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Informing climate adaptation: A review of the economic costs of natural disasters

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ABSTRACT

This paper reviews the empirical literature on the economic impacts of natural disasters to inform both the modeling of potential future climate damages and climate adaptation policy related to extreme events. It covers papers that estimate the short- and/or long-run economic impacts of weather-related extreme events as well as studies identifying the determinants of the magnitude of those damages (including fatalities). The paper also reviews the small number of empirical papers on the potential extent of adaptation in response to changing extreme events.

1. Introduction

A growing consensus in the scientific community holds that climate change could be worsening certain 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 weather-related extreme events (IPCC, 2012). Even nonexperts are perceiving a trend toward more or worse extreme events: a 2012 poll of US residents found that, by a margin of 2:1, people believe that the weather is getting worse, and a large majority believe that 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 the estimation of potential climate damages using integrated assessment models and the potential extent of climate adaptation to extreme events. The paper limits focus to empirical estimates of the economic costs of natural disasters and findings on the determinants of economic damages and fatalities. The paper then also provides an overview of the handful of empirical papers to date on the likely extent of adaptation in response to changes in extreme events. Given the focus on informing climate scholarship and policy, the paper looks specifically at hydrometeorological (or weather-related) disasters and not geophysical disasters, since confidence in the impact of climate change on hydrometeorological events is greater.[1] The review is focused on the empirical literature; it does not cover 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. While natural disasters can have profound social and political impacts (e.g., Lindell and Prater, 2003), those are not covered here.[2] Finally, as a further limit to the scope, this review is largely focused on literature published within the past couple of decades, a period during which new data sets and improved understanding of disaster losses has 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. Best estimates for the average annual cost of natural

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[1] There are some papers that group all natural hazards together, and those papers are included in this review.

[2] This paper also does not cover the public health literature examining health outcomes after a disaster or engineering studies, although reviews of both these areas would be useful complements to this review.

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disasters worldwide between 2000 and 2012 ranges between $94 billion and a little over $130 billion (see Section 3). 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, or multiple disasters close in time, can have very long-term, negative economic consequences. Natural disasters generate many transfers and can have substantial 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 predicting increases in adoption in response to climate change is difficult. 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 limited insight on potential future adaptation. Recent research is attempting to move beyond correlations, particularly by addressing the endogeneity of many disaster measures, and more work on this is needed.

The next section of the paper discusses the difficulties with obtaining empirical estimates of the total economic costs of natural disasters and summarizes the approaches taken in the literature. Section 3 provides an overview of annual disaster costs worldwide and trends over time. Section 4 is the heart of the paper summarizing the work on the economic impacts of weather-related disaster events in the short and long run. Section 5 then briefly discusses the question of whether and when natural disasters can have positive impacts. Section 6 reviews the work on the determinants of both disaster fatalities and damages. Section 7 provides a short overview of potential adaptation to changes in extreme events. Section 8 offers a brief comment on future research directions suggested by this review. Section 9 concludes.

2. An overview of the issues

The theoretically correct measure of economic impacts from a natural disaster is 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 the analysis.[3] 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 broadly classified disaster impacts into direct and indirect impacts. Direct impacts refer to the physical destruction from a disaster, and indirect impacts (some authors prefer the term higher-order impacts) are considered to be the follow-on consequences of that destruction (National Research Council, 1999). Note that 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 (ECLAC, 2003). Section 5 investigates the question of whether and when disasters can have a positive economic impact.

Table 1 presents a categorization of direct and indirect disaster impacts.[4] Direct impacts include damages to homes and contents, which can include nonmarket items like family heirlooms or old photographs. Firms may also sustain damage, including damage to buildings, contents, and other productive capital. This category also includes damage to the agriculture sector, such as damage to crops, livestock, or farm equipment. If production is interrupted from physical damage, this is also a direct cost. Infrastructure like roads and bridges can sustain direct damage. People can be killed or injured directly by the disaster. The disaster could also cause environmental degradation of various sorts—both market and nonmarket damages. Finally, I include as direct damages the costs of emergency response, such as evacuation and rescue, and clean-up costs, such as clearing debris from streets.

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). There could also be mortality and injury or environmental degradation, not from the impact of the hazard, but from follow-on impacts. For example, if dirtier generators are run due to power outages, the air pollution from those would be an indirect impact.

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. Two overarching complications arise when trying to measure the full economic costs in each of the categories in Table 1.[5] First, it is necessary to be very clear about the spatial and temporal scale being examined because different boundaries for analysis can generate 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 borne fully by the victims. If the individual receives aid, 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 damage.

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 undertake upgrades during the post-disaster reconstruction that they would have otherwise deferred. Looking only one year post-disaster may suggest a benefit to the construction sector, but looking over three years might diminish this benefit. And 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.

[3] Limited welfare analyses have been done, such as Garcia Valinas (2006), which estimated the welfare impact of water rationing policies due to a drought.

[4] Adam Rose has suggested drawing a distinction between stock and flow losses. Business interruption to damaged firms would be a direct flow loss and property damage would be a direct stock loss. Indirect flow losses would be general equilibrium effects. This is a more useful distinction when examining impacts to firms or running input-output or computable general equilibrium models, two methods common to this field but not covered in this review. Some categories of losses, however, such as emergency response spending or reductions in utility from losing power or having to evacuate, however, do not fall as neatly into stock or flow categories (see: National Research Council (2011)).

[5] For a discussion of related issues specific to drought, see: Ding et al. (2011).

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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 capital and lost production	Multiplier effects
Damage to infrastructure	Costly adaptation or utility reduction from loss of use
Mortality and injury	Mortality and injury
Environmental degradation	Environmental degradation
Emergency response and clean-up	

The second challenge is that it is quite easy to double-count losses (Cochrane, 2004). For example, assume that 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 may be used to fund rebuilding.

So, given these difficulties, what would be the most preferable measure of direct and indirect damages? The next two 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. Following that, an alternative approach, measuring the impact of disaster through changes in macroeconomic accounts is discussed. This has been the preferred approach of much of the literature, likely because good data are available on these variables, but the ease of data availability does not imply that macroeconomic variables are the best measure of disaster impacts, as I discuss further below. Section 2 concludes with a discussion of measurement problems and data availability that should be kept in mind when reviewing this literature.

2.1. Direct damages

The economic costs that first come to mind when thinking about natural disasters are damages 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 (or, for other assets, depreciated value). 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. 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.[6] 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. The deadweight loss of taxation is positive, however, and the marginal opportunity cost of a dollar of government spending is 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 borrowing, this cost would need to be included.

The homeowner could also receive insurance payouts if insured. This would again lessen the negative wealth shock to the homeowner. Homeowners who suffer capital losses but have insurance are paying for the loss ex ante through the insurance premiums instead of ex post. The insurance is a mechanism to smooth the loss over time. Insurance payments are often used as a proxy for economic costs, 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 can be an excellent data source, but they are not synonymous with total direct costs.

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 and obtaining estimates of many would require non-market valuation studies.

Destruction to the buildings, contents, inventory, and other capital of firms can be similarly analyzed. For destroyed capital, the correct measure of economic loss is the depreciated value of the lost asset. If production is lost from a delay in replacing damaged capital, then this lost production from downtime should also be counted as an economic loss. It is possible the replaced capital could be more productive than the capital destroyed if there has been technological change. This productivity bump will offset some of the economic loss but would presumably also be paid for, as the new capital would cost more than the depreciated value of the lost asset. 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. 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 for reasons already discussed. 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 summarize 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

[6] Several studies have examined how politics and media attention plays a role in the disaster aid process. See, for example: Garrett and Sobel (2003), Eisensee and Strömberg (2007), and Healy and Malhortra (2009).

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 be considered direct costs of a disaster. This would include the opportunity cost of people's time spent hauling away debris, for example, and 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, with attention to the issues mentioned above.

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, but I have not seen these estimated in the literature.

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. Similarly, the loss of such services could 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.

Some of the literature has focused on possible multiplier effects post-disaster. Consumer demand post-disaster may be higher for some sectors—such as construction—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 production, having negative ripple effects in the supply chain. 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 canceling out (National Research Council, 1999). For instance, if a firm fails to produce an output, its customer may simply purchase the good elsewhere. As another example, tourists may avoid a hurricane-stricken coast, but instead of not traveling, they may just frequent another area. Clearly the distributional impacts of a disaster 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 as spending in other areas is reduced or taxes increased on certain groups. 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, not as a result 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). 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.[7] 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 other negative emotions), which Adler (2004) argues should be measured and included in regulatory cost–benefit analysis when relevant.

Estimating higher-order effects is difficult. Rose (2004) notes the following challenges: indirect effects are hard to verify, modeling them can be difficult, the size of the impacts can vary 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 and, as such, are not included here.[8]

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) or annual growth. 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 perceive 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 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 remembering, however, that GDP is simply a measure of economic activity, not of welfare.

[7] 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).

[8] 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).

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The usual arguments on this point extend to the case of natural disasters.[9] Thus, the literature on the GDP impacts of disasters is reported here as this is the dominant empirical approach, but with this note of caution that GDP 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. In general, the data available on disaster impacts are on those things that are easily observable ex post. 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). 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.

Another difficulty with disaster data is that many high-magnitude events are complex, with multiple interrelated perils (Kron et al., 2012).[10] 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).

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: EM-DAT includes events with either more than 10 fatalities, more than 100 people affected (those needing emergency assistance), 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 (Kron et al., 2012). All of these databases acquire information from a variety of sources. All the papers in the literature adopt the definition of disaster event used for inclusion by the particular data set that they are using.

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, small events are not included, even though frequent lower-impact events could still cause substantial economic costs. A recent UN report has found the EM-DAT under-reported economic losses in the 40 low and middle income countries examined, such that total figures of direct losses could be up to 50% higher than those reported (UNISDR, 2013). Second, EM-DAT is focused on aiding humanitarian response. As such, 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 results that could be confirmed by multiple data sources.

3. Estimates of average costs, total costs, and trends over time

This section summarizes estimates of the total costs of disasters and trends over time in disaster occurrences, costs, and fatalities. Few researchers attempt to add up all disaster costs as discussed in the previous section, but Swiss Re, Munich Re, catastrophe modeling firms, and others engage in this exercise and offer their assessments of the total economic costs of specific types of events. To arrive at total estimates, information must be aggregated from a wide variety of sources—a time-consuming task, and one that is difficult for the consumer to evaluate when using a data set. For instance, Munich Re collects information from over 60 offices worldwide, international insurance associations, and also evaluates press reports, and when good data is not available, they use methods for extrapolating losses based on information about insurance claims, insurance penetration, type of event, and region impacted (Munich, 2011). EM-DAT, as mentioned above, also draws on multiple sources, and they give priority first to UN agencies and then the US Office of International Development, governments, and the Red Cross (Guha-Sapir et al., 2012). Beyond these global data sets, individual countries may also keep estimates of the impact of certain events. In the US, for example, the National Oceanic and Atmospheric Administration maintains a record of natural disasters where losses exceed $1 billion USD.

I collected estimates of the total costs of weather-related disaster events globally between 2000 and 2012 by year from the four main institutions engaging in this exercise: Swiss Re, Munich Re, CRED (EM-DAT), and Aon Benfield.[11] Results are shown in Fig. 1. The average annual cost worldwide for this time period ranges across the four sources from over $94 billion (EM-DAT) to over $130 billion (Aon

[9] The reasons for why GDP is a poor measure of welfare are summarized nicely in the first paragraph of Fleurbaey (2009, p. 1029): "As is well known, GDP statistics measure current economic activity but ignore wealth variation, international income flows, household production of services, destruction of the natural environment, and many determinants of well-being such as the quality of social relations, economic security and personal safety, health, and longevity. Even worse, GDP increases when convivial reciprocity is replaced by anonymous market relations and when rising crime, pollution, catastrophes, or health hazards trigger defensive or repair expenditures."

[10] The classification decisions governing a given 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.

[11] I would like to thank Steve Bowen at Aon Benfield, Bridget Carle at Swiss Re America, and Angelika Wirtz at the Munich Reinsurance Company for supplying the data.

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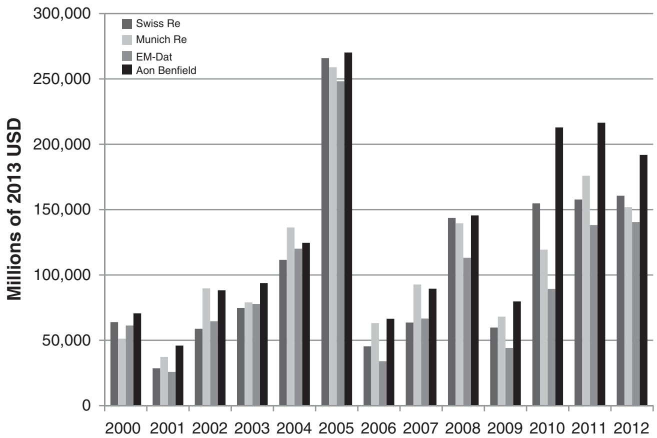

Fig. 1. Annual costs of weather-related disaster events worldwide.

Benfield). This is similar to results published using these same data sources but over slightly different time periods (e.g., Aon Benfield, 2013; Guha-Sapir et al., 2012; Rauch, 2011).[12]

There is geographic variation in damages. Economic losses 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% 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% of total damages (Miller et al., 2008).

All natural disasters are not equal. Worldwide, approximately 85% 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% were from climatological disasters (Mileti, 1999). Another US analysis also found that weather-related events were responsible for the most damage (Cutter and Emrich, 2005). These findings are 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 affected the most people (using the EM-DAT definition of affected, which is people needing immediate assistance during the emergency period post-disaster) (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% of landfalling hurricanes in the United States but are responsible for over 80% 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% of the total) accounting for over 80% 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., Holmes et al., 2008; Newman, 2005; Schoenberg et al., 2003).

Most data sets show an increase in the number of disasters over time. 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 attributable to both better reporting and to growing population and structures in hazardous areas (Burton et al., 1993). Munich Re believes that its global estimates are not subject to reporting bias in the last 20 years; in places like the United States and Western Europe, data are probably unbiased even further back—perhaps 30 to 40 years (Kron et al., 2012). Globally, Munich Re data shows increasing trends for weather-related events in all contents since 1980, but the increase is greatest in North America and Asia (Munich, 2012).

Disaster 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 and capital in hazardous areas, disproportionate increase in disasters in poorer areas, urbanization, economic globalization, and environmental degradation (Handmer, 2009).

To determine how much of the upward trend in losses over time is attributable to increased development in harm's way and an increase in the value of that development, multiple studies have standardized inflation-adjusted damages by some measure of wealth. If no upward trend is observed over time for these standardized losses, it suggests that that increases in wealth in hazardous areas are fueling the time trend in damages. For several countries and hazards, this exercise results in no upward trend in standardized losses (Charvériat, 2000; Pielke and Downton, 2000; Pielke and Landsea, 1998; Pielke et al., 2003). Two studies normalizing national disaster costs by the country's GDP, however, both find a roughly 2% per year increase in this ratio (one study uses years between 1970 and 2005 and the other 1980 to 2012) (Aon Benfield, 2013; Miller et al., 2008). And two studies focused on the US find that there may be an upward trend in costs, even after normalization (Barthel and Neumayer, 2012; Gall et al., 2011). Recent work on normalized losses from large thunderstorm events in the Eastern US between 1970 and 2009, coupled with thunderstorm forcing conditions over the same time period, finds that increases in the hazard are associated with increases in losses, consistent with the modeled effects of climate change (Sander et al., 2013). The conclusion from all these papers is that the majority of the upward trend in losses observed to date is due to more people and capital locating in hazardous areas, but even after correcting for this, there may be a small upward trend for certain regions and hazards, such that climate signals are beginning to be seen in historical loss data.

Fatalities, on the other hand, have shown a downward trend over time. 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). The largest killer is often heat waves; the European heat wave is responsible for the majority of worldwide disaster fatality between

[12] Different data sources allow for average annual estimates by location or hazard. For example, SHELDUS (Special Hazard Events and Losses Database for the United States), a county-level database of U.S. disaster losses, estimates an average of $11.5 billion a year (in 2009 US$, or $12.3 billion in 2012 US$) in direct disaster costs between 1960 and 2009 just for the US (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 (at over $74 billion, or $104 billion in 2012 US$) and many years of no damage (Pielke and Landsea, 1998).

2001 and 2010 (Ferris and Petz, 2012). The fatality burden of natural disasters is borne disproportionately by developing countries, and mortality in these countries can be high (Cavallo and Noy, 2010; Perry, 2000; Stromberg, 2007). Using the World Bank classification of low-, middle-, and high-income countries and the EM-DAT data, Stromberg (2007) finds 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 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.

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 authors 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% were actually damaged, 80% lost water, 40% lost sewer and wastewater treatment, 33% lost electricity, and over 20% 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). A comprehensive accounting of these types of costs and their trends over time is lacking.

4. Estimates of economic impacts

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. Within the studies of short-run impacts, I further classify the studies into multi-country studies, single country studies, and sector-specific studies. Many studies include country (or sub-country geography) fixed effects, and thus are identifying off changes within a country (or within sub-country geographies).

The majority of the multi-country and within country papers regress macroeconomic variables on some measure of disasters—occurrence, damage, or fatalities. They interpret this coefficient as a measure of the economic impact of disaster events. The overwhelming majority of these papers has no controls for physical aspects of the disaster event and takes the disaster measure as exogenous. This exogeneity assumption is tenuous. It seems apparent that while disasters could have an impact on economic indicators, it is also true that economic indicators could capture aspects of a society that influence disaster costs. Indeed, while the papers in this section examine the impact of disasters on GDP, Section 7 reviews papers that look at how GDP impacts disaster damages and fatalities, suggesting a two-way relationship between output and disaster impacts. In addition, there may be an omitted variable bias problem in that some measures not included in the model may influence economic outcomes and be correlated with disaster measures. For example, the costs and fatalities of a disaster are likely correlated with exposure in hazardous areas and this, in turn, could be correlated with income and production. As another example, socio-economic and political factors could influence both the macro-economy and disaster impacts. The endogeneity assumption could be a poor one even for papers that use disaster occurrence or frequency as the explanatory variable due to the inclusion criteria of the disaster databases. Raddatz (2006), notes, however, that incidence may be exogenous when he restricts his sample to low-income countries and controls for average GDP, since it is less likely that years of lower or higher GDP within a country change reporting substantially.

Overall, there are a few key takeaways from the papers that are discussed in this section:

- Impacts on GDP vary depending on the disaster measure and the countries in the sample. At the level of a country, many studies find that economies appear to have a lot of resiliency, especially for smaller-scale events and in higher income countries.
- That said, some newer research has found small, but persistent, long-term effects on economic growth of disasters, particularly severe ones or repeated events, and case studies of certain catastrophes have found persistent long-term effects, as well.
- Impacts are more negative at smaller scales. The country as a whole, while a focus of much of the literature, may not capture localized negative impacts.
- Impacts are worse the more severe the event.
- Aid, social safety nets, and countercyclical government spending may blunt negative macroeconomic impacts.
- Impacts vary 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 weather 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 can carry with them large distributional consequences.

4.1. 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 with panel data sets, which examine the relationship between natural disasters and macroeconomic variables. The second are within-country studies, which employ methods similar to those of the cross-country studies, only at a finer scale. The third group is made up of studies that look at the impacts of natural disasters on particular sectors of the economy. The studies in each subsection below are presented in chronological order.

4.1.1. Multicountry studies

The first two studies do not employ econometric approaches, but look only at summary statistics. As such, they fail to control for many correlated covariates and the results should not be given as much weight as the more recent papers. One of the first multicountry empirical estimations of short-run macroeconomic impacts of disasters was undertaken by Albala-Bertrand (1993), with 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, more recent, 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

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finds that in the year after a disaster, real median GDP drops almost 2%, but increases almost 3% 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 as a result of the event (Caselli and Malhotra, 2004). This work, like others using the EM-DAT data, is limited 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 3987 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. 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% 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 standardized measures of a disaster and a set of controls, including country fixed effects. His measures of disaster impacts are fatalities divided by population and costs as a percentage of the previous year's GDP, weighted by month of occurrence. He examines endogeneity by also examining disaster occurrence and, for a subsample for which data is available, physical measures of a disaster (Richter scale measures and wind speed). Noy finds that, in developing countries, the amount of property damage that a disaster causes negatively influences GDP growth, with an increase of one standard deviation in direct damages reducing output growth by around 9%. In developed countries, on the other hand, he finds an increase of less than 1%. GDP growth does not appear to be influenced by the number killed or affected by the event. Results are similar for using disaster occurrence. Discussed below, Noy finds no correlation between wind speed and growth; he notes this could be because it does not account for location and area covered by the storm, but also stresses the need for more work on exogenous disaster measures, as this is not what is found with the other measures.

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% of GDP. He takes an approach that differs from that of most other studies, developing a counterfactual projection of GDP 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 these severe disaster events for up to five years, with a median reduction in GDP of 4% 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, as well as lags. He does not address endogeneity except to note that with country fixed effects, the count measure is plausibly exogenous. 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. They simply assume that their measures are exogenous. 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.

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 severe disaster events greater than two standard deviations above the mean. 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% of GDP looking 18 months post-disaster. In contrast, they find that developing countries tend to follow a procyclical fiscal policy post-

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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% of GDP and government revenue rises 4.23% of GDP. Outstanding debt falls −0.72% of GDP.

This group of studies also 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 (Fomby et al., 2011; Hochrainer, 2009; Noy, 2009; Stephens, 2007). Note, that Noy (2009) finds no statistical impact of wind speed on output growth, but this could be due to the function form used and that it does not account for other measures of the storm, such as area and duration (see below for further discussion on the relationship of wind speed to damages). 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. Similarly, 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). 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).

4.1.2. Single-country studies

Some single-country studies take a subregion as the unit of analysis and proceed in a manner similar to 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 (Blundell–Bond). Noy and Vu find that deadly natural disasters are associated with 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%. 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 disaster with a 1% increase in the percentage of the population killed is associated with a fall in output of about 47 - billion Yuan (roughly US$ 7.4 billion). Increasing a disaster's direct damages by 1% reduces output growth by 0.24%; 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. The wind data is likely exogenous, increasing the confidence in results using this measure. 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 income of about 6.7%). 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, 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. This paper begins to shed light on some indirect effects of a disaster driven by how households absorb the income shocks. Post-disaster spending adjustments could have quite different overall welfare effects, depending on how they are distributed across expenditure categories, something worthy of more examination.

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. 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%), even when there is no effect on national-level macroeconomic indicators and the impact on state growth is netted out within one year. For hurricanes one standard deviation above the mean, growth is reduced by 0.93 percentage points. This impact disappears after one year. He finds that around 25% of the decline is from higher-income individuals moving out of the county post-hurricane. This paper provides some evidence of how demographic shifts can be related to larger economic impacts in the community—another interesting area for future research.

Deryugina (2013) also looks at the impacts of hurricanes on US 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 average earnings, but does find that the employment rate is lower five to ten years after the event and a negative impact on the construction sector, driven perhaps by a decline in housing starts. She also finds a substantial increase in nondisaster-related, government 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 fiscal impacts of disasters are larger than previously estimated without consideration of non-disaster programs by about three times; assuming dead-weight loss from taxation, these additional transfers have a cost. Deryugina argues that nondisaster payments may target individuals who are indirectly impacted by a disaster, whereas disaster aid targets those directly affected.

4.1.3. 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 dropped immediately following the hurricane, driven largely by a loss of rental income. Total employment was not impacted. 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. Construction employment increased but fell back to baseline sooner. 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 major effects of the disaster were distributional.

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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 include a measure of output from the beginning of the period and use 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%.

Ewing et al. (2003) examine the impact of a March 2000 tornado in Fort Worth, Texas, on local employment. The authors find employment growth lower in the two years after the tornado, but the response was heterogeneous. 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 (they find lower variance in the employment rate post-tornado for the manufacturing sector, for example, perhaps due to rebuilding).

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. Using EM-DAT data on droughts, floods, earthquakes, and storms, the authors develop an annual estimate of disaster intensity for each country. They separately examine different types of disasters, developing and developed countries, and agriculture versus nonagriculture sectors. The authors, like other studies, 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% 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.

Focusing instead on firm-level variables, Leiter et al. (2009) look at the impact of flooding on employment and asset accumulation of European firms two years post-disaster. 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 productivity declines after a major flood (the effect is decreasing in the amount of intangible assets). They also find 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.

Hsiang (2010) uses an exogenous measure of hurricanes—wind-field histories—to identify the impact of cyclones on economic impacts in various sectors of 28 countries in the Central America and the Caribbean over the period 1970 to 2006 (this is done to separate the impact of cyclones from the impacts of temperature, the main focus of the paper). He finds negative, short-run impacts in the agriculture, tourism, and mining sectors and a positive short-run impact in the construction sector. He finds that losses in the tourism sector persist for multiple years due largely to declines in the number of visitors at a statistically significant level out to the 3 years (declines in visitors from a trend of between roughly 1% and 3% a year and declines from a trend in total receipts of between 2.5% and 3.5%).

4.2. Long-run impacts

Although it is possible to develop models and plausible stories of how natural disasters could have long-term negative consequences, the empirical evidence is more limited and somewhat contradictory. 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. Three of the four studies found explicitly examining long-run impacts, however, find persistent and negative effects, at least for certain classes of events.

Skidmore and Toya (2002) find positive long-run impacts from climatic disasters. They couple historical disaster data for 89 countries with EM-DAT data. The authors regress average GDP growth (using ordinary least squares) on the total number of natural disaster events occurring in a country between 1960 and 1990 normalized for land area, a measure of historical disasters from 1800 to 1990, and a set of controls, including initial GDP. 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 measures of physical and human capital accumulation on disaster variables, 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.[13] 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% and in counties with a medium level of erosion decreased by 17%, relative to those with low erosion. He finds that the declines persisted, with only 14 to 28% of the values recovering over the long-term. Agricultural revenue also declined between 1930 and 1940, with around 70% 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. 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.

A working paper by Hsiang and Jina (2013) finds that tropical cyclones lead to a small suppression in annual growth rates and that this persists for longer than a decade, leading to more substantial cumulative impacts. They look at countries between 1950 and 2008 using an exogenous measure of cyclones: wind speed exposure and energy dissipation per unit area based on a physical model of all storms over

[13] The Dust Bowl is included here as a natural disaster 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.

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their time period. This measure had to be aggregated across storms within a country and year to match to the macroeconomic data. They estimate a first differences regression model including country and year fixed effects and country-specific trends in growth rates with spatially and temporally correlated errors. Various controls are added in robustness checks. They find that an extra meter per second of wind exposure decreases economic output by 0.38% two decades later and that this result holds for various subsets of countries and regions. Alternatively, a one standard deviation in cyclone exposure reduces GDP by 3.6% twenty years afterward, or almost two years of growth. This impact is most critical for countries repeatedly hit by storm events. Stronger events also have larger impacts.

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 has estimated the impact of flood risk on housing prices. These studies find a reduction in property values in the floodplain, sometimes larger than the present value of annual insurance premium payments (e.g., Bin and Polasky, 2004; Kousky, 2010a; MacDonald et al., 1990). 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 (e.g., Bin et al., 2008).

5. 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 (e.g., Cariaga, 2012; Hagenbaugh, 2004). These common accounts of positive economic impacts from a natural disaster often fall prone to what is referred to as the broken window 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 that they instead have to use for rebuilding.

This is 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. As another example, Baade et al. (2007) find 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.[14] 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 disasters generated net benefits when considered over a longer time period, a larger region, or when more sectors are included in the analysis. An early paper attempted to add up losses and external aid in an area hit by a hurricane to see if the transfers could outweigh the costs of a disaster for a specific community. For this case, the Alabama counties hit by the disaster did not benefit: the loss in assets outweighed outside assistance, much of which was not actually retained by the damaged communities (Chang, 1984). Finally, while many of the above-mentioned studies of GDP or GDP growth find negative impacts, some find positive impacts, at least in some time period (e.g., Albala-Bertrand, 1993; Jaramillo, 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.

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)), and suggested 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. 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 optimally undertaking upgrades of infrastructure before a disaster, such that post-disaster investments could create net benefits by inducing infrastructure upgrades that would have been justified even pre-disaster. I have not seen an empirical examination of this possibility.

The one empirical paper to look at 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.

6. Determinants of damages and fatalities

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. The potential for loss, or susceptibility of an area to loss, is often referred to as vulnerability. There is a distinct literature on this concept, emerging from the hazards and disasters research community. This work 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). These papers are generally not empirical economic research, and as such, are 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—mirror some of the findings discussed here (Burton et al., 1993).

The studies discussed here are focused at a country level and explore the hypothesis that institutional, political, and other national 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

[14] 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.

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could be higher. A more integrated economy can increase the multiplier effects of the initial damage from a disaster and countries with higher levels of 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. These studies may conflate vulnerability—the fact that certain factors make countries more susceptible to damage—and resilience—the ability of societies to recover post-disaster.

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. 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 will be underreported. No paper discusses the implication of this on findings.

In addition, many of these studies suffer from the same endogeneity problems discussed in Section 4, such as the possible reverse causality between GDP and damages. None of the EM-DAT based studies are able to control for disaster magnitude in the full sample as these data are frequently missing from the database. Most studies omit this as a control; whether and to what extent this influences results needs to be carefully examined. Given the potential endogeneity and lack of control for disaster magnitude, we need to use caution when interpreting these results. A related issue is the potentially high correlation between the various national variables used in these studies, as well as many plausible omitted variables that may bias results. These studies cannot distinguish between the various theories of what may be the underlying drivers in the observed correlations uncovered.

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 associated with any changes is long. 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.

6.1. 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 landlocked countries have fewer disasters when they regress the log of deaths on characteristics of the country, instrumenting for the number of disasters in the period. 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.

6.2. 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). For his instrumental variables model, he uses settler mortality risk as an instrument for institutional quality, but does not instrument the disaster measures. 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 (Gaiha et al., 2012; Raschky, 2008; Stromberg, 2007; Toya and Skidmore, 2007). Some evidence suggests, though, that the relationship may not be the same across hazards or countries. Examining specific hazards, Kahn finds that deaths from floods and windstorms are reduced the most by increases in income. Toya and Skidmore (2007) find that, in the Organisation for Economic Co-operation and Development countries, a 10% increase in income reduces natural disaster deaths by about 15%; in the developing country sample, the impact of income is still negative, but smaller in magnitude.

Kahn (2005) also found that fatalities were lower in countries with lower income inequality, democracies, and countries with higher-quality institutions. Other authors have extended this work, finding other variables that are predictors of fatalities. A summary of findings is shown in Table 2. Toya and Skidmore (2007) find that higher educational attainment levels, more openness, and stronger financial systems are correlated with 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).

Finally, there has been empirical examination of the role of natural systems in reducing fatalities.[15] Das and Vincent (2009) examine a 1999 Indian cyclone and find that wider mangroves were associated

[15] For more on the use of natural systems in hazard mitigation, see Kousky (2010b).

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Table 2
Summary of determinants of natural disaster fatalities.

Determinants of fatalities	Direction of significant effect	Source
GDP	↓	Kahn (2005), Stromberg (2007), Toya and Skidmore (2007), and Raschky (2008)
Income inequality	↑	Kahn (2005) and Stromberg (2007)
Presence of democracy	↓	Kahn (2005) and Gaiha et al. (2012)
Higher-quality institutions	↓	Kahn (2005) and Stromberg (2007)
Education	↓	Toya and Skidmore (2007)
Stronger financial system	↓	Toya and Skidmore (2007)
Wider mangroves	↓ for cyclones	Das and Vincent (2009)
Early warning system	↓ for cyclones	Das and Vincent (2009)

with statistically significantly fewer fatalities in their sample of 409 villages. This impact was significant only within 10 km of the coast and mangroves were found to be less effective with larger surges. They control for several potential confounding influences, such as distance to the coast, height of the storm surge (distinguishing it as one of the papers with physical control variables for disaster magnitude), topography, habitat suitability, and socio-economic variables. The coefficients on these controls indicate that early warning systems reduce fatalities. For readers interested in the role of natural capital in reducing disaster losses, there is a large modeling and scientific literature (biophysical modeling, field experiments) on this topic that is not reviewed here (see, for example: Gedan et al., 2011).

6.3. Damages

Two approaches have been taken in the literature to examine the determinants of disaster damages. The first mimics the literature just described on the determinants of disaster fatalities, and the second attempts to predict disaster damages from physical variables. We begin with the former approach; findings are summarized in Table 3.

Much of this literature focuses on the role of GDP and potential nonlinearities in the relationship between GDP and disaster damages. 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, using a negative binomial model on a set of 133 countries, 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 that 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 a worthy investment, and damages from disasters then 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, 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 capita 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.

Although this paper does not review qualitative case study papers, such examinations can help interpret the findings of the econometric studies. These case studies often show that 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 are also a

Table 3
Summary of determinants of natural disaster damages.

Determinants of fatalities	Direction of significant effect	Source
GDP	↓; U-shaped; inverted U-shape; depends on risk	Kahn (2005), Toya and Skidmore (2007), Noy (2009), Kellenberg and Mobarak (2008), Raschky (2008), and Schumacher and Strobl (2011)
Education (various measures)	↓	Toya and Skidmore (2007), Blankespoor et al. (2010), and Noy (2009)
Openness	↓	Toya and Skidmore (2007)
Higher-quality institutions	↓	Noy (2009)
More domestic credit or higher reserves	↓	Noy (2009)
Higher exports as a percentage of GDP	↓	Noy (2009)

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.

The second group of papers estimates 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 could be due to structures or infrastructure having thresholds where damages go from minimal to severe. He finds that damages have been increasing over time, rising by about 3% per year. Nordhaus also uses these results to predict future damage from hurricanes under climate change. He does not include institutional or economic covariates to compare with the above studies.

Mendelsohn et al. (2011) also examine hurricanes in the United States, but over more recent years—1960 to 2008—and using data on insured and uninsured property losses and infrastructure losses. They 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, however, this does not mean that these factors are negligible. They used inferred values for years between Census data points; this could be introducing error into these results. Finer scale data on these variables may be needed to detect their influence. Like Nordhaus, they couple their results with climate predictions to project changes in damages under climate change.

Examining the Philippines, Anttila-Hughes and Hsiang (2011) also find that 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%. They also find that an average wind exposure equates to a 1.9 to 2.7% probability of asset loss (excluding cars) for a household. Hsiang and Narita (2012), discussed further below, find that increasing wind speed by 1 m s^{-1} increases normalized damages by 10% in a pooled cross-section of countries between 1950 and 2008.

Pielke and Downton (2000) examine which precipitation-related variables best predict direct economic damages from riverine flood events in the United States over the period 1932 to 1997. They examine total damages, damages per capita, and damages per unit wealth. They find that the number of 2-day heavy precipitation events is one of the best predictors for all three, along with a year trend variable for total damage and damage per unit wealth and along with the number of wet days per weather station for per capita damage. The link between precipitation and flood damage is mediated by many factors, such as antecedent conditions, flood protective structures, and exposure. This partially explains the large amount of variance that their models cannot explain, along with non-linearities that they do not identify.

7. Risk reduction and adaptation

The negative impacts of disasters can be blunted by the adoption of risk reduction measures. 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. To estimate future climate change damages, however, some estimate of the likely extent of adaptation to changes in extreme events is needed.

Predicting what adaptation will take place as disaster risks change, however, is difficult. Similar to 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, it is possible to look at differences in disaster mitigation across areas facing different risks today as an indication of how adaptation will change as disaster risk changes. Hsiang and Narita (2012) examine the ability of countries to adapt to tropical cyclones by looking for different damages or fatality impacts from physically similar cyclone events across countries with different exposure to cyclones. They define exposure using physical measures of the storm: maximum wind speed during a given year and total energy per unit area dissipated by all storms. 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. Neumayer et al. (2012), in a working paper, take a similar approach, arguing that countries more prone to disasters will invest more in mitigation and that this will be more pronounced for the worst events. Using quantile regression at a country-year level over the period 1980 to 2008, and with unique access to data from Munich Re, the authors find evidence that damage is lower in the upper quantiles when a country's propensity (expected frequency and magnitude of hazards occurring) for tropical cyclones or floods is higher.

Anttila-Hughes and Hsiang (2011), in their study of the Philippines, examine the extent to which losses from typhoons vary with typhoon climatology. They find, as evidence of adaptation, that the marginal effect of typhoon exposure decreases with increases in the intensity of the typhoon climate. Specifically, they estimate that marginal losses fall by less than 3% with each 1 m s^{1-} increase in wind speed. Of note, however, average losses are still high, even when adaptation appears high.

Two papers take this same general approach but focus on heat waves. Southern and western US 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 US 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 US cities under climate change.[16]

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 state-by-year fixed effects (county fixed effects for mortality). 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%. 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% and an increase of 11% in energy consumption to help protect against weather extremes.

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

Adaptation will, of course, also depend on political will. Even when risk reduction 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-probability 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 on 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 an event which could spur mitigation, finding some suggestive evidence that the occurrence of a hurricane in the past 10 years that covered at least half of the current storm's 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 taken after the first event (Palecki et al., 2001).

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 were 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.

8. Future research needs

This review has suggested several remaining gaps in the empirical literature that warrant further research. First, as previously discussed, more work is needed that explicitly addresses endogeneity concerns. One approach is the search for possible instruments. Another, and which has been pursued by several papers recently, particularly with hurricanes, is to use physical measures of a disaster, such as wind speed. Noy (2009) has suggested the creation of an index of disaster intensity, but notes that collecting data from primary sources to create such an index for multiple hazards and countries would be a significant undertaking.

There are some gaps in the literature that may be difficult to fill due to limited data. 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 studies have empirically estimated indirect damages from disasters. This is an area in need of much more investigation. Similarly, very little work has evaluated nonmarket impacts of disasters. Finally, more empirical work on the economic impacts of shifts in post-disaster spending, altered risk perceptions, demographic shifts, or political changes, would be intriguing to pursue. Without comprehensive data sets, however, all such work will most likely have to be in the form of disaster-specific studies and then general findings drawn by looking across many empirical case analyses.

The empirical work on adaptation to potential changes in extreme events is quite small. More studies like those profiled in Section 7, which compare current risk reduction investments for different levels of risk, could help inform the extent of adaptation that is possible. In addition, there is a dearth of studies investigating the extent to which there is an adaptation deficit—that is, are we not even currently adapted to today's climate everywhere, let alone future climate? 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.

Finally, this review has limited itself to empirical studies of the economic impacts of weather-related disaster events. Parallel reviews of modeling studies, engineering estimates, case studies, and impacts of disasters on socio-political and health outcomes would be useful complements to this work.

9. Conclusion

Several devastating weather events since 2000—including the 2003 European heat wave, the 2004 Indian Ocean tsunami, Hurricane Katrina in 2005, the 2010 floods in Pakistan, and Hurricane Sandy in 2012—have spurred renewed interest in natural disasters. In the United States, 2011 saw a surge in media attention to disasters as many extreme event records were broken and a string of disasters all exceeded $1 billion in estimated 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 and tsunami in Japan.

Estimates of the average annual cost of weather-related extreme events since 2000 range between $94 billion and over $130 billion. Estimates of the full range of economic costs of disaster events, however, are limited by the lack of complete and systematic data worldwide, or even within countries. All data sets underestimate indirect losses, if they are included at all, and none include nonmarket impacts or costs to informal sectors of the economy. Damages do 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 many natural disaster events have a relatively modest impact on output and growth and which disappears fairly quickly. The impacts are larger for more severe events, however, and some recent papers suggest that natural disasters, particularly severe ones or multiple events, can have very long-term negative consequences. Impacts on macroeconomic variables are also more negative for smaller geographic areas 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 and sectors being hard hit, and others even benefitting from the reconstruction after the event.

Disaster losses have been increasing over time and there is some evidence that climate may be beginning to contribute to this trend, which was historically driven by increased value in high risk area—at least for certain hazards in certain areas. The work on the historical cost of disasters can be integrated with climate projections to begin to get some estimates of how damages may respond as the climate warms. Including adaptation in this work is more challenging. Some studies reviewed here have begun to examine how areas with different risk levels have invested differentially in hazard mitigation. Such studies, however, fail to account for timing of adaptation or separate measures that can be done in the short-term versus those that can only occur over a longer time span (such as substantial changes in development patterns). It is also difficult to capture how much hazard mitigation will be spurred by the salience of disaster occurrences or by the increasing attention being brought to them in the context of climate change.

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