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The Double-Edged Sword of Learning from Disasters:

Mortality in the Tohoku Tsunami

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Abstract

Learning from natural disasters is predominantly regarded as beneficial: Individuals and governments learn to cope and thereby reduce damage and loss of life in future disasters. We argue against this standard narrative and point to two principal ways in which learning from past disasters can have detrimental consequences: First, investment in protective infrastructures may not only stimulate settlement in hazard-prone areas but also foster a false impression of security, which can prevent individuals from fleeing to safe places when hazard strikes. Second, if disaster events in the past did not have catastrophic consequences, affected individuals do not take future events sufficiently seriously. As a consequence, learning from disasters is a double-edged sword that can prevent large scale damage and human loss most of the time but results in the worst case scenario when a disaster occurs at an unexpected scale and public preparedness measures fail. We demonstrate the devastating impact of misplaced trust in public preparedness measures and misleading lessons drawn from past experience for the case of the 2011 Tohoku tsunami. Our paper contributes to the literatures on 'negative learning' and 'hazard maladaptation' by demonstrating that a lack of past experience with tsunami mortality in a municipality substantively increases mortality in the Tohoku tsunami.

Man has three ways of learning. First, on meditation; that is the noblest. Secondly, on imitation; that is the easiest. Thirdly, on experience; that is the bitterest.

Attributed to Confucius, cited in Lee and Jones (2004, p. vii)

1. Introduction

The 2011 Tohoku tsunami that affected the entire East Coast of Honshu, Japan's main island, raised two questions: Why did so many people die during the event despite Japan's experience with tsunamis that should have resulted in sufficient disaster preparedness to avoid most of the deaths? Why did the Tohoku mortality vary widely between municipalities? The first question attracted much more attention in the media and among social scientists studying the social causes of disaster vulnerability than the second question. We develop an integrated answer to both questions arguing that local governments and affected citizens believed too much in infrastructural protection – tsunami walls and shelters – with the consequence that large parts of the affected population stayed close to the shore watching the incoming tsunami rather than fleeing inland or seeking to reach higher grounds.

Our article contributes to the growing literature on 'learning from disaster'. Many social scientists believe that natural disasters offer a window of opportunity for individuals and policy makers to learn and better adapt to natural hazards (Birkmann et al., 2010). For example, Lee and Jones' (2004) treatise on landslide risk assessment and Malone and Ho's (1995) analysis of learning from landslip disasters in Hong Kong both summarize the advantages of learning from previous disaster events. The dominant view is that at worst the lessons of disasters are ignored while at best learning from disasters leads to better adaptation or even prevention (Jasanoff, 1994).

Our analysis of mortality during the 2011 Tohoku tsunami in Japan challenges this optimistic view. Like others before us, we draw attention to the fact that learning from natural disasters has consequences that do not need to be beneficial (e.g., Oppenheimer et al., 2008; Meyer, 2011). We rely on a Bayesian concept of learning, in which the perceived probability that a tsunami is dangerous depends on priors which are updated when new relevant information occurs. Our definition is consistent with, but not identical to Oppenheimer et al.'s (2008, p. 158) definition of learning as “change in any aspect of the uncertainty of an outcome occurring as a result of theory development, modelling, observation, or experiment. Uncertainty (...) refer(s) to imprecision in the characterization of any outcome. An outcome is any quantity, process, or structure.” We argue that so many people died in this catastrophe *because* Japan is arguably the country in the world best protected against tsunamis, not despite of it. This clearly sounds counterintuitive, but in our interpretation, the Tohoku mortality was so high because governments and affected citizens' behaviour was influenced by having experienced previous, much weaker tsunamis. Japan was well protected for frequent tsunamis of medium to large sizes, but the Tohoku quake and therefore the tsunami were much more powerful than deemed possible before. Learning can indeed result in maladaptation defined as “action taken ostensibly to avoid or reduce vulnerability that impacts adversely on, or increases the vulnerability of (...) social groups” (Barnett and O'Neill, 2010, p. 211-212).

Our main contribution to the literature is, however, not at this aggregate level. Instead, this article takes the idea of maladaptation to natural hazards one step further by providing evidence that its extent depends on local experience. We are the first to argue and provide evidence that the suboptimal behavioural response to the tsunami – staying close to the coastline rather than fleeing inland or uphill – was more likely to occur in

municipalities that previously did not suffer significant tsunami mortality. Learning from disasters – defined as change in the adaptation to disaster risk based on new information and perceptions that facilitate behavioural changes – thus may have different consequences, depending on whether learning is supported by local history. The notion that tsunamis are truly dangerous is likely to have been more pronounced in municipalities which had experienced previous tsunami mortalities during living memory. In municipalities that did not suffer significant tsunami mortality in the recent past, public disaster prevention policies were more likely to provide a sense of safety which becomes potentially dangerous when the strength of a disaster exceeds the expected. We interpret our results as evidence for the preponderance of adaptive learning. As is well known, such learning is not entirely rational but all too human (Meyer, 2011). It results in what De Vries (2011a; 2011b) has dubbed “time vulnerability” or “temporal vulnerability” of affected individuals. In our case, the misleading experience of having escaped fatal tsunamis in the past lures individuals into the belief that the next experience is not going to be disastrous either.

We organise our argument as follows: We start by summarizing the case for beneficial learning from natural disasters. Understanding this narrative is important for appreciating why learning can have detrimental consequences instead. We then briefly review maladaptation to natural disasters in general before discussing how learning from relatively milder tsunamis resulted in a state of maladaptation for the much more powerful 2011 Tohoku tsunami and a surprisingly large aggregate death toll. The then following section presents our core contribution to the literature. We undertake a quantitative analysis of mortality across the 88 municipalities that experienced a run-up of water of at least one metre high to study what effect historical experience with

tsunamis at this local level had on the number of deaths during the extreme hazard event of the 2011 tsunami.

2. Beneficial Learning from Natural Disasters

Social scientists argue that governments and citizens have learned three important lessons and that these lessons reduce disaster mortality (Kahn, 2005; Anbarci et al., 2005; Neumayer and Plümper, 2009; Neumayer et al., 2014). First, disaster prevention and mitigation is possible. Second, mitigation suffers from collective action problems that can best be solved by public disaster preparedness policies. Yet, and this is the third lesson, knowledge that public policies are required does not automatically imply that governments invest sufficiently in these policies. Governments are more likely to act if citizens can hold them accountable for insufficiently protecting them from the impact of disasters, if governments are responsive and have sufficient financial resources at their disposal.

Until the age of enlightenment, humans perceived natural disasters as acts of god or gods and thought that disasters either are a punishment for humans' sins or instruments chosen by gods to remind humans of the superiority of gods. Where disasters are perceived as acts of god, disaster prevention appears to be futile at best and – at worst – may trigger the wrath of gods. Indeed, investment in disaster prevention and mitigation requires faith in the effectiveness of these measures.

Over time, the interpretation of natural disasters shifted further and further toward human responsibility. Disasters stopped being an act of nature, let alone an act of god, over which human beings exert no influence. According to Ted Steinberg (2013), “calling a disaster an (...) *act of nature* is a distraction. It is a result of poor planning and

a lack of preparation.” The World Bank and the United Nations reach the same conclusion. As a recent study by the organizations suggests, “death and damage do not primarily result from geological hazards” (World Bank and United Nations, 2010, p. 1). Instead, disasters are acts of “omission and commission” (ibid.) with the World Bank concluding that “disasters expose the cumulative implications of many earlier decisions, some taken individually, others collectively. (...) Prevention is possible (...) [though] many measures – private and public – must work well together for effective prevention.” (World Bank and United Nations, 2010, p. 1-2). In other words, natural hazards do not need to turn into disasters and they are more likely to become disastrous if people are exposed to the hazard and vulnerable to its impact (Oliver-Smith et al., 2012; Schumacher and Strobl 2011), i.e. are not resilient to fully absorbing the impact without damage to life or property (Schwab et al., 2007; Paul, 2011). Hazard adaptation is often constrained by existing entrenched practices. For example, individuals tend to respond to hazards in a way that enables them to continue practices which are however unsustainable in the longer term (see Barnett and O’Neill, 2010; O’Neill and Handmer, 2012; Bohensky and Leitch, 2014).

What we call natural disasters are therefore in fact disasters allowed for or at least exacerbated by human action. True, some hazards are completely unforeseeable or so extreme that no human action could prevent them from turning into disasters. For the most part, however, hazards only turn into disasters where humans have made insufficient efforts at prevention, mitigation, preparation and adaptation. Humans are not just victims but directly influence the social and economic consequences of natural disasters through their decisions. Therefore, learning from past disasters, understanding their causes and consequences in order to prevent or mitigate against future disasters is the main influence on disaster mortality that humans can exert.

Individuals can best avoid natural disasters by not settling in areas and regions that have a high disaster propensity. This is sometimes impossible and where possible is usually unattractive since properties and land in high-risk areas are either cheaper or settlement in such areas provides extra amenities such as access to the sea or an undisturbed view of the coastline. Also, often governments not only allow but positively encourage settlement in such areas and regions, either directly or by allowing or encouraging property developers whose profits depend on individuals moving there. Despite this collusion by public authorities, which prevents the first best solution to preventing disasters – or perhaps exactly because of this collusion – second-best disaster prevention typically requires the solution of collective action problems. At the very least, collective disaster mitigation measures are more efficient and often more effective, too. Private individuals underinvest in disaster mitigation for three main reasons. Firstly, such measures are costly. For examples, earthquake-proof construction increases the building costs by at least 10 per cent (Kenny, 2009), and a private dyke around the property or an artificial building elevation is very expensive. Secondly, many individuals neglect or ignore the probability of disasters altogether (Hough, 2010), consistent with more general evidence that individuals often ignore potential impacts that come with very small probability, unknown size and unknown timing (Camerer and Kunreuther, 1989; Kunreuther, 1996; Meyer, 2011). Thirdly, some of the devastation will affect not individuals directly exposed, but others in the wider sub-national region or even the entire country. Large-scale disasters cause significant collateral damage and macroeconomic distortions that impact the wider population (Lall and Deichmann, 2010; Hallegatte and Przyluski, 2010; Hallegatte 2012). Only governments can internalize these costs that private individuals will ignore.

Governments can tax citizens and can therefore easily overcome and resolve collective action problems and provide public goods. There is little doubt that by implementing a full battery of public disaster prevention, mitigation, preparation and adaptation measures (called public disaster preparedness policies for short below), governments can minimize loss of lives and economic damage if a hazard strikes. A loss minimizing political response to disaster risk would optimize policies on various levels: land-use plans that prevent settlements in high risk areas, public investment into dams and tsunami walls, public investment in rescue infrastructures such as shelters and early warning systems, publicly funded disaster response training, a clear and easily understandable communication of risk together with training on appropriate adaptive and responsive behaviour, strict regulations for public and private buildings and infrastructure, and public investment in emergency services and their technology.

In sum, human beings have learned that not the occurrence of natural hazards but their consequences are strongly influenced by human impact, that disaster preparedness measures are best and most efficiently organized at the societal level, so that governments and public administrations become the obvious agents for financing, providing, regulating, implementing and enforcing disaster preparedness measures.

Empirical studies support the case for the beneficial effects of learning from disasters. In Keefer et al. (2011) we show that earthquake propensity – being located on very active fault lines and therefore experiencing frequent earthquakes – reduces earthquake mortality in a global sample, holding the strength of quakes and population density constant, while in Neumayer et al. (2014) we demonstrate that higher disaster propensity also reduces economic damage from the top three disaster types, namely earthquakes, floods and tropical cyclones, which together account for roughly 70

percent of total worldwide economic damage from natural disasters. Similarly, Hsiang and Narita (2012) find that countries frequently hit by tropical cyclones experience lower human and economic loss. The experience of hurricane landfall in the recent past lowers subsequent hurricane damage in US counties (Sadowski and Sutter, 2008). Individuals and, more importantly, governments learn from past disasters to invest in disaster prevention, preparedness, mitigation and adaptation. Brody et al. (2009) point toward improvements in local flood mitigation policies after historical flood events in Florida. Conversely, very little beneficial learning seems to take place where disasters are rare events (Schad et al., 2012) or happen only at the very local level (Voss and Wagner, 2010).

There is therefore ample empirical evidence to support the view that private and public agents have learned how to reduce disaster mortality and economic damage. Yet, that disaster preparedness measures work well on average does not mean that they reduce the number of fatalities in all cases. In fact, in some cases learning from past disasters can prove disastrous and can severely increase the death toll, as we will show in the remainder of this article.

3. Maladaptation to Natural Disasters

Against the standard narrative of beneficial learning from natural disasters, some have argued that learning from natural disasters need not be unambiguously positive. Bohensky and Leitch (2014) show for the case of the 2011 Brisbane flood that much of the potential for learning with long-term beneficial and lasting impact was lost by focusing on attributing blame and exploiting political opportunities. Colten and Sumpter (2009) and Colten and Giancarlo (2011) point towards insufficient incorporation of historical lessons learned into hazard planning in New Orleans and the Mississippi Gulf

Coast. Meyer (2011) provides a detailed account of a whole range of behavioural biases that result in both public and private agents always and inevitably under-preparing for hazards.

Given the over-riding importance of public disaster preparedness policies, the quality of governance arrangements and the resource constraints governments face will impact on whether and to what extent actual governments follow a loss-minimizing strategy. Responsive and accountable governments spend more on disaster protection and mitigation measures than less responsive and less accountable governments. Even the allocation of food aid after and during disasters is more efficiently organized when governments strive for voters' support and re-election (Neumayer and Plümper, 2009). Richer societies are not per se protected from natural hazards, but richer societies build to higher standards, invest more in protective infrastructure, and can more effectively provide medical and food aid and clean drinking water after the disaster has occurred (Kahn, 2005; Anbarci et al., 2005).

One problem of the reliance on public protection measures is that individuals may not fully appreciate that, ultimately, no government investment in disaster preparedness policies and infrastructures will withstand all hazards. Governments face budget constraints and they need political support of the population to win elections. They therefore do not only have incentives to provide publicly visible disaster preparedness measures, at the same time they also face strong incentives not to invest 'too much' in these measures. Politicians cannot predict the future and therefore can neither know the timing nor the magnitude of coming disasters. Governments therefore need to choose the level of disaster mitigation policies under uncertainty. Naturally, this leads to political conflict about the optimal response. A compromise will be struck between

those who want to invest heavily in protection measures even though the economic and, potentially, the political costs will be high and those who believe that no major disaster will occur in the foreseeable future and disaster preparedness measures can remain modest. For example, the Netherlands is known to take a very precautionary stance, whereas the United States is known to take a much more risk-taking approach with respect to coastal flood protection (Hillen et al., 2010).

As a consequence, governments implement disaster preparedness policies which withstand some and perhaps the majority of hazard events, but they will never provide protection against all, or even the stronger hazards. Not even democratically elected, responsive and accountable governments in high-income countries and high disaster propensity locations will be willing to invest in policies that provide full safety from natural disasters. In addition, even if they wanted to it is difficult for policy makers to provide early warning systems and infrastructures that are guaranteed to protect the population from disaster. What is safe for 99 per cent of hazard events can fail when the 'big one' arrives, a hazard event that is either so large or so complex in its various dimensions that normal adaptive and protective measures prove hopelessly inadequate – see O'Neill and Handmer (2012) for the analysis of such a scenario for the 2009 'Black Saturday' bushfires in Australia that killed 172 civilians and resulted in damage of over \$3.5 billion.

Learning from disasters is therefore a double-edged sword: On the one hand, such learning increases public investment in infrastructures that protect and thus mitigate against the forces of nature and may improve adaptation to natural hazards and more appropriate reaction of affected people on an individual level. On the other hand, public and private investment into such infrastructures and the installation of early warning

systems not only encourage additional settlement in high-risk areas such as floodplains, the fault lines of tectonic plates, and low elevation areas near the coastline (Collenteur et al., 2015) but also stimulate a false notion of safety. Public safety measures may thus lure individuals into imprudent behaviour when hazard strikes. As Adger et al. (2013) conceptualize the issue, the extent to which individuals themselves undertake protective measures depends on the extent of protective public measures, which in turn forms part of an implicit social contract between individuals and the government. The problem is that the more individuals believe in the protection provided by public measures the less they will do individually. In the worst case, affected individuals delay leaving the endangered area or even stay in high-risk areas to watch the build-up of the disaster. As Barnett and O'Neill (2010, p. 212) have observed: "Adaptation strategies may increase the vulnerability of (...) groups if they (...) reduce incentives to adapt."

4. Evidence of Maladaptation For the Tohoku Tsunami

One cannot say that Japan was ill-prepared for tsunamis. In fact, Japan is arguably the world's best prepared country. Japan's modern disaster preparedness policies rest on four pillars: i) a strict building and construction code which is regularly updated and strengthened, ii) a rigorous earthquake drill system in schools and public and private institutions, iii) a sophisticated early warning system, which relies on sensors that record all seismic activities on the islands and off-shore, and iv) a sophisticated system of earthquake- and tsunami-resistant shelters, floodgates and tsunami protection infrastructures, including breakwaters, vertical concrete flood walls, compacted earth tsunami barriers, and sluice gate structures, among others (Chock et al., 2013), which we often simply refer to as walls in the following. With the exception of the building and construction regulations and the early warning system, these policies are

implemented, financed, and administered at the prefecture level (World Bank, 2012). Prefectures invest in tsunami walls and shelters, they finance public hospitals, and they organize annual earthquake drills.

Given the standard narrative of beneficial learning from past disasters and given that Japan seemed well prepared, how can it be that almost 16,000 people died and another 2,500 people went missing (http://www.npa.go.jp/archive/keibi/biki/higaijokyo_e.pdf) in a country whose central and local governments invested more than any other country into public disaster preparedness policies? The answer is that these very same public disaster preparedness policies resulted in maladaptation for the Tohoku tsunami: a false sense of security that reduces or even eliminates the incentives of individuals to take the right actions when an unexpectedly large hazard strikes.

The strength of the event when it occurred on Friday 11th March 2011 took the population and the public authorities by surprise. The Tohoku quake was an event of magnitude 9.0 on the Richter scale – the strongest earthquake ever recorded in Japanese history. According to Takeshi Koizumi (quoted in <http://www.telegraph.co.uk/news/worldnews/asia/japan/9920042/Tsunami-two-years-on-Japan-finally-gets-warning-system-that-would-have-saved-hundreds-of-lives.html>), one of JMA's senior coordinators for international earthquake and tsunami information, the JMA "had not expected a 9-plus magnitude earthquake." The major tremor stroke at 14.46 JST and had its epicentre at 38.322°N and 142.369°E, which is a point approximately 70 kilometres off the Japanese East Coast. The quake lasted for six minutes. It triggered a tsunami which first reached the Japanese East Coast at 15.12 JST. The JMA quickly responded to the seismic information it received and issued an earthquake and tsunami warning three minutes after the earthquake at 14:49 JST. The

first warning severely underestimated the height of the run-up waves. It rated the expected tsunami as "major" – the highest scale – but predicted that the tsunami would only reach 6 meters in Miyagi, 3 meters in Iwate and Fukushima, and 2 meters in Ibaraki and Chiba prefectures. The first warning was modified 25 minutes later, at 15:14 JST. In the updated warning, the JMA corrected the estimates tsunami height to 10 meters for Miyagi coast and to 6 meters for Iwate and Fukushima.

It was not before 15:30, however, that the JMA's tsunami predictions became reliable. At this time, the forecasts were based on global seismic data which indicated a much larger earthquake and therefore much higher waves (Japan Meteorological Agency, 2013). In actual fact, the tsunami reached a height of up to 10 meters. Much more important than tsunami heights are run-up heights, however, that is, how far above sea level the turbulent surge of water choked with debris rises when it reaches the shore. Run-up heights in Chiba, Fukushima, Ibaraki, Iwate, and Miyagi reached 8.13 meters, 21.01 meters, 9.65 meters, 40.57 meters, and 34.74 meters, respectively.

Post-disaster investigations identified five important flaws in the JMA's early warning system and in other public preparedness measures:

First, initial estimates of the earthquake were imprecise, but the JMA calculated and published the resulting tsunami height as if the predictions had been precise. Since the quake was stronger than initially assumed, the actual wave height was underestimated. This problem was exacerbated by the fact that historically JMA's warnings tended to suffer from the opposite problem: predicting higher waves than occurred, "thus creating a misperception that an actual tsunami would always be much smaller than the one predicted by official warnings" (Hasegawa, 2013, p. 19). Second, the highest scale 'major tsunami' already begins at fairly low levels and the label 'major tsunami' does not sound

urgent enough. 'Potentially devastating' would have been a better name for the highest category. Third, tsunami warnings are issued in 'estimated wave heights' which may fall dramatically short of run-up heights. Given tsunamis are very low frequency events, it is unclear whether Japanese individuals have learned the difference between tsunami height and run-up height, including the fact that run-up heights can exceed wave heights by factor 4 or 5. Fourth, in many municipalities public loudspeakers were used to disseminate the tsunami warning but the earthquake destroyed these in some municipalities, leaving individuals to learn about the event via other means (Hasegawa, 2013, p. 16). Of course, given that the first warning was potentially misleading, it remains unclear whether not being informed about the expected wave height was an advantage or a disadvantage. Fifth, Japanese municipalities frequently conduct evacuation drills, which seek to train the behaviour after earthquakes. A central element of these drills is evacuation to pre-defined gathering points. These points are safe from collapsing buildings, thus optimised for the low frequency event of earthquakes, but not optimised for the very low frequency event of tsunamis. In many affected municipalities, evacuation points were close to rivers and therefore prone to flooding. While the earthquake destroyed a few buildings, most infrastructures remained intact and were only destroyed by the tsunami. Likewise, only few were killed by the earthquake itself – the tsunami killed the vast majority of victims (Hasegawa, 2013, p. 16).

It is not possible to estimate the mortality impact of the Tohoku tsunami in the counterfactual scenario of the JMA immediately predicting the correct height of the tsunami at 10-15 meters in most coastal parts and run-up heights of up to 40 meters. In most prefectures, the time until the tsunami washed over the tsunami walls would have allowed the vast majority of people to flee far enough inland or to higher ground to be safe. What proved fatal for many, however, was not the JMA's initial flawed tsunami

warning as such, but its combination with the existence of tsunami walls and shelters which tempted many citizens into staying close to the coast, watching the incoming wave, taking pictures and shooting short movies with their cell phones instead of fleeing further inland or to higher ground. According to an official study published by the Japanese government in August 2011, only 58 per cent of people tried to reach higher ground in Miyagi and Fukushima (Oskin, 2015). Another study into the post-Tsunami disaster evacuation points the finger squarely at the moral hazard problem that comes with Japan's otherwise outstanding disaster preparedness policies (Hasegawa, 2013, p. 15-16):

“[T]he fact that these coastal towns had 5–10 m breakwaters built along the coast for protection against the inflow of tsunami waves further delayed the residents’ decision to flee. One evacuee from Ofunato City said: ‘When I first heard a tsunami warning for 3 metres, I thought that it would be all right because the breakwater in our town is higher than that.’ (...) In reality, the tsunami that hit the three prefectures had a 10–15 m mean inundation height and a 40 m run-up height in some places. (...) As a result, despite the early tsunami warning, many residents were caught by surprise when the actual tsunami arrived.”

With the predicted wave heights of the tsunami warning being too low, the walls and shelters lured many staying behind believing the wall would shield them and, failing that, the shelters would be safe. Often, neither was the case. A good example for this is the municipality of Kamaishi, a hilly city in which rescue would have been possible if only all citizens had chosen to run uphill. Instead, many stayed behind expecting that its

tsunami breakwater system, completed only three years prior, would provide adequate protection (Onishi, 2011b). For 884 of its inhabitants that expectation proved fatal.

A similar problem arose from public zoning of areas supposed to be of low or no risk of inundation. Many municipalities had hazard maps in place that marked out zones at risk and on the basis of which evacuation drills were organised. These maps were based on learning from past tsunamis but hugely underestimated the areas at risk for a mega-event like the 2011 tsunami. The maps left those residing outside the apparent risk zones in a false sense of security and in the belief that there was no need for evacuation when the tsunami warning came (Hasegawa, 2013, p. 18).

The Tohoku tsunami amply demonstrates the double edged sword of learning from past disasters. On the one hand, learning can be argued to have been beneficial. The early warning system that Japan has in place is the learning consequence from previous disasters and if we compare the actual tsunami warning to a situation without any warning, the warning definitely saved lives. One of the reasons for the extremely large death toll of the 2004 tsunami in the Indian Ocean was that there were either no or very poor early warning systems in place. Similarly for the system of tsunami walls and shelters: In comparison to a situation in which no tsunami wall existed *and* no warning was issued, the walls saved lives.

Yet, on the other hand, these learning achievements from past disasters at the public sector level resulted in maladaptation at the individual level: the worst case occurs when people feel safe behind and inside protective infrastructures that eventually fail. The existence of tsunami walls and shelters in combination with the underestimation of the wave height by Japan's Meteorological Agency strongly exacerbated the tsunami death toll. Not only public disaster preparedness policies can induce a false sense of

security; misleading individual experiences can also contribute to the impression of a lack of urgency and delay or prevent adequate individual responses. Just like government agencies were taken by surprise by the strength of the natural hazard, many individuals too were not prepared for the 'big one'. People living on Japan's East Coast had no experience with earthquakes and tsunamis of the Tohoku magnitude. All tsunamis they had experienced over their lifetime were smaller, and often much smaller. If the next event is significantly bigger than previous ones, reliance on the seeming safety of public measures becomes dangerous. Yet, in the next section we will provide evidence that the experience of tsunamis having killed people in the relatively recent past in some affected municipalities has had a mitigating impact on mortality in 2011.

5. A Promoter of More Successful Disaster Adaptation: Prior Experience of Fatalities

We now turn to the heart of our contribution to the literature on learning from natural disasters. Whilst maladaptation resulted in a surprisingly large death toll from the 2011 Tohoku tsunami in the aggregate, what explains variation in mortality across affected municipalities? Specifically, what are the conditions of more successful adaptation?

This section demonstrates with the help of a quantitative analysis that municipalities which had previously experienced actual tsunami mortality – even if this tsunami struck many decades ago – suffered fewer fatalities in 2011 than municipalities which had experienced previous tsunamis that remained moderate and did not take lives. This finding is in line with our argument that experiencing past tsunami mortality reduces the dangerous belief that tsunami walls and shelters provide sufficient protection from tsunamis. We also show that the experience of waves of several metres height in the past without fatalities did not result in systematically lower mortality in 2011.

Our unit of analysis is the municipality and our measures of experience that individuals living in a municipality will have had, and from which they could have learned, refer to the tsunami experience in these municipalities since the last major tsunami hit Japan in 1933. There have been other more minor tsunamis but the one from 1933 was the last major one and the only major one in living memory, i.e. the only one that some people who were still living in 2011 had personally experienced. The next major tsunami further back in time occurred in 1896.

Our first measure of past experience is the maximum wave height of previous tsunamis on the shore of the municipality. Ideally, we would have liked to use information on run-up height rather than wave height for historical tsunamis but unfortunately this more directly relevant information has far too many missings for historical tsunamis. Only for the 2011 tsunami is there almost complete information on run-up heights. Our second measure is the sum of people that died in a previous tsunami in that municipality. A sum total of 3,100 people have died from tsunamis since 1933 in the municipalities in our sample. Our two measures of past experience are correlated with each other but not very strongly ($r = 0.35$).

We analyze Tohoku tsunami deaths per municipality. There are 1,741 municipalities in our municipality shapefile of 2015. We are interested in municipalities where people could have plausibly been killed by the Tohoku tsunami and therefore we eliminated all municipalities with run-up heights below 1 metre. That leaves 88 municipalities with a record of 15,392 deaths in 2011. Our results are robust to restricting the sample to municipalities which experienced even higher run-ups of above 2.87 metres, which is the lowest run-up height in municipalities where people actually died in 2011.

We obtained run-up information for tsunamis in Japan from the National Geophysical Data Center/World Data Service Global Historical Tsunami Database (NGD/WDS) (http://www.ngdc.noaa.gov/hazard/tsu_db.shtml). For each run-up, the database includes, among other characteristics of the specific overland flow, geographical coordinates, maximum water height above sea level (run-up height), distance from source (the epicentre of the quake), and most importantly, casualties. The coordinates of each run-up were assigned to a municipality using the boundary shapefile from the Global Map Japan version 2.1 at the Geospatial Information Authority of Japan (http://www.gsi.go.jp/kankyochiri/gm_japan_e.html). The run-ups that could not be assigned to a municipality polygon in this way were matched to municipalities manually for cases with tsunami-related deaths in 2011 or by nearest distance to a polygon centroid for other cases.

We control for run-up heights and distance in kilometres from the location of the Tohoku quake (which is indicative for the time between the first tsunami warning and the arrival of the tsunami wave). It is only a proxy variable because the time between the outbreak of the earthquake and the first wave hitting the shore is not only determined by geographical distance but also by ocean depth and bathymetry, coastal characteristics and other factors. The maximum height of the tsunami run-up varies from 1.19 in the municipality of Yokosuka to 40.57 metres in Miyako. The distance from the epicentre varies from 82 kilometres in the municipality of Onagawa to 1,055 kilometres in Tosashimizu. The two measures are negatively correlated at $r = -0.59$. We tested for an interaction effect between the two measures as well as for non-linear effects of both measures but found no evidence that these represent better fitting models based on Akaike and Bayesian Information Criteria. These more complex models also hardly change the predictions from the simpler baseline model.

In addition, we control for a number of socio-economic factors that may explain variation in mortality at the aggregate municipal level. Specifically, we include the (log of) the total population in a municipality, the share of people older than 64, the share of people who have completed up to a senior high school degree, the share of people in employment and an index of the financial strength of a municipality, which refers to 2012 while all other socio-economic variables were obtained for 2010. Municipal statistics were obtained from the Regional Statistics Database at the Portal Site of Official Statistics of Japan, Statistics Bureau, Ministry of Internal Affairs and Communications (<https://www.e-stat.go.jp/SG1/chiiki/Welcome.do>). See the Appendix for summary descriptive variable statistics.

Our dependent variable is the count of Tohoku fatalities, for which the variance is greater than its mean. Due to this over-dispersion we use a negative binomial rather than a Poisson estimator. Standard errors are clustered on the 10 prefectures in which the 88 municipalities are located. Not clustering standard errors produces almost identical results, which suggests that potential model misspecifications that are correlated within prefectures have no major impact on the results.

We start with a model that does not include socio-economic variables other than population size (model 1). The two natural hazard strength measures and population size have the expected effects. The reported coefficients can be interpreted as semi-elasticities. For example, each additional metre of run-up height is estimated to increase the death toll by approximately 9 percent. Model 2 adds the other socio-economic variables, whereas model 3 additionally includes prefectures fixed effects to account for some unobserved heterogeneity across the 10 prefectures in which the 88 municipalities lie. The estimated effects for our hazard and learning variables are fairly

stable and therefore robust. However, only historical experience with actual tsunami fatalities has a statistically significant effect, whereas maximum historical wave height does not. We infer from the latter result that individuals do not seem to have systematically learned from historical experience with tsunami heights in their municipality. Municipalities with higher historical waves do not systematically experience lower mortality in 2011. The financial strength of a municipality has the expected negative effect. Better off municipalities can afford better mitigation policies. Surprisingly, the educational attainment level of the population in a municipality has a positive effect and the share of elderly people has no consistent effect. The elderly are less physically mobile but also have more tsunami experience such that the two effects go into opposite directions. It is unclear to us why municipalities with better educated populations suffered higher fatalities.

Table 1. Determinants of mortality in the 2011 tsunami.

	Model 1	Model 2	Model 3
maximum run-up height	0.0901** (0.0392)	0.0952*** (0.0290)	0.0949** (0.0472)
distance to quake epicentre	-0.0262*** (0.00184)	-0.0304*** (0.00493)	-0.0245** (0.0114)
sum of historical tsunami deaths	-0.00227*** (0.000572)	-0.00211*** (0.000404)	-0.00262*** (0.000621)
maximum historical wave height	-0.0359 (0.0388)	-0.0179 (0.0201)	-0.0264 (0.0224)
ln population	0.669** (0.306)	1.119*** (0.213)	1.354*** (0.313)
employment share		28.42 (19.68)	37.03 (30.66)
financial strength index		-2.490** (0.967)	-2.262** (1.070)
educational attainment		12.34*** (4.026)	16.98*** (5.372)
share of older people		0.740 (8.998)	-2.400 (10.38)
Observations	88	88	88

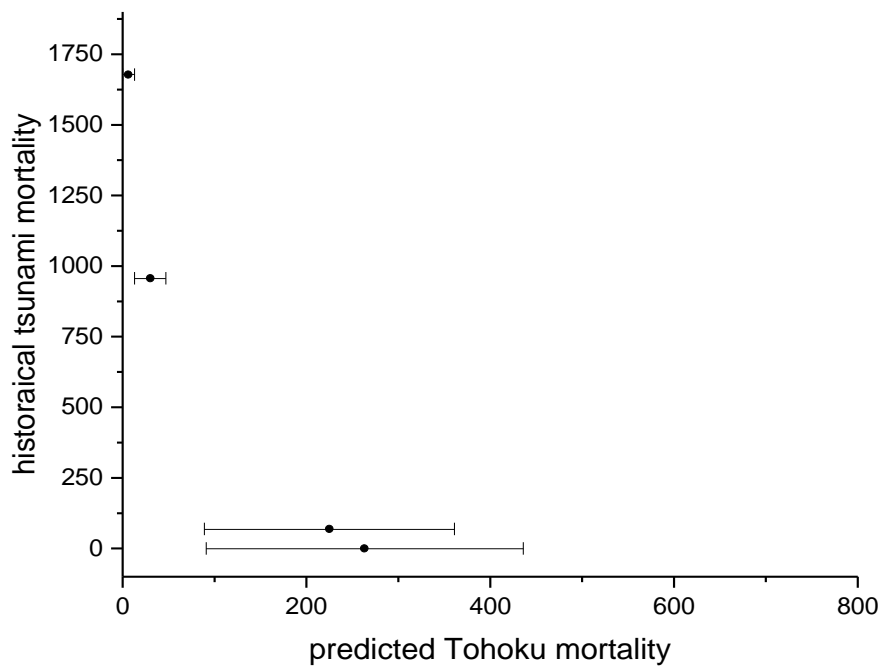
Note: Dependent variable is number of people killed by Tohoku tsunami in a municipality. Negative binomial estimation. Model 3 includes prefecture fixed effects. Standard errors adjusted for clustering on prefecture level in parentheses. Significance levels: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

To provide a more substantively meaningful interpretation for the historical tsunami fatality experience we report predicted deaths varying the values of this learning variable, keeping all the other variables at the values as observed in the sample. We base this analysis of substantive effects on model 1 but results are similar for basing the analysis on models 2 or 3 instead. This analysis of substantive effects demonstrates that the sum of historical tsunami deaths has a strong effect.

Municipalities with high historical tsunami mortality experienced low mortality in the Tohoku quake in comparison to municipalities with no or few historical tsunami deaths. Because of the skewed nature of the historical deaths variable – only 7 out of the 88 observations experienced such tsunami fatalities since 1933 – we assess percentiles

across the range of strictly positive values of this variable only. At zero historical fatalities, predicted mortality is 263, at the median of positive values (69 historical deaths), it is 225, falling to 30 at the 75th and to 6 at the 90th percentile (representing 957 and 1,678 historical deaths, respectively). As figure 1 shows, these are estimated with sufficient precision such that the effect at high historical mortality is statistically different from the effect at low or zero historical mortality.

Figure 1: The predicted effect of historical tsunami mortality.



What is the likely causal mechanism for these striking results? Of course, our quantitative analysis cannot and does not aim at the individual predictors of disaster mortality. Only individual-level data could explain why some individuals stayed in low elevation areas until the tsunami flooded over the tsunami walls while others left the coastal area immediately after Japan's Meteorological Agency issued a tsunami warning,

however imperfect it was, and why many individuals searched safety in tsunami shelters, while others ran for nearby hillsides.

Nevertheless, we submit that the most likely reason why fewer people died in 2011 in municipalities, which had historical experience suggesting that tsunamis can kill substantial numbers of people, is that systematically more individuals have learned to distrust tsunami walls and shelters and run for higher ground in these municipalities. In other words: if previous tsunamis killed people in the municipality, more individuals have learned that tsunamis are dangerous. If, however, nobody got killed in a municipality during previous tsunamis, fewer individuals learn that tsunamis are dangerous despite tsunamis of potentially several metres high. We cannot explore here how exactly individuals learned and memorised the lessons of the past and what role, if any, social networks and local public discourses may have played. We leave this to future research.

One reason that speaks in favour of our interpretation of the likely causal mechanisms is that, with one exception, there is no evidence that municipalities which historically had experienced tsunami fatalities had systematically better public protection infrastructure in place than other municipalities. The one exception is Fudai. Despite fierce political opposition, Fudai's mayor, Kotaku Wamura, who survived an earlier tsunami and therefore made it his personal mission to protect his city by a floodgate high enough to withstand even high run-ups (Birmingham and McNeill, 2014). Fudai built a tsunami wall that was 15.5 meters height. Its costs totalled 3.5 billion Yen, roughly one quarter of Japan's per capita income for each of Fudai's citizens. The floodgate was criticised as wasteful at the time it was built and thereafter, even though the construction was greatly facilitated by mountains on both sides of the dam such that

the construction merely needed to close a gap between mountains (Daily Mail, 2011). Wamura seems to have been the only mayor popular enough to be able to afford pushing forward with a pet project that was expensive in the short run and saved lives only many years after Wamura's death. He simply did not allow others to water down his plans to build a tsunami wall much higher than in most other municipalities.

Fudai was the exception not the rule, and our findings thus support Hasegawa's (2013, p. 18) contention, based on interviews with survivors, that in many municipalities prior experience with smaller and comparably harmless tsunamis "created a feeling of reassurance with respect to risk and thus made some of the population more vulnerable". Our findings also suggest that previous experience in the municipality mattered more than the national or global experience with tsunamis. Individuals' expectations of whether their municipality is at risk of a fatal impact exerts a larger influence on behaviour than the general idea that tsunamis can be mortal, in which case we would not find that the historical experience of tsunami fatality in a municipality has an effect on mortality in this municipality in the 2011 tsunami.

6. Conclusion

Natural hazards turn into disasters when the affected population is ill prepared and governments fail to invest in infrastructures that mitigate the dire effects of the forces of nature (World Bank and United Nations, 2010). However, infrastructures built to protect from disaster have ambiguous consequences: they often prevent and even more often reduce disaster mortality if natural hazard events remain within the expected range. At the same time, however, these infrastructures promise safety from natural hazards though perfect security cannot be guaranteed. When the forces of nature exceed expected levels, protective infrastructures increase mortality because they

increase the likelihood that individuals become imprudent when hazards strike. Thus, protective infrastructures and other preparedness policies cause a moral hazard problem in the broader sense – in the sense that public investment in protection causes individuals to accept more risks than they should. The Tohoku tsunami offers a good example: Japan was well prepared for tsunamis, but not for a tsunami the size of the Tohoku event. The Tohoku case demonstrates the dangers if affected citizens – feeling safe behind tsunami walls, in tsunami shelters and in neighbourhoods declared safe by the government – are tempted to not take individual precautionary measures as a consequence, which in the Tohoku event would have been to run inland or climb hills.

We have shown that maladaptation to an unexpectedly large extent is influenced by historical experience at the local level. Municipalities that previously experienced tsunami mortality during living memory suffered fewer fatalities during the Tohoku tsunami. In the absence of systematic differences in public protection measures correlated with such historical experience, these findings are strongly suggestive that more people felt safe behind tsunami walls in places that did not experience significant tsunami mortality in the past, while in municipalities with high historical tsunami mortality the affected individuals were more likely to maintain a healthy scepticism and thus take additional precautionary measures.

Individuals that have previously experienced only light variants of a disaster type can learn to become imprudent under the spell of a false impression of safety that public preparedness measures create. The worst case of a natural disaster does not necessarily occur in the absence of such measures, but when these measures unexpectedly fail after having worked for long periods of time. True, in the case of the Tohoku tsunami the initial severe under-estimate of the strength of the hazard event is likely to have played

a major role for increasing overall mortality but such failure in public protection measures form part and parcel of natural disaster events. Put simply, without failure in public protection measures even strong hazard events are unlikely to turn into major disasters in highly prepared countries like Japan.

Since individuals' expectations largely determine their behaviour once disasters occur, disaster behaviour drills need to avoid the notion of a maximum hazard strength based on historical experience and instead repeatedly rehearse scenarios of hazard magnitudes which in living memory have never been reached. At the same time, governments that invest in protective infrastructures and other safety measures need to make it clear to citizens that this protection only buys time, not necessarily lives. Effective and beneficial learning from past natural disasters requires individuals to heed the correct lessons from the past: safety devices are not fail-proof. Our analysis supports those experts who call "for a stop to more coastline engineering, saying money should be spent instead on education and evacuation drills" (Onishi, 2011a). The Japanese people, like all others living in highly prepared disaster-prone locations, need to learn the ultimate lesson, namely that infrastructures for disaster protection simply cannot provide full safety.

Appendix: Summary Statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
Tohoku death toll	88	174.91	449.32	0	3,173
maximum run-up height	88	9.84	9.68	1.19	40.57
distance to quake epicentre	88	332.70	196.95	82	1055
sum of historical tsunami deaths	88	35.23	207.52	0	1678
maximum historical wave height	88	4.23	4.77	0	29
ln population	88	10.20	1.22	8.04	13.86
employment share	88	0.47	0.04	0.39	0.62
financial strength index	88	0.47	0.28	0.12	1.48
educational attainment	88	0.40	0.04	0.31	0.49
share of older people	88	0.27	0.05	0.16	0.39

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