2.5}$ exposure between greatest exposed group and lowest exposed group



Low-income
Lower-middle-income
Upper-middle-income
High-income
$PM_{2.5}$ disparity

- $PM_{2.5}$ exposure is predicted to reduce across all income regions by 2100.
- Disparity in $PM_{2.5}$ exposure is predicted to reduce by 2100, but persists at ~5 μg m^{-3}.
- High-income region is exposed to lowest $PM_{2.5}$.
- Low- and lower-middle-income regions are exposed to highest $PM_{2.5}$.

Carly Reddington, c.l.s.reddington@leeds.ac.uk

Future $PM_{2.5}$ exposure and the WHO Air Quality Guideline

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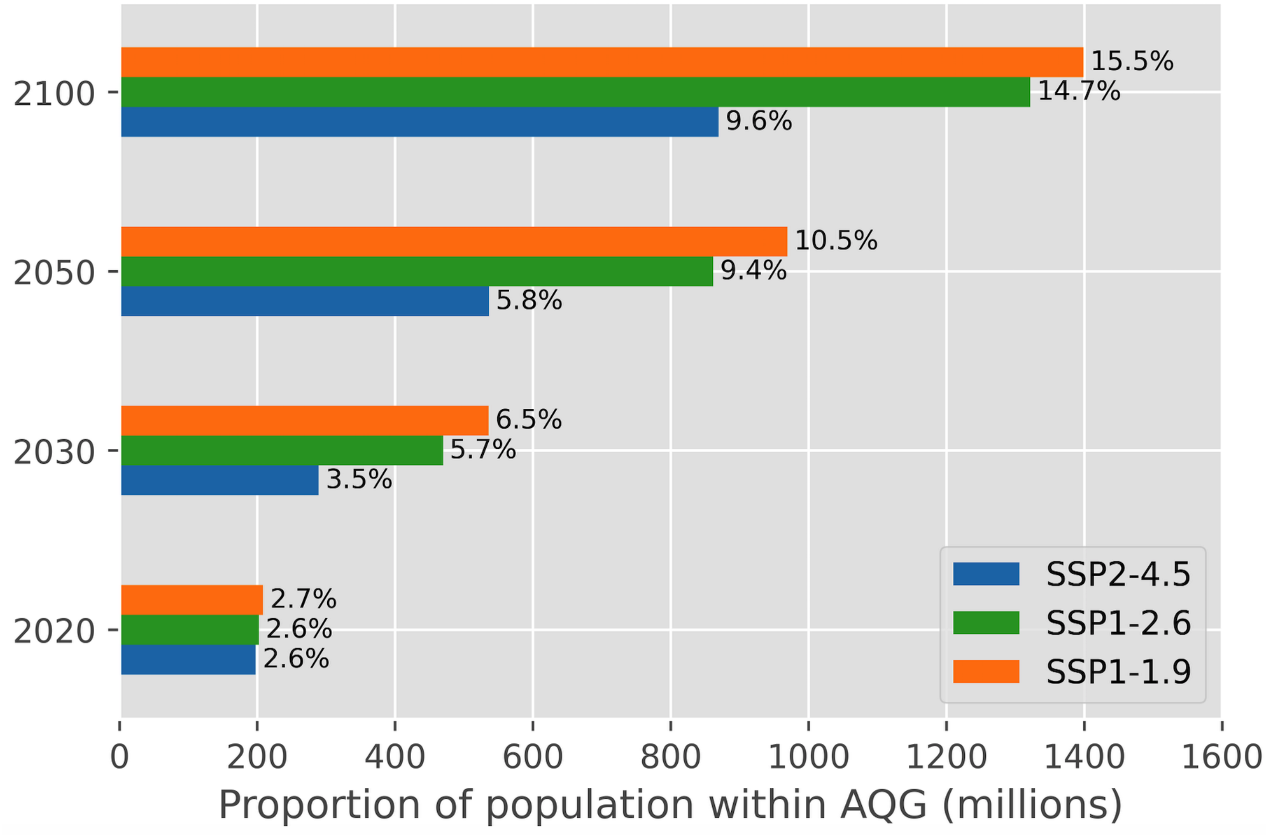
Proportions of the world's population that are projected to come into compliance with the WHO Air Quality Guideline for $PM_{2.5}$ (5 μg m^{-3}) under different scenarios.



Following a strong decarbonisation future pathway could bring over half a billion more people into compliance with the WHO AQG by 2100.

Carly Reddington, c.l.s.reddington@leeds.ac.uk

Future $PM_{2.5}$ exposure and the WHO Air Quality Guideline

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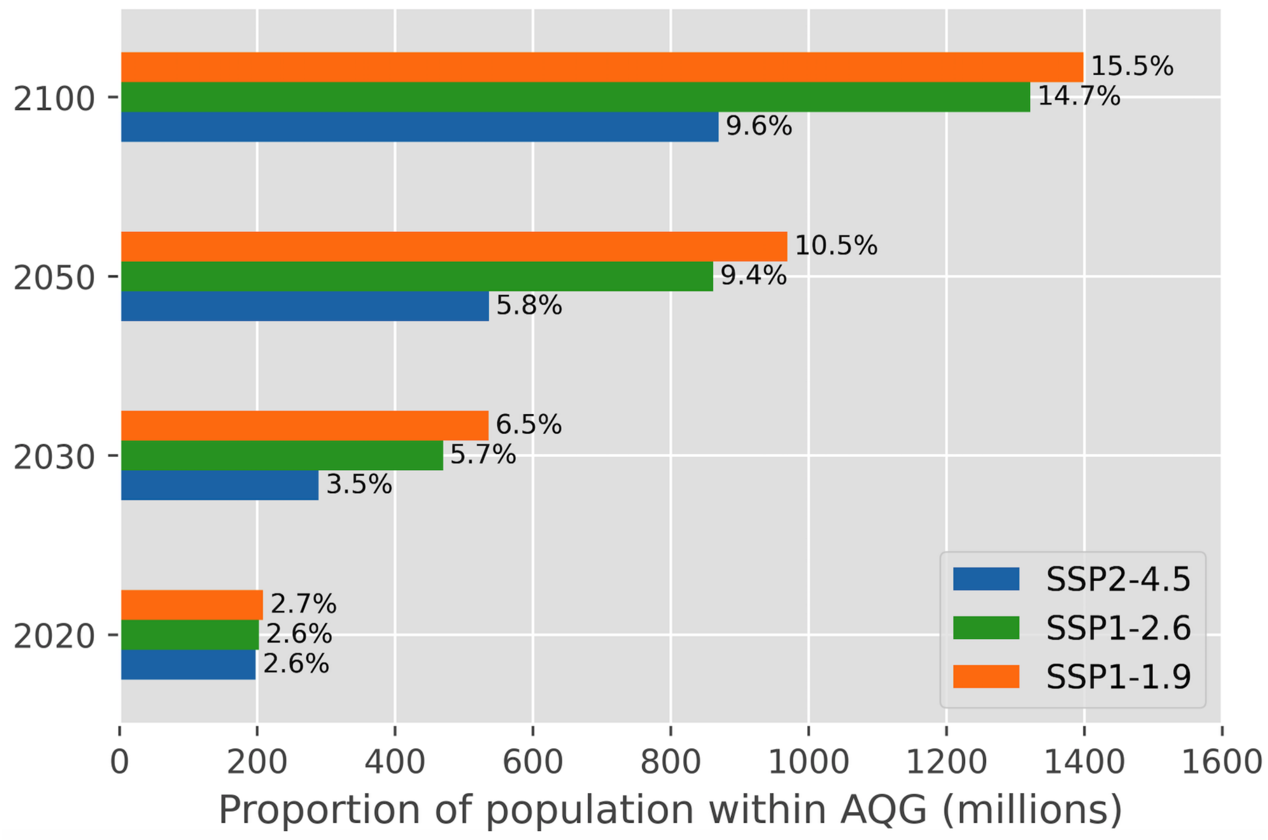
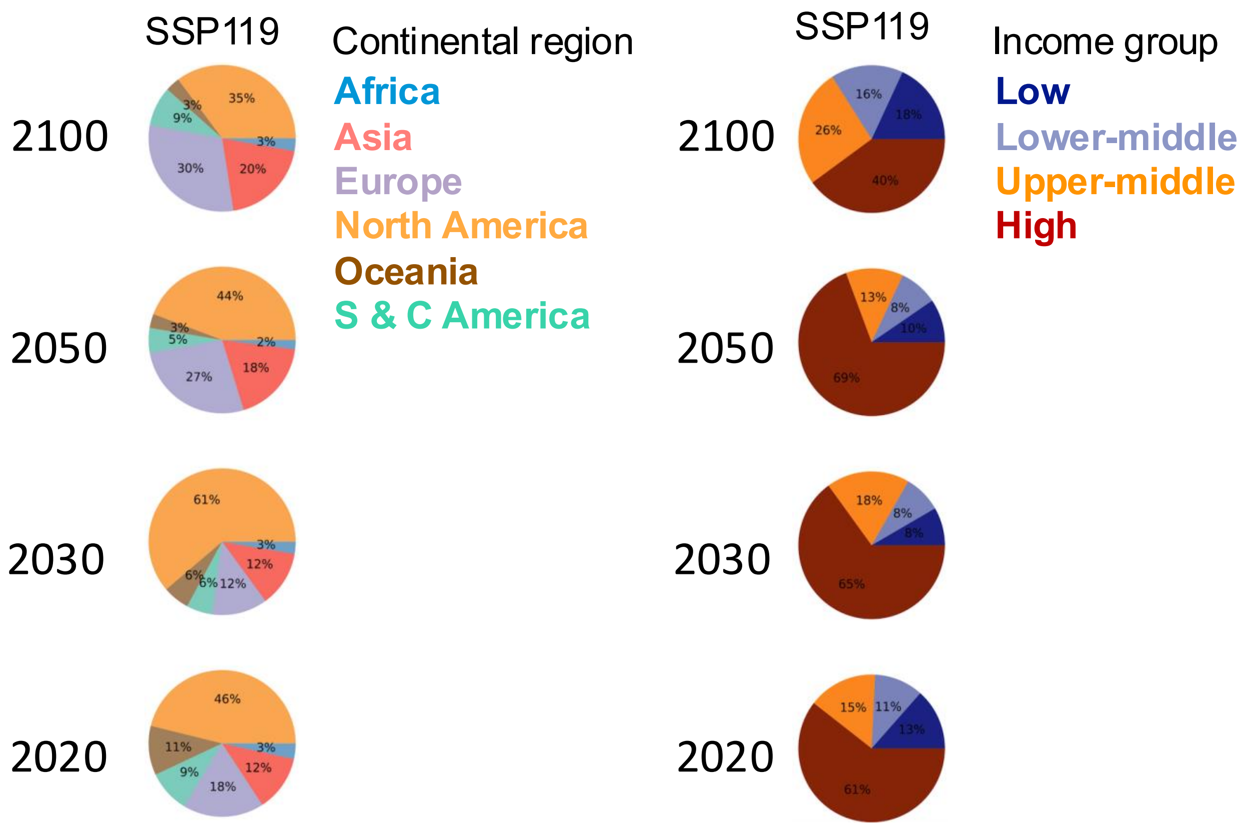
Proportions of the world's population that are projected to come into compliance with the WHO Air Quality Guideline for $PM_{2.5}$ (5 µg m^{-3}) under different scenarios.





Carly Reddington, c.l.s.reddington@leeds.ac.uk

Avoiding future $PM_{2.5}$-attributable mortality

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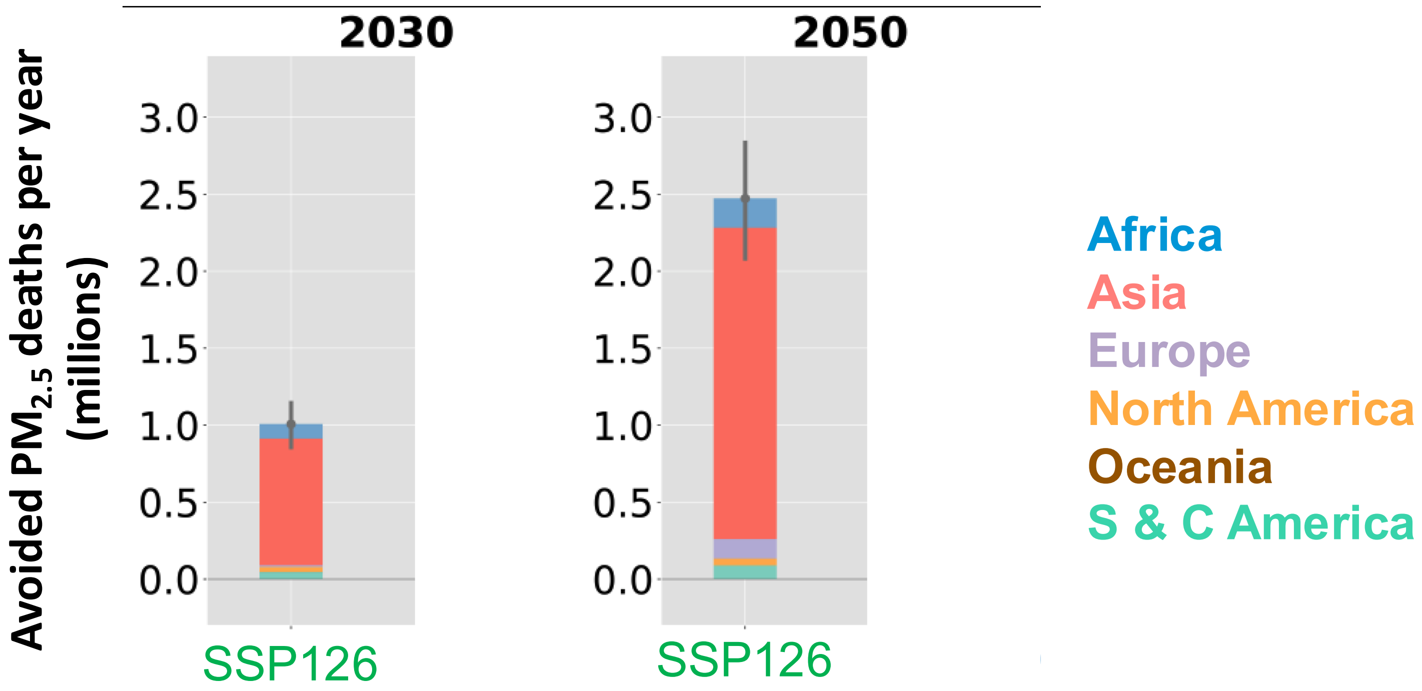
$PM_{2.5}$-related premature deaths that could be avoided by following a decarbonisation scenario relative to the middle-of-the-road scenario.



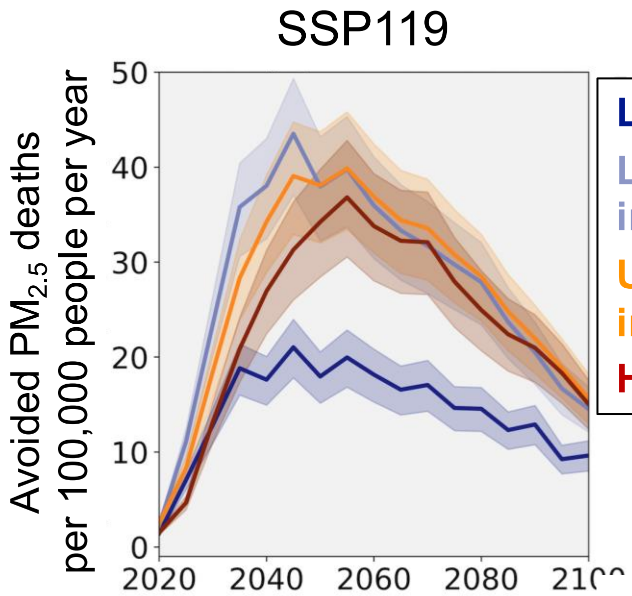
- SSP126: Moderate climate mitigation could avoid **~2.48M** deaths in 2050.
- SSP119: Strong climate mitigation could avoid **~2.95M** deaths in 2050.

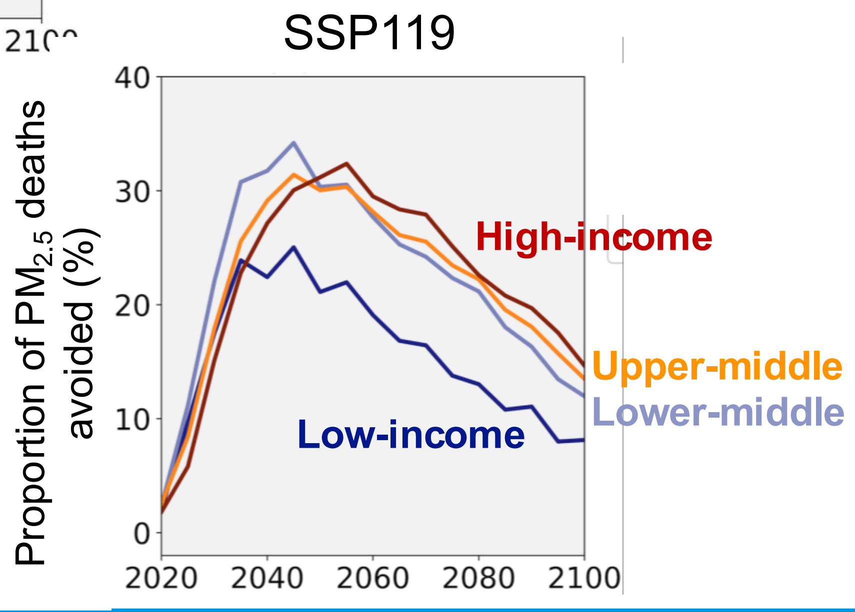
Carly Reddington, c.l.s.reddington@leeds.ac.uk

Avoiding future $PM_{2.5}$-attributable mortality

- The greatest health benefits of decarbonisation are predicted to occur in the middle- and high-income regions.

- The smallest health benefits are predicted to occur low-income region.





Carly Reddington, c.l.s.reddington@leeds.ac.uk

Summary of results

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- ✓ Decarbonisation has the potential to generate substantial health benefits by averting millions of premature deaths associated with air pollution.
- ✓ Global socioeconomic disparity in $PM_{2.5}$ exposure is predicted to reduce by the end of the century.

- The number of averted $PM_{2.5}$-attributable deaths is greatest in high- and middle-income populations, with the fewest in low-income populations.

- A large fraction of the world's population (~85%) could remain exposed to concentrations above the WHO AQ Guideline for $PM_{2.5}$ in 2100.
- Low-income populations are predicted to benefit the least and continue to be exposed to $PM_{2.5}$ concentrations that are over three times that of the AQG.

Carly Reddington, c.l.s.reddington@leeds.ac.uk

Overall summary

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- Important to consider changes to the air pollution health burden under future climate policies to try to maximise co-benefits to climate and air quality.

⇒ Health and other co-benefit metrics should be incorporated into net zero policies to improve non-climate outcomes and minimise trade-offs.

- **Middle and low-income countries continue to be exposed to high levels of air pollution**, even in the strongest mitigation scenario with exposure inequalities projected to persist.

⇒ Climate mitigation & AQ control measures should be better targeted towards lower-income regions with high $PM_{2.5}$ exposures.

- More research is required about how Earth system feedbacks impact the air pollution health burden in a future warming world.

Carly Reddington, c.l.s.reddington@leeds.ac.uk

Any questions?

Further reading:

Reddington et al. (2023). Earth's Future (https://doi.org/10.1029/2023EF003697)
Turnock et al. (2023). GeoHealth (https://doi.org/10.1029/2023GH000812)
Turnock et al. (2022). Earth's Future (https://doi.org/10.1029/2022EF002687)

Carly Reddington, c.l.s.reddington@leeds.ac.uk