DISCUSSION PAPER

July 2012 ■ RFF DP 12-28

Informing Climate Adaptation: A Review of the Economic Costs of Natural Disasters, Their Determinants, and Risk Reduction Options

Carolyn Kousky

1616 P St. NW
Washington, DC 20036
202-328-5000 www.rff.org

RESOURCES FOR THE FUTURE

Informing Climate Adaptation: A Review of the Economic Costs of Natural Disasters, Their Determinants, and Risk Reduction Options

Carolyn Kousky

Abstract

This paper reviews the empirical literature on the economic impacts of natural disasters to inform both climate adaptation policy and the estimation of potential climate damages. It covers papers that estimate the short- and long-run economic impacts of weather-related extreme events as well as studies regarding the determinants of the magnitude of those damages (including fatalities). The paper also includes a discussion of risk reduction options and the use of such measures as an adaptation strategy for predicted changes in extreme events with climate change.

Key Words: natural disaster damages, climate adaptation, risk mitigation

JEL Classification Numbers: Q54, D1, E2, O1

Contents

Informing Climate Adaptation: A Review of the Economic Costs of Natural Disasters, Their Determinants, and Risk Reduction Options

Carolyn Kousky*

1. Introduction

A growing consensus in the scientific community holds that climate change could be worsening weather-related natural disasters. The Intergovernmental Panel on Climate Change (IPCC) released a special report in early 2012, which notes that climate change could be altering the frequency, intensity, spatial extent, duration, and/or timing of many climate-related extreme weather events (IPCC 2012). Even nonexperts are perceiving a trend toward more or worse extreme events: a 2012 poll of U.S. residents found that, by a margin of 2:1, people believe that the weather is getting worse, and a large majority believe climate change contributed to the severity of several recent natural disasters (Leiserowitz et al. 2012).

This paper reviews what we know about the economic impacts of natural disasters to inform both climate adaptation policy and the estimation of potential climate damages using integrated assessment models. It first reviews empirical estimates of the economic consequences of natural disasters and summarizes findings on the determinants of economic damages and fatalities. The paper then provides an overview of risk reduction measures that could be used to adapt to changing extremes. Since confidence in the impact of climate change on hydrometeorological (or weather-related) events is greater, the paper looks specifically at hydrometeorological disasters, and not geophysical disasters (although some papers group all natural hazards together and those papers are included as well). The review is focused on the empirical literature; it does not address the theoretical literature on the economic impacts of disasters or simulation- and modeling-based studies. The focus of this review is also limited to economic impacts, although it should be noted that natural disasters can have profound social and political impacts (e.g., Lindell and Prater 2003), as well. Finally, as a further limit to the scope, this review is largely focused on literature published within the past couple of decades, a

* Carolyn Kousky is a fellow at Resources for the Future, kousky@rff.org. This paper was prepared for a workshop on Climate Change Adaptation and Integrated Assessment Modeling at the National Bureau of Economic Research in Cambridge, Massachusetts, on May 17–18, 2012.

period during which new data sets and improved understanding of disaster losses have emerged. Recent working papers are included, in addition to peer-reviewed studies.

Estimating the full range of economic costs from natural disasters is difficult, both conceptually and practically. Complete and systematic data on disaster impacts are lacking, and most data sets are underestimates of all losses. The work reviewed here suggests negative consequences of disasters, although communities tend to have a lot of resilience, recovering in the short- to medium-term from all but the most devastating events. The worst disasters can have permanent economic consequences. Negative impacts are more severe for developing countries and smaller geographic areas. Damages also, intuitively, increase with the severity of the event. Natural disasters generate many transfers and can have large distributional consequences, with some groups suffering devastating losses and others coming out ahead, even if overall impacts are close to neutral. Consequences are less severe in higher-income countries, countries with better institutions, and those with a higher level of education. Risk reduction options are available, but their adoption faces many barriers. Many groups fail to adopt risk reduction strategies for myriad reasons, although the occurrence of a disaster has been shown in some cases to increase investments in reducing risks. In addition, some evidence suggests that areas more prone to hazards invest more in reducing their impacts, providing some insight regarding future adaptation.

The next section of the paper discusses the difficulties with obtaining empirical estimates of all economic costs of natural disasters and the approaches taken in the literature. Section 3 reviews the empirical estimates of economic impacts, both in the short and long term. Section 4 then briefly discusses the question of whether and when natural disasters can have positive impacts. Section 5 summarizes the work on the drivers of both disaster damages and fatalities. Section 6 gives a short overview of trends influencing the magnitude of disaster losses. Section 7 discusses risk reduction and adaptation possibilities at all levels, from the nation state to the individual. Section 8 concludes.

2. An Overview of the Issues

The theoretically correct measure of economic impacts from a natural disaster would be the change in welfare that occurred as a result of the event. Welfare can be evaluated ex post, as the compensation required to avoid loss, or ex ante, which accounts for uncertainty (Rose 2012). Although thinking in terms of hypothetical welfare measures can be instructive, a complete welfare analysis is usually quite difficult empirically and would require making a number of assumptions and simplifications in analysis. If society were risk-neutral, ex ante welfare could be evaluated with the expected economic loss (Rose 2012). Scholars interested in empirical estimates (as opposed to modeling results, which can be useful in estimating welfare calculations) have attempted to measure observable disaster damages and follow-on economic impacts as a rough approximation of the net economic costs of a disaster.

Various lists and typologies of disaster impacts have been created. Most scholars of disasters have generally classified disaster impacts into direct and indirect impacts. Direct impacts have been described as the physical destruction from a disaster, and indirect impacts (some authors prefer the term *higher-order* impacts) are considered the consequences of that destruction (National Research Council 1999). In this way, direct damages refer to damages to structures, contents, and infrastructure that occur as a direct result of experiencing the hazard. Direct impacts also include mortality and injury caused directly by the hazard. Indirect damages refer to lost economic activity, such as loss of potential production, increased costs of production, loss in expected income, and other welfare losses, which occur as a result of the initial damage. Direct and indirect damages include nonmarket impacts, such as declines in the quality of life, environmental degradation, or lost recreational amenities, for example. In theory, it should be possible to sum up all direct and indirect losses to generate a measure of the total economic costs of a disaster. In practice, this is quite difficult, for several reasons discussed in this section.

Furthermore, although it is convenient to speak in the shorthand of losses, costs, or damages from a disaster, in practice, this review—like the work it summarizes—focuses on the net impact of disasters (Economic Comission for Latin America and the Caribbean [ECLAC] 2003). Section 4 below investigates the question of whether and when disasters can have a positive economic impact.

The approach of dividing disaster impacts into direct and indirect damages and summing them appears to be a theoretically straightforward accounting method for estimating the total economic impact of natural disasters; however, the difficulty in practice has led much of the literature to focus instead on the impact of disasters on macroeconomic variables. This approach is another lens through which to view disasters and is clearly not additive with direct and indirect damages (ECLAC 2003). The assumption is that direct and indirect effects would be reflected in macroeconomic accounts if the disaster was significant. The focus on macroeconomic variables is probably due in part to the fact that good data are available on them, but the ease of data availability does not imply that macroeconomic variables are the best measure of disaster impacts, as I discuss further below.

The literature includes very few comprehensive treatments of what counts as a disaster loss and how such losses should be measured. Rose (2004) is a helpful exception. I briefly lay out a basic categorization here and mention some of the measurement challenges. I first discuss direct and indirect damages and then turn to the question of macroeconomic impacts. The section will conclude with a discussion of the difficulties inherent in actually measuring economic losses and what data are available to do so.

Table 1 presents a categorization of the direct and indirect impacts from a natural disaster. Direct damage includes damaged homes and contents, which can include nonmarket items like family heirlooms or old photographs. Firms may also sustain damage, and this could include damage to buildings, contents (including inventory), and other productive capital. This category also includes damage to the agriculture sector, such as damage to crops, livestock, or farm equipment. Infrastructure like roads and bridges can also be damaged. People can be killed or injured directly by the disaster. The disaster could also lead to environmental degradation of various sorts—both market and nonmarket damages. Finally, I include in direct impacts the costs of emergency response, such as evacuation and rescue and the clean-up costs, such as clearing debris from streets.

Table 1. Direct and Indirect Impacts from a Disaster

Direct impacts	**Indirect Impacts**
Damage to homes and contents	Business interruption (for those without direct damage)
Damage to firm structures, inventory, and contents	Multiplier effects
Damage to infrastructure	Costly adaptation or utility reduction from loss of use
Mortality and injury	Mortality and Morbidity
Environmental degradation	
Emergency response and clean-up	

Indirect losses include business interruption costs to those businesses that did not sustain direct damage but may not be able to operate because, for example, their supplier was damaged, their workers evacuated, or they lost power. It also includes the multiplier effects from reductions in demand or supply (more on these below). In addition to causing business interruption, loss of infrastructure or other lifelines (e.g., power, sewage, or water) can lead to utility loss to households in terms of a diminished quality of life or could cause both households and businesses to adopt costly measures (such as increased commuting time as a result of damaged roads or the extra costs of running a private generator when the electricity is out).

Two main complications arise when trying to measure the full economic costs in each of the categories in Table 1. First, it is necessary to be very clear about the spatial and temporal scale being examined because a different drawing of the boundaries of the analysis can lead to different results. For example, consider the economic costs of a disaster from the point of view of a homeowner who lost her home. Some direct losses, such as the home, are reimbursed by insurance or aid from government or other groups, and some losses are unreimbursed and borne fully by the victims. That is, assets that are replaced (some may not be) are either from intertemporal transfers of the individual or interpersonal transfers from one person to another (National Research Council 2006). If the individual receives disaster aid from the government, the economic cost of the disaster to that person will be the value of the lost home minus the amount of the aid. From the perspective of society, however, the aid is just a transfer from one taxpayer to another and thus should not be added or subtracted from the direct damage to the home.

Temporal boundaries can also matter. As an example, it has been shown (see below) that construction sectors can experience a boom right after a disaster as people rebuild. A couple of years afterward, however, they may face a lull because people will undertake upgrades during the post-disaster reconstruction that they would have deferred until further into the future. Looking only one year post-disaster may suggest a benefit to the construction sector, but looking over three years might diminish this benefit. And to highlight again the point made in the preceding paragraph, although the construction sector may get a benefit, had the disaster not occurred, the funds spent on rebuilding would have been spent elsewhere in the economy, with a higher utility to the homeowner; thus, post-disaster spending should not simply be counted as a benefit of the disaster.

The second challenge is that it is quite easy to double-count losses. For example, assume a machine is damaged irreparably in a flood. The value of that machine is the net present value of the future returns from its operation. Thus the value of the machine and the lost production of it should not both be counted as a loss (Rose 2004). As another example, one would not want to count both the aid disbursed by government and the rebuilding costs because much of the aid is probably used for the rebuilding.

So, given these difficulties, what would be the most preferable measure of direct and indirect damages? The next three sections discuss in more detail the challenges confronting an analyst, who must comprehensively assess the economic loss from a natural disaster, in arriving at a total estimate of the disaster impacts shown in Table 1.

2.1. Direct Damages

The economic cost that usually first comes to mind when thinking about natural disasters is damage to buildings and contents. Though seemingly straightforward to measure, getting the precise economic costs of this impact is not theoretically trivial. Consider a house that is completely destroyed. The economic loss could be measured as either the market value of the house right before the disaster hit or the replacement cost to rebuild it. The most appropriate measure is the market value at the time of disaster impact. The replacement cost could be higher or lower for several reasons. Post-disaster, some materials may be in short supply and more expensive substitutes used or higher prices charged, for example, or labor may be in short supply and thus wages higher, driving the cost of rebuilding above what it would have been before the disaster (Olsen and Porter 2008). This is often referred to as *demand surge*. Although these higher costs are a loss to the homeowner, they are a gain to the suppliers and builders; therefore, from the point of view of society as a whole, they are “just” transfers. On the flip side, if business interruption is severe and more laborers are looking for temporary work, rebuilding costs could be lower. This again would be a savings to the homeowner that, from the perspective of society as a whole, would offset the loss to the worker.

This picture is complicated by government disaster aid payments. For the individual, aid will lessen the economic impact of a disaster. From the point of view of society, the government aid is a transfer from one taxpayer to another, as stated above. The deadweight loss of taxation is positive, however, and the marginal opportunity cost of a dollar of government spending is in most cases likely to be greater than $1; therefore, one might want to include this cost of government spending. However, it is not necessarily the case that disaster aid will require new taxation because funds may instead be diverted from another use. In such a case, it is possible that this diversion could lessen the deadweight loss of taxation if the aid was less distortionary than the funds in their nondisaster use. If the funds were from increased government borrowing, this cost of federal borrowing would need to be included.

The homeowner could also receive insurance payouts if he or she had disaster insurance. This would again lessen the negative wealth shock to the homeowner. Assuming risk-based pricing of insurance and well-diversified companies, claims payouts should not be considered a cost of a disaster. They are often used as a proxy for economic costs, however, as they should theoretically be closely correlated with the lost value of the homes and structures—at least in areas with high take-up rates of insurance. Further, insurance companies usually keep extremely good records and so are an excellent data source.

In addition to the cost of the lost home, other direct losses to the homeowner include the time lost to the rebuilding effort, emotional trauma or stress, and loss of nonmarket items of value, such as baby photographs or family keepsakes. These losses are rarely included in disaster damage estimates.

Destruction to the buildings, contents, inventory, and capital of firms can be similarly analyzed. For destroyed capital, depreciation must also be considered, and the correct measure of economic loss is the depreciated value of the lost asset. If production is lost from the delay in replacing damaged capital, then the lost production from delay should also be counted as an economic loss. The literature examining possible positive impacts of disasters is premised on the notion that replaced capital could be more productive than the capital destroyed if there has been technological change (discussed in Section 5 below). This productivity bump could not be so high as to make the firm better off, or else they would have already upgraded the capital. Still, the productivity increase will offset some of the economic loss. If the firm receives disaster aid such that the upgrade is, in a sense, free to the firm, then it could, in theory, be better off post-disaster if the productivity bump is great enough. Again, though, from the point of view of society, the aid is simply a transfer.

Infrastructure damage is another category of direct loss from a natural disaster. Again, the depreciated value is the correct measure of economic loss. Delays in repair and rebuilding can trigger indirect costs, discussed next, through an interruption in use or service.

Especially in the developing world, loss of life and injury from disasters can be large, and these are direct costs of a disaster. An enormous debate centers on how to value loss of life and injury, and I will not rehash that here, except to note that a value-of-a-statistical life (VSL) estimate based on disaster risk explicitly would be the best measure. To my knowledge, very few, if any, VSL estimates have looked explicitly at natural disaster risk, although one comparative stated preference study finds that willingness to pay (WTP) to reduce mortality risk is greater for terrorism than for natural disasters and that reducing the mortality risk from natural disasters is valued about the same as that from traffic accidents, even though the latter is a much higher risk (Viscusi 2009). Injury and illness can be measured in quality-adjusted life-years or similar measures.

Direct damages can also include environmental degradation. For such nonmarket losses, an estimate of society’s total WTP to have avoided the loss ex ante is a measure of the economic loss. Again, a large literature addresses nonmarket valuation techniques that can be applied to obtain such estimates, which will not be discussed here (see, for example, Freeman 2003).

Finally, emergency response and debris clean-up could also be considered direct costs of a disaster. This would include the opportunity cost of people's time spent hauling away debris, for example, or the costs of evacuation. Many of these costs are borne by governments, and if the interest is in total economic impacts to society as a whole, care must be taken in correctly estimating these costs. Issues that must be considered include whether new taxation was required, if government indebtedness increased, and/or what the funds would have been spent on in the absence of a disaster.

Although this paper is focused exclusively on economic impacts, previous work has examined broader impacts, including demographic shifts post-disaster. For example, it was found that after Hurricane Andrew, low-income groups moved into areas that had been damaged (potentially because these areas were cheaper), the proportion of middle-income groups in damaged areas declined, and the wealthy remained (perhaps because insurance and self-protection were more affordable for this group; (Smith *et al.* 2006). Such changes could have welfare effects.

2.2. Indirect Damages

Disasters can be viewed as a negative capital shock to a region. This has follow-on economic consequences in addition to the value of the lost assets. First, economic losses are not exclusive to firms or households that sustain direct physical damage. If electricity or water is lost, for instance, it can cause business interruption to even firms that are not themselves directly damaged. This is a widely recognized disaster cost. Similarly, the loss of such services can lead to a decline in the quality of life for households, and thus a utility loss, and could also lead to the need for costly measures to compensate, although this is rarely discussed in the literature. Such compensating actions could involve longer travel times due to a road outage or the purchase of battery-powered lighting in response to a loss of electricity, for instance. These are indirect damages to include in estimates of total costs.

Attention in the literature has focused on possible multiplier effects post-disaster. Consumer demand post-disaster may be higher for some sectors—such as construction, particularly if aid or insurance is funneled to rebuilding—and lower for others as consumers forgo some expenditures to use their funds for rebuilding. These types of expenditure changes could have economic multiplier effects within the community (positive or negative). A similar story can be told for business interruption. This could decrease demand for inputs and reduce outputs, having negative ripple effects in the supply chain; although here, aid and insurance could mute these impacts if such funds allow for a faster resumption of normal business activity.

From the perspective of the whole economy, however, multiplier effects may well be zero, with positive and negative impacts cancelling out (National Research Council 1999). For instance, if a firm fails to produce an output, its customer may simply purchase the good elsewhere. This is a loss for the disaster-impacted firm but a gain for a competitor, and thus a wash from the point of view of the whole economy. As another example, tourists may avoid a hurricane-stricken coast, but instead of not traveling, they may just frequent another area. Again, this may be a wash from the point of view of the entire economy, but clearly the distributional impacts could be quite large and could have significant consequences for individuals, firms, or communities.

If a government does make changes to taxation or resource allocation post-disaster, this could have indirect economic effects. For hard-hit countries, particularly small or poor countries, this is a distinct possibility and would need to be evaluated. Countries can also receive international assistance (which, again, would be a transfer from a global perspective). Case study evidence suggests that donors do not necessarily provide additional aid after a disaster, but simply reallocate aid budgets (Benson and Clay 2004).

Mortality or illness could also occur, as a result not of the hazard but of the initial damage. For instance, if water becomes contaminated as a result of the shutdown of a treatment plant and this leads to illness, it would be an indirect cost of the disaster. After hurricane Katrina, an increase in mortality rates was observed because the storm destroyed much of the health infrastructure of the city (Stephens 2007). These would be deaths classified as an indirect cost.

Finally, disasters could cause people to alter their risk perceptions. This could then induce behavioral responses and a reallocation of resources. These could have economic consequences, such as workers requiring a risk premium post-disaster (on this point in the context of terrorism, see: Rose 2012), but are not further considered in this review. Similarly, utility functions may be state dependent and may change after a disaster, such that ex ante valuations are not the same as ex post valuations.[1] A complete welfare assessment would need to consider these possibilities. Notably, positive utility gains could occur via public aid post-disaster if people feel good about helping those in need and reassured that if they are victims, aid will be forthcoming. Likewise, utility losses could be associated with any increases in fear (or

[1] If individuals wrongly assess risk before a disaster strikes, then ex ante efficiency, achieved through insurance contracts, may not be the same as ex post efficiency. The implications of this for federal disaster aid are discussed by Jaffee and Russell (2012).

other negative emotions), which Adler (2004) argues should be measured and included in regulatory cost–benefit analysis when relevant.

Economists exhibit some hesitancy regarding estimations of higher-order effects, and the complications discussed above hint at why. Rose (2004) notes the following concerns: indirect effects are hard to verify, modeling them can be difficult, the size of the impacts can very substantially depending on the resiliency of the economy and pace of recovery, and the modeling of such effects could be manipulated for political purposes (e.g., inflating the multiplier). Still, when calculated carefully, they are a true cost of the disaster and should be included in any complete accounting. Most estimates of their magnitude have been done through modeling rather than empirical analysis.[2]

2.3. Macroeconomic Approaches

The majority of economic studies, instead of attempting to estimate direct or indirect costs, evaluate the impact of natural disasters on macroeconomic indicators, primarily gross domestic product (GDP). It is thus worth saying a word about how these estimates of disaster impacts relate to estimates of direct and indirect economic effects.

It is possible that the direct and indirect effects of a disaster could be large enough to have macroeconomic effects, including impacts on economic growth, balance of payments, fiscal revenues, levels of indebtedness, and investment rates (ECLAC 2003). If damages are severe, output could decline. Output could also increase from post-disaster reconstruction. It is unclear, on net, how these effects would balance out. Damages to firms could alter imports and exports. Government spending for emergency response, if high enough, could change indebtedness. Tax revenue could be impacted. If serious price increases result from the disaster, this could fuel inflation. Foreign direct investment could fall if companies see too great a risk or too much damage.

Some of these impacts are essentially indirect economic impacts that should be counted in total economic impact estimates. More often, however, macroeconomic variables are used as a

---

[2] One exception is a paper that estimates the lost consumer surplus from four Florida hurricanes between 1995 and 1998 that caused power outages for homeowners, finding losses of between $1.8 million and $2.7 million, although based on some strong assumptions (Vogel 2000). Modeling work is not discussed here, except to note that the two predominant approaches to date have been input–output models and computable general equilibrium models, both of which can capture, to some extent, the indirect effects of disasters (Okuyama 2008).

proxy for the direct and indirect impacts just discussed. For example, government spending is often used as a measure of the damages from a disaster but need not be directly related to economic losses. Similarly, GDP is often used to capture total economic impacts. It is worth stressing, however, that GDP is simply a measure of economic activity, not of wealth or welfare. The usual arguments on this point extend to the case of natural disasters. The literature on the GDP impacts of disasters is reported here, but with this strong note of caution that it is a poor proxy for either total economic costs or welfare impacts of a disaster event.

2.4. Measurement Problems

The thorny theoretical problems involved in estimating the economic consequences of disasters are coupled with extreme data limitations that make actual estimates far from what would be the hypothetical "true" disaster costs. Many scholars have stressed the need for reliable, comprehensive, systematically collected disaster loss data (e.g., Thomas 2001). Good data on disaster losses are needed for a range of purposes, including cost–benefit analysis of mitigation measures, government preparedness planning, calibration of loss models, and risk analysis for insurers and other entities. Even in highly developed countries with generally good record-keeping, comprehensive disaster loss data are difficult to come by. The United States does not keep systematic records in one location of losses associated with natural hazards. Many experts have called for such a database to be developed and maintained by the federal government (e.g., National Research Council 1999), but thus far it has not occurred.

In general, the data available on disaster impacts are on those things that are easily observable ex post. For instance, depreciated replacement value is the best estimate of damage to structures and assets, but is not available in most data sets (Mileti 1999); replacement cost is more likely to be observed. Because public expenditures are fairly easy to observe and often are already measured in some form in most countries, they are frequently used as a proxy for losses; but, as already mentioned, public expenditures on reconstruction may not match the magnitude of losses to capital (Cavallo and Noy 2010). Most disaster data sets do not include indirect losses or damages to nonmarket goods and services; therefore, most disaster loss data probably underestimate the full economic impact of disasters (Mileti 1999; Mitchell and Thomas 2001).

Another difficulty with disaster data is that many high-magnitude events are complex, with multiple interrelated perils (Kron et al. 2012). For instance, strong hurricanes bring with them high winds, torrential rain, and storm surge; these could further trigger landslides. Severe storms could include damage from wind, hail, flooding, lightening, and tornadoes. Earthquakes can trigger tsunamis or fires. This makes classifying disasters for comparison across events difficult.

Finally, some countries have much better record-keeping than others. Some countries may not have institutions that are tasked with damage estimation, and in some places post-disaster assessments may be difficult. Further, developing countries may have an incentive to exaggerate damages to gain international aid and, regardless, obtaining good damage estimates in developing countries can be a challenge because insurance penetration is low, book keeping is often poor, and much economic activity occurs in informal sectors (Toya and Skidmore 2007). Very little is known empirically about disaster impacts on informal sectors of the economy.

Thus, all disaster numbers should be interpreted with some degree of caution. In addition, the nature of the database can influence the conclusions drawn about disaster losses, as noted by Gall et al. (2009). For instance, different databases include different items in the estimate of damages (e.g., just direct damages, or both direct and indirect), which can cause differences in rankings of events. In their comparison of disaster damage estimates in the United States across three different databases, Gall et al. (2009) find that, although all three databases agree that hurricanes and tropical storms are the most damaging hazard in the United States, they differ on which hazard is ranked second—earthquakes, severe weather, or floods.

At an international scale, three primary data sets are available for cross-country, multiple-hazard analysis. These are the Centre for Research on the Epidemiology of Disasters' (CRED's) Emergency Events Database (EM-DAT), Swiss Re's Sigma, and Munich Re's NatCatSERVICE. EM-DAT has a humanitarian focus, and the reinsurance databases (Sigma and NatCatSERVICE), not surprisingly, focus on insured and material losses. The databases have different thresholds for the inclusion of events (Kron et al. 2012). EM-DAT includes events with more than 10 fatalities, more than 100 people affected, a declaration of a state of emergency, or a call for international assistance. Events are included in Sigma if overall losses exceed US$ 86.6 million, insured losses exceed US$ 43.3 million (both in 2010 dollars), or there are 20 or more fatalities or missing persons. NatCatSERVICE includes any event in which harm to people or property damage occurs. All of these databases acquire information from a variety of sources.

EM-DAT is publicly accessible, whereas the reinsurance databases are not, although statistical analyses are published by the firms. This means that for almost every cross-country, multihazard paper, the EM-DAT data are used. Because of this, a few things should be kept in mind about these data. First, given the threshold for inclusion mentioned above, small events are not included, even though frequent lower-impact events could still cause substantial economic costs. Second, EM-DAT is focused on aiding humanitarian response. As such, it has no threshold for damages, so events in more developed countries with a high level of damage but low loss of life and no call for international aid may fail to be included. Finally, EM-DAT data are compiled from multiple sources and are only as good as those sources. Sources include the United Nations, governmental and nongovernmental organizations, insurance companies, research institutes, and the press. The sources are ranked according to their trustworthiness in providing accurate and complete data. Collecting disaster data is a difficult process, and CRED should be commended on the work done to create and maintain this database. It is the best source for consistent, multicountry natural disaster data available. That said, we would be more confident in our estimates of the economic impacts of natural disasters if multiple data sources all found the same results. With so much of the literature relying on this one data source, any problems with the data will propagate through all analyses.

3. A Review of Impact Estimates

Post-disaster activity has been grouped into three stages: (1) the emergency phase of humanitarian assistance and immediate emergency response; (2) the rehabilitation and recovery phase, which includes work undertaken to restore normal functioning of the community; and (3) the reconstruction phase of longer-term rebuilding and reallocation of resources (ECLAC 2003). Mapping studies to these categories is difficult, and findings here are instead grouped into estimates of short-run impacts (up to five years) and long-run impacts. Those discussions are preceded by an overview of estimates of average economic losses and how losses and fatalities have been trending over time.

3.1. Average Losses and Trends Over Time

Many observers have noted that the number of disasters has been increasing over time. For example, the EM-DAT data suggest that about 100 disasters were reported per year in 1980, and since 2000, more than 300 disasters have been reported per year (Bloom and Khanna 2007). Looking at the EM-DAT data in five-year intervals since 1985, all natural disasters have increased in frequency with the exception of insect infestations (Gaiha et al. 2012). This increase is probably attributable both to better reporting and to growing population and structures in hazardous areas (Burton et al. 1993). Munich Re believes its global estimates to be subject to reporting bias if one looks further back in history than the last 20 years; but in places like the United States and Western Europe, data are fairly unbiased even further back—perhaps 30 to 40 years (Kron et al. 2012). Looking at the US data for Munich Re since 1980, an upward trend is still observable, suggesting the explanation for the increase is more people and structures in hazardous areas and not just improved reporting.

In terms of the expected cost of disasters, looking across several disaster data sources, the estimated average annual cost of recorded disasters globally between 1970 and 2000 was between $700 million and $3.3 billion (the year for these estimates is not given, but they are assumed to be in 2000 US$, so this would be $932 million to $4.4 billion in 2012 US$); (Charvériat 2000).[3] SHELDUS (Special Hazard Events and Losses Database for the United States),[4] a county-level database of U.S. disaster losses, estimates an average of $11.5 billion a year in 2009 US$ ($12.3 billion in 2012 US$) in direct disaster costs between 1960 and 2009 (Gall et al. 2011). Normalized data for hurricane damages in the United States suggest an annual average of $4.8 billion in direct damages ($6.7 billion in 2012 US$), with the highest losses occurring in 1926 (over $74 billion, or $104 billion in 2012 US$) and many years of no damage (Pielke and Landsea 1998). Munich Re, looking at worldwide natural disasters between 1990 and 2010, estimated overall losses of, on average, $110 billion (Rauch 2011).

These losses, in inflation-adjusted terms, appear to be growing over time along with disaster incidence (of course, losses in part influence whether something is categorized as a disaster). The reported cost of disasters globally grew 15-fold between the 1950s and the 1990s (Benson and Clay 2004). For the United States, SHELDUS data indicate that the decadal annual mean loss has been steadily increasing (Cutter and Emrich 2005). Experts disagree over what is driving the increase in damages. Contributing factors may include an increasing frequency and/or magnitude of extreme events, increasing population, disproportionate increase in disasters in poorer areas, urbanization, economic globalization, and environmental degradation (Handmer 2009).

If losses are standardized by some measure of wealth, to account for increases in development in risky locations and increases in the value of that development, some studies find no upward trend in losses over time, suggesting that increases in wealth in hazardous areas are fueling the higher observed losses. For instance, looking just at hurricanes, when direct damages in the United States are normalized for changes in population and wealth, no consistent increase

---

[3] This includes data from ECLAC, which based its estimates on only a subset of all disasters but did include indirect damages; data from CRED, which has economic data on only about a third of all disasters; and Munich Re, which conducts its own estimation (Charvériat 2000).

[4] Information on SHELDUS is available online at http://webra.cas.sc.edu/hvri/products/SHELDUS.aspx.

in damages is apparent over the 1925 to 1995 time period (Pielke and Landsea 1998). Similarly, standardizing hurricane damages to account for inflation, population growth, and GDP growth, Pielke et al. (2003) find no increase in direct hurricane damages in Cuba between 1903 and 1998, and Charvériat (2000) finds no clear trend of increasing disaster damages in the Caribbean between 1970 and 1999 using the CRED data. A global analysis of disaster damages finds a modest 2 percent increase in disaster losses when they are normalized for changes in inflation and exposure; but when the U.S. 2004–2005 experience is removed, or when data are normalized for differences in relative per capita wealth, the trend becomes insignificant (Miller et al. 2008). On the other hand, using the SHELDUS data, Gall et al. (2011) estimate that inflation-adjusted per capita damages from natural disasters, as well as inflation-adjusted per capital damages as a percentage of a state's GDP, have been increasing in the United States over the period 1960 through 2009, suggesting that more than just wealth adjustments are driving the trend. And an analysis of U.S. hurricane data found that, if historical hurricanes are assumed to strike today's property-at-risk, 2000–2010 still accounts for 8 of the costliest 30 tropical cyclones (Blake et al. 2011).

In contrast to damages, fatalities have shown a consistent downward trend. The EM-DAT data show no rise in the number of individuals killed (with the exception of disasters occurring in Africa), and the number killed per disaster shows a decline (Stromberg 2007). Fatalities in the United States from hurricanes have been declining over time, even including the large death toll from Hurricane Katrina (Blake et al. 2011). When deaths from inland flooding associated with a hurricane's precipitation are included in the mortality analysis, however, no downward trend is apparent in deaths from hurricanes in the United States over the 1970 to 2007 time period (Czajkowski et al. 2011).[5] This could be because most of the reduction in deaths occurred before 1970 and/or because of the inclusion of freshwater drowning in the hurricane death totals.

The fatality burden of natural disasters is borne disproportionately by developing countries, and mortality in these countries can be high (Perry 2000; Stromberg 2007; Cavallo and Noy 2010). Using the World Bank classification of low-, high-, and middle-income countries and the EM-DAT data, Stromberg (2007) find that low-income countries are home to one-third of the world's population but account for almost two-thirds of all fatalities. Brooks and Adger (2003) use the EM-DAT data to rank countries over time on measures of disaster risk. When examining

[5] The authors exclude Hurricane Katrina.

the percentage of the population killed and affected by climate-related disasters, they find that almost all of the top-ranked countries are developing countries. They also find that about half of them remain fairly consistent in their ranking over the 1970s, 1980s, and 1990s.

Economic losses, on the other hand, tend to be higher in developed countries, but as a proportion of GDP, these losses can often be lower (Anderson 1990; Mitchell and Thomas 2001). When looking simply at inflation-adjusted damage estimates of disasters over the past several decades, the greatest concentration in losses (roughly 36 percent of the total) appears in the United States, followed by China and then Europe; when differences due to differences in economic development are removed, India and China then account for 90 percent of total damages (Miller et al. 2008).

All natural disasters are not equal. Worldwide, approximately 85 percent of direct losses from natural hazards are the result of severe atmospheric and hydrologic events (Gall et al. 2011). Similarly, an analysis of disaster damages in the United States between 1975 and 1994 found that 80 percent were from climatological disasters as opposed to, say, earthquakes and volcanoes (Mileti 1999). Again in the United States, a third analysis found that weather-related events were responsible for the most damage (Cutter and Emrich 2005). This is notable because climate change is expected to alter the climatological disasters, and these represent the bulk of disaster costs in most places. Flooding is often the most common disaster and the one with the largest impacts. Worldwide, floods are the most costly natural disaster (Miller et al. 2008). Although one estimate has droughts as the most deadly natural disaster worldwide, floods have impacted the most people (Stromberg 2007). In the United States, floods are the natural disaster that accounted for the most lives lost and the most property damage over the twentieth century (Perry 2000). Between 1975 and 1998, floods caused an estimated $106 billion in damages in the United States and more than 2,400 deaths (Mitchell and Thomas 2001).

In addition, it is the most severe events that cause the bulk of the damage. For example, hurricanes of category 3 and higher account for roughly 20 percent of landfalling hurricanes in the United States but are responsible for over 80 percent of the damage (Pielke and Landsea 1998). Jagger et al. (2008) also look at hurricanes, examining normalized insured losses (adjusted so that damages reflect what they would have been if the storm had hit in the year 2000) between 1900 and 2005. They, too, find that losses are highly skewed, with the top 30 events (17 percent of the total) accounting for over 80 percent of losses. It is not just hurricanes for which the most severe events cause the majority of damage; a range of natural disasters, from wildfires to earthquakes, have fat-tailed damage distributions (e.g., Schoenberg et al. 2003; Newman 2005; Holmes et al. 2008).

All of the estimates of disaster damages neglect many types of damage, as mentioned earlier. For instance, although difficult to measure, disasters may have a large impact on the informal sector in developing countries (Anderson 1990). Some have attempted to measure certain classes of omitted damage categories. For example, in an attempt to assess the magnitude of business interruption loss, a survey of businesses following a severe flood in Des Moines found that, although only 15 percent were actually damaged, 80 percent lost water, 40 percent lost sewer and wastewater treatment, 33 percent lost electricity, and over 20 percent lost phone service for some amount of time (Webb et al. 2000). Another type of often-unmeasured impact is costly adjustments to maintain compliance with various regulations. For instance, extreme rainfall events can lead to violations of water quality criteria. New York City's water supply has seen short-term spikes in turbidity from high-intensity rainfall events, leading to operational measures (such as increased use of disinfection or shutting down aqueducts) to preserve drinking water quality (USEPA Region 2 2006). Presumably, if such events became more common or more severe, other measures would need to be taken to protect drinking water, at a cost to the city. These are added costs of operation due to the disaster. A comprehensive accounting of these types of costs is lacking.

A couple of studies have attempted to predict disaster damages from physical variables of their magnitude. Nordhaus (2010) examines landfalling hurricanes in the United States between 1900 and 2008, finding that damages normalized by GDP rise with the ninth power of windspeed. He suggests that this is due to structures or infrastructure having thresholds such that damages go from minimal to severe. He finds that damages have been increasing over time, rising by about 3 percent per year. Mendelsohn et al. (2011) also examine hurricanes in the United States, but over more recent years—1960 to 2008—and find that (a) property and infrastructure damages increase inversely with the 86th power of minimum pressure at landfall and the 5th power of windspeed and (b) minimum pressure is a better predictor of damages. Counterintuitively, they find that population and income variables are statistically insignificant in predicting damages; as the authors note, this does not mean that these factors are negligible. Examining the Philippines, Anttila-Hughes and Hsiang (2011) find that detailed wind data can predict tropical cyclone damages, as measured by the EM-DAT data; the authors determine that a one-meter-per-second increase in wind exposure increases losses by about 22 percent. They also find that an average wind exposure equates to a 1.9 to 2.7 percent probability of asset loss (excluding cars) for a household. Such studies could be useful initial work on estimating how disaster damages may change if the magnitude of hazards increases, ceteris paribus.

3.2. Short-Run Impacts

The short run is defined here as one to five years post-disaster. Studies of short-run impacts are grouped in this section into three categories for ease of discussion. The first are multicountry studies, often over time, that examine the relationship between natural disasters and macroeconomic variables. They tend to assume that disasters are exogenous and use various measures of disaster impact to explain changes in macroeconomic outcomes. The second are within-country studies. Some of these employ methods similar to those of the cross-country studies, only at a finer scale; others are not panel data sets, but instead examine pre- and post-disaster trends. The third group is made up of studies that look at the impacts of natural disasters on particular sectors of the economy, often focusing on one event.

In general, most of the research finds no or small negative impacts on macroeconomic variables from disaster occurrences, although there are mixed results in the literature with some finding a small, positive impact on GDP or GDP growth. Impacts are worse the more severe the event, as would be expected. Economic impacts are more negative when looking at smaller geographic areas, whether it is smaller countries or localities within countries. The studies also show, however, that most economies have a lot of resiliency and rebound quickly, with most studies finding that impacts disappear within a few years. That said, impacts are worse and more persistent in developing countries. Aid, social safety nets, and countercyclical government spending in general may blunt negative macroeconomic impacts. Impacts vary quite considerably by sector, with some sectors seeing large negative impacts and some coming out neutral or ahead. Most of these distributional impacts are intuitive, with sectors more exposed to climate experiencing larger damages and those involved in reconstruction seeing temporary booms. They also depend on the amount and nature of post-disaster transfers. These findings help remind us that even if changes in the macroeconomy are small, disasters carry with them huge distributional consequences.

3.2.1 Multicountry Studies

The multicountry studies are presented in chronological order. The first two do not employ econometric approaches, but look only at summary statistics. All the other papers take the disaster event as exogenous and regress some measure of the event—occurrence, damage, or fatalities—on macroeconomic variables. Only a few papers note that, although the occurrence of a disaster is probably exogenous, damages may not be, and thus attempt to address this with instrumental variables.[6] This possibility should be more completely explored in future work. Further, it is possible, given the reporting requirements of the EM-DAT data, that occurrence may not be fully exogenous because, as income increases, death rates and calls for aid may decline, although this is not discussed in the literature. Most of the papers also examine factors that alter the magnitude of their findings; these results are summarized at the end of this subsection.

One of the first multicountry empirical estimations of short-run macroeconomic impacts of disasters was undertaken by Albala-Bertrand (1993), who examines a sample of 28 disasters in 26 countries over the time period 1960 to 1979. The analysis focuses on the impact of natural disaster events on GDP, the growth rate of GDP, and the rate of inflation up to three years post-event by a simple before-and-after analysis of the values of these variables. He finds that disasters do not impact GDP and may have a slight positive impact on GDP growth. He finds no impact on rates of inflation. Examining in more detail the government response, he finds an increase in the trade deficit, reserves, and capital flows in the short run. A similar analysis was undertaken in a working paper from the Inter-American Development Bank using the EM-DAT data, but restricting the focus to 35 disasters in 20 Latin American and Caribbean countries between 1980 and 1996 (Charvériat 2000). Looking at average impacts, Charvériat finds that in the year after a disaster, real median GDP drops almost 2 percent, but increases almost 3 percent in the next two years. Any GDP decline, then, is compensated by subsequent growth.

An unpublished 2004 paper using the EM-DAT data from 1975 to 1996 finds no empirical support for the hypothesis that growth rates are higher post-disaster when the capital–labor ratio decreases (Caselli and Malhotra 2004). This work, like others using the EM-DAT data, is restricted by the fact that the majority of disasters in the database have missing direct damage estimates, reducing the sample when this variable is included (for this paper, the sample is reduced from 3,987 disasters to 510). Caselli and Malhotra estimate reduced-form equations with the difference in the log of output as the dependent variable and include a variety of controls, including country and year fixed effects. When the authors include simple dummy variables for the occurrence of a disaster (for up to three years post-event), or a disaster in which damage as a percentage of the initial capital stock is greater than the median, they find no significant effects. These findings suggest that disasters do not have substantial growth effects.

[6] The papers in this section examine the impact of disasters on GDP, the next section reviews papers that look at how GDP impacts disasters, suggesting a two-way relationship between output and damages.

The authors next regress annual GDP growth on contemporaneous and lagged dummies for disasters with destruction of capital and those with loss of life (destruction of labor). The authors find a significant negative impact on current growth following disasters with a major loss of life but no other significant results.

Raddatz (2006) examined the impacts of several types of shocks, including natural disasters (the only results discussed here), on the output of 40 low-income countries over the period 1965 to 1997. He uses a panel vector autoregression model, assuming that disaster occurrence is exogenous. Using the EM-DAT data, his disaster variable is the number of large disasters in a given country and given year (using an International Monetary Fund definition of "large"). Raddatz mentions the possibility that incidence is endogenous, but notes that this will be less of a concern in his sample because he restricts the sample to low-income countries and controls for average GDP. So a problem will arise only if the probability of an event being added to the data is greater in a year with relatively low income compared to the country's average. His results indicate that climatic disasters generate declines in real per capita GDP of 2 percent one year after the event. Any impact disappears after five years. Overall, external shocks, climatic disasters included, explain a very low portion of the variance in real per capita GDP for these countries. He also finds that government expenditures follow the same trend as GDP post-disaster but that, for natural disasters, this change is small.

There was a small boom in multicountry studies starting in 2009. Noy (2009) used the EM-DAT data on all sudden-onset disaster types (no drought or famine) for a panel of 109 countries over the years 1970 to 2003. Noy regresses GDP growth on a measure of disasters and a set of controls, including country fixed effects. He uses standardized measures of disaster impacts: fatalities divided by population and costs as a percentage of the previous year's GDP, weighted by month of occurrence. He also estimates an instrumental variable model considering damage as a percentage of previous GDP as endogenous. Noy finds that, in developing countries, the amount of property damage a disaster causes negatively influences GDP growth, with an increase of one standard deviation in direct damages reducing output growth by around 9 percent. In developed countries, on the other hand, he finds an increase of less than 1 percent. GDP growth does not appear to be influenced by the number killed or affected by the event.

Hochrainer (2009) looks at a data set drawn from both EM-DAT and NatCatSERVICE data for 225 disasters between 1960 and 2005 where losses exceeded 1 percent of GDP. He takes an approach that differs from that of most other studies, developing a counterfactual projection of GDP in a without-disaster state and comparing this to actual GDP post-disaster. He uses an autoregressive integrated moving average model to forecast GDP in the hypothetical no-disaster world. Hochrainer finds negative impacts on GDP for up to five years, with a median reduction in GDP of 4 percent below baseline five years post-event.

A working paper by Jaramillo (2009) uses 36 years from the EM-DAT data (excluding drought) for a panel of 113 countries. He estimates a dynamic panel model with country fixed effects, measures of contemporary disaster impacts, and impact measures of the preceding few years. Jaramillo finds that, for countries with low incidences of natural disasters, the amount of disaster damage in the current period increases GDP growth, with the effect fading away after a few years. He finds that an increase of one standard deviation in the share of damages in the last two to three years increases today's GDP growth around 0.3 percentage points. For medium disaster incidence, the only significant disaster variable is the cumulative percentage killed, and the effect is negative, corresponding to a decrease of 1 percentage point of annual GDP growth for an increase of one standard deviation in the aggregate share of the population killed. Finally, for the high-incidence group, the only significant variable is the contemporary percentage killed, and the impact is positive on growth, with a 1 to 1.5 percentage point increase per one standard deviation increase.

Cuñado and Ferreira (2011), in a recent working paper, look exclusively at the impact of floods on the growth rate of real per capita GDP for a panel of 118 countries between 1985 and 2008. Unlike the majority of other studies, they do not use EM-DAT data but the Global Archive of Large Flood Events maintained by the Dartmouth Flood Observatory. Using vector autoregressions with country fixed effects, they find that floods have a positive impact on GDP growth with a mean impact of about 1.5 percentage points. This positive impact is found not in the year of the event, but in the year after the event; it peaks two years after the event. The result is driven by developing counties; when separate regressions are run, floods do not have a significant impact on GDP growth in developed countries. When the authors pull out agricultural output and examine it separately, they find that the impact is negative but insignificant in the first year and positive in the second.

A working paper from the Inter-American Development Bank finds no discernible impact of natural disasters on economic growth in both the short and long run (Cavallo et al. 2010). The authors use a comparative case study approach with the EM-DAT data to identify a synthetic control group of countries that plausibly would have had the same trends in GDP as those countries hit by a disaster. The authors restrict their attention to "large" disasters (using a cutoff value of the 75th, 90th, or 99th percentile of the global distribution of disaster deaths) that occurred before the year 2000. The authors find a negative impact on GDP only in countries with large events that were followed by radical political revolution; other events do not have any significant impact on GDP.

Noy and Nualsri (2011) look at a panel of 42 countries for the period 1990 to 2005 using all disaster types in the EM-DAT data. They develop a variable of quarterly disaster damages standardized by GDP and look only at disaster events greater than two standard deviations above the mean to specifically focus on large events. Instead of focusing on the economic impact of natural disasters, they examine government response in terms of revenue, spending, and debt using a panel vector autoregression method estimated using the generalized method of moments. They compare developed and developing countries separately and include country and year fixed effects. For developed countries, Noy and Nualsri find that government consumption rises right after a disaster and then slowly declines. Government revenue drops right after the event and, despite some improvements, remains lower at the end of their time period. Government payment increases, reaching a high point three quarters after the disaster. Outstanding debt also increases, accumulating over 8 percent of GDP looking 18 months post-disaster. In contrast, they find that developing countries tend to follow a procyclical fiscal policy post-disaster. They find that government consumption, revenue, payments, and outstanding debt all decrease after an event, and government cash surplus increases. Specifically, they find that consumption decreases −0.68 percent of GDP and government revenue rises 4.23 percent of GDP. Outstanding debt falls −0.72 percent of GDP.

This group of studies identifies several factors that alter the magnitude of impacts. Almost all of the studies (and some discussed in the next section) confirm that more intense events produce larger negative economic impacts on GDP or GDP growth (Stephens 2007; Hochrainer 2009; Noy 2009; Fomby et al. 2011). Aid and remittances may lessen the impact (Hochrainer 2009). Developing countries appear to be harder hit by disasters (Noy 2009), a finding that will be echoed by the studies in Section 5. The procyclical behavior by developing countries in response to disasters found by Noy and Nualsri (2011) could be exacerbating the negative macroeconomic outcomes of natural disasters. A similar finding regarding the vulnerability of developing countries is that countries with large informal sectors of the economy are likely to suffer more from disasters because insurance and reconstruction aid largely do not reach these sectors (Charvériat 2000). In addition to the greater vulnerability of developing countries, a couple of studies confirm that disasters have a larger impact in countries in which the economic damages as a proportion of the size of the economy is high, such that smaller countries are more likely to see a drop in GDP post-disaster, whereas disasters can be absorbed by larger economies (Charvériat 2000; Noy 2009).

3.2.2. Single-Country Studies

Some single-country studies take a subregion as the unit of analysis and generally find impacts at these smaller scales that are similar to those found in the multicountry studies. Noy and Vu (2010) undertake a province-level analysis in Vietnam to examine the impact of natural disasters on output. They standardize variables from the EM-DAT data, using the number killed and affected per capita and the dollars of direct damage as a percentage of provincial output as the key explanatory variables. Their dependent variable is output or output growth and they include its lag as an independent variable. They use a generalized method of moments estimator for dynamic panels (the Blundell–Bond approach). Noy and Vu find that deadly natural disasters lower annual output. When looking at output growth, higher direct damages lead to higher levels of growth. The impacts of damage on GDP growth, though, are quite small, with a 1 percentage point increase in damage (as a percentage of output) increasing output growth by about 0.03 percent. This positive effect seems to be driven by regions with access to reconstruction funds and/or higher initial development.

Focusing on China, Vu and Hammes (2010) undertake a similar analysis. They define their disaster variables in the same way and also use the Blundell–Bond approach for dynamic panels with year and region fixed effects. The authors find that increases in natural disaster fatalities reduce output: a 1 percent increase in the percentage of the population killed leads to a fall in output of about 47 billion Yuan (roughly US$ 7.4 billion). A 1 percent increase in direct damages reduces output growth by 0.24 percent; fatalities do not significantly impact growth.

Anttila-Hughes and Hsiang (2011) look at tropical cyclones in the Philippines using a province-level panel data set of storm incidence based on wind data coupled to household survey data. They use a difference-in-differences approach with province and year fixed effects. They find that average income (net of transfers) falls the year after a tropical cyclone (using average wind exposure, this is equivalent to a drop in incomes of about 6.7 percent). This loss is persistent several years after the storm for low-income households, but higher-income households see an increase in income a few years after the storm, thus recovering much of the lost income. In one of the few studies to begin to examine the follow-on impacts of the negative wealth shock of a disaster, the authors find that the drop in income translates into an almost one-for-one reduction in expenditures by households, mostly in the categories of human capital investment (medicine, education, and high-nutrient foods) and not on pure consumption goods (recreation, alcohol, and tobacco). Likely related to this, they find that infant mortality (driven by female mortality) increases the year after a cyclone hits.

Strobl (2011) looks at the impact of landfalling hurricanes between 1970 and 2005 on county growth rates in the United States. He develops a hurricane destruction index based on monetary loss, local wind speed, and local exposure variables to use as an explanatory variable in a county fixed-effects model with a spatial autoregressive error term using a contiguity matrix. Strobl finds that a county's economic growth falls by an average of 0.45 percentage points (average annual county-level growth is 1.68 percent), even when there is no effect on national-level macroeconomic indicators and the impact on state growth is netted out within one year. For a hurricane one standard deviation above the mean, growth is reduced by 0.93 percentage points. This impact disappears after only one year. He finds that around 25 percent of the decline is from higher-income individuals moving out of the county post-hurricane.

Deryugina (2011) also looks at the impacts of hurricanes on U.S. counties. She uses propensity score matching to find a control group of counties with equal hurricane risk and then uses a difference-in-differences approach and an event study approach. She finds no change in population, earnings, or employment rates up to 10 years post-hurricane, but does find a negative impact on the construction sector, driven perhaps by a decline in housing starts. She also finds a substantial increase in nondisaster-related transfer payments (largely increases in medical and unemployment assistance). These social safety nets, though not designed for disasters, may be responsible for the lack of change in economic indicators she finds, promoting greater resilience. The findings also indicate that the transfers following disasters are larger than previously estimated; assuming a 15 percent deadweight loss from taxation, she finds that the transfers have a real cost of $98 per capita per hurricane. Deryugina argues that nondisaster payments may target individuals who are indirectly impacted by a disaster, whereas disaster aid targets those directly affected.

3.2.3 Sector-Specific Studies

A handful of studies look at sectoral impacts of natural disasters. These studies highlight the winners and losers of natural disasters even when overall economic impacts may be neutral.

Guimaraes et al. (1992) examine the impact of Hurricane Hugo, which hit South Carolina in 1989. The authors use a regional econometric model to project the economy in a "without-Hugo" state. The authors find that total personal income in South Carolina dropped immediately following the hurricane, driven largely by a loss of rental income. Total employment was not impacted. Contrary to the findings of Deryugina (2011), for six quarters post-Hugo, construction income increased, but then fell again two years after the disaster. The authors postulate that rebuilding post-disaster may move forward some renovations or repairs that otherwise would have occurred later, thus causing a boom and then a drop from a projected without-Hugo baseline. Construction employment increased but fell back to baseline sooner and did not dip as significantly. Forestry and agriculture sustained large losses. Retail trade, transportation, and public utility income declined immediately post-event and then rose above baseline for more than a year. Overall, income gains were neutral, and the authors conclude that the major effects of the disaster were distributional.

Loayza et al. (2009), in a World Bank working paper, look at the impact of different natural disasters on different sectors using cross-country panel data from 1961 to 2005, again with the disaster data taken from EM-DAT. They, too, use a measure of output from the beginning of the period in the equation and a Blundell–Bond estimator. Overall, they find that severe disasters never have a positive impact on growth, but events of lesser magnitude can increase growth in some sectors. Impacts in developing countries are larger, with more sectors impacted, and impacted to a larger degree. They find that droughts and storms have a negative impact on the growth of agricultural output; floods have a positive impact, but only for moderate events. The authors find no significant effect of natural disasters on industrial sectors and only floods have a significant (and positive) impact on service sector growth. A typical drought will reduce agricultural growth in developing countries by 3 percentage points over five years, and a flood will increase growth by about 1 percentage point; in comparison, over the time period, these countries saw an average annual per capital growth of 1.35 percent.

Ewing et al. (2003) examine the impact of a March 2000 tornado in Fort Worth, Texas, on local employment. They undertake an intervention analysis, using an autoregressive moving-average time series model. The authors find employment growth lower in the two years after the tornado, but the response was heterogeneous across firms. The employment growth rate was largely unaffected in some industries, such as construction, real estate, government, and transportation and utilities, whereas others had higher employment, notably the mining sector, and still others (e.g., services and retail) had negative impacts. In some sectors, the variance was affected (Ewing et al. find lower variance in the employment rate post-tornado for the manufacturing sector, for example, perhaps due to rebuilding demand).

More recently, Fomby et al. (2011) echo many of the findings of Loayza et al. (2009). The paper examines the trend in GDP growth by year post-disaster with data on 84 countries over the period 1960 to 2007 in a dynamic panel data model. The disaster data come from EM-DAT; using only droughts, floods, earthquakes, and storms, the authors develop an annual estimate of disaster intensity for each country. They separate out the different types of disasters, developing from developed countries, and agriculture from nonagriculture sectors. As in other studies, Fomby et al. find that impacts are worse for more severe events, and developing countries are harder hit. Droughts negatively affect growth in developing countries, with a cumulative negative impact of about 2 percent after four years; the impact is stronger when only agricultural growth is considered. In developed countries, only the agriculture sector experiences a negative impact from drought, and with recovery, the net impact is close to zero. For moderate floods in developing countries, the authors find a positive impact on the agriculture sector one year after the event and in other sectors two years after the event; not so for severe floods. The results provide some indication of a positive response in agriculture from moderate floods in developed countries, as well. The response to storms is less statistically significant than the response to droughts and floods.

Focusing instead on firm-level variables, Leiter et al. (2009) look at the short-run (two years post-disaster) impact of flooding on employment and asset accumulation of European firms. Using a difference-in-difference methodology and firm-level data that classify firms depending on whether they were in an area that experienced a major flood in 2000, the authors find that productivity declines in the short run after a major flood (the effect is decreasing in the amount of intangible assets) and that total assets decline for firms with high levels of tangible assets. This reverses for firms with largely intangible assets. Employment growth is higher post-flood.

3.3. Long-Run Impacts

Although it is possible to develop models and plausible stories of how natural disasters could have long-term negative consequences in certain cases, the empirical evidence is limited; this review found only three studies of long-run impacts. This could partially be because many of the short- to medium-run papers discussed in the previous section saw any impact disappear after a few years, and so are essentially findings of no long-run impact. It has been argued that longer-run impacts may occur from severe disasters when they interact with other factors to accelerate changes that were already beginning to occur (National Research Council 2006), which might explain the results of the Hornbeck (2009) paper, discussed below.

Skidmore and Toya (2002) examine the impact of climatic disasters on long-run economic growth and other macroeconomic variables on a set of 89 countries. They couple historical data on disasters with EM-DAT data. The authors regress (using ordinary least squares) the total number of natural disaster events occurring in a country between 1960 and 1990, normalized for land area and a measure of historical disasters from 1800 to 1990 (along with a set of controls, including initial GDP), on average GDP growth over the same time period.

The assumption is that pooling across so many years gives a measure of long-run impacts. They find that average annual growth rates of GDP are positively correlated with the frequency of climatic disasters. To explore the determinants of the positive relationship, they regress disaster variables on measures of physical and human capital accumulation, finding an increase in the latter after climatic disasters. They also find an increase in total factor productivity after climatic disasters.

Jaramillo (2009), discussed above, also investigates the long-term effects of disasters. He estimates a Solow-style structural model, with cumulative measures of disaster impacts as a variable to capture the influence of disasters on a country's steady-state growth rate. He finds that, for countries that have had a high proportion of their population affected by natural disasters, the cumulative impact of disasters on the growth rate is negative and permanent. For other groups of countries, he finds no long-run impact.

Hornbeck (2009) uses a balanced panel of 769 counties between 1910 and the 1990s, based on Census data and erosion data, to examine the impact of the Dust Bowl.[7] He compares outcomes (as relative change since 1930) for counties with different levels of erosion, controlling for pre-Dust Bowl characteristics and state-by-year fixed effects. Hornbeck finds substantial long-run costs: between 1930 and 1940, the per-acre value of farmland in highly eroded counties decreased by 28 percent and in counties with a medium level of erosion decreased by 17 percent, relative to those with low erosion. He finds that the declines persisted, with only 14 to 28 percent of the values recovering over the long-term. Agricultural revenue also declined between 1930 and 1940, with around 70 percent of the initial drop persisting until the 1990s. Hornbeck finds limited agricultural adjustment, probably due to inelastic demand for land in other sectors as well as credit constraints from the Great Depression. Most adjustment occurred through migration. He finds larger population declines in more eroded counties. The Dust Bowl, unlike some other disasters, semi-permanently reduced the productivity of a fixed factor of production.

Another line of research offers some additional insight on the long-term impacts of disasters. Hedonic studies that estimate how disaster risk is capitalized into property values can give some indication of persistent costs associated with disaster risk. A relatively large literature

[7] The Dust Bowl is included as a natural disaster here because, although impacts were exacerbated by farming practices, a severe drought triggered the dust storms. This highlights the fact that natural hazards become disasters only when they interact with other human actions, as here, or when they occur where development and people could be harmed.

has estimated the impact of flood risk on housing prices. These studies generally find a reduction in property values in the floodplain, sometimes larger than the present value of annual insurance premium payments (e.g., MacDonald et al. 1990; Bin and Polasky 2004; Kousky 2010). It is more difficult to identify such reductions, however, in areas where risk is strongly correlated with other amenity values, such as coastlines exposed to hurricanes.

4. Can Disasters Have Positive Impacts?

Some authors have suggested that disasters can have a positive economic impact. This idea is sometimes picked up by the media: for example, *USA Today* reported after Hurricanes Ivan, Frances, and Charley that many businesses saw a boost as a result of the hurricane and the U.S. economy could see a slight bump from the hurricanes (Hagenbaugh 2004). As a more recent example, one U.S. newspaper reported that tornadoes can boost local property markets (Cariaga 2012).

These common accounts of positive economic impacts from a natural disaster often fall prone to what is referred to as the broken windows fallacy. This is a reference to Frédéric Bastiat who, around 1850, wrote about a shop owner whose window was broken. Some onlookers convinced everyone that it was actually better for the economy because now the window-fixer would be employed and he would pay others, and so on, creating ripple effects in the economy. Our intuition suggests that the simple destruction of capital should not be a net benefit, and the error in the fallacy is the neglect of the fact that had the shop owner not needed to repair a window, he would have used the funds elsewhere—the broken window did not create new economic activity, but just diverted funds from one use to another. Similarly, owners of homes destroyed by tornadoes or hurricanes would have spent money elsewhere generating higher utility that they instead had to use for rebuilding.

This is just a reminder of the discussion earlier that where the boundaries of analysis are drawn can have a large impact on the results. There could indeed be benefits to some sectors of the economy from a natural disaster, as found in some of the above-mentioned studies. For a few more examples, looking exclusively at the construction sector one to three years post-disaster for 28 disasters in 26 countries between 1960 and 1979, Albala-Bertrand (1993) finds an increase in the growth rate of construction output for up to two years post-event. Baade et al. (2007) found that, although taxable sales dropped immediately after Hurricane Andrew, they then increased and remained high for over a year, giving Miami an actual bump in taxable sales.[8] Another study finds that Hurricane Bret in 1999 reduced the natural unemployment rate in Corpus Christi, Texas, in the four years post-event (Ewing et al. 2005). These findings, however, do not mean that the economy is, on net, better off.

Some of the above-mentioned studies of GDP or GDP growth also found positive impacts, at least in some time period (e.g., Albala-Bertrand 1993; Jaramillo H. 2009; Noy 2009). These types of analyses, however, highlight again the limitations of using GDP as a welfare measure and should not be taken as an indication that the destruction of capital and fatalities are, on net, welfare improving for a society. In addition, several other studies find no or negative impacts.

A slightly different story is sometimes told regarding the ability of disasters to be a positive economic impact that is not so obviously fallacious. Several authors have referenced Schumpeter's model of creative destruction (whether they do so correctly, however, has been debated [Benson and Clay 2004; Cuaresma *et al.* 2008]), suggesting that a natural disaster that destroys capital stocks could lead to higher growth because the disaster triggers investment in upgraded capital or new technologies that enhance productivity.

Absent market barriers, firms would have invested in technology improvements without the disaster if the benefits outweighed the costs. So any productivity bump from the new investments cannot, in principle, make the firm better off than it would have been without the disaster. If, however, government aid pays for upgrades that increase productivity, such that these investments are free to the firm, the individual firm could be better off post-disaster, but not society on net, because the payment from the government is a transfer from other taxpayers, as discussed above. It has also been noted, however, that the rebuilding and reconstruction after a natural disaster can lead to improvements in local infrastructure (Ascent Investment Partners 2011). It is more plausible that governments may not be undertaking upgrades of infrastructure that would be, on net, positive even without a disaster and that post-disaster investments, in this way, could create a net benefit in this area. I have not seen an empirical examination of this possibility.

[8] Such positive impacts on taxable sales were seen after Hurricane Andrew, but were not seen after the Rodney King riots in Los Angeles; Baade et al. (2007) argue that this is due to a rupturing of social institutions that are necessary for rebuilding following the riots.

The one empirical paper to look at an aspect of the Schumpeterian argument is Cuaresma et al. (2008). The authors examine the relationship between disasters and an estimate of the research and development stock in imports in a sample of developing countries between 1976 and 1990 using gravity equations, which relate aggregate trade flows to aggregate GDP and the distance between the countries. They find that the relationship between technology absorption and disasters is generally negative; it is positive only in high-GDP countries. It does not appear, from this analysis, that natural disasters lead to increased knowledge spill-overs post-disaster in the short or long run for most developing countries.

5. Determinants of Damages and Fatalities

The impacts of disasters are often discussed as being related to both the hazard and vulnerability—meaning the potential for loss and the susceptibility to damage or fatalities. The simple point is that the same hazard occurring in different locations will have different impacts. A distinct literature centers on the concept of vulnerability, emerging from the hazards and disasters research community. This research has assumed that vulnerability is a social condition and has attempted to identify those factors that make some people and places more vulnerable (Cutter et al. 2003); it is often focused on communities or individuals. This research sheds some light on the determinants of disaster losses, but as it is generally not empirical economic research, it is not within the scope of this review. However, findings from this work—such as that lower levels of income and education make groups more vulnerable (Burton et al. 1993)—mirror some of the findings discussed here.

This section presents an overview of the empirical economic studies that have been undertaken to uncover the determinants of disaster impacts. They attempt to answer the question, why do some countries or communities have higher damages and higher fatalities? Although some areas are simply more prone to certain hazards, this alone does not account for the observed variation in economic losses and fatalities. All of these studies explore the hypothesis that governmental conditions and policies play a role in determining disaster impacts. It has been argued theoretically that richer countries, for instance, have a higher value for safety and more income to pay for risk reduction measures, and as such should have lower losses and fewer fatalities when a hazard occurs. On the other hand, some have observed that richer countries also have more structures and wealth in hazardous areas, so damages could be higher. A more integrated economy can increase the multiplier effects of the initial damage from a disaster, and countries with higher development may be more likely to reduce and spread the costs of disasters through savings and transfers (Benson and Clay 2004), recovering more quickly. Other hypotheses concern preparedness, response, and recovery. Countries with more advanced institutions may be better prepared to respond to an event, containing losses. Countries with higher levels of education may pay more attention to disasters and have the information and resources to invest in risk reduction measures.

The investigation of these hypotheses appears to have been launched by Kahn (2005). The studies generally use multicountry panels and regress some measure of disaster losses or fatalities on possible explanatory variables. Again, most studies, but not all, use the EM-DAT data as their source for information on disaster occurrences and estimates of the associated losses and fatalities. The studies vary, though, in the time period covered and the subsample of countries included. Most begin their analysis around 1980, although one uses data back to 1960 (Toya and Skidmore 2007), even though earlier observations are more prone to error and reporting bias. Also, one must remember that the EM-DAT data does not contain damaging, but nonfatal disasters that did not generate a call for international assistance. In this sense, damages to richer countries may be underreported. No paper discusses the implication of this on findings. In addition, none of these studies is able to control for disaster magnitude in its full sample as these data are frequently missing from EM-DAT. Most studies omit this as a control; whether and to what extent this influences results should be explored. Finally, very few of the papers address the possible reverse causality between GDP and damages; a striking oversight given the papers in the previous section.

The papers also vary in whether they use region or country fixed effects. Kahn (2005) argues that looking at within-country changes in variables such as governance and income would require accurate data on those changes annually, which is unlikely to exist. Further, a long latency probably occurs between changes in variables that can be measured annually, such as income, and the full impacts, given the slower turnover in structures and infrastructure. He thus chooses to use only region fixed effects. Kellenberg and Mobarak (2008), on the other hand, use country fixed effects and argue that this is an important improvement. But they find that once these fixed effects are added, the negative coefficient on income becomes much less robust, suggesting, as the authors note, that richer countries have improved institutions that influence disaster losses and these institutions are captured in the fixed effects, or, as Kahn (2005) argued, that the latency period is longer. It could also be that within-country variation in income and other explanatory variables is not sufficient to fully identify the effect.

The findings of the studies are discussed according to whether they are seeking to explain variation in the number of natural disasters, natural disaster fatalities, or natural disaster damages.

5.1. Frequency of Events

Kahn (2005) is one of only a few papers to examine how the number of disasters varies across countries. He looks at a panel of 73 countries responsible for the vast majority of natural disasters and deaths in the EM-DAT data for the years 1980 to 2002. Using probit models, he finds that richer nations do not experience more disaster events than poorer ones, although they are less likely to experience floods (his explanation is that richer countries can invest in infrastructure to control extreme rainfall events, limiting the frequency at which they become floods). Another study similarly found no correlation between the level of development and exposure to natural hazards (Stromberg 2007). Geography, however, is of course critical in explaining the probability of a disaster (Kahn 2005). Along those lines, Gaiha et al. (2012), in an unpublished working paper using the EM-DAT data, find that land-locked countries have fewer disasters when they regress the log of deaths on characteristics of the country, using an instrumental variables approach for the assumption that the number of disasters in the period is endogenous. They also find that countries with more disasters in the 1970s tended to have more disasters in the 1980–2004 time period, suggesting some persistence in hazard risk over time.

5.2. Fatalities

As stated, Kahn's (2005) paper appears to have launched this small literature. With the dependent variable as the total disaster deaths experienced in a year, he ran ordinary least squares, instrumental variables, and count models on his panel of 73 countries (Kahn 2005). Across his models, he finds that richer nations experience fewer deaths from natural disasters. This is a robust finding echoed by all the follow-on studies (Stromberg 2007; Toya and Skidmore 2007; Raschky 2008; Gaiha et al. 2012). Some evidence suggests, though, that the relationship may not be the same across countries. Toya and Skidmore (2007) regress the natural log of deaths in a given country and year on a set of potential explanatory variables taken from a range of sources. They find that, in Organisation for Economic Co-operation and Development countries, a 10 percent increase in income reduces natural disaster deaths by about 15 percent; in the developing country sample, the impact of income is still negative, but smaller in magnitude. These results support the summary statistics reported in Section 3.1 that clearly show higher fatalities in developing countries.

Kahn (2005) also found that fatalities were lower in countries with lower income inequality, democracies, and countries with higher-quality institutions. (A summary of findings is shown in Table 2.) Examining specific hazards, he finds that deaths from floods and windstorms are reduced the most by increases in income. Other authors have extended this work, finding other variables that are predictors of fatalities. Toya and Skidmore (2007) find that higher educational attainment levels, more openness, and stronger financial systems have lower deaths. Raschky (2008) uses EM-DAT data between 1984 and 2004 and runs log-log regressions of fatalities and losses on country-level variables. He finds, in addition to income, that improvements in government stability and in indicators of the investment climate decrease deaths. Again running regressions of the log of fatalities on country-level variables for the period 1980 to 2004, Stromberg (2007) finds that more effective governments have lower fatalities. In one disagreement with the earlier literature, Stromberg (2007) finds, in contrast to Kahn (2005), no impact of income inequality on fatalities (they both use the Gini coefficient as their measure of inequality but taken from different sources; Stromberg analyzes two more years of EM-DAT data and includes a broader range of disasters). In another disagreement with Kahn (2005), Gaiha et al. (2012) find no impact of democracies on fatalities (it is unclear how Gaiha et al. constructed their democracy variable, making it difficult to compare directly to Kahn; another difference is that Gaiha et al. do not use a country–year panel, but examine all fatalities in the 1980–2004 period as a function of previous disasters and average values for country-level variables).

Table 2. Summary of Natural Disaster Fatality Determinants

Determinants of fatalities	Direction of significant effect	Source
GDP	↓	Kahn 2005; Stromberg 2007; Toya and Skidmore 2007; Raschky 2008
Income inequality	↑; –	Kahn 2005; Stromberg 2007
Presence of democracy	↓;–	Kahn 2005; Gaiha et al. 2012
Higher-quality institutions	↓	Stromberg 2007
Education	↓	Toya and Skidmore 2007
Stronger financial system	↓	Toya and Skidmore 2007

5.3. Damages

Much of the literature on the determinants of natural disaster damages focuses on the role of GDP and potential nonlinearities in the relationship. Kahn (2005) and Toya and Skidmore (2007) find that countries with higher income levels have lower damage. These findings were extended by Kellenberg and Mobarak (2008), who find, for a set of 133 countries, using a negative binomial model, that for floods, landslides, and windstorms, damages increase with increases in GDP per capita until a certain point ($5,044, $3,360, and $4,688, respectively) and then decline. They argue this could be due to choices in favor of consumption over risk reduction at low income levels (such as increasing urbanization or declines in an environmental good that had been mitigating disaster impacts, such as mangroves) but that, at some point, improvements in disaster preparedness and response or in mitigation technologies become worth investment, and damages from disasters decline. Raschky (2008) finds just the opposite relationship: initial levels of development can reduce losses, but at higher wealth levels, economic damages increase. It is worth remembering that Kellenberg and Mobarak's specifications include country fixed effects (and all of these studies also include year fixed effects), whereas Kahn, Toya and Skidmore, and Raschky do not.

Schumacher and Strobl (2011) try to reconcile these results, finding that the relationship between GDP and disaster damage depends on the risk a country faces. Because one key explanation for an income-loss relationship is that increases in income lead to a higher demand for risk reduction and allow for the adoption of costly risk reduction measures, they argue that base-level risk must play a role in the relationship. They argue that, for two countries with equal wealth, the one with lower hazard rates should invest less in mitigation and then could conceivably suffer more damages when an event does occur. Using a country-level panel data set for the years 1980 to 2004 and an index of hazard exposure, the authors estimate Tobit models. They interact their hazard measure with GDP per captia and GDP per capita squared, finding an inverse U relationship for losses and wealth for low-hazard countries but a U-shaped relationship for nations with a high hazard index. When they examine their results by disaster type, this relationship appears to hold for windstorms, earthquakes, and landslides, but not for droughts, floods, or volcanoes.

Other variables besides income have also been found to influence natural disaster damages. Toya and Skidmore (2007) find that increases in schooling and openness reduce damages as a share of GDP. Higher female education has been found to lower losses from disasters, again in country-level panel regressions using EM-DAT data (Blankespoor et al. 2010). Noy (2009) finds that disasters in countries with higher illiteracy have a larger negative impact on GDP growth. He also finds that countries experience less impact on the macroeconomy if they have stronger institutions, higher per capita incomes, bigger governments, more domestic credit, higher reserves, or higher levels of exports as a percentage of GDP.

The macroeconomic impacts of natural disasters will depend in part on how vulnerable the economy is to such events. An example comes from a within-country study of Dominica (Benson and Clay 2004). In Dominica, banana exports had historically been the principal source of livelihoods. They also are a fast and low-cost way to regain income after a disaster; this sector is fairly resilient to hurricanes. In the mid-1990s, the agricultural economy of Dominica diversified when banana exports fell because of an increase in prices and a loss in preferential access to some markets. This had the perverse impact, however, of making the sector more vulnerable to hurricanes. Agriculture's share of the economy has been declining, though, with increases in tourism, manufacturing, and financial services, which are less vulnerable to hurricanes as long as they are not catastrophic.

6. Trends

Needless to say, disaster damages depend on the population and structures in hazardous areas. Many authors have explained findings of increased damages from disasters over time by the increase in structures and wealth in harm's way. Some authors have argued that three trends are likely to continue to increase assets in peoples in hazardous areas in the coming years. These are very briefly reviewed.

(1) Increasing urbanization. The world has seen increasing trends in urbanization. The year 2008 marked the first time that more than 50 percent of the world's people lived in cities (Bloom and Khanna 2007). In developing countries, the rate of urbanization is incredibly rapid, and some have suggested that these countries are exhibiting inefficiently high levels of urban concentration given the negative health and economic outcomes when urban density increases are not accompanied by the necessary institutions, planning, and management (Henderson 2002).

One impact of increasing urbanization is that the economic consequences of disasters hitting large cities can be more severe than those of disasters occurring in low-density areas because of the higher concentrations of people, infrastructure, assets, and economic activity. However, the impact of increasing urbanization on disaster risk will vary depending on the income of the country. Disaster impacts could be reduced if concentrating people together allows for greater access to relief institutions and is the result of improved building and planning that may not exist in rural areas; conversely, in low-income countries, the density of urban areas may overwhelm response capabilities, or cluster people in inferior housing with poor emergency response time (Kellenberg and Mobarak 2008). Of concern for disaster damages, the largest growth in the share of people living in urban areas is occurring in developing countries (Bloom and Khanna 2007); these are areas that may not have the resources for effective ex ante mitigation and ex post response. Climate change itself could exacerbate these trends as impacts materialize. For instance, if climate change drives down the profitability of agriculture, more farmers will move to urban areas, which could have general equilibrium effects on a slightly longer time frame, with urban wages declining and rents increasing because of slow migration from rural areas (Kahn 2009). These patterns could require a change in the way humanitarian assistance is handled, with a greater emphasis on neighborhoods over individuals, protecting livelihoods, and restoring markets (Bloom and Khanna 2007).

(2) Growth in coastal populations and sea level rise. Human population tends to concentrate on coasts. The area that is less than 10 meters above sea level along coasts makes up 2 percent of the world's land area but is home to 10 percent of its population, with an urbanization level of 60 percent (as opposed to a world average urbanization of 50 percent; (McGranahan *et al.* 2007).[9] Coastal populations have been increasing around the world. Much of the growth has occurred, not just in developing countries, but in large cities in the developing world (Tonnetts 2002). Indeed, the least developed countries have a higher proportion of their urban populations living along the coast (McGranahan et al. 2007).

This costal concentration is particularly concerning given projections of sea level rise (SLR).[10] Not only are many areas projected to become inundated, but as the sea level rises, storm surges will reach further inland, pushing flood risk into areas where it was previously minimal. One study in Maryland finds that the costs from increased periodic flooding could exceed those of simple inundation (Michael 2007). Tebaldi et al. (2012) estimate the return periods associated with extreme storm surges influenced by SLR along the U.S. coast and compare those with baseline estimates of no SLR (assuming no change in the nature of extreme events). At the vast majority of locations, the 100-year surge comes more frequently, ranging from around every 75 years to every year in a few locations. The impact on disaster damages will depend on capital mobility, depreciation rates, coordination factors for adaptation, risk awareness, risk aversion, information on climate impacts, and political boundaries (Nordhaus 2010).

---

[9] In 2000, coastal counties accounted for 13 percent of U.S. land area but over 50 percent of the population; the higher population density is due both to higher productivity and increased quality of life, and these have been increasing over time (Rappaport and Sachs 2003).

[10] Several papers examine the vulnerability of coastal areas in the United States under assumptions of SLR. Strauss et al. (2012) simulate SLR for the United States, accounting for local high-tide levels, and use this to estimate land area, housing, and population within six meters of the local high tide. They find that approximately 9,000 square kilometers of dry land is less than one vertical meter above high tide (where some impacts are expected by mid-century), with 1.9 million housing units and 3.7 million people. Titus et al. (2009) project that, under business-as-usual, the majority of land below one meter along the U.S. Atlantic Coast would develop; this would require large investments in shore protection and would threaten coastal wetlands. Nordhaus (2010) estimates that the vulnerability of capital stock to hurricanes roughly doubles with one meter of SLR; assuming no adaptation, this is an increase in damages of 0.5 percent per year over the next 100 years.

(3) Globalization. Though hard to predict, the increased interdependency of households, regions, and the global economy could increase the ripple effects from disasters. There is growing concern that the current nature of complex and interdependent supply chains has increased the vulnerability of many industries to disaster events (Gray 2012).

7. Risk Reduction and Adaptation

The negative impacts of disasters can be blunted by the adoption of risk reduction activities. Note that the hazards literature, and this paper, refers to these actions as *mitigation*, whereas in the climate literature, mitigation refers to reductions in greenhouse gas emissions. The already established mitigation measures for natural disasters can be seen as adaptation tools for adjusting to changes in the frequency, magnitude, timing, or duration of extreme events with climate change.

Predicting what adaptation will take place, however, is difficult. The Ricardian approach launched by Mendelsohn et al. (1994) of examining how climate change may impact agriculture by assessing the impact of variations in today's climate on the value of farmland, can be applied to disasters by looking at differences in disaster mitigation and response across areas facing different risks. This could be an indication of how adaptation will change as disaster risk changes. Hsiang and Narita (forthcoming) examine the ability of countries to adapt to tropical cyclones by looking for evidence of adaptation in terms of lower damages or fatality impacts from physically similar cyclone events in countries with different exposure to cyclones. Regressing normalized damages on a country's exposure, they find that countries that are more exposed to tropical cyclones have slightly lower marginal losses from a storm. This suggests that countries do adopt mitigation measures, but that they are costly, as damages are reduced only slightly. Of course, the authors do not actually observe mitigation activity, so this is an indication only of adaptive potential.

Another paper took this same general approach but focused on heat waves. Southern and western U.S. cities are at less risk from excess death from heat-related extremes than are northern areas, demonstrating adaptation to current climates (Kalkstein and Greene 1997). Examining mortality from heat waves, Kalkstein and Greene (1997) match U.S. metropolitan statistical areas (MSAs) with populations over 1 million with analog MSAs with climate similar to global climate model predictions for the initial MSA. This allows for a consideration of adaptation mechanisms, assuming that communities are fairly optimally adjusted to current climate variables. They note that it is unlikely that full adaptation will occur in response to climate changes, at least over short to medium time scales, as major changes in structures and land use are unlikely to take place. The authors are thus overestimating adaptation. Nonetheless, they still find increases in mortality, sometimes quite substantially, for U.S. cities under climate change.[11] On the same topic, Deschênes and Greenstone (2011) look at mortality and energy consumption as a function of temperature in the United States over a 35-year period. The authors model temperature semiparametrically, estimate different models for different age groups, and include county (for mortality) and state-by-year fixed effects. They find that an additional day with mean temperature above 90°F, leads to an increase in the annual age-adjusted mortality of about 0.11 percent. Intuitively, they also find that energy consumption increases during heat extremes. When they examine only counties that are hotter, on average, they find little evidence that they are better adapted to handle hot days. They use these findings to estimate mortality and energy consumption under climate scenarios, assuming no change in demographics, technology or relative prices. They find an increase in age-adjusted mortality in the United States of about 3 percent and an increase of 11 percent in energy consumption to help protect against weather extremes.

Adaptation will also depend on political will to invest in changes. Even when measures have been shown to be cost-effective, it has been observed that it is difficult to inspire adoption. For public investments it has been argued that this is because politicians, first, have a limited time in office and are unlikely to be judged on how they address low-risk threats and, second, have many other issues vying for their attention (Posner 2006). That said, the occurrence of a natural disaster can serve as a focusing event, increasing attention to the risk and thus leading to more investments in mitigation.

Sadowski and Sutter (2008) note this propensity of communities to adopt risk mitigation measures in the aftermath of a disaster. They look at the impact of a landfalling hurricane between 1950 and 1999 as a proxy for mitigation, finding some suggestive evidence that a hurricane in the past 10 years that covered at least half of the storm's current path reduces damages in a county by the equivalent of about one category on the Saffir–Simpson scale. With more frequent extreme events, we may thus see increased investments in risk reduction. In another example, a severe heat wave in 1995 caused excess mortality in St. Louis, Missouri, and Chicago, Illinois. Four years later, another severe heat wave occurred, and excess death was found to have declined, partially as a result of investments in improved warning and response

[11] Small reductions in winter mortality do not offset this, and it has been found that only 20 to 40 percent of excess deaths are simply displacement.

taken after the first event (Palecki et al. 2001). On the other hand, Gaiha et al. (2012) find that the frequency of disasters in a previous period increases the number in a later period, suggesting no or ineffective mitigation. Specifically, they find that countries with a 5 percent higher frequency of disasters (as defined by the EM-DAT data) in the 1970s had a roughly 2 percent higher frequency of disasters between 1980 and 2004. They found similar results for fatalities. The evidence is thus a bit inconclusive on whether more disasters are likely to inspire more mitigation.

The rest of this section reviews mitigation options available for countries, subnational jurisdictions, and individuals and businesses that choose to invest in risk reduction; it also offers a brief discussion of insurance. To the extent that risk reduction activities have been or are being adopted in anticipation of changes in extremes, those adaptation measures are also discussed. A review of the literature, however, suggests that, despite extensive theoretical discussion of how to adapt to extremes, and even some incorporation of mitigation measures into government planning documents (e.g., Government of Ontario 2011), little physical investment or behavioral change is apparent to date.

When considering disaster mitigation, short-term changes, such as the adoption of hurricane shutters, frequently come to mind. Thinking of adaptation, however, as "end-of-the-pipe" adjustments, like shutters or increasing the market penetration of air conditioning, will underestimate how fully communities are adapted to their present disaster risk: infrastructure, building architecture, street geometries, and even institutions such as emergency response are all adapted to a current climate, and changing these to fit with a new risk profile, if sufficiently different, could be a very long-term process (Ewing et al. 2003). Further, past institutions can be a constraint on our ability to adapt. Libecap (2011), for instance, argues that the water rights institutions in the American West, which developed to promote agriculture in an arid region, increase the costs today of water management that would be valuable in the face of climate change.

7.1. The Nation

National-level governments have three primary types of risk reduction activities available to them: (a) engaging in preparedness and planning, (b) funding and building protective infrastructure, and (c) funding or incentivizing the adoption of risk reduction strategies by others. (State insurance is discussed in Section 7.4.)

The work discussed above in Section 4 found that countries with better institutions had lower disaster impacts. One possible explanation is that stable and established institutions can invest in pre-disaster planning and preparedness, which results in less damage when hazards do occur. A first preparedness investment is simply information provision about impending events. In addition to information provision, institutions at all levels need have plans in place to shift into emergency operations when a disaster occurs.

A telling example comes from the 2003 heat wave in France, in which close to 15,000 people died. Part of the explanation of the disastrous impact of the heat wave is that advanced warning on the severity of the event was limited, it was difficult for many organizations (e.g., nursing homes and nonemergency response bureaucracies) to change from normal operations to an emergency mode, and the government did not treat the situation as an emergency until too late (Lagadec 2004). Pre-planning for such an event could lead to better emergency response and thus lower loss of life. Similarly, preparation suggestions for dealing with pandemic influenza (Mounier-Jack and Coker 2006) could be useful for climate-related diseases; these suggestions include establishing systems for the early detection and characterization of diseases, preparation for ramping up vaccine production, research and development into treatment and prevention (including vaccines), planning for international coordination of surveillance and dissemination of treatment, and stockpiling of drugs.

National-level governments can also invest in protective infrastructure for certain types of events. Levees and reservoirs can be built to hold back floodwaters, and sea walls can guard against storm surges. These can be effective at lowering damages. For instance, estimates suggest that the levees and reservoirs built by the U.S. Army Corps of Engineers prevented around $19 billion in flood damages during the 1993 flood on the Missouri and Mississippi Rivers (Interagency Floodplain Managment Review Committee 1994). That said, some have argued that, although societies can reduce the consequences of relatively more frequent events, such mitigation efforts could perversely increase their vulnerability to less frequent, but higher-magnitude events (Kates et al. 2006). For instance, suppressing forest fires can lead to larger fires when they do occur as a result of fuel build-up (Prestemon et al. 2002). As another example, a 100-year levee may protect an area behind it from smaller-scale flood events, but the protection could also encourage more development in the area, thus increasing damages when the less frequent, larger flood occurs; this is referred to as the “levee effect” (Tobin 1995).

Finally, federal governments can encourage others to adopt risk reduction measures. One way is by funding part or all of the costs. An example comes from the United States. The Federal Emergency Management Agency (FEMA) has a mitigation grants program, which funds part of the costs of disaster mitigation efforts by individuals and local governments. A study of a sample of FEMA mitigation grants between 1993 and 2003 estimated that every $1 spent on the grants provides roughly $4 of benefit in terms of avoided damages (National Institute of Building Sciences 2005).

7.2. Subnational Jurisdictions

Subnational jurisdictions have many options available to reduce disaster impacts. First, land use changes and land use planning can reduce exposure in hazardous areas. Reducing density in the most at-risk areas is one way to reduce losses; although in places where risks are coupled to high amenity values, it might not be cost-effective.

An extreme form of land use management is full retreat from risky areas. Communities only rarely choose not to rebuild after a disaster (Kates et al. 2006), however, suggesting that retreat in response to climate change may be limited. The value of amenities associated with many risky locations is simply too high. For instance, it is thought that the benefits from urbanization are so great, particularly in developing countries, that small disaster probabilities will not deter increases in density in the coming years (Lall and Deichmann 2010). In smaller and less dense areas, however, Lall and Deichmann (2010) note that investments in large-scale mitigation may not be cost-effective, and relocation may be more common.

This is the pattern observed to date, where relocation from disaster risk has been small and localized. One example from the United States is the town of Valmeyer, Illinois. It used to be located on the Mississippi River. After the vast majority of the town was severely damaged in the 1993 floods, the entire community relocated to higher ground (the population at the time of the flood was around 900). In addition to smaller towns, relocation is also sometimes undertaken for a few properties, as opposed to entire communities. In the United States, FEMA sometimes purchases properties with a history of flooding and converts the land to open space. This was done on a large scale following the 1993 floods on the Missouri and Mississippi Rivers. Closer examination of several communities, such as Arnold, Missouri, found these “buy outs” to have net benefits (FEMA 1997). Retreat from hazardous areas may also be more likely after very extreme events. This could be a result of changing risk perceptions, excessive damage to capital stocks, or large loss of life. For instance, U.S. Census data suggest that New Orleans is 29 percent smaller as of 2010 than it was pre-Katrina, and St. Bernard Parish is 50 percent smaller (Robertson 2011).

Relocation as adaptation is already being undertaken in some small island nations where SLR will, with almost complete certainty, eradicate a way of life this century. The president of the Maldives has proposed setting aside tourism revenue in a national fund so that the country can purchase land in countries with higher ground for relocation of the entire population when the time comes (Henley 2008). The president of Kiribati is trying to relocate young citizens now to New Zealand and Australia to prevent the need for mass migration in the future (Russell 2009). If climate disasters become more frequent, it could also induce more migration. Saldaña-Zorrilla and Sandberg (2009) use a spatial econometric model to examine emigration between 1990 and 2000 in Mexican municipalities, finding it higher from municipalities with a high frequency of natural disasters, especially if they are nonmarginalized. In those communities, a 10 percent increase in disaster frequency increases emigration rates by 1 percent.

Finally, retreat may be required to preserve other assets that are valued highly by the community. For instance, in Texas, the Open Beaches Act makes all beaches public. As a result of erosion, storm events, and possibly SLR, however, those beaches are migrating inland in some places and during some time periods, such that homeowners can find themselves located on a public beach. As of 2006, the Texas General Land Office had a policy to pursue legal action against those in violation, prioritizing homes that significantly restrict public access to the beach, pose an imminent safety threat, or are located on state-owned submerged land. In 2010, however, the Texas Supreme Court held that Texas did not have a rolling easement with respect to sudden changes in property lines due to storms. This issue of protecting beaches and coastal ecosystems will be one many states and communities will have to confront as the sea rises.

Another policy option for subnational jurisdictions is the adoption of tougher building codes. Building codes set minimum levels of safety for structures. Often new building codes are applied to new or updated construction, and not to existing buildings; this leaves a stock of structures that are below standard and more likely to sustain damage. Of course, a code is only as good as its enforcement and continued updating. An analysis of home damage after Hurricane Andrew found that new homes sustained more damage, most likely because of the erosion of the building of code over time (Fronstin and Holtmann 1994).[12]

[12] The Insurance Institute for Business and Home Safety recently rated Gulf Coast states in the United States on the strength of their building codes and enforcement measures (Insurance Institute for Business & Home Safety 2011). Florida and Virginia came out in the lead, far ahead of the laggards of Texas, Delaware, and Mississippi.

Building structures to withstand natural hazards is often more costly; therefore, such practices are less likely to be adopted in developing countries. For instance, urban areas in Latin America and the Caribbean often have poor-quality structures, insufficient planning, and little investment in infrastructure, making them more vulnerable (Charvériat 2000). Some observers have called for more international aid to help lower-income countries improve their disaster mitigation, through practices such as building safer structures.

To protect loss of life, communities can adopt warning systems and evacuation policies. For example, Bangladesh developed an effective warning system for cyclones, giving people enough time to evacuate and protect livestock; although warnings for inland riverine flooding are still fairly poor (Benson and Clay 2004). Conversely, the massive death toll from the Indian Ocean tsunami in 2004 has been attributed to poor monitoring and warning (Marris 2005). Even with good warnings, however, many income-constrained smallholders may not have the resources to respond (Benson and Clay 2004), and the extent to which individuals heed warnings and evacuation messages is in part determined by characteristics of the individuals, situational factors, and the social context (National Research Council 2006). It has been observed that people often “normalize” disaster situations, being reluctant to take different courses of protective action, and they will often not act unless they have a clear blueprint of what they need to do (National Research Council 2006). Unintended interactions may occur between the ability to foresee hazards and evacuate safely and development in those areas. Sadowski and Sutter (2005) argue that, although the improvements in warning systems and evacuation procedures in the United States have reduced the lethality of hurricanes, these improvements have also increased damages because it is now safer to live in risky areas.

Although the literature addresses the political economy of evacuation and factors motivating individuals to stay or leave, few studies have estimated the costs of evacuation. In one of these studies, Whitehead (2000) estimated the opportunity costs of hurricane evacuations, using survey data of households affected by Hurricane Bonnie, which hit the North Carolina coast in 1988. Making assumptions about the probability of evacuation and the expenditures, including time costs, he finds that the total costs of hurricane evacuation in North Carolina coastal counties range from roughly $1 million to $26 million, depending on the intensity of the storm (category 1–5 hurricane). Costs increase if a mandatory evacuation is put in place, as the total number evacuating increases.

Like national level governments, subnational governments can also invest in protective infrastructure. This could be gray infrastructure, such as dams and levees, or green infrastructure, such as mangroves and wetlands, that work to contain events and lower damages. Residents are often, at least when not income-constrained, willing to pay for these types of investments. For example, one study found positive WTP for hurricane protection in New Orleans, with category 5 levees preferred over coastal restoration and improved transportation (although the latter two measures are positively valued by some) (Landry *et al.* 2011).[13]

As mentioned above, preparation for one scale of event could exacerbate damages in more severe situations, as in the hypothesized levee effect. Even if damages are not worse for more severe events, however, risk reduction strategies that work for lower-magnitude events may be ineffective for higher-magnitude events. For example, although an obvious adaptation to increased heat waves is improved penetration of air conditioning, in Chicago in both 1995 and 1999, power outages occurred as a result of the huge increase in demand for electricity. Another example comes from Hurricane Katrina. Models of potential losses assumed that the pumps in New Orleans would keep flooding in the city to a minimum. However, the extreme nature of Katrina led to an evacuation of people, including pump managers, as well as a power outage; this reduced pumping capacity and led to flood damage in the city that was much more extensive than expected (RMS 2005). These complications should be kept in mind by risk managers if disaster severity worsens with climate change.

7.3. Individuals and Firms

Many options are available to home and business owners to reduce damages should they experience a natural hazard event. The first is choosing where to locate. If located in a hazard-prone area, there are various structural changes to one's building that would make it better able to withstand disasters, or behavioral responses that could be undertaken, like keeping valuables out of an often-flooded basement.

As stated earlier, many disaster locations have high amenity values, like coastal areas, with many homeowners feeling that the benefits outweigh the disaster risk. In places without such high amenities, many studies have found a reduction in property values, suggesting that individuals must be compensated for being located in hazardous areas (e.g., Bin and Polansky 2004; Kousky 2010). When risks or the impacts of a disaster become too extreme, relocation will occur, as found by Hornbeck (2009).

[13] Landry et al. (2011) also find a high WTP for flood protection (but not transit improvements) of New Orleans in a sample of all U.S. residents, perhaps suggesting value to those outside the community in protecting areas that are unique cultural or economic assets to the country.

Studies have routinely found, however, that individuals and businesses often fail to adopt risk reduction activities. As one example, a 2006 survey of 1,100 homeowners along the Atlantic and Gulf Coasts found that 83 percent had done nothing to fortify their homes against hurricanes, 68 percent had no hurricane “survival kit” ready, and 60 percent had no family disaster plan (Goodnough 2006)—even though the survey was conducted less than a year after Katrina called attention to hurricane risk. Similarly, a survey of 1,500 Florida homeowners found that the majority did not have any window coverage or shutters. Slightly more than one-quarter of respondents did have complete coverage of all windows (having 100 percent coverage is critical for keeping the home’s envelope unbreached), but in many cases, the coverage was provided with subpar materials (Peacock 2003). A survey of businesses in areas affected by large natural disasters found that the average business does very little in terms of disaster preparedness (Webb et al. 2000). When they do adopt risk reduction measures, businesses prefer those that are inexpensive and uncomplicated as well as those that provide protection against a range of hazards (Webb et al. 2000).

Many factors may explain why individuals and businesses sometimes do not invest in what appear to be economically beneficial risk reduction measures. They may underestimate the probability of a disaster, make decisions on a very short time horizon, or face budget constraints (Kunreuther 2006). In addition, for risk reduction measures that are public goods, individuals may choose to free ride. The public good problem arises in the case of wildfire risk, for example, where it has been found that homeowners in fire-prone areas may be underinvesting in averting activities, such as fuel treatment and the creation of defensible space because the homeowner captures only some of the benefits (e.g., Shafran 2008). In the above-mentioned survey of shutters in Florida, the author found that when people were asked why they had no shutters, 57 percent said they did not need them and 19 percent said they could not afford them (Peacock 2003). Higher-income homeowners, those who had lived longer in their homes, those located in a community with stronger building codes, those having neighbors with shutters, and those with knowledge of hurricane risk were more likely to have envelope coverage (Peacock 2003). The survey of firms found that larger businesses are more likely to have done something to prepare for disasters, as are firms with prior disaster experience (Webb et al. 2000). One should remember that the range of financial conditions and expectations is such that the same event does not constitute the same hazard for everyone (Burton et al. 1993).

Other mitigation measures, when closely examined, turn out not to necessarily produce net benefits, explaining low adoption. A common strategy for reducing flood damages to a home is elevation. Recent work in Texas found that elevating all structures in the 100-year floodplain by two feet or eight feet would reduce expected damages from a riverine flood by 40 percent or 89 percent, respectively, and would reduce storm surge losses by 16 percent or 64 percent (Czajkowski et al. 2012). Although these seem like huge benefits, costs were also huge. The study team found that the costs outweighed the benefits for existing construction in most places, although some selective elevating could be done (Czajkowski et al. 2012). Elevating new construction is less costly and thus could more often generate net benefits—this is one reason why new building codes are often limited to new construction, where compliance is cheaper.

7.4. Insurance

Finally, it is worth saying a word about insurance. Although insurance does not usually lower the actual economic damages of an event, it can be used to manage the remaining risk after any risk reduction measures have been adopted. Some have argued that wider take-up of insurance would make more funds available post-disaster, which could lessen the impact on individuals and perhaps reduce ripple effects in the local community. It is not clear how much of an impact it would have on societywide costs from disasters.

One strategy suggested for obtaining such benefits from insurance is comprehensive insurance from the individual to the nation state. In the context of the United States, Kunreuther and Pauly (2006) discuss a four-layer scheme. The first layer is individual self-insurance (this is equivalent to the deductible on an insurance policy) to reduce moral hazard. The amount of self-insurance could vary with income. Layer two is the purchase by homeowners of private disaster insurance (they conceive of an all-hazards policy bundled with traditional homeowners coverage). The third layer is reinsurance and catastrophe bonds purchased in the private market by primary insurance companies. The fourth layer is a form of government backstop against truly large losses, either in the form of a state fund, multistate pool, and/or federal reinsurance for catastrophe layers. Several papers have discussed how to effectively design a federal program of reinsurance or federal backstopping for catastrophic losses.[14] Kunreuther and Pauly note that this layering scheme would need to be coupled with restrictions on disaster aid; assistance for low-

---

[14] Lewis and Murdoch (1996) suggest excess-of-loss contracts to private insurers and reinsurances, with coverage and payouts based on insurance industry losses. The authors argue that catastrophe losses must be diversified intertemporally as well as spatially, and that firms have a limited ability to do this. Litan (2006) similarly argues for a federal catastrophe reinsurance program for high layers with post-event assessments and incentives for mitigation available to insurance companies and state insurance programs.

income homeowners; and the adoption of risk reduction measures, such as building codes and land use regulations.

For events that are too large for a country to handle, many authors have suggested placing risks into the financial markets. Increasing disaster losses led the government of Mexico in 2006 to transfer some of its earthquake exposure—and then, in 2009, also its hurricane exposure—to the capital markets. Catastrophe bonds[15] and other mechanisms for offloading disaster risk into the markets can be useful to governments in that they can provide multiyear coverage at a stable price, ensure the availability of funds immediately following an event, and offer an approach that is politically more feasible than a government reserve (Michel-Kerjan et al. 2011). The potential of such instruments is still being developed and explored.[16]

Although such a layering scheme could help spread disaster risk and ensure funds for reconstruction, globally, take-up rates at all proposed levels are often quite low. At the individual level, highly developed countries have much larger penetration of insurance, although in some places coverage is far from complete. In places where coverage for different disasters requires additional policies beyond standard homeowners policies, such as in the United States, the penetration of disaster coverage specifically may also be lower. Developing countries have far less advanced insurance markets. Swiss Re (2012) reports a $254 billion gap worldwide between total economic losses (estimated at $370 billion) and insured losses from all disasters in 2011.

Further hamstringing take-up of disaster coverage, insurance companies have been scaling back disaster coverage in some areas, or for some perils, because private insurance markets are concerned about adverse selection, the catastrophic nature of the risk, or consumer unwillingness to pay the required premiums. It is indeed true that insuring fat-tailed risks, such

---

[15] Generally, catastrophe bonds are issued by (re)insurance companies that set up a separate legal structure called a *special purpose vehicle* to issue the bond and invest the proceeds in low-risk securities. Investors in the bond receive the interest on the investment as well as some fraction of the premiums paid by the (re)insurer. If the natural disaster for which the bond is designed does not occur, investors get their principal back at the end of the time period of the bond. If the event occurs—the trigger—the investors lose their money as it is given to the (re)insurer to cover claims.

[16] If buyers are present, catastrophe bonds could be used to cover the higher end of the distribution of catastrophe risks, but there are reasons to be skeptical about demand. The possibility of total loss means that catastrophe bonds are usually given a noninvestment-grade rating. The modeling used for the pricing is difficult for lay people to follow, which might discourage some investors. Some had argued that catastrophe bonds would be attractive to investors because they were unlikely to be correlated with the market. However, this assumption may not hold; a catastrophe bond failed to meet an interest payment when Lehman Brothers failed (Hartwig 2009). However, on the difficulty with insurance that does not require an insurable interest, see Jaffee and Russell (2012).

as natural disaster damages, is quite expensive, and homeowners may be unwilling to pay the required loadings (Kousky and Cooke 2012). Some trends show private insurance companies reducing coverage in some U.S. markets, such as along the Gulf Coast, for example. This may put more pressure on state insurance programs in the United States, raising questions of pricing, equity, and moral hazard (Kousky 2011). In other countries, such as France, federal programs provide disaster coverage to avoid the problems in the private market, and some research suggests benefits from these programs; for example, state insurance in some European countries has very low operating expenses, and these savings can be passed on to customers (von Ungern-Sternberg 2004).

One group with very low insurance take-up is small-scale famers in the developing world who are dependent on rain-fed agriculture, and thus sensitive to climate extremes. The amounts of coverage an individual farmer would purchase, however, are very small, and the transaction costs to verify losses would make traditional insurance too costly to provide to this group. Weather index insurance has been offered as a possible solution. These are policies that pay out when rainfall (or some other weather-related index) falls above or below a set threshold. They thus have smaller transaction costs because losses do not need to be evaluated at a property level, but the farmers still bear some risk, as the policy is not perfectly correlated with their losses. There has been some debate in the literature, however, as to if and how well such insurance products are understood and are likely to be used as effective risk management tools. A survey and experimental game in Ethiopia and Malawi found that many farmers lacked understanding of core insurance concepts and, not surprisingly, this was correlated with education level; farmers with a better understanding of insurance had a higher demand for it (Patt et al. 2010).

One question that has been frequently asked is whether climate change will alter the insurability of natural disaster risks. The simple question of insurance capacity suggests that the industry is capable of handling very large events. For instance, estimates of insured losses from Katrina are $43.6 billion, but this did not threaten the industry (King 2008). However, the Congressional Research Service notes this is, in part, because (a) insurance companies limited their exposure in hurricane areas and raised rates as much as was allowed by state regulators after Hurricane Andrew and the 2004 hurricanes and (b) the industry had a high level of policyholder surplus and high investment income going into 2005 (King 2008). As changes in extremes materialize, prices for weather-related disasters may continue to increase, and some of the risk may shift to the public sector. What this means for government disaster policy deserves further scrutiny.

8. Conclusion

Several devastating weather events since 2000—including the 2003 European heat wave, the 2004 Indian Ocean tsunami, Hurricane Katrina in 2005, and the 2010 floods in Pakistan—have spurred interest in natural disasters recently. In the United States, 2011 saw a surge in media attention to disasters as many extreme event records were broken with a string of disasters all causing over $1 billion in damages including a blizzard, tornadoes, wildfires, and flooding. Swiss Re (2012) estimated economic losses from disasters (natural and anthropogenic) in 2011 worldwide to be over $370 billion—a record driven by the earthquake in Japan.

Estimates of the average annual cost of disasters using publicly available data range from $932 million to $12.3 billion (in 2012 US$). These estimates are limited by the lack of complete and systematic data on disaster losses worldwide, or even within countries. All data sets underestimate indirect losses, if they are included at all, and none includes nonmarket impacts or costs to informal sectors of the economy. We can therefore expect the hypothetical true amount to be higher. Damages also vary by disaster type, with climate-related events, and flooding in particular, responsible for a larger share of damages and fatalities. Damages are also not borne equally, with developing countries bearing a larger share of the burden, particularly in terms of the loss of life.

Despite these costs, the research to date suggests that natural disasters have a relatively modest impact on output and growth. The impacts are larger for more severe events, with some devastating disasters having severe and long-term negative impacts. Impacts on macroeconomic variables are also more negative for smaller geographic areas, as smaller economies are less capable of observing an event, and in developing countries. Higher-income countries, countries with higher levels of education, and those with higher-quality institutions face smaller negative impacts. The largest impact of natural disasters is often distributional, with some groups being hard hit, and others even benefitting from the reconstruction after the event.

Some research has focused on understanding the general relationships between the magnitude of disasters and damage levels; this work, in addition to research on impacts more broadly, could help inform both (a) estimates of how changes in extremes with climate change might alter the losses society faces and (b) how to incorporate these into climate models. Given the regional variation, including damages from extreme events in integrated assessment models may be best accomplished using regional or country-level models. In this way, the Climate Framework for Uncertainty, Negotiation and Distribution (or, FUND) model has been used to look at the economic impacts of increases in hurricane activity (Naritaa et al. 2010). The authors use the income elasticity of storm damage of −0.514, drawing exclusively on the work of Toya and Skidmore (2007) reported above. They estimate coefficients in their function for disaster damages from EM-DAT data, finding their estimates highly sensitive to the time period examined. They also have a parameter for increases in intense storms with climate change. This type of effort could be more carefully accomplished by integrating more of the findings from the literature.

Several remaining gaps in empirical studies warrant further research. Efforts to fill some of these gaps are limited by data availability. For instance, little empirical work has assessed the impact of multiple disasters occurring fairly close in time or the cumulative impact of many small events. These questions are hard to tackle with the EM-DAT data and thus may require taking a single-country and single-hazard focus. In addition, few empirical studies have estimated empirically indirect damages from disasters. This is an area in need of much more investigation. Similarly, very little work has evaluated nonmarket impacts of disasters. Again, without comprehensive data sets, such work will most likely have to be in the form of disaster-specific studies and analyses of general findings gathered from the work of many empirical case analyses.

Finally, the empirical work on adaptation to potential changes in extreme events is quite small. More studies like those profiled at the beginning of Section 7, which compare current risk reduction investments for different levels of risk, could help inform the extent of adaptation that is possible. More work on the costs and benefits of different adaptation strategies—especially beyond one-off, household-level investments, but including larger community-level changes—would also be a helpful contribution to this emerging literature.

References

Adler, M.D. 2004. Fear Assessment: Cost–Benefit Analysis and the Pricing of Fear and Anxiety. *Chicago-Kent Law Review* 79: 977–1053.

Albala-Bertrand, J.M. 1993. *Political Economy of Large Natural Disasters*. Oxford, UK: Clarendon Press.

Anderson, M.B. 1990. Which Costs More: Prevention or Recovery? In *Managing Natural Disasters and the Environment*, edited by A. Kreimer and M. Munasinghe. Washington, DC: The World Bank, 17–27.

Anttila-Hughes, J.K., and S.M. Hsiang. 2011. Destruction, Disinvestment, and Death: Economic and Human Losses Following Environmental Disaster. Working paper. Columbia University.

Ascent Investment Partners. 2011. Natural Disasters Not a Threat to Muni Ratings. *Municipal Market Comments,* August. St. Louis, MO: Ascent Investment Partners, Montage Investments.

Baade, R.A., R. Baumann, and V. Matheson. 2007. Estimating the Economic Impact of Natural and Social Disasters, with an Application to Hurricane Katrina. *Urban Studies* 44(11): 2061–2076.

Benson, C., and E J. Clay. 2004. *Understanding the Economic and Financial Impacts of Natural Disasters*. Disaster Risk Management Series no. 4. Washington, DC: The World Bank.

Bin, O., and S. Polasky 2004. Effects of Flood Hazards on Property Values: Evidence Before and After Hurricane Floyd. *Land Economics* 80(4): 490–500.

Blake, E.S., C.W. Landsea, and E.J. Gibney. 2011. *The Deadliest, Costliest, and Most Intense United States Tropical Cyclones From 1851 to 2010 (and other Frequently Requested Hurricane Facts)*. NOAA Technical Memorandum NWS NHC-6. Miami, FL: National Oceanic and Atmospheric Administration, National Weather Service, National Hurricane Center.

Blankespoor, B., S. Dasgupta, B. Laplante, and D. Wheeler. 2010. The Economics of Adaptation to Extreme Weather Events in Developing Countries. Working paper. Washington, DC: Center for Global Development.

Bloom , D.E., and T. Khanna. 2007. The Urban Revolution. *Finance & Development: A Quarterly Magazine of the IMF* 44(3).

Brooks, N., and W.N. Adger. 2003. *Country Level Risk Measures of Climate-Related Natural Disasters and Implications for Adaptation to Climate Change*. Norwich, UK: Tyndall Centre for Climate Change Research.

Burton, I., R.W. Kates, and G.F. White. 1993. *The Environment as Hazard*. New York City, NY: The Guilford Press.

Cariaga, V. 2012. Tornadoes, Other Disasters Have Lasting Impact on Real Estate. *Investor's Business Daily*, March 8.

Caselli, F., and P. Malhotra. 2004. Natural Disasters and Growth: From Thought Experiment to Natural Experiment. Unpublished draft paper. Harvard University.

Cavallo, E., S. Galiani, I. Noy, and J. Pantano. 2010. Catastrophic Natural Disasters and Economic Growth. IDB-WP-183. Washington, DC: Inter-American Development Bank, Department of Research and Chief Economist.

Cavallo, E., and I. Noy. 2010. The Economics of Natural Disasters: A Survey. IDB-WP-124. Washington, DC: Inter-American Development Bank.

Charvériat, C. 2000. Natural Disasters in Latin America and the Caribbean: An Overview of Risk. Working paper no. 434. Washington DC: Inter-American Development Bank, Research Department.

Cuaresma, J. ., J. Hlouskova, and M. Obersteiner. 2008. Natural Disasters as Creative Destruction? Evidence from Developing Countries. *Economic Inquiry* 46(2): 214–226.

Cuñado, J., and S. Ferreira. 2011. The Macroeconomic Impacts of Natural Disasters: New Evidence from Floods. Presented at the Agricultural and Applied Economics Association's 2011 AAEA & NAREA Joint Annual Meeting. Pittsburg, PA.

Cutter, S.L., B. J. Boruff, and W.L. Shirley. 2003. Social Vulnerability to Environmental Hazards. *Social Science Quarterly* 84(2): 242–261.

Cutter, S.L., and C. Emrich. 2005. Are Natural Hazards and Disaster Losses in the U.S. Increasing? *EOS, Transactions, American Geophysical Union* 86(41): 381, 388–389.

Czajkowski, J., H. Kunreuther, and E. Michel-Kerjan. 2012. *A Methodological Approach for Pricing Flood Insurance and Evaluating Loss Reduction Measures: Application to Texas*.

Philadelphia, PA: Center for Risk Management and Decision Processes, The Wharton School, University of Pennsylvania.

Czajkowski, J., K. Simmons, and D. Sutter. 2011. An Analysis of Coastal and Inland Fatalities in Landfalling U.S. Hurricanes. *Natural Hazards* 59: 1513–1531.

Deryugina, T. 2011. The Role of Transfer Payments in Mitigating Shocks: Evidence from the Impact of Hurricanes. Urbana-Champaign, IL: University of Illionois.

Deschênes, O., and M. Greenstone. 2011. Climate Change, Mortality, and Adaptation: Evidence from Annual Fluctuations in Weather in the U.S. *American Economic Journal: Applied Economics* 3(152–185).

ECLAC (Economic Commission for Latin America and the Caribbean). 2003. *Handbook for Estimating the Socio-economic and Environmental Effects of Disasters*. Santiago, Chile: ECLAC.

Ewing, B., J.B. Kruse, and M.A. Thompson. 2005. Empirical Examination of the Corpus Christi Unemployment Rate and Hurricane Bret. *Natural Hazards Review* 6(4): 191–196.

Ewing, B.T., J.B. Kruse, and M.A. Thompson. 2003. A Comparison of Employment Growth and Stability before and after the Fort Worth Tornado. *Environmental Hazards* 5: 83–91.

FEMA (Federal Emergency Management Agency). 1997. *Report on Costs and Benefits of Natural Hazard Mitigation*. Washington, DC: FEMA.

Fomby, T., Y. Ikeda, and N.V. Loayza. 2011. The Growth Aftermath of Natural Disasters. *Journal of Applied Econometrics* doi: 10.1002/jae.1273.

Freeman, A.M. 2003. *The Measurement of Environmental and Resource Values : Theory and Methods*. Washington, DC: RFF Press.

Fronstin, P., and A.G. Holtmann. 1994. The Determinants of Residential Property Damage Caused by Hurricane Andrew. *Southern Economic Journal* 61(2): 387–397.

Gaiha, R., K. Hill, and G. Thapa. 2012. Have Natural Disasters Become Deadlier? ASARC Working Paper, Australia South Asia Research Centre, Arndt-Corden Department of Economics, Australian National University.

Gall, M., K.A. Borden, and S.L. Cutter. 2009. When Do Losses Count? Six Fallacies of Natural Hazards Loss Data. *Bulletin of the American Meteorological Society* June: 799–809.

Gall, M., K.A. Borden, C.T. Emrich, and S.L. Cutter. 2011. The Unsustainable Trend of Natural Hazard Losses in the United States. *Sustainability* 3: 2157–2181.

Goodnough, A. 2006. As Hurricane Season Looms, States Aim To Scare. *New York Times*, May 31.

Government of Ontario. 2011. *Climate Ready: Ontario's Adaptation Strategy and Action Plan 2011–2014*. Ontario, Canada: Queen's Printer for Ontario.

Gray, A. 2012. Disasters Expose Flaws in Assumptions. *Financial Times*, March 19.

Guimaraes, P., F.L. Hefner, and D.P. Woodward. 1992. *Wealth and Income Effects of Natural Disasters: An Econometric Analysis of Hurricane Hugo*. Columbia, SC: Division of Research, College of Business Administration, University of South Carolina.

Hagenbaugh, B. 2004. Economic Growth from Hurricanes Could Outweigh Costs. *USA Today*, September 26.

Handmer, J. 2009. Adaptive Capacity: What Does It Mean in the Contect of Natural Hazards? In *Adaptation to Climate Change*, edited by E. L. Schipper and I. Burton. London, UK: Earthscan**,** 213–227.

Hartwig, R.P. 2009. Financing Catastrophe Losses Amid a Financial Catastrophe. Presented at the Bahamas Weather Conference. Nassau, Bahamas.

Henderson, V. 2002. Urbanization in Developing Countries. *The World Bank Research Observer* 17(1): 89–112.

Henley, J. 2008. The Last Days of Paradise. *The Guardian*, November 10.

Hochrainer, S. 2009. Assessing the Macroeconomic Impacts of Natural Disasters: Are There Any? Policy Research Working Paper no. 4968. Washington DC: The World Bank, Sustainable Development Network Vice Presidency, Global Facility for Disaster Reduction and Recovery Unit.

Holmes, T.P., R.J. Huggett, Jr., and A.L. Westerling. 2008. Statistical Analysis of Large Wildfires. In *The Economics of Forest Disturbances: Wildfires, Storms, and Invasive Species*, edited by T. P. Holmes, J. P. Prestemon, and K. L. Abt. Springer Science, 59–77.

Hornbeck, R. 2009. The Enduring Impact of the American Dust Bowl: Short and Long-Run Adjustments to Enviromental Catastrophe. Working Paper 15605. Cambridge, MA: National Bureau of Economic Research.

Hsiang, S.M., and D. Narita. Forthcoming. Adaptation to Cyclone Risk: Evidence from the Global Cross-Section. *Climate Change Economics*.

Insurance Institute for Business and Home Safety. 2011. *Rating the States: An Assessment of Residential Building Code and Enforcement Systems for Life Safety and Property Protection in Hurricane-Prone Regions*. Tampa, FL: Insurance Institute for Business and Home Safety.

Interagency Floodplain Managment Review Committee. 1994. *Sharing the Challenge: Floodplain Management into the 21st Century*. Report of the Interagency Floodplain Managment Review Committee to the Administration Floodplain Management Task Force. Washington, DC: Interagency Floodplain Management Review Committee.

IPCC (Intergovernmental Panel on Climate Change). 2012. *Managing the Risks of Extreme Events and Disasters To Advance Climate Change Adaptation*. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Edited by C. B. Field, V. Barros, T. F. Stockeret al. Cambridge, UK: Cambridge University Press.

Jaffee, D., and T. Russell. 2012. The Welfare Economics of Catastrophic Loss. Paper presented at the Universities Research Conference on Insurance Markets and Catastrophe Risk held by the National Bureau of Economic Research. May 11–12, Cambridge, MA.

Jagger, T.H., J.B. Elsner, and M. A. Saunders. 2008. Forecasting U.S. Insured Hurricane Losses. In *Climate Extremes and Society*, edited by H. F. Diaz and R. J. Murnane. Cambridge, UK: Cambridge University Press, 189–206.

Jaramillo H., C.R. 2009. *Do Natural Disasters Have Long-Term Effects on Growth*? Documentos CEDE no. 24. Bogotá, Colombia: Universidad de los Andes.

Kahn, M.E. 2005. The Death Toll from Natural Disasters: The Role of Income, Geography, and Institutions. *The Review of Economics and Statistics* 87(2): 271–284.

Kahn, M.E. 2009. Urban Growth and Climate Change. *Annual Review of Resource Economics* 1(1): 333–350.

Kalkstein, L.S., and J.S. Greene. 1997. An Evaluation of Climate/Mortality Relationships in Large U.S. Cities and the Possible Impacts of a Climate Change. *Environmental Health Perspectives* 105(1).

Kates, R.W., C.E. Colten, S. Laska, and S.P. Leatherman. 2006. Reconstruction of New Orleans after Hurricane Katrina: A Research Perspective. *Proceedings of the National Academy of Sciences* 103(40): 14653–14660.

Kellenberg, D.K., and A.M. Mobarak. 2008. Does Rising Income Increase or Decrease Damage Risk from Natural Disasters. *Journal of Urban Economics* 63(3): 788–802.

King, R. O. 2008. *Hurricane Katrina: Insurance Losses and National Capacities for Financing Disaster Risks (updated)*. CRS Report for Congress. Washington, DC: Congressional Research Service.

Kousky, C. 2010. Learning from Extreme Events: Risk Perceptions after the Flood. *Land Economics* 86(3): 395–422.

Kousky, C. 2011. Managing the Risk of Natural Catastrophes: The Role and Functioning of State Insurance Programs. *Review of Environmental Economics and Policy* 5(1): 153–171.

Kousky, C., and R. Cooke. 2012. Explaining the Failure To Insure Catastrophic Risks. *The Geneva Papers* 37: 206–227.

Kron, W., M. Steuer, P. Low, and A. Wirtz. 2012. How To Deal Properly with a Natural Catastrophe Database - Analysis of Flood Losses. *Natural Hazards and Earth Systems Sciences* 12: 535–550.

Kunreuther, H. 2006. Disaster Mitigation and Insurance: Learning from Katrina. *The ANNALS of the American Academy of Political and Social Science* 604(March): 208–227.

Kunreuther, H., and M. Pauly. 2006. Rules Rather Than Discretion: Lessons from Hurricane Katrina. *Journal of Risk and Uncertainty* 33: 101–116.

Lagadec, P. 2004. Understanding the French 2003 Heat Wave Experience: Beyond the Heat, A Multi-Layered Challenge. *Journal of Contingencies and Crisis Management* 12(4): 160–169.

Lall, S.V., and U. Deichmann. 2010. Density and Disasters: Economics of Urban Hazard Risk. *WIDER Angle* February.

Landry, C.E., P. Hindsley, O. Bin, J. B. Kruse, J.C. Whitehead, and K. Wilson. 2011. Weathering the Storm: Measuring Household Willingness-to-Pay for Risk-Reduction in Post-Katrina New Orleans. *Southern Economic Journal* 77(4): 991–1013.

Leiserowitz, A., E. Maibach, C. Roser-Renouf, and J.D. Hmielowski. 2012. *Extreme Weather, Climate & Preparedness in the American Mind*. Yale University and George Mason University. New Haven, CT, Yale Project on Climate Change Communication.

Leiter, A.M., H. Oberhofer, and P.A. Raschky. 2009. Creative Disasters? Flooding Effects on Capital, Labour and Productivity within European Firms. *Environmental Resource Economics* 43: 333–350.

Lewis, C.M., and K.C. Murdock. 1996. The Role of Government Contracts in Discretionary Reinsurance Markets for Natural Disasters. *The Journal of Risk and Insurance* 63(4): 567–597.

Libecap, G.D. 2011. Institutional Path Dependence in Climate Adaptation: Coman's "Some Unsettled Problems of Irrigation". *American Economic Review* 101(February): 64–80.

Lindell, M.K., and C.S. Prater. 2003. Assessing Community Impacts of Natural Disasters. *Natural Hazards Review* 4(4): 176–185.

Litan, R.E. 2006. *Sharing and Reducing the Financial Risks of Future "Mega-Catastrophes"*. Issues in Economic Policy no. 4. Washington, DC: The Brookings Institution.

Loayza, N., E. Olaberría, J. Rigolini, and L. Christiaensen. 2009. Natural Disasters and Growth: Going beyond the Averages. Policy Research Working Paper no. 4980. Washington, DC: The World Bank, East Asia and Pacific Social Protection Unit & Development Research Group.

MacDonald, D.N., H.L. White, P.M. Taube, and W.L. Huth. 1990. Flood Hazard Pricing and Insurance Premium Differentials: Evidence from the Housing Market. *The Journal of Risk and Insurance* 57(4): 654–663.

Marris, E. 2005. Inadequate Warning System Left Asia at the Mercy of Tsunami. *Nature* 433(6 January): 3–5.

McGranahan, G., D. Balk, and B. Anderson. 2007. The Rising Tide: Assessing the Risks of Climate Change and Human Settlements in Low Elevation Coastal Zones. *Environment and Urbanization* 19(1): 17–37.

Mendelsohn, R., K. Emanuel, and S. Chonabayashi. 2011. The Impact of Climate Change on Hurricane Damages in the United States. Policy Research Working Paper Series. Washington, DC: The World Bank.

Mendelsohn, R., W.D. Nordhaus, and D. Shaw. 1994. The Impact of Global Warming on Agriculture: A Ricardian Analysis. *The American Economic Review* 84(4): 753–771.

Michael, J.A. 2007. Episodic Flooding and the Cost of Sea-Level Rise. *Ecological Economics* 63: 149–159.

Michel-Kerjan, E., I. Zelenko, V. Cardenas, and D. Turgel. 2011. *Catastrophe Financing for Governments: Learning from the 2009–2012 Multicat Program in Mexico*. OECD Working Papers on Finance, Insurance, and Private Pensions no.9. Paris, France: OECD Publishing.

Mileti, D.S. 1999. *Disasters by Design*. Washington, DC: Joseph Henry Press.

Miller, S., R. Muir-Wood, and A. Boissonnade. 2008. An Exploration of Trends in Normalized Weather-Related Catastrophe Losses. In *Climate Extremes and Society*, edited by H. F. Diaz and R. J. Murnane. Cambridge, UK: Cambridge University Press, 225–247.

Mitchell, J.T., and D.S.K. Thomas. 2001. Trends in Disaster Losses. In *American Hazardscapes: The Regionalization of Hazards and Disasters*, edited by S. L. Cutter. Washington, DC: Joseph Henry Press, 77–113.

Mounier-Jack, S., and R. Coker. 2006. Pandemic Influenza: Are Europe's Institutions Prepared? *European Journal of Public Health* 16(2): 119–121.

Naritaa, D., R.S.J. Tol, and D. Anthoff. 2010. Economic Costs of Extratropical Storms under Climate Change: An Application of FUND. *Journal of Environmental Planning and Management* 53(3): 371–384.

National Institute of Building Sciences. 2005. *Natural Hazard Mitigation Saves: An Indepdendent Study To Assess the Future Savings from Mitigation Activities*. Washington, DC: Multihazard Mitigation Council.

National Research Council. 1999. *The Impacts of Natural Disasters: A Framework for Loss Estimation*. Washington, DC: The National Academies Press.

National Research Council. 2006. *Facing Hazards and Disasters: Understanding Human Dimensions*. Washington, DC: The National Academies Press.

Newman, M.E.J. 2005. Power Laws, Pareto Distributions and Zipf's Law. *Contemporary Physics* 46(5): 323–351.

Nordhaus, W.D. 2010. The Economics of Hurricanes and Implications of Global Warming. *Climate Change Economics* 1(1): 1–20.

Noy, I. 2009. The Macroeconomic Consequences of Disasters. *Journal of Development Economics* 88(2): 221–231.

Noy, I., and A. Nualsri. 2011. Fiscal Storms: Public Spending and Revenues in the Aftermath of Natural Disasters. *Environment and Development Economics* 16: 113–128.

Noy, I., and T.B. Vu. 2010. The Economics of Natural Disasters in a Developing Country: The Case of Vietnam. *Journal of Asian Economics* 21: 345–354.

Okuyama, Y. 2008. *Critical Review of Methodologies on Disaster Impact Estimation*. Background paper prepared for the World Bank–U.N. Assessment on the Economics of Disaster Risk Reduction. Niigata, Japan: International University of Japan.

Olsen, A., and K. Porter. 2008. *A Review of Demand Surge Knowledge and Modeling Practice*. Boulder, CO: Willis Research Network.

Palecki, M.A., S.A. Changnon, and K.E. Kunkel. 2001. The Nature and Impacts of the July 1999 Heat Wave in the Midwestern United States: Learning from the Lessons of 1995. *Bulletin of the American Meteorological Society* 82(7): 1353–1367.

Patt, A., P. Suarez, and U. Hess. 2010. How Do Small-Holder Farmers Understand Insurance, and How Much Do They Want It? Evidence from Africa. *Global Environmental Change* 20: 153–161.

Peacock, W.G. 2003. Hurricane Mitigation Status and Factors Influencing Mitigation Status among Florida's Single-Family Homeowners. *Natural Hazards Review* 4(3): 149–158.

Perry, C.A. 2000. *Significant Floods in the United States During the 20th Century—USGS Measures a Century of Floods*. USGS Fact Sheet 024–00. Lawrence, KS: U.S. Geological Society.

Pielke, R.A., Jr., and C.W. Landsea. 1998. Normalized Hurricane Damages in the United States: 1925–95. *Weather and Forecasting* 13: 621–631.

Pielke, R.A., Jr., J. Rubiera, C.W. Landsea, M.L. Fernandez, and R. Klein. 2003. Hurricane Vulnerability in Latin America and The Caribbean: Normalized Damage and Loss Potentials. *Natural Hazards Review* 4(3): 101–114.

Posner, R.A. 2006. Efficient Responses to Catastrophic Risk. *Chicago Journal of International Law* 6(2): 511–525.

Prestemon, J.P., J.M. Pye, D.T. Butry, T.P. Holmes, and D.E. Mercer. 2002. Understanding Broadscale Wildfire Risks in a Human-Dominated Landscape. *Forest Science* 48: 684–693.

Raddatz, C. 2006. Are External Shocks Responsible for the Instability of Output in Low-Income Countries? *Journal of Development Economics* 84(1): 155–187.

Rappaport, J., and J.D. Sachs. 2003. The United States as a Coastal Nation. *Journal of Economic Growth* 8: 5–46.

Raschky, P.A. 2008. Institutions and the Losses from Natural Disasters. *Natural Hazards and Earth System Sciences* 8: 627–634.

Rauch, E. 2011. *Global Natural Catastrophe Update*. Munich, Germany: Munich Re.

Risk Management Solutions. 2005. *Hurricane Katrina: Profile of a Super Cat: Lessons and Implications for Catastrophe Risk Management*. Newark, CA: Risk Management Solutions.

Robertson, C. 2011. Smaller New Orleans after Katrina, Census Shows. *New York Times*, February 3.

Rose, A. 2004. Economic Principles, Issues, and Research Priorities in Hazard Loss Estimation. In *Economic Principles, Issues, and Research Priorities in Hazard Loss Estimation*, edited by Y. Okuyama and S. Chang. Heidelberg, Germany: Springer, 13–36.

Rose, A. 2012. Macroeconomic Consequences of Terrorist Attacks: Estimation for the Analysis of Policies and Rules. In *Benefit Transfer for the Analysis of DHS Rules and Regulations*, edited by K. Smith and C. Mansfield. Cheltenham, UK: Edward Elgar.

Russell, C. 2009. First Wave. *ScienceNews* 175(5).

Sadowski, N.C., and D. Sutter. 2005. Hurricane Fatalities and Hurricane Damages: Are Safer Hurricanes More Damaging? *Southern Economic Journal* 72(2): 422–432.

Sadowski, N.C., and D. Sutter. 2008. Mitigation Motivated by Past Experience: Prior Hurricanes and Damages. *Ocean & Coastal Management* 51(4): 303–313.

Saldaña-Zorrilla, S.O., and K. Sandberg. 2009. Spatial Econometric Model of Natural Disaster Impacts on Human Migration in Vulnerable Regions of Mexico. *Disasters* 33(4): 591–607.

Schoenberg, F.P., R. Peng, and J. Woods. 2003. On the Distribution of Wildfire Sizes. *Environmetrics* 14(6): 583–592.

Schumacher, I., and E. Strobl. 2011. Economic Development and Losses Due to Natural Disasters: The Role of Hazard Exposure. *Ecological Economics* 72: 97–105.

Shafran, A.P. 2008. Risk Externalities and the Problem of Wildfire Risk. *Journal of Urban Economics* 64: 488–495.

Skidmore, M., and H. Toya. 2002. Do Natural Disasters Promote Long-Run Growth? *Economic Inquiry* 40(4): 664–687.

Smith, V., J. Carbone, J. Pope, D. Hallstrom, and M. Darden. 2006. Adjusting to Natural Disasters. *Journal of Risk and Uncertainty* 33(1): 37–54.

Stephens, K.U. 2007. Testimony to the U.S. Senate, Committee on Homeland Security and Govermental Affairs, Ad Hoc Subcommittee on Disaster Recovery. Post-Catastrophe Crisis: Addressing the Dramatic Need and Scant Availability of Mental Health Care in the Gulf Coast.

Strauss, B.H., R. Ziemlinski, J.L. Weiss, and J.T. Overpeck. 2012. Tidally Adjusted Estimates of Topographic Vulnerability to Sea Level Rise and Flooding for the Contiguous United States. *Environmental Research Letters* 7: 014033.

Strobl, E. 2011. The Economic Growth Impact of Hurricanes: Evidence from U.S. Coastal Counties. *The Review of Economics and Statistics* 93(2): 575–589.

Stromberg, D. 2007. Natural Disasters, Economic Development, and Humanitarian Aid. *Journal of Economic Perspectives* 21(5): 199–222.

Swiss Re. 2012. *Natural Catastrophes and Man-Made Disasters in 2011: Historic Losses Surface from Record Earthquakes and Floods*. Sigma. Zurich, Switzerland: Swiss Re.

Tebaldi, C., B.H. Strauss, and C.E. Zervas. 2012. Modelling Sea Level Rise Impacts on Storm Surges along U.S. Coasts. *Environmental Research Letters* 7: 014032.

Thomas, D.S.K. 2001. Data, Data Everywhere, But Can We Really Use Them? In *American Hazardscapes: The Regionalization of Hazards and Disasters*, edited by S. L. Cutter. Washington, DC: Joseph Henry Press, 61–76.

Titus, J.G., D.E. Hudgens, D.L. Trescott, M. Craghan, W.H. Nuckols, C.H. Hershner, J.M. Kassakian, C.J. Linn, P.G. Merritt, T. M. McCue, J.F. O'Connell, J. Tanski, and J. Wang. 2009. State and Local Governments Plan for Development of Most Land Vulnerable to

Rising Sea Level along the U.S. Atlantic Coast. *Environmental Research Letters* 4: 044008.

Tobin, G.A. 1995. The Levee Love Affair: A Stormy Relationship. *Water Resources Bulletin* 31(3): 359–367.

Tonnetts, J. 2002. Coastal Cities: Living on the Edge. *Environmental Health Perspectives* 110(11).

Toya, H., and M. Skidmore. 2007. Economic Development and the Impacts of Natural Disasters. *Economics Letters* 94(1): 20–25.

U.S. Environmental Protection Agency Region 2. 2006. *Report on the City of New York's Progress in Implementing the Watershed Protection Program, and Complying with the Filtration Avoidance Determination*. New York, NY: USEPA Region 2 New York City Watershed Team with assistance from the New York State Department of Health Bureau of Water Supply Protection.

Viscusi, W. 2009. Valuing Risks of Death from Terrorism and Natural Disasters. *Journal of Risk and Uncertainty* 38(3): 191–213.

Vogel, R.M. 2000. Lost Consumer Surplus from Natural Disaster. In *Southwestern Economic Proceedings Selected Papers of the 2000 Meeting*, edited by J. S. Kaminarides and D. R. Marburger. San Antonio, Texas: 67-74.

von Ungern-Sternberg, T. 2004. *Efficient Monopolies: The Limits of Competition in the European Property Insurance Market*. Oxford, UK: Oxford University Press.

Vu, T. B., and D. Hammes. 2010. Dustbowls and High Water, the Economic Impact of Natural Disasters in China. *Asia-Pacific Journal of Social Sciences* 1(December): 122–132.

Webb, G.R., K.J. Tierney, and J. M. Dahlhamer. 2000. Businesses and Disasters: Empirical Patterns and Unanswered Questions. *Natural Hazards Review* 1(2): 83–90.

Whitehead, J.C. 2000. *One Million Dollars a Mile? The Opportunity Costs of Hurricane Evacuation*. Greenville, NC: Department of Economics, East Carolina University.