Atmos. Chem. Phys. Discuss., 13, 24023–24050, 2013
www.atmos-chem-phys-discuss.net/13/24023/2013/
doi:10.5194/acpd-13-24023-2013

Atmospheric Chemistry and Physics Open Access Discussions

Modeled global effects of airborne desert dust on air quality and premature mortality

D. Giannadaki[1], **A. Pozzer**[2], **and J. Lelieveld**[1,2]

[1]The Cyprus Institute, P.O. Box 27456, 1645 Nicosia, Cyprus
[2]Max Planck Institute for Chemistry, Hahn-Meitnerweg 1, 55128, Mainz, Germany

Received: 19 July 2013 – Accepted: 1 September 2013 – Published: 11 September 2013

Correspondence to: D. Giannadaki (d.giannadaki@cyi.ac.cy)

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

Abstract

Fine particulate matter is one of the most important factors contributing to air pollution. Epidemiological studies have related increased levels of atmospheric particulate matter to premature human mortality caused by cardiopulmonary disease and lung cancer. However, a limited number of investigations have focused on the contribution of airborne desert dust particles. Here we assess the effects of dust particles with an aerodynamic diameter smaller than 2.5 µm ($DU_{2.5}$) on human mortality for the year 2005. We used the EMAC atmospheric chemistry general circulation model at high resolution to simulate global atmospheric dust concentrations. We applied a health impact function to estimate premature mortality for the global population of 30 yr and older, using parameters from epidemiological studies. We estimate a global cardiopulmonary mortality of about 402 thousand and about 10 thousand by lung cancer in 2005. The associated years of life lost are about 3.47 million and 96 thousand per year due to cardiopulmonary disease and lung cancer, respectively. We estimate the global fraction of the cardiopulmonary and lung cancer deaths caused by atmospheric desert dust to be about 1.7 %, though in the 20 countries most affected by dust this is much higher, about 15–50 %. These countries are primarily found in the so-called "dust belt" from North Africa across the Middle East and South Asia to East Asia.

1 Introduction

Increased levels of fine particles in the air from anthropogenic and natural origin show that air quality has decreased on regional and global scales (Akimoto, 2003, Gerasopoulos et al., 2006; IPCC, 2007; Anenberg et al., 2010; Van Donkelaar et al., 2010; EEA, 2012). A large number of epidemiological studies have demonstrated that atmospheric particulate matter (PM) pollution causes morbidity and premature mortality. The long term exposure to fine particulate matter with an aerodynamic diameter smaller than 2.5 µm ($PM_{2.5}$) is associated with adverse health impacts including an increased risk of premature mortality by cardiopulmonary disease and lung cancer (Cohen et al., 2005; Krewski et al., 2009; Pope et al., 2009; Lepeule et al., 2012; Lim et al., 2012).

Because of their small size $PM_{2.5}$ particles can penetrate the deep parts of the lungs and the smallest ones even the alveoli, the gas exchange cavities of the lungs. Particles of a size smaller than about 0.1 µm can pass into the blood and affect other organs. The fine $PM_{2.5}$ particles can lead to cardiopulmonary and lung cancer health risks and premature mortality. Most of the studies that relate air quality and human health have focused on the impact of anthropogenic particulate matter (such as PM by combustion engines). Relatively little work has been devoted to the impact of natural $PM_{2.5}$ such as mineral dust. In the atmosphere large amounts of desert dust can travel thousand kilometers from their sources, which represents one of the main natural contributions to airborne PM (Kojima et al., 2006; Mahowald et al., 2010; Ginoux et al., 2012).

In many regions the levels of $PM_{2.5}$ exceed by far the WHO limit ($10\,\mu g\,m^{-3}$) and the European Standard on Ambient Air Quality and Cleaner Air for Europe ($25\,\mu g\,m^{-3}$, Directive 2008/50/EC) due to regular dust events. North Africa and the Middle East are the main dust sources (over 60 % of the global dust load), and therefore the potential risk to health is higher for populations in these regions. South and East Asia, with high population densities, are also affected by severe dust events. Unfortunately, in these parts of the world epidemiological studies and adequate air quality data are lacking. Several studies mention adverse health effects of the cardiorespiratory system and lungs that are associated with dust, but very few present quantitative results (De Longueville et al., 2010, 2013). The Global Burden of Disease (GBD) assessment for 2010 includes desert dust as part of $PM_{2.5}$ pollution though did not define the dust related mortality explicitly (Lim et al., 2012).

In this work we assess the long-term effect of airborne desert dust particles with an aerodynamic diameter smaller than 2.5 µm ($DU_{2.5}$) on human mortality for the year 2005 in the 231 countries as reported by the United Nations. We also estimate the associated annual years of life lost. We use a high-resolution global atmospheric chemistry-climate general circulation model to simulate global atmospheric dust concentrations. Subsequently, we apply a health impact function to estimate premature mortality for the global population of 30 yr and older in 2005. We use epidemiological parameters from cohort epidemiological studies. We follow the same methodology as Lelieveld et al. (2013) who applied the same model and health impact function to assess the premature mortality caused by anthropogenic $PM_{2.5}$ and O_3 pollution for the global population of 30 yr and older in the same period. In the following section we present the methodology and the data we used for this analysis.

2 Methodology

We use the following human health impact function to estimate the global annual premature mortality due to airborne desert dust ($DU_{2.5}$) (Anenberg et al., 2010; Lelieveld et al., 2013). This health impact function relates changes in pollutant concentrations to changes in mortality:

$$\Delta Mort = y_0(1 - e^{-\beta \Delta X})Pop, \tag{1}$$

where $\Delta Mort$ is the change in annual mortality due to a pollutant (in our study airborne desert dust), y_0 is the baseline mortality rate (BMR) for a given population, β is the concentration response function (CRF), ΔX the change in concentration of a given pollutant X relative to clean conditions, and Pop is the total population with an age of 30 yr and older exposed to the pollutant. This age category coincides with the epidemiological studies in which the CRFs for different causes of mortality have been derived.

BMR data describe the number of deaths in a particular year for the population under consideration. These data were obtained from the World Health Organization (WHO) Statistical Information System on the country-level (WHO, 2012), based on the International Classification of Diseases 10th Revision (ICD-10) classification system. The range of ICD-10 codes used in this study for cardiopulmonary mortality is I00–I99, J00–J99, and for lung cancer mortality is C33–C34. For the countries for which the WHO does not provide national mortality data for the specific year and the relevant diseases, the appropriate WHO sub-regional level BMR data were used for each country (the Global Burden of Disease: 2004 update, WHO, 2008). Country level data were used for 36 countries and regional data were assigned to 195 countries (in total 231 countries as documented by the United Nations and CIESIN). The assigning of sub-regional data to country level BMR does not lead to significant uncertainty in the analysis. The calculated ΔMort scales linearly with the BMR so that countries and regions with relatively high baseline mortality rates have proportionally higher excess mortality due to air pollution.

The CRF describes the increased risk of a population to certain diseases when exposed to a particular pollutant. In this study, the CRF has been derived from the log-linear relationship between the change in pollutant concentration and the relative risk (RR) of health impacts, as established in epidemiological cohort studies and given by the function:

$$RR = e^{\beta \Delta X} \tag{2}$$

We used the *RR*s from the epidemiological study by Krewski et al. (2009) to derive the CRFs for $DU_{2.5}$. Krewski et al. used data from the American Cancer Society (ACS) Cancer Prevention Study II (CPS-II) cohort, which included participants who were at least 30 yr in age at the time of enrollment. For detailed information about the CRFs used in this study we refer to Krewski et al. (2009), as discussed by Lelieveld et al. (2013). According to this cohort study a 10 µg m^{-3} increase in the concentration of $PM_{2.5}$ is associated with an increase of 12.9 % (95 % CI: 9.5–16.4 %) in cardiopulmonary (CPD) and 13.7 % (95 % CI: 5.6–22.5 %) in lung cancer mortality. Thus the mortality risk for cardiopulmonary disease (CPD) is RR = 1.129, giving a CRF = 0.012133. The mortality risk for lung cancer is RR = 1.137 and yields a CRF = 0.012839.

Because of the lack of epidemiological studies about the impact on premature mortality due to the long-term exposure to desert dust, the concentration response functions applied here have been based on epidemiological cohort studies by the American

Cancer Society (ACS), which may not be representative for other countries. For regions that are strongly affected by desert dust particulates and also have different living conditions compared to the USA, like in many African, Middle East and Asia regions (with high baseline mortality rates), the ACS results are likely to be less representative (Cohen et al., 2005). Similarly as the GBD assessment (Lim et al., 2012), we assume that $DU_{2.5}$ affects human health the same way as $PM_{2.5}$ in the ACS cohort study and therefore we implicitly assume that particle size matters more than their composition.

The concentrations of dust ($DU_{2.5}$) we used for the year 2005 were obtained by Pozzer et al. (2012a, b) applying the EMAC atmospheric chemistry-climate general circulation model (Jöckel et al., 2006; Pringle et al., 2010; de Meij et al., 2012; Astitha et al., 2012). We assumed for the global background a dust concentration of $7.5\,\mu g\,m^{-3}$ below which no premature mortality occurs (Cohen et al., 2005; Ezzati et al., 2002). Our main analysis is based on the $7.5\,\mu g\,m^{-3}$ background concentration, although there are studies that indicate health impacts even at lower concentrations. In Sect. 4 we will discuss sensitivity calculations for which different background concentrations are used.

The model has a horizontal resolution of about $1.1^{\circ} \times 1.1^{\circ}$ (~100 km latitude and longitude near the equator), and a vertical resolution of 31 levels up to the lower stratosphere. Near-surface concentrations were used for this study, i.e. being the average in the lowest model level extending over about 60 m. We used 2005 median dust $DU_{2.5}$ concentrations due to the episodic nature of desert dust outbreaks, transport and deposition, and the intra-annual variability of these outbreaks. In the sensitivity analysis we discuss how the mortality rates change if we consider annual mean rather than median $DU_{2.5}$ concentrations. Model evaluation based on in situ and remote sensing observations indicates that the simulations reproduce the atmospheric distribution of dust in time and space. The seasonal distribution of aerosol optical depth is well represented by the model, and the model results largely agree with observed $PM_{2.5}$ and desert dust concentrations and deposition (Pozzer et al., 2012a, b; de Meij et al., 2012; Astitha et al., 2012).

We used population statistics for the year 2005, on a country level from the United Nations Department of Economic and Social Affairs (UNDES 2011) database and gridded global population numbers from the Columbia University Center for International Earth Science Information Network (CIESIN) database with a resolution of 2.5 × 2.5 arc-minutes (about 0.04° × 0.04°; CIESIN, 2005). We used the global population of 30 yr and older for the population variable (Pop) in the health impact function to be consistent with the ACS CPS-II cohort epidemiological research. The global population of 30 yr and older was computed by applying the fraction of people of age ≥ 30 in each country, to the appropriate grid cells of CIESIN data to obtain the total and gridded target populations.

We also estimate the years of life lost (YLL) of the defined populations (30 yr and older) by applying the calculated premature mortality caused by dust pollution to the following function:

$$\Delta YLL = \Delta Mort(YLL_0/y_0) \tag{3}$$

where ΔYLL is the YLL due to premature mortality caused by airborne desert dust $DU_{2.5}$, YLL_0 is the baseline YLL and y_0 is the baseline mortality rate. Baseline YLL refer to years of life lost from cardiopulmonary diseases and lung cancer. Data were obtained from the WHO Health Statistics and Health Information System for the year 2004 with 3 % discounting and age weights, where younger ages are given a higher weight than the later years in an individual's life (WHO, 2008).

The used health impact function and RRs are based on the most comprehensive epidemiological cohort studies available, and are widely acknowledged as being the most representative (for a discussion we refer to Lelieveld et al., 2013). In the next section we present the calculated global dust $DU_{2.5}$ concentrations, the premature (excess) mortality due to dust and the associated YLL. The calculations have been performed at the resolution of the most detailed dataset (i.e., 0.04° of the population data) and then aggregated to higher levels up to those of countries.

3 Results

The global median modeled dust $DU_{2.5}$ concentrations ($\mu g\,m^{-3}$) for 2005 are presented in Fig. 1. To calculate the premature mortality due to long term exposure to desert dust we applied a “clean air” global background dust concentration threshold of $7.5\,\mu g\,m^{-3}$, below which we assume that dust does not have negative effects on human health. Model calculated regional distributions and budgets of aerosol pollution are discussed in Pozzer et al. (2012b). The regions most strongly affected by mineral dust particles are North Africa, the Middle East, South and East Asia.

Applying the health impact function (Eq.1) for the population of 30 yr in age and older to our model output suggests a significant contribution of desert dust to premature human mortality. We estimate that the exposure of the global population (≥30 yr) to ambient $DU_{2.5}$ levels in the year 2005 caused about 402 thousand premature deaths by cardiopulmonary disease, CPD (i.e. an annual mortality of 137 per million capita), and about 10 thousand by lung cancer (3 deaths per million capita per year).

The countries with the highest premature mortality in 2005, caused by CPD, are Egypt with about 70 thousand, Pakistan with about 52 thousand, and Nigeria with 41 thousand. Other countries with high mortality due to dust are China, Sudan, India, Iraq, Saudi Arabia, Iran, and Niger with several thousand premature deaths. Unsurprisingly, these countries are located in the “dust belt”, an area of strong desert dust sources that extends from the west coast of North Africa, through the Middle East, South and Central Asia to eastern China. When premature mortality is normalized to the number of individuals the country ranking changes significantly, with Mauritania, Niger and Iraq being the top three countries with highest per capita excess mortality, followed by Egypt, Mali, Chad, Sudan, Senegal, Saudi Arabia, and Turkmenistan (Table 1). Egypt, Pakistan and Nigeria, which are the top three countries in absolute numbers, are the 4th, 20th, and 19th, respectively, in the per capita ranking. This is related to the much higher population densities of the latter three countries compared to Mauritania, Niger and Iraq. An estimated global total of about 3.47 million yr of life lost (YLL) is caused by dust-induced CPD.

Dust has a less extensive impact through lung cancer mortality compared to CPD although the numbers of deaths are still highly significant (globally about 10 thousand people in 2005). The countries with highest premature mortality caused by dust-induced lung cancer are China with about 2.5 thousand deaths, Pakistan with about 1.3 thousand, Egypt with about 800, and Sudan, Iraq, Nigeria, India, Saudi Arabia, Iran and Turkmenistan with several hundred deaths per year. The ranking of countries with the highest per capita mortality differs from the absolute ranking, with Turkmenistan, Iraq and Mauritania being the top three (Table 1). Similar to the CPD mortality rankings this difference is related to the smaller population densities in the latter countries. Globally, dust particles are estimated to cause about 96 thousand years of life lost due to lung cancer. Also unsurprisingly, almost all lung cancer mortality is found to occur in the dust belt.

The global premature mortality by cardiopulmonary disease and lung cancer due to the long-term exposure to desert dust with an aerodynamic diameter $\leq 2.5\,\mu m$ is shown in Fig. 2. Table 1 shows the top 20 countries with the highest CPD and lung cancer mortality, and the top 20 countries with the highest per capita mortality. In Table 2 we present the percentage ratio of the country mortality due to CPD diseases and lung cancer caused by inhaling dust particles relative to the total (all causes) CPD, and lung cancer mortality. We estimate that about 53 % of the total CPD mortality in Mauritania and Niger is related to airborne desert dust. Iraq and Saudi Arabia are the third and the fourth in the ranking with about 35 % and 34 % respectively, Egypt follows with about 32 % and Mali with 30 %. In total 15 countries in and around the dust belt zone have a ratio of 20 % and higher, while about 1.8 % of the total global CPD mortality is caused by the long-term exposure to desert dust $DU_{2.5}$. The ratios and ranking of the countries are similar for the case of lung cancer (Table 2).

Mauritania and Niger are the top two in the ranking with about 55 % of the total lung cancer mortalities attributed to airborne desert dust, and Iraq follows with about 36 %.

In total 16 countries have a ratio of 20 % and higher, while 0.7 % of the total global lung cancer mortality is related to the long-term exposure to desert dust. Mauritania, Niger and some other countries in the dust belt are very close to the main Saharan dust sources, and the populations are exposed to high concentrations of $DU_{2.5}$ throughout the year (median concentrations in inhabited areas from 20 to 150 $\mu g\, m^{-3}$ or more, and much higher annual mean concentrations). The fraction of the population ≥ 30 yr in some of these countries is relatively small and the baseline mortality rates high (WHO, 2003).

4 Sensitivity calculations

For our central calculations we used a threshold dust concentration of 7.5 $\mu g\, m^{-3}$, assuming that below this level the long-term exposure to $DU_{2.5}$ does not contribute to mortality. Similar thresholds for $PM_{2.5}$ were also applied in several previous studies (Ezzati et al., 2002; Ostro, 2004; Cohen et al., 2005). In contrast, some studies assume that $PM_{2.5}$ can be harmful for human health even at lower concentrations (WHO, 2004, 2005). Since the use of such thresholds is not unambiguous, we performed a sensitivity analysis assuming different threshold concentrations, i.e. 0, 5, and 10 $\mu g\, m^{-3}$ and apply the same methodology to compare to our central results (with 7.5 $\mu g\, m^{-3}$).

When we do not assume a threshold concentration, we estimate that the exposure of the global population of age 30 yr and older to ambient $DU_{2.5}$ levels in the year 2005 caused about 849 thousand deaths by CPD (290 deaths per million capita) and about 28 thousand by lung cancer (9 deaths per million capita). When we assume a threshold of 5 $\mu g\, m^{-3}$, we estimate an excess mortality of about 476 thousand deaths by CPD (162 deaths per million capita) and 12 thousand by lung cancer (4 deaths per million capita). For the case of the highest threshold of 10 $\mu g\, m^{-3}$ we estimate 352 thousand deaths by CPD (120 deaths per million capita) and 8 thousand by lung cancer (3 deaths per million capita). The associated total (from both CPD and lung cancer) years of life

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

lost are about 7.2, 4.1 and 3.1 million years respectively (for 0, 5, 10 $\mu g\,m^{-3}$). Fig. 3 shows the calculated global annual mortality due to $DU_{2.5}$ for 2005 for the 4 cases.

The comparison of the theoretical case of non-dust (zero background concentration) in the atmosphere to our central results (7.5 $\mu g\,m^{-3}$) yields about 2.1 times higher CPD mortality and 2.8 times higher lung cancer mortality. The use of 5 $\mu g\,m^{-3}$ as the global background dust concentration increases CPD and lung cancer mortality due to $DU_{2.5}$ by about 1.2 times compare to the 7.5 $\mu g\,m^{-3}$ threshold, while the use of 10 $\mu g\,m^{-3}$ somewhat decreases the annual mortality (about 0.9 times relative to the 7.5 $\mu g\,m^{-3}$ for both CPD and lung cancer). The number of countries with significant numbers of deaths expands by reducing the background from 7.5 $\mu g\,m^{-3}$ to 0 dust concentrations, including countries from other regions like Turkey, USA, Russia, Ukraine, Japan, Mexico, Italy, Greece, Brazil, Spain and others. Therefore, by applying 7.5 $\mu g\,m^{-3}$ our results may be considered conservative.

In a second sensitivity test we used the *mean* instead of the 2005 *median* dust ($DU_{2.5}$) concentrations. In the long term health impact studies and reports as well as in the European and United States Clean Air Directives annual mean concentrations are used for the particulate matter pollution. As mentioned earlier, in this study we used for our main analysis median concentrations to limit the effect of severe episodic dust outbreaks, which would drive annual mean concentrations towards much higher levels. The justification for using the median is that during severe dust events people might limit exposure by avoiding outdoor activity. It is however interesting to examine how the excess mortality would change if we use annual mean concentrations for our calculations. For this case study we use the 7.5 $\mu g\,m^{-3}$ threshold dust concentration.

Following the same methodology, we calculate about 622 thousand premature deaths from CPD (212 per million capita), and 16 thousand from lung cancer (6 per million capita) globally. Hence the use of annual mean $DU_{2.5}$ concentrations in the health impact function (Eq. 1) increases the excess mortality by more than half to 220 thousand individuals by CPD and 6 thousand by lung cancer compared to the central study with median dust concentrations. The associated years of life lost are 5.3 million and 156 thousand years for CPD and lung cancer, respectively. The ranking of the countries with relatively high premature mortality is not significantly influenced by this assumption. Also because of this choice of using medians rather than means, our central results should be considered conservative.

5 Discussion

As indicated earlier there is a lack of epidemiological cohort studies in regions that are strongly affected by airborne desert dust, notably in the dust belt. The concentration response functions applied here have been based on epidemiological cohort studies by the American Cancer Society (ACS), which may not be representative for countries in which $DU_{2.5}$ dominates $PM_{2.5}$. The toxicity of chemical components of $PM_{2.5}$ in different parts of the world, the way each compound acts onto the cardiovascular and respiratory systems and the exposure conditions are not necessarily the same. In the countries in and around the dust belt, where exposure conditions may be different from the USA and where high baseline mortality rates prevail, region specific epidemiological cohort studies are needed (Cohen et al., 2005; De Longueville et al., 2013).

A critical assumption in this work is, therefore, that desert dust $DU_{2.5}$ is equally toxic as $PM_{2.5}$ in the ACS epidemiological study. Our estimates are based on this study, as it is one of the most comprehensive and also considered representative for other regions (COMEAP, 2009). The proportion of dust in this study, from which epidemiologic CRFs were derived, is not known so these response functions likely incorporate some impact of dust exposure. It should be emphasized that although some experts classify all $PM_{2.5}$ components as equally toxic, others consider $DU_{2.5}$ the least toxic aerosol constituent (Cooke et al., 2007). For that reason the premature mortality estimates presented here are chosen to be relatively conservative (i.e., using the median and 7.5 $\mu g\,m^{-3}$ threshold concentrations).

Many epidemiological studies have demonstrated that atmospheric $PM_{2.5}$ causes mortality and hospital admissions as a result of CPD and lung cancer. However, only a small number of studies examine the health responses due to Saharan and other dust sources (De Longueville et al., 2010, 2013; Karanasiou et al., 2012). These studies that address health effects of desert dust particles are based on time-series analyses in specific regions (e.g. Mediterranean cities). Time-series studies mainly assess the short-term effects of particulate matter pollution on health, by relating day-to-day variations in air pollution to mortality and morbidity counts within the same geographical area.

A systematic review by De Longuivelle et al. (2013) of the available literature on the relationship between desert dust, air quality and human health has highlighted notable gaps. Their survey emphasizes clear impacts of dust on human health and mortality in many parts of the world (e.g. Bell et al., 2008; Mallone et al., 2011; Nastos et al., 2011; Neophytou et al., 2013; Perez et al., 2008; Sajani et al., 2011, and others). Further, studies reported that in Korea, dust events are associated with increased daily mortality (Lee et al., 2007). Saharan dust outbreaks have been associated with an increased daily mortality of 8.4 % per 10 µg m^{-3} in PM$_{10-2.5}$ in Barcelona, Spain (Perez et al., 2008). Mallone et al. (2011) found evidence of effects of PM$_{2.5-10}$ and PM$_{10}$ on natural and cause-specific mortality in Rome, Italy, with stronger estimated effects on cardiac mortality during Saharan dust outbreaks. They estimated the respiratory mortality due to increases in PM$_{2.5-10}$ (10.8 µg m^{-3}) to range from 2.64 % to 12.65 % [with a 95 % confidence interval (CI) of 1.18–25.42 %]. Associations of PM$_{2.5-10}$ with cardiac induced mortality were stronger on Saharan dust days (9.73 %; 95 % CI, 4.25–15.49 %) than on dust-free days (0.86 %; 95 % CI, −2.47 % to 4.31 %). Neophytou et al. (2013) found a 2.43 % (95 % CI: 0.53, 4.37) increase in daily cardiovascular mortality associated with each 10 µg m^{-3} increase in PM$_{10}$ concentrations on dusty days.

De Longuivelle et al. (2013) pointed to the imbalance between the areas most exposed to dust and the areas most studied in terms of health effects. For example, health effects of dust in eastern Asian countries appear to be relatively frequently studied, as well as health effects due to Saharan and other desert dust sources in Europe and America. However, no study about the dust impact on health in West Africa has been published thus far, despite the proximity of the Sahara where dust events are more frequent and intense than anywhere else in the world. We hope that our estimates of high dust-induced mortality in African (and other) countries help motivate such studies.

Very little research has generally been done on the effects of natural mineral dust on human health. Our results on the global premature mortality rates caused by mineral dust cannot be directly compared to the above short-term effect studies, because our methodology is based on long-term epidemiological cohort studies. Our results nevertheless reinforce many of the previous findings, showing a substantial increase of mortality and morbidity in relation to dust events, which will hopefully help motivate continued epidemiological investigations, including cohort studies.

A detailed uncertainty analysis of our methodology is presented in Lelieveld et al. (2013). They carried out a statistical uncertainty analysis assuming random errors, by propagating the quantified errors of all terms in Eq. (1), estimated from the 95 % confidence intervals (CI95) reported in the ACS studies. The global averages show a statistical uncertainty range up to about ±5 %. At the country level the uncertainties are higher. Note that this analysis only addresses statistical uncertainty, while non-representativeness of the applied concentration response factors outside the USA and the toxicity issue mentioned above add to the uncertainty.

In this analysis we focus on the enhanced mortality due to mineral desert dust. Other sources like road dust, dust from industrial activities, agricultural and other human activities are not included as they are not represented in our emission data base. Further, our model does not account for re-suspension of dust after its deposition, which may be especially important in the urban environment. The impact of anthropogenic $PM_{2.5}$ on the dust properties is also not examined. Dust outbreaks may also cause health impacts due to the simultaneous atmospheric transport of anthropogenic pollution (Erel et al., 2007; Kallos et al., 2007) and of harmful micro-organisms (Polymenakou et al., 2008). It has been observed that dust particles rapidly mix with acids and organic components (Ma et al., 2010), which can be relevant for large urban and industrial centers (e.g., Cairo, Beijing, Tehran etc.) where both dust and anthropogenic pollution concentrations are high. In these areas it is likely that the toxicity of dust does not deviate from other particulate constituents of the same size category. Altogether, using the median rather than the mean, applying a threshold background level of 7.5 µg m^{-3}, not accounting for $DU_{2.5}$ sources other than desert dust, neglecting particle re-suspension and only accounting for the age category of ≥30 yr likely cause our estimates to represent a lower limit, in spite of $DU_{2.5}$ being perhaps less toxic than $PM_{2.5}$.

6 Conclusions

We applied a human health impact function to modelled global fine particulate matter concentrations to estimate the premature mortality caused by airborne desert dust with an aerodynamic diameter ≤2.5 µm in the year 2005. Our model results indicate a large number of premature deaths by cardiopulmonary disease and a significant number of deaths by lung cancer, mostly in the dust belt region between North Africa and eastern China. We estimate a total number of premature deaths of about 412 thousand from cardiopulmonary diseases and lung cancer, and 3.56 million years of life lost per year. The countries with the highest dust related mortality are Egypt, Pakistan, Nigeria, China, Sudan and other countries in and around the dust belt. If we consider the per capita mortality the ranking changes, with Mauritania, Niger, Iraq, Egypt and Mali being the top 5 counties with the highest per capita mortality. We estimate the global per capita mortality caused by $DU_{2.5}$ to be about 0.014 % per year, while the global fraction of the total cardiopulmonary and lung cancer deaths caused by exposure to desert dust is about 1.7 %.

We performed a sensitivity analysis by applying different background levels below which no health effects are assumed. The threshold concentration appears to sensitively influence our results, indicating more than twice the number of premature deaths (877 thousand/year) when we assume that no threshold exists below which $DU_{2.5}$ does not influence health compared to our central estimate (412 thousand/year for a 7.5 µg m^{-3} threshold concentration). If we use annual mean $DU_{2.5}$ concentrations for 2005 rather than median concentrations, the global number of premature deaths increases to 638 thousand/year (>1.5 times higher compared to our central estimate).

We stress that our results refer to the effects of fine particulate desert dust ($DU_{2.5}$) on the population of ≥30 yr based on the CRFs from the epidemiological study by Krewski et al. (2009) based on the ACS/CPS-II cohort, which can be expected to cause significant uncertainty in our calculations for regions and countries for which these data may not be representative (i.e. outside the USA and Europe). We nevertheless believe that our central estimates of premature mortality due to $DU_{2.5}$ are likely to represent lower limits.

Appendix A

Abbreviations and acronyms

ACS/CPS	American Cancer Society/Cancer Prevention Study
BMR	Baseline Mortality Rate
CI	Confidence Interval
CIESIN	Columbia University Center for International Earth Science Information Network
CRF	Concentration Response Function
CPD	Cardiopulmonary Disease
$DU_{2.5}$	Dust particles with an aerodynamic diameter smaller than 2.5 µm
ECHAM	European Centre Model Hamburg
EMAC	ECHAM/MESSy Atmospheric Chemistry, MESSy Modular Earth Submodel System
GBD	Global Burden of Disease
ICD-10	International Classification of Diseases – 10th revision
LC	Lung Cancer

Mort	Annual mortality
$PM_{2.5}$	Particulate Matter with an aerodynamic diameter smaller than 2.5 µm
$PM_{2.5-10}$	Particulate Matter with an aerodynamic diameter between 2.5 µm and 10 µm
PM_{10}	Particulate Matter with an aerodynamic diameter smaller than 10 µm
Pop	Total population with an age of $\geq$ 30 yr
RR	Relative Risk
UNDES	United Nations Department of Economic and Social Affairs
UNPD	United Nations Population Division
WHO	World Health Organization
YLL	Years of Life Lost

Acknowledgements. The research leading to these results has received funding from the European Research Council under the European Union's Seventh Framework Programme (FP7/2007-2013)/ERC grant agreement no. 226 144. We are grateful to John S. Evans and colleagues at the Cyprus International Institute for Environmental and Public Health for fruitful discussions.

References

Akimoto H.: Global air quality and pollution, Science, 302, 1716–1719, 2003.

Anenberg, S. C., Horowitz, L. W., Tong, D. Q., and West, J. J.: An estimate of the global burden of anthropogenic ozone and fine particulate matter on premature human mortality using atmospheric modeling, Environ. Health Perspect., 118, 1189–1195, 2010.

Anenberg, S. C., West, J. J., Horowitz, L. W., and Tong, D. Q.: The global burden of air pollution on mortality, Environ. Health Perspect., 119, 158–159, 2011.

Astitha, M., Lelieveld, J., Abdel Kader, M., Pozzer, A., and de Meij, A.: Parameterization of dust emissions in the global atmospheric chemistry-climate model EMAC: impact of nudging and soil properties, Atmos. Chem. Phys., 12, 11057–11083, doi:10.5194/acp-12-11057-2012, 2012.

Brook, R. D., Rajagopalan, S., Pope, C. A. III, Brook, J. R., Bhatnagar, A., Diez-Roux, A. V., Holguin., F., Hong, Y., Luepker., R. V., Mittleman, M. A., Peters, A., Siscovick, D., Smith Jr., S. C., Whitsel, L., and Kaufman, J. D.: Particulate matter air pollution and cardiovascular disease – An update to the scientific statement from the American Heart Association, J. Am. Heart Assoc., doi:10.1161/CIR.0b013e3181dbece1, 2010.

Brunekreef, B. and Holgate, S. T.: Air pollution and health, The Lancet, 360, 1233–1242, 2002.

Center for International Earth Science Information Network (CIESIN), Columbia University; United Nations Food and Agriculture Programme (FAO) and Centro Internacional de Agricultura Tropical (CIAT): Gridded Population of the World, Version 3 (GPWv3): Population Density Grid, Future Estimates. Palisades, NY: Socioeconomic Data and Applications Center (SEDAC), Columbia University, Available from http://sedac.ciesin.columbia.edu/gpw (last access: July 2012), 2005.

Cohen, A. J., Anderson, H. R., Ostra, B., Pandey, K. D., Krzyzanowski, M., Künzli, N., Gutschmidt, K., Pope, A., Romieu, I., Samet, J. M., and Smith, K.: The global burden of disease due to outdoor air pollution, J. Toxicol. Environ. Health, 68, 1–7, 2005.

Committee on the Medical Effects of Air Pollutants (COMEAP): Long-Term Exposure to Air Pollution: Effect on Mortality, Health Protection Agency, UK, ISBN 978-0-85951-640-2, 2009.

Cooke, R. M., Wilson, A. M., Tuomisto, J. T., Morales, O., Tainio, M., and Evans, J. S.: A probabilistic characterization of the relationship between fine particulate matter and mortality: Elicitation of European Experts, Environ. Sci. Technol., 41, 6598–6605, 2007.

De Longueville, F., Hountondji, Y.-C., Henry, S., and Ozer, P.: What do we know about effects of desert dust on air quality and human health in West Africa compared to other regions?, Sci. Total Environ. 409, 1–8, 2010.

De Longueville, F., Ozer, P., Doumbia, S., and Henry, S.: Desert dust impacts on human health: an alarming worldwide reality and a need for studies in West Africa, Int. J. Biometeorol., 57, 1–19, 2013.

De Meij, A., Pozzer, A., Pringle, K. J., Tost, H., and Lelieveld, J.: EMAC model evaluation and analysis of atmospheric aerosol properties and distribution, Atmos. Res., 114–115, 38–69, 2012.

Dockery, D. W., Pope, C. A. III, Xu, X., Spengler, J. D., Ware, J. H., Fay, M. E., Ferris, B. G., and Speizer, F. E.: An association between air pollution and mortality in six U.S. cities, N. Engl. J. Med., 329, 1753–1759, 1993.

Erel, Y., Kalderon-Asael, B., Dayan, U., Sandler, A.: European atmospheric pollution imported by cooler air masses to the Eastern Mediterranean during the summer, Environ. Sci. Technol., 41, 5198–5203, 2007.

Ezzati, M., Lopez, A. D., Rodgers, A., Hoorn, S. V., and Murray, C. J. L.: The Comparative Risk Assessment Collaborating Group: Selected major risk factors and global and regional burden of disease, Lancet, 360, 1347–1360, 2002.

European Environment Agency Technical Report: Particulate matter from natural sources and related reporting under the EU Air Quality Directive in 2008 and 2009, No. 10, 2012.

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D. W., Haywood, J., Lean, J., Lowe, D. C., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schulz, M., and Van Dorland, R.: Changes in Atmospheric Constituents and in Radiative Forcing. In: Climate Change 2007: The Physical Science Basis. Contribution of 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 and New York, NY, USA, 153–160, 2007.

Franck, U., Odeh, S., Wiedensohler, A., Wehner, B., and Herbarth, O.: The effect of particle size on cardiovascular disorders – The smaller the worse, Sci. Total Environ., 409, 4217–4221, 2011.

Gerasopoulos, E., Kouvarakis, G., Babasakalis, P., Vrekoussis, M., Putaud, J. P., and Mihalopoulos, N.: Origin and Variability of particulate matter (PM_{10}) mass concentrations over the Eastern Mediterranean, Atmos. Environ., 40, 4679–4690, 2006.

Ginoux, P., Prospero, J.M., Gill, T.E., Hsu, N.C., Zhao, M.: Global-scale attribution of anthropogenic and natural dust sources and their emission rates based on MODIS Deep Blue aerosol products, Rev. Geophys., 50, RG3005, 2012.

Jöckel, P., Tost, H., Pozzer, A., Brühl, C., Buchholz, J., Ganzeveld, L., Hoor, P., Kerkweg, A, Lawrence, M.G., Sander, R., Steil, B., Stiller, G., Tanarhte, M., Taraborelli, D., van Aardenne, J., Lelieveld, J.: The atmospheric chemistry general circulation model ECHAM5/MESSy: Consistent simulation of ozone from the surface to the mesosphere, Atmos. Chem. Phys., 6, 5067–5104, doi:10.5194/acp-6-5067-2006, 2006.

Kallos, G., Astitha, M., Katsafados, P., and Spyrou, C.: Long-Range transport of anthropogenically and naturally produced particulate matter in the Mediterranean and north Atlantic: current state of knowledge, J. Appl. Meteorol. Climatol., 46, 1230–1251, 2007.

Karanasiou, A., Moreno, N., Moreno, T., Viana, M., de Leeuv, F., and Querol, X.: Health effects from Saharan dust particles, ETC/ACM Technical Paper 2011/4, 2012.

Kojima, T., Buseck, P. R., Iwasaka, Y., Matsuki, A., and Trochkine, D.: Sulfate-coated dust particles in the free troposphere over Japan, Atmos. Res., 82, 698–708, 2006.

Krewski, D., Burnett, R. T., Goldberg, M. S., Hoover, K., Siemiatycki, J., Abrahamowicz, M., and White, W. H.: Part I: Replication and Validation. In: Reanalysis of the Harvard Six Cities Study and the American Cancer Society Study of Particulate Air Pollution and Mortality. A Special Report of the Institute's Particle Epidemiology Reanalysis Project, Health Effects Institute, Cambridge, MA, 2000a.

Krewski, D., Burnett, R. T., Goldberg, M. S., Hoover, K., Siemiatycki, J., Jerrett, M., Abrahamowicz, M., and White, W. H.: Part II. Sensitivity Analysis. In: Reanalysis of the Harvard Six Cities Study and the American Cancer Society Study of Particulate Air Pollution and Mortality. A Special Report of the Institute's Particle Epidemiology Reanalysis Project, Health Effects Institute, Cambridge, MA, 2000b.

Krewski, D., Jerrett, M., Burnett, R. T., Ma, R., Hughes, E., Shi, Y., Turner, M. C., Pope III, C. A., Thurston, G., Calle, E. E., and Thun, M. J.: Extended follow-up and spatial analysis of the American Cancer Society Study linking particulate air pollution and mortality, Health Effects Institute, Boston, MA, 2009.

Lee, J. T., Son, J. Y., and Cho, Y. S.: A comparison of mortality related to urban air particles between periods with Asian dust days and without Asian dust days in Seoul, Korea, 2000-2004, Environ Res., 105, 409–413, 2007.

Lelieveld, J., Barlas, C., Giannadaki, D., and Pozzer, A.: Model calculated global, regional and megacity premature mortality due to air pollution, Atmos. Chem. Phys., 13, 7023–7037, doi:10.5194/acp-13-7023-2013, 2013.

Lepeule, J., Laden, F., Dockery, D., and Schwartz. J.: Chronic exposure to fine particles and mortality: An extended follow-up of the Harvard Six Cities Study from 1974-2009, Environ. Health Perspect., 120, 965–970, 2012.

Lim, S. S., Vos, T., Flaxman, A. D., Danaei, G., and Shibuya, K.: A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: a systematic analysis for the Global Burden of Disease Study 2010, Lancet, 380, 2224–2260, 2012.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Ma, J., Chen, Y., Wang, W., Yan, P., Liu, H., Yang, S., Hu, Z., and Lelieveld, J.: Strong air pollution causes widespread haze-clouds over China, J. Geophys. Res., 115, D18204, doi:10.1029/2009JD013065, 2010.

Mahowald, N. M., Kloster, S., Engelstaedter, S., Moore, J. K., Mukhopadhyay, S., McConnell, J. R., Albani, S., Doney, S. C., Bhattacharya, A., Curran, M. A. J., Flanner, M. G., Hoffman, F. M., Lawrence, D. M., Lindsay, K., Mayewski, P. A., Neff, J., Rothenberg, D., Thomas, E., Thornton, P. E., and Zender, C. S.: Observed 20th century desert dust variability: impact on climate and biogeochemistry, Atmos. Chem. Phys., 10, 10875–10893, doi:10.5194/acp-10-10875-2010, 2010.

Mallone, S., Stafoggia, M., Faustini, A., Gobbi, G. P., Marconi, A., and Forastiere, F.: Effect of Saharan dust on the association between particulate matter and daily mortality in Rome, Italy, Environ. Health Perspect., 119, 1409–1414, 2011.

Nastos, P. T., Kampanis, N. A., Giaouzaki, K. N., and Matzarakis, A.: Environmental impacts on human health during a Saharan episode at Crete island – Greece, Meteorol. Zeitschr., 20, 517–529, 2011.

Neophytou, A., Yiallouros, P., Coull, B., Kleanthous, S., Pavlou, P., Pashiardis, S., Dockery, D., Koutrakis, P., and Laden, F.: Particulate matter concentrations during desert dust outbreaks and daily mortality in Nicosia, Cyprus, J. Exp. Sci. Environ. Epidemiol., 23, 275–280, 2013.

Ostro, B.: Outdoor air pollution: assessing the environmental burden of disease at national and local levels, World Health Organization (WHO) Environmental Burden of Disease Series No. 5, 2004.

Perez, L., Tobias, A., Querol, X., Künzli, N., Pey, J., Alastuey, A., Viana, M., Valero, N., González-Cabré, M., and Sunyer, J.: Coarse particles from Saharan dust and daily mortality, Epidemiology, 19,800–807, 2008.

Polymenakou, P. N., Mandalakis, M., Tselepides, A., and Stephanou, E. G.: Particle size distribution of airborne microorganisms and pathogens during an intensive African Event in the Eastern Mediterranean, Environ. Health Perspect., 116, 292–296, 2008.

Pope, C. A. III, Burnett, R. T., Thun, M. J., Calle, E. E., Krewski, Ito, K., and Thurston, G. D.: Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution, JAMA, 287, 1132–1141, 2002.

Pope III, C. A., Burnett, R. T., Thurston, G. D., Thun, M. J., Calle, E. E., Krewski, D., and Godleski, J. J.: Cardiovascular mortality and long-term exposure to particulate air pollution:

Epidemiological evidence of general pathophysiological pathways of disease, Circulation, J. Am. Heart Assoc., 109, 71–77, 2004.

Pope III, C.-A.„ Ezzati, M., and Dockery, D. W.: Fine-particulate air pollution and life expectancy in the United States, N. Engl. J. Med., 360, 376–386, 2009.

Pozzer, A., Zimmermann, P., Doering, U. M., van Aardenne, J., Tost, H., Dentener, F., Janssens-Maenhout, G., and Lelieveld, J.: Effects of business-as-usual anthropogenic emissions on air quality, Atmos. Chem. Phys., 12, 6915–6937, doi:10.5194/acp-12-6915-2012, 2012a.

Pozzer, A., de Meij, A., Pringle, K. J., Tost, H., Doering, U. M., van Aardenne, J., and Lelieveld, J.: Distributions and regional budgets of aerosols and their precursors simulated with the EMAC chemistry-climate model, Atmos. Chem. Phys., 12, 961–987, doi:10.5194/acp-12-961-2012, 2012b.

Pringle, K. J., Tost, H., Message, S., Steil, B., Giannadaki, D., Nenes, A., Fountoukis, C., Stier, P., Vignati, E., and Lelieveld, J.: Description and evaluation of GMXe: a new aerosol submodel for global simulations (v1), Geosci. Model Dev., 3, 391–412, doi:10.5194/gmd-3-391-2010, 2010.

Sajani, S. Z., Miglio, R., Bonasoni, P., Cristofanelli, P., Marinoni, A., Sartini, C., Goldoni, C. A., De Girolamo, G., and Lauriola, P.: Saharan dust and daily mortality in Emilia-Romagna (Italy), Occup. Environ. Med., 68, 44–451, 2011.

Samet, J. M., Dominici, F., Curriero, F. C., Coursac, I., and Seger, S. L.: Fine particulate air pollution and mortality in 20 U.S. cities, 1987-1994; New Eng. J. Med., 343, 1742–1749, 2000.

Solomon, P. A., Wexler, A. S., and Sioutas, C.: Special issue of Atmospheric Environment for air pollution and health: Bridging the gap from sources-to-health outcomes, Atmos. Environ., 45, 7537–7539, 2011.

United Nations Department of Economic and Social Affairs (UNDES), Population Division: World Population Prospects: the 2010 Revision, population data files of the UNDES, available at: http://esa.un.org/unpd/wpp (last access: 28 June 2011), 2011.

Van Donkelaar, A., Martin, R. V., Brauer, M., Kahn, R., Levy, R., Verduzco, C., and Villeneuve, P. J.: Global estimates of ambient fine particulate matter concentrations from satellite-based aerosol optical depth: Development and application, Environ. Health Perspec., 118, 847–885, 2010.

WHO (World Health Organization): The world health report, 2003.

WHO (World Health Organization): Health Aspects of Air Pollution, 2004.

WHO (World Health Organization): Air quality guidelines, Global update 2005.

WHO (World Health Organization): The global burden of disease: 2004 update, Health Statistics and Health Information Systems (WHOSIS), Geneva, mortality data files of the WHO regional burden of disease estimates for 2004, available at: http://www.who.int/healthinfo/global_burden_disease/estimates_regional/en/index.html (last access: 2008), 2008.

WHO (World Health Organization): World Health Organization, Health Statistics and Health Information Systems (WHOSIS), Geneva, data files of the WHO Mortality Database, available at: http://www.who.int/healthinfo/statistics/mortality_rawdata/en/index.html (last access: 26 November 2012), 2012.

Table 1. Top twenty countries with the highest annual premature cardiopulmonary and lung cancer mortality for the population ≥ 30 yr old in 2005.

DUST ($DU_{2.5}$)								
	Cardiopulmonary mortality				Lung cancer			
	Total (thousands)		% per capita		Total (thousands)		% per capita	
1	Egypt	70	Mauritania	0.46	China	2.5	Turkmenistan	0.013
2	Pakistan	52	Niger	0.46	Pakistan	1.3	Iraq	0.007
3	Nigeria	41	Iraq	0.29	Egypt	0.8	Mauritania	0.006
4	China	32	Egypt	0.26	Sudan	0.6	Niger	0.006
5	Sudan	25	Mali	0.25	Iraq	0.5	Sudan	0.006
6	India	23	Chad	0.24	Nigeria	0.5	Saudi Arabia	0.005
7	Iraq	22	Sudan	0.23	India	0.5	Kuwait	0.004
8	Saudi Arabia	19	Senegal	0.21	Saudi Arabia	0.4	United Arab Emirates	0.004
9	Iran	19	Saudi Arabia	0.21	Iran	0.4	Palestinian Territory	0.004
10	Niger	16	Turkmenistan	0.20	Turkmenistan	0.3	Mali	0.003
11	Algeria	11	Kuwait	0.18	Niger	0.2	Bahrain	0.003
12	Mali	8	United Arab Emirates	0.17	Algeria	0.1	Chad	0.003
13	Chad	6	Gambia	0.16	Morocco	0.1	Libyan Arab Jamahiriya	0.003
14	Senegal	6	Burkina Faso	0.13	Mali	0.1	Qatar	0.003
15	Morocco	5	Libyan Arab Jamahiriya	0.13	Syrian Arab Republic	0.1	Egypt	0.003
16	Burkina Faso	4	Bahrain	0.13	Yemen	0.1	Senegal	0.003
17	Syrian Arab Republic	4	Qatar	0.13	Afghanistan	0.1	Pakistan	0.003
18	Mauritania	4	Guinea-Bissau	0.12	Chad	0.1	Israel	0.002
19	Turkmenistan	4	Nigeria	0.11	Kazakhstan	0.1	Gambia	0.002
20	Yemen	4	Pakistan	0.10	Senegal	0.1	Mongolia	0.002

Table 2. Top twenty countries with the highest percentage of dust induced cardiopulmonary and lung cancer mortality relative to total CPD and LC mortality (for the population ≥ 30 yr old in 2005).

	Percent dust induced mortality relative to all causes			
	Cardiopulmonary		Lung cancer	
1	Mauritania	53	Mauritania	55
2	Niger	53	Niger	55
3	Iraq	35	Iraq	36
4	Saudi Arabia	34	Saudi Arabia	35
5	Egypt	32	Egypt	34
6	Mali	30	Mali	31
7	Kuwait	29	Kuwait	30
8	United Arab Emirates	28	United Arab Emirates	29
9	Chad	28	Sudan	29
10	Sudan	28	Chad	28
11	Senegal	24	Senegal	26
12	Libyan Arab Jamahiriya	21	Libyan Arab Jamahiriya	22
13	Bahrain	21	Bahrain	22
14	Qatar	21	Qatar	22
15	Turkmenistan	20	Turkmenistan	21
16	Gambia	19	Gambia	20
17	Burkina Faso	15	Burkina Faso	16
18	Oman	15	Oman	16
19	Guinea-Bissau	14	Guinea-Bissau	15
20	Syrian Arab Republic	13	Syrian Arab Republic	14

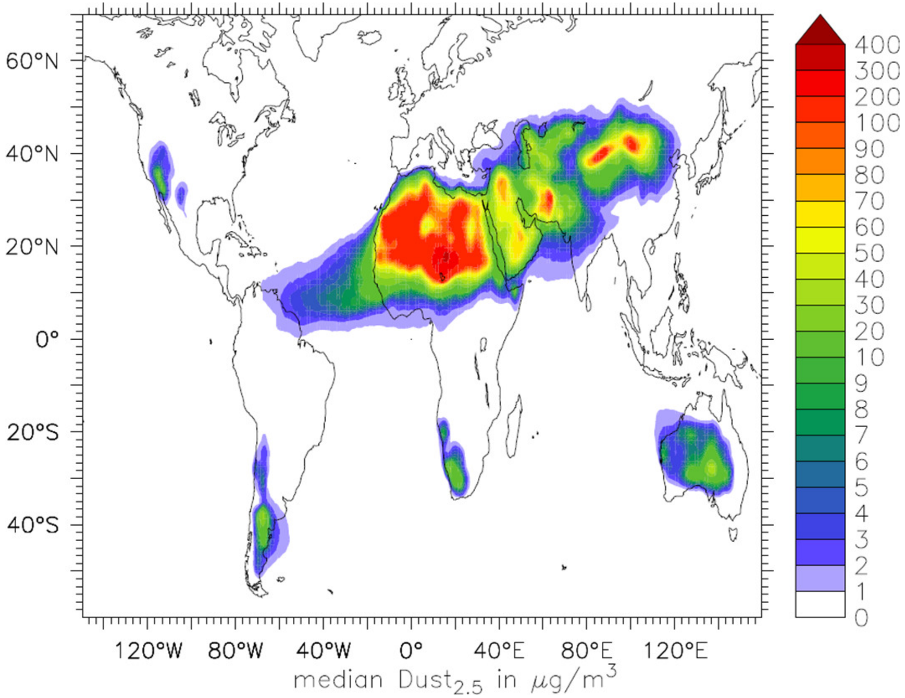

Fig. 1. Model calculated median dust concentrations (DU$_{2.5}$ in µg m^{-3}) in 2005.

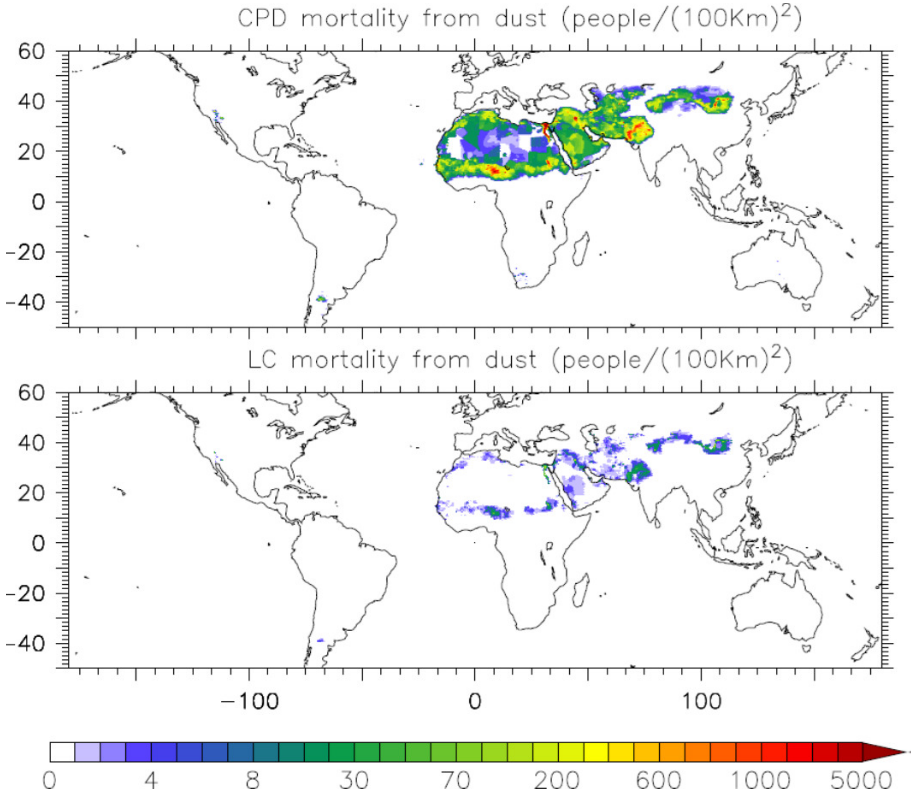

Fig. 2. Global premature mortality by cardiopulmonary disease (top) and lung cancer (bottom) (in individuals per 100 × 100 km^2) due to dust ($DU_{2.5}$) for the population ≥ 30 yr in 2005.

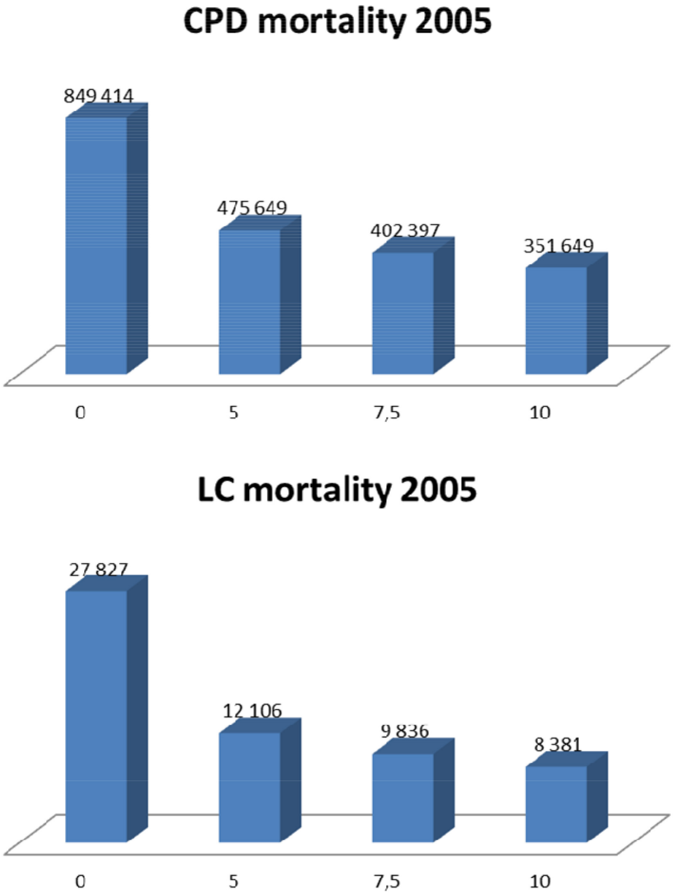

Fig. 3. Total premature mortality by cardiopulmonary disease (top) and lung cancer (bottom) due to dust ($DU_{2.5}$) for the population ≥ 30 yr in 2005. Mortality calculations are based on 4 different background dust concentrations (0, 5, 7.5 and 10 micrograms per cubic meter).