Electronic Supplementary Material 1

Climatic Change

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

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Section A: Additional figures and tables

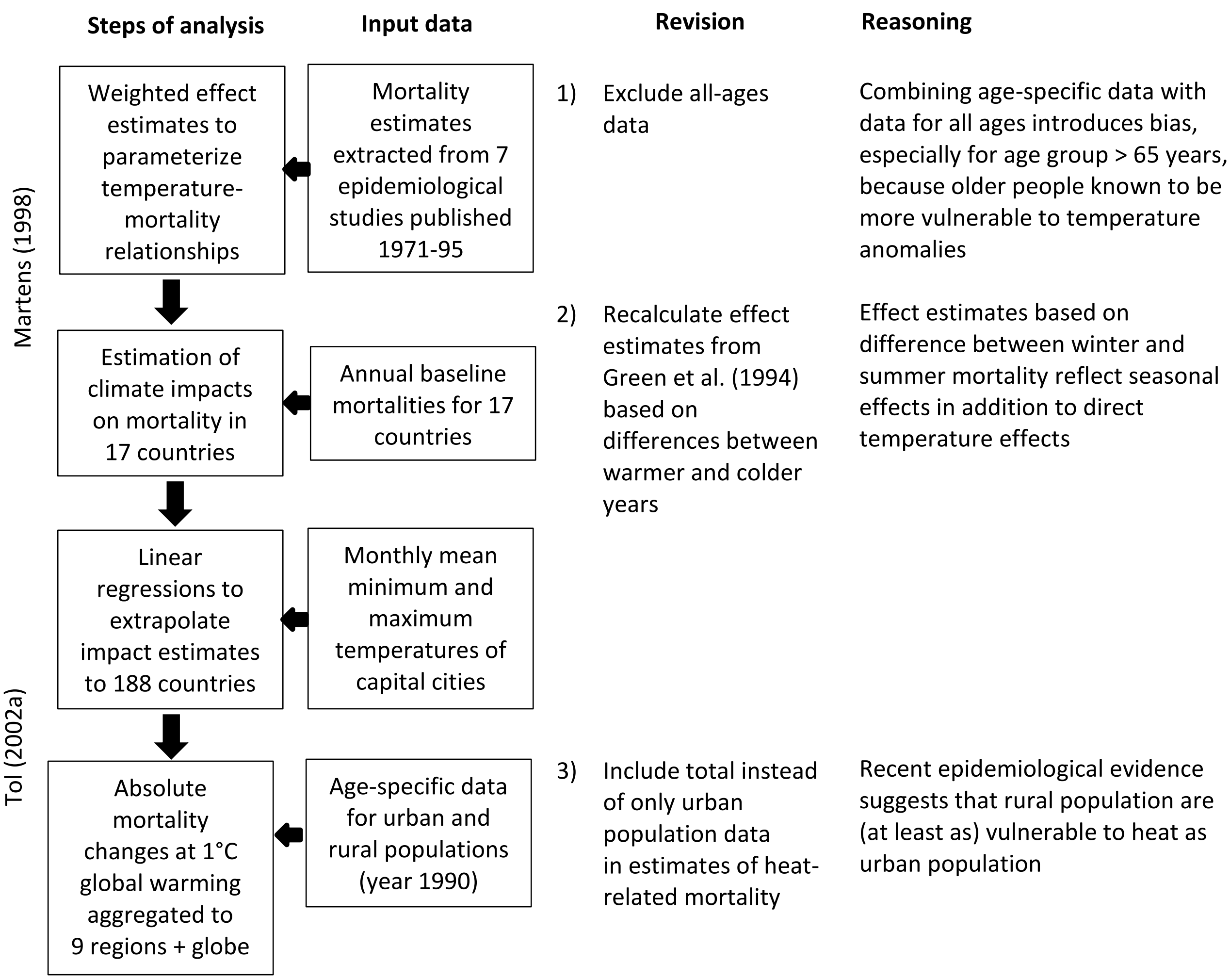

Fig. S1 Outline of our reanalysis of estimated changes in cardiovascular mortality due to climate change entering the FUND model. The third and fourth column detail where and why we revise assumptions made by Martens (1998) and Tol (2002a)

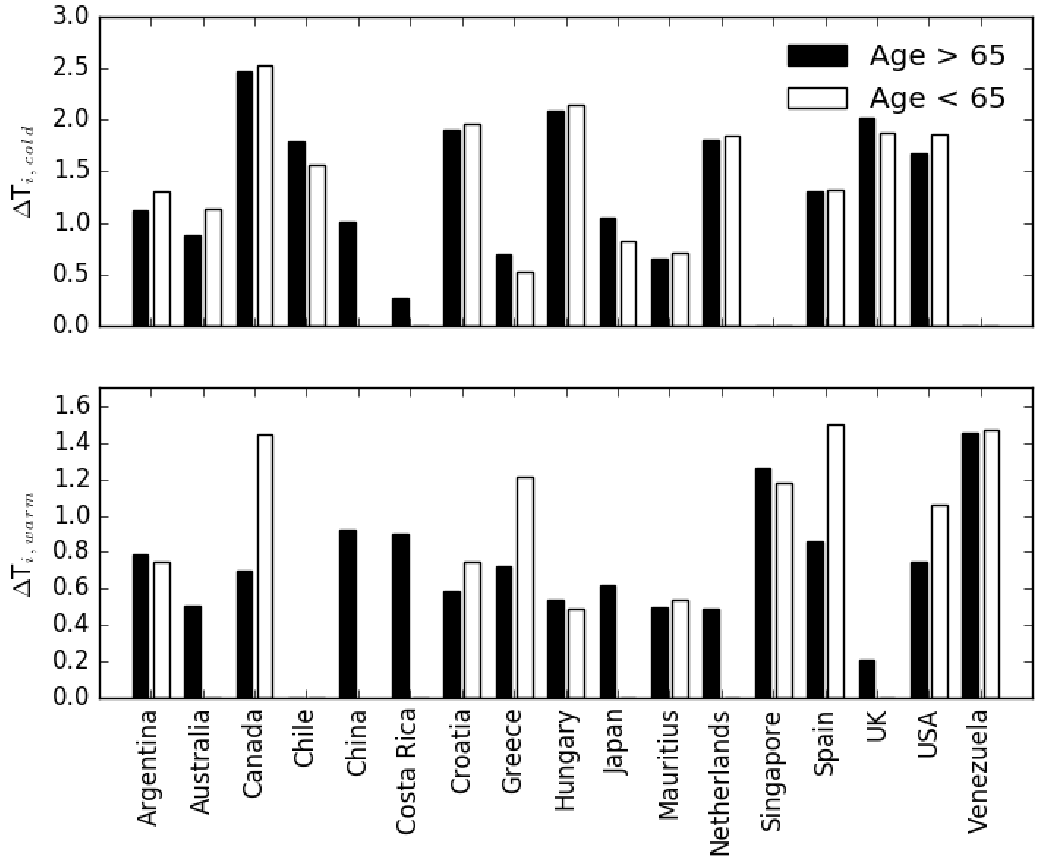

Fig. S2 Country-specific compound measures $\overline{\Delta T}_{i,cold}$ (top), $\overline{\Delta T}_{i,warm}$ (bottom) of temperature differences applied by Martens (1998) to derive cardiovascular mortality projections (estimated according to Eq. 2). Note that $\overline{\Delta T}_{i,cold}$, $\overline{\Delta T}_{i,warm}$ comprise temperature differences with respect to the city specific MMTs, summarize the averaging procedure across months and GCMs undertaken by Martens (1998), and incorporate differences between the future and baseline climate. Results for age group > 65 years (black bars) were used to re-assess cardiovascular mortality projections according to Eq. 3

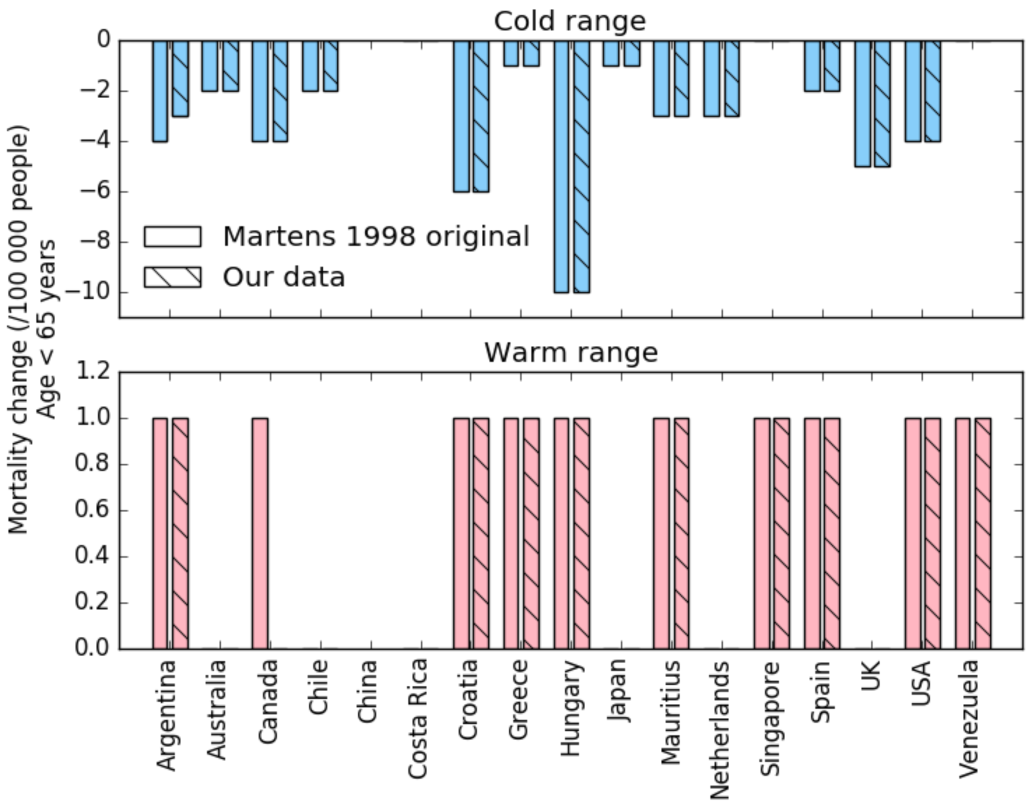

Fig. S3 Consistency-check for reanalysis of projected mortality based on Eq. 3. Plain bars show original data of country-specific annual changes in people < 65 years dying due to cardiovascular diseases at approx. 1.2°C global warming from Martens (1998). Hatched bars show re-calculated mortality changes, using $\overline{\Delta T}_{i,cold}$, $\overline{\Delta T}_{i,warm}$ estimates based on age group >65 years data (see Fig. S1) and original $\overline{\beta}_{cold,<65}$, $\overline{\beta}_{warm,<65}$ estimates given in Martens (1998) (see Table S1). Except for small differences (cold-related mortality in Argentina, heat-related mortality in Canada) our reanalysis yields the same results as obtained by Martens (1998)

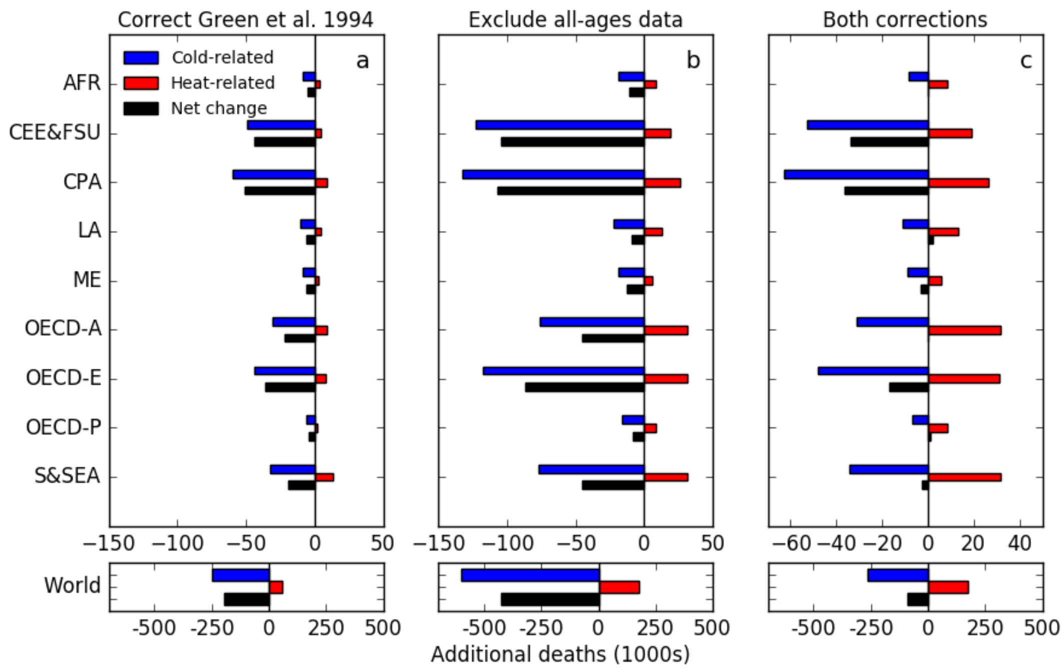

Fig. S4 As Fig. 5, but showing intermediate steps of our data reanalysis. Regional mortality projections for FUND regions for 1°C global warming are based on modified temperature-mortality relationships a) correcting extracts from Green et al. 1994, b) excluding all-ages data, c) applying both corrections at once (the same as Fig. 5d)

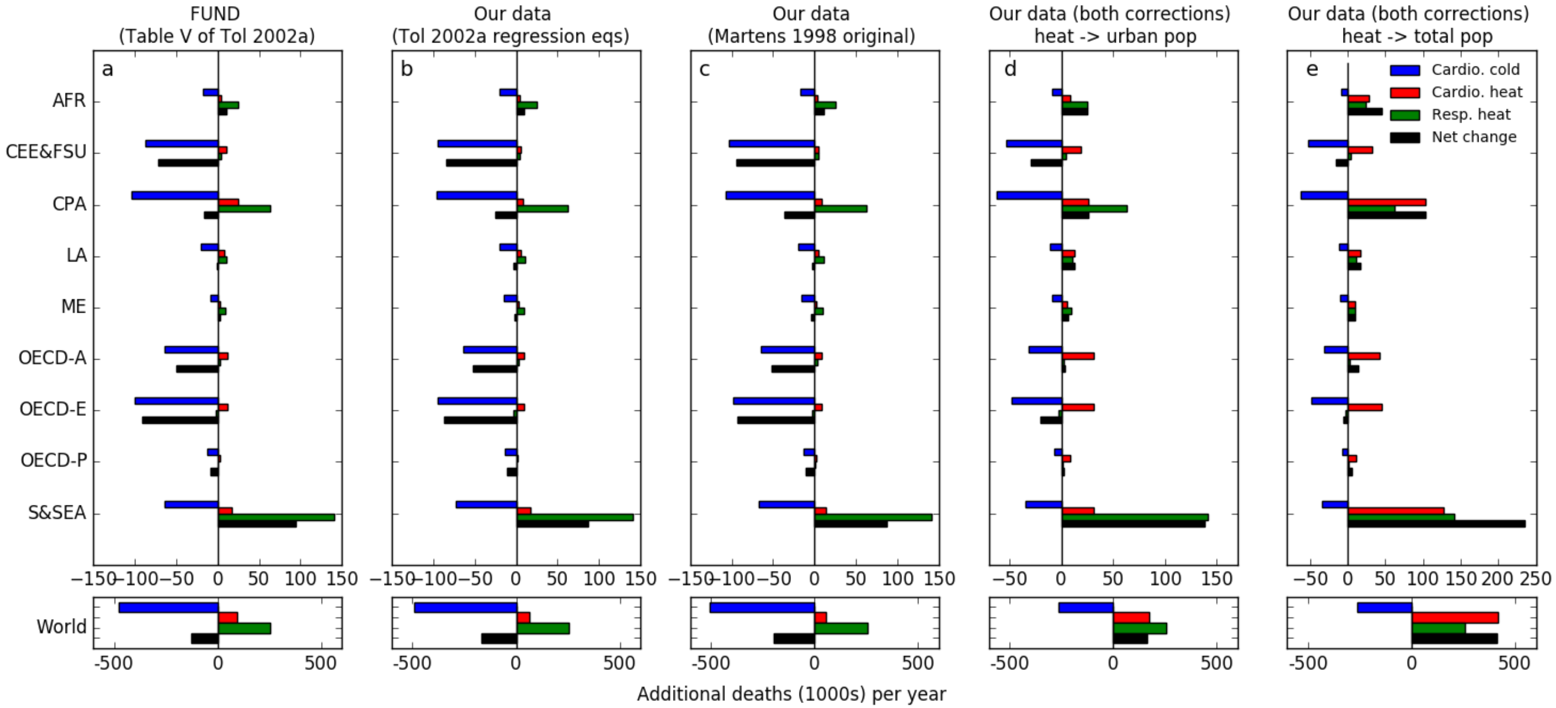

Fig. S5 As Fig. 5, but accounting for additional annual deaths due to increases in heat related respiratory mortality incorporated in the FUND model (directly extracted from Table V of Tol 2002a). Data on respiratory mortality (green) is the same in each of the panels, making a difference in terms of net mortality effects (black) only. Tol (2002a) assumes that heat related respiratory mortality affects the entire population

Table S1 Percent change in mortality from cardiovascular diseases for 1°C increase in average temperature in the warm (above MMT) and cold (below MMT) temperature range. Original source data (mean and SE) is directly reported from Table 2 of Martens (1998). Bracketed data of study 6a* and 6b* correspond to corrected estimates based on Green et al. (1994) (see Table S3). Weighted effect estimates are cited from Martens (1998) or stem from our reanalysis.

	Age < 65						Age > 65						All ages					
	Warm			Cold			Warm			Cold			Warm			Cold		
	Study #[a]	β_j mean	s_j SE	Study #	β_j mean	s_j SE	Study #	β_j mean	s_j SE	Study #	β_j mean	s_j SE	Study #	β_j mean	s_j SE	Study #	β_j mean	s_j SE
	5a	5.8	3.5	5a	-3	1.6	5a	3.7	2.2	5a	-2.8	1.3	2	1.1	0.6	1a	-2.4	0.8
	7b	0.5	0.3	5b	-1.8	2.1	5b	22	6.4	5b	-3.8	1.3				1b	-2.8	0.9
	7d	2.8	1.4	6a	-9.3	0.9	7b	8.7	4.4	6a	-10.6	0.5				2	-1.2	0.6
				6b	-10	1.1	7d	15.1	7.7	6b	-9.7	0.9				3	-2.5	1.5
				6a*	(-1.5)	(0.6)				6a*	(-2.1)	(0.5)				4a	-0.8	0.4
				6b*	(-2.6)	(0.7)				6b*	(-3)	(1)				4b	-2.4	1.2
				7a	-1.2	0.6				7a	-1.9	1				4c	-3.1	1.6
				7b	-0.9	0.5				7b	-1	0.5						
				7c	-1.3	0.7				7c	-2	1						
				7d	-0.6	0.3				7d	-1.7	0.9						
Weighted effect estimates ($\bar{\beta}$)																		
Martens (1998)		**0.7**			**-1.6**			**1.6**			**-4.1**							
Reanalysis control																		
All ages double count		0.7			-1.6			1.6			-3.3							
All ages double count (without study 4[b])		0.7			-1.6			1.6			-4.1							
Reanalysis revision ($\tilde{\beta}$)																		
All ages double count (corrected study 6)		0.7			-1.2			1.6			-1.7							
Exclude all ages data		0.6			-1.7			6.7			-5.0			1.1			-1.5	
Exclude all ages data (corrected study 6)		0.6			-1.1			6.7			-1.9							

[a] Original studies: 1 Langford&Bentham (1995), 2 Kunst et al. (1993), 3 West&Lowe (1976), 4 Sakamoto-Momiyama&Katayama (1971), 5 Pan et al. (1995), 6 Green et al. (1994), 7 Bull&Morton (1975, 1978); [b] The combined effect estimate reported by Martens (1998) for cold-related mortality in the age group > 65 was only reproducible if we disregarded study 4

Table S2 Recalculation of effect estimates from Green et al. (1994), entering meta-analysis of Martens (1998) as study 6 (see Table S1). Effect estimates are calculated as "mean ratio of winter to summer mortality divided by the difference in winter and summer minimum temperature [15°C)]" (Martens 1998). Simple averages are computed to combine data for different sexes and age groups

Extract from Table 1 of Green et al. (1994) Mean ratio of winter to summer mortality in Israel during 1976-85			
Sex	Age group	Ischaemic heart disease	Stroke
Male	45-64	1.29	1.51
	65-74	1.51	1.55
	75+	1.67	1.50
Female	45-64	1.50	1.48
	65-74	1.46	1.29
	75+	1.74	1.47
Re-calculation of effect estimates entering Table 2 of Martens (1998) % change in health endpoint per 1°C increase in average temperatures			
Combined	45-65	$\frac{1.29+1.50}{2\times15}\times100 = 9.3$	$\frac{1.51+1.48}{2\times15}\times100 = 10.0$
	>= 65	$\frac{1.51+1.67+1.46+1.74}{4\times15}\times100 = 10.6$	$\frac{1.55+1.50+1.29+1.47}{4\times15}\times100 = 9.7$

Table S3 Modified calculation of effect estimates from Green et al. (1994) (study 6*, see Table S1). Here effect estimates are calculated as the mean difference between relative mortality in colder and warmer years divided by the mean temperature differences between these years (2°C). As in Table S2 simple averages are computed to combine data for different sexes and age groups. Standard errors (SE) are based on variance among age groups and sexes

Extract from Tables 2 and 3 of Green et al. (1994) % above monthly mean mortality for colder and warmer years in Israel during 1976-85							
		Ischaemic heart disease			Stroke		
Sex	Age group	Cold	Warm	Difference	Cold	Warm	Difference
Male	45-64	13.7	11.8	1.9	19.94	13.4[b]	6.54
	65-74	23	16.9	6.1	21.4	14.9	6.5
	75+	29.1	25.7	3.4	18.6	16	2.6
Female	45-64	22.1	17.9	4.2	19.6	15.8[b]	3.8
	65-74	19.8	18.2	1.6	23	11.6	11.4
	75+	23.1[a]	17.8[a]	5.3	21.6	18.4	3.2
Modified effect estimates entering our reanalysis % change in health endpoint per 1°C increase in average temperatures							
				Mean	SE	Mean	SE
Combined	45-65			1.5	0.6	2.6	0.7
	>= 65			2.1	0.5	3.0	1.0

[a]We interchanged these values between colder and warmer years compared to Green et al. (1994), because inspection of their Fig. 4 revealed that they had wrongly been placed in Table 2.

[b]These values correspond to age group 45+; we replaced the original values because p>0.1 in these cases

Table S4 Estimates of MMT (°C) for selected cities as reported by Martens (1998) and calculated as given percentile of mean daily temperatures for the current climate (1981-2010). City-specific temperature percentiles were adopted from Gasparrini et al. (2015a), using the 81st percentile (overall median) for extra-tropical and 60th percentile for tropical cities, if they did not form part of this meta-study. Temperature data was taken from bias-corrected simulations of HadGEM2 as provided as part of the ISI-MIP project (Warschawski et al. 2014), choosing the grid cell including the specific city

Country (city)	MMT from Martens (1998)	Temperature percentile	MMT Our estimate
Mauritius (Mauritius)	25	60th	24
Argentina (Buenos Aires)	20	81st	22
Venezuela (Caracas)	20	60th	26
Costa Rica (San Jose)	20	60th	24
Chile (Santiago)	20	81st	18
China (Beijing/Guangzhou)	20/20	80th/82th	22/29
Singapore (Singapore)	25	60th	27
Japan (Tokyo)	20	87th	24
Netherlands (Amsterdam)	16.5	81st	16
Greece (Athens)	20	81st	24
Hungary (Budapest)	20	81st	19
UK (London)	20	92nd	18
Spain (Madrid)	20	76th	18
Croatia (Zagreb)	20	81st	19
USA (New York/Los Angeles)	20/23	80th /95th	20/23
Canada (Toronto)	20	80th	17
Australia (Melbourne/Sydney)	20/20	90th/83th	22/22

Table S5 Minimum and maximum monthly mean temperatures (°C) for capital cities (T_{min}, T_{max}) of countries analysed in Martens (1998). Data was extracted from the updated Leemans & Cramer (1991) database, which provides globally gridded monthly mean temperature data on land based on 1931-1960 climatology. The grid cell chosen included the city location, except for some coastal cities, where neighbouring grid cells were selected instead

Country	Capital city	T_{min}	T_{max}
Mauritius	Port Louis	19.8	25.6
Argentina	Buenos Aires	10	23.5
Venezuela	Caracas	20.2	21.9
Costa Rica	San Jose	22.4	24.4
Chile	Santiago	7.4	19
China	Beijing	-5.2	26.1
Singapore	Singapore	26.2	27.4
Japan	Tokyo	4.1	25.8
Netherlands	Amsterdam	2.5	17.1
Greece	Athens	9.6	27.6
Hungary	Budapest	-2	21
UK	London	3.7	16.6
Spain	Madrid	6	24.1
Croatia	Zagreb	0.4	21.6
USA	Washington DC	2.4	25.4
Canada	Toronto	-9.6	20.5
Australia	Canberra	4.9	19.4

Table S6 Regression equations used to extrapolate cold and heat-related changes in cardiovascular mortality for age groups <65 and >65 years ($M_{r,a}$) to countries worldwide, based on minimum and maximum monthly mean temperatures (T_{min}, T_{max}) in capital cities (see Fig. 4) (note that we drop the country index *i* compared to Eqs. 4–5 here for better readability). R^2 of the equations used in FUND are reported to 'vary between 0.22 and 0.51' (Tol 2002a)

	Cold		Heat	
Tol (2002a) for FUND:				
	$M_{cold,<65}$= -2.98 + 0.09 T_{min}	R^2 = *NA*	$M_{warm,<65}$= -1.46 + 0.09 T_{max}	R^2 = *NA*
	$M_{cold,>65}$= -162.65 + 5.66 T_{min}	R^2 = *NA*	$M_{warm,>65}$= -41.00 + 3.46 T_{max}	R^2 = *NA*
Based on original data of Martens (1998):				
	$M_{cold,<65}$= -3.72 + 0.14 T_{min}	R^2 = 0.39	$M_{warm,<65}$= -1.02 + 0.07 T_{max}	R^2 = 0.25
	$M_{cold,>65}$= -172.74 + 6.56 T_{min}	R^2 = 0.51	$M_{warm,>65}$ = -14.19 + 1.74 T_{max}	R^2 = 0.32
Based on our reanalysis of Martens (1998):				
Correct Green et al. (1994)	$M_{cold,<65}$= -2.82 + 0.11 T_{min}	R^2 = 0.46	As above	
	$M_{cold,>65}$ = -71.73 + 2.72 T_{min}	R^2 = 0.51		
Exclude all-ages data	$M_{cold,<65}$= = -3.80 + 0.15 T_{min}	R^2 = 0.38	$M_{warm,<65}$= -1.20 + 0.08 T_{max}	R^2 = 0.26
	$M_{cold,>65}$ = -210.64 + 8.0 T_{min}	R^2 = 0.51	$M_{warm,>65}$= -59.18 + 7.26 T_{max}	R^2 = 0.32
Both corrections	$M_{cold,<65}$= -2.67 + 0.11 T_{min}	R^2 = 0.43	As above	
	$M_{cold,>65}$ = -79.97 + 3.04 T_{min}	R^2 = 0.51		

Table S7 FUND regional definitions adopted from Anthoff and Tol (2014)

Acronym	Name	Countries
AFR	Africa	Algeria, Egypt, Libya, Morocco, Tunisia, Western Sahara, Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Congo-Brazzaville, Congo-Kinshasa, Cote d'Ivoire, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea- Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mauritania, Mozambique, Namibia, Niger, Nigeria, Rwanda, Senegal, Sierra Leone, Somalia, South Africa, Sudan, Swaziland, Tanzania, Togo, Uganda, Zambia, Zimbabwe
CEE&FSU	Central and Eastern Europe and former Soviet Union	Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Hungary, FYR Macedonia, Poland, Romania, Slovakia, Slovenia, Yugoslavia, Armenia, Azerbaijan, Belarus, Estonia, Georgia, Kazakhstan, Latvia, Lithuania, Moldova, Russia, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
CPA	Centrally Planned Asia	China, Hong Kong, North Korea, Macau, Mongolia
LA	Latin America	Belize, Costa Rica, El Salvador, Guatemala, Honduras, México, Nicaragua, Panama, Argentina, Bolivia, Brazil, Chile, French Guyana, Guyana, Paraguay, Perú, Surinam, Uruguay, Venezuela
ME	Middle East	Bahrain, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syria, Turkey, United Arab Emirates, West Bank and Gaza, Yemen
OECD-A	OECD-America	United States of America, Canada
OECD-E	OECD-Europe	Andorra, Austria, Belgium, Cyprus, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Liechtenstein, Luxembourg, Malta, Monaco, Netherlands, Norway, Portugal, San Marino, Spain, Sweden, Switzerland, United Kingdom
OECD-P	OECD-Pacific	Japan, Australia, New Zealand
S&SEA	South and Southeast Asia	Afghanistan, Bangladesh, Bhutan, India, Nepal, Pakistan, Sri Lanka, Brunei, Cambodia, East Timor, Indonesia, Laos, Malaysia, South Korea, Myanmar, Papua New Guinea, Philippines, Singapore, Taiwan, Thailand, Vietnam

Table S8 Number of additional cardiovascular deaths (1000s) at 1°C increase in global mean temperature aggregated to FUND model regions, directly taken from Table V of Tol (2002a) and based on our data reanalysis. We follow Tol (2002a) in assuming that heat-related cardiovascular mortality affects the urban population only. For an illustration of results see Fig 4

	FUND		*Our calculations based on*						
	Table V of Tol (2002a)		Regression equations of Tol (2002a)		Martens (1998) original		Martens (1998) revised: both corrections		
	Cold	Heat (urban)	Cold	Heat (urban)	Cold	Heat (urban)	Cold	Heat (urban)	Heat (total)
AFR	-18.2	4.7	-20.1	4.5	-16.8	3.4	-8.3	8.5	29
CEE&FSU	-87.5	10.7	-94.5	6	-103.8	4.8	-52.7	18.8	33.1
CPA	-103.4	24.3	-96.4	8.8	-107.8	8.6	-62.7	26.3	103.3
LA	-20	8.1	-19.7	5.2	-19.1	4.6	-10.9	13	17.3
ME	-8.9	2.5	-14.7	3.3	-16.3	2.4	-9.1	5.9	10
OECD-A	-64.4	11.4	-64.2	9	-64.2	9	-31.3	31.5	42
OECD-E	-99.8	11.7	-94	9.8	-97.9	8	-48	31.1	44.9
OECD-P	-13.1	3.5	-13.4	2	-13.4	2	-6.9	8.2	11.2
S&SEA	-63.8	17.5	-72.3	17.5	-67.2	13.2	-34.2	31.7	127.7
World	-479.1	94.4	-489.3	66.1	-506.5	56	-264.1	175	418.5
Balance		**-384.7**		**-423.2**		**-450.5**		**-89.1**	**+154.4**

Notes: 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. México), OECD-E: OECD Western Europe, OECD-P: OECD Pacific (excl. South Korea), S&SEA: South and Southeast Asia (see Table S7 for list of countries)

Section B: Additional caveats with regard to Martens (1998) and Tol (2002a)

We see at least four additional caveats regarding Martens (1998) and Tol (2002a) that were too fundamental to be addressed in our reanalysis, but would need to be overcome when recalibrating FUND (and related IAMs) based on an entirely new empirical mortality data basis.

First, Martens assumes a V-shaped relationship between temperature and mortality (Fig. 2) as usually resulting from the analysis of data at *daily* resolution. This relationship does not hold, though, when looking at monthly or seasonal averages of temperature and mortality (Davis et al. 2004; Honda et al. 2013). Nevertheless, Martens' meta-analysis combines studies based on daily, monthly and seasonal time-series without accounting for these important differences in temporal resolution. Most importantly, Martens (1998) should have estimated mortality changes based on projections of *daily* temperatures (instead of monthly means) given his assumption on the existence of a V-shaped relationship.

Second, as pointed out by Martens (1998) himself, combining city-specific percent changes in mortality with country-wide baseline mortalities to derive country-level mortality projections may introduce large errors. Obviously, the climate in capital cities is not at all representative for the whole of the countries, especially in large countries, and temperature-mortality relationships may differ strongly across regions and different cities. Since Tol (2002a) directly uses the country-level estimates of Martens (1998) and assumes once again that the climate observed in capital cities is representative for the countries, the errors are further amplified in FUND.

Third, for 16 out of the 20 cities considered, Martens (1998) did not take the MMT value from published studies, but uniformly set it to 20°C. Obviously, the MMT is critical for defining temperature ranges where cold versus heat-related excess mortality occurs. To judge the strength of this bias, we re-assessed MMTs for the cities considered by Martens (1998) (Table S4). For some of the cities our estimates of current MMTs indeed differ substantially from the value assumed by Martens (1998).

Forth, recent empirical work corroborates that temperature-mortality relationships are highly non-linear (e.g. Gasparrini et al. 2015a), while Martens (1998) assumes linearity between temperature and changes in mortality.

Section C: Additional references

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