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Aerosol exposure versus aerosol cooling of climate: what is the optimal emission reduction strategy for human health?

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Abstract. Particles, climate change, and health have thought-provoking interactions. Air pollution 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 globally, 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 for climate change initiated by particles. As a case study the "total health effect" from ship emissions was derived by subtracting the number of deaths caused by exposure with the estimated number of lives saved from the cooling effect of the emissions. The analysis showed that, with current level of scientific understanding, it could not be determined whether ship emissions are negative or positive for human health on a short time scale. This first attempt to approximate the combined effect of particle emissions on health shows that reductions of particulate air pollution will in some cases (black carbon) have win-win effects on health and climate, but sometimes also cause a shift from particle 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.

1 Introduction

Huge efforts are made around the globe to reduce anthropogenic aerosol particle emissions, because inhaled particulate air pollution is one of the major environmental threats for human health (Lopez et al., 2006). However, removing aerosol particles and their precursor gases (hereafter 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?

The purpose of this paper is to discuss difficulties and solutions in the search for an optimal policy for reduction of air pollution to benefit human health without side effects from climate change (Löndahl, 2009). Three research areas are involved; (1) health effects of aerosol exposure, (2) climate effects of aerosols, and (3) health effects of climate change. It is beyond the scope of this work to present a complete survey of the interactions between these fields. However, also a less detailed analysis may serve to highlight key issues that need to be considered. Therefore, a simplified calculation is carried out in a first attempt to estimate the order of magnitude of the "total health effects" of anthropogenic aerosol emissions from a specific source of air pollution (oceangoing shipping). Based on current level of understanding the "total health effects" is here defined as the sum of the number of deaths caused by aerosol exposure and the climate change, respectively.

The paper is divided into three main parts. Firstly a brief background is provided on the current level of knowledge about health effects from exposure to aerosols, impacts of aerosols on climate and health effects of climate

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change (Sect. 2). Thereafter, as an illustration, a back-of-the-envelope calculation is made of the "total health effects" of ship emissions (Sect. 3). Finally, the results are discussed in their broader context of scientific uncertainties and policy measures for emission reductions (Sect. 4).

2 Background

2.1 Health effects of aerosol exposure

Extremely high levels of airborne particulate matter from major pollution episodes in the past, like London 1952, are well-known to cause severe negative health effects. But also much lower concentrations of particulate matter, as experienced in most populated areas at present, have impacts on mortality (Pope and Dockery, 2006). The relationship between concentration and response seems to be linear, without a lower threshold (Samoli et al., 2005). Urban particulate matter (PM_{10}) is estimated to cause 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 from 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 presumably 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 particles (UFPs, <100 nm), have been of much concern in recent years. UFPs typically originate from combustion processes or condensation of vapours with low volatility, and appear in high number concentrations in many environments.

2.2 Climate effects of aerosols

The human influence on climate is often expressed in terms of radiative forcing (RF). The change in RF is usually defined as the net alteration in irradiance ($\mathrm{W\,m^{-2}}$) since 1750 at "top of the atmosphere", which is similar to the height of the tropopause. According to IPCC (2007) it is "virtually certain" (i.e. $>99\%$ probability) that anthropogenic emissions of aerosols result in a total cooling effect on the global 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 $-1.1\,\mathrm{W/m^2}$ (without black carbon $-1.4\,\mathrm{W/m^2}$). The radiative forcing of carbon dioxide is about $+1.7\,\mathrm{W/m^2}$.

Most 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 direct reflection of radiation. They also have a substantial impact on cloud reflectivity, precipitation pattern, atmospheric circulation system, heat distribution and melting of ice. Most important for RF is the indirect effect, which involves the influence of the aerosol particles on cloud properties. It is usually split into the first and second indirect effect. The first indirect effect is the increase in cloud droplet concentration and decrease in droplet size that is caused by elevated levels of aerosols (Twomey, 1974). This leads to an increased reflection of solar radiation back into space. The reduced cloud droplet size also bring about the second indirect effect, which is an assumed alteration of precipitation efficiency, increase in cloud lifetime (Albrecht, 1989) and increase in cloud thickness (Pincus and Baker, 1994).

Many of the atmospheric processes are determined by the size of the aerosol particles, but other properties may be fundamental and especially the light absorption by black carbon has been of much interest during recent years. 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 dominate, even if positive effects, such as reduction of winter deaths, may occur on a local level. Low-income countries, with low adaptive capacity, are particularly vulnerable since climate change will act as a stressor multiplier.

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 1961–90 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 very complex interactions 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

In this case study we make a first attempt to estimate "total health effects" from a specific source of air pollution. The purpose is to encourage further discussion and to achieve a rough estimate of the magnitude of the total health outcome. Although the calculations are sketchy they may serve as a starting point for further refinement. The chosen source of pollution is emissions from oceangoing shipping since these, compared to most other sources of air pollution, are relatively well-known from both a climate and a health perspective (e.g. Corbett et al., 2007; Fuglestvedt et al., 2008). The question we try to answer is: what would the loss of human lives have been in year 2000 with zero emissions from shipping if equilibrium was established and both exposures to aerosols and feedbacks from climate change are considered?

The scenario in this case study is hypothetical, but not irrelevant. Shipping is a sizeable 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. SO_x is contributing to particle formation processes which cool the atmosphere through direct reflection of light and increased cloud albedo. 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 (Eyring et al., 2010). PM may be both warming and cooling depending on the amount of black carbon in the particles.

There is a variety of technology options for reducing SO_x, NO_x, PM and greenhouse gas emissions from oceangoing shipping (ICCT, The International Council on Clean Transportation, 2007). These may for instance be lowering sulphur content in the fuel, engine modifications or exhaust-gas cleaning systems (e.g. scrubbers and/or filters). There is also a potential to reduce emissions by adjusting ship routes and optimize vessel speeds. Diesel engines are predicted to be the dominating propulsion system for at least the next 20 years, but the use of other power systems based on biofuel, wind or solar cells may increase (Eyring et al., 2010).

3.1 Calculation of the "total health effect"

The results of the case study are illustrated in Fig. 1. Three versions (Case A, B and C) are considered. Case A uses the temperature change from shipping emissions modelled by Skeie et al. (2009). Case B excludes CO_2 from the calculations and Case C use a global temperature change derived from other data of RFs.

3.1.1 Case A

The "total health effects" ($N_{\text{deaths,total}}$) of ship emissions can be calculated as the sum of the deaths due to exposure ($N_{\text{deaths,exposure}}$) and the deaths due to climate change ($N_{\text{deaths,cooling}}$) from the same source of air pollution:

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

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. It is estimated that exposure to air pollution from oceangoing shipping were responsible for 63 000 (43 000–83 000) deaths globally year 2000 (Corbett et al., 2007). Based on radiative forcings (RFs) from Fuglestvedt et al. (2008) the global temperature change ($\Delta T_{\text{surface}}$) this year was -0.05 °C because of emissions from shipping (Skeie et al., 2009). No uncertainty range is presented, but from the uncertainties in the used RFs and climate sensitivity, the range is presumably around -0.10 to -0.01 °C (see further below).

Although no linear relationship between climate change and human health exists, a first approximation of the number deaths from ship emissions would be

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	Water expansion is decreased due to cooling. Increasing ice melting because of black carbon on snow.

$$N_{\mathrm{deaths,cooling}} = \Delta T_{\mathrm{surface}} \cdot \theta_{\Delta T} \quad (2)$$

where $\theta_{\Delta T}$ is a constant representing the number of deaths caused by one degree warming. As previously mentioned, a climate change of 0.4 °C resulted in 160 000 deaths (Campbell-Lendrum et al., 2003; McMichael et al., 2006). This gives a value of $\theta_{\Delta T}$ of about 400 000 deaths/°C and hence a life loss of −20 000 (−40 000 to −4000). Thus, the "total health effect" ($N_{\mathrm{deaths,total}}$), considering both the number of lives saved by the atmospheric cooling effect and the deaths from exposure to air pollutants, can be estimated to 43 000 (14 000 to 69 000) deaths year 2000.

3.1.2 Case B

Case B, where CO_2 is excluded in the calculation, is of interest for several reasons. Firstly, current legislation mainly focuses on the short-lived unhealthy substances. Secondly, CO_2 will probably not be reduced much because diesel engines are predicted to dominate shipping during the foreseeable future (Eyring et al., 2010) and thirdly, equilibrium after a decrease of CO_2 needs hundreds of years to establish because of its long atmospheric life time.

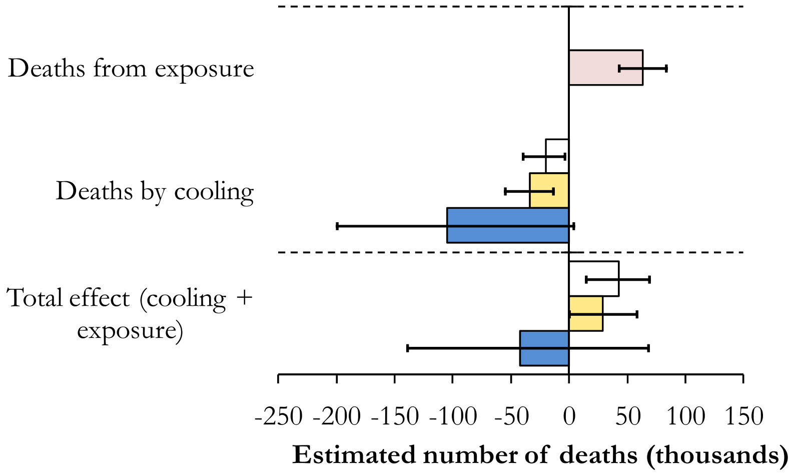

Fig. 1. The "total health" outcome in terms of mortality of ship emissions. White bars (Case A) use the temperature change calculated by Skeie et al. (2009), yellow bars (Case B) is the same scenario but with the warming from CO_2 omitted in the calculation and blue bars (Case C) are derived from the radiative forcing (RF) provided by Eyring et al. (2010). The difference in health outcomes between case B and C is mainly attributable to varying parameterizations of the aerosol indirect effect. The shown standard deviation does not include the uncertainty of the constant $\theta_{\Delta T}$, which is the number of deaths caused by one degree Celsius warming.

If CO_2 is excluded, the RF attributable to the remaining substances, which basically are SO_x, NO_x and PM, is about -0.11 (-0.16 to -0.07) $W\,m^{-2}$ (Fuglestvedt et al., 2008). The temperature change ($\Delta T_{\text{surface}}$) caused by a change in RF can, when equilibrium is established, be approximated as

$$\Delta T_{\text{surface}} = \lambda \cdot \text{RF} \tag{3}$$

where λ is the climate sensitivity parameter. The climate sensitivity parameter from IPCC (2007), which was used by Skeie et al. (2009) above, is 0.8 (uncertainty around 0.5–1.2) $K W^{-1} m^2$. With this value, current ship emissions of SO_x, NO_x and PM cause a cooling of about -0.085 (-0.14 to -0.034) °C. The number of deaths from climate change would be $-34\,000$ ($-55\,000$ to $-14\,000$) and the "total health effect" 29 000 (-500 to 58 000).

3.1.3 Case C

A version of the case study using other data of RFs from shipping is relevant since there are several assessments of these values and a considerable variation among them (Balkanski et al., 2010; Capaldo et al., 1999; Dalsoren et al., 2007; Endresen et al., 2003; Eyring et al., 2007; Fuglestvedt et al., 2008; Lauer et al., 2007). The largest deviation between them is found in the estimates of the aerosol indirect effect. Eyring et al. (2010) have summarized the results and found a mean RF of -0.328 (-0.598 to -0.032, if the standard deviations of the RFs are added as the square root of the sum of the variances) $W\,m^{-2}$. The "total health effect" with this larger negative RF is $-42\,000$ ($-139\,000$ to 68 000) deaths (Fig. 1). Calculations are made as described for Case A and B.

4 Discussion

4.1 Scientific uncertainties

There are considerable scientific uncertainties in the fields of health effects of aerosol exposure, climate effects of aerosols, and health effects of climate change. Consequently, an even larger uncertainty arise when these research areas are added together to assess "total health effects". Are calculations of "total health effects", such as exemplified in the case study, valid? Is the number of associated deaths over- or underestimated? This section summarizes some of the key uncertainties and generalizations.

The link between particle exposure and health effects is well established. The scattered scepticism about the health assessments of particle exposure, especially regarding the small relative risk usually found and the potential confounding factors in epidemiological studies (Vedal, 1997), is opposed by the consistency of the findings. Correct exposure assessments is a main difficulty in epidemiology. 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 in large parts of the world spend most of their time indoors (Leech et al., 2002) where the exposure is uncertain. However, the problems with measurements of exposure are more likely to reduce than to enhance the estimated effect size. 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).

There are noteworthy uncertainties in the understanding of climate change. It has not yet been possible to fully determine the climate sensitivity (the temperature response to a change in RF) from past records. The observed warming trend is consistent with both high climate sensitivity to greenhouse gases together with a large cooling from aerosols and a low sensitivity to the warming gases combined with a minor aerosol cooling. Evaluations of previous IPCC reports and their predictions indicate that IPCC tend to underestimate the climatic changes in many respects (Fussel, 2009; Rahmstorf et al., 2007).

The scientific knowledge of interactions between aerosols and climate is in part low, especially concerning the different indirect effects. Among other things, there is a need to improve accuracy in the estimates of aerosol emission sources and their history, the vertical structure of aerosol and its optical properties. The first indirect, or cloud albedo, effect has been observed in case studies (e.g. ship tracks), but experimental evidence for a global forcing is lacking (IPCC, 2007). The understanding of the second indirect, or cloud lifetime, effect is by IPCC regarded to be "very low". Case C, using the mean RF from Eyring et al. (2010), illustrates the substantial difference in health outcome mainly depending on how the indirect aerosol effect is accounted for.

The most fundamental uncertainty in the calculation of "total health effects" is probably the link between climate change and health. The precise number and uncertainty range of the constant $\theta_{\Delta T}$ (i.e. the number of deaths caused by one degree Celsius warming) used in our case study is unclear for several reasons. First, only certain health effects were included in the 2000 estimate. Several factors were not included such as impacts on infectious diseases other than malaria, extreme weather events other than heat waves, and climate change related impacts on allergen levels, population displacement, water shortage, and conflicts over natural resources. Incorporating these would most likely increase $\theta_{\Delta T}$. Second, there are still large uncertainties of the magnitude and extent of different health effects due to climate change. Third, the constant $\theta_{\Delta T}$ was estimated for the last decades of the 20th century. If the global temperature continues to increase the negative health outcomes may be vastly deviating from this period because of feed-back mechanisms or tipping points of the climate system (Hansen et al., 2008). Tipping points may for example be Amazon rainforest dieback, instability of the West Antarctic ice sheat, 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. The constant $\theta_{\Delta T}$ is thus not a fixed number, but rather a function of global temperature (i.e. $\theta_{\Delta T}(T)$) with higher values for increasing temperatures. To find better approximations of this function is crucial and a major challenge for future research.

The time response scales have to be taken into account. In the case study it is assumed that temperature equilibrium is established. However, it takes decades before equilibrium is reached after an adjustment of the short-lived emission components and hundreds of years until the effects of CO_2 are realized. For this reason CO_2 was omitted in Case B. The cooling effects of the short-lived components dominate year 2000, but with a time horizon of 500 years shipping will switch to a positive RF because of accumulated CO_2 (Fuglestvedt et al., 2008).

In addition, the health responses have various time scales. Health disorders from exposure to air pollution may follow immediately (e.g. heart failures) or after years of inhaling toxic substances (e.g. lung cancer). Similarly, some health consequences from climate change are instantaneous (e.g. drowning, injuries) while others may be more long-term (e.g. malnutrition from decreasing crop production). The assumption of steady state is theoretical, but difficult to circumvent and therefore commonly used in risk assessments.

The geographical distribution of the pollution sources is essential. Because of the short atmospheric life time of SO_x, NO_x, ozone and aerosol particles they are not evenly distributed around the globe. The health effects from exposure to oceangoing shipping are primarily found at the coasts of South East Asia, Europe and North America where most ship traffic occurs.

With the exception of densely populated mega deltas in Asia and small island nations, the regions that are most vulnerable to climate change are largely located elsewhere than those that are affected from exposure effects of decreased air quality. However, the assumption of negative health outcomes from climate change in all regions due to alteration of shipping emissions seems reasonable as a first guess. Global mean temperatures appears to follow the global mean radiative forcing quite closely (Shindell and Faluvegi, 2009), which means the simplified estimate of temperature change used in Case B and C is feasible for large parts of the world.

Since the people suffering from health effects from climate change are demographically rather separate from those suffering from exposure to ship emissions, the number of deaths appears possible to add as in the case study (Eq. 1). There may be exceptions. Exposure to extreme heat will increase and the groups being at higher risk to heat episodes, which is elderly and people with cardiovascular and respiratory disorders (McMichael et al., 2006), are also at risk from particle exposure. However, to include a correction for co-variances, that some people would be affected by both exposure and climate change of ship emissions, is redundant in an approximate calculation. This is not only because of the demographic differences, but also because a very small fraction of the population is affected by exposure (which means it is unlikely for a person to be influenced to a large extent by both aerosol exposure and climate change).

Other environmental effects and trade-offs between various pollutants need to be acknowledged. For example secondary ozone from ships may worsen the effects of aerosol particles from other sources. 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). In the case of shipping, the emissions are also a source of acidification (SO_2) and fertilization (NO_x), which in turn influences biodiversity and carbon uptake. If SO_x from shipping is decreased without an accompanying decrease in NO_x an increase in aerosol nitrate is favored, which could counteract some of the reduction benefits (Lauer et al., 2009).

In summary, the calculated "total health effects" of ocean-going shipping is highly uncertain, but not completely invalid. Especially, as argued above, the constant $\theta_{\Delta T}$ (deaths per degree warming) is probably largely underestimated. With a higher value it would be more favourable for human health to keep ship emissions. The approximation in the case study might thus be regarded as careful. Our example of ship emissions addresses "total health effects" for year 2000. A calculation for future scenarios, which is of interest for policy making, is even more complex because of uncertain feedbacks and tipping points.

4.2 Strategies for emission reduction

Although the estimate of "total health effects" made in the case study is uncertain, it clearly shows that the advantages for human health of some anthropogenic air pollution components have a potential to outweigh the disadvantages. There are other sources of air pollution that, in similarity with ship emissions, has a short term cooling effect. These are for instance agricultural waste burning, biomass burning and sulphate emitting industry (Unger et al., 2010). In some cases the "total health effect" from these sources may be negative. This means it could be preferable for health to concentrate on decreasing the warming components of the emissions such as greenhouse gases and black carbon (which is both unhealthy to inhale and warming).

It is an intricate task for politicians and decision makers to design proper measures in order to avoid environmental hazards that are entangled with both sizeable scientific uncertainties and potentially large negative outcomes (as global warming or deaths by air pollution). In the case of shipping, 70% of the global emissions occur within 400 km from land (Corbett et al., 1999). Reducing sulphur in the fuel by ∼80% for this part of the shipping saves 34 000 (of 87 000) lives year 2012 (Winebrake et al., 2009). The additional benefit of reducing sulphur in the fuel for the remaining 30% of the shipping only saves 7000 lives extra. These sulphur reductions are not even half as efficient from an exposure point of view. From a climate perspective the cooling effect of SO_x is larger in the clean air far away from the coastal regions. Geographically differentiated regulations might be the best option.

To maintain one environmental problem (particulate air pollution) in order to reduce the burden of another (climate change), is close to geoengineering and is certainly dubious (Fuglestvedt et al., 2009; Morton, 2007). Deliberate manipulation of the climate system is problematic. History shows that such interventions often bring about unexpected new difficulties. Nevertheless, because of the risk that anthropogenic emission will move the climate system beyond an irreversible tipping point, there is an urgent need to develop strategies and metrics for regulation of short-lived cooling components in the atmosphere (Arneth et al., 2009). Improvements of air quality must be linked with efforts to counteract the increased warming.

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References

Air Quality Criteria for Particulate Matter: Research Triangle Park, NC, US Environmental Protection Agency, 2004.

Albrecht, B. A.: Aerosols, Cloud Microphysics, and Fractional Cloudiness, Science, 245, 1227–1230, 1989.

Andreae, M. O., Jones, C. D., and Cox, P. M.: Strong present-day aerosol cooling implies a hot future, Nature, 435, 1187–1190, 2005.

Arneth, A., Unger, N., Kulmala, M., and Andreae, M. O.: Clean the Air, Heat the Planet?, Science, 326, 672–673, 2009.

Balkanski, Y., Myhre, G., Gauss, M., Rädel, G., Highwood, E. J., and Shine, K. P.: Direct radiative effect of aerosols emitted by transport: from road, shipping and aviation, Atmos. Chem. Phys., 10, 4477–4489, doi:10.5194/acp-10-4477-2010, 2010.

Barnett, T. P., Adam, J. C., and Lettenmaier, D. P.: Potential impacts of a warming climate on water availability in snow-dominated regions, Nature, 438, 303–309, 2005.

Capaldo, K., Corbett, J. J., Kasibhatla, P., Fischbeck, P., and Pandis, S. N.: Effects of ship emissions on sulphur cycling and radiative climate forcing over the ocean, Nature 400, 743–746, 1999.

Campbell-Lendrum, D., Corvalán, C. F., and Prüss-Ustün, A.: How much disease could climate change cause?, in: Climate change and human health: Risks and responses, edited by: McMichael, A. J., Campbell-Lendrum, D., Corvalán, C. F., Ebi, K. L., Githeko, A. K., Schrega, J. D., and Woodward. A., World Health Organization, Geneva, 133–158, 2003.

Clarke, A. D. and Noone, K. J.: Soot in the Arctic Snowpack – A Cause for Perturbations in Radiative-Transfer, Atmos. Environ., 19, 2045–2053, 1985.

Confalonieri, U., Menne, B., Akhtar, R., Ebi, K., Hauengue, M., Kovats, R. S., Revich, B., and Woodward, A.: Human health, in: Climate Change 2007: Impacts, Adaptation and Vulnerability, Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Parry, M. L., Canziani, O. F., Palutikof, J. P., van der Linden, P. J., and Hanson, C. E., Cambridge University Press, Cambridge, UK, 391–431, 2007.

Corbett, J. J., Fischbeck, P. S., and Pandis, S. N.: Global nitrogen and sulfur inventories for oceangoing ships, J. Geophys. Res., 104, 3457–3470, 1999.

Corbett, J. J., Winebrake, J. J., Green, E. H., Kasibhatla, P., Eyring, V., and Lauer, A.: Mortality from ship emissions: A global assessment, Environ. Sci. Technol., 41, 8512–8518, 2007.

Costello, A., Abbas, M., Allen, A., Ball, S., Bellamy, R., Friel, S., Grace, N., Johnson, A., Kett, M., Lee, M., Levy, C., Maslin, M., McCoy, D., McGuire, B., Montgomery, H., Napier, D., Pagel, C., Patel, J., de Olivera, J., Redclift, N., Rees, H., Rogger, D., Scott, J., Stephenson, J., Twigg, J., Wolff, J., and Patterson, C.: The Lancet-UCL Commission: Managing the health effects of climate change, Lancet, 373, 1693–1733, 2009.

Crutzen, P. J.: Albedo enhancement by stratospheric sulfur injections: A contribution to resolve a policy dilemma?, Climatic Change, 77, 211–219, 2006.

Dalsoren, S. B., Endresen, O., Isaksen, I. S. A., Gravir, G., and Sorgard, E.: Environmental impacts of the expected increase in sea transportation, with a particular focus on oil and gas scenarios for Norway and northwest Russia, J. Geophys. Res., 112, D02310, doi:10.1029/2005JD006927, 2007.

Ebi, K. L. and McGregor, G.: Climate change, tropospheric ozone and particulate matter, and health impacts, Environ. Health Persp., 116, 1449–1455, 2008.

Endresen, O., Sorgard, E., Sundet, J. K., Dalsoren, S. B., Isaksen, I. S. A., Berglen, T. F., and Gravir, G.: Emission from international sea transportation and environmental impact, J. Geophys. Res., 108, 4560, doi:10.1029/2002JD002898, 2003.

Eyring, V., Isaksen, I. S. A., Berntsen, T., Collins, W. J., Corbett, J. J., Endresen, O., Grainger, R. G., Moldanova, J., and Schlager, H. S. D. S.: Transport impacts on atmosphere and climate: Shipping, Atmos. Environ., doi:10.1016/j.atmosenv.2009.04.059, in press, 2010.

Eyring, V., Stevenson, D. S., Lauer, A., Dentener, F. J., Butler, T., Collins, W. J., Ellingsen, K., Gauss, M., Hauglustaine, D. A., Isaksen, I. S. A., Lawrence, M. G., Richter, A., Rodriguez, J. M., Sanderson, M., Strahan, S. E., Sudo, K., Szopa, S., van Noije, T. P. C., and Wild, O.: Multi-model simulations of the impact of international shipping on Atmospheric Chemistry and Climate in 2000 and 2030, Atmos. Chem. Phys., 7, 757–780, doi:10.5194/acp-7-757-2007, 2007.

Fuglestvedt, J., Berntsen, T., Myhre, G., Rypdal, K., and Skeie, R. B.: Climate forcing from the transport sectors, P. Natl. Acad. Sci., USA, 105, 454–458, 2008.

Fuglestvedt, J., Berntsen, T., Eyring, V., Isaksen, I., Lee, D. S., and Sausen, R.: Shipping Emissions: From Cooling to Warming of Climate-and Reducing Impacts on Health, Environ. Sci. Technol., 43, 9057–9062, 2009.

Fuglestvedt, J., Shine, K. P., Berntsen, T., Cook, J., Lee, D. S., Stenke, A., Skeie, R. B., Velders, G. J. M., and Waitz, I. A.: Transport impacts on atmosphere and climate: Metrics, Atmos. Environ., doi:10.1016/j.atmosenv.2009.04.044, in press, 2010.

Fussel, H. M.: An updated assessment of the risks from climate change based on research published since the IPCC Fourth Assessment Report, Climatic Change, 97, 469–482, 2009.

Haines, A., Smith, K. R., Anderson, D., Epstein, P. R., McMichael, A. J., Roberts, I., Wilkinson, P., Woodcock, J., and Woods, J.: Energy and health 6 - Policies for accelerating access to clean energy, improving health, advancing development, and mitigating climate change, Lancet, 6(370), 1264–1281, 2007.

Hansen, J. and Nazarenko, L.: Soot climate forcing via snow and ice albedos, P. Natl. Acad. Sci. USA, 101, 423–428, 2004.

ICCT 2007: Air Pollution and Greenhouse Gas Emissions from Ocean-going Ships: Impacts, Mitigation Options and Opportunities for Managing Growth, edited by: Friedrich, A., Heinen, F., Kamakaté, F., and Kodjak, D., The International counsel on clean transportation, 43–55, 2007

IPCC 2007: Climate Change 2007: The Physical Science Basis, Contribution of the Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Cambridge University Press, Cambridge, UK, 2007.

Kalkstein, L. S. and Greene, J. S.: An evaluation of climate/mortality relationships in large US cities and the possible impacts of a climate change, Environ. Health Persp., 105, 84–93, 1997.

Katsouyanni, K., Pantazopoulou, A., Touloumi, G., Tselepidaki, I., Moustris, K., Asimakopoulos, D., Poulopoulou, G., and Trichopoulos, D.: Evidence for interaction between air-pollution and high-temperature in the causation of excess mortality, Arch. Environ. Health, 48, 235–242, 2005.

Lauer, A., Eyring, V., Hendricks, J., Jöckel, P., and Lohmann, U.: Global model simulations of the impact of ocean-going ships on aerosols, clouds, and the radiation budget, Atmos. Chem. Phys., 7, 5061–5079, doi:10.5194/acp-7-5061-2007, 2007.

Leech, J. A., Nelson, W. C., Burnett, R. T., Aaron, S., and Raizenne, M. E.: It's about time: A comparison of Canadian and American time-activity patterns, Journal of Exposure Analysis and Environmental Epidemiology, 12, 427–432, 2002.

Lenton, T. M., Held, H., Kriegler, E., Hall, J. W., Lucht, W., Rahmstorf, S., and Schellnhuber, H.J.: Tipping elements in the Earth's climate system, P. Natl. Acad. Sci. USA, 105, 1786–1793, 2008.

Lohmann, U. and Feichter, J.: Global indirect aerosol effects: a review, Atmos. Chem. Phys., 5, 715–737, doi:10.5194/acp-5-715-2005, 2005.

Löndahl, J.: Experimental Determination of the Deposition of Aerosol Particles in the Human Respiratory Tract, Ph. D., Lund University, Lund, Sweden, 1–15, 2009.

Lopez, A. D., Mathers, C. D., Ezzati, M., Jamison, D. T., and Murray, C. J.L.: Global and regional burden of disease and risk factors, 2001: systematic analysis of population health data, Lancet, 367, 1747–1757, 2006.

McMichael, A. J., Woodruff, R. E., and Hales, S.: Climate change and human health: present and future risks, Lancet, 367, 859–869, 2006.

Morton, O.: Is this what it takes to save the world?, Nature, 447, 132–136, 2007.

Oberdorster, G., Sharp, Z., Atudorei, V., Elder, A., Gelein, R., Kreyling, W., and Cox, C.: Translocation of inhaled ultrafine particles to the brain, Inhal. Toxicol., 16, 437–445, 2004.

Patz, J. A., Campbell-Lendrum, D., Holloway, T., and Foley, J. A.: Impact of regional climate change on human health, Nature, 438, 310–317, 2005.

Pincus, R. and Baker, M. B.: Effect of Precipitation on the Albedo Susceptibility of Clouds in the Marine Boundary-Layer, Nature, 372, 250–252, 1994.

Pope, C. A. and Dockery, D. W.: Health effects of fine particulate air pollution: Lines that connect, J. Air Waste Manage., 56, 709–742, 2006.

Rahmstorf, S., Cazenave, A., Church, J. A., Hansen, J. E., Keeling, R. F., Parker, D. E., and Somerville, R. C. J.: Recent climate observations compared to projections, Science, 316, p. 709, 2007.

Ramanathan, V. and Carmichael, G.: Global and regional climate changes due to black carbon, Nat. Geosci., 1, 221–227, 2008.

Samoli, E., Analitis, A., Touloumi, G., Schwartz, J., Anderson, H. R., Sunyer, J., Bisanti, L., Zmirou, D., Vonk, J. M., Pekkanen, J., Goodman, P., Paldy, A., Schindler, C., and Katsouyanni, K.: Estimating the exposure-response relationships between particulate matter and mortality within the APHEA multicity project, Environ. Health Persp. 113, 88–95, 2005.

Schlesinger, R. B., Kunzli, N., Hidy, G. M., Gotschi, T., and Jerrett, M.: The health relevance of ambient particulate matter characteristics: Coherence of toxicological and epidemiological inferences, Inhal. Toxicol., 18, 95–125, 2006.

Shindell, D. and Faluvegi, G.: Climate response to regional radiative forcing during the twentieth century, Nat. Geosci., 2, 294–300, 2009.

Skeie, R. B., Fuglestvedt, J., Berntsen, T., Lund, M. T., Myhre, G., and Rypdal, K.: Global temperature change from the transport sectors: Historical development and future scenarios, Atmos. Environ., 43, 6260–6270, 2009.

Twomey, S.: Pollution and Planetary Albedo, Atmos. Environ., 8, 1251–1256, 1974.

Unger, N., Bond, T. C., Wang, J. S., Koch, D. M., Menon, S., Shindell, D. T., and Bauer, S.: Attribution of climate forcing to economic sectors, P. Natl. Acad. Sci. USA, 107, 3382–3387, 2010.

Vedal, S.: Ambient particles and health: Lines that divide, J. Air Waste Manage., 47, 551–581, 1997.

Winebrake, J. J., Corbett, J. J., Green, E. H, Lauer, A., and Eyring, V.: Mitigating the Health Impacts of Pollution from Oceangoing Shipping: An Assessment of Low-Sulfur Fuel Mandates, Environ. Sci. Technol., 43, 4776–4782, 2009.