2011 Tohoku, Japan Earthquake Catastrophe Modeling Response

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LISBOA 2012

SUMMARY

The 2011 Tohoku, Japan Earthquake and Tsunami, occurring on Friday March, 11, 2011, was an industry-changing event for the global insurance industry. As part of its services for its insurance clients, Risk Management Solutions (RMS) conducted an extensive ‘catastrophe response’, which included ongoing development of earthquake and tsunami modeling parameters and other information for the management of risk in the immediate aftermath of the event to 1 year later. This paper discusses this process, illuminating the procedures to develop tools for risk assessment in real time, as well as an insurance industry loss estimate. On April 11, 2011, RMS estimated that the earthquake and tsunami would most likely cost between JPY1,750 and 2,840 billion (USD$21.0-34.0 billion) to the global insurance industry (RMS, 2011a). One year later, in April 2012, the total industry loss estimate is tracking well, though the estimates for individual lines of business vary compared to reported losses.

Keywords: catastrophe modeling, Tohoku Japan Earthquake, risk, insured loss

1. INTRODUCTION

Catastrophe models are used across the insurance industry to assess and manage property and casualty (P&C) risk. People or structures at risk (exposure) are input to these models, which consist of the three main components of hazard, damage, and financial modeling, to estimate loss. These models are probabilistic in nature, with the ability to consider all possible events, defined in a stochastic event set, which could impact a portfolio at risk. A key output from a model is the exceedance probability (EP) curve, which estimates the probability of exceeding a certain loss threshold. RMS models estimate losses from different perils (e.g., earthquakes, hurricanes) and their related hazards (e.g., tsunami, storm surge) that could impact the global insurance market.

In the aftermath of a natural catastrophe event impacting the industry, RMS releases timely information to its clients to manage its risk (e.g., allocating capital, deploying claims adjusters, etc). Depending on the significance of the event, an industry loss estimate is also released to the general market. The ability to gather and deploy relevant and useful information is challenging. Very quickly following the event, RMS realized that – as was the case in Hurricane Katrina in 2005 – its response to this event would be under much scrutiny. Moreover, given the nature of Japanese risk transfer, it would be a significant loss to the reinsurance market. This paper discusses the details of how RMS developed a suite of data for risk assessment, including:

- Stochastic earthquake events
- Ground motion and tsunami accumulation footprints
- Damage loss ratios by line of business by prefecture
- Field reconnaissance damage investigations
- Life and health implications
- Scope of secondary consequences and other consequences outside modeling scope
- Industry and economic loss estimates
- Assessment of short-term risk changes

2. HOW CATASTROPHE MODELERS RESPOND TO THE 2011 TOHOKU, JAPAN EARTHQUAKE AND TSUNAMI

On Friday, March 11, 2011, a powerful M9.0 earthquake occurred offshore of the east coast of the Tohoku region on the Island of Honshu, Japan. Occurring at 2:46 p.m. local time, ground shaking duration lasted for over five minutes in many areas, including Tokyo. The earthquake triggered a series of devastating tsunami, inundating 52,600 hectares (525 km^2) of land along the coastline. The 2011 disaster was both a major humanitarian and insured loss event. As of April 2012, there are more than 15,800 confirmed deaths, with approximately 3,100 people missing (NPAoJ, 2012). The events following the earthquake, including the tsunami, were unprecedented in recent times, from which many lessons can be learned for catastrophe modeling and disaster research.

To convey the implications and scale of the 2011 Tohoku, Japan Earthquake, the term 'Super Cat' is used to describe it and its secondary consequences (i.e., tsunami and Fukushima Daiichi Nuclear Disaster). Super Cat was coined after Hurricane Katrina to describe the largest catastrophes, where secondary consequences become significant factors in loss generation. Three principal elements of the secondary consequences found in this Super Cat event were containment failures (e.g., sea wall failure), evacuation (e.g., mandatory evacuation surrounding Fukushima Daiichi Nuclear Power Plant), and systemic economic impacts.

Following the March 11, 2011 event, RMS started its event response process with the first notification the earthquake had occurred (Fig. 1.1). There were different stages of response for the clients and media including: development of source and hazard characterization, providing an economic loss estimate, industry exposure refinement, applying field reconnaissance findings, and tsunami accumulation footprint development. Event response also involved the development of an insurance industry-wide loss estimate (RMS, 2011a). A study on the post-event seismic risk was carried out at RMS and a report was released to clients 10 months following the earthquake, providing factors to adjust the short-term risk estimates in the current RMS Japan earthquake model (RMS, 2012).

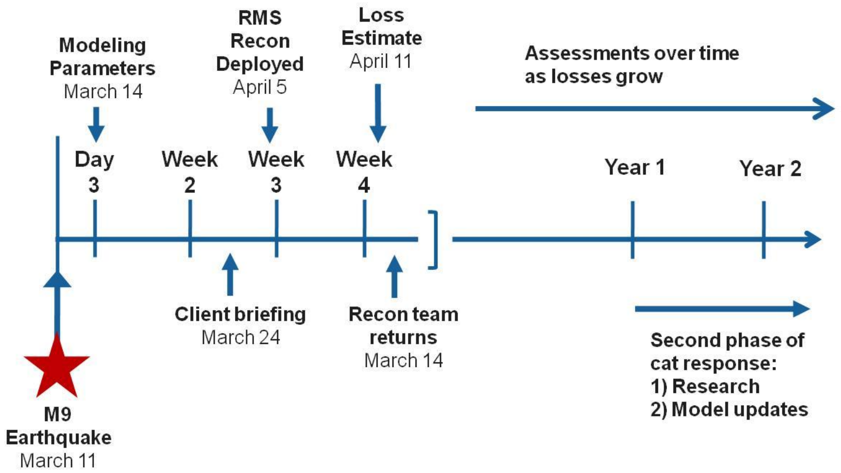

Figure 1.1. Timeline of RMS catastrophe event response for March 11, 2011 Tohoku, Japan event

2.1. Developing and Refining Model Components

Within 36 hours of the event, RMS released its first report of information for clients which included a preliminary source characterization, detailed impact report based on information collected from the media and internet, and Japanese insurance industry information. Within 72 hours, RMS provided an economic loss estimate, MMI maps with GIS files, a ground shaking footprint file, a tsunami accumulation footprint, prefecture-level damage ratios for various line of business, and a selection of source characterizations from the RMS models. Over the following 2 weeks, RMS continued to refine the different deliverables as more data and information became available.

2.1.1. Source model characterization

The March 11, 2011 M9.0 event took place on the subduction interface boundary where the Pacific Plate is being pushed underneath Japan along the Japan Trench. An area of approximately 450 km long and 150 km wide in the central section of the trench ruptured. The historical earthquake record of the Japan Trench does not contain earthquakes of the size of the 2011 event; the maximum “credible earthquake” assumed along this section of the Japan Trench was considered to be M8.3 (RMS, 2012).

In order to begin understanding the wider impacts of the event, the seismic source was characterized using information available through the USGS and the JMA within the first few hours of the event. This information was shared with clients in a format so that they could input the event into the RMS model to have preliminary loss estimate for their exposures before a ground motion footprint could be developed. The characterization is also leveraged in future catastrophe model updates.

2.1.2. Ground motion footprint

A ground motion footprint is developed following an event to provide a more detailed estimate of the shaking hazard within the affected area. Ground shaking measurements (MMI, PGA, Sa) are estimated for different spatial resolutions using ground motion recordings during the event. In the case of large events in which field reconnaissance teams are dispatched, they can assist in refining the ground motion footprints with their observations. The RMS footprints are made available to clients such that they can run their exposures in the models to estimate loss from ground shaking.

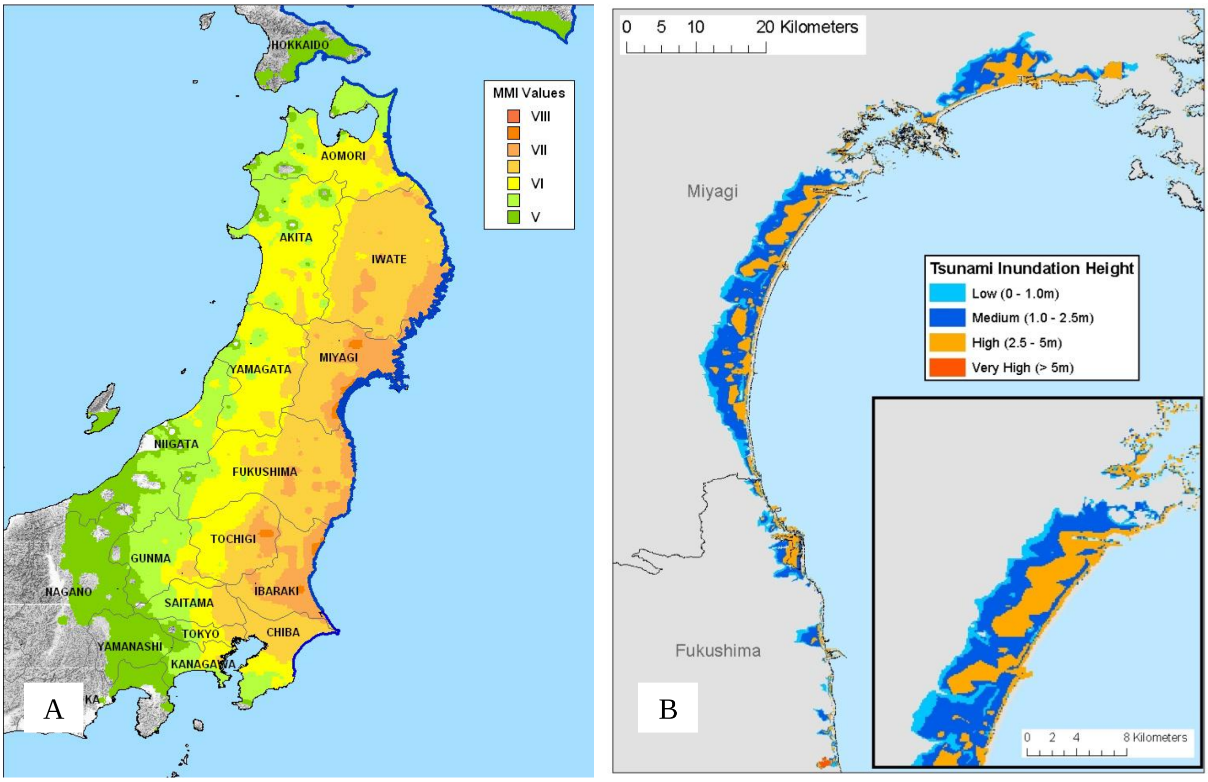

Figure 2.1. (A) The impact zone of the 2011 Tohoku Earthquake and Tsunami, showing ground shaking (red to green shading) felt across Honshu, and the northeastern coastal areas affected by the tsunami (dark blue). (B) RMS tsunami accumulation footprint for March 11, 2011 Tohoku, Japan Tsunami. (RMS, 2011a)

Ground shaking damage from the 2011 event covered a very large area (Fig. 2.1A), extending more than 500 km from north to south, with ground motions recorded at over 380 stations across Japan (RMS, 2012). Within 100 km of the rupture, ground motions were higher than expected, particularly at the high frequencies. This trend was reversed beyond 100 km, where ground motions were lower than predicted, particularly for the mid- and longer periods. The coastal plains in the epicentral region were the hardest hit by the high ground motions, but since many of these areas were then subsequently inundated by the tsunami waves, understanding the ground shaking impacts alone (i.e., separate from tsunami) is not possible.

Within weeks of the earthquake, a ground motion footprint for input into the RMS model was developed using the USGS ShakeMap for the event, which is dependent on instrument readings from the Japanese seismic monitoring networks. The USGS ShakeMap for the Tohoku event went through much iteration, corrected and refined by the instrument readings, and RMS worked to adjust its footprint to use the latest version. (On March 28, 2011, there had been 11 iterations of the ShakeMap; the 14^{th} and last iteration was published on August 18, 2011).

2.1.3. Tsunami accumulation footprint

The March 11, 2011 event was unique in that much of the damage was due to the tsunami inundation. Developing a tsunami accumulation footprint, which estimates the inundation extent and height of the tsunami, is critical in assessing damage and estimating loss. High (fine) resolution information on the exposure at risk is critical in using this type of footprint. RMS released a tsunami accumulation footprint following the March 11, 2011 earthquake and tsunami for client use in estimating loss to their detailed exposures (Fig. 2.1B; RMS, 2011a). The footprint was developed using an optimal interpolation technique that relied on observed flood extents, and it was calibrated with high resolution DTM data and SRTM data to derive the flooded areas. Along with property damage estimates, a tsunami accumulation footprint can also be used to assess the life and health impacts from the event.

2.1.4. Damage loss ratio estimations

In order to better assess the extent of damage, catastrophe modelers must understand the structural behavior of buildings at risk. Within RMS earthquake models, vulnerability curves relating ground shaking to mean damage ratio (MDR) are used to estimate loss. There is a range of vulnerability curves developed for different building types (e.g., steel, concrete) for building coverages, as well as estimations of damage to the buildings' contents and potential loss-of-use (i.e., Business Interruption). The Japanese building codes are some of the most rigorous in the world (due to high seismic risk) and thus moderate to severe damage to buildings and casualties from ground shaking was limited to older structures and regions experiencing the highest recorded ground motions (RMS, 2011a). Much of the damage to buildings and casualties resulted from the massive tsunami triggered by the M9.0 earthquake.

RMS worked on providing regional loss ratio estimates within days of the March 11, 2011 earthquake and tsunami. Originally, only ground-up (economic) loss ratios by line of business (e.g., residential, industrial) were provided for the prefecture level. Much of the information and data was remotely collected while RMS colleagues in Japan performed rapid field assessments in the days following the event. As more information became available and there was refinement of the RMS industry exposure, gross (insured) and ground-up loss ratios at the prefecture- and city-levels by line of business were provided to clients. Further refinement of these loss ratio estimates was developed from the RMS field reconnaissance team reports (in the field from April 5 through April 14, 2011).

2.1.6. Casualty modeling & life and health advisories

To assess the risk to human exposures (number of fatalities and injuries) from the March 11, 2011 earthquake and tsunami, two types of hazard, ground shaking and tsunami inundation, are considered separately. The most significant contributor to injury and death from ground shaking is partial or total building collapse. On March 21, 2011, RMS models indicated that fatalities attributed solely to ground shaking would have likely numbered in the hundreds (RMS, 2011b).

Estimating casualties due to tsunami is extremely difficult. The number of casualties is dependent on the tsunami inundation depth, population exposed, presence of mitigation measures like seawalls and evacuation routes, and time elapsed between the seismic event and arrival of the first tsunami wave. Rough approximations of fatalities and serious injuries can be made using a tsunami accumulation footprint (e.g., Fig 2.1B) overlain onto geographically distributed human exposures. Exposure within a certain band of inundation height can be assigned a fatality or injury rate (RMS, 2011b).

The life and health implications from the earthquake, tsunami, and Fukushima Daiichi nuclear disaster were addressed with a client advisory within 10 days of the event, including commentary for detailed impact summary reports. The Tohoku event produced the largest number of policy claims for life and health insurers since the 2001 World Trade Center attacks. Most of the deaths following the event were from the tsunami, with minimal casualties related to building collapse. While RMS does not include nuclear consequences within its natural perils, it does model nuclear power plant sabotage in its terrorism model suite. Some of this knowledge was applied to the Fukushima Daiichi to discuss potential short- and long-term effects of radiation release. The commentary on the nuclear disaster was provided to help clarify conflicting media reports and to provide a framework for the interpretation of reports on the developing situation.

2.2. Field Reconnaissance

For significant catastrophic events (i.e., events that impact the insurance industry and catastrophe modeling), RMS either participates with larger reconnaissance teams (e.g., EERI, EEFIT) or sends its own teams of engineers into the field. The Tohoku, Japan earthquake and tsunami were unique in that the uncertainty of the nuclear disaster prevented the immediate dispatch of teams into the field. Starting on April 5, 2011, for approximately two weeks, the field reconnaissance team toured the affected regions with Japanese colleagues. Among the goals of the reconnaissance was (1) ascertain the extent and severity of damage from the earthquake and tsunami, (2) estimate the amount of damage in the Tokyo prefecture (as this would escalate total loss estimates), (3) understand the different modes of damage to various industrial facilities, and (4) collect data and information for future modeling and sharing with other researchers worldwide.

Figure 2.2. RMS field reconnaissance photos of severe structural damage to a commercial building in Sendai (top left); Minami Sanriku hospital vertical evacuation plan to 3rd floor was insufficient (top left); Onagawa tsunami devastation showed heavy, mid-rise concrete structures toppled (bottom left); damage to industrial rail lines at port in Ishinomaki (bottom right). (Source: RMS Recon)

There were a number of specific observations from the field reconnaissance work that were used to better inform the industry loss estimate and refine prefecture-level loss ratios. First, older structures (pre-1981) were more likely to suffer severe damage from ground shaking (shown in Fig. 2.2). Various types of industrial facilities were affected differently by the event. Clean rooms for manufacturing small electronics were particularly sensitive to high acceleration ground shaking and the ports in areas affected by tsunami suffered severe damage to their infrastructure and contents (Fig. 2.2). In Onagawa (Miyagi Prefecture), the tsunami caused heavier, concrete structures to become buoyant and topple on their sides (Fig. 2.2), a mode of damage not observed previously. Throughout the tsunami-inundated region, there were examples of inadequate evacuation plans (Fig. 2.2).

2.3. Addressing Other Event Implications

The M9.0 earthquake, tsunami, and nuclear disaster resulting from March 11, 2011 includes additional factors and uncertainties that are not directly modeled but need to be considered when assessing the insurance industry impact. Modeled uncertainties can be compounded by Super Cat characteristics and loss amplification. In the case of the 2011 Tohoku, Japan earthquake and tsunami, the business interruption and contingent business interruption impacts on commercial and industrial lines were the biggest unknowns and critical in determining industry-wide impacts.

Non-modeled loss, like losses from the nuclear disaster, can be too difficult to quantify in a meaningful range, and thus they cannot be included within uncertainty ranges placed around loss estimates. Insurance and reinsurance loss can be extremely sensitive to deviations in the mean and/or the overall distribution of modeled loss. This distribution is represented by the standard deviation or coefficient of variation (standard deviations divided by the mean). In some instances, small difference in modeled losses can be significantly amplified or reduced according to insurance financial structures.

2.4. Formulating Industry Loss Estimations

RMS responds to significant catastrophes affecting the insurance industry by providing an industry-wide loss estimate. Modeling and industry information developed following an event is used by the RMS client base to assist them with their risk management, loss reserving, and capital management decisions. As such, the timing of industry loss estimate and accompanying data is important. Because of the variety of implications (e.g., tsunami, nuclear disaster) following the 2011 Tohoku, Japan event, time was taken to develop an accurate and complete loss estimate (RMS, 2011a). Timing of the loss estimate was influenced by two main factors: (1) clients needed information to make capital allocation decisions, and (2) RMS was cognizant of the importance of a meaningful report that would stand up to future scrutiny. A meaningful range of industry loss is usually broken down by lines of business. These numbers are developed using RMS models with industry exposure, preliminary loss estimates by re/insurers, and other insights from significant historical events (e.g., knowledge of previous Super Cats).

2.4.1. Economic loss estimation

One approach to developing an insurance industry loss is first to develop an 'economic' loss estimate (based on all property at risk) and then determine the scope of property covered by insurance. The advantages of an economic loss estimate are to convey the magnitude of the event's loss relative to other catastrophes. In the case of Tohoku, RMS released a total economic loss estimate of $200-300 billion USD (4-5% of Japanese GDP; JPY16.2-24.3 trillion) on March 14, 2011, including infrastructure damage, from a combination of the earthquake shaking, tsunami inundation, and secondary consequences. On March 23, 2011, the Japanese government (Japanese Cabinet Office, 2011) estimated damage from the event to cost JPY16-25 trillion ($197-308 billion USD).

2.4.2. Industry exposure development

The scope of property covered by insurance is estimated using an industry exposure database. The RMS industry exposures for Japan estimate the total insured value across all lines of business and include representative financial structures for the market. These include the residential, Kyosai, commercial, and industrial lines of business.

Residential insured risk is ceded to J.E.R., the Japanese Earthquake Reinsurance Company, in the event of a loss-causing earthquake. Liability is allocated to J.E.R., participating non-life insurance companies, and the Japanese government according to the size of the loss (JER, 2010). For the Tohoku earthquake, JPY1,224 billion in total residential claims have been paid as of April 2012 (GIAJ, 2012), and it is estimated that J.E.R. is liable for JPY165 billion, non-life insurers JPY504 billion, and the Japanese government JPY555 billion.

Co-operatives or Kyosai, also provide insurance to their members and are classified according to affiliation (e.g., agricultural, fishery, consumer, etc.). Earthquake coverage purchased through a regulated co-operative is most often included as part of the standard policy and covers building and contents losses at an amount less than the total sums insured (TSI) for fire coverage. As a result, relative to their participation in the market, co-operatives cover a larger portion of the earthquake damage.

Commercial and industrial insured exposure is low, as earthquake insurance take-up rates among Japanese corporations remain low. Additionally, business interruption (BI) remains a small share of the total insured sum for commercial and industrial risks.

2.4.3. April 2011 insured loss estimate

In Table 2.1, the estimated losses by line of business from April 11, 2011 are presented alongside reported losses as of April 2012. It should be noted that some claims are still being processed – particularly on the commercial and industrial lines. Overall, both the residential and co-operatives losses were higher than expected and the life insurance losses (death benefit payouts) were less than projected. There is little available public data on the losses from commercial/industrial and other lines of business.

Table 2.1. RMS total insured loss estimates from the 2011 Tohoku Earthquake and Tsunami (*net of Japanese government liability) reported April 11, 2011 (RMS, 2011a) compared to loss estimates reported as of April 2012 (GIAJ, 2012; LIAJ, 2012; Artemis, 2012). Conversion rate from March 11, 2011 of 83.19 JPY = $1 USD used in table below.

Line of Business	April 11, 2011		Reported Losses as of April 3, 2012	
	In JPY	In USD$	In JPY	In USD$
Residential*	330–460 billion	$4.0–5.5 billion	670 billion	$8.0 billion
Co-operatives (Kyosai)	540–710 billion	$6.5–8.5 billion	890 billion	$10.7 billion
Commercial/Industrial	460–750 billion	$5.5–9.0 billion		
Other (railway, marine and aviation, auto)	170–250 billion	$2.0–3.0 billion		
Property Total	**1,500-2,600 billion**	**$18.0-26.0 billion**		
Life (death benefits)	250–670 billion	$3.0–8.0 billion	201 billion	$2.4 billion
Overall Total (All Lines)	**1,750-2,830 billion**	**$21.0-34.0 billion**		

Based on the information available within the first four weeks of the 2011 Tohoku Earthquake and Tsunami, RMS (2011a) estimated the total insured loss to property coverage is between JPY1,500 and 2,160 billion (USD$18 and 26 billion). This total (Table 2.1) was derived from several lines of business, including residential, co-operative, commercial and industrial (including BI and CBI), marine, aviation, and auto. These losses consider the impacts of post-event loss amplification (PLA), particularly to the commercial and industrial lines, as well as the uncertainty of certain assumptions in arriving at these estimates. No consideration was given to additional impacts from the damage to nuclear power facilities in Fukushima (as nuclear risks are excluded from all coverages). After combining the potential total death benefit payout, the total insurance loss from this event was estimated to be between JPY1,750 and 2,830 billion (USD$21 and 34 billion).

2.4.4. Reported losses as of April 2012

As of April 2012, losses for residential, co-operatives, and life lines of business had somewhat stabilized and total claims were being reported by various agencies. The total paid out claims for residential losses was approximately JPY 670 billion (USD$8.0 billion), minus Japanese government liability, as of April 2012 (GIAJ, 2012). The Life Insurance Association of Japan (2012) was reporting approximately JPY 201 billion (USD $2.4 billion) in life insurance losses (death benefit payouts) on March 15, 2012. Losses to the co-operatives were primarily from Zenkyoren, which was reporting losses of at least JPY 890 billion (USD$10.7 billion) as of January 2012, which would trigger its top reinsurance layer (Artemis, 2012).

2.4.5. One year retrospective on industry loss estimate

The relative success of the April 2011 industry loss estimate is testament to the experience and knowledge contained within the RMS Cat Response team. Much work was done across modeling components and an intimate knowledge of the Japanese insurance industry was employed to refine the suite of data for risk assessment.

Industry loss estimation is highly uncertain in the days and weeks following a large event, such as the Tohoku earthquake and tsunami. Total claims take time to compute as some payouts do not occur until 6 months to 1 year after the event, as in the case of contingent business interruption policies. Though ranges around total losses per line of business were provided 1 month after the event (RMS, 2011a), longer term lessons include understanding whether there is a changing landscape of hazard (and thus risk) as a result of the event, as well as any incorrect assumption on the insured exposure and its vulnerability to ground shaking. Moreover, the event has provided data on improving our understanding of the impacts of tsunami inundation.

Underestimation of the residential and co-operative losses in April 2011 indicates that a review of the RMS insured exposure estimates is needed. This is both a function of the nature of the Japanese insurance market, as well as construction practices within Japan. Data of high resolution and good quality takes time to accumulate in order to develop and validate an industry-wide estimation of exposure. Also, the overestimation of the life (death benefits) was somewhat unavoidable because of the uncertain casualty counts inherent following the large tsunami. This may be an issue not easily solved for future events, as each tsunami event is unique and fatality counts are uncertain as the full accounting of the many missing (still numbering in the thousands as of April 2012) is never complete (NPAoJ 2012; RMS, 2011b).

2.5. Assessment of Short-term Risk Changes

Since the Tohoku event‘s occurrence, the seismic hazard research community has been working to understand whether other related damaging earthquakes can now be expected around Japan and how this great event may have affected the timing (advance or delay) of other earthquakes in the region. As the Tohoku region is subject to an ongoing aftershock sequence with short-term increased levels of seismicity, RMS conducted a series of sensitivity tests on the occurrence rates within the RMS model to understand potential impacts on risk metrics. Occurrence rate changes due to both static stress and post-event seismicity changes result in a range of risk impacts across the prefectures of Northeast Honshu. The timing of this study – released in early February 2012 – was critical in that the reinsurance contract renewals for the Japan insurance industry is April 1st (RMS, 2012).

Average Annual Loss (AAL) is a catastrophe modeling output that is often utilized for risk management decisions in the insurance industry. The change in the short-term risk (i.e., within two years of the event’s occurrence) in the RMS study – as a function of both static stress and post-event elevated seismicity – was expressed as a change in the AAL, as well as 100-year return period loss. Fig. 2.3 presents a map of the relative change in ground-up (economic) AAL across the affected region for static stress changes only. This analysis highlighted the challenges in estimating short-term earthquake risk in Japan following the 2011 Tohoku Earthquake, as occurrence rate changes cannot be resolved exclusively by analyzing static stress changes on known seismic sources.

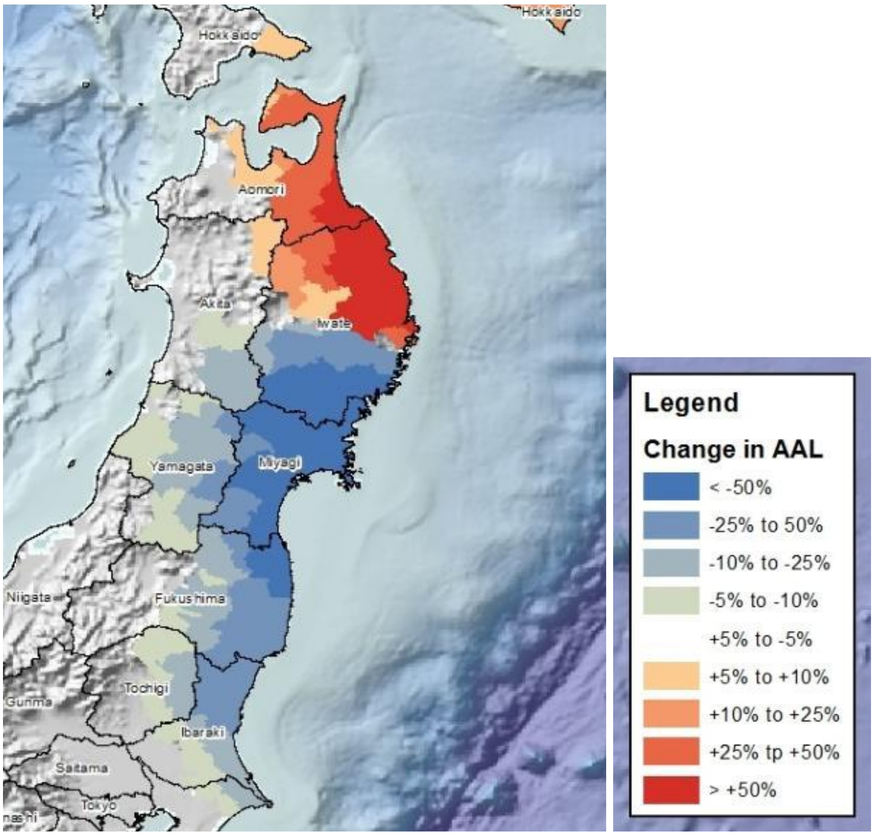

Figure 2.3. Change in risk (as measured by change in ground up average annual loss) in the region as a result of static stress changes following the 2011 Tohoku event; warmer (red) colors indicating areas of increased risk and cooler (blue) colors indicating areas of decreased risk, changes within ±5% are not shown. (Source: RMS 2012)

3. IMPLICATIONS FOR FUTURE CATASTROPHE MODELS

The 2011 Tohoku, Japan Earthquake and Tsunami are highly significant for catastrophe modeling and the global insurance industry. It is an extreme event that tested the scope of catastrophe models, providing insight for future catastrophe model development across all perils. In the year following the event, other sources have supported and confirmed the RMS economic and insured loss estimates, thus showing the value of an extensive event response process following catastrophes. For future Super Cat events, catastrophe modelers are now equipped with more high quality information as a result of studying the Tohoku event. There will be better representation of non-modeled losses and uncertainties in economic and industry loss estimates.

Catastrophe modeling agendas at RMS were impacted directly by the Tohoku event, both in the short- and long-term. Most recently, RMS provided a study of the short-term changes in risk in Japan by RMS for client use during the April 1, 2012 renewal season (RMS, 2012). Long-term impacts crossed over into other regions (e.g., U.S., Europe) and other perils (e.g., hurricane, flood). A need for more sophisticated tsunami modeling in Japan was identified quickly. Also, better understanding of (contingent) business interruption impacts is critical for modeling industrial and commercial risks in the sophisticated insurance markets across the globe. Field reconnaissance priorities are starting to include not only surveying physical damage but capturing the impacts on industrial facilities and their capacity for operation.

The experience of the 2011 Tohoku, Japan earthquake and tsunami provides an opportunity for re-evaluation of the Japan earthquake catastrophe models, as well as methodologies for earthquake modeling across the globe. Following large earthquakes, it takes time for relevant data to be collected and distilled into actionable insights. RMS is actively researching and collaborating with the larger scientific community to understand any updated views of hazard. Moreover, RMS continues to collaborate with clients who have collected detailed claims data, as well as with the earthquake engineering community, to incorporate new insights into the vulnerability of property from earthquakes and other secondary hazards (e.g., fire following earthquake, liquefaction, landslides, and tsunami).

ACKNOWLEDGEMENT

The authors would like to thank the RMS Cat Response team for the Tohoku Earthquake and Tsunami, including Trey Apel, Munish Arora, Hesaam Aslani, Maiclaire Bolton, Jason Bryngelson, Carlos Cabrera, Manabu Masuda, Gilbert Molas, Guy Morrow, Robert Muir-Wood, Marleen Nyst, Emily Paterson, Mohsen Rahnama, Pooya Sarabandi, Hemant Shah, Maura Sullivan, Craig Van Anne, Vikram Vyas, Chesley Williams, and Don Windeler. Also, acknowledgement of support goes to RMS Japan, OYO-RMS, and ERS. Thank you to the Kajima Technical Research Institute.

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