Atmos. Chem. Phys. Discuss., 10, 15055–15073, 2010
www.atmos-chem-phys-discuss.net/10/15055/2010/
doi:10.5194/acpd-10-15055-2010

Atmospheric Chemistry and Physics Discussions

Aerosol exposure versus aerosol cooling of climate: what is the total health outcome?

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Received: 9 June 2010 – Accepted: 10 June 2010 – Published: 21 June 2010

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Particles, climate change, and health have thought-provoking interactions. Emission of aerosol particles is one of the largest environmental problems concerning human health. On the other hand, aerosol particles can have a cooling effect on climate and a reduction of those emissions may result in an increased temperature, which in turn may have negative health effects. The objective of this work was to investigate the "total health" effects of aerosol emissions, which include both exposure to particles and consequences of climate change initiated by particles. As a case study the "total health" effect from ship emissions were estimated by adding the number of deaths from aerosol emission exposure to the calculated number of lives saved from the cooling effect of the particles. The analysis indicated an annual mortality from ship emissions of 26 000 (minimum uncertainty range −5000 to 52 000), with 60 000 deaths from direct aerosol exposure and 34 000 lives saved by the cooling effect of particles. This is the first attempt to calculate the combined effect of particle emissions on health. We conclude that measures to reduce particulate air pollution will in some cases (black carbon) have win-win effects on health and climate, but for most particulates cause a shift from exposure-related health effects towards an increasing risk of health consequences from climate change. Thus, measures to reduce aerosol emissions have to be coupled with climate change mitigation actions to achieve a full health benefit on a global level.

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Abbreviations

λ: climate sensitivity parameter
C: number of deaths caused by one degree warming
CCN: cloud condensation nuclei
DALYs: disability adjusted life years
ΔF: change in radiative forcing
$N_{deaths,cooling}$: number of deaths caused by the cooling (if negative lives are saved)
PM_x: particulate matter with diameter <x µm
RF: radiative forcing
$\Delta T_{surface}$: temperature change at ground level
UFPs: ultrafine particles, <100 nm in diameter

1 Introduction

Huge efforts are made around the globe to reduce anthropogenic particle emissions, because inhaled particulate air pollution is one of the major environmental threats for human health (Lopez et al., 2006). However, removing aerosol emissions in order to reduce negative health effects will at the same time influence climate (IPCC, 2007). Climate change will, in turn, have negative impacts on health. This raises the question: What is the optimal emission reduction strategy to save human lives?

This article focuses on the interactions between health effects of aerosol exposure, climate effects of aerosols, and health effects of climate change (Löndahl, 2009). Recent publications on ship emissions have made a first attempt to quantify such inter-linkages possible. Our aim was to estimate the total health effects of anthropogenic aerosol emissions, by combining the negative health consequences of aerosol exposure and positive health consequences of a less warmed climate. The results are discussed in its broader context of complex interactions between aerosols, climate, and health, and differences in time and space responses.

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2 Background

2.1 Health effects of aerosol exposure

Extremely high levels of airborne particulate matter are well-known from major pollution episodes in the past, like London 1952, to cause negative health effects. In addition, low concentrations of particulate matter, as in most populated areas, have impacts on mortality (Pope and Dockery, 2006). The relative risk of premature death is estimated to be about 1.06 ± 0.03 per 10 µg/m^3 increase of $PM_{2.5}$ (particulate matter <2.5 µm). The relationship between concentration and response seems to be linear, without a lower threshold (Samoli et al., 2005). Urban particulate matter (PM_{10}) causes about 800 000 premature deaths each year in the world and indoor smoke from solid fuels another 2 million deaths (Lopez et al., 2006). This corresponds to a total annual loss of about 50 million disability adjusted life years (DALYs).

Primarily cardiovascular and respiratory disorders are linked to PM exposure. Other responses, such as damage to the central nervous system by ultrafine particles, have been suggested (Oberdorster et al., 2004). Susceptible subgroups have been identified that are more vulnerable to PM exposure than the average population. Among these are people with pre-existing heart and lung diseases, elderly, children and possibly also infants (Air Quality Criteria for Particulate Matter, 2004). Other factors that probably contribute are genetic predisposition, socioeconomic status and maybe diabetes, medication use, gender, health care availability, educational attainment, housing characteristics and amount of outdoor activity.

It has not been possible to identify a single characteristic of particles that accounts for the toxicity. Inhaled particles interact with the body through a variety of pathways and the effects may depend on different particle characteristics such as chemistry, size, shape, biological activity or radioactivity. Air quality guidelines have so far mostly focused on the mass of PM_{10} or $PM_{2.5}$. Several studies indicate that small particles, which contribute less to the total particulate mass, are more closely linked with adverse health outcomes than larger ones (Schlesinger et al., 2006). Especially the ultrafine

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particles (UFPs, <100 nm), have been of much concern in recent years. UFPs typically originate from combustion processes or condensation of gases with low volatility and appear in high number concentrations in many environments.

2.2 Climate effects of aerosols

There are many uncertainties concerning the interaction between the climate system and aerosol particles.

Figure 1 summarizes much of the current understanding of human influence on the atmosphere expressed in terms of radiative forcing (RF). The change in RF is in this case defined as the net alteration in irradiance ($W m^{-2}$) since 1750 at "top of the atmosphere", which is similar to the height of the tropopause. The radiative forcing attributable to those ship emissions that probably will be decreased by future regulations, i.e. SO_x, NO_x and PM, is about −0.11 (−0.07 to −0.16) (Fuglestvedt et al., 2008). According to IPCC (2007) it is "virtually certain" (i.e. >99% probability) that anthropogenic emissions of aerosols are in total cooling the climate. Hence, increases in greenhouse gas concentrations would probably have caused more warming than observed if not anthropogenic aerosols had been present. Although uncertainties are substantial, it is estimated that the cooling by aerosols, black carbon included, is around $-1.1\ W/m^2$ (without black carbon $-1.4\ W/m^2$). The radiative forcing of carbon dioxide is about $+1.7\ W/m^2$. Many of the greenhouse gases, as for example carbon dioxide, are long-lived in the atmosphere and remain there for decades or centuries. Aerosols are on the other hand short-lived. Within a few days or weeks an aerosol particle is most likely washed out by rain or deposited by diffusion or gravitational forces. Thus the greenhouse gas warming is expected to be more pronounced in the future when aerosol emissions no longer continue to increase (Andreae et al., 2005).

Aerosols do not influence the climate system only by altering the RF. They also have a substantial impact on precipitation pattern, atmospheric circulation system, heat distribution and melting of ice. At atmospheric vapour pressures aerosol particles acting as cloud condensation nuclei (CCN) are necessary for formation of cloud

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droplets. Anthropogenic emissions of aerosols leads to a range of different indirect effects (Lohmann and Feichter, 2005). The main mechanism is the conversion of cloud droplets to raindrops that is slowed down by higher CCN concentrations. A larger number of small droplets are formed rather than a few precipitating raindrops. This increases cloud albedo by reflecting more sun light back into space, the so called first indirect or Twomey effect (Twomey, 1974). It also increases the cloud lifetime, the so called secondary indirect or Albrecht effect (Albrecht, 1989). However, globally the amount of precipitation must balance the amount of evaporation and thus a suppressed precipitation from shallow clouds result in an increased precipitation and rain intensity from deeper clouds (Rosenfeld et al., 2008; Tao et al., 2007).

There is no specific aerosol property that is most essential in the interaction with climate. Small particles (<0.5 µm including UFPs) are crucial for the cloud processes and larger particles are, apart from cloud interactions, also important because of their reflection and absorption of light. Black carbon (soot) changes global and regional climate through several different mechanisms (Ramanathan and Carmichael, 2008). It reduces the albedo of the planet by absorption of solar radiation and has a number of complex interactions with clouds. When deposited on snow, the light absorption of soot not only reduces surface albedo but also increases snowmelt (Clarke and Noone, 1985; Hansen and Nazarenko, 2004). This effect is especially crucial for the Himalayan glaciers which are acting as water reservoirs for more than one-sixth of the Earth's population. When the glacier storage capacity decreases, the irregular precipitation in this region will cause both periods of drought and floods (Barnett et al., 2005).

2.3 Health effects of climate change

Climate change will contribute to a range of direct and indirect health consequences world-wide, including effects from extreme climate events, changes in infectious disease transmission, and impacts on air quality, water quantity and quality, and food production and security (see Table 1) (e.g. Costello et al., 2009; Confalonieri et al., 2007; McMichael et al., 2006; Patz et al., 2005). Globally negative health effects

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dominate, even if positive effects, such as reduction of winter deaths, may occur on a local level. Low-income countries, with low adaptive capacity, where climate change will act as a stressor multiplier are particularly vulnerable. It has been estimated that climate change caused a loss of 160 000 lives or 5.5 million DALYs from malaria, malnutrition, diarrhoeal disease, heat waves and floods in year 2000 because of the 0.4 °C heating compared to the 1961–1990 average climate (Campbell-Lendrum et al., 2003; McMichael et al., 2006). Hence, the adverse health effects induced by climate change were in year 2000 estimated to be about 10% of that due to aerosol exposure (Lopez et al., 2006; Campbell-Lendrum et al., 2003).

When both exposure to aerosols and their climate impact are considered, it is obvious that decreased aerosol emissions would have a very complex interaction with human health (Table 1). Climate change (temperature) also interacts with effects of air pollution (e.g. tropospheric ozone formation) creating further interactions at the impact level (Kalkstein and Greene, 1997; Katsouyanni et al., 1993).

3 Case study – ship emissions

Emissions from shipping are relatively well-known from both a climate and a health perspective (Corbett et al., 2007; Fuglestvedt et al., 2008). Shipping is a major source to sulphur oxides (SO_x), nitrogen oxides (NO_x) and PM in the atmosphere. Efforts are made to reduce these substances since they are adverse for health and cause air pollution related stresses such as acidification, ground-level ozone and nitrogen nutrient loading in sensitive ecosystems. SO_x, NO_x and PM from ships also have a substantial impact on climate (see Fig. 1). SO_x is contributing to particle formation processes which cool the atmosphere through direct reflection of light and increased cloud cover. Chemical reactions with NO_x alter the concentrations of two important greenhouse gases; it increases ozone levels but decreases methane. The overall effect of NO_x is a minor cooling. PM may be both warming and cooling depending on the amount of black carbon in the particles. To prohibit adverse health effects, efforts are

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currently made to reduce the ship emissions by regulating the concentration of sulphur in the fuel and by exhaust-gas cleaning systems (e.g. scrubbers and/or filters). We analyzed what the "total health" effects would be from a change to zero emissions of SO_x, NO_x and PM from shipping, considering the interactions between aerosols, health, and climate change.

3.1 Calculation of the "total health" effect

The "total health" effects of ship emission were estimated as follows:

$$N_{\text{deaths, total}} = N_{\text{deaths, cooling}} + N_{\text{deaths, exposure}} \quad (1)$$

Information on mortality from ship emission, the total radiative forcing from ship emission, and mortality from climate change in year 2000 was collected from the literature. Exposure to air pollution from shipping are responsible for 60 000 (20 000–100 000) deaths globally each year (Corbett et al., 2007).

The radiative forcing from ship emissions has been estimated to −0.07 (−0.03 to −0.13) $W\,m^{-2}$ (Fuglestvedt et al., 2008). However, this number includes both the accumulated effect of all greenhouse gases emitted since 1870 and the effect of the short lived gases and particles. In this context it is more relevant to consider only the constituents of the pollution that are affected by regulations (i.e. exclude CO_2). The radiative forcing attributable to these substances, which basically are SO_x, NO_x and PM, is about −0.11 (−0.07 to −0.16) $W\,m^{-2}$ (Fuglestvedt et al., 2008).

The temperature change ($\Delta T_{\text{surface}}$) caused by a change in radiative forcing (ΔF) can, when equilibrium is established, be approximated as

$$\Delta T_{\text{surface}} = \lambda \cdot \Delta F \quad (2)$$

where λ is the climate sensitivity parameter. The climate sensitivity parameter from IPCC (2007) is 0.8 (0.5–1.2) $K\,W^{-1}\,m^2$ (a doubling of CO_2, which corresponds to a radiative forcing of 3.7 $W\,m^{-2}$, result in a warming of 3 (2–4.5) °C). Using this, current ship emissions of SO_x, NO_x and PM cause a cooling of about −0.085 (−0.042 to −0.145) °C.

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Because SO_x and PM are short-lived in the atmosphere equilibrium is reached within a few decades (Fuglestvedt et al., 2009).

Although no linear relationship between climate change and human health exists, a qualified guess of the number of lives ($N_{\text{deaths,cooling}}$) saved by the cooling from ships would be

$$N_{\text{deaths,cooling}} = \Delta T_{\text{surface}} C \quad (3)$$

where C is a constant representing the number of deaths caused by one degree warming. A climate change of 0.4 °C resulted, as previously mentioned, in 160 000 deaths. This gives a value of C of about 400 000 deaths/°C.

3.2 Estimated "total health" effect

The results of the different calculations are shown in Fig. 2. Our analyses suggest that the "total health" effect ($N_{\text{deaths,total}}$) of ship emissions is about 26 000 deaths annually, considering the number of lives saved by the atmospheric cooling effect of particle emissions from ships and the deaths from exposure to air pollutants.

The number of lives saved by the cooling from ship emissions of SO_x, NO_x and PM was calculated to be 34 000, based on the estimate of 400 000 deaths per °C increase from climate change.

The uncertainty of C is unknown. With an uncertainty of zero the total number of deaths caused by ship emissions is in the range −5000 to 52 000 because of the uncertainties of the radiative forcing, the climate sensitivity and the estimate of deaths caused by exposure. As a comparison, an uncertainty of C of 400 000 ± 200 000 increases the range to −10 000–57 000 deaths.

4 Discussion

Our calculations suggest that improved control of ship emissions would most likely save thousands of lives. However, there is more complexity in the issue of ship emissions

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than outlined above. Because of the short atmospheric life time of SO_x and PM their effects are not evenly distributed around the globe. In the calculations the health effects of aerosol exposure are estimated on a local scale while the cooling effect is a global average. South East Asia, Europe and North America where most ship traffic is found, would benefit most from ship emission reductions, whereas most regions that are the most vulnerable to climate change are located elsewhere, with the exception of some of the coastal megadeltas and small island nations.

The time response scales differ as well. A health disorder may follow within a few days after exposure to air pollution, whereas health effects from decreased cooling have a long time delay.

Interactions between various pollutants need to be acknowledged. For example secondary ozone from ships may worsen the effects of aerosol particles from other sources. On the other hand air quality may decrease when sunlight and temperature increase because of altered chemical reaction rates and changes in air flow patterns (Ebi and McGregor, 2008).

From a health perspective, emissions of SO_x, NO_x and PM from ships should be reduced, especially in the vicinity of densely populated areas. Considering the cooling impact of these airborne particles on climate, emission reductions need to be linked with efforts to counteract the increased warming that otherwise may follow. Ideally the use of fossil fuels should be abandoned. Black carbon emissions on the other hand (particularly soot and indoor smoke from solid fuels) are both heating the atmosphere and cause adverse health effects. Measures to reduce black carbon emission will, thus, create win-win situations for both health and climate mitigation.

The more general scientific uncertainties also need to be considered when estimating the "total health" effects of aerosol emissions. These are related to the confidence in the calculations of health consequences of exposure to particles, of climate impact of the particles and of health outcomes of climate change.

The link between particle exposure and health effects is well established. The scattered scepticism about the health assessments of particle exposure, especially

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regarding the small relative risk usually found and potentially confounding in epidemiological studies (Vedal, 1997), is opposed by the consistency of the findings. Problems with exposure assessment are also more likely to reduce than to enhance the estimated effect size. A majority of the epidemiological studies rely on ambient monitoring data and not on personal exposure measurements. There are often large local differences in the concentration of pollutants. Moreover outdoor air pollution levels may be misleading, considering that people spend most of their time indoors (Leech et al., 2002) where the exposure is uncertain. Indeed, the effect estimates of PM on mortality tend to be higher when the exposure is calculated with more focused spatial resolution or when local sources, such as traffic, are accounted for (Pope and Dockery, 2006).

The interaction between aerosols and climate is considered to be "low" or "medium to low" by IPCC (Fig. 1). However, IPCC has probably been cautious in their estimates of the climate effects of anthropogenic emissions. In an evaluation of previous IPCC reports and their predictions of future climate (Rahmstorf et al., 2007) finds that IPCC tend to underestimate the atmospheric changes in many respects. Since the second IPCC report was published in 1992 global observed average surface temperature has been close to or above the worst case scenarios (Fig. 1.1, p. 98, IPCC, 2007).

The largest difficulty in the estimates probably regards the link between climate change and health. The uncertainty of the constant C (i.e. the number of deaths caused by one degree Celsius warming) used in our calculations is unknown for several reasons. First, considering that only certain health effects were included in the 2000 estimate, calculations of future health effects from climate based on this value would be an underestimation of the real number. Among the factors not included were allergen levels, population displacement, water shortage, infectious diseases, extreme weather events and conflicts over natural resources. Second, there are still large uncertainties of the magnitude and extent of different health effects due to climate change. Third, there are several uncertainties connected with global climate models, ranging from knowledge gaps in atmospheric sciences (particularly feed-back mechanisms and tipping points of the climate system) to the IPCC emission scenarios (Hansen et al.,

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2008). Tipping points may for example be Amazon rainforest dieback, instability of the West Antarctic ice sheat, Sahara greening, boreal forest dieback, Arctic sea-ice loss, changing in the El Ninõ southern oscillation (ENSO), alteration of the Atlantic deep water formation or chaotic multistability of the Indian monsoon (Lenton et al., 2008). The health consequences of such events would be considerable.

Regardless of the level of scientific knowledge of the various mechanisms involved in the calculation of the "total health" effect of ship emissions the case study clearly shows that, based on current understanding, the net outcome is uncertain. There are other sources of air pollution that, in similarity with ship emissions, potentially has a large cooling effect in proportion to its health consequences during exposure. Efficient biomass combustion in power plants may be one such source. It presumably has a negative radiative forcing since emitted particles usually contain large fractions of salts that may act as cloud condensation nuclei, whereas the direct emission of greenhouse gases is low. If the power plant is located in a remote area it has a moderate influence on exposure to toxic aerosols. In theory, it would make sense to reduce only the black carbon component from biomass combustion as well as shipping, to keep the cooling effects of aerosols. This raises the question of geoengineering. One suggestion for geoengineering the climate has been to reduce short-lived aerosol particles in the troposphere for health purposes, while at the same time injecting particles into the stratosphere for climate reasons (Crutzen, 2006). However, it is dubious to maintain one environmental problem (particulate air pollution) in order to reduce the burden of another (climate change), especially with current level of knowledge.

5 Conclusions

Some aerosols, such as black carbon (soot) are negative for both health and climate and efforts for reduction emissions will have great health benefits. Other aerosols, especially sulphates and cloud condensation nuclei, have considerable cooling effects on the climate, and emission reductions will contribute to an increased global warming.

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Policies to promote access to non-polluting and sustainable sources of energy would, thus, have great potential both to improve public health and to mitigate climate change (Haines et al., 2007).

Acknowledgements. We thank Mats Bohgard, Christoffer Boman, Andreas Massling, Pontus Roldin, Staffan Sjögren and Christer Åhgren for valuable comments and discussions. This work was supported by EUCAARI (European Integrated Project on Aerosol Cloud Climate Air Quality Interactions).

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Table 1. Climate change, health, and aerosol effects (modified from McMichael et al. (2006) by adding the right column).

Environmental effect	Beneficial (+) and adverse (–) health effects	Aerosol effect
Warmer temperatures	+ Aero-allergen production: Shorter pollen season in some regions + Crop increases in too-cold regions (at a limited warming) – Aero-allergen production: Increased allergic disordes due to longer pollen season – Food-poisoning: Increased risk at higher temperature (especially salmonellosis) – Water-borne infection: Cholera risk might be amplified by water warming – Release of accumulated pollutants in some regions (e.g. mercury)	Totally cooling, but some aerosol components such as black carbon are heating atmosphere.
Temperature extremes	+ Reduced winter deaths in some countries – Increased mortality due to thermal stress	Reducing heat waves.
Floods	– Injuries/deaths – Infectious diseases – Mental health disorders – Exposure to toxic pollutants – Sewage and animal wastes into waterways and drinking water supplies	Increasing heavy rainfall, but decreasing floods caused by a warmer atmosphere. Influencing Himalayan glaciers.
Droughts	+ Water-borne infection: Less risk where heavy rainfall diminishes – Crop reduction, especially in low-latitude regions	Unclear if aerosol decreases precipitation in some areas. Influencing Himalayan glaciers.
Ecosystem changes	+ Possibly more fish in some regions – Food poisoning, unsafe drinking water – Infectious diseases, e.g. malaria dengue, tickborne viral disease – Decreased fish yields, impaired crops	A variety of effects depending on both climate change and toxicity of the particles.
Sea-level rise	– Drinking water damages due to salination of freshwater – Population displacement – Exposure to coastal storms – Coastal soil	Decreasing water expansion due to cooling. Increasing ice melting because of black carbon on snow.

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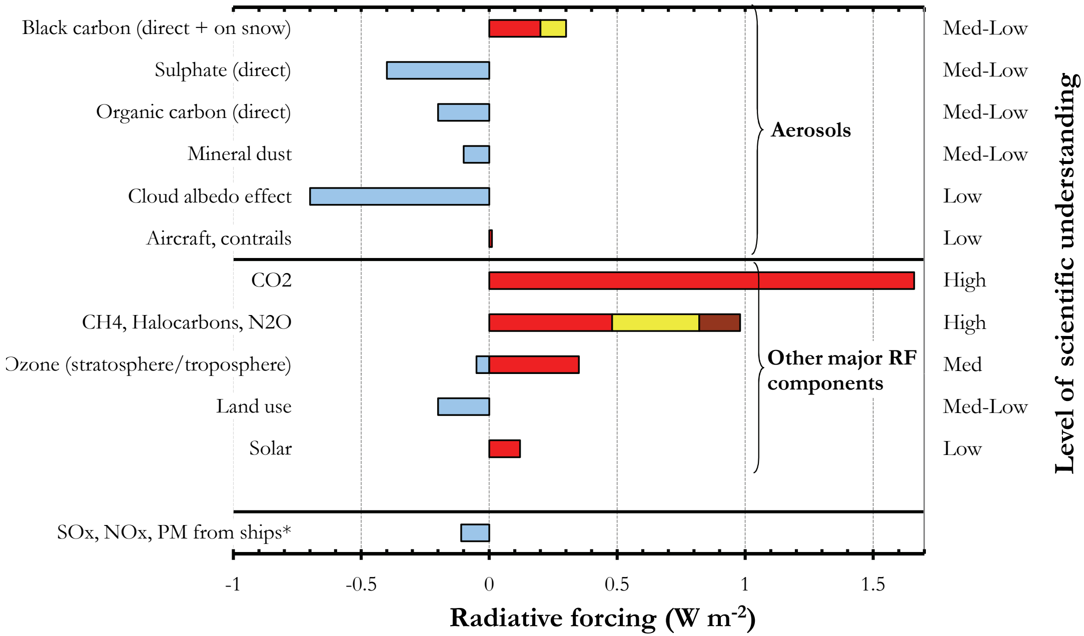

Fig. 1. Global average radiative forcing due to anthropogenic influence through different mechanisms (IPCC, 2007). It should be noted that especially the forcing of black carbon has been argued to be as high as 0.9 (0.4–1.2) $W\,m^{-2}$ (Ramanathan and Carmichael, 2008). The radiative forcing of ship emissions (SO_x, NO_x and PM) is both shown separately and included in the other bars.

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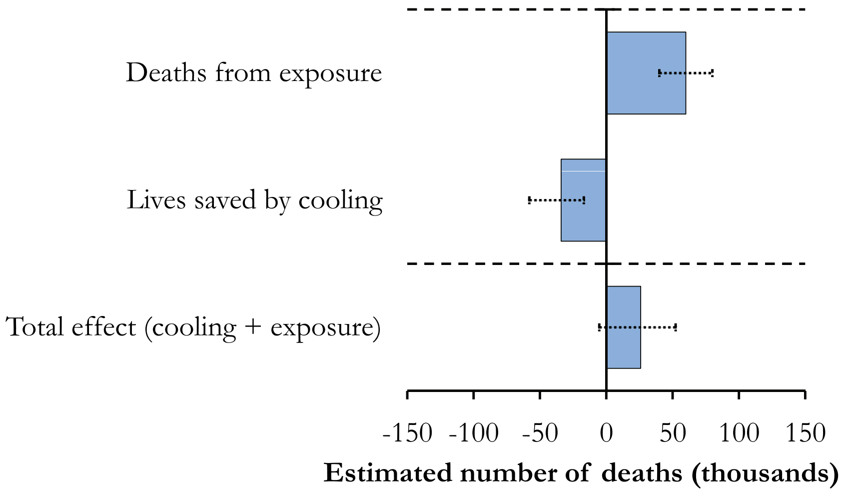

Fig. 2. The "total health" outcome in terms of mortality of ship emissions. Bars show standard deviation if the uncertainty of the constant *C*, which is the number of deaths caused by one degree Celsius warming, is zero. The uncertainty range of *C* is substantial, but it will nevertheless not increase the uncertainty of the "total effect" dramatically.

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