AIR POLLUTION: OBSCURING THE FULL EXTENT OF GLOBAL WARMING

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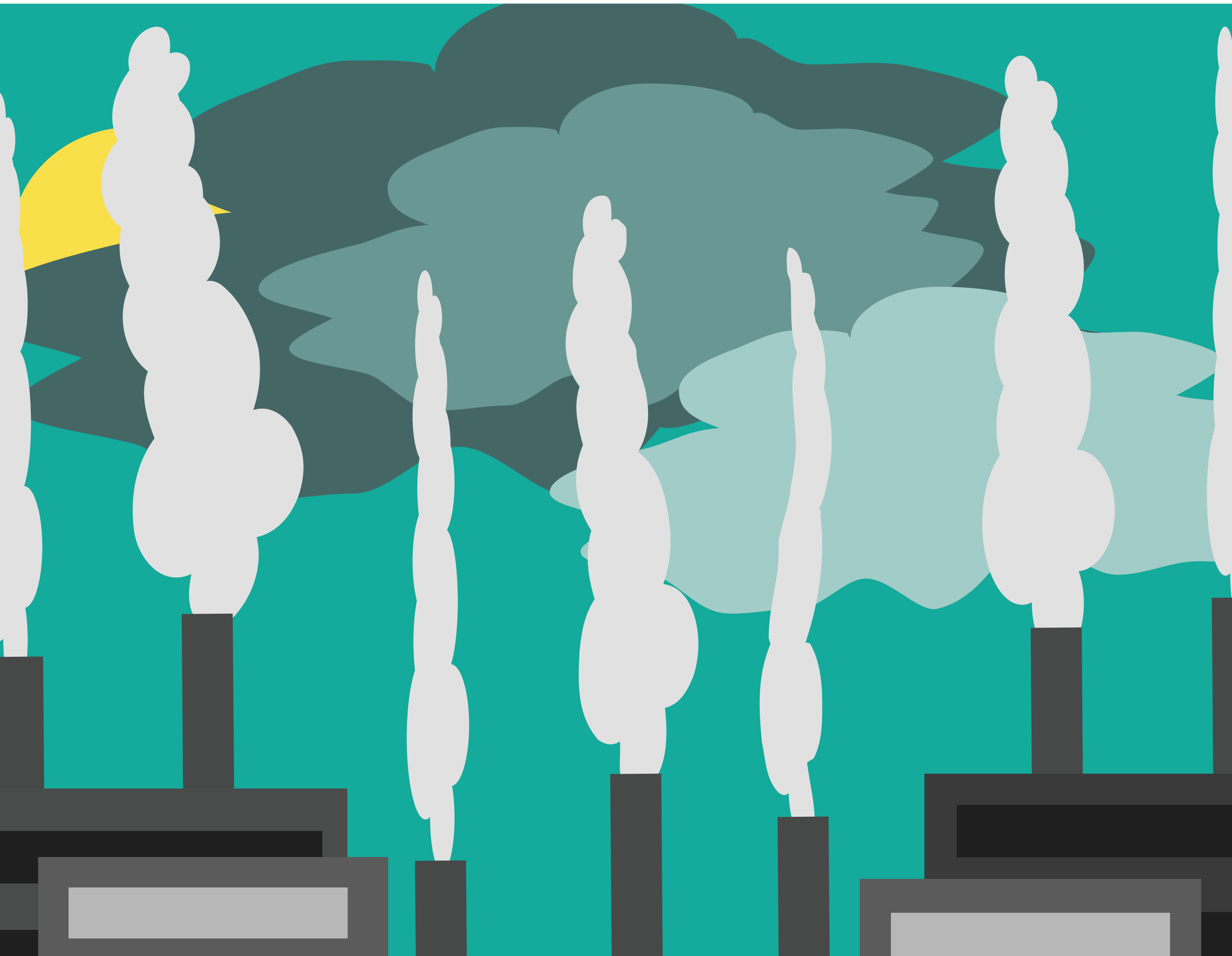

AEROSOLS AND AIR POLLUTION

Atmospheric aerosols (suspended dust, smoke, sulphates, organics, sea-spray or similar particles of about a millionth of a metre in size) are major contributors to air pollution. In the air quality research community, aerosol particles are termed *Particulate Matter (PM)*. Aerosol air pollution is typically measured as the total mass of particles smaller than a particular size (e.g. 10 µm for PM_{10} and 2.5 µm for $PM_{2.5}$). Air quality is regulated in terms of exposure to a particular *PM* standard. Air pollution has been a serious problem since the eighteenth century when the invention of the steam engine increased the amount of coal burning. Prior to that, air pollution was a problem due to wood and coal burning, although not as severe. In 1905, the term 'smog' was coined and it described the combination of smoke and fog that was visible in many industrialised cities. London experienced the most frequent and severe smog events, which resulted in many 'excess' deaths. The worst of these occurred in December 1952 when there were 4,000 excess deaths. During this period, smoke mass concentrations reached 4,460 µg m^{-3}. Dublin, as recently as 1982, also experienced severe smog events with smoke concentrations exceeding 700 µg m^{-3}, and excess deaths of approximately 20 per day (see Figure 1). This is to be compared with a current EU yearly exposure limit of 25 µg m^{-3} for $PM_{2.5}$ and 50 µg m^{-3} sustained over a 24-hour period, 35 times in one year for PM_{10}.

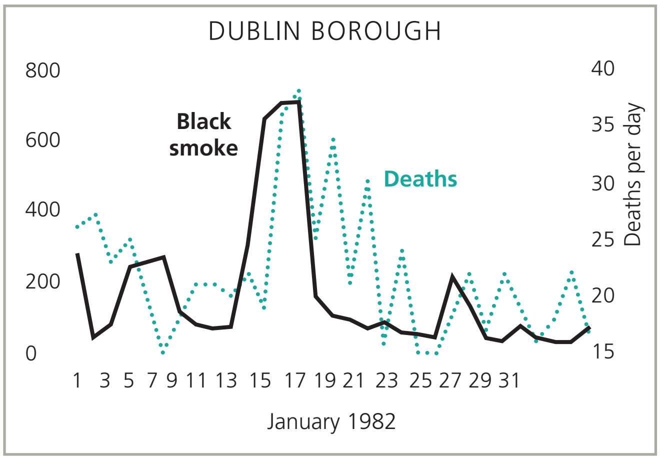

Fig. 1: Black smoke and excess deaths during the 1982 Dublin smog event. Black smoke concentration is µg m-3. Courtesy of Professor Luke Clancy.

These pollution events typically occur during winter anti-cyclonic conditions, which are generally accompanied by lower (colder) temperatures, leading to increased coal-burning. Concomitant with colder conditions are stable atmospheric boundary layers which suppress the dispersion of pollution. Further exacerbating the situation are very stable surface layers of 100–200m depth, which trap the pollution and confine it to a thick layer close to the ground.

In addition to the London-type smog, there is chemically-produced smog known as photochemical smog. Photochemical smog is produced through gas phase reactions in strong sunlight, typically involving hydrocarbons, nitrous oxide and ozone, and is a frequent phenomenon encountered in megacities such as Los Angeles, Mexico City, Tokyo, Beijing, Johannesburg and Athens. The main health impacts of *PM* relate to respiratory and cardiovascular effects. Some of the smoke products are considered carcinogenic, potentially resulting in increased morbidity and premature mortality. The EU's Clean Air For Europe (CAFE) programme estimates that 348,000 premature deaths occur per year in Europe due to exposure to $PM_{2.5}$. Figure 2 illustrates the estimated loss in life expectancy attributable to exposure to $PM_{2.5,}$ from anthropogenic emissions in Europe (*EEA, 2007*). The data are calculated from emissions for the year 2000 and for targeted emission reductions by the year 2020.

While air pollution, particularly aerosol air pollution, has been steadily decreasing in the developed world, it has become an increasing problem in developing countries, not only on urban megacity scales but also on regional and almost hemispheric scales. Inter-continental and hemispheric transport of pollution is now regarded as a serious concern, impacting on local- and regional-scale air quality.

ATMOSPHERIC AEROSOLS AND CLIMATE

Aerosols are not all bad. Although aerosols reduce visibility through the formation of haze layers, these haze layers produce beautifully-coloured pink-to-red sunset skies. In addition to colourful sunsets, these haze layers reduce the amount of solar energy transmitted

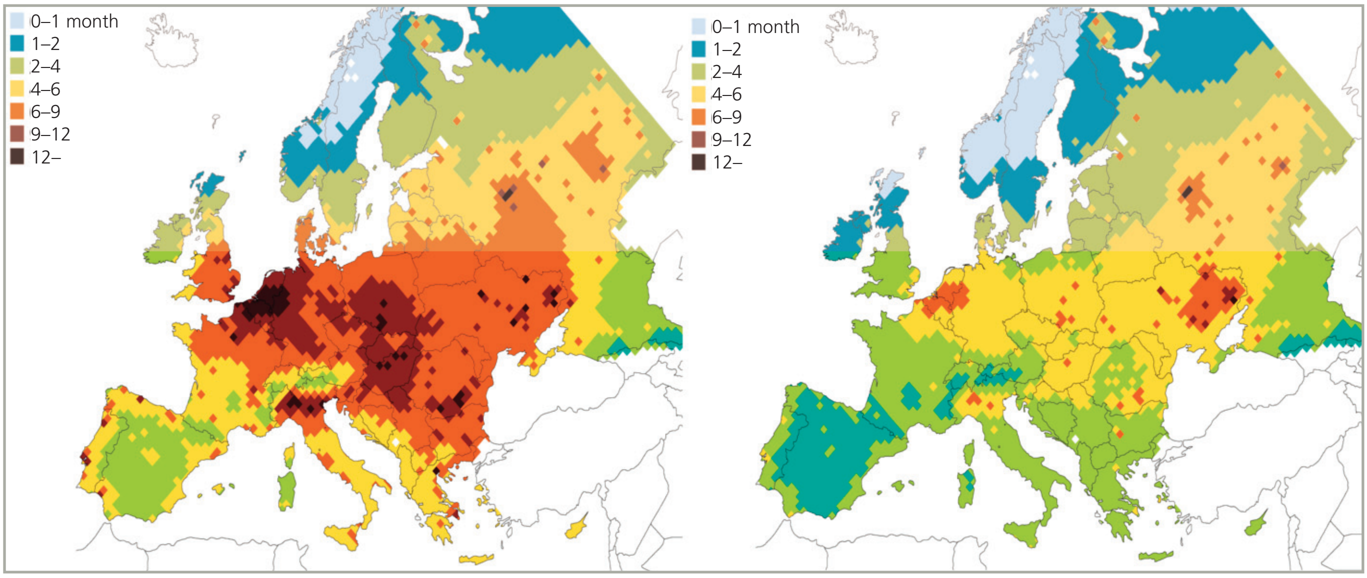

Fig. 2: Estimated loss in life expectancy attributable to exposure to fine particulare matter (PM$_{2.5}$) from anthropogenic emissions for the year 2000 (left) and projected reduced emissions for the year 2020 (right). Graphics are regenerated based on data from EEA Report No. 2/2007. Courtesy of Dr Zbigniew Klimont and Dr Markus Amann.

through the atmosphere as the haze reflects some of the sun's incoming rays back out to space. In addition to forming haze layers, aerosols are essential for the formation of clouds as they provide condensation nuclei for cloud water drops and ice particles to form on. Without these nuclei, there would be no clouds, no precipitation and no hydrological cycle. Further, these clouds provide the most reflecting layers in the atmosphere, also reducing the amount of solar energy transmitted through the atmosphere. These reflecting layers have a net effect of cooling down the planet—without these haze and cloud layers, the global temperature would be of the order of ~10°C higher. Changes in the abundance of these aerosols lead to changes in the reflection, or cooling efficiency, of these haze and cloud layers. This effect of increased aerosol abundance on increased cloud reflectance is readily visualised over marine stratiform clouds overlying shipping lanes. Figure 3 (centre) displays so-called 'ship tracks'—tracks of higher reflectance in layered clouds produced by the aerosol pollution emitted from the ships stacks. Increased aerosol availability can also influence precipitation and cloud lifetime, depending on the cloud type. For shallow stratiform clouds, an increase in aerosol availability reduces precipitation onset, leading to more persistent clouds, while for deep convective clouds, an increase in aerosol availability can lead to more intense precipitation (*Rosenfeld et al., 2008*). At very high aerosol concentrations, the absorbing 'black carbon' component of aerosol pollution can cause sufficient heating of the aerosol layer to impact on dynamics and suppress convection and even cloud formation (*Rosenfeld et al., 2008*). Given these potential effects, have these reflecting aerosol-cloud layers been partly off-setting greenhouse gas-induced global warming?

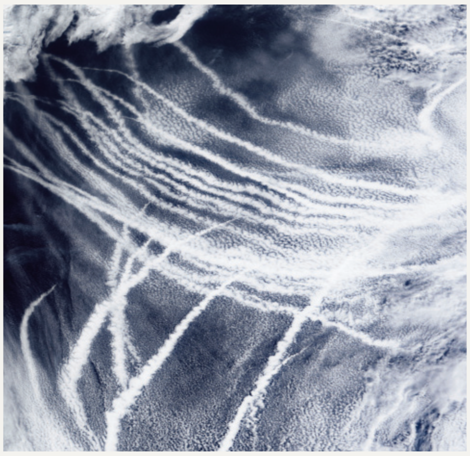

Fig. 3: Ship tracks seen on marine stratiform clouds.

Radiative Forcing: In simple terms, radiative forcing is the rate of energy change per unit area of the globe as measured at the top of the atmosphere and often it refers to the change since pre-industrial conditions (approximately year 1750) to the current day.

More accurately, the radiative forcing of the surface-troposphere system due to the perturbation in, or the introduction of, an agent (say, a change in greenhouse gas concentrations) is the change in net (downward minus upward) irradiance (solar plus longwave, in Wm^{-2}) at the tropopause, after allowing for stratospheric temperatures to re-adjust to radiative equilibrium, but with surface and tropospheric temperatures and state held fixed at the unperturbed values.

The Inter-governmental Panel on Climate Change (IPCC) Assessment Report 4 (AR4) concluded that the aerosol contribution to **radiative forcing** amounted to a cooling effect that partly off-set the warming induced by the accumulation of greenhouse gases (GHGs) in the atmosphere. This suggests that aerosols have been obscuring the true rate of global warming, or, specifically, the climate-temperature sensitivity to CO_2-induced global warming. One would intuitively expect a lower level of brightness, or dimming, if more solar radiation is reflected back out to space. Over the past 40 years, both dimming and brightening trends have been observed, the explanation of which converges towards an aerosol influence on climate.

Dimming is a term associated with a decadal decrease in surface solar radiation, while brightening refers to an increase in surface solar radiation. Studies (*Lieipert, 2002, Wild et al., 2004; Wild, 2009*) have shown a widespread decrease in surface solar radiation at a variety of locations worldwide between 1960 and 1990. Increasing aerosol concentrations associated with increased air pollution over the period are considered responsible for the dimming (*Stanhill and Cohen, 2001*). Changes in cloud reflectance and cloud amount contribute to the dimming (*Liepert, 2002*); however, in a particular study over Europe (*Norris and Wild, 2007*), it was concluded that cloud amount could not explain the dimming and that the aerosol direct effects (reflectance by haze layers) and indirect effects (modification of cloud reflectance) were the predominant causes of the trend.

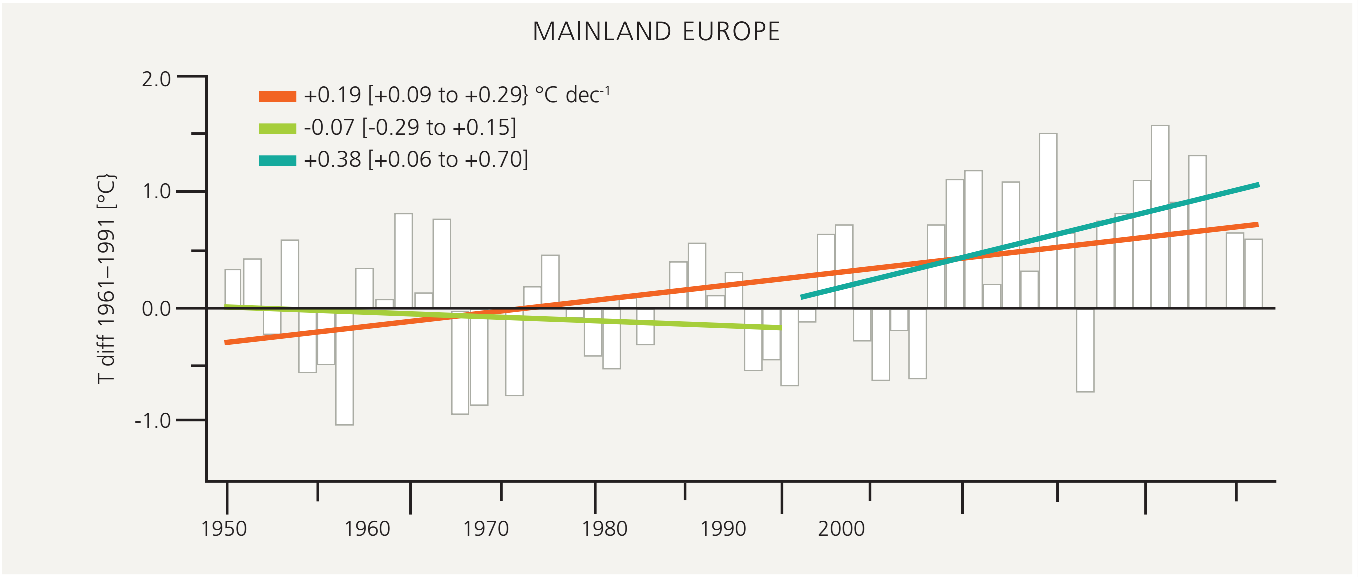

Fig. 4: Temperature rise over mainland Europe since 1950. Annual temperature differences for the period 1950 to 2005 with respect to the 1961–90 climatological mean for mainland Europe (45°–55°N; 5°–15°E). Linear regression lines and decadal trends with 95% confidence interval show the temperature decline from 1950 to 1980 (green), and the temperature rise to be twice as large for the period 1981 to 2005 (blue) than for the whole period 1950 to 2005 (red). Copyright of American Geophysical Union (2009), reprinted from Philipona *et al.*, (2009), Geophys. Res. Lett., 36, L02806, doi:10.1029/2008GL036350.

The period from 1990 to the present shows a reversal of the trend into a brightening trend (*Wild et al., 2005*). The dimming effect appeared to have been obscuring, or suppressing, greenhouse warming with reduced, or even negative trends, for global temperatures over the period as greenhouse gases continued to accumulate. In Europe, as the trend reversed from dimming to brightening, rapid temperature rise became evident since the mid-1980s when, thereafter, the decadal rise in temperature has been +0.38°C per decade (Figure 4), significantly higher than in any other period since the pre-industrial era (*Philipona et al., 2009*). The brightening has been associated with reduced aerosol pollution since the 1980s, as developed countries implemented policies to clean up air pollution.

FUTURE DIRECTIONS: INTERACTIONS BETWEEN AEROSOL AIR POLLUTION AND CLIMATE

Atmospheric aerosols have played an important role in partly offsetting global warming due to greenhouse gases to date. The IPCC AR4 has produced the most informed estimates of radiative forcing between 1750 and 2005. From this assessment, the combined direct and indirect aerosol effects amount to -1.2 W m^{-2}, which can be effectively regarded as an equivalent reduction in the positive forcing by greenhouse gases. The IPCC estimates the net forcing due to anthropogenic activities to be +1.5 W m^{-2}. This positive forcing has led to a global temperature increase of the order of 0.8°C. The European Union, leading the way in climate policy development, has set a long-term (i.e. by the year 2050) target of an upper limit of 2°C to the increase in global temperature.

Until recent times, climate policy has been handled separately from air pollution problems, where, in the latter case, adverse health effects from *PM* and ecosystem damage have been the biggest drivers of policies to improve air quality. The gradual cleaning of air to protect public health and the environment, brought about by policies to abate air pollution in recent decades, has revealed the greater extent of global warming and the temperature rise caused by greenhouse gas emissions.[1] The trend refers to recent multi-decadal trends, noting that the rate of increase over the last 3–5 years has reduced, likely due to natural variability and the predominance of La Niña or drought conditions over the past few years. La Niña is a coupled ocean-atmosphere phenomenon that can lead to cooling effects in certain regions.

The current rate of temperature increase is estimated to be 0.3°–0.4°C per decade. As a result, the predicted temperature increase by the year 2030 is 1.9°C—almost reaching the long-term target limit (*Raes and Seinfeld, 2009*). If there were only long-lived greenhouse gases (LLGHG, e.g. CO_2), the past temperature increase would have been approximately double the actual increase since the pre-industrial era. Without emission reductions, looking into the future, temperature will increase by about 0.2°C per decade. However, taking account of the presence of aerosols, an approximate 50% obscuring of the temperature increase is evident up until the 1990s, after which a further and more rapid rise in temperature, resulting from aerosol emission controls is evident and approaches the temperature increase from LLGHG alone.

Only with a reduction in aerosol emissions and LLGHG emissions can the dual target of clean air and minimal temperature rise be achieved. Such combined policy development, while in the near term accelerating temperature rise, in the long term can be expected to result in a sustainable temperature rise. Sophisticated policy development is underpinned by the construction of sophisticated climate and air pollution assessment models. Current climate models do not yet contain treatments of aerosol emissions, formation, transformation or radiative effects to a high enough level of sophistication. This limitation results from the aerosol life-cycle being one of the most complex systems to model and the challenges of modelling the formation of aerosols to global-scale radiative impacts will remain for some time.

Generally, air pollution and global warming abatement policies are synergistic, as emissions of air pollutants and carbon dioxide are predominantly derived from the same source, *viz*. the combustion of fossil fuels. Policies aimed at reducing reliance on fossil fuels will deliver dual benefits by reducing air pollution and greenhouse gas emissions. However, there can also be conflicts between the policy areas. For example, climate policies promote the use of biomass for heating (both residential and industrial) as it is considered carbon-neutral, but increased biomass use can lead to a further increase in emissions of air pollutants, including particulate matter, NO_x and a range of more toxic emissions. It is important that these conflicts are borne in mind when formulating emission abatement policies so that net benefits are delivered for society by ensuring the appropriate balance between the protection of human health, the environment and our global climate.

EMISSION TRENDS, POLLUTION TRENDS AND FUTURE PROJECTIONS—AN IRISH PERSPECTIVE

Partly as a result of the CAFE air pollution strategy, ozone precursor and aerosol primary emissions along with secondary precursor emissions have been reducing for at least 10 years. In Ireland, passenger cars are among the top sources of CO, NOx, PM2.5 and non-methane volatile organic compounds (NMVOCs). The Irish-scale emission trends are illustrated in Figure 5 (overleaf) for NOx, which influences ozone levels as well as nitric acid and nitrate aerosol; for SOx which influences the levels of sulphate aerosols, and for $PM_{2.5}$ which also includes primary emissions of soot (black) carbon (*O'Dowd et al., 2012*). The most rapid reduction trend is seen for SOx.

Analysis of data from the Mace Head Global Atmospheric Watch Supersite (WMO) for monitoring essential climate variables and regional scale air pollution reveals a reduction in aerosol pollution, with reduced emissions resulting in an increase in surface solar radiation. A similar trend is also observed at Met Éireann's regional WMO Valentia Observatory. (See Figure 6 overleaf).

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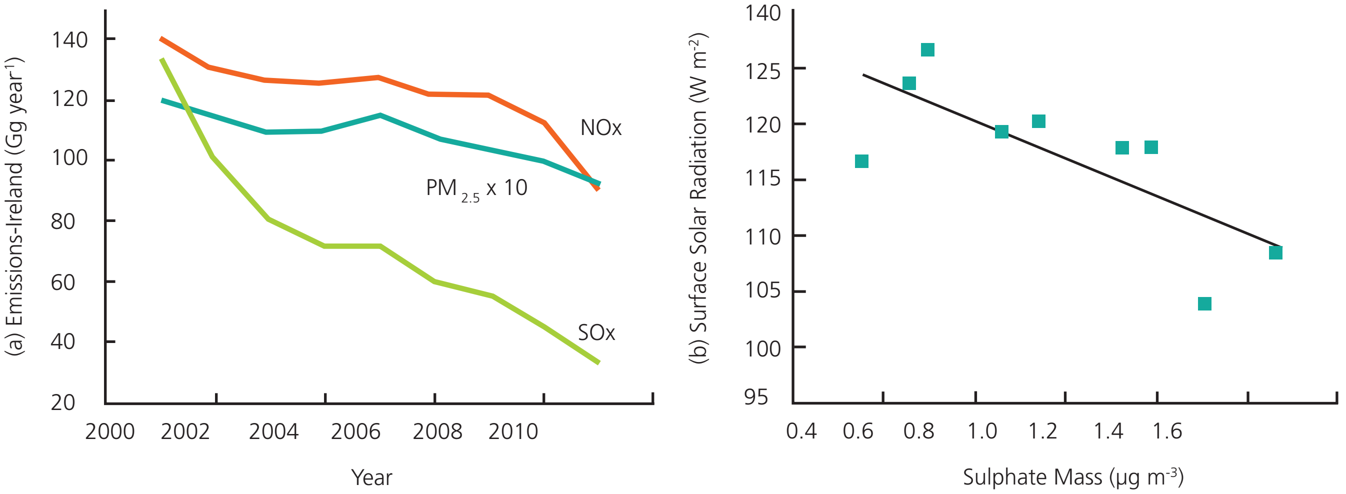
Fig. 5: (a) NOx, SOx and PM2.5 emissions from Ireland from 2001 to 9; (b) surface solar radiation versus sulphate mass at Mace Head, 2002–11. Sulphate decreased from 1.5 μg m-3 in 2001, to ~0.5 μg m-3 in 2009. Surface solar radiation increases in line with sulphate mass reductions.



The reducing emissions trend manifests itself in a striking anti-correlation between aerosol sulphate and surface solar radiation. Sulphate is selected for demonstration purposes as it is typically regarded as the major pollutant from fossil fuel combustion; however, it should be regarded as a surrogate rather than a driver of the trend as it is highly correlated with both ammonium and nitrate ions, both of which are predominantly anthropogenic in origin. It should also be recognised that in very polluted environments (i.e. environments where there is sufficient black carbon aerosol to influence convection), a reduction in aerosol abundance could increase the cloud amount, and consequently reduce surface solar radiation; though such extreme pollution is uncommon in Europe these days.

Representative Concentration Pathways: RCP6: Stabilisation without overshoot pathway leading to a radiative forcing of 6 W m^{-2} (~850 ppm CO_2 eq) at stabilisation after 2100; emissions peak at ~11 PgC per year^{-1} around 2050, reducing to ~4.5 PgC per year^{-1} by 2100. SO_2 emissions reduce almost linearly until 2100 to less than 25% of current emissions (110 Tg SO_2 year^{-1} in 2000 to 25 Tg SO_2 year^{-1} in 2100).

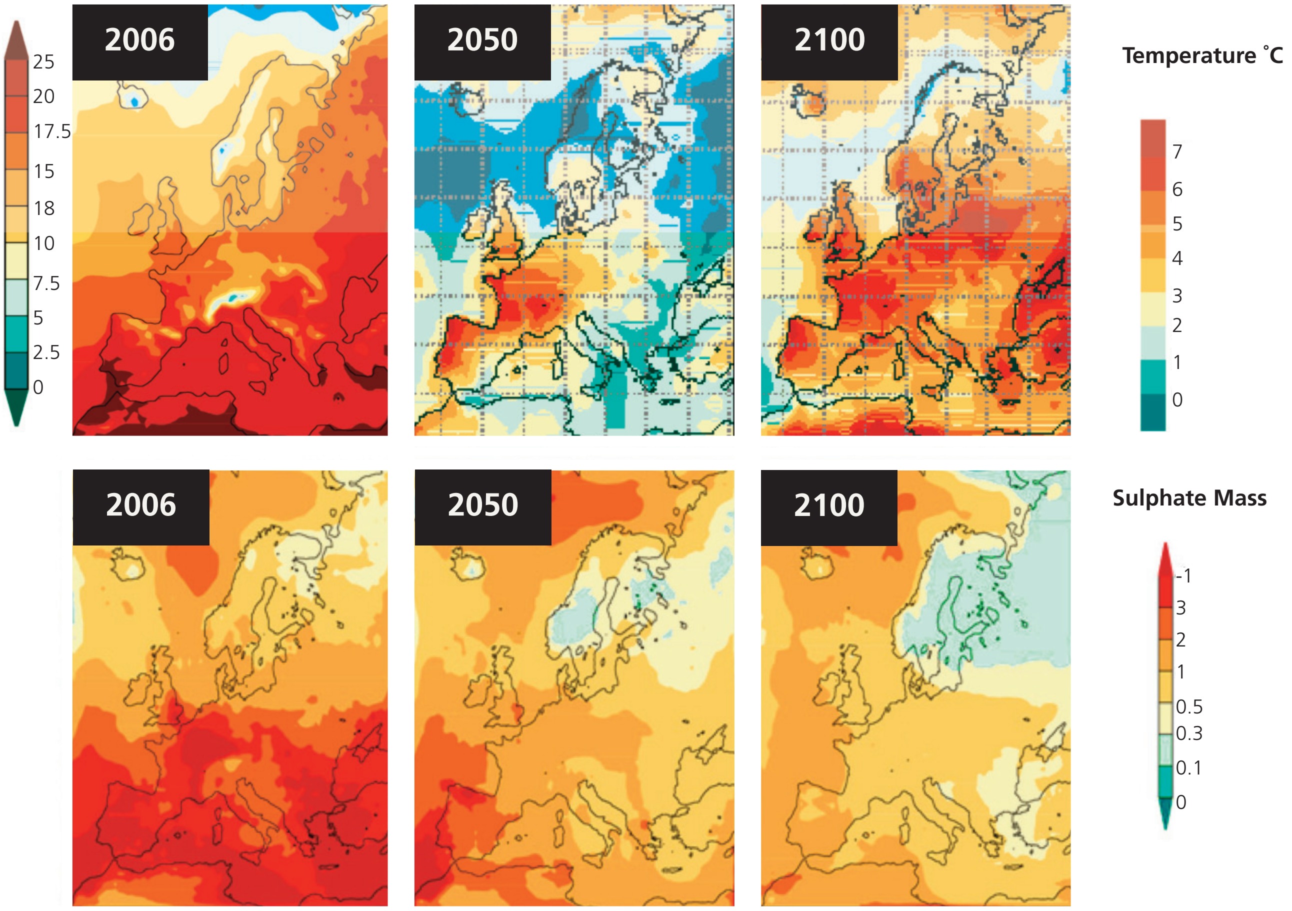


Fig. 6: Regional Climate Model projection of temperature changes and sulphate mass concentrations over Europe into the future using the RCP6.0 emissions scenario projection. Time-slice years are taken for 2006, 2050 and 2100. Colour bar on left-hand side represents temperature for 2006, while upper-right colour bar represents temperature change for 2050 and 2100 relative to 2006. Lower-right colour bar represents sulphate ($PM_{2.5}$) mass (μg m-3) for time-slice years 2006, 2050 and 2100.

Significant progress has been made since 1990 in reducing the emissions of many air pollutants including from industry, residential heating and the transport sectors. Carbon reductions in the transport sector have been achieved mainly by improved vehicle technology and cleaner fuels. Nevertheless, many cities and other urban areas are facing challenges in meeting concentration limits set in EU legislation for air quality pollutants, particularly in the case of road transport, and residential heating where there is a reliance on solid fuel. The Environmental Protection Agency (EPA) has reported higher levels of particulate matter in smaller towns than in larger cities in Ireland as a result of the use of bituminous 'smoky' coal for residential heating in smaller towns, where coal bans do not exist (see EPA Annual Report, 2012).

Passenger transport demand (pkm) increased by 33% in the EU-12 and by 9% in the EU-15 between 1999 and 2009 (EEA, 2011). There was a small decrease in (pkm) between 2008 and 2009, most likely due to the effects of the economic recession. However, the reduction in demand is significantly less than the fall in GDP during the same period, indicating that many passenger journeys are unavoidable and are made regardless of income level (EEA, 2011). The European Commission's 2011 White Paper on Transport has set the target of a 60% reduction in direct GHGs from transport by 2050, compared to a 1990 baseline (EC, 2011). Very significant changes in the proportions of the population using different transport modes, away from conventionally fuelled car transport, will be needed to achieve this target.

Looking into the most likely future pollution storylines, the IPCC AR5 Representative Concentration Pathway 6 (RCP6) is selected as the most likely development scenario for CO_2 and SO_2 emissions (*Goosse et al, 2012).* This scenario leads to a radiative forcing of 6 Wm^{-2} by 2100. Figure 6 illustrates the current sulphate mass loadings, along with temperature fields, over Europe for August 2006, and future trends based on the RCP6.0 emission and economic development pathway for the time-slice years 2050 and 2100 *(Coleman et al., 2012).* As the time-slice years progress, sulphate air pollution reduces further and regional scale temperatures increase. For Ireland, temperature rises of up to 3°C by 2050, and up to 6-7°C by 2100, are predicted. Similar regional scale temperature increases are seen across various locations in Europe. The projected increase in temperature results from the combined effect of increased CO_2 concentrations and reduced aerosol concentrations and is consistent with the IPCC AR4 best estimate, whereby globally-averaged surface temperature increases would be between 2.5°C and 4.7°C above pre-industrial levels by the year 2100. The full range of projected global temperature increases by 2100 was found to be 1.8 °C–7.1°C depending on the various scenarios and uncertainties in climate sensitivity considered. Regional-scale temperature increases of the magnitude close to the upper range of the global average projections are not to be unexpected. This synopsis is also consistent with *The Royal Society Climate Change: a summary of the science (2010)* report; however, it should also be acknowledged that concomitant with the reduction in negative radiation forcing associated with the reduction of the aerosol component of air pollution, there is also a reduction in the positive forcing associated with tropospheric ozone as its precursor gas (e.g. NO_x and NMVOC's) emissions are simultaneously reduced.

IN CONCLUSION

- Aerosol air pollution has been obscuring the full extent of GHG-induced global warming;
- Aerosol emissions are being reduced to improve air quality and public health;
- This will reduce aerosol abundance leading to less cooling but to improved human health outcomes;
- Less cooling from cleaner air leads to increased net warming from GHGs;
- **REDUCTIONS** in GHG emissions and air quality pollutants are essential and must be undertaken in concert, in order to mitigate global warming and improve public health and the environment.

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