Ten strategies to systematically exploit all options to cope with anthropogenic climate change

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Abstract

The frequency and severity of many types of extreme weather events may be changing because of climate change. To date, most vulnerability studies and resulting toolkits for decision makers, while state of the art, only address a specific subset of possible extreme weather events and mitigation and adaptation efforts. This paper extends Haddon’s strategies to facilitate a holistic, systematic analysis of the options that communities have to cope with uncertain impacts from multiple hazards in multiple sector of society. This framework distinguishes between efforts to reduce the hazard, the exposure, and the vulnerability, thus helping end the semantic confusion of the meaning of adaptation and mitigation. Two case studies demonstrate the merits of the proposed framework. First, we show how the framework can facilitate the systematic identification of mitigation and adaptation strategies for a sector such as human health. Second, we apply the framework to a particular hazard, anthropogenic climate change, in three cities in US Northeast. We find that the three cities pursue a range of strategies, with varying degrees of effort. Comparing cities reveals that some still have unused capacities, especially in terms of reducing the exposure and vulnerability to climate-enhanced hazards. Spreading efforts across multiple feasible strategies increases the robustness of the cities’ policy approach and diversifies the cities’ investment in the face of an uncertain future. Subsequent work, such as a cost-benefit analysis, would help a decision maker to evaluate policy options and steer research efforts appropriately.

Keywords

Climate change Mitigation Adaptation Emergency management Strategic planning Cities

1 Introduction

For the last century, low-frequency natural hazards have led to "billion dollar disasters" (Blunden and Arndt 2013), with average yearly damages outpacing inflation and GDP growth rates (MunichRe NatCatService 2013; Pielke et al. 2008). To prevent damage, many techniques have been adopted, for instance, building codes requiring increased wind protection in hurricane prone areas (Florida Building Code 2010), and levees built along rivers and coasts (FEMA 2012). Institutions, such as insurance, provide aid following an event (FEMA|NFIP 2014). The USA has had a decreasing trend in the number of fatalities due to weather-related phenomena (National Weather Service 2013), because of the improved warning systems and protective structural measures.

Anthropogenic climate change could alter the frequency and intensity of some severe weather events, increasing some types of weather-related damages and decreasing others (Intergovernmental Panel on Climate Change, e.g., Solomon et al. 2009). These changes may require society to change their response periodically by updating building codes or employing other measures. A need for repeated readjusting may render recent construction unacceptably risky, or major expenditures worthless. Societies have to adopt a structured, strategically well-thought through approach to anthropogenic climate change.

Unfortunately, the end state of anthropogenic climate change will not be known for hundreds of years. Regardless of future greenhouse gases emissions, we are already committed to decades of global warming (e.g., Zickfeld et al. 2013). For multiple generations, it appears that society will have to deal with evolving frequencies and intensities of extreme weather events. Thus, societies will have to go beyond periodic rebalancing trade-offs under new circumstances and aim for robust planning under uncertain changing conditions.

Since anthropogenic climate change cannot be reversed in the short term or even intermediate term, there are three main policy options: mitigation, adaptation, and emergency management and recovery. Unfortunately, different stakeholders and organizations use different definitions. Some sources define mitigation as reducing greenhouse gas emission and attenuating anthropogenic climate change itself (California Department of Water Resources 2008; Environmental Protection Agency 2013). Others define mitigation as "stopping the cycle of destruction, rebuilding, and renewed destruction" (Federal Emergency Management Agency 2013). For the purposes of this paper, we will use the EPA's definition of "mitigation" described above (EPA 2013). We define "adaptation" as the "efforts by society or ecosystems to prepare for or adjust to future climate change" (EPA n.d.), which coincides with FEMA's definition of "mitigation" (Klima and Jerolleman 2014). We define emergency management as "the organization and management of resources and responsibilities for dealing with all aspects of emergencies, in particularly preparedness, response and rehabilitation" (FEMA 2007).

Many cities have mitigation, adaptation, or emergency management and recovery plans. Inventories of mitigation plans suggest possible improvements in design, metrics, and implementation and progress monitoring (Blackhurst et al. 2011), similarly for adaptation plans (Bierbaum et al. 2013; FEMA 2011) and emergency management plans (National Council on Disability 2009).

Many groups offer decision tools for coping with changing climate. For instance, the Georgetown Climate Centers provides toolkits for urban heat (Grannis 2011), and for sea-level rise (Hoverter 2012), the Community Rating System works to incent individual flood management techniques in the National Flood Insurance Program (FEMA|NFIP 2014), other groups aim to reduce the source problem of greenhouse gas emissions (e.g., United Nations Development Programme 2010), and still others introduce multi-hazard economic analyses (Ehlen and Vargas 2013). While these efforts are all state of the art, each only addresses a subset of possible disaster responses; the debate is fragmented by societal sector (e.g., health, agriculture, tourism, and energy), and there is semantic confusion. It will likely be easier to engage policy makers and the general public to start planning for changing climate if all sectors carry consistent easy-to-understand messages into the public.

This paper consists of five parts. First, we discuss the definition of risk and its inherent uncertainty. Second, we discuss one framework that has the ability to characterize a full range of risk thinking, Haddon's strategies (Haddon 1973). Third, we apply the framework to a current societal hazard (anthropogenic climate change) and discuss the impacts on just one sector (health). Fourth, we use the framework to assess the comprehensiveness of three US cities' plans to cope with climate change. These two case studies demonstrate the framework's capability to facilitate discussions on damage prevention across sectors and hazards, systematically structure the assessment of viable options to prevent damage (e.g., monetary losses, deaths and injuries, business continuity losses, and social disruptions) from a hazard, and broadly demonstrate our definition of mitigation, adaptation, and emergency management and recovery in a way applicable throughout all sectors. The paper concludes with a discussion of the potential benefits of the proposed framework.

2 An overview of risk definitions

This section reviews the most important risk definitions and describes the uncertainties of the components of risk and their interactions. The definitions (Occupational Health & Safety Group 2007; California Department of Water Resources 2008; Environmental Protection Agency 2013; EPA n.d.; FEMA 2007) are listed in Table 1.

Table 1

Definitions of the most important risk-related terms

Term	Definition	Reference
Risk	Metric composed of hazard, exposure, and vulnerability	Occupational Health & Safety Group (2007)
Hazard	Condition or event that has the ability to release energy that hurts people or damages property	–
Exposure	Amount of people and valuable assets that are affected by the hazard	–
Vulnerability	Amount of damage people and assets that are likely to be experience when faced with certain types of hazards	–
Hazard mitigation	Reduction of greenhouse gas emission and attenuating anthropogenic climate change itself	California Department of Water Resources (2008), Environmental Protection Agency (2013)
Mitigation	Disruption of “the cycle of destruction, rebuilding, and renewed destruction”	Federal Emergency Management Agency (2013)
Adaptation	“Efforts by society or ecosystems to prepare for or adjust to future climate change”	EPA (not dated)
Emergency management	“The organization and management of resources and responsibilities for dealing with all aspects of emergencies, in particularly preparedness, response and rehabilitation”	FEMA (2007)

Classically, risk is defined as a combination of hazard, exposure, and vulnerability (Fig. 1; Occupational Health & Safety Group 2007). Hazard describes a condition or event that has the ability to release energy that hurts people or damages property. It is virtually certain that anthropogenic climate change, for example, exacerbates temperature changes, heat waves, sea-level rise, storm surges and cyclones, drought, and heavy precipitation events (IPCC 2014). Exposure describes how many people and valuable assets are affected by the hazard. For example, the risk caused by hurricanes would be low if nobody lived along the Gulf Coast where hurricanes make landfall. Vulnerability defines how much damage people and assets are likely to be experience when faced with certain types of hazards. For example, the hurricane risk is low if people live along the Gulf Coast, but good evacuation measures are in place and their houses and infrastructure are fortified to be hurricane resistant.

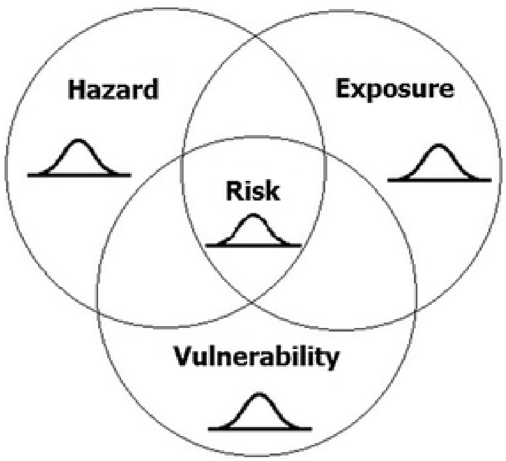


Fig. 1

A schematic depicting the three components of risk: hazard, exposure, and vulnerability. The schematic distributions symbolize the uncertainty inherent to each part of risk

Each of the three components of risk (hazard, exposure, and vulnerability) is subject to uncertainty. For instance, consider a snowfall event: The hazard, the amount of snowfall in any one 24-hour period, even given the best forecasts, is uncertain with 1-foot errors possible. The exposure, how many people and buildings will be exposed to that snowfall, is uncertain, varying, for example, with daily commuting and ongoing development. The vulnerability, how likely a particular roof is to collapse or a particular person is to freeze to death, also varies widely. Uncertainty is inherent to all risk components and is symbolized by probability distributions in each component of risk shown in Fig. 1.

Of course, hazards can result in both potential losses and potential benefits, which different stakeholders might experience at some point in the future. For instance, if rainfall increases, agricultural conditions might improve (benefit), but flooding might become more frequent (loss). Additionally, feedback mechanisms exist. For instance, levees may protect flood-prone areas from the most often occurring floods (benefit). But, they also encourage construction in flood-prone areas, thereby increasing the damage resulting from extremely high water levels (loss). A current flood experience might leave the community more vulnerable to a subsequent flood because of the flood damages incurred earlier (benefit), or more resilient because increased awareness prompts additional adaptation measures (benefit). Furthermore, flood-proofing a house reduces its vulnerability (benefit) but also increases its value, so the economic damage is higher if it gets wiped out completely (loss). Feedbacks may also be observed between different sectors; for instance, increasing temperatures may increase algae blooms in the water resource sector, causing additional complications in the health sector. Additionally, losses for one stakeholder can mean benefits for another stakeholder. For example, the damage experienced by a homeowner provides a business opportunity for a construction contractor.

The discussion has already become quite complicated, as demonstrated in Fig. 2. The flowchart begins with just a few hazards (top) and ends with the damages/benefits (bottom), with vulnerable objects in the middle. For societies, the vulnerable "objects" are the different sectors at risk (e.g., health, agriculture, industry), and they face both risks and opportunities. Good and bad first-order interactions and feedbacks are included in the flowchart as Exacerbation, Deterioration, Adaptation, and Mitigation. To reduce complexity, the remainder of this paper will focus on the portion of the flowchart indicated by the black polygon in Fig. 2.

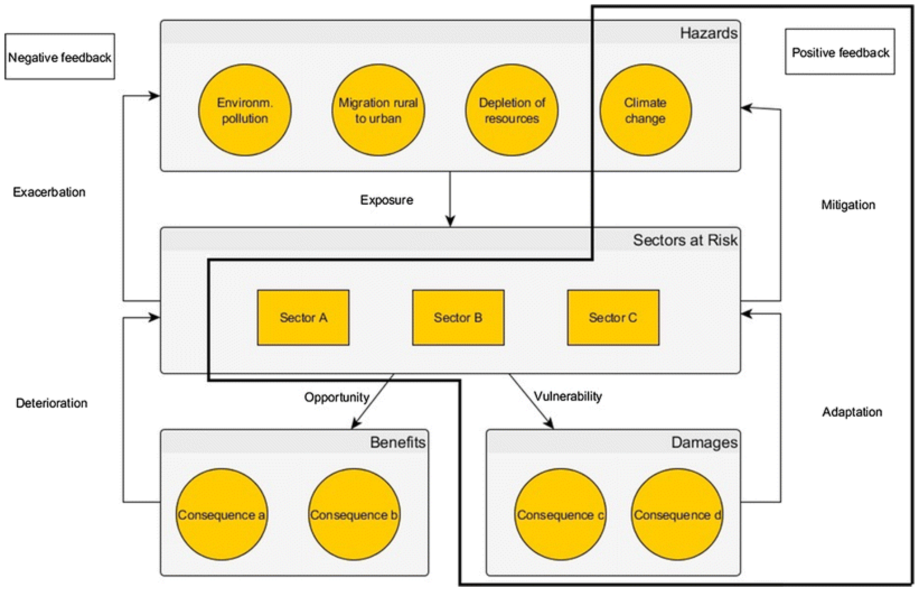


Fig. 2

General framework. The case study will concentrate on the portion indicated by the *black polygon*

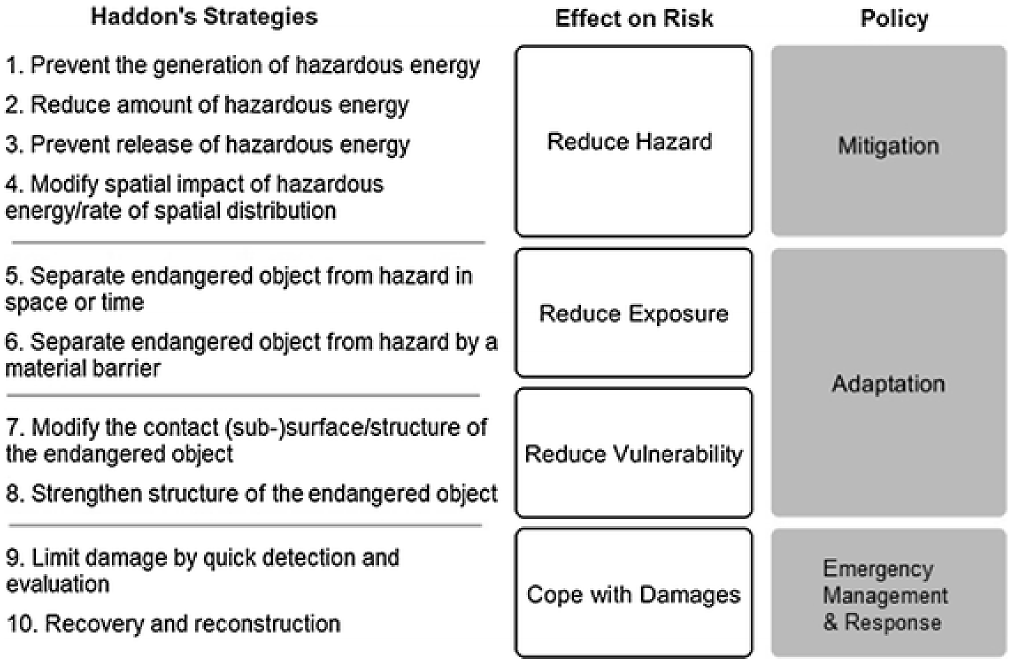
3 Method: Haddon's strategies

Faced with a similar complexity of risk in the medical field, Haddon proposed a framework to structure the analysis of options to decrease risk (Haddon 1973). First, Haddon framed hazards in terms of energy (e.g., thermal, kinetic, or electrical). For instance, picking up a baby creates potential energy. If the baby falls, this potential energy becomes a hazard to the baby. Other examples discussed include tornados, bombs, moving vehicles, and tectonic tensions. Haddon then imagined that there were several different stages before the hazardous energy could cause damage. For each stage, Haddon proposed a category of strategies to reduce risk.

Haddon's strategies can be grouped into four types based on our definition of risk (Table 2). Strategies 1–3 are intended to decrease the released energy (reduction of hazard, or mitigation). Strategies 4–6 are meant to keep the object out of harm's way (reduction of exposure, or adaptation). Strategies 7–8 aim at decreasing the vulnerability of the object (reduction of vulnerability, or adaptation). Strategies 9–10 represent emergency management and recovery after damage has occurred. While all other strategies are anticipatory in their nature, these strategies are reactive. Haddon provides numerous examples from different fields for each strategy.

Table 2

Definitions of mitigation, adaptation, and emergency management using Haddon's strategies as a framework



FEMA's definition of "hazard mitigation" is synonymous with our definition of adaptation

In some cases, it is difficult to draw a sharp line between strategies. For example, strategy 7 is almost a continuum between strategies 6 and 8. Wearing a shoe to prevent harm (strategy 6) is similar to carpeting the floor (strategy 7), as both strategies put physical barriers between the vulnerable object and the hazard.

Haddon's strategies distinguish themselves from other frameworks, because they are based on a one-dimensional sequence of stages that makes them easily generalizable for different types of hazards. It is also possible to extend the framework multi-dimensionally or in a tree structure, with one hazard leading to a number of damages. The damages could be the result of completely separate processes, or their processes could share subsets of stages. Given the innumerable impacts and resulting damages of some hazards, such differentiation might be necessary.

It is important to note that, while Haddon's strategies are intended to help users consider all options, they do not imply that a comprehensive set of feasible and desirable options exists. In fact, it may be impossible to come up with feasible and desirable solutions for each of the ten strategies. Returning to our baby example, there is no feasible way of making a baby's head harder (strategy 8). Instead, having the baby wear a helmet (strategy 6) or covering the floor with a soft carpet (strategy 7) would be feasible. Furthermore, Haddon's strategies do not include relative costs or benefits to help the user decide between strategies. Rather, this framework is a way to identify comprehensively possible strategies to reduce damages, thus informing the options in the subsequent cost-benefit analysis.

Caveats aside, Haddon's strategies have already been successfully applied to a topic outside of the medical field. Hoss et al. (2013) have proposed a framework based on Haddon's strategies to assist decision makers in multi-layered safety efforts for flood risk management. The framework highlighted three categories of safety efforts: hazard reduction, decreased exposure, and decreased vulnerability. This succinct and simple framing has proved attractive to policy makers and was included in an advice piece by a committee to the Dutch Minister of Public Works (Councils for the Environment and Infrastructure 2011).

4 Analysis: applying Haddon's strategies to anthropogenic climate change

In the next step, we apply Haddon's strategies to anthropogenic climate change. First, we define the hazardous energy as an excess of radiant energy, caused by an increased level of greenhouse gases in the atmosphere. Next, we perform a risk assessment to understand the paths along which this hazard energy might pose either damages or benefits. Finally, we identify strategies at (if possible) each of Haddon's ten steps.

Unlike some of our previous examples for Haddon's strategies, for anthropogenic climate change, there are many branches from the hazardous energy to damages. To identify these branches, a community should first complete a risk assessment to identify possible damages for at-risk sectors. For this case study, we use the sample risk assessment shown in Table 3.

Table 3

Risk assessment: climate-related symptoms and the damages they cause in selected sectors of society

Climate-related SYMPTOMS	Agriculture, forestry, and ecosystems	Water resources	Human health	Industry, settlements, and society
Temperature change	Increased yields in colder environments Decreased yields in warmer environments Increased insect outbreaks	Effects on water resources relying on snow melt Effects on some water supply	Reduced human mortality from decreased cold exposure	Reduced/increased energy demand for heating/cooling Declining air quality, especially in cities Reduced transportation disruption from snow, ice Effects on winter tourism
Heat waves/warm spells	Reduced yields in warmer regions due to heat stress Wildfire danger increases	Increased water demand Water quality problems, e.g., algal blooms	Increased heat-related mortality, especially for the elderly, chronically sick, very young and socially isolated	Reduction in quality of life for people in warm areas without A/C Impact on elderly, very young and poor
Heavy precipitation events	Damage to crops Soil erosion Inability to cultivate land due to waterlogging of soils	Adverse effects on quality of surface and ground water Contamination of water supply Water stress may be relieved	Increased number of death, injuries, infectious respiratory and skin diseases	Disruption of settlements, commerce, transport and societies due to flooding Pressures on urban and rural infrastructure Loss of property
Drought	Land degradation Crop damage/failure Increased livestock deaths Increased number of wildfires	More wide-spread water stress	Exacerbated malnutrition Increased number of water and food-borne diseases	Water shortage for settlements, industry and societies Reduced hydropower generation potentials

Climate-related SYMPTOMS	Agriculture, forestry, and ecosystems	Water resources	Human health	Industry, settlements, and society
Hurricanes and storm surges	Damage to crops Windthrow (uprooting) of trees Damage to coral reefs	Power outages cause disruption of public water supply	Increased number of death, injuries, water and food-borne diseases Posttraumatic stress disorders	Withdrawal of risk coverage in vulnerable areas by private insurers Potential for population migrations Loss of property
Sea-level rise	Salinization of irrigation water, estuaries and freshwater systems	Decreased freshwater availability due to salt-water intrusion	Increased number of deaths/injuries by drowning in floods Migration-related health effects	Costs of coastal projection versus costs of land-use relocation Potential for movement of populations and infrastructure

Adapted from Cities Alliance (2008)

Next, Haddon's strategies are applied based on four "S's": Source, Symptom, Sector, and Suffering. To simplify the discussion, we will focus on a portion of Fig. 2, indicated by the polygon (just anthropogenic climate change, a few sectors, and the corresponding damages). Consequently, while this case study applies Haddon's strategies to anthropogenic climate change, it is incomplete. There are more sectors, and more types of damages, benefits, and feedback mechanisms for each sector.

Figure 3 depicts Haddon's strategies applied to anthropogenic climate change. All strategy categories seek to reduce damages, but do so at different points between the hazard and the damage. Strategies 1–4 use mitigation to reduce the source of the risk: the greenhouse gases. The strategy categories entail reducing the emission of greenhouse gases (strategy 1), reducing the demand for greenhouse gas emissions (strategy 2), preventing warming of the Earth (strategy 3), for example, by implementing carbon sequestration, and decreasing the rate of global warming (strategy 4), for example, through geoengineering.

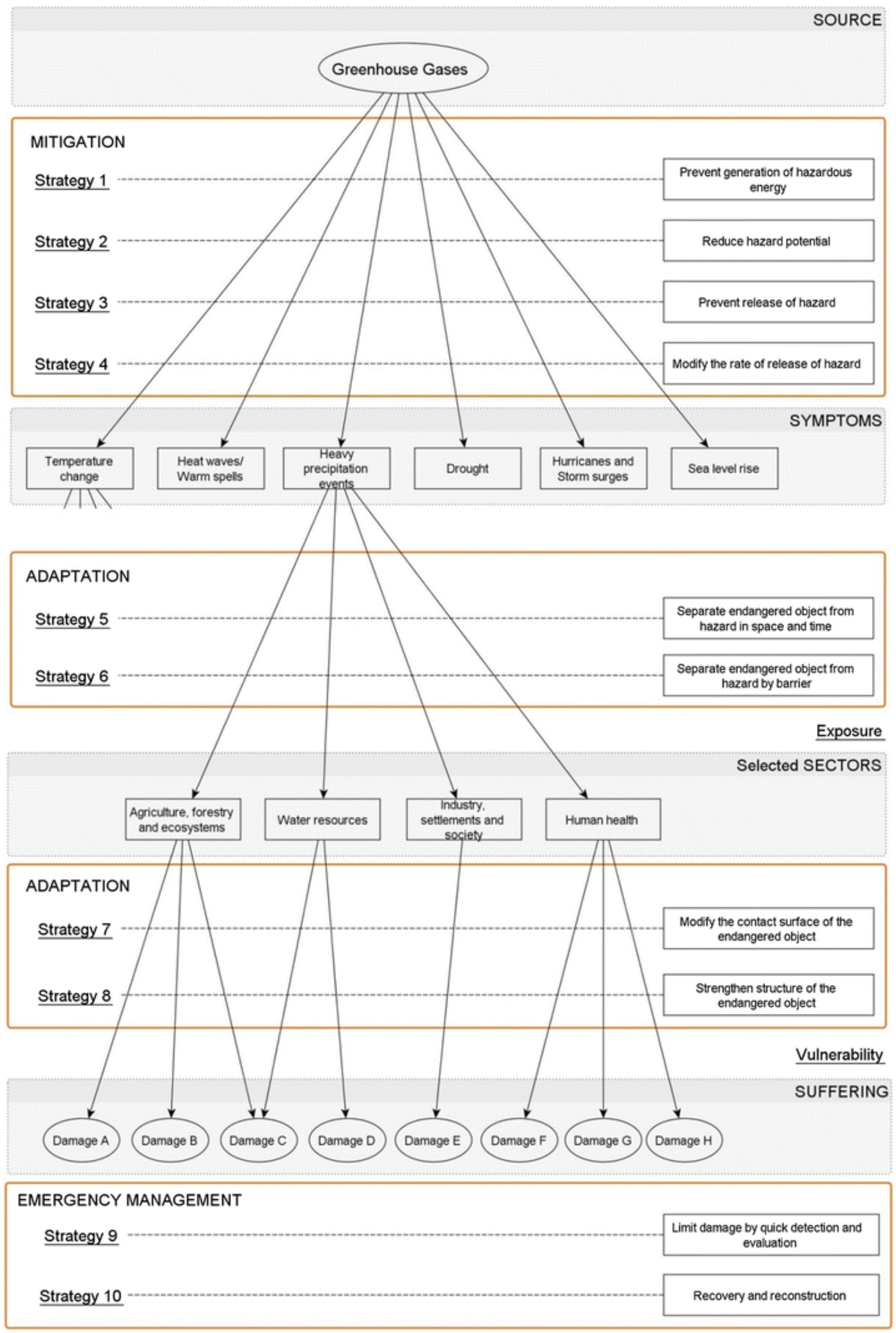


Fig. 3

Haddon’s strategies applied to anthropogenic climate change. This figure is incomplete. There are more sectors and more damages per sector. The figure solely serves the purpose of schematizing the framework application

Next, we divide the hazard posed by increased levels of atmospheric greenhouse gases into a few representative climate-related symptoms: temperature change, heat waves/warm spells, heavy precipitation events, droughts, hurricanes and storm surges, and sea-level rise. Along each of these six branches, strategy categories 5–6 begin to explore possible adaptation techniques to reduce exposure. The actions that each strategy category entails depend on the symptom that is being responded to and the sector that is being addressed. Additional symptoms may exist, but for ease of discussion, we will not include them in this example application.

Beginning at strategy category 7, we start distinguishing by societal sectors. Adapting the study as shown in Table 3, we highlight four representative sectors: (1) agriculture, forestry and ecosystems; (2) water resources; (3) human health; and (4) industries, settlements and society. Note the sectors are merely used to structure thinking; unlike greenhouse gases, climate-related symptoms, and damages, the sectors cannot be quantified. After having introduced societal sectors, strategy categories 7–8 continue to explore possible adaptation techniques, this time to reduce vulnerability rather than exposure. Depending on other environmental factors and stakeholder interest, multiple societal sectors may employ very different adaptation techniques for the same hazard. For example, the health sector might promote reducing the exposure to harmful weather conditions, while agriculture might prioritize making their crops less vulnerable to the changing weather conditions.

Finally, we note that each symptom can cause multiple types of damages, or suffering, in each sector. The risk assessment shown in Table 3 depicts as many as three damages for each symptom; in reality, there may be many more types of damages for each symptom. After identifying these types of damages, strategy categories 9–10 explore possible emergency management and recovery techniques to reduce damages.

Each strategy category alters the probability distribution of one of the underlying risk components: hazard, exposure, or vulnerability. For example, mitigation would be successful if the probability of high water levels in a river is reduced (e.g., the probability distributions are shifted or skewed toward lower water levels). Exposure reduction would be successful if houses were elevated or moved so that the probability of the river water reaching their door steps is reduced. Vulnerability reduction would be successful if the first floors of buildings are waterproofed, thus reducing the probability of any flood damage to the first floor.

As previously discussed, not all possible strategies to reduce anthropogenic climate change damages are both feasible and desirable. Additionally, although early interventions affect many more branches than later interventions, this is not to say that they are more efficient; interventions deep down in the branches can be much more customized to the problem and therefore may be more cost-effective, more predictable, and more politically expedient. To understand these trade-offs, one could use Haddon’s strategies to quantify interactions and inform a subsequent cost-benefit analysis.

4.1 Case study 1: application to the human health sector

In our first case study, we applied Haddon’s strategies to one of the four sectors in Fig. 3: Human Health. For other sectors, strategies 1–4 would remain the same. Here, strategies 5–10 apply specifically to the Human Health sector. We find that Haddon’s strategies illuminates strategies that might not be normally considered as viable ways to improve human health. For instance, a practitioner might focus on extreme weather events that cause human health damages, such as heat waves or floods. It may appear that “energy efficiency” would not be connected to this. However, using Haddon’s strategies, we can examine the full system causing the damages, thus illuminating how energy efficiency would reduce GHG emissions and therefore reduce human health damages from climate change (Table 4).

Table 4

Finding solutions for one branch of the framework applied to anthropogenic climate change: damages caused by heavy precipitation events in the Human Health sector

Strategy	Real-life measures (for just one branch)	Policy
SOURCE	**Anthropogenic Climate Change**	
1. Prevent generation of hazardous energy (Don't emit greenhouse gases)	Alternative/renewable energy Decarbonization (better cars, different transportation options, integrated building design etc.) Carbon tax/Carbon markets	Mitigation
2. Reduce hazard potential (Reduce demand for greenhouse gas emissions)	Energy demand management Energy efficiency	
3. Prevent release of hazard (Prevent warming)	Recover methane from land fills Carbon sequestration Scrapping carbon out of atmosphere Solar radiation management	
4. Modify the rate of release of the hazard (Slow down warming)	Geoengineering	
SYMPTOM	**Heavy Precipitation Events**	
5. Separate endangered object from hazard in space or time	Relocation Land use planning/Zoning Evacuation	Adaptation
6. Separate endangered object from hazard by barrier	Improved roofing	
SECTOR	**Human Health**	
7. Modify the contact surfaces	Increase capacity of storm sewers	
8. Strengthen structure of the endangered object	Sink foundation in deeper than typical flooded areas	
SUFFERING	**Increased number of death, injuries, infectious respiratory and skin diseases**	
9. Limit damage by quick detection and evaluation	Medical aid	Emergency Management & Recovery
10. Recovery and reconstruction		

FEMA's definition of "hazard mitigation" is synonymous with our definition of adaptation

4.2 Case study 2: application to three US cities

Next, we used Haddon's strategies to consider three cities' efforts to reduce climate change damages. Table 5 gives the breakdown of strategies given in the climate action and climate adaptation plans for three cities faced with similar climate-induced symptoms: Pittsburgh (City of Pittsburgh 2006, 2007a, b, 2013a, b; Pittsburgh City Planning 2013; Pittsburgh Climate Initiative 2012), Philadelphia (City of Philadelphia 2007a, b, 2009, 2010, 2011, 2012a, b; Dews and Schwarz 2013), and Washington D.C. (District of Columbia 2006, 2010a, b, c, 2013, n.d.). Note the table focuses only on enacted policies; it does not judge the extent of implementation or enforcement.

Table 5

Case Study 2: Comparison of mitigation and adaptation plans for the cities Washington D.C., Philadelphia PA, Pittsburgh PA using the proposed framework

		Washington, D.C.						Philadelphia, PA							Pittsburgh, PA					
		Climate-specific Planning				General Planning		Climate-specific Planning				General Planning			Climate-specific Planning		General Planning			
		Comprehensive Plan (with 2011 updates)	DDOT Climate Adaptation Plan	A climate of Opportunity	Sustainable DC Vision Plan	Homeland Security and Emergency Managem. Agency	Fire and Emergency Medical Services	Local Action Plan for CC	Greenworks Philadelphia	City-Wide Vision 2035	Climate Change Adaptation	Emergency Action Plan	Hazard Mitigation Plan	Public Assistance Workbook	Pittsburgh Climate Initiative	Plan PGH	All Hazards Plan	Emergency Operations Plan	Pittsburgh Strategic Planning	Pittsb. Zoning & Development Review Board
	SOURCE	2006/ 2011	2010	2010	2012	2011	2013	2007	2009	2011	2013	2010	2012	2012	2009	2013	2006	2007	2013	2013
Mitigation	1. Prevent generation of hazardous energy (Clean energy)	●		●	●			●	●	●	●				●	●				
Mitigation	2. Reduce hazard potential (Energy efficiency)	●	●	●	●			●	●	●	●				●	●				
Mitigation	3. Prevent release of hazard (Absorb GHG)	●		●	●			●	●	●	●				●	●				
Mitigation	4. Modify rate of release of hazard (Geo-engineering)																			
	SYMPTOM																			
Adaptation	5. Separate object from hazard in space and time (Zoning)				●			●		●			■		●	●	■		■	■
Adaptation	6. Separate object from hazard by barrier	●			●			●	●		●		■		●	●				■
	SECTOR																			
Adaptation	7. Modify the contact surfaces (Soften impact)	●	●	●	●				●	●	●		■			●			■	■
Adaptation	8. Strengthen structure of object		●	●	●			●	●	●	●		■		●	●			■	■
	SUFFERING																			
EM & Resp.	9. Limit damage by quick detection and response					■	■				●	■	■				■	■		
EM & Resp.	10. Recovery and reconstruction					■						■	■	■						

Circles indicate that the corresponding plans focus on coping with climate change. Squares stand for general plans that are relevant to handling climate change, but have not been reviewed from that perspective yet

First, we observe that while no one plan covers all of the strategies, most cities focus on using clean energy (strategy 1), saving energy (strategy 2) and strengthening the objects at risk (strategy 8). That said, different cities have enacted different policies to deal with similar hazards, e.g., green printing in the city hall versus covering 30 % of the city with a tree canopy. Additionally, some plans are meant for an early stage and mainly encourage risk assessment, data collection, and public education efforts rather than taking tangible actions. This demonstrates that multiple solutions exist even when focusing on a particular strategy, thus suggesting that cities can use benchmarking studies to help inform their climate action plans.

Second, we find that the implications of climate change for zoning (strategy 5), emergency planning (strategy 9), and recovery and reconstruction (strategy 10) are much less often considered in the cities' climate and sustainability plans. However, many actions in these areas have co-benefits; for example, more public transportation might be implemented to reduce traffic congestion rather than reducing greenhouse gas emissions.

To include efforts that have the co-benefit of reducing climate change damages, we examined a few select hazard mitigation, emergency operation, and strategic planning documents. The latter plans do not consider climate change explicitly, but are planning tools that could be employed to cope with it. Using this whole-systems view, we find that the three cities engage in nine of the ten strategies to varying extent. Some few strategies like capturing CO_2 (strategy 3) appear rather neglected, mainly because the studied climate plans focus on quality of life rather than industry and business. No city considered geoengineering (strategy 4). It is apparent that zoning (strategy 5) and emergency management (strategy 9) and recovery (strategies 10) are not routinely being reviewed from the perspective of climate change yet. To arrive at comprehensive climate plans, cities need to update their zoning, emergency management, and recovery practices as well.

5 Discussion

The proposed framework makes possible what Haddon strongly advocated: “the systematic analysis of options.” As previously discussed, the framework has three benefits. First, it defines mitigation and adaptation on physical underpinnings, thus hopefully preventing much of the semantic confusion that inhibits discussions today, thereby making the message carried into the public easier to understand and more coherent, and it will help generate more support for proposed policies. Second, it facilitates systematic assessment of the options that different sectors have to prevent damages. Third, the generic setup makes the framework applicable to many kinds of hazards and sectors. Having a common basis to compare approaches will facilitate identifying policies with benefits across multiple hazards and sectors.

Additional benefits exist. One advantage is that this framework provides a basis to begin quantitative evaluation of policy options through appropriate metrics, such as a cost-benefit analysis. For example, in case of flood risk management, exposure can be measured by how many people are exposed to a particular inundation depth (Hoss et al. 2013). Identifying metrics for adaptation and mitigation facilitates the evaluation of policy options and research efforts to determine the most robust or cost-effective strategy.

The framework also suggests timelines for when strategies should be implemented and their time scale of effectiveness. Strategy categories 1–4, the climate change mitigation strategies, have the potential to reduce all sorts of damages (i.e., they affect all branches of the flowchart in Fig. 3), but will take many decades before their effect is felt. All other strategies have immediate benefits if and only if a disaster happens, for example, if a heat wave or drought actually occurs. However, the strategies are applicable at different times in the lifecycle of infrastructure. Strategy categories 5–6, the adaptation to reduce exposure strategies, can be expensive to implement with existing infrastructure, but may be cost-effective during new construction or reconstruction after a disaster. For example, instead of rebuilding after a flood, one could relocate out of the floodplain or construct new buildings with higher floor levels. Strategy categories 7–8, the adaptation to reduce vulnerability strategies, can be applied to both new and existing infrastructure prior to the hazard. For the latter, these are the only cost-effective strategies in many cases.

The proposed framework can be applied to both direct and indirect effects of hazards. For example, weather-related disasters overseas such as typhoons can severely impact domestic economic sectors (Leverman 2014). Additionally, there are interdependencies between sectors, as described by, for example, Robinson et al. (1998). For example, Shih (2009) showed that the energy and transportation sectors are highly dependent, so that disruptions in one sector are likely to have major consequences for the other. Therefore, when working through the ten steps of the proposed framework, stakeholders should not only consider locally occurring hazards, but also regional and global events and those impacting other sectors. Specifically, stakeholders should first identify the relevant non-local hazards, then assess their impact on the sector, and finally for each hazard go through the proposed ten steps to devise countermeasures.

Good policy should be a diverse package of adaptation and mitigation measures (IPCC 2012, The President’s Climate Action Plan 2013, etc.). This framework aids in understanding the interaction between adaptation and mitigation. First, the effectiveness of implemented adaptation and mitigation measures are not independent of each other. For instance, in flood risk management, building a levee around a community will reduce the frequency of flooding, thus making measures that only benefit when the community floods were less cost-efficient. Second, adaptation might buy time to implement mitigation. Third, since multiple stakeholders may act and decide simultaneously at different levels, multiple stakeholders might be able to orchestrate action that would lead to synergies between adaptation and mitigation and therefore increase cost-effectiveness. The proposed framework can facilitate these three types of interaction to compile effective packages of adaptation and mitigation measures. Subsequent work, such as cost-benefit analysis, would help a decision maker to evaluate policy options and steer research efforts appropriately.

Notes

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