6. Moberg, A., Bergström, H., Ruiz Krisman, J. & Svanerud, O. *Climatic Change* **53**, 171–212 (2002).
7. Sutton, R. T. & Dong, B. *Nature Geosci.* **5**, 288–292 (2012).
8. Statistics Sweden (accessed 28 October 2013); http://www.scb.se/
9. Oudin Åström, D., Forsberg, B., Edvinsson, S. & Rocklöv, J. *Epidemiology* **24**, 820–829 (2013).
10. Fouillet, A. *et al. Int. J. Epidemiol.* **37**, 309–317 (2008).
11. Palecki, M. A., Changnon, S. A. & Kunkel, K. E. *Bull. Am. Meteorol. Soc.* **82**, 1353–1367 (2001).

Paul Knappenberger[1*], Patrick Michaels[1] and Anthony Watts[2]

[1]Cato Institute, 1000 Massachusetts Ave, NW, Washington DC 20001, USA, [2]IntelliWeather, 3008 Cohasset Rd Chico, California 95973, USA.

*e-mail: pknappenberger@cato.org

Reply to 'Adaptation to extreme heat in Stockholm County, Sweden'

Oudin Åström *et al.* reply — We thank Knappenberger and colleagues for their interest in our research[1]. Their correspondence expresses two concerns: a possible bias in the temperature data[2] and appropriate consideration of adaptation to extreme-heat events over the century. To clarify, we estimated the impacts of observed climate change over the century on temperature-related mortality; our purpose was not to determine what caused the climatic changes. Our study aimed to examine the health impacts of temperature extremes on the population during the period 1980–2009, given the societal and infrastructure changes that occurred over the twentieth century, if this population had experienced the climate of the period 1900–1929. We did not adjust for actual adaptation responses because the low public awareness of the health hazards of high ambient temperature suggests that there would have been limited autonomous adaptation, and because data were not available to adjust for any actual adaptation responses. We did not compare the relative risk of mortality during an extreme day between 1900–1929 and 1980–2009, as this would be misleading.

With respect to the temperature data, we compared the station data recorded during the two study periods (1900–1929 versus 1980–2009). To limit the influence of regional and decadal variability, we used the standard approach of comparing patterns over 30-year time periods. The observed changes are the result of natural processes, including regional climate variability, and anthropogenic influences, including urbanization[3].

Our method of comparing the climate during two 30-year periods is valid for any two periods. Sensitivity analyses using different reference periods when calculating the cut-off temperatures (1910–1939, 1920–1949, 1930–1959, 1940–1969 and 1950–1979) limit the influence of the Atlantic Multidecadal Oscillation (AMO)[4]. For all periods that were investigated, the increase in the number of excess heat extremes ranges from 77 for the reference period 1930–1959 to 158 for the reference period 1950–1979. The AMO during the 1990s was similar to the warm state of 1931–1960 during which there was an increase in the number of heat extremes, albeit not to the extent of the original reference period.

We appreciate the opportunity to correct any misperceptions about adaptation to heat extremes in Stockholm. Our data indicate that there is no adaptation to heat extremes on a decadal basis or to the number of heat extremes occurring each year. Although another study observed a reduction in the population health impact of hot and cold extremes over the twentieth century[5], this decrease should not be confused with adaptation to climatic change. As in the studies cited by Knappenberger *et al.*, socio-economic development, epidemiological transitions and health system changes were and continue to be the main drivers of changes in population sensitivity — not explicit, planned actions to prepare for climate change impacts. These changes also apparently increased population resilience to climate change. Whether future development pathways will continue to increase resilience will also depend on many factors other than climate change. Importantly, it is not appropriate to assume that historic trends will continue, with or without climate change. ❐

References

1. Oudin Åström, D., Forsberg, B., Ebi, K. L. & Rocklöv, J. *Nature Clim. Change* **3**, 1050–1054 (2013).
2. Moberg, A., Bergström, H., Ruiz Krisman, J. & Svanerud, O. *Climatic Change* **53**, 171–212 (2002).
3. IPCC *Climate Change 2013: The Physical Science Basis* (eds Stocker, T. F. *et al.*) (Cambridge Univ. Press, 2013).
4. Sutton, R.T. & Dong, B. *Nature Geosci.* **5**, 788–792 (2012).
5. Oudin Åström, D., Forsberg, B., Edvinsson, S. & Rocklöv, J. *Epidemiology* **24**, 820–829 (2013).

Daniel Oudin Åström[1*], Bertil Forsberg[1], Kristie L. Ebi[1] and Joacim Rocklöv[2]
[1]Department of Public Health and Clinical Medicine, Division of Occupational and Environmental Medicine, Umeå University, 901 87 Umeå, Sweden, [2]Department of Public Health and Clinical Medicine, Division of Epidemiology and Global Health, Umeå University, 901 87 Umeå, Sweden.
*e-mail: daniel.astrom@envmed.umu.se

COMMENTARY:

Costing natural hazards

Heidi Kreibich, Jeroen C. J. M. van den Bergh, Laurens M. Bouwer, Philip Bubeck, Paolo Ciavola, Colin Green, Stephane Hallegatte, Ivana Logar, Volker Meyer, Reimund Schwarze and Annegret H. Thieken

The proposed 'cost assessment cycle' is a framework for the integrated cost assessment of natural hazards.

Reported costs of natural hazards are at historically high levels, and are rising due to the ever increasing cost of events with large-scale effects.

The Thailand flood in 2011, for example, shut down scores of factories, damaging global car manufacturing and electronics industries. In 2013, Typhoon Haiyan in the Philippines caused many casualties and displaced thousands of people. Globally in 2013, natural hazards caused damage estimated at US$125 billion[1]. Property damage has doubled about every seven years over the past four decades[2].

But such assessments generally do not reflect the complete set of costs of natural hazards, which comprise direct, business interruption, indirect, intangible and risk

Box 1 | Definitions of cost categories.

Definitions of cost categories differ between communities dealing with different types of hazard. The following terminology is largely based on the classification of costs introduced to the flood damage literature by Parker and co-workers[15]. New aspects are the addition of risk mitigation costs, as well as considering business interruption costs as a separate cost category (Supplementary Table 1). The reason for choosing this classification is that these cost categories require different cost assessment methods[7].

Direct costs are damage costs that occur as a result of the direct physical impact of a hazard on humans, economic assets or any other object. Examples include the destruction of buildings, contents and infrastructure, or the loss of life.

Business interruption costs occur in areas directly affected by the hazard. Business interruptions take place if, for example, people are not able to carry out their work because their workplace is either destroyed or made inaccessible. They also occur if industrial or agricultural production is reduced due to water scarcity.

Indirect costs occur inside or outside the hazard area, often with a time lag. They are induced by either direct damage or business interruptions. Examples are negative feedbacks to the wider economy, such as the production losses of suppliers and customers of the companies directly affected by the hazard.

Intangible costs refer to damage to people, goods and services that are not easily measurable in monetary terms because they are not traded on a market. All cost categories described before may be tangible or intangible costs (Supplementary Table 1). Intangible costs include, for instance, costs associated with environmental impacts, health impacts and impacts on cultural heritage.

Risk mitigation costs are part of the total cost of natural hazard risk management, and are thus considered an essential cost category. The direct costs of risk mitigation refer to any costs attributed to research and design, the set-up, operation and maintenance of infrastructure, or other measures for the purposes of risk mitigation. The indirect costs of risk mitigation relate to any secondary costs (externalities) occurring in economic activities or localities that are not directly linked to such infrastructure investment. The intangible costs refer to any non-market health or environmental impacts of risk mitigation measures, such as environmental damage due to the development of a structural risk mitigation measure.

mitigation costs (see Box 1 for definitions). In fact, most assessments only account for direct costs, and even these are thought to be at least 50% higher than internationally reported[3]. Substantial indirect and intangible damage, caused, for instance, by disruptions of global supply chains or environmental and health impacts, are often neglected[3].

A better understanding of total costs and their physical and societal drivers is needed for efficient risk management[4,5]. Regions can be left under-protected unless all costs are considered. Optimal investment in risk mitigation requires that each measure is used to the point where the marginal benefit of risk reduction is equal to the cost of achieving that reduction[6]. Investment in risk management will be suboptimal unless the total costs of natural hazards, including those of risk mitigation, are fully understood (Supplementary Information).

Efficient risk management requires a comprehensive analysis of the probabilities of extreme events as well as of the various effects and associated costs resulting from natural hazards. A generally accepted framework is the 'risk management cycle', which describes the consecutive phases followed when aiming to reduce the impacts of hazardous events: emergency response, recovery and reconstruction, risk analysis and risk reduction (Fig. 1).

Costs are incurred in all phases of the risk management cycle and need to be comprehensively assessed — more so than they are at present — to improve risk management decisions. Such costs comprise those for damage (including recovery) and risk mitigation. Damage costs include direct, business interruption, indirect and intangible costs. Risk mitigation costs arise due to emergency response, planning (including risk analyses) and risk reduction measures.

Because budgets for risk management are limited, the choice of appropriate measures, the assessment of the costs and effects of such measures, and their prioritization are crucial for decision makers. Thus, cost assessments need to become an integral part of efficient risk management with the aim of minimizing the total costs related to all the risk management phases. Our vision for an integrated cost assessment in risk management is represented by what we call the cost assessment cycle (Fig. 1). It is based on a comprehensive compilation and synthesis of currently available and applied methods for the cost assessment of natural hazards[7].

Natural hazard risk depends on climate variability, climate change and changes in exposure and vulnerability[8]. Because of its dynamic nature, cost assessment should be a continuous process able to detect relevant changes in risk and initiate appropriate adaptation to changes[9]. The objective is to establish a systemic cost assessment framework.

We propose a four-phase continuous costing, as described below.

Phase 1: Contextualization

Cost assessments are purpose-oriented[10]. This means that cost assessments for a private company, a municipality or a whole country differ in various aspects. It is important to clearly define the aim and scope of the assessment and the relevant hazards. Identifying system boundaries, such as spatial scales and time horizons, is also important as these will determine the required analysis and assessment of cost categories. The relevant cost categories are defined on the basis of preliminary assessments or expert judgments. Socio-economic aspects that might influence the system's recovery or response after a hazardous event are taken into account.

Potential risk mitigation measures and strategies can be identified through open dialogue with relevant stakeholders. The costs of these potential strategies are then assessed in the following step.

Phase 2: Cost assessment

Cost assessment is conducted for all relevant cost categories identified in phase 1. It aims to achieve comprehensiveness and avoid double-counting. Appropriate cost assessment methods are selected based on available overviews and guidelines[7]. Method selection depends on the specific properties of different cost categories and fields of application (for example, investments in structural measures, land use planning or insurance), as well as on relevant hazard types and sectors at risk. It needs to be decided whether it is necessary or helpful to include intangible costs in monetary terms or whether they should be considered in a non-monetary or qualitative way, for example, through multi-criteria approaches.

To account for changes in risk, scenarios for the future development of major risk drivers are created and used for assessing costs up to a specified time horizon. Potential changes in the cost estimates based on these scenarios are described, and their influence on the evaluation of risk mitigation measures (phase 3) is assessed. Uncertainties pertinent to the dynamic scenarios need to be quantified, clearly communicated and taken into account in the decision-making process[11].

Phase 3: Decision support

Economic cost assessment supports the choice between alternative risk mitigation strategies. Cost assessment figures are integrated in decision-support frameworks, such as cost–benefit analysis, multi-criteria analysis and robust decision making[11,12]. They assist decision makers in evaluating different risk mitigation strategies under uncertainty. The choice between alternative decision-support frameworks and their associated decision rules, such as the weighting of evaluation criteria, should be made transparent to the decision makers. The choice made can substantially influence the results of an evaluation and the ranking of options.

When decision makers feel that uncertainties are too high to make a decision on pre-selected risk mitigation strategies, more detailed or precise cost estimates need to be achieved by putting more effort into data collection and modelling (return to phase 2).

Alternatively, additional criteria, such as robustness (performance of an option under different future scenarios), flexibility (ability to adjust a risk mitigation strategy according to future risk changes) and the precautionary principle (measures that are taken in the face of uncertainty to avoid harm to human health or the environment) can be considered in the evaluation of risk mitigation strategies[11,13].

Phase 4: Monitoring

The continuous monitoring of the actual damage caused by natural hazards and the cost of their risk reduction should be established by the responsible authorities[14]. Although damage can only be recorded in the aftermath of natural hazard events, the expenditures for risk reduction can be collected continuously, for example, on an annual basis across the multiple levels of the administrations involved. Such evaluations of damage and risk mitigation costs should be fed into national and international open-access databases to improve the evidence basis for decision making. These data may then be used to update, improve, validate and adjust cost assessment models and cost estimates, which serve as inputs for phases 2 and 3. Furthermore, new information on the expected development of the major risk drivers is used to update the cost estimates (phase 2). It should be verified regularly whether such new insights or other developments are leading to necessary adjustments in the decision context of risk management (phase 1). Updated cost estimates are used for a new evaluation of risk mitigation strategies (phase 3). If necessary, decisions are revised, and the chosen risk mitigation strategies are adjusted.

Making better, more informed decisions for natural hazard risk management will become even more important under global environmental change. So far, such decisions are hampered by biased and uncertain cost estimates. The proposed framework for integrated, continuous cost assessment in natural hazard risk management throughout the new cost assessment cycle could provide more efficient solutions. It initiates the continuous monitoring of all damage and risk mitigation costs associated with climatic and other natural hazards. This enables the early assessment of the efficiency of risk mitigation strategies. The cost assessment cycle is linked to the risk management cycle, which has proved to be an effective framework for risk management[2]. The resulting new, extended framework would allow more integrated cost assessment and improved decision making for natural hazard risk management. ❐

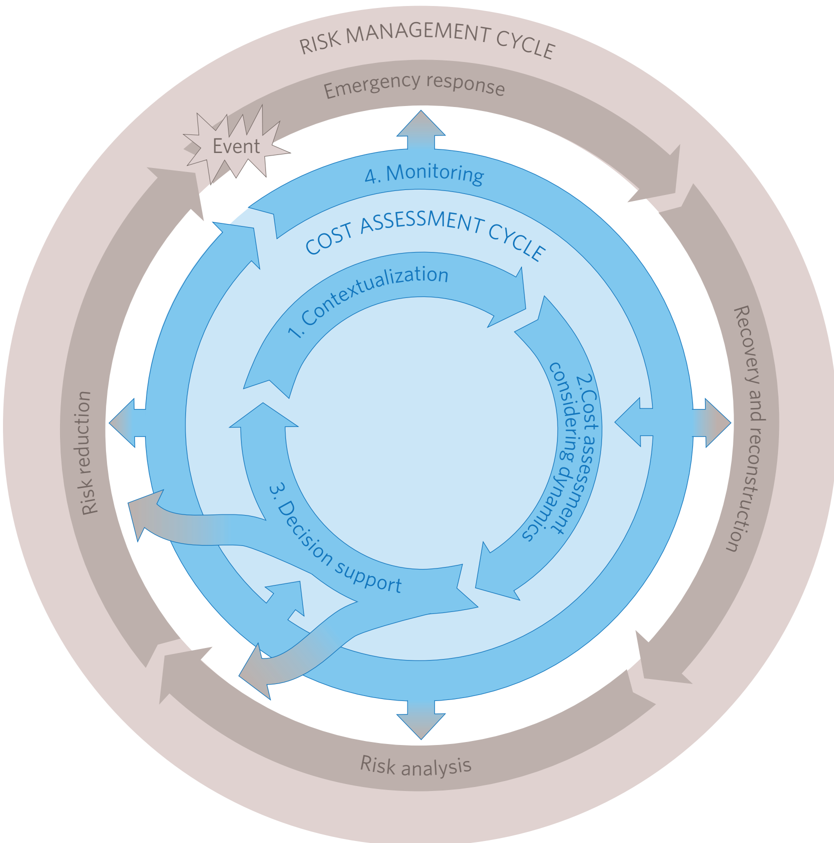

Figure 1 | The proposed framework for integrated, continuous cost assessment in natural hazard risk management throughout the new cost assessment cycle.

Heidi Kreibich[1], Jeroen C. J. M. van den Bergh[2,3,4,5], Laurens M. Bouwer[5,6], Philip Bubeck[1†], Paolo Ciavola[7], Colin Green[8], Stephane Hallegatte[9], Ivana Logar[10], Volker Meyer[11], Reimund Schwarze[11], Annegret H. Thieken[12] are at [1]GFZ German Research Centre for Geosciences, Section 5.4 Hydrology, Telegrafenberg, Potsdam 14473, Germany, [2]Institute of Environmental Science and Technology, Universitat Autònoma de Barcelona, Edifici Cn, Campus UAB, 08193 Bellaterra, Spain, [3]ICREA – Catalan Institution for Research and Advanced Studies, Passeig Lluís Companys, 23 08010 Barcelona, Spain, [4]Faculty of Economics and Business Administration, VU University Amsterdam, 1081 HV, The Netherlands, [5]Institute for Environmental Studies, VU University Amsterdam, 1081 HV, The Netherlands, [6]Deltares, PO Box 177, Delft, 2600 MH, The Netherlands, [7]Department of Physics and Earth Sciences, University of Ferrara, Via Saragat 1, 44122 Ferrara, Italy, [8]Flood Hazard Research Centre, Middlesex University, London, NW4 4BT, UK, [9]The World Bank, Sustainable Development Network, 1818 H Street NW, Washington, DC 20009, USA, [10]Swiss Federal*

Institute of Aquatic Science and Technology (EAWAG), Überlandstrasse 133, 8600 Dübendorf, Switzerland, [11]Helmholtz Centre for Environmental Research — UFZ, Department of Economics, Permoserstraße 15, D-04318 Leipzig, Germany, [12]University of Potsdam, Institute of Earth and Environmental Sciences, Karl-Liebknecht-Strasse 24-25, D-14476 Potsdam, Germany. †Present address: adelphi, Caspar-Theyss-Straße 14a, D-14193 Berlin, Germany.
**e-mail: kreib@gfz-potsdam.de*

References

1. *Overall Picture of Natural Catastrophes in 2013 Dominated by Weather Extremes in Europe and Supertyphoon Haiyan* (Munich Reinsurance Company, 7 January 2014); http://go.nature.com/V8x4QN
2. *A Science Plan for Integrated Research on Disaster Risk: Addressing the Challenge of Natural and Human-induced Environmental Hazards* (ICSU, 2008).
3. *Global Assessment Report on Disaster Risk Reduction 2013* (UNISDR, 2013).
4. Bouwer, L. M., Crompton, R. P., Faust, E., Höppe, P. & Pielke, R. A. Jr *Science* **318,** 753 (2007).
5. Hall, J. W., Brown, S., Nicholls, R. J., Pidgeon, N. F. & Watson, R. T. *Nature Clim. Change* **2,** 833–834 (2012).
6. Young, R. A. in *Cost-benefit Analysis and Water Resources Management* (eds Brouwer, R. & Pearce, D) 13–45 (Elgar, 2005).
7. Meyer, V. *et al. Nat. Haz. Earth Syst. Sci.* **13,** 1351–1373 (2013).
8. Huggel, C., Stone, D., Auffhammer, M. & Hansen, G. *Nature Clim. Change* **3,** 694–696 (2013).
9. Goble, R. & Bier, V. M. *Risk Analysis* **33,** 1942–1951 (2013).
10. *Natural Hazards, Unnatural Disasters: the Economics of Effective Prevention* (The World Bank, 2010).
11. Kunreuther, H. *et al. Nature Clim. Change* **3,** 447–450 (2013).
12. Haasnoot, M., Middelkoop, H., Offermans, A., van Beek, E. & van Deursen, W. P. A. *Clim. Change* **115,** 795–819 (2012).
13. Iverson, T. & Perrings, C. *Glob. Environ. Change* **22,** 161–177 (2012).
14. *A Comparative Review of Country-level and Regional Disaster Loss and Damage Databases* (UNDP, 2013).
15. Parker, D., Green, C. & Thompson, C. S. *Urban Flood Protection Benefits: A Project Appraisal Guide* (Gower, 1987).

Acknowledgments

The research was supported by the European Community's Seventh Framework Program through the Coordination Action Project 'Costs of Natural Hazards' (CONHAZ), Grant Agreement number 244159. This document reflects the authors' views only and not those of the European Community.

Additional information

Supplementary information is available in the online version of the paper.

COMMENTARY:

China's response to the air pollution shock

Peter Sheehan, Enjiang Cheng, Alex English and Fanghong Sun

Faced with serious air pollution, China is aggressively reshaping its energy system, building on recent progress with renewables and on available supplies of gas. This should help contain global warming and provide new impetus to climate change negotiations.

Over the past decade China accounted for over two-thirds of the growth in global CO_2 emissions from energy use. In 2012, its emissions far surpassed those of other major countries and regions[1] (Fig. 1). This reflects rapid economic growth in a massive country whose energy system remains largely based on fossil fuels, despite strong progress in renewable energy. This emissions growth has long spelt danger for the global climate. A gradual process to halt the rise in China's emissions by 2030 will alone add over 10% to the already high global level of CO_2 emissions from energy use in 2012. China's response to the air pollution crisis suggests that its government is taking action that will bring emissions under control much more abruptly than previously evisaged. Such a rapid process of emissions control could improve prospects of holding global warming to less than 2°C and have important implications for both climate modelling and international climate negotiations.

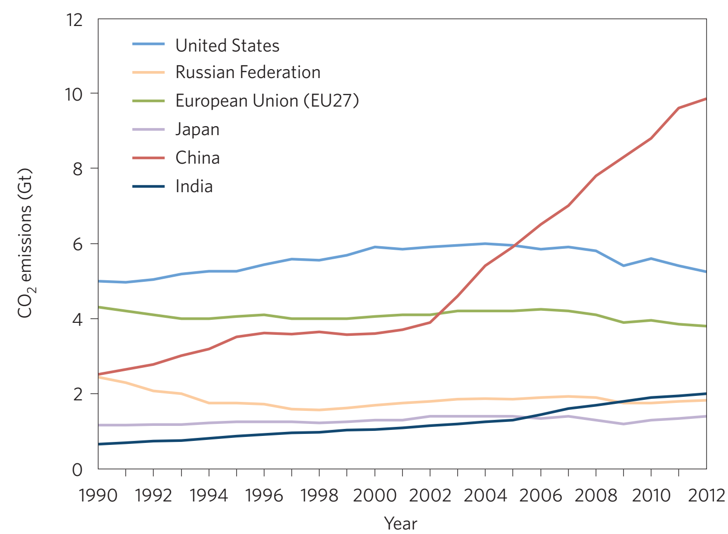

Figure 1 | CO_2 emissions from fossil-fuel use and cement production for selected countries and regions. Figure reproduced from ref. 1.

China's pollution shock

During 2013, air pollution in China became a major economic and social issue across the country ('the pollution shock'). In January 2013, thick smog blanketed Beijing and northern China, covering 2.7 million square kilometres and affecting more than 600 million people. Although varying with weather and other factors, air pollution remained high in many parts of China throughout 2013. It reached extreme levels in Harbin in October 2013 and in