Huber, V., Ibarreta, D., Frieler, K. (2017): Cold- and heat-related mortality: a cautionary note on current damage functions with net benefits from climate change. - Climatic Change, 142, 3, 407-418

DOI: 10.1007/s10584-017-1956-6

Climatic Change, *Accepted 14 March 2017*

Cold and Heat Related Mortality: A Cautionary Note on Current Damage Functions with Net Benefits from Climate Change

Veronika Huber[1*], Dolores Ibarreta[2], Katja Frieler[1]

1 Potsdam Institute for Climate Impact Research, Telegraphenberg A 31, 14473 Potsdam, Germany

2 European Commission - Joint Research Center, Edificio EXPO, Calle Inca Garcilaso 3, 41092
Sevilla, Spain

*Corresponding author: huber@pik-potsdam.de

Abstract

Several economic assessments of climate change build on the assumption that reductions of cold-related mortality will overcompensate increases in heat-related mortality at least for moderate levels of global warming. Due to the lack of suitable epidemiological studies with sufficient spatial coverage, many of these assessments rely on one particular dataset: projections of temperature-related mortality in 17 countries published almost 20 years ago. Here, we reanalyse this dataset with a focus on cardiovascular mortality, and present evidence for two flaws in the original analysis, which would imply a significant bias towards finding net mortality benefits from climate change: i) the combination of mortality data for all ages with data specific to the elderly, and ii) the confounding of seasonal effects with direct temperature effects on mortality. This bias appears to be further amplified in the integrated assessment models FUND and ENVISAGE, and related economic assessment tools relying on the same calibration scheme, because heat-related cardiovascular mortality is assumed to affect urban populations only in these models. In an exemplary calculation, we show that while FUND currently projects a net reduction of approximately 380,000 deaths from cardiovascular diseases globally per year at 1°C of global warming, correcting for the two potential flaws and assuming equal vulnerability of urban and rural populations would result in a net increase of cardiovascular mortality, with approximately 150,000 net additional deaths globally per year. Our findings point to the urgent need of renewing damage functions on temperature-related mortality currently applied in some of the most widely used integrated assessment models.

Keywords: climate change impacts, human health, temperature-related mortality, damage function, integrated assessment model

Acknowledgements: The study was undertaken as part of a scientific collaboration between the Potsdam Institute for Climate Impact Research and the Joint Research Center of the European Commission. The views expressed are purely those of the authors and may not in any circumstances be regarded as stating an official position of the European Commission. We thank Simon Gosling and three anonymous referees for very helpful comments on earlier versions of the manuscript.

1 Introduction

Recent economic analyses have shown that human health impacts may contribute disproportionally to overall damage costs of climate change (e.g., Houser et al. 2015). Therefore, the specific form and parameterization of damage functions to describe climate-sensitive health outcomes in these assessments may critically influence the magnitude of estimated total damage costs.

Here, we are concerned with the epidemiological databasis on temperature-related mortality of one of the most widely used integrated assessment models (IAMs) FUND. When Tol (2002a, b) first integrated temperature-related mortality into FUND, it constituted a major step forward in integrated assessment modelling. While many other IAMs work with relatively few, broad impact categories (e.g., market and non-market impacts), FUND explicitly incorporates different sectors (i.e., human health, agriculture, sea level rise, etc.), for which quantitative knowledge on climate impacts exist.

One of the challenges with such 'bottom-up' approaches has always been to find datasets at suitable temporal and spatial resolution to construct damage functions, in particular for global-scale IAMs such as FUND. Specifically, most of the epidemiological studies, projecting temperature-related mortality under climate change, present their results only at the spatial resolution of small number of individual cities, regions, or countries (see review by Huang et al. 2011). The functions used in FUND to describe climate-induced changes in temperature-related mortality derive from a meta-analysis published almost twenty years ago (Martens 1998). At the time this meta-analysis constituted one of the few empirically based studies providing mortality projections with broader geographical scope (i.e., 17 countries worldwide).

Here, we reanalyse the data presented by Martens (1998), with the objective to test the robustness of one of Martens' major conclusions, namely that "[in most cities] global climate change is likely to lead to a reduction in mortality rates due to decreasing winter mortality". Our reanalysis reveals a number of questionable assumptions underlying Martens' results, including two potential flaws in the data handling. We subsequently investigate how the bias in Martens' mortality projections that result from these flaws propagates into FUND's empirical databases on temperature-related mortality. We find that the assumptions made by Tol (2002a) in the extrapolation of Martens' data to FUND regions further amplify the identified bias, contributing to the likely overestimating of net health benefits from climate change in the model.

Our findings are relevant today, although they concern epidemiological data published almost two decades ago, and they are relevant beyond FUND itself. The reason is that FUND has been used in several recent economic assessments of climate damages, including latest assessments of the social costs of carbon (SCC) for regulatory purposes in the UK and US (Fig. 1). Moreover, ENVISAGE (Roson and van der Mensbrugghe 2012), another broadly used IAM, ultimately relies on the same data as FUND through a prominent economic assessment of climate impacts on human health (Bosello et al. 2006) (Fig. 1). The latter together with original results of Martens (1998) have been influential in shaping the public opinion about climate impact on heat and cold related mortality (Lomborg 2007). Last but not least, due to the persistent lack of more up-to-date global estimates of temperature-related mortality impacts (Huang et al. 2011), Tol's equations have even be used in recent non-economic quantitative assessments of climate change impacts (Hayashi et al. 2010).

Our study goes beyond previous critique of the same data by Ackerman and Stanton (2008) by providing additional quantitative evidence for the likely bias in estimates of temperature-related mortality impacts underlying FUND, ENVISAGE and related economic assessments of climate damage costs. Ackerman and Stanton (2008) relate this bias to three conceptual shortcomings in the use of Martens' (1998) data by Tol (2002a) and Bosello et al. (2006): i) the lack of accounting for acclimatization in temperature-mortality relationships, ii) missing out on extreme events by neglecting daily temperature variability, and iii) the unsupported assumption that heat-related (cardiovascular) mortality does not affect rural populations. We revisit their third point of criticism, but embed this in a more detailed quantitative reanalysis of Martens (1998) and the use of his data in Tol (2002a). Because of the flaws we believe to reveal in their original analyses, our study provides important evidence that the update of damage formulations on temperature-related mortality in FUND and related economic assessment tools is indispensable now.

2 Material and Methods

2.1 Data Sources

We retrieved the relevant source data on published temperature-mortality relationships from Table 2 of Martens (1998) (Online Resource 1 Table S1). Out of the full dataset presented by Martens (1998), Tol (2002a) uses results for cardiovascular deaths in the age groups < and > 65 years, and heat-related respiratory deaths in all ages. Our reanalysis only concerns cardiovascular mortality, because projections for respiratory mortality are based on an extremely low sample size (one data point) and because Martens (1998) only documents projections for cardiovascular mortality in detail. We took the given projections of annual additional cardiovascular mortality (per 100,000 people) for a scenario of approximately 1.2 °C increase in global mean temperature (GMT) in 17 countries together with the corresponding age group specific mortality baselines from Table 3 of Martens (1998).

For the extrapolation of mortality projections to countries worldwide, we followed Tol (2002a) and extracted the minimum and maximum mean monthly temperatures in capital cities from the (updated) Leemans and Cramer (1991) database, which provides mean monthly temperatures on a global grid based on 1931-1960 climatology (Online Resource 1 Table S5). To derive total additional annual deaths in FUND regions, we used age-specific population data per country, for urban and total area, taken from the UN Population Division (2014). Tol (2002a) does not specify the exact source of the population data used in his analysis. As default we applied population data for the year 1990.

2.2 Outline of reanalysis

Our reanalysis consisted of the following four steps (Online Resource 1 Fig. S1).

1. Reassessment of V-shaped relationship between ambient temperature and changes in mortality. We followed Martens (1998) assuming a V-shaped relationship between ambient temperature and changes in mortality (Fig. 2), i.e. mortality rates increase linearly as temperatures drop below or rise above a site-specific minimum mortality temperature (MMT). We calculated combined effect estimates $\bar{\beta}$ (percent changes in mortality for a 1°C temperature change) as described by Martens (1998), weighting individual data points β_j by their inverse variance (square of the standard error s_j) as follows:

$$\bar{\beta} = \frac{\sum \frac{1}{s_j^2} \beta_j}{\sum \frac{1}{s_j^2}} \qquad (1)$$

where *j* indexes the epidemiological studies that entered Martens' meta-analysis (see Online Resource 1 Table S1). Estimates were derived separately for the cold and warm range (below and above MMT), and age groups < and > 65 years: $\overline{\beta}_{cold,<65}$, $\overline{\beta}_{warm,<65}$, $\overline{\beta}_{cold,>65}$, $\overline{\beta}_{warm,>65}$.

These calculations uncovered two questionable assumptions in the meta-analysis of Martens (1998). First, Martens integrated all-ages data into age-specific estimates in order to increase sample sizes (Martens, personal communication). Yet, one would expect that this choice creates a significant bias in the age group > 65 years, because older people are known to be especially vulnerable to temperature excursions from the comfort range, showing higher changes in mortality rates than the average population (Vardoulakis et al. 2014, Lee and Kim 2016). Second, the data points Martens extracted from Green et al. (1994) were suspiciously higher than any other data considered in the cold range (Fig. 2). Referring back to Green et al. (1994) showed that Martens considered simple differences between winter and summer mortality reported in this study (Online Resource 1 Table S2). Therefore, the data points from Green et al. (1994) entering Martens' meta-analysis obviously include seasonal effects not directly related to temperature, biasing results towards higher cold-related mortality (see e.g., Kinney et al. 2015 on the risk of confounding seasonal and temperature effects in the studies of temperature-related mortality).

To investigate the influence of these assumptions on Martens' mortality projections, we corrected for them one by one: i) excluding all ages data, ii) modifying estimates based on Green et al. (1994) by considering reported differences between cold and mild winters (aiming to isolate direct temperature effects; Online Resource 1 Table S3), and iii) applying both modifications together. These calculations resulted in a new set of revised estimates (denoted $\tilde{\beta}$ below) for each modification applied (Online Resource 1 Table S1).

2. *Revised projections of relative mortality changes for 17 countries.* Martens (1998) originally used monthly mean temperature projections for capital cities together with assumptions on city-specific MMTs (Online Resource 1 Table S4) to estimate changes in cardiovascular mortality due to climate change. Since we did not have access to these temperature projections we used the given data on country- and age-specific annual baseline mortalities ($B_{i,a}$), projected mortality changes ($C_{i,r,a}$) and weighted effect estimates ($\bar{\beta}_{r,a}$) to back-calculate an average annual measure of the applied local temperature changes (incorporating differences with respects to the city-specific MMTs and between the baseline and future climate), according to

$$\overline{\Delta T}_{i,r} = \frac{C_{i,r,a}}{B_{i,a}\bar{\beta}_{r,a}} \tag{2}$$

where *i* is the country index, *r* indexes the temperature range (warm or cold), and *a* defines the age group (< or >65 years) (the same indices are used in Eqs. 3-6). We chose to use data for age group > 65 years only here, because of the small absolute mortality numbers in age group < 65 years, which introduce large rounding errors (Online Resource 1 Fig. S2). Based on $\overline{\Delta T}_{i,r}$ and after rearranging Eq. 2, revised annual mortality estimates $\tilde{C}_{i,r,a}$ can be calculated according to

$$\tilde{C}_{i,r,a} = B_{i,a}\tilde{\beta}_{r,a}\overline{\Delta T}_{i,r} \tag{3}$$

We are aware that Eqs. 2 and 3 represent an extreme simplification compared to the standard method of deriving annual attributable mortality from temperature-mortality relationships at daily scale (e.g., Vardoulakis et al. 2014). Therefore, we tested the validity of this approach for the purpose of our study by reproducing part of the original mortality projections of Martens (1998) (Online Resource 1 Fig. S3).

3. Extrapolation of mortality change estimates to countries worldwide. We derived linear regression equations linking country-specific, cold- and heat-related mortality projections in the two age groups ($M_{i,r,a}$) with minimum and maximum mean monthly temperatures in capital cities ($T_{min,i}$, $T_{max,i}$) as done by Tol (2002a):

$$M_{i,cold,a} = p_0 + p_1 T_{min,i} \tag{4}$$

$$M_{i,warm,a} = p_0 + p_1 T_{max,i} \tag{5}$$

where p_0 and p_1 are regression parameters. We calculated four different sets of regression equations using i) original mortality projections of Martens (1998) ($C_{i,r,a}$), and ii) our revised projections ($\tilde{C}_{i,r,a}$), correcting separately as well as simultaneously for the two potential flaws in Martens (1998). Following Tol (2002a), we linearly rescaled given mortality projections to a 1°C increase in GMT (relative to the 1.16°C GMT increase considered by Martens (1998)), such that, e.g., $M_{i,r,a} = f C_{i,r,a}$ with $f \approx 0.862$. These equations, in addition to those given in Tol (2002a) (see Online Resource 1 Table S6) were used to extrapolate mortality projections to countries worldwide, resulting in a dataset comprising 188 countries.

4. Calculation of absolute mortality estimates and aggregation to FUND regions. Total aggregate number of additional annual deaths (D_r) were calculated using age-specific population data per country ($P_{i,a}$), and then summed across countries to yield results for the 9 FUND regions presented in Tol (2002a) and the world (Online Resource 1 Table S7 for definition of regions):

$$D_r = \sum_i \sum_a P_{i,a} M_{i,r,a} \tag{6}$$

Following Tol (2002a) we first assumed that heat only affects the urban population whereas cold affects the entire population. In a second step, we relaxed this assumption and calculated additional deaths from heat exposure based on total population data.

This step is important because recent epidemiological research suggests that rural populations might even be more vulnerable to heat than urban populations (Shi et al. 2015). We are aware of the fact that applying the same relationship to both urban and rural population introduces an additional error, because vulnerabilities are known to be different. However, since our main goal has been to test the sensitivity of FUND's parameterization to specific assumptions made in the underlying analyses by Martens (1998) and Tol (2002a), rather than providing a recalibration of FUND, we think our approach albeit simplistic is valid for the given purpose.

All data and programming code (Python 2.7.11) is available as Online Resource 2.

3 Results

Comparing the original temperature-mortality relationships of Martens (1998) with the results of our reanalysis (Fig. 2) shows that the two flaws we identified in his data handling have mainly two effects. First, Martens' decision to use data for all ages to parameterize age-group specific functions introduce a bias towards lower relative mortality change per 1°C warming in the age group > 65 years, especially in the warm range (Fig. 2b). Second, Martens' questionable way of extracting estimates from Green et al. (1994) leads to the overestimation of combined mortality change in the cold range in both age groups (compared to our reanalysis based on modified estimates from Green et al. 1994; Fig. 2).

In accordance, Martens would have projected considerable higher increases in heat-related mortality in the elderly (> 65 years) in nearly all of the 17 countries considered (Fig. 3) if he had excluded all ages data from the corresponding part of his meta-analysis. The results of our reanalysis also clearly show, that a considerable part of the reductions in cold-related mortality in the age group > 65 years reported by Martens (1998) are due to his misinterpretation of Green et al. (1994). The latter can also be seen in age group < 65 years, but differences between Martens' (1998) original projections and our reanalysis are generally smaller.

Next, we aimed at reproducing the extrapolation of Martens country-specific results to all countries and the subsequent aggregation to FUND regions as presented by Tol (2002a). Since the regression equations we derived based on Martens' original projections were not exactly the same as the equations given in Tol (2002a) (Fig. 4, Online Resource 1 Table S6), we used both sets of equations to extrapolate data to all countries. The corresponding aggregated mortality estimates at 1°C global warming for the 9 FUND regions and the world are qualitatively very similar to the data reported by Tol (2002a) (Fig. 5 a-c): Reduction in cold-related cardiovascular mortality overcompensate increases in heat-related cardiovascular mortality in all regions, with a considerable net reductions in annual deaths at the global level (in FUND approximately 380,000 fewer deaths annually, Online Resource 1 Table S8)

In order to investigate how the bias revealed in Martens (1998) translates into regional mortality projections underlying FUND's damage functions, we calculated an additional set of regression equations based on our reanalysis of Martens (1998), applying the two corrections simultaneously (Fig. 4) (for supplementary results, applying the corrections one at a time, see Online Resource 1 Fig. S4). The corresponding mortality projections for FUND region are quite different to the mortality data currently used in the model: increases in heat-related cardiovascular mortality now outweigh reductions in cold-related cardiovascular mortality in 4 out of 9 regions, with a much lower net balance of approximately 90,000 fewer deaths per year (Fig. 5d, Online Resource 1 Table S8).

In a last step, we tested the sensitivity of Tol's regional numbers to his assumption on the complete resistance of rural populations to heat-related cardiovascular stress. Using our reanalysis of Martens (1998) and now also assuming that heat affects both urban and rural populations, we find stronger absolute increases in heat-related mortality than reductions in cold-related mortality in all regions but CEE&FSU and OECD-E (Fig. 5e). Globally the net balance has now shifted from negative to positive with approximately 150,000 additional deaths annually (Online Resource 1 Table S8).

4 Discussion and conclusions

In this study, we set out to reproduce the empirical data basis on temperature-related cardiovascular mortality, entering FUND and other economic assessment tools relying on the same calibration scheme (e.g., ENVISAGE). Following Martens (1998) and Tol (2002a) to the extent possible, our estimates matched FUND's regional mortality projections for 1°C global warming with respect to a considerable net benefit of global warming due to strong reductions in cold-related mortality. Yet, addressing two flaws identified in the data handling of Martens (1998) and one questionable assumption made by Tol (2002a) indicated that both studies are likely biased towards finding a net reduction of mortality under global warming – a bias that is transmitted into the damage functions of FUND, ENVISAGE and related economic assessment tools.

Since we consider cardiovascular mortality only, while FUND also accounts for heat-related respiratory diseases, one could argue that our results on net mortality effects cannot be directly compared to FUND. Therefore, in a supplementary analysis we included the regional estimates on heat-related respiratory mortality presented by Tol (2002a) in the calculation of net effects (Online Resource 1 Fig. S4). As would be expected we find differences in absolute numbers and on the regional level, but the major qualitative difference between FUND and our reanalysis (a net reduction contrary to a net increase in global additional deaths) remains. It is also important to note that FUND currently ignores cold-related respiratory diseases, despite their albeit inferior to cardiovascular diseases but still non-negligible contribution to all-cause cold-related mortality (Ebi&Mills 2013).

One obvious conclusion from our study is that the damage functions on temperature-related mortality to date employed in FUND and ENVISAGE need to be urgently replaced. Hsiang (2016) recently outlined methodological requirements for empirical studies to measure the climate effect on economic and social outcomes (including human health), potentially providing the basis for improved calibrations of IAMs. In light of these requirements, both econometric and epidemiological research on temperature-related mortality has made major advances since the publication of Martens (1998) almost twenty years ago. In particular, improved methods now better account for temporal displacement (i.e., ‘harvesting’, and delayed cold effects) inherent in temperature-mortality relationships (Deschênes and Greenstone 2011, Gasparrini 2014). Due to the assemblage of large datasets on temperature-related mortality in cities (counties) across geographical regions and the development of customized meta-analytical approaches (Gasparrini et al. 2015a, Gasparrini et al. 2015b, Nordio et al. 2015) the first knowledge is emerging on factors that may explain across space and time differences in observed exposure-response curves. For example, there is now evidence that the increasing usage of air condition has strongly attenuated heat effects on mortality in the United States over time (Nordio et al. 2015, Barreca et al. 2016).

It has also been firmly established that populations across countries and world regions are acclimatized to their local climate, with MMTs dependent on latitudes or mean annual temperatures (Guo et al. 2014, Tobias et al. 2017). Similarly, recent literature confirms the finding of earlier studies (Kalkstein & Greene 1997) that due to acclimatisation current heat-mortality relationships are weaker in warmer cities (Barreca et al. 2016), translating into relatively smaller heat impacts expected under climate change (Schwartz et al. 2015). Furthermore, there is some indication that deviations of temperatures in the cold range exert stronger effects in regions with relatively mild climates (Guo et al. 2014, Huang et al. 2015, Nordio et al. 2015). Interestingly, this recent evidence on temperature-related mortality across climate zones provides an additional argument for the urgent need of updating FUND’s damage functions. In fact, the regression equations used by Tol (2002a) and in this study to extrapolate mortality projections to countries worldwide imply that the cooler (warmer) the country today the greater the expected reduction (increases) in cold(warm)-related mortality in the future. Thus, what follows from the equations is exactly the opposite of what would be expected based on the most recent literature (for the supplementary discussion of further conceptional caveats regarding Martens (1998) and Tol (2002a) see Online Resource 1 section B).

So, given the important advances since the publication of Martens (1998), why is is not straightforward to provide a new empirical data basis on temperature-related mortality for recalibrating FUND and other global scale IAMs? Importantly, even in the most comprehensive recent studies on temperature-related mortality across space (covering almost 400 cities in 13 countries on 4 continents, Gou et al. 2014, Gasparrini et al. 2015a) there are major data gaps remaining (e.g., all of Africa). It is controversially discussed whether one should extrapolate known exposure-response relationships to these unexplored locations differing strongly in terms of health care systems and infrastructure (Deschênes 2014). It is also important to note that while studies such as Gou et al. (2014) and Gasparrini et al. (2015a) represent a major step forward in our understanding of *current* temperature-mortality relationships across space, this new data has so far not been used to project temperature-related mortality under different scenarios of climate change. To our knowledge there is at present only one globally-gridded dataset on temperature-related mortality projections (Honda et al. 2014, WHO 2014), with the important limitations that one single exposure-response curve derived from Japanese cities is employed across the global, that cold-related mortality is neglected entirely, and that only the age group > 65 years is considered. Last but not least, in order to derive damage functions to be integrated into IAMs, mortality projections will need to be analysed as a function of different degrees of GMT rise (James et al. 2017), instead of the more conventional approach of analysing future shifts in mortality along the dimension of time (see, e.g., recent studies by Schwartz et al. 2015, Lee and Kim 2016, Guo et al. 2016). With the exception of one study on temperature-related years of life lost in Brisbane, Australia (Huang et al. 2012), we are not aware of any other study that has attempted to specifically derive the relationship between differential changes in GMT and corresponding changes in temperature-related mortality.

In conclusion, we show that the mortality projections of Martens (1998) and their extension by Tol (2002a) have found their way into several recent economic assessments of climate change, most prominently through the application of the widely used IAMs FUND and ENVISAGE. Therefore, the bias for which we provide evidence here is relevant also for the results of these assessments, such as estimates of the SCC or economy-wide damage costs. Although temperature-related mortality is only one of the many climate impact channels to be considered, the likely overestimation of benefits of climate change in this sector would obviously translate into the underestimation of total climate damage costs. Thus, it would be expected that the comparatively low global damage estimates derived from FUND and ENVISAGE (Revesz et al. 2014) will be revised towards higher costs, once these models rely upon improved global projections for cold- and heat-related mortality.

5 References

Ackerman F, Stanton EA (2008) A comment on "Economy-wide estimates of the implications of climate change: Human health". Ecological Economics 66: 8-13

Aldy JE, Krupnick AJ, Newell RG, Parry IWH, Pizer WA (2010) Designing Climate Mitigation Policy. Journal of Economic Literature 48: 903-934

Barreca A, Clay K, Deschênes O, et al (2016) Adapting to Climate Change: The Remarkable Decline in the US Temperature-Mortality Relationship over the 20th Century. J Polit Econ 124:105–159. doi: 10.3386/w18692

Bosello F, Roson R, Tol RSJ (2006) Economy-wide estimates of the implications of climate change: Human health. Ecological Economics 58: 579-591

Deschênes O (2014) Temperature, human health, and adaptation: A review of the empirical literature. Energy Econ 46:606–619. doi: 10.1016/j.eneco.2013.10.013

Deschênes O, Greenstone M (2011) Climate Change, Mortality, and Adaptation: Evidence from Annual Fluctuations in Weather in the U.S. Am Econ J Appl Econ 3:152–185. doi: 10.1257/app.3.4.152

Ebi KL, Mills D (2013) Winter mortality in a warming climate: a reassessment. Wiley Interdisciplinary Reviews-Climate Change 4: 203-212

Gasparrini A (2014) Modeling exposure-lag-response associations with distributed lag non-linear models. Stat Med 33:881–899. doi: 10.1002/sim.5963

Gasparrini A, Guo Y, Hashizume M, et al (2015a) Mortality risk attributable to high and low ambient temperature: a multi-country study. Lancet 44:16 pages.

Gasparrini A, Guo Y, Hashizume M, et al (2015b) Temporal variation in heat–mortality associations: A multicountry study. Environ Health Perspect 123:1200–1207. doi: 10.1289/ehp.1409070

Green MS, Harari G, Kristal-Boneh E (1994). Excess winter mortality from ischaemic heart disease and stroke during colder and warmer years in Israel. An evaluation and review of the role of environmental temperature. European Journal of Public Health 4: 3-11

Greenstone M, Kopitsy E, Wolvertony A (2013) Developing a Social Cost of Carbon for US Regulatory Analysis: A Methodology and Interpretation. Review of Environmental Economics and Policy 7: 23–46. doi:10.1093/reep/res015

Guo Y, Gasparrini A, Armstrong B, Li S, Tawatsupa B, Tobias A et al (2014) Global Variation in the Effects of Ambient Temperature on Mortality: A Systematic Evaluation. Epidemiology 25:781-789

Guo Y, Li S, Liu DL, et al (2016) Projecting future temperature-related mortality in three largest Australian cities. Environ Pollut 208:66–73. doi: 10.1016/j.envpol.2015.09.041

Hayashi A, Akimoto K, Sano F, Mori S, Tomoda T (2010) Evaluation of global warming impacts for different levels of stabilization as a step toward determination of the long-term stabilization target. Climatic Change 98: 87-112

Honda Y et al., (2014) Heat-related mortality risk model for climate change impact projection. Environmental Health and Preventive Medicine 19: 56-63

Houser T, Hsiang S, Kopp R, Larsen K, et al (2015) Economic Risks of Climate Change: An American Prospectus. New York: Columbia University Press, 384 pp. ISBN 9780231174565

Hsiang SM (2016) Climate Econometrics. Annu Rev Resour Econ 1–33. doi: 10.3386/w22181

Huang C, Barnett AG, Wang X, Tong S (2012) The impact of temperature on years of life lost in Brisbane, Australia. Nat Clim Chang 2:265–270. doi: 10.1038/nclimate1369

Huang C, Barnett AG, Wang X, Vaneckova P, FitzGerald G, Tong S (2011) Projecting Future Heat-Related Mortality under Climate Change Scenarios: A Systematic Review. Environmental Health Perspectives 119:1681-1690

Huang C, Chu C, Wang X, Barnett AG (2015) Unusually cold and dry winters increase mortality in Australia. Environ Res 136:1-7. doi: 10.1016/j.envres.2014.08.046

IWG (2010) Interagency Working Group on Social Cost of Carbon. Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis under Executive Order 12866. February. United States Government.

IWG (2016) Interagency Working Group on Social Cost of Greenhouse Gases. Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866. August. United States Government

James R, Washington R, Schleussner C-F, et al (2017) Characterizing half-a-degree difference: a review of methods for identifying regional climate responses to global warming targets. Wiley Interdiscip Rev Clim Chang e457. doi: 10.1002/wcc.457

Kalkstein LS, Greene JS (1997) An evaluation of climate/mortality relationships in large US cities and the possible impacts of a climate change. Environmental Health Perspectives 105: 84-93

Kinney PL, Schwartz J, Pascal M, Petkova E, Le Tertre A, Medina S, Vautard R (2015) Winter season mortality: will climate warming bring benefits? Environmental Research Letters 10: 064016

Lee JY, Kim H (2016) Projection of future temperature-related mortality due to climate and demographic changes. Environ Int 94:489–494. doi: 10.1016/j.envint.2016.06.007

Leemans R, Cramer W (1991) Updated as: the CLIMATE database version 2.1. http://www.pik-potsdam.de/~cramer/climate.html. Accessed 15 July 2015

Lomborg B (2007) Cool it: the skeptical environmentalist’s guide to global warming. Knopf Publishing Group, United States

Martens WJM (1998) Climate change, thermal stress and mortality changes. Social Science & Medicine 46: 331-344

Nordio F, Zanobetti A, Colicino E, et al (2015) Changing patterns of the temperature-mortality association by time and location in the US, and implications for climate change. Environ Int 81:80–86. doi: 10.1016/j.envint.2015.04.009

Revesz R, Howard P, Arrow K, et al (2014) Improve economic models of climate change. Nature 508:173–175

Roson R, van der Mensbrugghe D (2012) Climate change and economic growth: impacts and interactions. Int J Sustain Econ 4:270–285. doi: 10.1504/IJSE.2012.047933

Schwartz JD, Lee M, Kinney PL, et al (2015) Projections of temperature-attributable premature deaths in 209 U.S. cities using a cluster-based Poisson approach. Environ Heal 14:85. doi: 10.1186/s12940-015-0071-2

Shi L, Kloog I, Zanobetti A, Liu P, Schwartz JD (2015) Impacts of temperature and its variability on mortality in New England. Nature Climate Change 5, 988–991. doi:10.1038/nclimate2704

Srinivasan UT, Carey SP, Hallstein E, Higgins PAT, Kerr AC, Koteen LE, Smith AB, Watson R, Harte J, Norgaard RB (2007) The debt of nations and the distribution of ecological impacts from human activities. PNAS 105: 1768–1773. doi: 10.1073/pnas.0709562104

Tobías A, Armstrong B, Gasparrini A (2017) Brief Report. Epidemiology 28:72–76. doi: 10.1097/EDE.0000000000000567

Tol RSJ (2002a) Estimates of the damage costs of climate change. Part 1: Benchmark estimates. Environmental & Resource Economics 21: 47-73

Tol RJS (2002b) Estimates of the damage costs of climate change. Part II: Dynamic estimates. Environmental & Resource Economics 21: 135-160

Tol RSJ (2005) Emission abatement versus development as strategies to reduce vulnerability to climate change: An application of FUND. Environment and Development Economics 10: 615-629

Tol RSJ (2009) The economic effects of climate change. J Econ Perspect 23:29–51. doi: 10.1257/jep.23.2.29

Tol RSJ (2013) The economic impact of climate change in the 20th and 21st centuries. Climatic Change 117: 795-808

UN Population Division (2014) Urban and Rural Population by Age and Sex (URPAS). 3rd edition. http://www.un.org/en/development/desa/population/publications/dataset/urban/urbanAndRuralPopulationByAgeAndSex.shtml. Accessed 1 September 2015

Vardoulakis S, Dear K, Hajat S, Heaviside C, Eggen B, McMichael AJ (2014) Comparative Assessment of the Effects of Climate Change on Heat-and Cold-Related Mortality in the United Kingdom and Australia. Environmental Health Perspectives 122:1285-1292

Watkiss P, Downing TE (2008) The social cost of carbon: Valuation estimates and their use in UK policy. The Integrated Assessment Journal 8: 85–105

WHO, 2014. Quantitative risk assessment of the effects of climate change on selected causes of death, 2030s and 2050s. http://www.who.int/globalchange/publications/quantitative-risk-assessment/en/. Accessed 19 April 2016

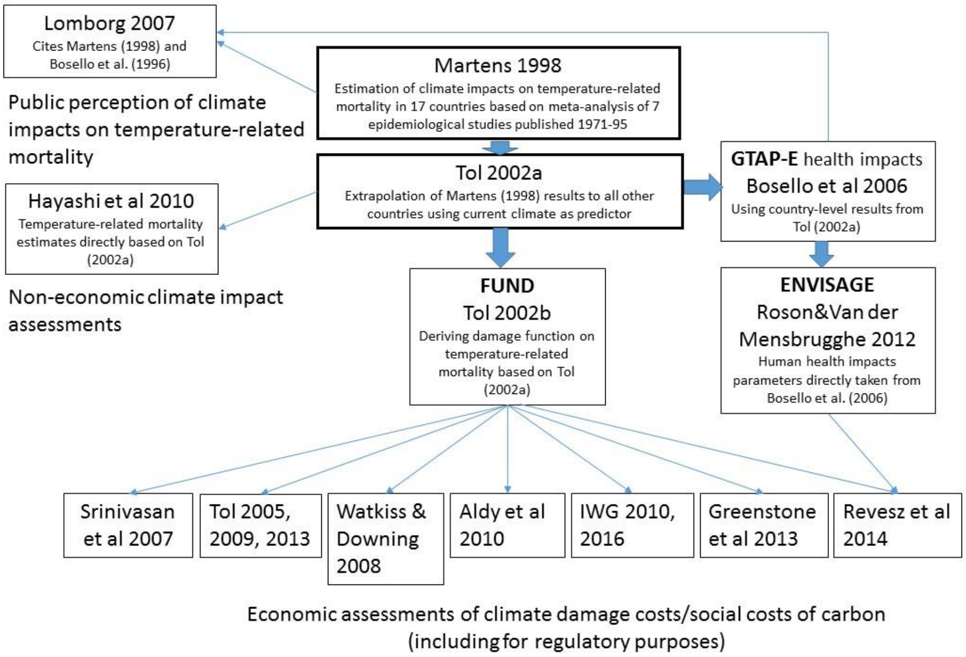

Fig. 1 Use of temperature-related mortality projections by Martens (1998) and Tol (2002a) in economic (and non-economic) assessments of climate damages, including integrated assessment modelling with the models FUND and ENVISAGE.

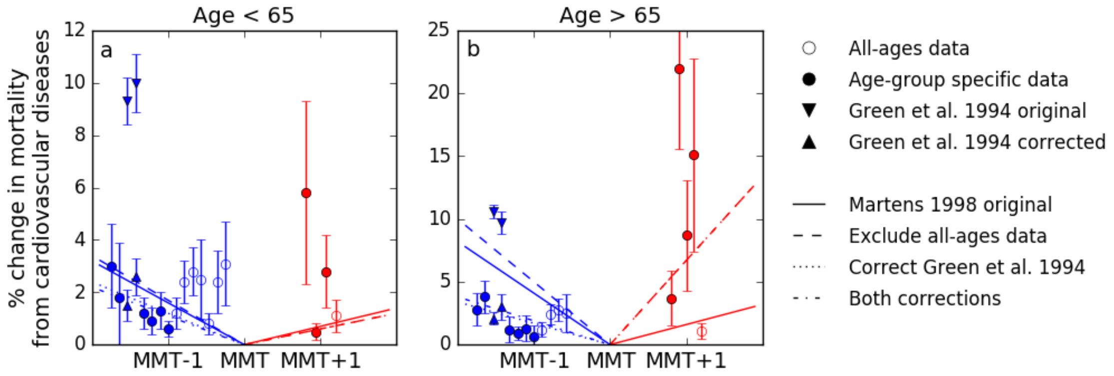

Fig. 2 Temperature-mortality relationships from Martens (1998) (solid lines) and revised versions from our reanalysis (broken lines) for a) age group < 65 years, and b) > 65 years. Symbols show individual estimates β_j (± s_j) of changes in cardiovascular mortality for an increase of 1°C in the cold range (blue, temperature <MMT) and in the warm range (red, temperature > MMT), used to calculate combined effect estimates $\bar{\beta}$ (and $\tilde{\beta}$), i.e., to parameterize the slopes (see Eq. 1). Note that data points are displaced along the x-axis for better visibility, and that slopes are *not* regression lines.

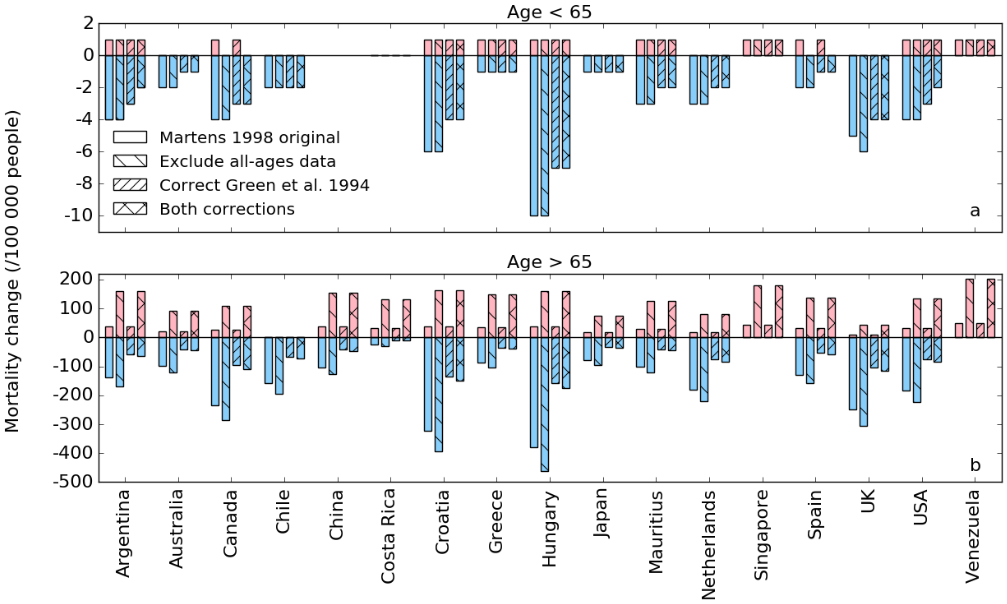

Fig. 3 Annual changes in people dying due to cardiovascular diseases at approximately 1.2°C global warming (a) < 65 years old and (b) > 65 years old in 17 countries based on Martens (1998). Decreased cold-related mortality (temperature < MMT, see Fig. 2) is shown in blue, increased heat-related mortality (temperature > MMT) in red. Plain bars depict original estimates of Martens (1998), hatched bars show results based on revised temperature-mortality functions (cf. broken lines in Fig. 2)

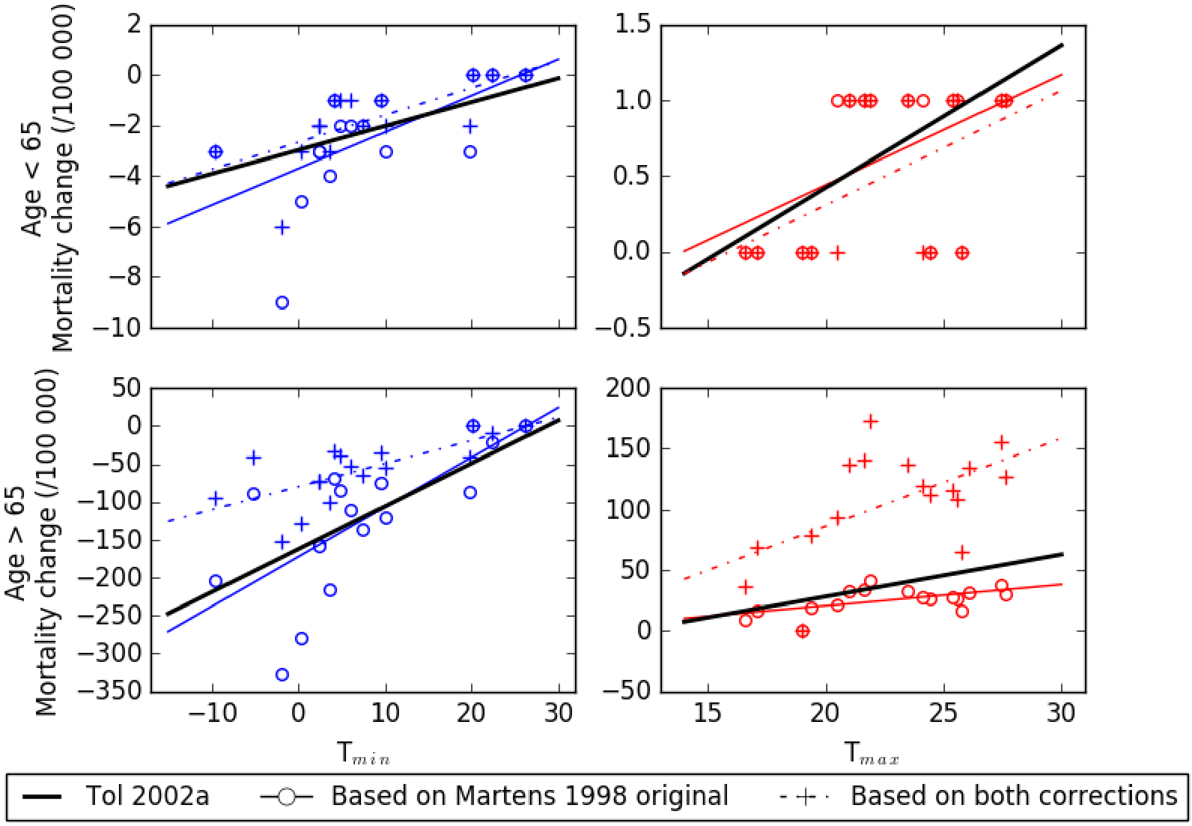

Fig. 4 Linear regressions used by Tol (2002a) and in our reanalysis to extrapolate cold (blue) and heat (red) related changes in cardiovascular mortality for age groups < 65 and > 65 years (cf., Fig. 3) to countries worldwide, as a function of minimum and maximum monthly mean temperatures in capital cities (T_{min}, T_{max}). For equations see Online Resource 1 Table S6

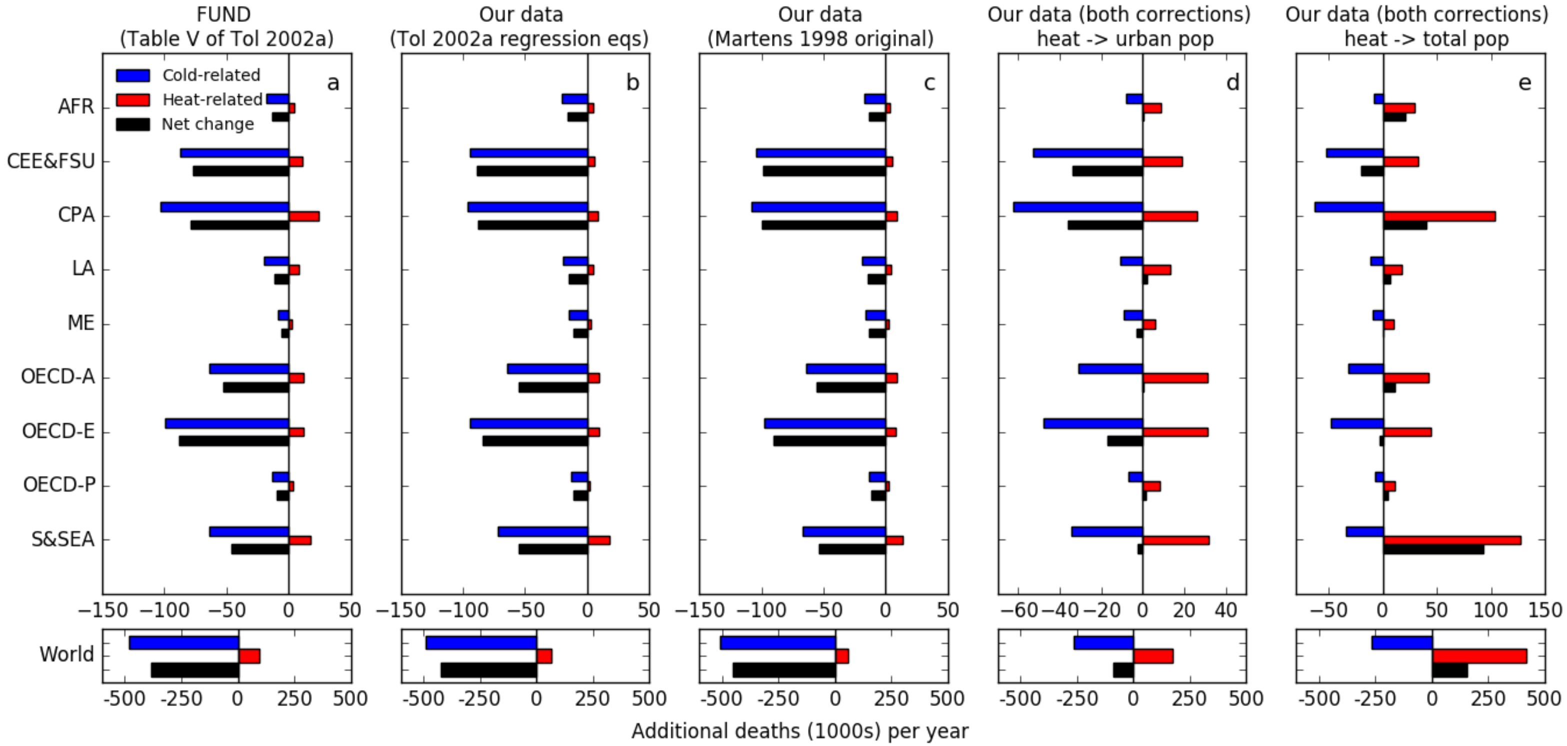

Fig 5 Regional (top) and global (bottom) number of additional annual cardiovascular deaths (1000s) at 1°C increase in global mean temperature (a) as reported by Tol (2002a) and (b-e) as estimated based on regression equations shown in Fig. 4 (see also Online Resource 1 Table S6). (a-d) is based on the assumption that heat affects only urban populations as in the FUND model; (e) is based on the assumption that both urban and rural populations are affected. Region abbreviations: AFR: Africa, CEE&FSU: Central and Eastern Europe and the former Soviet Union, CPA: Centrally planned Asia, LA: Latin America, ME: Middle East, OECD-A: OECD - America (excl. Mexico), OECD-E: OECD Western Europe, OECD-P: OECD Pacific (excl. South Korea), S&SEA: South and Southeast Asia (see Online Resource 1 Table S7 for list of countries)