Cambridge Centre for Risk Studies

NatCat and FinCat Correlation

IMPACTS OF SEVERE NATURAL CATASTROPHES ON FINANCIAL MARKETS

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Impacts of Severe Natural Catastrophes on Financial Markets

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Section 1: **Executive Summary**

In this report we explore the potential for very large natural catastrophes to trigger market shocks and subsequent economic downturns that would have an impact on both sides of an insurance company's balance sheet: the losses that would be paid out in claims from their property casualty underwriting portfolio and the devaluations and reduction in returns that would occur to the financial assets in their investment portfolio.

To date, few natural catastrophes have registered any impact on the shape of the global market. The most costly natural catastrophe of history, 2005's Hurricane Katrina, moved the New York Stock Exchange by less than a single percentage point with its $150 billion in direct damages. The last decade has presented a growing number of high-cost natural catastrophes (six have caused destruction costing $10 billion or more), and 2017 represented a record year for loss as a result of significant floods, earthquakes and hurricanes impacting major economies, such as Hurricane Harvey in the Southern USA, Hurricane Maria in the Caribbean, and major mudslides in India, Bangladesh and Nepal. Despite this devastation, trading volumes remain steadily high and investment portfolios do not appear to have been impacted by these relatively localised but severe disasters.

Historically it has been man-made risks that have posed the greatest threats to market continuity; events such as the 1929 Wall Street Crash and 2008's subprime financial crisis caused significant enough shocks to distort global markets. These events removed more than $10 trillion in anticipated GDP from economies across the world. Since 2009, the Cambridge Centre for Risk Studies has modelled a number of hypothetical scenarios as stress tests for investment portfolios and financial risk management, including GDP output and investment hygiene, and that would cause significant levels of market impact: a territorial war between China and Japan, a virulent flu pandemic, and a breakdown of the European Union, etc. In 2014, a study into the macroeconomic impact of a global mass protest movement, 'Millennial Uprising' (also sponsored by Munich Re). In each of these cases, both historical and hypothetical, the Centre observed that direct and indirect economic losses of over $1 trillion are those that correlate to significant detrimental change in the markets.

Given the increase in accrued damages from natural catastrophes worldwide, the growing exposure from industrialisation of developing nations and network of global industry and high-cost assets, the potential loss vectors for future natural catastrophes are growing. Climate change is a factor, contributing to the frequency of floods, hurricanes and droughts. If a future natural catastrophe could cause a disruption of economic output of a trillion dollars or more, could this trigger a stock market devaluation that would impact investment portfolios?

Over the course of several years, the Cambridge Centre for Risk Studies has identified a number of potential 'Trillion Dollar Nat-Cats', by using the Cambridge Global Risk Index to identify cities at risk from major natural catastrophes. From these, six scenarios across three threat groups are featured and analysed extensively in this report for their potential effect on markets and investment portfolios.

Scenario summaries

The six scenarios consist of two major earthquakes, two tropical windstorm events, and two volcanic eruptions. These are each extreme events with remote return periods, but entirely plausible from our understanding of geological and climate sciences. Two separate scenarios are presented for large magnitude earthquakes impacting modern megacities. The first of these is a magnitude 7.7 earthquake on the Newport-Inglewood fault system impacting Los Angeles and the surrounding area, including ports, airports, and industry, causing over $850 billion in damages. The second scenario is of a magnitude 8.3 earthquake in the Kantō subduction zone affecting Tokyo and parts of central Japan, compounded by an accompanying tsunami. The Tokyo earthquake event is estimated to cause $1.37 trillion in damages, both insured and uninsured. In both cases, recovery from the quake takes several years and requires substantial government stimulus.

The first of the two hurricane scenarios impacts Miami and the Florida coast, causing $1.35 trillion in damage, including extensive property loss in the affected areas. The second is a transitioning hurricane that retains wind strength as its track takes it over the property concentrations of the East Coast of United States including New York and the New Jersey area, causing $1.15 trillion in damage. Hurricane recovery periods are significantly shorter than the earthquake events – around one and two years, respectively.

The third threat class concerns large scale VEI 6 eruptions of two historically active volcanos with the potential to impact high concentrations of exposure in the regions around them. The first is the eruption of Mount Marapi in West Sumatra, Indonesia, which last erupted in 1815, causing significant climatic change worldwide. Tephra deposits from this eruption are distributed across Singapore and Malaysia by prevailing winds, affecting air travel and disrupting vital global supply chains. The second scenario describes the eruption of Mount Rainier in Washington, United States, which buries several major US airports and sea ports in tephra. Tephra deposits are swept as far away as the east coast of Canada, impacting air travel following the eruption. In both cases, global temperatures are affected by the eruptions, leading to three years of climate abnormalities, global food shortages and soaring inflation.

Economic and market consequences

Each of these scenarios is highly destructive and results in the destruction of around a trillion dollars of physical property and infrastructure, and affects populations of millions of people. It disrupts the business activities of entire regions, and halts the economic output for a lengthy period of time, taking several years for the economy to recover. The economic impacts are also felt far beyond the damaged region itself. Customers, suppliers, and trading partners of disrupted businesses are also affected, in neighbouring regions and even in far-away countries. The interconnectivity of modern business means that the spill-over effects result in consequential amplifiers of this shock throughout the global economy.

We estimate that these events trigger reduced growth in global GDP for several years following the event, with total loss of the GDP that might otherwise be expected (GDP@Risk) ranging from $1.9 trillion (Tokyo earthquake) to $7.6 trillion (eruption of Mount Rainier). These are significant multiples of the costs of the property damage loss. None are quite large enough on their own to trigger a global recession (negative growth for more than two quarters) although some come close and cause several years of weakened national economies. The weakened economies that result would be more vulnerable to any other shocks that could occur coincidentally during the recovery period, and make a recession more likely.

These economic effects are of sufficient magnitude that they have significant effects on the financial markets, much more severely than natural catastrophes have had in the past. Market shocks include the devaluation of various classes of investment assets, changes in interest rates, changes in currency exchange rates and sovereign credit ratings, and bond yields, even in high quality asset classes. Equity markets, which are typically volatile to shocks and news events, have strong temporary downturns. Stock exchanges in the countries directly impacted are worst affected, but all major exchanges around the world see contagion from this effect and suffer lesser versions of the same shocks. Estimates of likely drops in stock exchange share price indices range from a 6% crash on the Nikkei following the Tokyo earthquake to a 20% loss to the S&P500 after the Mount Rainier eruption.

There are a few winners as well as many losers – with disparities favouring the sectors that gain from future reconstruction investment, and competitors of the disrupted businesses gaining in market share.

Investment portfolio impacts

We model a high quality investment portfolio representing typical structures similar to those reported by major global insurance and reinsurance companies, with an asset composition of geographical markets and financial instruments that reflect the expected liabilities and exposures of their underwriting activities in international markets around the world. The nature of high quality investment portfolios is that they are robust to short term market fluctuations, but these investment portfolios are not immune to the levels of market depreciations that occur from events of this magnitude. We estimate that the perturbations in the markets that would result from these scenarios would mean a reduction in returns to typical investment portfolios of this type in the single figures of percentage reductions, for example 6% in the event of the Florida hurricane scenario, with some potential for double digit reductions in returns from some variations in portfolio structure. Other types of portfolio structures, representing other investment strategies that might be typical of other types of institutional investors, such as those looking for aggressive growth, conservative or balanced investment strategies, are likely to see more severe reductions in yields depending on their asset mix and geographical structures.

Variation in impacts and durations

These six events, chosen for their approximate scale of destruction, do not all have the same impacts on the financial markets. The role of the United States as a driver of the global economy means that events that occur in the US and impact the direct output of the US economy are more significant and have a larger spill-over than those occurring elsewhere. The duration of the recovery is significant in determining the overall economic consequence, which will have implications for how government and foreign investment would potentially respond to try to minimise reconstruction time when events of this scale occur. The ensuing changes in inflation, interest rates, employment, national debt levels, foreign investment, and other macroeconomic factors affect a wide variety of financial investment asset classes that will affect the returns from the mix of these in any investment portfolio.

How many events could trigger similar scales of losses?

This report examines six potential natural catastrophe scenarios that could trigger a loss of a trillion dollars or more in either physical damage or loss to economic output. We have demonstrated that this level of loss is above the threshold that would cause correlated reduced returns from an insurance investment portfolio combined with large underwriting loss pay outs. There are potentially several more candidate scenarios beyond these six, for natural or climatic events on a similar or worse scale that could cause loss to both sides of the insurers' balance sheet.

In generating the Cambridge Global Risk Index, an estimate of potential shocks to the global economy that could result from threat events impacting cities that generate around half of the world's GDP, the research team at the Cambridge Centre for Risk Studies identified natural catastrophe scenarios with potential for trillion dollar economic losses.[1] In addition to evaluating the earthquakes, windstorms, and volcanic eruptions that could potentially impact major concentrations of economic exposure around the world, the study also identified further scenarios. These include rare and extreme events such as the potential for multiple river systems to flood multiple major cities in Europe, a typhoon and associated flooding impacting the South China coastline; extreme flooding in many cities in Asia during an extreme monsoon season; a tsunami that impacted many cities around the Pacific rim; and other climatic and geophysical risks.

It is also possible that market-impacting losses could result from multiple natural catastrophe events occurring in a single year or within a season of a few months. Several smaller events could cause a combined loss that would be sufficient to trigger the kinds of market consequences described here, particularly if they occurred within a short period of time. These could be coincidental occurrences of independent events, such as the occurrence of earthquake events at the same time as windstorms. It could also result from a sequence of weather events that may have underlying correlation, such as a series of hurricanes making landfall on highly populated regions during an active season, or from a destructive hurricane in the US transitioning into an extra-tropical cyclone that hits Europe with strong wind speeds. Underlying weather cycles such as the North Atlantic Oscillation and El Niño Southern Oscillation could result in clusters of severe weather events on different sides of the globe, including hurricanes, typhoons, monsoon rain fall patterns, wild fires, and droughts.

How much worse could it get?

For this study we selected events of large magnitude, around the trillion dollar threshold of loss that would cause effects on the market. More destructive events are possible, and these would cause significantly greater market impacts. Multi-trillion events, or even larger, would be even more disruptive to the markets and potentially result in even greater depreciations to investment portfolios and balance sheet impacts. This report has not analysed how increased scales of loss would impact insurers' balance sheets, but estimates suggest that increases in the scale of loss from a destructive event could have non-linear consequences – i.e. these could potentially cause tipping points for large scale devaluation of investment portfolios and major balance sheet impacts.

The magnitudes of the chosen scenarios are thought to be towards the upper end of current scientific constraints, but it is plausible that even larger magnitude events could occur. Certain circumstances could also make these example scenarios even more destructive and costly than our best estimate assumptions – secondary follow-on perils such as major flood events following hurricanes, or conflagrations following earthquakes, could greatly increase the total resultant loss. Volcanic eruptions can occur that are orders of magnitude larger than the VEI 6 ('colossal') events we model – there have been more than 60 known VEI 7 ('super-collossal') eruptions in geological history and records of VEI 8 ('mega-collossal') eruptions.

[1] Cambridge Centre for Risk Studies (2016); *Global Risk Outlook for 2017*

All large-scale catastrophes are followed by cost inflation as a result of suddenly increased demand for repair and reconstruction resources. Our modelling assumes standard assumptions about post-disaster inflation rates, but demand-driven inflation is very non-linear and under more pessimistic assumptions cost escalation could make a disaster very much more expensive, and greatly increase the recovery time, both of which would generate more impact on the financial markets.

Our assessment assumes that markets react rationally and proportionately. It is possible that markets could respond more negatively to these events. For example if a future catastrophe were to impact concentrations of headquarters of high value companies – perhaps Silicon Valley in Northern California, or clusters of locations of the big companies of the digital economy (Google, Apple, Facebook, Amazon), even if the companies themselves are not disabled from functioning, then investor sentiment could mark down these sectors more strongly and cause market downturns beyond those expected.

The scenarios could potentially have even more economic impact if they were compounded by follow-on catastrophes. The 2011 Tohoku earthquake in Japan triggered a tsunami that caused a nuclear meltdown. Similar follow-on catastrophes could magnify the impact of a trigger event. Natural catastrophes could potentially cause widespread and lengthy power outages and disruptions to communications and information technology that could prove to be bigger amplifiers of economic loss than has been expected here. Catastrophes exploit the weaknesses in a system. It is possible to imagine scenarios where a natural catastrophe damaged a biological research laboratory and enabled the release of a pathogen that caused a global pandemic. There are events in history where natural catastrophes have triggered geopolitical crises, and resulted in social unrest, political and civil disorder, regional conflicts, and interstate wars. A natural catastrophe may not need to be the cause of a further crisis – any additional events that coincidentally occur while the region and the economy is still weakened and recovering will have a stronger market impact than if they happened at another time. And conversely if the natural catastrophe were to occur during a period of economic or financial crisis, the consequences could be very much more severe.

Finally, it is also possible that very much larger market impacts could also occur from several large magnitude natural catastrophe events occurring in a single year or season. The insurance industry is becoming used to ever-increasing record years for total losses from major catastrophes. An extreme year could see unexpectedly large numbers of massive catastrophes coinciding in different regions of the world, with a resultant market perturbation that would be damaging for the balance sheet.

How likely is this scale of loss?

In Section 4, we present the six scenarios in detail and conclude with a summary of the return periods of the loss level that each scenario represents for its own geographical market and peril. Each has a very low annual probability, i.e. a long return period, mostly over a thousand years, so individually each scenario might potentially be discounted as being too remote to be of concern to enterprise risk managers. However, the return period for an occurrence of any one of these events, which has the ability to disrupt market returns from high quality investment portfolios, is estimated to be around 1-in-200 years, around the benchmark for Solvency II capital requirements.

The number of events that could cause balance sheet impacts from underwriting loss combined with reduced investment returns may make this a material consideration for capital risk management.

The commonly-accepted assumption that market risk has a very low correlation with underwriting risk, may be challenged by work of this type. There are clearly levels at which market risk can be triggered by large loss events.

The use of scenarios derived from catastrophe science and events for which probabilities can be estimated is a tractable method for assessing the correlation between market risk and underwriting risk. A scenario-based method could potentially offer a higher confidence assessment for correlation assumptions that could inform or replace conventional methods, such as copula modelling.

Reports like this one and models of scenario events can be used to improve tail correlation assumptions between market risk and underwriting risk.

Section 2: **Introduction**

Correlation between Market Risk and Underwriting Risk

Investment assets are subject to market volatility. In the Great Financial Crisis after 2008, insurers saw devaluations of their investment assets in the order of 20%, with some individual insurance companies disclosing asset devaluations of over 50%.[2] In addition to reducing an insurer's ability to pay claims, this reduction in size of the investment portfolio diminishes an insurer's income – typically 20% of an insurer's income comes from investment returns. Economic downturns and recessions also play a part in market volatility: demand for insurance shrinks, lapse rates increase, and premium rates soften.

Risk benchmarks

Property Natural Catastrophe is one of the most volatile classes of insurance, with the potential for large claims pay outs from natural hazard events, such as tropical storms, earthquakes, and floods. Insurers must satisfy regulators that they hold sufficient capital for specific return periods of loss. Regulations are different in each market, but Solvency II insurance regulation in European markets is benchmarked to 0.05% annual probability of exceedance of loss (1-in-200).

It is a commonly accepted assumption that market risk has a very low correlation with underwriting risk, i.e. that downturns in the market are rarely triggered by the incidence of natural catastrophes and the claims pay outs that result. This assumption is borne out from analysis of large numbers of natural catastrophes that have caused insurance industry losses over past decades and stock market asset valuation fluctuations over the same period – there is very little statistical correlation between the two. There is the chance of random coincidence but no evidence that natural catastrophes cause stock market adjustments or that market adjustments trigger natural catastrophes.

Relative scale of losses

The fact that natural catastrophes do not typically move markets is not in itself surprising. Even the largest catastrophes seen in recent years have had little effect on the main stock exchanges. Significant natural catastrophes cause losses of tens of billions of dollars of destruction of which insurance pay outs that cover only a small proportion of the cost. There have been six natural catastrophe events costing $10 billion or more in the past decade. However these losses are relatively minor in comparison with the scale of the money markets: in on an average day NYSE trading volumes are around $169 billion.

Impact of major natural catastrophes

The costliest natural catastrophe recorded to date is the 2005 landfall of Hurricane Katrina in Louisiana, with an estimated destructive cost of around $150 billion, of which $62 billion was covered by the insurance industry.[3] This is less than a single percentage point of movement on the New York Stock Exchange. The markets were generally unmoved by the Hurricane Katrina loss: the S&P500 index saw an eight-day 3% rally in the days following the hurricane.

The second most expensive natural catastrophe in history, at around $122 billion reconstruction cost, was the 2011 Tohoku earthquake, tsunami, and subsequent nuclear power plant meltdown in Japan. The events caused initial market turbulence; the Tokyo Nikkei index declined 1.7% on the same day though later rallied.[4] International markets across the world dipped slightly with European stocks down 1%, but US markets were trended upwards and continued doing so after the earthquake.

Other major natural catastrophes have tended to have similarly minimal impacts on the markets.[5] The world's most destructive tsunami on 26 December 2004 killed 230,000 people in 14 countries around the Indian Ocean but there was no obvious impact from the world's stock markets: the S&P dipped 3.8% 20 trading days later but later rallied by as much as 35%.

2 Schich (2009)

3 Munich Re (2015)

4 CNN (2011)

5 Nasdaq (2011)

World Trade Center Attack, 9/11, 2001

The most recent catastrophe with a significant impact on markets was the 9/11 attack on the World Trade Center and Pentagon building, with destructive costs estimated at over $90 billion, of which around $32 billion was covered by the insurance industry.[6] Stock markets were closed for the week following the attack. When the market re-opened, the S&P continued its decline from pre-9/11 (it had previously fallen 16%) and lost a further 11.6% in four trading days. The downturn was relatively short-lived and most market indices recovered to pre-9/11 levels within a month.

Could any natural catastrophe cause a market correction?

Is it possible that a natural catastrophe could cause a market correction that would have a significant material impact on an insurer's investment portfolio? In this report, we determine the potential for very large catastrophes to trigger market shocks and subsequent economic downturns that would have an impact on both sides of an insurance company's balance sheet.

What kind of events cause market shocks?

Market adjustments and devaluations occur periodically from a wide range of different causes. The markets typically refer to a devaluation of the stock market by up to 5% as a 'correction'. When a devaluation of 10% or more occurs within a single quarter, this is commonly referred to as a 'crash'.[7] A crash may have a more sustained fall, but most reach the trough of their decline within a six-month period. Recovery from a financial crisis can take many years and a weakened economy can be fragile and experience further crises and devaluations during the recovery. Devaluations of the stock market beyond 15-20% have typically triggered some period of recession (continued negative growth in the economy), with very large stock market crashes, such as the Wall Street Crash of 1929, and the Great Financial Crisis of 2008, being followed by lengthy periods of recession and stagnant or slow economic recovery.

Studies of past stock market crashes provide historical catalogues of events with measurements of peak-to-trough falls as indicators of the severities of the market correction.[8]

Crashes Greater Than	Number of Crises	Average Interval (Yrs)
10%	12	16
20%	9	21
40%	6	32
80%	1	190

Table 1: US Stock Market Crashes since 1800, by peak-to-trough severity

Table 1 summarises the historical catalogue of 28 financial crises by their peak-to-trough severity in the United States since 1800 – i.e. the % of total value of the stock market lost in the crash, from peak measurement to the bottom of the cycle, typically within a period of less than six months. This shows that, for example, a market crash where the stock market has decreased by 20% or more has occurred on average every 21 years over the past two centuries, and a crash of over 40% has occurred on average every 32 years.

The causes of financial crises are conventionally divided into:

- exogenous shocks: triggers from outside the financial system such as a war or a political event;
- endogenous shocks: the financial system corrects valuations or adjusts credit and liquidity.

Less than 10% of financial crises are exogenous. The larger and more frequent causes of stock market crashes are endogenous, where traders lose confidence in market fundamentals and withdraw credit or force a run on banks. The triggers for these include asset value bubble collapses, banking runs, pricing shocks, sovereign defaults, and potentially more recently technological threats such as flash crashes. The Cambridge Centre for

[6] Grossi (2009)

[7] Business Insider (2017)

[8] Reviews of Historical Catalogues of Financial Crises are presented in, for example, Reinhart and Rogoff (2010) and Allen and Gale (2009). A standardised catalogue of historical financial crises has been derived from original research by Cambridge Centre for Risk Studies (publication in preparation)

Risk Studies has studied several of these financial crisis mechanisms and developed stress test scenarios as hypothetical examples.[9]

Severity of events causing stock market shocks

CCRS analyses historical and hypothetical events to understand how the economic fundamentals of an event are correlated to the potential market corrections that would result. Economic output is commonly affected by events that occur, and lost economic production relative to the output that would have been expected without the event occurrence – 'GDP@Risk'- is a measure of the event severity. CCRS estimates GDP@Risk for hypothetical events and, where possible, for historical events. CCRS has published more than 12 stress tests with an estimate of GDP@Risk to the global economy. These studies have also included macroeconomic modelling of the effect of these events on key stock market indicators, such as the S&P500. Historical events have well recorded stock market movements, and, although economic output loss is less verifiable, it can be reasonably estimated.

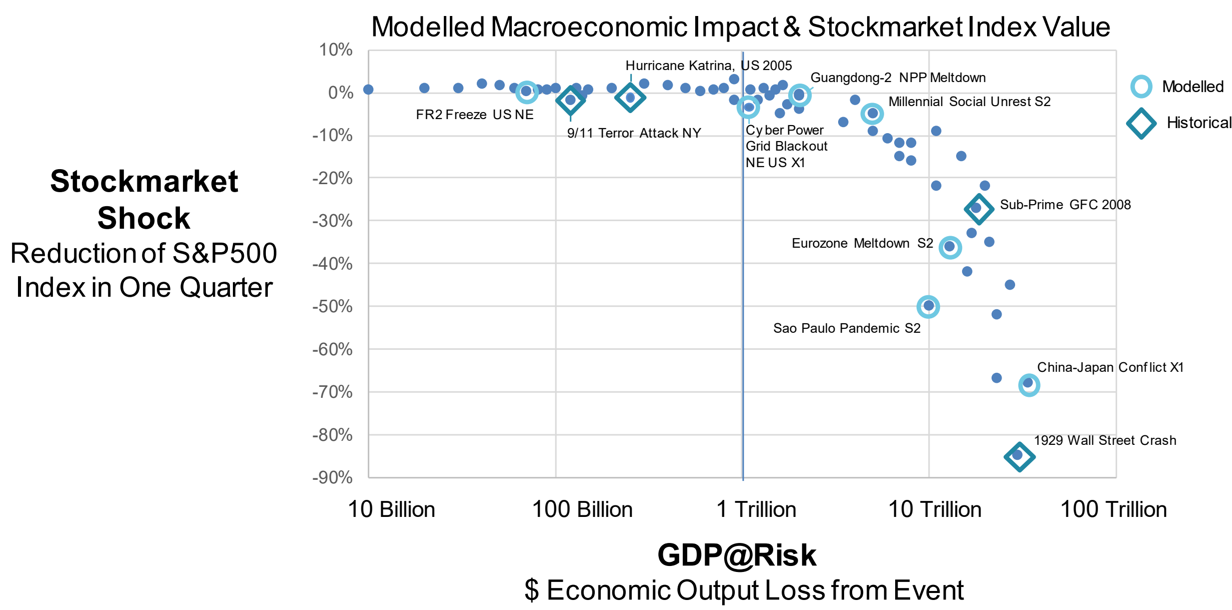

Figure 1: Economic Output Loss and Stock Market Shock from Events, exhibiting the impact of trillion dollar effects on market values

Figure 1 posits a plot of the economic output loss from events, both modelled and historical, correlated with the amount of stock market devaluation shock in a single quarter. The horizontal axis of economic output loss is presented on a logarithmic scale. A number of these plotted events are hypothetical and are analysed using macroeconomic modelling techniques. Historical events are shown with recorded stock market devaluation and estimated global output loss as GDP@Risk.

This chart shows that events that cause very large economic output losses can trigger significant stock market shocks. Minor events are indistinguishable from daily volatility in the markets and market corrections. The inflection point for the level of severity of economic output loss that is correlated with identifiable stock market movements appears to be from around the 1 trillion loss level.

Trillion dollar scenarios

CCRS considers that systemic market impacts occur when event shock losses exceed $1 trillion. The focus of much of the research work being undertaken at CCRS is on catastrophe scenarios that have the potential to trigger economic output losses in excess of a trillion dollars. The Centre is currently studying potential 'trillion dollar scenarios' from a wide range of causes, including finance economics and trade risks, geopolitics and

[9] Financial crisis mechanisms studied by CCRS include asset bubble collapse (Global Property Crash Stress Test Scenario); sovereign default (Eurozone Meltdown Stress Test Scenario); De-Americanization of the global financial system (Dollar Deposed Stress Test Scenario); food and oil price spiral (High Inflation World Stress Test Scenario)

security, technology and space, health and humanity as well as the natural catastrophe risks being explored in more detail here.

If a natural catastrophe event could cause a disruption of economic output of a trillion dollars or more, estimates strongly suggest this has the potential to trigger a stock market devaluation that would impact investment portfolios.

Physical Destruction (Stock Loss) vs Economic Output Loss (Flow Loss)

The most notable characteristic of natural catastrophes is the destruction of physical assets – damage to property, machinery, and infrastructure. The severity of destruction of a natural catastrophe is typically measured in terms of the total cost of destroyed physical assets, usually as a repair cost, reconstruction estimate, or lost value of the damaged property. This is sometimes referred to as the 'economic loss', or 'ground-up loss', to distinguish it from the insurance pay out, which is typically only a proportion of the total repair bill.

In this report, we distinguish the 'destructive cost' of an event from its 'loss of economic output'. Economic output is lost during a destructive event when the physical means of production are put out of action, or are unable to function because of damage to power, transportation, and utility infrastructure, and the labour pool is made homeless or unable to travel to work. In addition, demand for goods are typically reduced during the initial societal disruption and loss of earnings for the affected population, which increases the economic impact of the event. (The stimulus to the local economy of reconstruction investment is considered below).

Third party estimates of 'economic loss' (destructive cost) from an event may, in addition to the costs of damaged property, sometimes include business interruption loss, which is a limited amount of lost revenue or profit that depended on the buildings that were damaged beyond usability. It does not typically describe all the lost economic output that results from a destructive event of this type. Insurance coverages often pay out for business interruption loss from a damaged commercial property, so this estimate may be included in the 'economic loss' or 'ground-up loss' as an input into the estimate of insurance liability for an event.

In economics terms, the difference between 'destructive' cost and loss of economic output ('economic loss') is one of 'stock' against 'flow'. A natural catastrophe typically causes a lot of stock loss and as a result also causes a flow loss. The full impact of a catastrophe is the combined total of stock loss and flow loss. Flow loss is much more difficult to assess than stock loss, which the statistical catalogue principally estimates.

Catastrophes in the early 20th century appear to have caused significantly more destructive cost than economic output loss, even in the most industrialised and advanced economic regions of the world. This may be changing as economic growth is outstripping property appreciation, economic productivity is becoming more vulnerable to disruption, and increasingly interconnected global trading relationships are amplifying localised disruption throughout the trading network. In this study, we model the economic loss from six very destructive natural catastrophes. For these six events, the economic output loss (flow loss) is typically three times the destructive cost (stock loss) of the event. We believe that for large catastrophe events of the future, economic output loss will far exceed the destructive cost.

Trillion dollar natural catastrophes

So far, there has not been a natural catastrophe that has generated an economic loss of a trillion dollars. However, it is worth considering whether events of this magnitude are possible, and what geographies, markets, and assets they would compromise if they did.

The record for the costliest catastrophes is continuously being broken. In 1992, Hurricane Andrew in Florida USA caused $25 billion in damage at the time ($43 billion adjusting to 2017). In 1995, the Californian Northridge Earthquake in set a new record of $49 billion ($90 billion adjusting to 2017). By 2005, Hurricane Katrina's record was for $150 billion ($211 billion in 2017). In 2017, Hurricane Harvey became the costliest natural disaster in the United States since Katrina, with an estimated destructive cost of $125 billion.

The increasing cost of the most extreme events is driven by the accumulation and increasing value of assets in areas of hazard, rather than an increase in the severity of events, although over time we are also likely to experience even more extreme magnitude events that each have very long return periods. If the cost of the most extreme events continues to increase, then it may be only a matter of time before we experience the first trillion dollar natural catastrophe.

Section 3: **Objectives of the Study**

Motivation

Empirical analysis suggests that destructive natural catastrophes have become more costly and more frequent over recent decades.[10] This is mainly due to the increased exposures in the areas at risk, with rising wealth and increased population concentrations in hazardous areas such as coastal regions and earthquake-prone cities. It is also possible that the occurrence of extreme weather events could be becoming more frequent as a result of climate change, although scientific evidence for this is hotly debated.

The insurance market visualises risk transfer into a top-down hierarchy where losses cascade through from the insured policyholders to the ultimate bearers of risk – the re/insurers. When a natural catastrophe occurs, the extent of physical damage determines total economic losses, although a large proportion is usually uninsured (red arrow in Figure 2 below). The insured losses, therefore, are borne by the global insurance market (blue arrows). Claims first affect the primary insurers, but as they only absorb part of these losses, a proportion of this direct exposure is transferred to reinsurers. Among reinsurers, this concentrated risk is diversified through retrocession, while passing only a fraction of losses to the broader financial markets and other institutions through securitisation. Thus, re/insurers retain most of this natural catastrophe related risk.

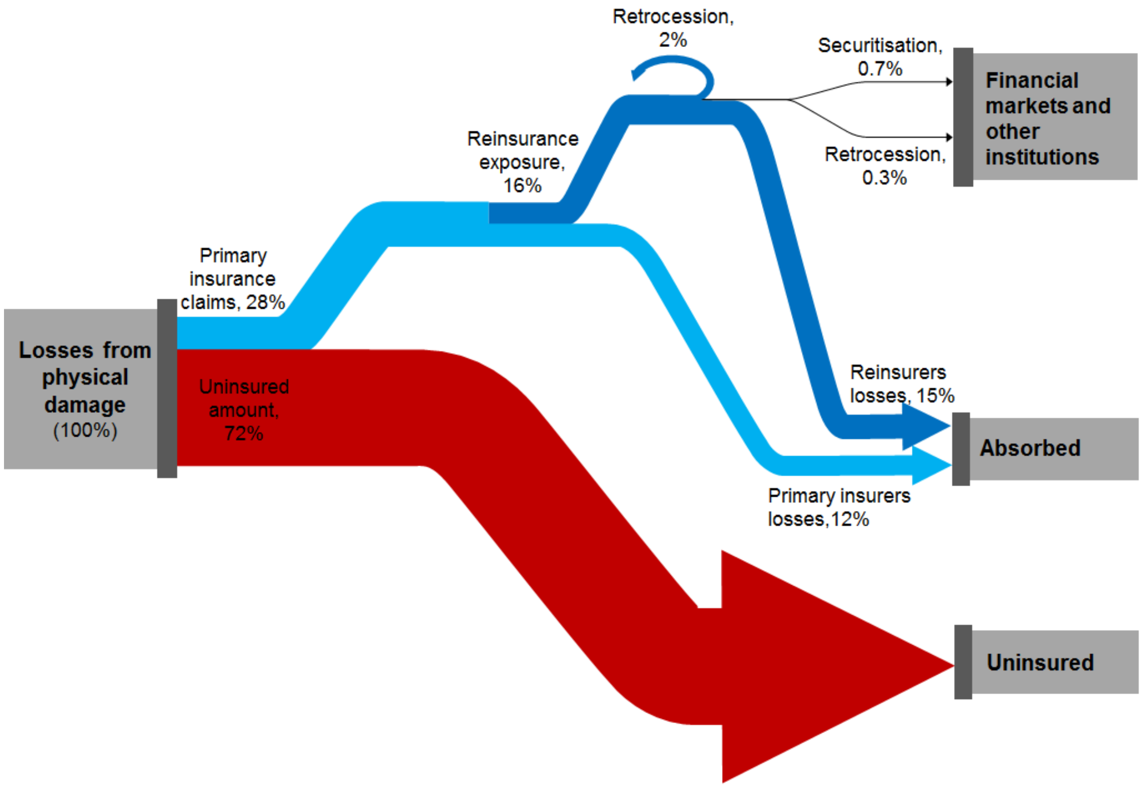

Figure 2: Nat Cat Risk Transfer within the global insurance industry (Data source: von Dahlen and von Peter, 2012; Re-analysis: Cambridge Centre for Risk Studies)

In this research, we present an illustration of the risks posed by highly plausible but extreme natural catastrophes ("Nat Cats"). These scenarios are meant to serve as representative examples of such catastrophes and do not constitute any predictions. Our analysis is aimed at improving the understanding of the potential impact of catastrophes on the economy and financial markets, to assist with financial investment planning, contingency planning and operational risk management, and to help insurers and reinsurers with assessments of balance sheet risks from underwriting losses combined with reductions in investment returns.

[10] Global Reinsurance Forum (2014)

Each Nat Cat scenario may reveal aspects of potential vulnerability for an organisation but these are primarily intended to identify pathways for improving overall resilience to exogenous shocks with wide-ranging impacts.

Research Questions

In line with our motivation for this study, we set out to answer three key research questions:

1. What are the macroeconomic impacts of natural disasters such as earthquakes, hurricanes and volcanic eruptions?
2. To what extent do these natural catastrophes affect financial and capital markets?
3. What are the financial impacts of such disaster events on standardized portfolios and investments?

Literature Review

The academic literature on this subject is plagued with mixed conclusions on the severity of the impacts of such disasters on the financial markets; most studies were carried out at a regional scope and therefore do not extend across borders. There exists a notable gap in literature uncovering the linkages on the international economic spill-over effects of major natural disasters and also in understanding optimal policy responses in the aftermath of a disaster (Zaman, Cavallo, and Noy 2010). While most of these studies provide empirical evidences based on original research, they tend to be limited in scope partly due to data availability and suffer from lack of sufficient elaboration on the intuition behind the transmission of shocks through the system.

Natural disasters can have wide-ranging effects on the real economy such as lower growth characterized by GDP loss due to loss of property and life, inflation for certain goods due to excess demand, deteriorating trade balance leading to exchange rate fluctuations, to name a few (Abe et al. (2014); Groth et al. (2011); Melecky and Raddatz (2015); Hochrainer (2000); Parker (2016)). These impacts necessitate the need for: *government intervention* in the form of aid programs, investing in infrastructure and providing fiscal stimulus for boosting economic growth; and *central bank intervention* to maintain financial stability in financial markets through appropriate policy measures to provide the required liquidity and dampen asset price volatilities. Moody's report on understanding the impact of natural disasters describe the multi-pronged effects at the sovereigns and supra-nationals level when a country is hit by a natural disasters (Moody's 2016). They note that such disasters affect countries by: (i) contracting economic output, (ii) increasing poverty, (iii) worsening trade and fiscal balances, (iv) increasing debt-to-GDP levels and (v) exerting downward pressure on exchange rates while exerting upward pressure on prices. Certain natural disasters also render equity markets vulnerable ((Worthington and Valadkhani (2004); (Ferreira and Karali 2015)) as they impact return rates based on expected recovery times. Foreign exchange markets, however, tend to be less impacted by natural disasters due to government intervention to limit volatility and adjust interest rates following major destructive events (Hatase, et al (2013)).

Section 4: **Trillion Dollar Natural Catastrophe Scenarios**

Selecting scenarios

We selected six examples of natural catastrophe scenarios that could potentially cause around a trillion dollars of destruction cost to rebuild damaged property and built infrastructure. It is not an exhaustive list of all candidate scenarios around the world that could cause a trillion dollars of property loss but is intended as illustrative examples. We chose two examples from each of the most destructive insured perils of earthquake, tropical windstorm (hurricane, typhoon, cyclone), and volcanic eruption. Flood was considered but in many areas of the world flood risk is not a standard exposure of the private insurance market, more typically being covered by national pools or government programmes.

This meant focussing on the areas where very large concentrations of populations, commerce, and high value property could potentially be impacted by large magnitude events, determined by the local seismicity, cyclonic meteorology, and locations of active volcanoes. The largest high value concentrations at risk also tend to be the areas of highest insurance penetration in developed economies, so these represent potential exposures for large international insurers. We were not concerned about the probabilities of these events occurring – by their definition, events of this scale are rare and have long return periods. We consider the likelihood of events of this scale later in this report.

Cambridge Global Risk Index

An indicator of cities most at risk from natural catastrophes is provided by the Cambridge Global Risk Index, updated each year by Cambridge Centre for Risk Studies since 2015. We used our own studies of potential large magnitude events and the likelihood of these impacting 300 cities worldwide that constitute over half of global GDP, to identify cities with the greatest risk of economic output loss from the selected threats of earthquake, tropical windstorm, and volcanic eruption. The risk index, GDP@Risk, is a measure of annual expected loss, derived from convolving the frequency and severity of events from minor to catastrophic. This index provides a ranking of cities most at risk from disruption to their economic output, but does not provide estimates of the potential property damage costs of these events.

RMS Natural Catastrophe Models

We are grateful for the generous assistance provided by Risk Management Solutions, Inc., in providing output from their natural catastrophe models to help us select candidate scenarios, and for the detailed modelling of the property damage that would result from the scenarios selected.

Volcanic Eruption Risk Analysis

We are grateful to the volcanologists from the Department of Geography at University of Cambridge for their assistance in screening and prioritizing the volcanoes of the world by their potential to impact regions of high property value with large magnitude explosive eruptions, to select the candidate scenarios.

Earthquake scenarios

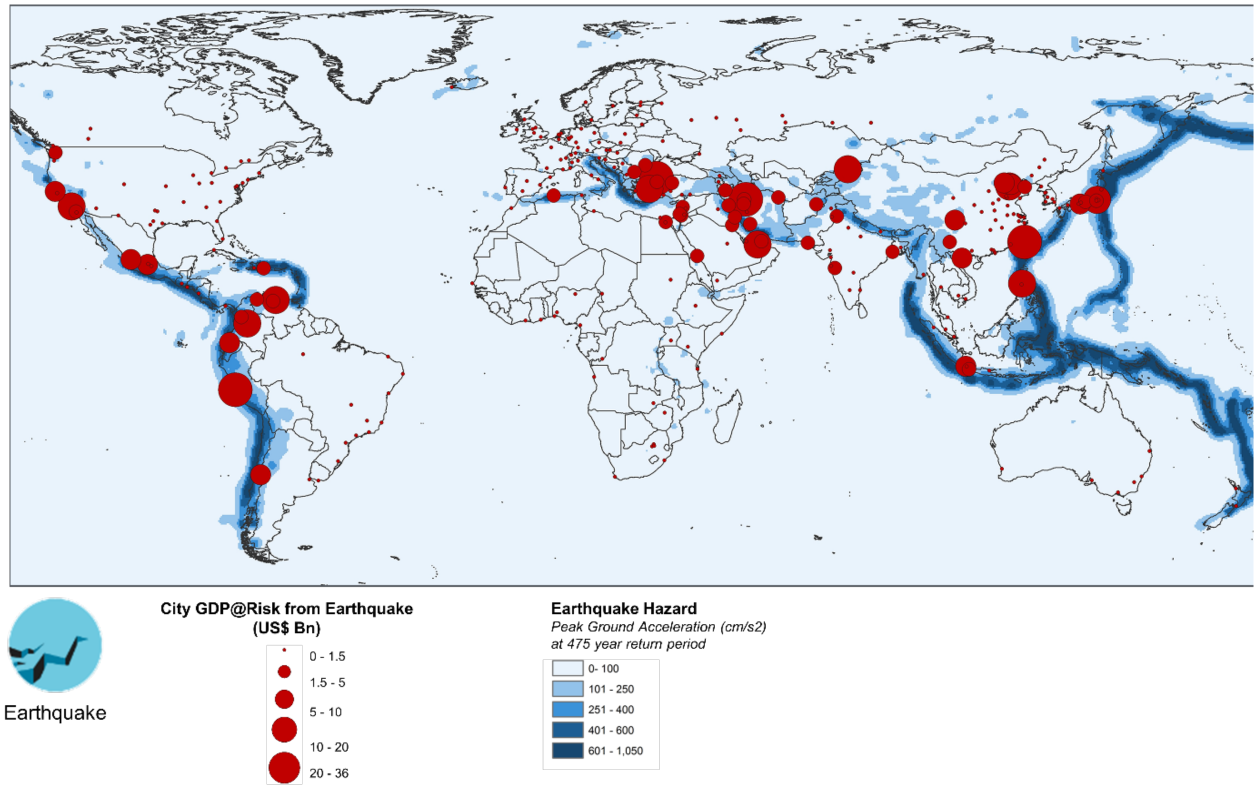

Figure 3: Risk of Economic Shock from Earthquake. Cities of the world most at risk from disruption to their economic output by destructive earthquakes. (source: Cambridge Global Risk Index)

Most earthquakes of small and moderate magnitude are unable to generate a trillion dollars of property damage. The geographical extent of the earthquake footprint is unlikely to encompass the quantities of property and the intensities of ground shaking generated are unlikely to cause damage levels at that scale. A loss as high as a trillion dollars can only result from a very large magnitude earthquake generating strong ground shaking intensities over a wide area, occurring near the centre of a large metropolitan concentration of high value property. The cities where the seismology suggests that this scale of loss could be possible are Los Angeles and San Francisco in United States, and Tokyo in Japan.

RMS maintains a North American Earthquake Model and a Japan Earthquake model. These models consist of tens of thousands of stochastic simulations of earthquakes that are located on known faults and that represent the state-of-the-art in likelihood of fault rupture, attenuation patterns of ground shaking, engineering assessments of vulnerability of different types of property, and potential for follow-on disasters. This is combined with a database of the total industry exposure of locations, types, and value of property across the geographical areas that are impacted. RMS provided the event loss table from their models to help us identify candidate scenarios that fit the criteria we were looking for. Events were selected and RMS provided detailed geographical loss analysis of each of these events. The return period of losses are taken from considering the probability of that level of loss being exceeded in the entire geographical model – i.e. the annual probability of exceeding the loss level generated by the selected Los Angeles scenario from all earthquake events in North America and the annual probability of exceeding the selected Tokyo scenario loss level from all earthquake events in Japan. Note that this loss analysis was carried out prior to the release of the RMS version 17 NAEQ model.

EQ-LA: Newport-Inglewood Earthquake

RMS Analysis Summary

- 2011 US FFEQ ILC
- Analysis Vintage: Sept 2015

- Event Name: CA Newport-Inglewood Flt – All Seg FM2 c
- Maximum Magnitude: 7.7
- Event ID: 20077557
- Source ID: 1461
- Scenario Analysis: Shake + Fire + EQSL with PLA
- Analysed with Industry Exposure Database: 2011 US FFEQ ILC; Building, Contents, BI value per postal code
- Earthquake Casualty Analysis
- Scenario Analysis: Worker's Compensation, 2014 Cost Severities
- Scenario Analysis: Shake Only no PLA
- Analysed with Industry Exposure Database: EDM: 2011 US WC IED; Number of employees per postal code

Event description and modelled losses

The magnitude 7.7 (Mw) Newport-Inglewood earthquake strikes the right-lateral fault line in Southern California, which is part of the continental transform San Andreas Fault. The RMS modelled loss from this earthquake is $863.1 billion in total damages, both insured and uninsured. This estimation reflects damage arising from claims under property, content, workers' compensation, and business-interruption policies, as well as the costs of demolition, clean-up, and reparations.

Analysis of impact to the economy

To the modelled estimate of property destruction, Cambridge Centre for Risk Studies has added an analysis of the impact of this event on the economy of the region, and its spill-over effects to the national economy and international trading partners, including how long it would take for output and consumption to return to normal. Recovery from the devastating Los Angeles' earthquake takes several years. Personal consumption dips 89% in the first year after the event due to population displacement and supply restrictions. National potential output also falls by 11% due to the destruction of physical and human capital stocks. Exacerbated by port closures, national import and export rates fall by a maximum of 8% during the first six months of modelled recovery. Although industrial output slowly recovers to pre-disaster levels thereafter, the impact of the earthquake reflects a permanent loss to the economy.

The estimated value of capital stock damages are summarised in Table 2 below:

Table 2: Estimates of capital stock value destroyed by the Newport-Inglewood earthquake (Source: RMS)

Capital Stocks	Amount (Billion US$)
- Physical (Building, contents, Business interruption)	
Residential	372.4
Commercial	476.5
- Human (Total Casualty: 71,251)	
Workers' Compensation	14.2
Total capital stock value	863.1

Exposure information and industry-wide implications by trade

Figure 4 further illustrates the extent of impact caused by the earthquake, overlaid with major ports located in the disaster zone. Most of the coastal airports and seaports are severely damaged and must be shut down immediately following the earthquake.

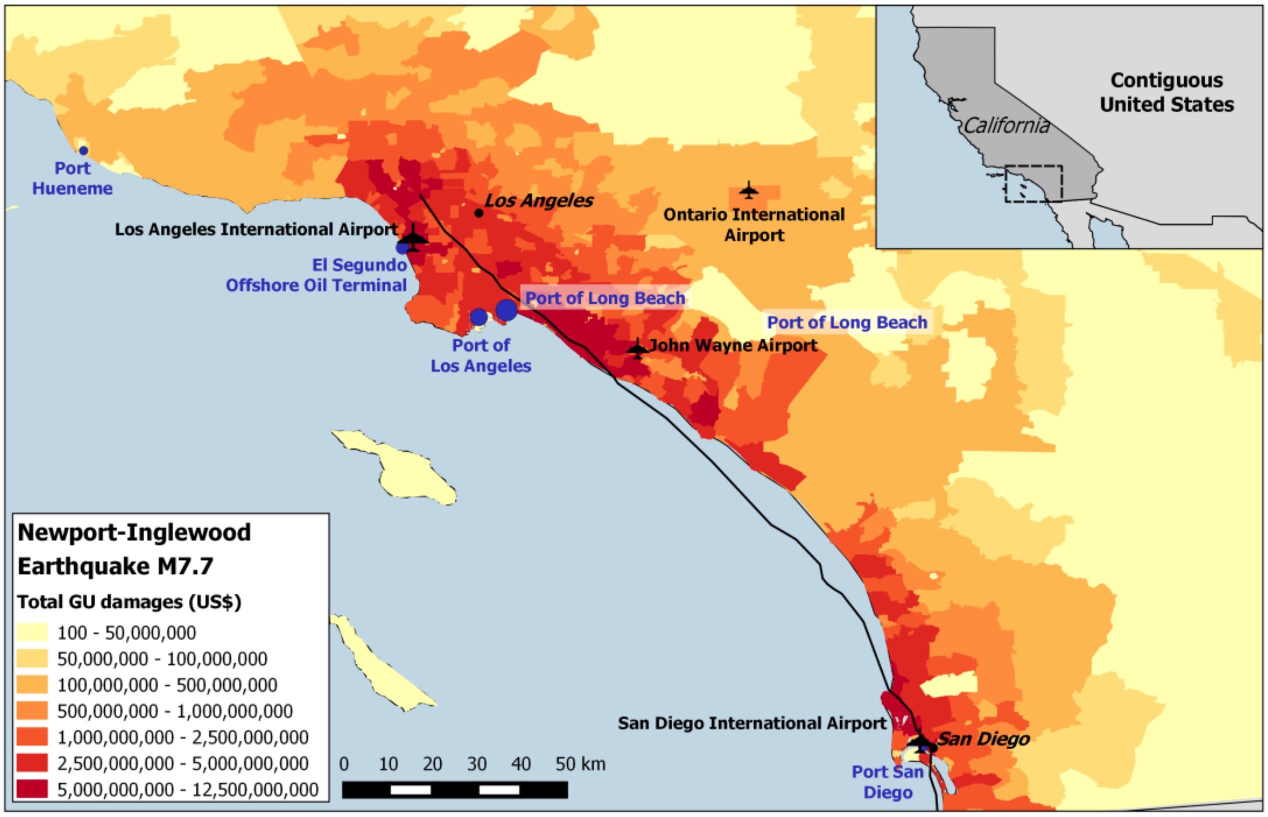

Figure 4: Newport-Inglewood earthquake - Total ground-up damages estimated by RMS and overlay of major ports affected in the disaster zone (Source: RMS)

Most ports are restored to operating conditions within two quarters, although it will take almost one year for aviation and maritime traffic to resume pre-disaster levels. Table 3 details the list of affected major ports that are shut down following the earthquake.

Table 3: Summary list of major ports damage by proportion in the Los Angeles disaster zone[11]

List of major ports damaged in the Los Angeles disaster zone	
Airports in California, US	**Enplanement, 2014**
Ontario International	2,037,346
Los Angeles International	34,314,197
John Wayne Airport	4,584,147
San Diego International	9,333,152
Total US airports affected	50,268,842
Total US enplanement (2014)	759,987,683
Proportion of airports affected (by % of US)	**6.6%**
Seaports in California, US	**Port calls capacity 2014**
El Segundo Offshore Oil Terminal	27,904,402

[11] Datasets retrieved from US Federal Aviation Administration, Passenger Boarding for US Airports (Online). Available from: http://www.faa.gov/airports/planning_capacity/passenger_allcargo_stats/passenger/; US Department of Transportation, Maritime Administration (Online). Available from: http://www.marad.dot.gov/resources/data-statistics/

Port of Long Beach	159,070,439
Port of Los Angeles	114,320,388
Port San Diego	5,285,314
Port Hueneme	5,374,104
Total US seaports affected	311,954,647
Total US port calls capacity (2014)	3,418,774,062
Proportion of seaports affected (by % of US)	**9.1%**

Consolidating damages and long-term recovery efforts

Recovery from the devastating Los Angeles' earthquake takes several years. Personal consumption dips 89% in the first year due to population displacement and supply restrictions because of disrupted maritime and aviation traffic. National potential output also falls by 11% as a result. Exacerbated by port closures, national import and export rates fall by a maximum of 8% during the first six months of recovery. Although industrial output slowly recovers to pre-disaster levels thereafter, the impact reflects a permanent loss to the economy.

The government is also assumed to implement stimulus packages by raising bond yields to minimise foreign investors' capital flight, and hasten and facilitate reconstruction, which boost private consumption, business investment, and public investment temporarily. Global stocks are expected to rebound quickly, while weaker, domestically-tied companies are expected to weaken further. The economic growth rates are spurred in the second year before the economy pulls back and stabilizes to almost pre-disaster levels.

EQ-TKY: Tokyo Earthquake

RMS Analysis Summary

- RMS Japan EQ Model
- Analysis Vintage: Sept 2015
- Event Name: Sagami_1703 M8.1
- Maximum Magnitude: 8.3
- Event ID: 803097
- Source ID: 3486
- Analysed with Industry Exposure Database: 2015 JPEQ EED: Building values only per Chome
- Scenario Analysis: Shake + Fire no PLA
- Tsunami Analysis: Global Tsunami Scenario Catalog; RiskLink Tsunami Accumulation Footprints

Event description and modelled losses

A magnitude 8.3 (Mw) earthquake strikes along the Sagami Trough, impacting the densely-populated Kantō Region, including the Tokyo Metropolis. Over 36 million people live in the Tokyo metropolitan area and another 43 million in the wider Kantō Region. The underwater fault rupture of the Sagami earthquake generates a series of significant tsunami waves that inundate parts of the coastline.

The RMS modelled loss estimate is that the Tokyo earthquake would lead to US$ 1.37 trillion in total damages, both insured and uninsured. This estimation reflects damages arising from claims under building value across all lines of business.

The associated tsunami loss is estimated to add a further 10% to the shaking damage. Tokyo Bay acts as a natural buffer, protecting Tokyo city, the region with the highest concentration of exposure. Historical tsunami wave heights recorded in the area are well within tidal range.

The total estimated value of capital stock damage is summarised in Table 4 below.

Table 4: Estimates of capital stock value damaged by the Sagami earthquake (Source: RMS)

Capital Stocks	Amount (Billion US$)
Earthquake	
Commercial	360.7

Residential	829.2
Industrial	53.8
Total shaking damage	1,243.7
Tsunami (≤ 10% *shaking damage*)	124.4
Total capital stock value destroyed	1,368.1

Analysis of impact to the economy

To the modelled estimate of property destruction, Cambridge Centre for Risk Studies has added an analysis of the impact of this event on the economy of the region, and its spill-over effects to the national economy and international trading partners, including how long it would take for output and consumption to return to normal.

Full recovery from the Tokyo earthquake would take several years. Personal consumption dips to 79% in the first year due to population displacement and restricted supplies from the disrupted maritime and aviation traffic. National potential output also falls up to 21% due to the destruction of capital stocks. Further exacerbated by port closures, national import and export rates fall by almost 40% during the first six months. Although industrial output slowly recovers back to pre-disaster levels, the impact of the earthquake reflects a permanent loss to the economy.

Figure 5 illustrates the extent of impact caused by the earthquake overlaid with the location of major cities and ports lying within the disaster zone. Most of the coastal airports and seaports are severely damaged due to the shake and tsunami waves and are shut down immediately after the disaster.

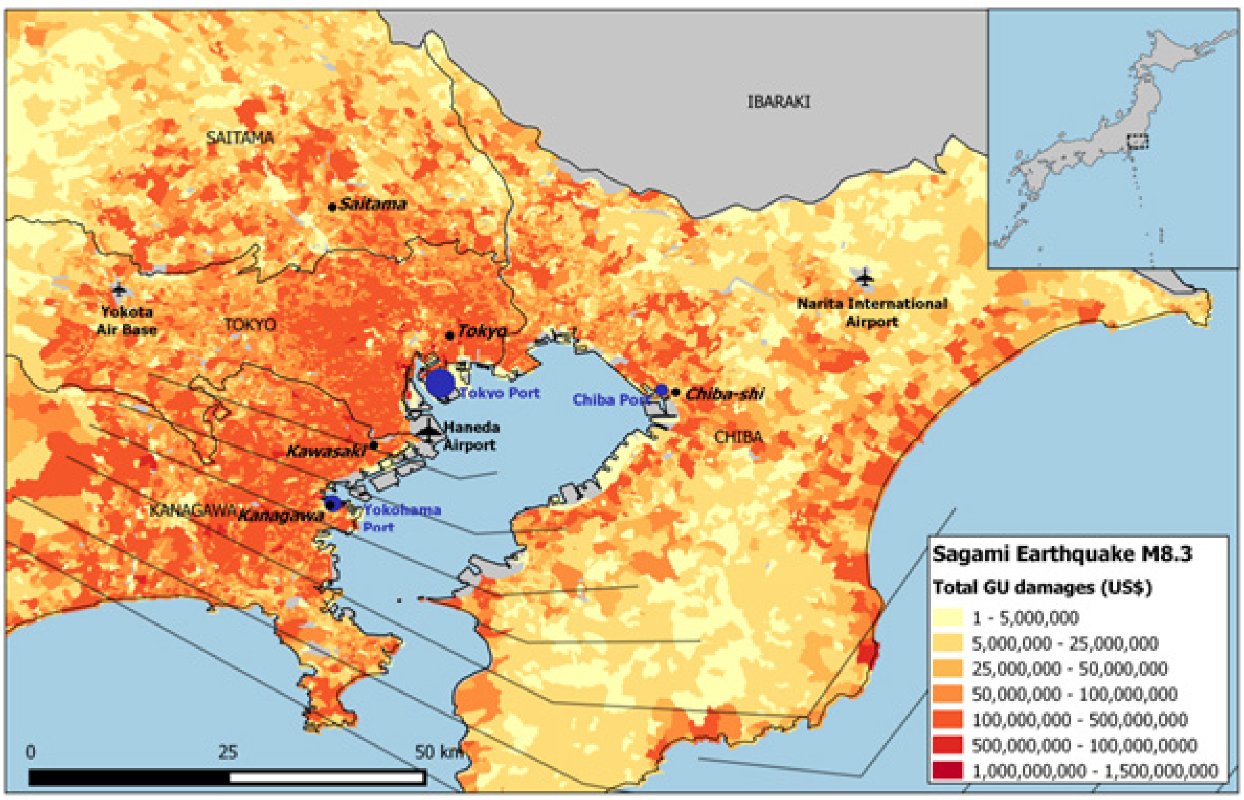

Figure 5: Tokyo earthquake - Total ground-up damages estimated by RMS and overlay of major ports affected in the disaster zone (Source: RMS)

Most ports are restored to operating conditions within two quarters, although it takes almost a year for aviation and maritime traffic to resume at pre-disaster levels. Table 5 details the list of major affected ports that had to be shut down following the natural catastrophe.

Table 5: Summary list of the disruption to major ports and airports as a result of the Tokyo earthquake scenario[12]

List of major ports damaged in the Sagami disaster zone	
Commercial airports in Tokyo, Japan	Enplanements 2013
Haneda Airport	68,577,825
Narita International Airport	32,465,439
Total affected commercial airports in Japan	101,043,264
Total Japan enplanement (2013)	249,376,351
Proportion of airports affected (by % of Japan)	**40.5%**
Seaports in Tokyo, Japan	**Port capacity 2014**
Tokyo Port	4,500,000
Yokohama Port	2,888,220
Chiba Port	41,780
Total affected seaports in Japan	7,430,000
Total Japan port capacity (2014)	19,688,382
Proportion of seaports affected (by % of Japan)	**37.7%**

Consolidating damages and long-term recovery efforts

Full recovery from the Tokyo earthquake takes several years. Personal consumption dips to 79% in the first year due to population displacement and restricted supplies from the disrupted maritime and aviation traffic. National potential output also falls up to 21%.

Market sentiments also suffers from the shake-up as the Tokyo Stock Exchange is among the critical economic and financial infrastructure impacted which sends large volatility waves across global stock indices as stock trading in Japan is closed for three full days. Further exacerbated by port closures, national import and export rates fall by almost 40% during the first six months. Although industrial output slowly recovers back to pre-disaster levels, the impact reflects a permanent loss to the economy.

The government also implements stimulus packages to hasten and facilitate reconstruction which boost private consumption, business investment, and public investment temporarily. Economic growth speeds up in the second year before the economy pulls back and stabilizes to almost pre-disaster levels.

[12] Commercial airport enplanement source https://en.wikipedia.org/wiki/List_of_the_busiest_airports_in_Japan#2013_final_statistics; Seaport capacity: http://data.worldbank.org/indicator/IS.SHP.GOOD.TU/countries, https://en.wikipedia.org/wiki/Port_of_Tokyo, http://www.jiffa.or.jp/en/news/entry-2824.html

Tropical Windstorm scenarios

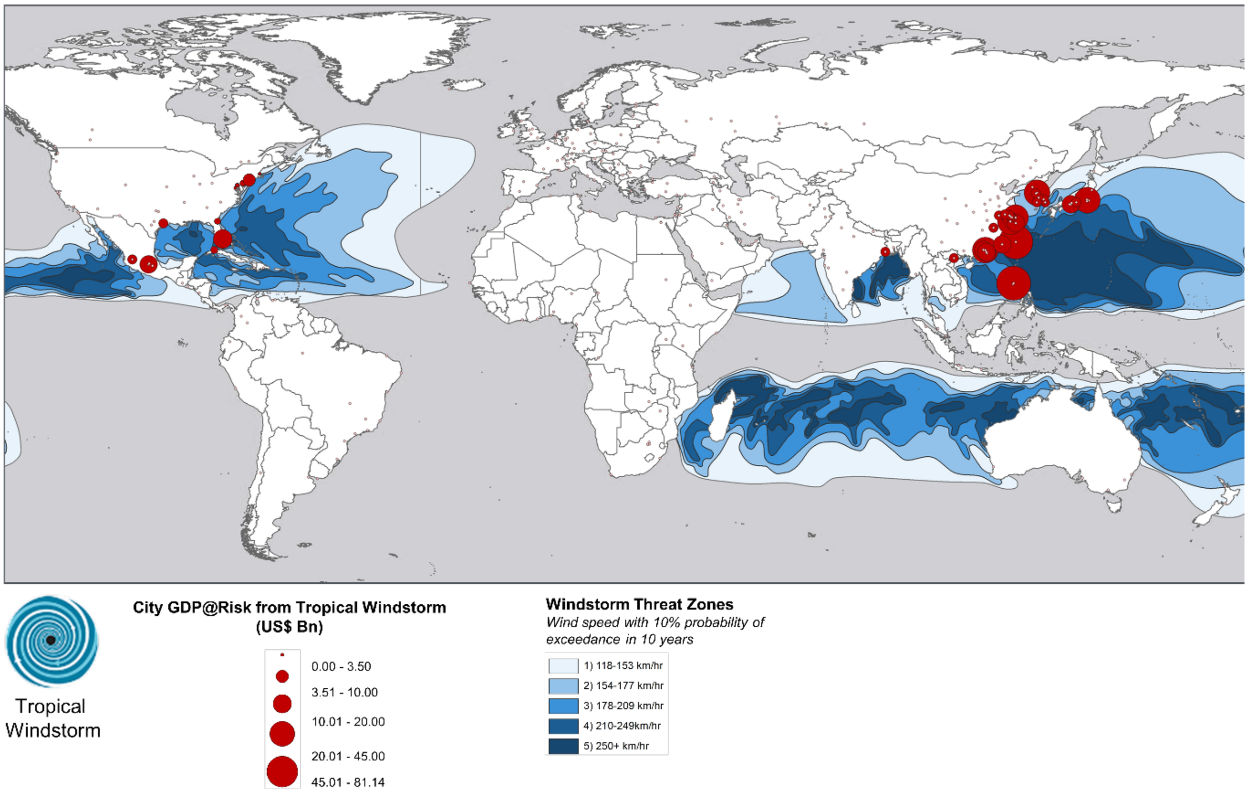

Figure 6: Risk of Economic Shock from Tropical Windstorm. Cities of the world most at risk from disruption to their economic output by hurricanes, typhoons or tropical cyclones. (source: Cambridge Global Risk Index)

Tropical windstorms are intense cyclonic weather systems that form in tropical latitudes over the sea, fuelled by warm sea surface temperatures causing evaporation. They are known by different names in certain parts of the world: as hurricanes in the Americas, as typhoons in southeast Asia, and as tropical cyclones in Australia and the Indian subcontinent.

The windspeeds that can be generated by severe tropical windstorms can be destructive to property, made worse by missile debris and the intense rainfall associated with most of these types of storms. The low pressure weather system pulls sea surfaces higher and drives storm surge flood waters onto the shoreline as the windstorm makes landfall, causing additional damage from flooding and wave action. Storms travel long distances, and can make multiple landfalls, so their track patterns are the key concern for identifying scenarios where property damage could potentially exceed a trillion dollars. Several tropical windstorms are usually generated in each ocean basin each season, with their track patterns varying, so the number of landfalling events is highly variable each year, but occasionally a series of storms follow similar tracks, potentially impacting the same areas with repeat windstorms in a short period of time.

Storm characteristics such as the central pressure, the radius of the storm, forward velocity, and point of landfall determine the severity of the damage that can be caused. Tropical windstorms die as they move inland away from the oceans that fuel them, so major cities on the ocean coastlines at tropical latitudes are most at risk. Tropical windstorms can still be a threat at latitudes further north than the tropics, as they can transition to extra-tropical cyclones, which are less structured weather systems but are still capable of generating destructive windspeeds and sizeable storm surges.

Temperate windstorms that occur at higher latitudes of the world are much weaker wind systems, and although they can impact very large areas such as multiple countries in Europe, they have much less potential to create property loss exceeding a trillion dollars.

Cities with the potential to contribute to a trillion dollar property loss from a tropical windstorm include the major cities in Florida and along the southeast coast of United States, New York, and major cities along the coastlines in southeast Asia, most notably Tokyo, Japan.

RMS models tropical cyclones in all the major oceanic basins. For this study RMS made available analysis from the RMS North Atlantic Hurricane Model which consists of tens of thousands of stochastic simulations of hurricanes with different meteorological characteristics and tracks patterns that characterize the behaviour of tropical windstorms in the North Atlantic, with the ability to cause major damage in United States and other territories in Caribbean and central and Latin America. This is combined with a database of the total industry exposure of locations, types, and value of property across the geographical areas that are impacted.

RMS provided the event loss table from the RMS North Atlantic Hurricane Model to help us identify candidate scenarios that fit the criteria we were looking for. We selected two events with property losses around a trillion dollars, with different geographical characteristics – one impacting Miami in Florida and the other impacting the New York and New Jersey metropolitan area. RMS provided detailed geographical loss analysis of each of these events. The return period of losses are taken from considering the probability of that level of loss being exceeded in the United States.

HU-FL: Florida Hurricane

RMS Analysis Summary

- RMS North American Hurricane Model v13
- Analysis Vintage: Sept 2015
- Peril: Wind Storm
- Region: North America
- US Landfall State: FL; two landfalls: Florida Bay in Monroe County, and Santa Rosa Island, near Pensacola
- US Landfall Category CAT 4
- EventID 2870790
- SourceID 27360
- Name Stochastic Storm
- Description AL2 AFL4 BFL5 CFL5 DFL3 GA1 LA0 MS0 SC0 GM3 AN0 BS4 CH3 CY0 PR0 TC2; SAL0 SAFL2 SBFL5 SCFL3 SDFL0 SGA1 SLA0 SMS0 SSC1 SBS2
- Industry Loss: IED_EED_OP_EP; EP and AAL metrics for Wind-Only, Wind+Default Surge, and Wind+Full Surge model runs of US IED, US EED, and Offshore Platform IED

Event description and modelled losses

What begins as a normal tropical system of low-pressure clouds and thunderstorms rapidly intensifies upon entering the Gulf Stream, growing to a Category 4 hurricane in under 6 hours. . The hurricane makes landfall in Florida with sustained winds of over 147 mph into Florida Bay, Monroe County. After moving across the Gulf of Mexico, it makes second landfall near the Santa Rosa Island, near Pensacola, but with lower sustained winds of 127 mph and at Category 3 intensity. The RMS model loss estimate for this Florida hurricane is US$1.35 trillion of total ground-up (GU) loss, i.e. the total property loss whether insured or not, after recognising known salvage and subrogation.

Analysis of impact to the economy

To the modelled estimate of property destruction, Cambridge Centre for Risk Studies has added an analysis of the impact of this event on the economy of the region, and its spill-over effects to the national economy and international trading partners, including how long it would take for output and consumption to return to normal.

Recovery from the hurricane event takes around a year, after a sharp decline of up to 17% in output potential immediately following the shock.

Potential output improves after three quarters. Further exacerbated by port closures, national import and export rates fall by approximately 5% within a fortnight of the disaster. Repopulation of the affected area takes up to two years following the evacuation, as many homes are too damaged to return to.

Personal consumption dips to 83% in the first quarter after the disaster before slowly recovering over the next seven quarters as the government implements stimulus packages to facilitate reconstruction works. The national economy picks up and, by the middle of the second year, national output is restored to pre-disaster levels, although the output loss suffered during the disaster registers a permanent loss to the economy.

Exposure information and industry-wide implications by trade

Figure 7 illustrates the extent of impact caused by the hurricane, overlaid with the locations of major ports and cities in the disaster zone. Most of the coastal airports and seaports are severely damaged due to the sustained wind, and are shut down immediately after the disaster.

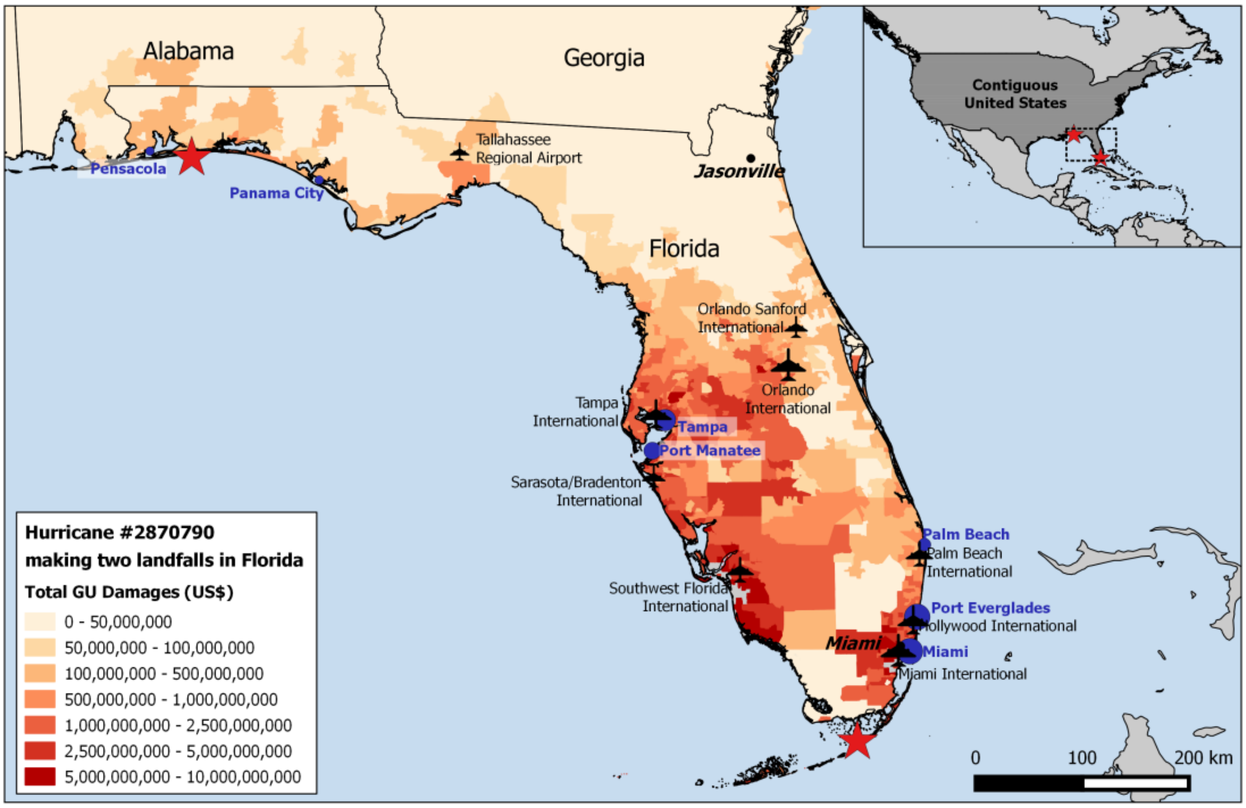

Figure 7: Hurricane making two landfalls in Florida – Total GU losses estimated by RMS with overlay of major cities and ports affected in the disaster zone (Source: RMS)

Most ports are restored to operating conditions within two weeks, though it takes almost a year for aviation and maritime traffic to resume at pre-disaster levels. Table 6 details the list of major affected ports that are shut down temporarily following the catastrophe.

Table 6: Summary list of the disruption to major ports and airports as a result of the Florida hurricane scenario

Major ports and airports disrupted by the Florida hurricane scenario	
Commercial airports in Florida, US	**Enplanements 2014**
Miami International	19,468,523
Orlando International	17,278,608
Hollywood International	11,987,607
Tampa International	8,531,561
Southwest Florida International	3,942,387
Palm Beach International	2,926,242
Orlando Sanford International	998,135

Sarasota/Bradenton International	598,219
Tallahassee Regional Airport	339,078
Total affected commercial airports in US	66,070,360
Total US enplanement (2014)	759,987,683
Proportion of airports affected (by % of US)	**8.7%**
Seaports in Florida, US	**Port calls capacity 2014**
Port Everglades	51,588,445
Port of Miami	31,042,945
Port of Tampa	28,618,146
Port Manatee	4,314,921
Port of Palm Beach	1,459,270
Port Panama City	999,448
Port of Pensacola	494,535
Total affected seaports in US	118,517,710
Total US port capacity (2014)	3,418,774,062
Proportion of seaports affected (by % of US)	**3.5%**

HU-NJ: New Jersey Superstorm

RMS Analysis Summary

- RMS North American Hurricane Model v13
- Analysis Vintage: Sept 2015
- Peril: Wind Storm
- Region: North America
- US Landfall State: NJ
- US Landfall Category CAT 4
- EventId 2868768
- SourceID 25338
- Name Stochastic Storm
- Description CT4 DC0 DE1 MA1 MD0 ME0 NC0 NH0 NJ4 NY4 PA1 RI1 VA0 VT0 WV0 CA2 BM0; SCT2 SDE1 SMA1 SMD0 SME1 SNC0 SNH0 SNJ2 SNY3 SRI2 SVA0

Event description and modelled losses

The hurricane forms in the Caribbean Sea north of Panama, and moves quickly northward, making landfall on the New Jersey coast. While moving ashore into Ocean County, the Category 4 hurricane causes 146 mph winds which also impact the New York metropolitan area. Similar to Hurricane Sandy that had weakened before it impacted New York in 2012, the storm is not classified as a hurricane when it makes landfall, and so is termed a superstorm instead.

The RMS modelled loss for the New Jersey Superstorm event is US$ 1.15 trillion of total ground-up (GU) loss, i.e. the total property loss whether insured or not, after recognising known salvage and subrogation.

Analysis of impact to the economy

To the modelled estimate of property destruction, Cambridge Centre for Risk Studies has added an analysis of the impact of this event on the economy of the region, and its spill-over effects to the national economy and international trading partners, including how long it would take for output and consumption to return to normal.

The windstorm results in damage to critical economic and financial infrastructure. Recovery of the economy following the New Jersey Superstorm event takes around a year after an immediate and sharp decline of up to 14%. Further exacerbated by port closures, imports and exports for the country fall by approximately 10% within a fortnight of the disaster.

The New York Stock Exchange is among the facilities impacted, and is closed for three days, causing investor concerns that result in market volatility of stock indices across the world.

During the first two years, personal consumption dips to 86% within the first quarter before slowly registering signs of recovery as the government implements stimulus packages to facilitate reconstruction work. The national economy picks up until by the middle of the second year national output is restored to pre-disaster levels, although the output loss suffered during the disaster indicates a permanent loss to the economy.

Exposure information and industry-wide implications by trade

Figure 8 illustrates the spatial extent of impact caused by the hurricane, overlaid with major ports and cities located in the disaster zone. Most of the coastal airports and seaports are severely damaged due to the sustained wind impact, and are shut down immediately after the disaster.

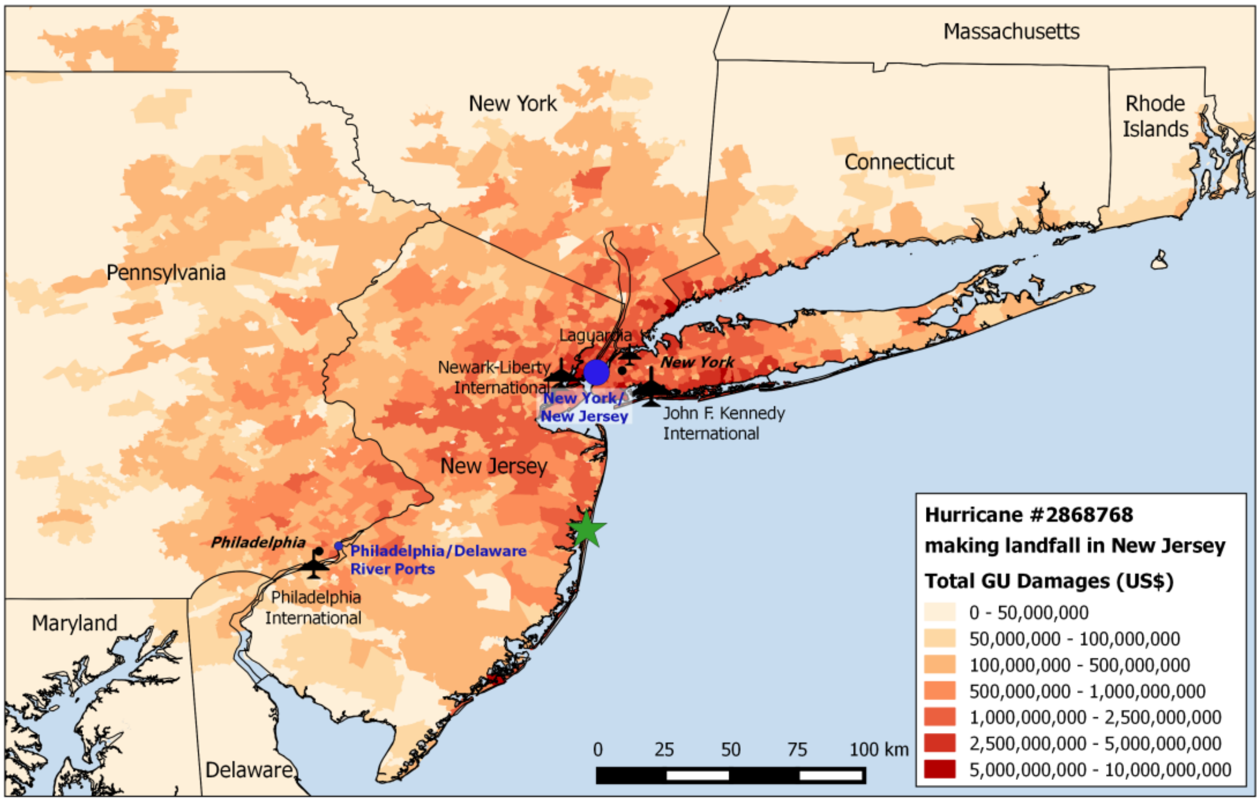

Figure 8: Hurricane making two landfalls in New Jersey – Total GU losses estimated by RMS and overlay of major cities and ports affected in the disaster zone (Source: RMS, Re-analysis: CRS)

Most ports are restored to operating conditions within two week following the hurricane, though it takes almost a year for aviation and maritime traffic to resume at pre-disaster levels. Table 7 details the list of major affected ports that are shut down temporarily following the natural catastrophe.

Table 7: Summary list of the disruption to major ports and airports as a result of the New Jersey windstorm scenario

Major ports and airports disrupted by the New Jersey Windstorm Scenario	
Commercial airports in New Jersey, US	**Enplanements 2014**

John F. Kennedy International Airport	26,244,928
Newark Liberty International Airport	17,680,826
Philadelphia International Airport	14,747,112
LaGuardia Airport	13,415,797
Total affected commercial airports in US	72,088,663
Total US enplanement (2014)	759,987,683
Proportion of airports affected (by % of US)	**9.5%**
Seaports in New Jersey, US	**Port calls capacity 2014**
Port of New York and New Jersey	284,869,775
Delaware River Port	69,971,812
Port of Albany	1,881,708
Total affected seaports in US	356,723,295
Total US port capacity (2014)	3,418,774,062
Proportion of seaports affected (by % of US)	**10.4%**

Volcanic eruption scenarios

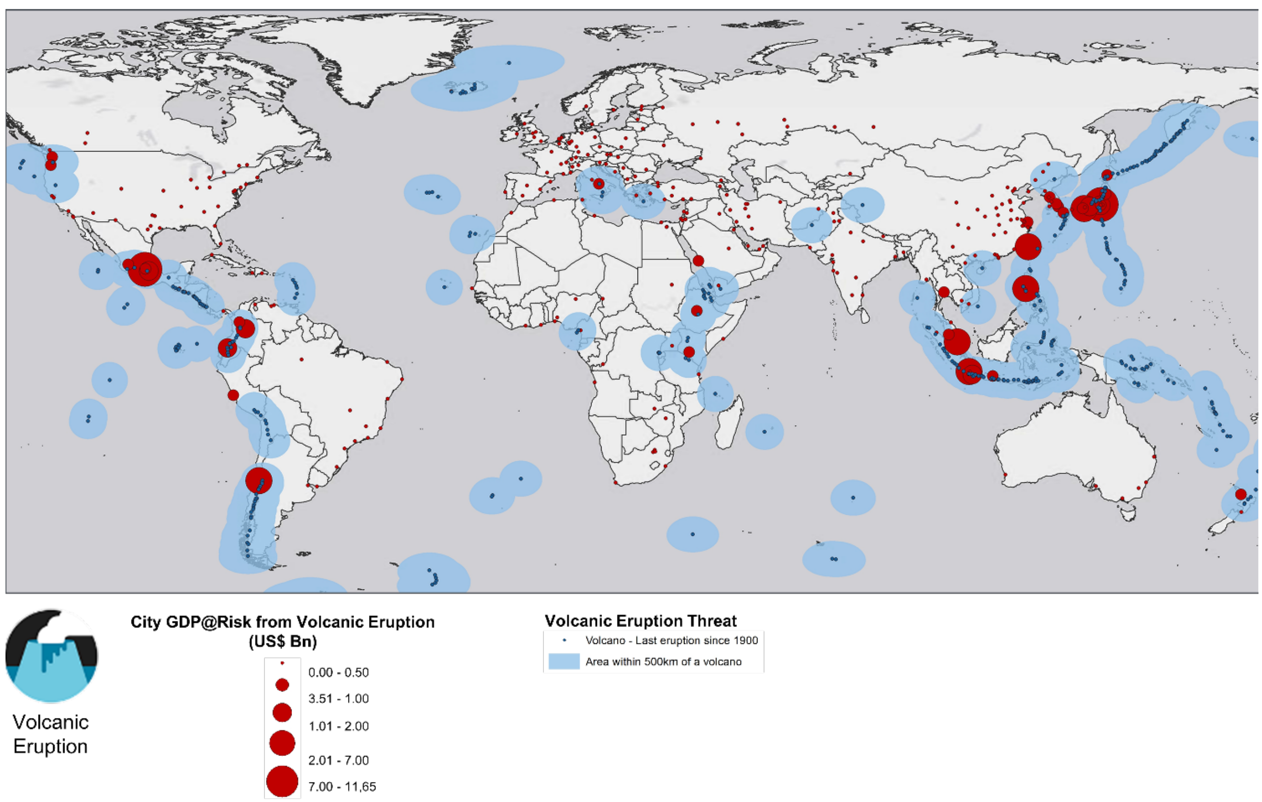

Figure 9: Risk of Economic Shock from Volcanic Eruption. Cities of the world most at risk from disruption to their economic output by volcano activity. (source: Cambridge Global Risk Index)

Volcanic eruptions causing property damage to major urban areas are rare, but large eruptions have the potential to impact very large areas with ashfall deposits that can bury buildings, destroy infrastructure, and be costly to remove. Property insurance policies typically include volcano damage as a covered peril. To identify locations where volcanoes could potentially cause trillion dollar losses, an extensive exercise was undertaken to identify all the active volcanoes within 500km of major cities, as shown in Figure 9. The analysis identified the potential disruption to city economic output of around a trillion dollars, expressed as GDP@Risk. A volcanic eruption of at least Volcanic Explosivity Index 6 (categorised as 'collossal') was selected as the scenario of interest, which results in the ejection of more than 10 cubic kilometres of ash ejected from the volcano, and has a potential to produce damaging ash deposits at distances of hundreds of kilometres from the volcano, and lighter levels of ash that will damage machinery and prevent aircraft from travelling at distances of thousands of kilometres. An eruption of VEI 6 occurs somewhere in the world around once a century.

Cities identified as being threatened by volcanoes were reviewed by volcanologists from Department of Geography at University of Cambridge to identify suitable candidate scenarios for detailed modelling.

The volcano scenarios (VO-MA and VO-RA) concern two active volcanoes located near major cities and concentrations of property value. Mount Marapi, the most active volcano in Sumatra, Indonesia, which last erupted in 2014, and Mount Rainier, a volcano which last erupted in 1894. Both have had eruptions within the historical record of VEI 2 eruptions, but both have the potential to erupt with a VEI > 8 (described as super-colossal), with far-reaching effects.

Modelling volcanic eruption ash footprints

A web-interface 3-dimensional model (Ash3d) for Eulerian atmospheric tephra transport and deposition developed by the United States Geological Survey (USGS) is used in our study to simulate the impacts of the volcano depositions and ash clouds.[13]

The Ash3d models the transport of volcanic ash into a three-dimensional (3D) grid of cells, dependent upon a user-specified tephra volume and plume height. Subjected to a time-dependent 3D wind field imported from a numerical weather predicted model, the model outputs demonstrate the potential volcanic hazards not limited to the immediate areas of the volcano, but also forecasts the spatial extent, magnitude of tephra deposition, and concentration of ash clouds dispersal.

VO-MA: Eruption of Mount Marapi

Event definition and exposure information

A 'colossal' (VEI 6) volcanic eruption occurs at Mount Marapi, a volcano located in the province of West Sumatra, Indonesia. The eruption is the next significant to occur in Indonesia after Mount Tambora, one of the most violent eruption in recorded history in 1815.

The eruption causes volcanic ash clouds and fine tephra deposits to be transported across the Malacca Straits towards Singapore and Malaysia. An ejecta volume of more than 50 km^3 rises to a 34 km column height into the atmosphere and causes heavy (>25 mm) tephra spread in at least three provinces within 48 hours of the eruption.

13 Mastin et al. (2013).

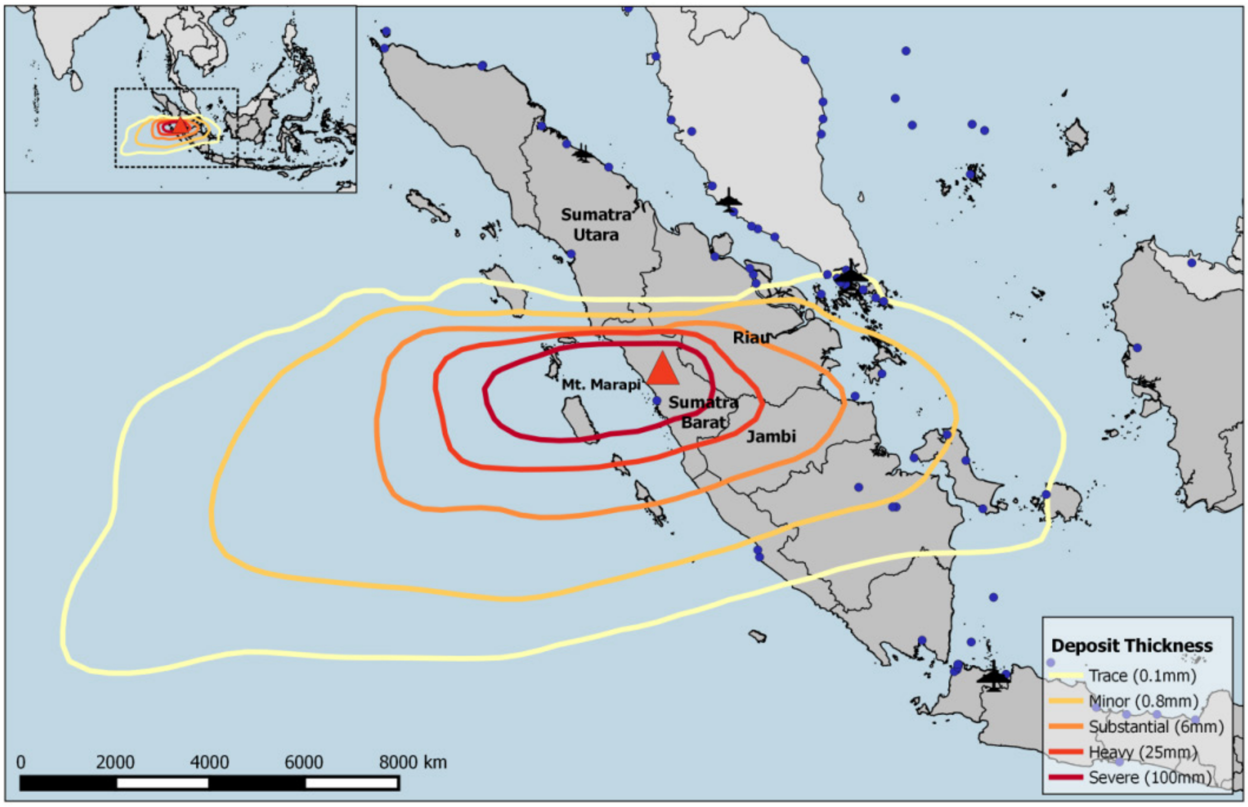

Figure 10: Tephra deposit thickness over Mount Marapi and Indonesia modelled by the Ash3d simulation

The immediate aftermath of the eruption is devastating. Figure 10 illustrates one of the main outputs from the Ash3d model, reflecting the extent and impact of tephra deposits for the given prevailing wind patterns of the region. Padang, the capital of West Sumatra, is heavily impaired by ash fall and almost the entire province and its critical infrastructure is covered in more than 25 mm of tephra, such that 100% of the capital stocks in West Sumatra are damaged. Neighbouring provinces, Jambi and Riau, are also affected by minor (<6 mm) tephra deposits, summing the total Indonesian capital stocks damage up to 3%.

The localised wind conditions in Southeast Asia are subjected to seasonal variations in regional monsoons and therefore are highly mercurial year-round. A more localised effect, known as the Sumatra Squall, features strong wind gusts developing over Indonesia and move eastward towards Singapore and Malaysia.

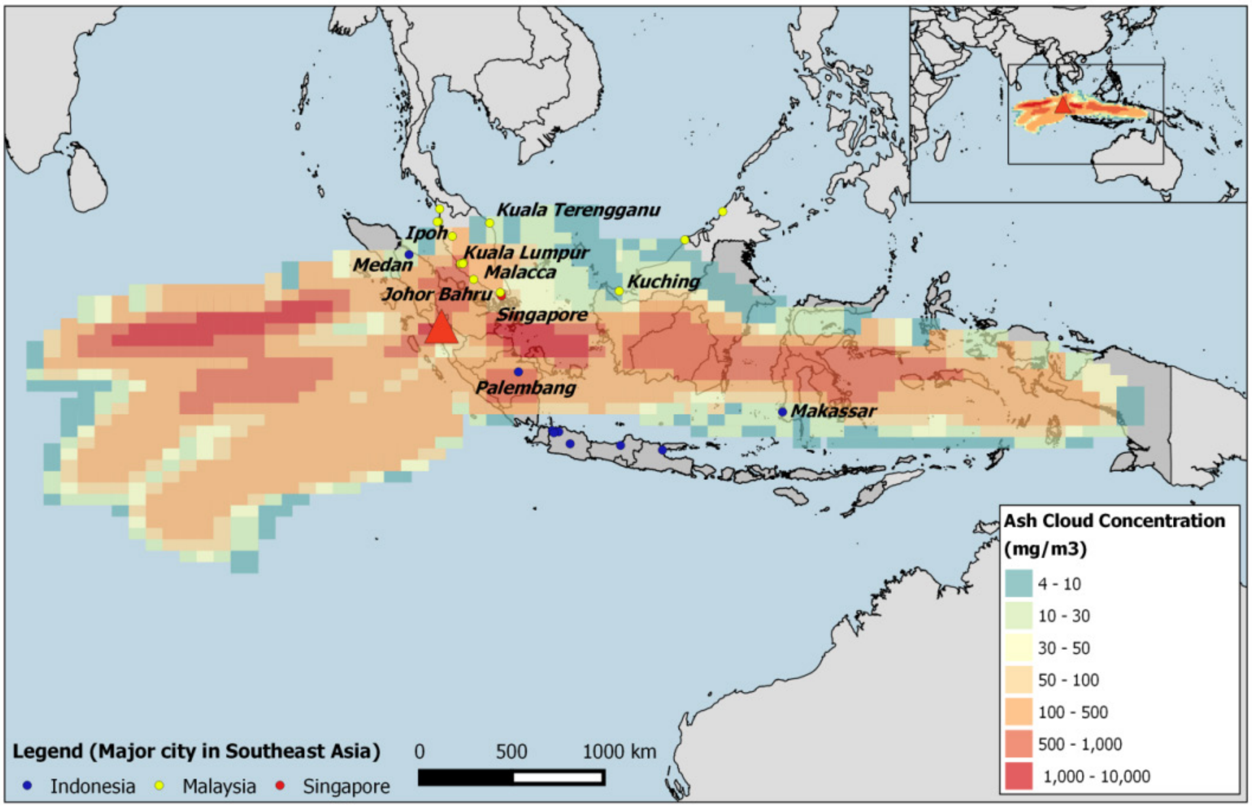

Figure 11: Ash cloud concentration over Southeast Asia modelled by the Ash3d simulation

Carried by strong wind gusts from Indonesia, visibility in various airports across Indonesia, Malaysia, and Singapore is also extremely low. Large cities affected in Peninsula Malaysia include: Malacca, Kuala Lumpur, Ipoh, Kuala Terengganu; while those in East Malaysia include Kuching (Figure 11).

The aviation industry is significantly impacted and many industry sectors such as manufacturing and tourism suffer from severely disrupted supply chains and restricted cross-border trades and economic activities.

Table 8: Airports in Southeast Asia closed by the No Fly Zone (NFZ) limit of 4mg/m³

List of major airports affected by volcanic ash cloud (visibility)		
Airports in Indonesia	Enplanement 2014	
Kualanamu International Airport		8,304,710
Sultan Hasanuddin International Airport		9,623,337
Total Indonesian airports affected		27,036,834
Total Indonesia enplanement (2014)		17,928,047
Proportion of airports affected (by % of Indonesia)		**20.2%**
Airport in Malaysia	Enplanement 2014	
Kuala Lumpur International Airport	48,000,000	
Total Malaysia airports affected		48,000,000
Total Malaysia enplanement (2014)		83,300,000
Proportion of airports affected (by % of Malaysia)		**57.6%**
Airport in Singapore	Enplanement 2014	

Singapore Changi Airport	54,100,000	
Total airports affected		54,100,000
Total Malaysia enplanement (2014)		54,100,000
Proportion of airports affected (by % of Singapore)		**100%**

Table 8 above summarises Southeast Asian airports that are closed due to poor visibility and health issues resulting from the Mount Marapi eruption. The aviation industry is significantly impacted, and many industry sectors such as manufacturing and tourism suffer from severely disrupted supply chains and restricted cross-border trades and economic activities.

Long-term effects: The long volcanic winter

The long-term impacts of the Mount Marapi eruptions are also significant. Global mean temperatures fall 1°C for up to three years, resulting in harsh climate abnormalities that lead to major global food shortages. Unpredictable rainfall patterns and unusually low summer temperatures cause massive crop failures across the world, leading to soaring food prices and high global inflation in the summer months of the second year. It is not until the beginning of the third year after the eruption that technological advances catch up with the crisis and help to rebalance global food supply and demand.

VO-RA: Volcanic Eruption of Mount Rainier (VO-RA)

Event definition and exposure information

A 'colossal' (VEI 6) eruption occurs at Mount Rainier, a volcano located in the US state of Washington. The eruption is the most significant to occur in the Contiguous United States since the 1980 eruption of Mount St. Helens, also located in Washington State. Volcanic ash clouds and fine tephra deposits are transported considerable distances across to the south of Canada and the eastern US. An ejecta volume of more than 50 km^3 rises to a 34 km column height into the atmosphere and causes heavy (>25 mm) tephra deposition in at least three US states within 48 hours of eruption.

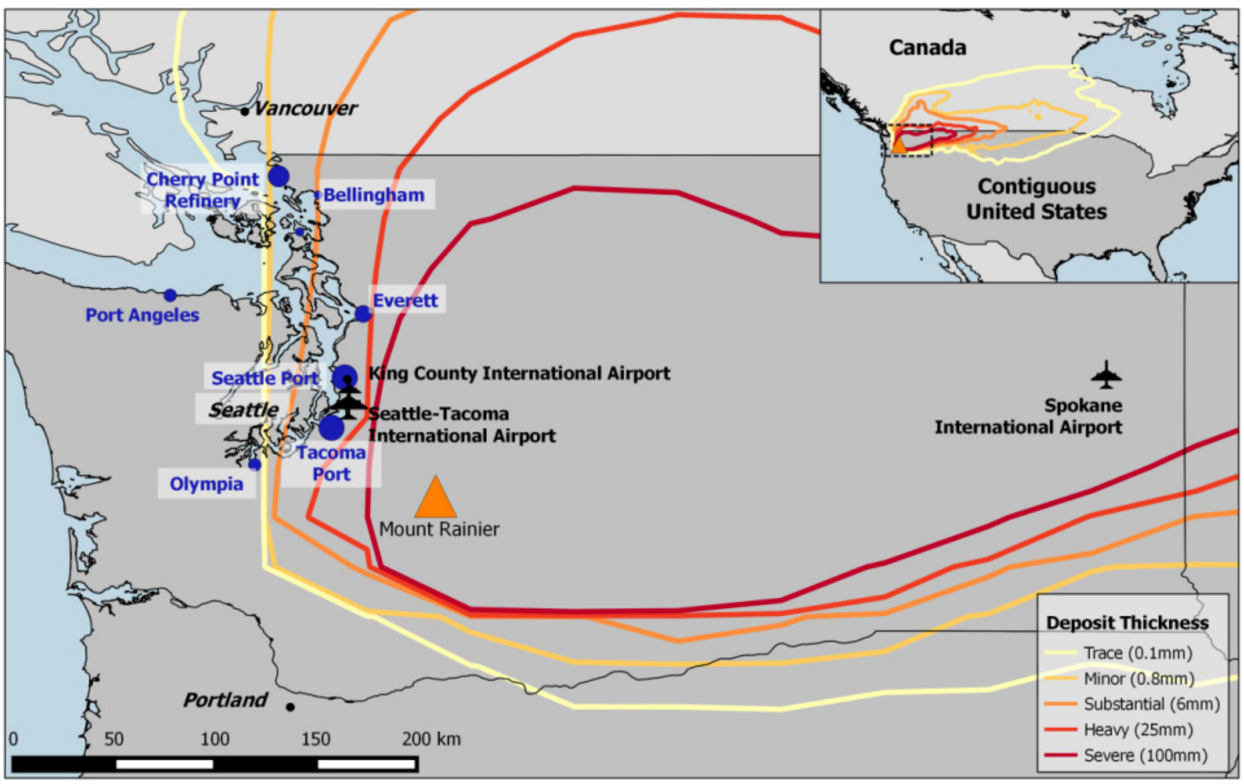

Figure 12: Tephra deposit thickness over the state of Washington modelled by the Ash3d simulation

Figure 12 illustrates one of the main outputs from the Ash3d model, reflecting the extent of tephra deposition categorised according to the tephra thickness, for the given prevailing wind patterns of the region. The city of Seattle is heavily impaired by the thick tephra deposition and, with almost the entire state and critical infrastructure blanketed with more than 6mm of tephra, capital stocks are badly damaged by the eruption. The neighbouring states of Montana and Idaho are also affected by minor (<6 mm) tephra depositions, summing the total US capital stocks damage at slightly more than 3%.

Thick tephra depositions from the eruption also bury three major airports and seaports, listed in Table 9. These ports represent close to 2.5% of the country's total port traffic. Extensive repair works to the structural damages are expected to take place, resulting in port closures of up to two years.

Table 9: Major ports affected by Mount Rainier tephra depositions

Major ports affected by Mount Rainier tephra depositions	
Airports in Washington, US	**Enplanement 2014**
Seattle-Tacoma International Airport	17,888,080
Spokane International Airport	1,445,572
King County International Airport	20,418
Total US airports affected	**19,354,070**
Total US enplanement (2014)	759,987,683
Proportion of airports affected (by % of US)	**2.5%**
Seaports in Washington, US	**Port calls capacity 2014**
Port of Everett	2,924,285
Port of Seattle	38,948,526
Port of Tacoma	41,493,128
Total US seaports affected	**83,365,939**
Total US port calls capacity (2014)	3,418,774,062
Proportion of seaports affected (by % of US)	**2.4%**

Besides tephra deposition, the ash clouds also create major problems for continuing transportation.

The strong prevailing winds blow from the southwest Pacific Ocean, where clouds form along the coast and move into the Seattle area. Hence, when Mount Rainier erupts, volcanic ash clouds and fine tephra deposits are transported through vast distances across to the south of Canada and the east coast of Contiguous US (Figure 13). Large cities affected in Canada include Vancouver, Calgary, Edmonton, Ottawa and Montreal, while those in Contiguous US include Portland and Boston. Subjected to the strong prevailing southwest winds, accumulation of ash clouds makes visibility in various airports across the US and Canada extremely low.

Ash falls are also known to stay in the atmosphere for up to three weeks (USGS, a), shutting down the all affected airports and seaports temporarily. As a result of the massive aviation disruption caused by the Icelandic Eyjafjallajokull eruption in 2010, the operating procedures in the aviation industry have since been updated: the boundary of the No-Fly Zone (NFZ) is defined to that of ash concentrations greater than 4 mg/m^3 (CAA, 2010). Regions that experience ash cloud concentrations more than 50 mg/m^3 are also deemed unsafe per the minimum health respirable exposure limit recommended by the International Volcanic Health Hazard Network (USGS, b).

Airports and seaports with modelled ash cloud concentrations greater the NFZ threshold of 4 mg/m^3 remain closed for at least one month, severely disrupting tourism, as well as exports and imports of goods and services.

Imports and exports are significantly impacted, with many industry sectors such as manufacturing and tourism suffering from severe supply chain disruptions, restricting cross-border trades and economic activities.

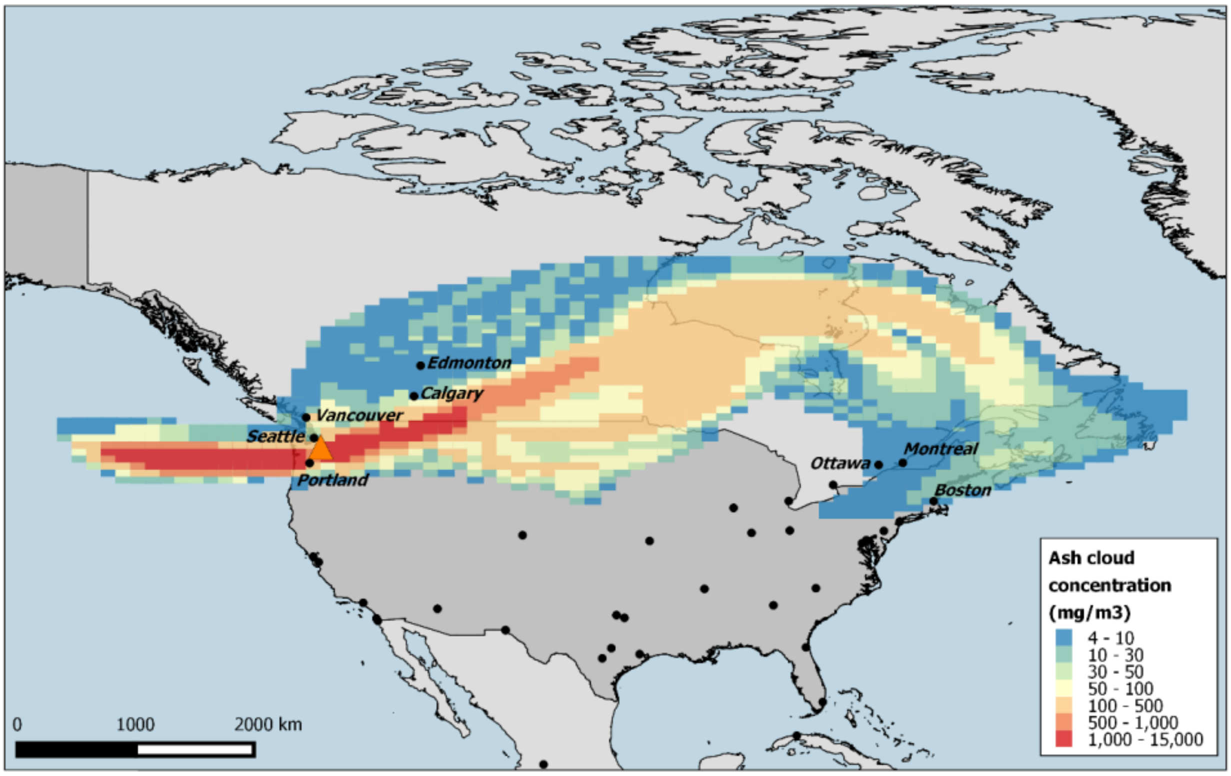

Figure 13: Ash cloud concentrations over the US and Canada modelled by the Ash3d simulation

Table 10 below summarises the list of airports in both the US and Canada that are closed due to visibility and health issues resulting from the Mount Rainier eruption. Accounting for almost 4% and 55% of total enplanements in the US and Canada respectively, imports and exports are significantly impacted, with many industry sectors such as manufacturing and tourism suffering from severe supply chain disruptions, restricting cross-border trades and economic activities.

Table 10: Airports in the US and Canada closed by the No-Fly Zone (NFZ) limit of 4mg/m^3

List of major airports affected by volcanic ash cloud (visibility)	
Airports in US	**Enplanements 2014**
Portland International	7,878,760
Manchester	1,032,964
General Edward Lawrence Logan International	15,425,869
Syracuse Hancock International	987,169
Duluth International	153,583
Range Regional	11,617
Billings Logan International	420,113
Bangor International	288,939
Portland International Jetport	837,820

Total US airports affected	**27,036,834**
Total US enplanement (2014)	759,987,683
Proportion of airports affected (by % of US)	**3.6%**
Airports in Canada	**Enplanements 2014**
Calgary International Airport	14,666,729
Edmonton International Airport	7,710,267
Winnipeg James Armstrong Richardson International Airport	3,626,250
Ottawa Macdonald–Cartier International Airport	4,472,365
Montréal–Pierre Elliott Trudeau International Airport	14,174,375
Québec City Jean Lesage International Airport	1,449,413
Halifax Stanfield International Airport	3,620,107
St. John's International Airport	1,555,795
Victoria International Airport	1,634,887
Vancouver International Airport	18,944,527
Total Canada airports affected	**71,854,715**
Total Canada enplanements (2014)	130,590,000
Proportion of airports affected (by % of Canada)	**55.0%**

Long-term effects: The long volcanic winter

The long-term impacts of volcanic eruptions are significant as global temperatures decrease due to the sheer volume of volcanic ash and sulphuric acid particulates ejected into the atmosphere raising the Earth's albedo brightness. The eruption of Mount Rainier cools global mean temperatures by 1°C for up to three years, resulting in harsh climate abnormalities that lead to major global food shortages.

Unpredictable rainfall patterns and unusually low summer temperatures cause massive crop failures across the world, leading to food prices soaring and global inflation rates rising in the summer months of the second year. It is not until the beginning of the third year after the eruption that technological advances catch up with the crisis and help to rebalance global food supply and demand.

Probabilities of Losses of this Magnitude Occurring

The return periods of events are assigned by the exceedance probability of losses from that peril in that specific geography. These are derived from the event loss tables of the various regional RMS models.

		Return Period (yrs)	Annual Probability	Probability of Non-Occurrence
EQ-LA	Newport-Inglewood Earthquake, CA, USA	1,100	0.00091	0.9991
HU-FL	Florida Hurricane	1,200	0.00083	0.9992
EQ-TKY	Tokyo Earthquake	1,400	0.00071	0.9993
HU-NJ	New Jersey Superstorm	1,150	0.00087	0.9991
VO-RA	Eruption of Mt Rainier, Washington, US	3,000	0.00033	0.9997
VO-MA	Eruption of Mt Marapi, Indonesia	750	0.00133	0.9987
All Events Combined		**200**	**0.00498**	**0.9950**

For the volcanic eruptions, the return periods are assessed for the specific volcano.

The table above shows the annual probability of an event with this loss level or greater occurring in this geography from this peril. The combined probability of non-occurrence can be used to assess the probability that one of these ‘trillion dollar’ property loss events could occur in a given year.

Although each of the individual events has a long return period, and might potentially be discounted as being too remote to be of concern to business managers, the return period for an occurrence of one of these events, which has the ability to disrupt market returns from high quality investment portfolios, is estimated to be around 200 years, around the benchmark for Solvency II capital requirements.

Section 5: **Impacts on the Economy and Financial Markets**

Though the physical devastation of a natural catastrophe is limited by geography, the economic and financial knock-on impacts can be felt worldwide. For example, a flood in Thailand caused by monsoon rains in the fall of 2011 significantly disrupted many industrial supply chains including the global PC industry, as roughly a quarter of all global hard drive manufacturing facilities then operated in the country (Makan & Simon, 2011). The pattern of this type of stress is determined by the placement of the affected economies within the complex web of interdependencies, which determines their exposure and vulnerability to natural catastrophes.

Overview of Macroeconomic Modelling Framework

The nature of our research questions determined two different research tracks within the project – (i) one that explained the effects of shocks on several macro-economic and financial variables to gain insights into how they are effected by natural disasters, and (ii) another which computed the impacts of these macroeconomic responses to such shocks on standardised portfolios, which would provide suitable investment recommendations. Consequently, two different models, viz., the Oxford Economics Global Economic Model (GEM) and Portfolio Impacts Model (PIM), which is an in-house model specifically developed for this purpose, were used to effectively carry out research (see Figure 14). Review of the models, the methodology used for each, and the interpretation of their comprehensive results are provided in Appendices 2 and 3.

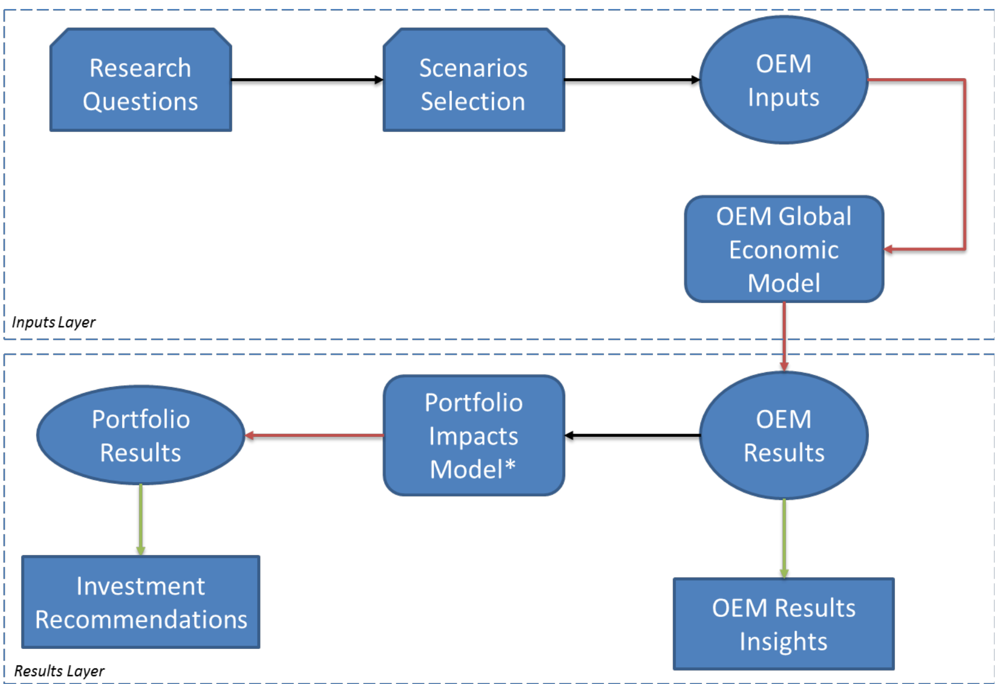

Figure 14: Research methodology work flow

Major equity markets

One key output indicator is the performance of the equity markets is the stock market indices (Figure 15), which are commonly used as proxies for investor sentiment that reflect their perception of the state and outlook for an economy. While considering the maximum downturn, the baseline case (i.e., without any shock), on an average, predicts economic growth throughout the 5-year event window of 2018 – 2022. On the other hand, the natural catastrophe scenarios unambiguously forecast negative impacts on the global economy. The Dow Jones Global Index falls by 19% for the event window under the Mount Rainier volcano (VO-RA) scenario due to the impact on US stock exchanges where trading is assumed to be suspended for three days. Under this scenario, the Wilshire 5000 Total Market Index consequently drops by over 25%.

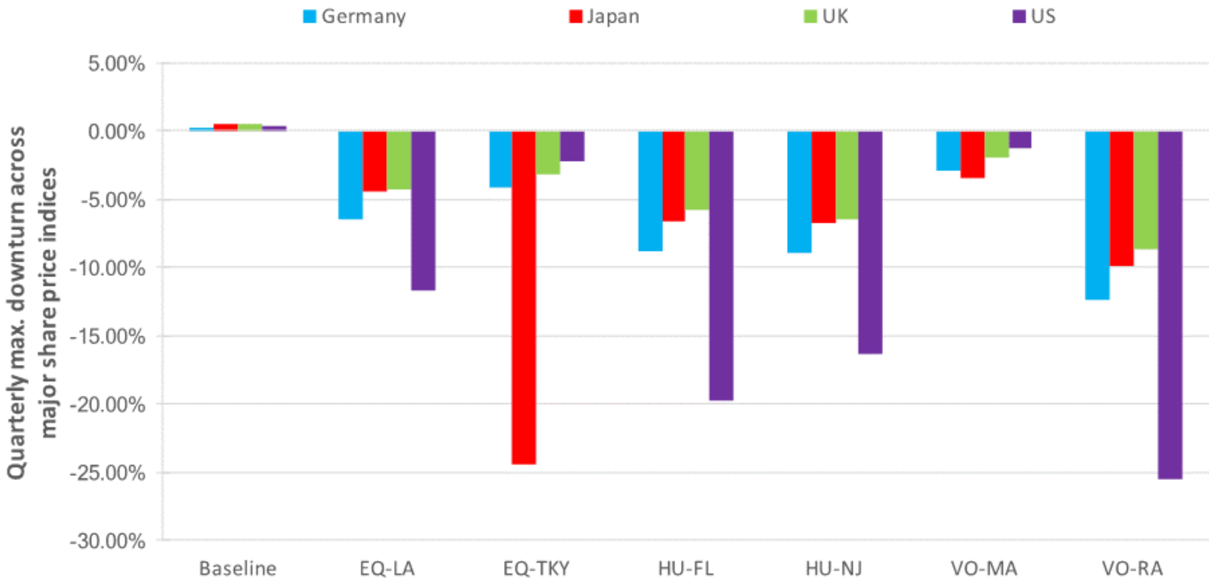

Figure 15: Maximum downturns across major share price indices, demonstrating 'worst case' impacts across scenarios.

Table 11: Maximum quarterly downturn from 2017Q4 across major share price indices, demonstrating 'worst case' impacts across scenarios.

	Baseline	EQ-LA	EQ-TKY	HU-FL	HU-NJ	VO-MA	VO-RA
Germany	0.21%	-6.42%	-4.13%	-8.75%	-8.88%	-2.88%	-12.33%
Japan	0.50%	-4.43%	-24.41%	-6.56%	-6.68%	-3.45%	-9.95%
UK	0.49%	-4.25%	-3.20%	-5.84%	-6.40%	-1.92%	-8.64%
US	0.43%	-11.73%	-2.28%	-19.75%	-16.32%	-1.24%	-25.48%
World	0.64%	-7.75%	-5.87%	-13.90%	-11.52%	-2.81%	-18.98%

Sovereign Credit Rating

In our study (Table 12), the US sovereign bonds are downgraded by three levels following the eruption of Mount Rainier (VO-RA). Germany has been the most resilient economy since all scenarios yield no changes to its sovereign ratings. Meanwhile Japan's sovereign ratings are downgraded after the earthquake in Tokyo (EQ-TKY). These downgrades indicate that the US and Japan while remaining committed to their financial obligations such as coupon payments became more vulnerable to adverse economic conditions and uncertainties after large-scale natural catastrophe events. Credit ratings for the US after two hurricane events (HU-FL and HU-NJ) and an earthquake event in Los Angeles (EQ-LA) are subject to minor downgrades indicating that confidence in the US government bonds is less affected and that perceived risks are not significantly altered, despite higher risks of default.

Table 12: Maximum impact to quarterly sovereign credit rating

	Baseline	EQ-LA	EQ-TKY	HU-FL	HU-NJ	VO-MA	VO-RA
Germany	AAA	AAA	AAA	AAA	AAA	AAA	AAA
Japan	A	A	BBB	A	A	A	BBB
UK	AA	AA	AA	AA	AA	AA	AA
US	AAA	A	AA	A	A	AA	BBB

Economic growth rates

Table 13 represents the minimum quarterly GDP growth rates across major economies in the event window of study. Except for Germany, all scenarios result in recession in all major economies around the world. EQ-TKY and VO-MA are the least impactful scenarios, since they result only in negative growth rates in Japan, while hurricane scenarios and VO-RA undermine GDP growth in multiple regions. VO-RA cause the largest negative impact among all scenarios as the US economy falls by 18.6% quarter-on-quarter, triggering a worldwide recession which lasts four consecutive quarters. Both earthquake scenarios and VO-MA result in the smallest GDP loss across all scenarios.

Table 13: Maximum quarterly growth rates of major economies and the world

	Baseline	EQ-LA	EQ-TKY	HU-FL	HU-NJ	VO-MA	VO-RA
Germany	0.6%	0.2%	0.4%	-0.1%	-0.1%	0.5%	-0.6%
Japan	-0.9%	-0.4%	-10.7%	-0.3%	-0.4%	-0.4%	-0.9%
UK	1.2%	0.1%	0.7%	-0.4%	-0.4%	0.6%	-1.0%
US	1.5%	-9.0%	1.0%	-14.9%	-12.0%	1.3%	-18.6%
WORLD	2.4%	-0.7%	1.6%	-2.3%	-1.6%	1.8%	-3.4%

GDP@Risk

When significant level of local damage impacts the national economy, a country's GDP growth typically deviates from the projected trend. This numerically translates to the "GDP@Risk" metric, which is calculated as the total difference in output loss between the baseline projections and the scenario-specific projections. The main output from the model is a five-year estimate for the world economic output, which is repeated for each scenario and the impacts are then compared with the baseline to compute the world gross domestic product (GDP) at risk from each scenario. The total output loss over five years starting Q1 2018 to Q4 2022 denotes GDP@Risk in our analysis.

Table 14 summarises these expected economic output losses for each scenario, both as the total lost economic output over five years, and as a percentage of the baseline 5-year GDP values.

Table 14: Nat Cats and their impacts on GDP@Risk (US$ trillion output loss) over five years

LOCATION	Baseline 5-yr GDP (US$ Tn)	GDP@Risk (US$ trillion)					
		EQ-LA	EQ-TKY	HU-FL	HU-NJ	VO-MA	VO-RA
Germany	19.76	0.09 (0.46%)	0.04 (0.20%)	0.12 (0.61%)	0.12 (0.61%)	0.05 (0.25%)	0.12 (0.61%)
Japan	31.02	0.06 (0.19%)	0.90 (2.90%)	0.11 (0.35%)	0.10 (0.32%)	0.09 (0.29%)	0.21 (0.68%)
UK	14.64	0.12 (0.82%)	0.08 (0.55%)	0.05 (0.34%)	0.17 (1.16%)	0.07 (0.48%)	0.20 (1.37%)
US	91.45	1.89 (2.07%)	0.28 (0.31%)	0.28 (0.31%)	2.38 (2.60%)	0.39 (0.43%)	3.39 (3.71%)
WORLD	**428.51**	**3.81 (0.89%)**	**1.89 (0.44%)**	**2.35 (0.55%)**	**3.59 (0.84%)**	**2.51 (0.59%)**	**7.63 (1.78%)**

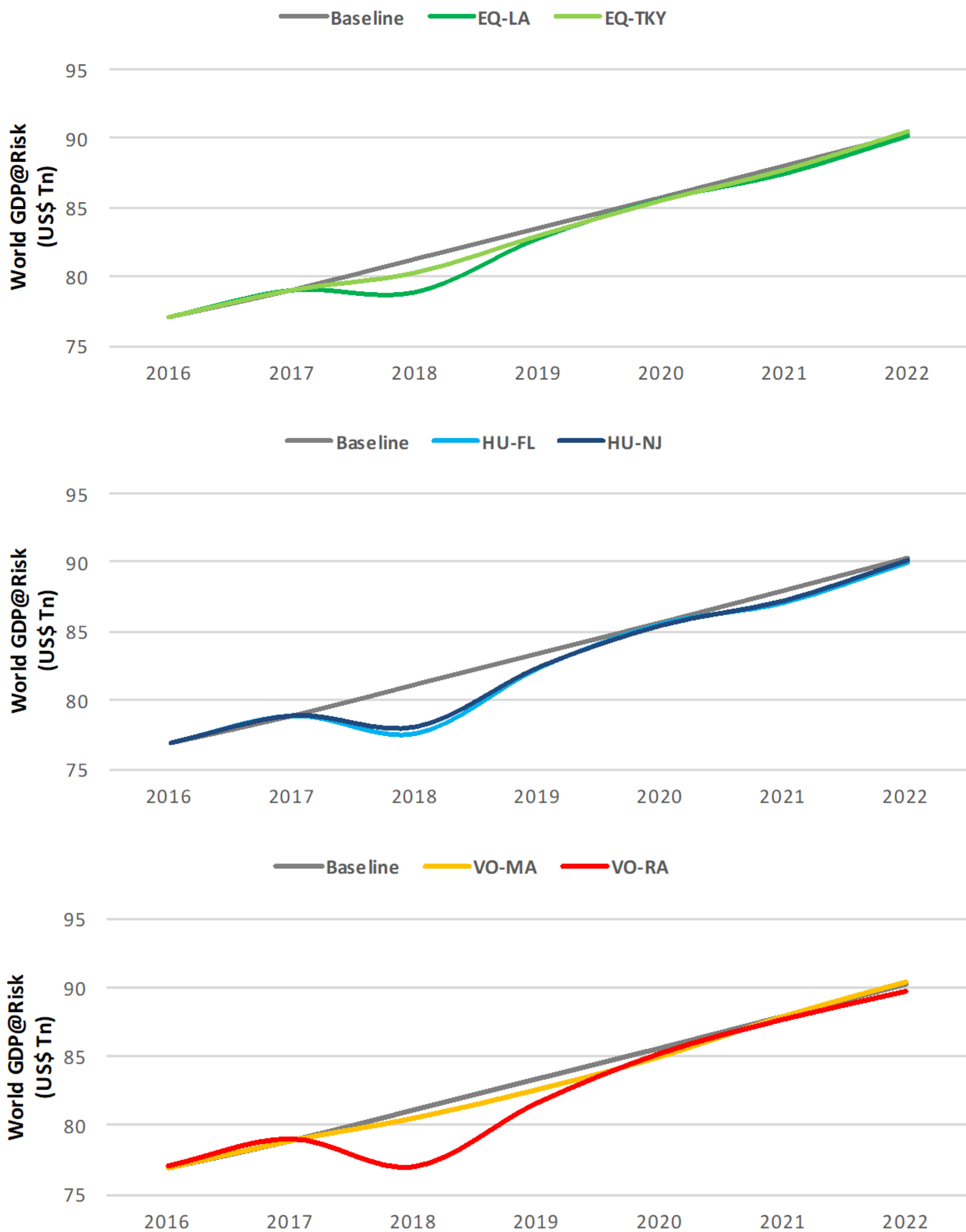

Figure 16: Estimated GDP@Risk over five years due to natural catastrophes

In the short-term up to $7.6tn (1.8%) of all global output is lost across all catastrophe scenarios between 2018 and 2022. The earthquake at Los Angeles (EQ-LA) is the only scenario without a significant output loss as it causes a global economic downturn only for the two quarters of the analysis period (2018 Q2-Q3). Catastrophe events occurring outside of the United States, i.e. the Tokyo earthquake (EQ-TKY) and eruption of Mount Marapi (VO-MA) in Indonesia, tend to have a relatively smaller economic impact compared with events originating in the US.

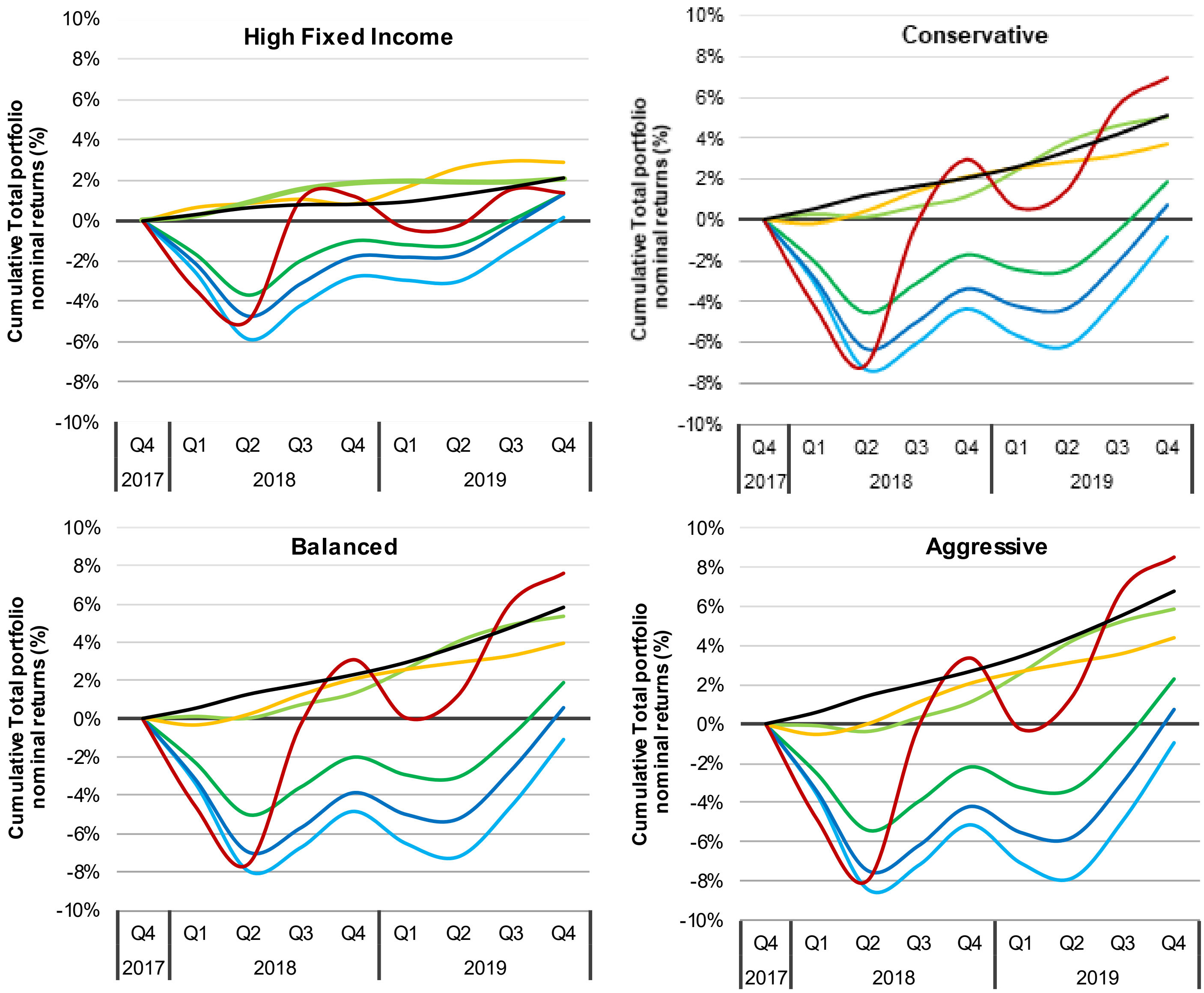

Figure 17: Comparison across portfolio structures and cumulative total portfolio nominal returns across scenario variants

Figure 17 shows the scenario impacts by scenarios across all portfolio structures when we compare the impacts of the scenarios measured in terms of cumulative nominal returns. Across all portfolio structures and scenarios, there are significant deviations from the baseline projections during the first year of the shocks, which was applied over a five-year period starting in 2018 Q1.

The Tokyo earthquake and Mount Marapi eruption scenarios have no significant impact on the portfolios. This is likely because the locations affected by the catastrophes have a limited role in their impacts on the global economy especially when the portfolios themselves are geographically diversified to absorb shocks arising in major financial centres around the world. In the Florida hurricane scenario, and to a similar extent for the

New Jersey hurricane and the Tokyo earthquake scenarios, the Aggressive portfolio performs the worst with a maximum loss of up to 9% with significant volatility in returns compared to the baseline. On the contrary, in the in the Mount Rainier eruption, High Quality Fixed Income portfolio suffers the worst as returns do not revert to the baseline, resulting in a permanent loss in asset value. Of all the scenarios, the Mount Rainier eruption scenario shows the strongest recovery after the initial shock.

Aggressive portfolio returns tend to recover faster compared with their less aggressive portfolio counterparts. Towards the end of the event window, the cumulative returns of most portfolios end up slightly above the baseline projection. This trend is consistent with common asset class patterns, where economic shocks have the largest impact on equities, in general. Consequently, the Aggressive portfolio is the most responsive due to its large equity share.

Regardless of the scenario, investors in High Fixed Income portfolio may be least at risk from any financial market disruption, except for the VO-RA scenario (which has a high inflation component) that could seriously undermine the performance of portfolios with large share of fixed income instruments. This portfolio also displays poor performance due to small overall returns.

Impact on Returns by Asset Class and Geography

Equity Markets

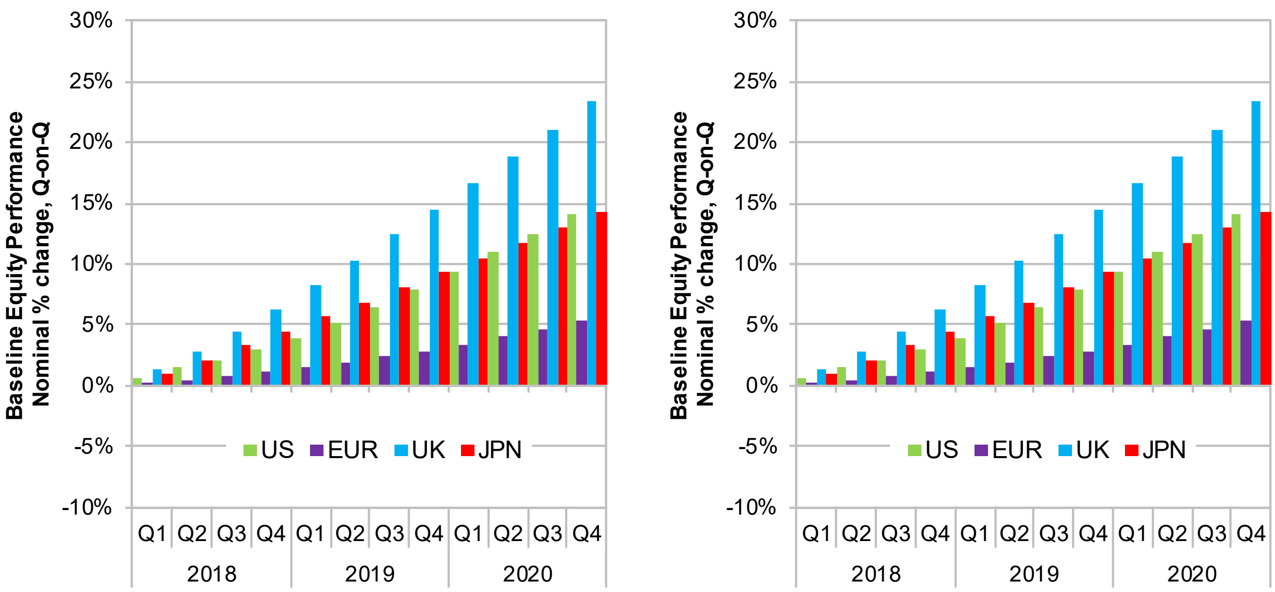

Figure 18: Comparison of equity performance by geography in nominal quarter on quarter change (%) between Baseline and the earthquake in Los Angeles scenario

Figure 18 shows the market impacts on equity performance by geography in comparison to the baseline. where country-specific impacts primarily results from the degree of exposure of each country's economic fundamentals and responses to the applied shocks. Taking the earthquake in Los Angeles scenario as an example, we observe that holding US-based equity assets (W5000) offers the least returns (-9.7%) in the stock market, and only begins to generate positive returns by 2020Q1. UK (FTSE) registered the fastest recovery as it started generating positive returns in the fourth quarter of the first year of shock, whereas returns for Japanese (TOPIX) and European (DAX) equites recover from the shock only by the end of 2019.

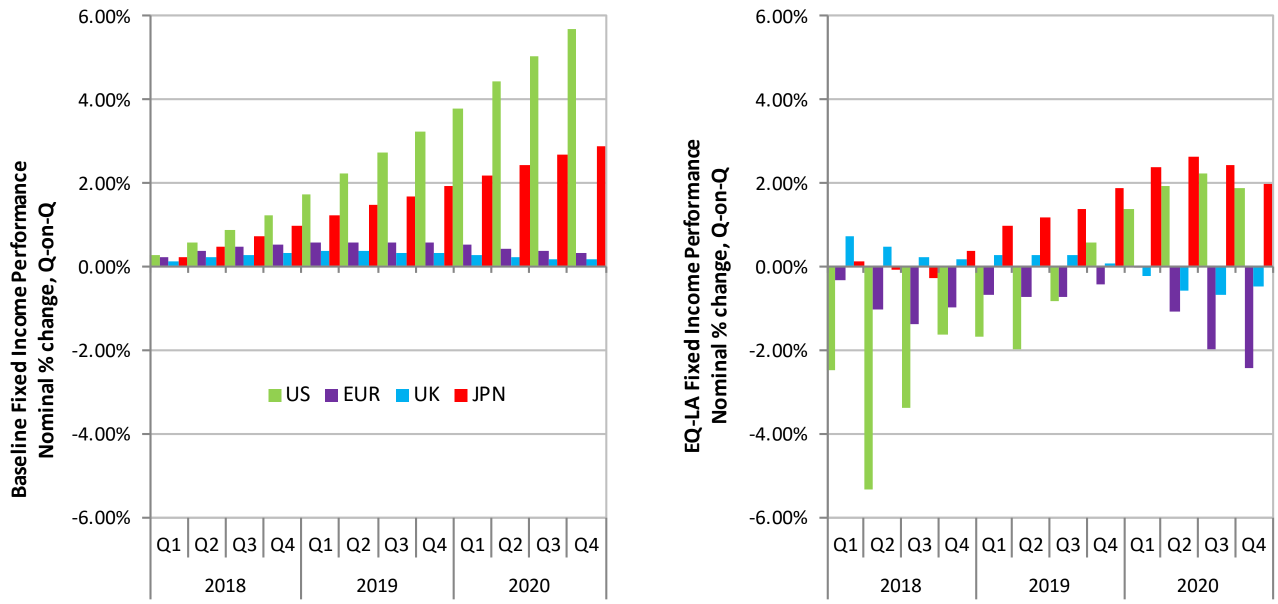

Figure 19: Comparison of fixed income performance by geography in nominal quarter on quarter change (%) between Baseline and earthquake in Los Angeles scenario

Figure 19 illustrates the market impacts on fixed income performance by geography between the earthquake in Los Angeles scenario and Baseline. The US is affected the most (-5.35%) in the bond market, but it recovers by the end of the second year following the shock. Meanwhile, European fixed income instruments are subject to negative returns throughout the event window. While UK bonds fared slightly better in terms of returns in the initial period following the shock, they begin to yield negative returns in the third year of the event window. The Japanese bond market was quite resilient to the shock as it consistently generated positive returns throughout this period, except for two quarters (2018 Q2 and Q3).

Despite the overall negative performance on fixed income instruments, like in the case of equities, the recovery of the latter is more robust than the former. This suggests that higher share of equities would serve as a better investment option for high-yield seeking investors. This inference is also consistent with the Aggressive portfolio performance in the longer run.

- All scenarios have negative impacts on economic growth and financial markets but the extent to which they impact each of these markets differ
- The speed of recovery depends largely on the country and the state of the economy
- The short term impacts can be explained with more confidence than medium/long term ones

Macroeconomic variables

In the labour market, the poor macroeconomic conditions result in more layoffs therefore resulting in a higher unemployment rate. This increase in unemployment coupled with higher rates of inflation leads to lower average real earnings for employees. It is to be noted that, in the near-term[14] real earnings appear to increase temporarily before decreasing, due to the *sticky wages* response. However, in the short-term the combined effect of an increase in the inflation rate with decrease in average earnings explains the observed decrease in average real earnings. On the other hand, the reduction in available labour due to casualty losses could drive up the demand for labour and therefore lead to a temporary increase in wage rates. Depending on the severity of the impact of the event on lives lost, the loss of work force may have non-trivial effects on the unemployment rate. This in turn could determine the price levels prevailing in the economy. For instance, if the unemployment was already at a minimum and that there was a higher demand for workers for reparation and reconstruction, the wages would go up. Due to this increase in the cost of capital, the price levels would also be driven upwards. The interplay of variables is shown in Figure 20.

[14] Time period that constitutes immediately following the shock, which is a smaller interval than the *short term*

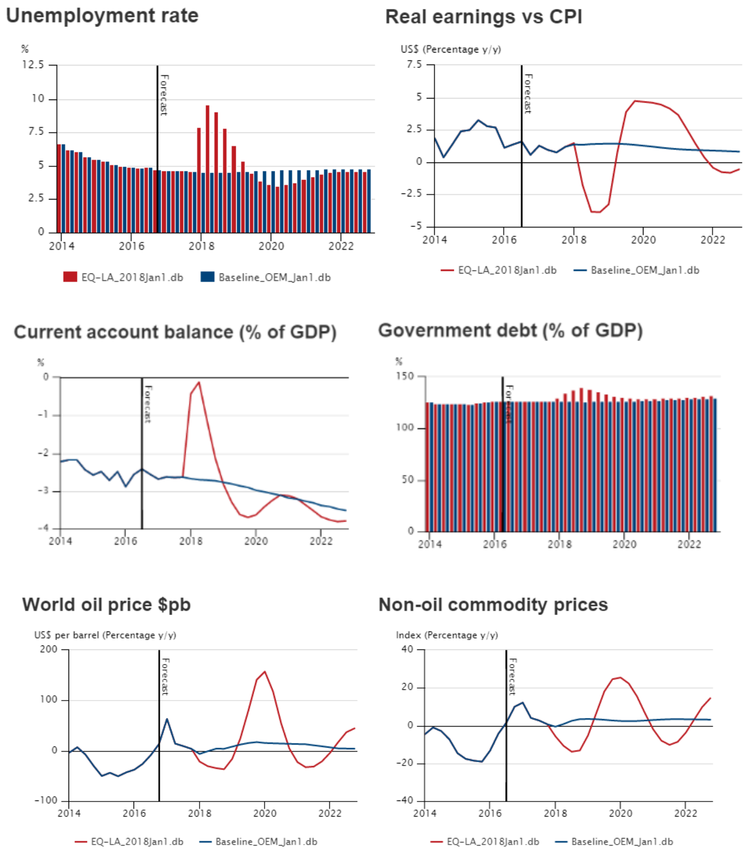

Figure 20: Modelled impact of EQ-LA on the US economy and key variables of global economy

In the trade sector, as explained earlier, the economic disruption to production due to the earthquake results in a decrease in exports while the poor macroeconomic conditions characterized by a decrease in purchasing capacity results in a decrease in imports. Note that the magnitude of change in both variables need not necessarily be the same in the short-term. Both these effects result in a decrease in the absolute values of visible trade balance[15] of the US, however, the larger decrease in GDP in the US in comparison results in an increase in the visible trade balance, when measured as a percentage of GDP. Furthermore, in the near-term, due to the appreciation of the EER, the visible trade balance increases temporarily. This is due to the *inverted J-curve effect*, which is defined where the "total value" of exports remain the same while the total value of imports decreases due to this currency appreciation in part due to pre-existing (legacy) trade contracts, which explains the observed increase in the visible trade balance. The current account balance[16] (measured as a percentage of GDP) also increases in the short-term due to this decrease in GDP. While the level of external borrowing does not change in the model[17] due to the decrease in GDP, the debt-to-GDP ratio is also found to increase.

World commodity prices diminish due to the confidence shock and poor macroeconomic conditions. However, for the volcano scenarios where certain commodity prices (oil and food) are shocked positively, there is an increase in the corresponding prices due to these modelling input assumptions. In all scenarios, there is a reduction in the total world trade because of trade-related shocks from the origin country to its trade partners.

[15] Defined as the difference between net exports and net imports of goods of a country

[16] Measures the difference between the country's savings and its investment. Its main components are visible balance (trade of goods), invisible balance (trade of services), investment income (dividends, remittances from abroad) and net transfers (international aid)

[17] In the model, this might require deliberate or exogenous action by the user

Section 6: **Further Discussion**

International Spill-overs

International spill-overs are defined as the trend of variables of interest in all countries except the country where the shock originates. The spill-over effects from a catastrophe, unlike domestic impacts, vary from country to country and relies on the specific scenario in question. However, there are general trends in international spill-overs and certain scenario specific variations that could be found in the model results. In this sub-section, we present the general trends in the international spill-overs[18].

The GDP of the countries tend be on the decline due to poor macroeconomic conditions that result from the shock transmission through the trade network and due to lower consumer confidence *(shocked variable)*. The economic conditions observed in the previous Section are also observed in the form of lower consumer spending and decreasing trends for fixed investments. Since, there is no fiscal adjustment explicitly defined in the model inputs, there is no change in government consumption. Furthermore, the transmission of shock through the trade network manifests itself in the form of reduced imports and exports of these countries.

In the labour market, there is a reduction in average earnings due to this economic disruption, and thus real earnings also fall in cases where the deflationary pressures are not excessive. Furthermore, due to negative growth outlook because of the transmitted shock, there is a decrease in total employment. Productivity of the economy also falls due to poor economic conditions. However, the unit labour costs temporarily increase due to *sticky wages* (because of legacy contracts) but then decline once the labour market adjusts. It is noteworthy that the available labour force does not change due to the absence of casualty damage especially since these countries are geographically removed from the origin of the shock.

Because of shock propagation through the trade network and due to lower confidence in general, the exports and imports of both goods and services are negatively affected. However, since the GDP loss tends to be higher than the loss in trade, the visible trade balance and therefore the current account balance (measured as a percentage of GDP) of these countries improve. There is evidence of deteriorating balance sheet which substantiates the poor macroeconomic conditions. Furthermore, the loss in GDP also results in an increase in the debt-to-GDP ratio since both the debt levels and government borrowing remain the same.

Consumer goods prices decreases due to the weak economic prospects and low aggregate demand. The central bank responds to this deflationary pressure by lowering the interest rates, causing larger investment outflows and a lower demand for government bonds, increasing bank yields. Finally, the effective exchange rate depreciates because of the large investment outflows by investors seeking higher returns elsewhere. This effect, in turn, reduces the demand for the local currency and therefore results in currency depreciation. It is to be noted that there are several effects that interplay in the economy because of delayed response by some variables to the shock as well as due to their economic structure.

Variants

While there are general trends in the international spill-over effects, there are also some variations in these trends resulting in points of departures for certain variables in some cases. We discuss four key variants of interest in this sub-section.

In the case of ***extreme deflation***, the real earnings tend to increase despite lower average earnings. This is so because the sudden drop in levels of inflation corresponding to higher real earnings until the average earnings catches up. Notably, the average earnings do not adjust immediately because of pre-existing wage contracts promising a previously agreed remuneration to the employee.

Whenever the ***shock does not originate in the US,*** the bond yields appear to decrease. This effect could be explained by the flight-to-quality behaviour of the investors, wherein they rush to withdraw investments from risky environments in order to invest in safe government bonds despite the low interest rates that the latter offers . Such behaviour indicates their lack of confidence in the future growth of the domestic and even the world economy in the short-term.

[18] We refer the interested reader to the detailed XL file provided for a closer inspection on the other one-off exceptions that are not captured here

Germany and Eurozone, in general, have very similar trends for all scenarios. However, in comparison to other countries, it is to be noted that their interest rate remains unaffected in response to these spill-over effects in the economy. This is perhaps due to them being in the European Monetary Union (EMU) wherein their monetary policy efforts are co-ordinated between the Member States and Germany cannot implement individual monetary policy on its own discretion.

For the two ***volcano scenarios***, both the trade balance and the current account balance decrease (both measured as a percentage of GDP). This is probably because these deteriorating balances fully counteract the decrease in GDP. Also, the CPI inflation is higher in these scenarios because of the effects of positively shocking the commodity prices. It is to be noted that the central bank's response to inflation is a looser monetary policy (characterized by lowering of interest rates) which might seem counter-intuitive at first. However, it is to be borne in mind that the poor macroeconomic conditions due to lower GDP levels and weaker domestic demand do not point towards a heated economy. As a response, the central bank therefore aims to provide economic stimulus by lowering interest rates as opposed to raising them in response to higher CPI inflation.

A summary of the domestic impacts and the international spill-over effects of these shocks on macroeconomic variables of interest can be found in Table 15. The cells in red indicate the variant with respect to the general trends for the international spill-over effects. For a general comparison between the domestic impacts and the international spill-overs, a direct comparison between the general trends for each of these needs to be made using the first two columns containing trend arrows. A more visual stylized representation of the causal links between the financial system and the larger economy is shown in Table 16.

Interpretation of OEM Results with confidence shocks

All analyses on the OEM model outputs are based on the first order responses focussing particularly on the immediate and short-term (ST) impacts, i.e., until 2020. All trends in the results are with respect to the baseline OEM forecast. The medium and long-term impacts on these variables are harder to explain because of feedback effects arising from ST impacts and possible dominance of lagged effects[19] which may be reinforcing or undermining. The method of scientific inquiry used here is causal or deductive wherever possible and in other cases involves inference of the best explanation.

The impacts on exchange rates due to changes in the interest rates depends on ERPT, ToT and whether the trade is carried out in PCP or LCP *(see below for expansion of these terms).* It is also to be noted that this model does not account for exogenous actions. For instance, markets may, in reality, respond differently, even counterintuitively, to what models may suggest, to the Fed raising the interest rates, perhaps due to rational expectations by the investors that Fed has raised rates expecting future inflation in anticipation of President Trump's aggressive fiscal policies.

The expansions of the abbreviations used in this section are as below *(see footnotes for more details):*

- **IRF** = Impulse Response Function[20]
- **CPI** = Consumer Price Index
- **CB** = Central Bank
- **AD/AS** = Aggregate Demand/ Aggregate Supply
- **ZLB** = Zero Lower Bound[21]
- **ERPT** = Exchange Rate Pass Through[22]
- **ToT** = Terms of Trade[23]
- **PCP/LCP** = Producer Currency Pricing / Local Currency Pricing
- **NPV** = Net Present value

[19] Lagged effects are quite common in macroeconomics due to their transmission through multiple channels

[20] It is the response of the variables of interest to the exogenous shocks to the system

[21] It is the case where the short-term nominal interest rates are near zero, which limits the capacity of the central bank to stimulate the economy without the use of unconventional monetary policy

[22] The extent to which the change in exchange rates affects price levels in the economy

[23] The ratio of an index of a country's export prices to that of its index of import prices

- **EER** = Effective Exchange Rate[24]
- **UIP** = Uncovered Interest Rate Parity[25]
- **PPP** = Purchasing Power Parity[26]

In the remainder of this section, we focus on the impacts of the natural disasters on the domestic economy broken down by financial markets and macroeconomic responses to the shock for all the scenarios. We also discuss the international spill-over effects of such shocks.

Table 15: Summary of domestic and international spill over trends for variables of interest (model with confidence shocks)

OEM VARIABLES		DOMESTIC IMPACTS	INTERNATIONAL SPILL OVERS				
				Variants			
		General trends	General trends	*Extreme deflation*	*Non-US originating shock*	*For Germany & Eurozone*	*Volcano scenario*
GDP related	GDP	-1	-1	-1	-1	-1	-1
	Consumer Spending	-1	-1	-1	-1	-1	-1
	Fixed Investment	0	-1	-1	-1	-1	-1
	Government Consumption	0	0	0	0	0	0
	Domestic Demand	-1	-1	-1	-1	-1	-1
	Exports	-1	-1	-1	-1	-1	-1
	Imports	-1	-1	-1	-1	-1	-1
Labour related	Average Earnings	-1	-1	-1	-1	-1	-1
	Real Earnings	-1	-1	1	-1	-1	-1
	Productivity	-1	-1	-1	-1	-1	-1
	Unit Labour Costs	1	1	1	1	1	1
	Total employment	-1	-1	-1	-1	-1	-1
	Labour Supply	-1	0	0	0	0	0
	Unemployment Rate	1	1	1	1	1	1
Trade related	Exports of Goods	-1	-1	-1	-1	-1	-1
	Imports of Goods	-1	-1	-1	-1	-1	-1
	Exports of Services	-1	-1	-1	-1	-1	-1
	Imports of Services	-1	-1	-1	-1	-1	-1
	Visible Trade Balance (% of GDP)	1	1	1	1	1	-1
	Current Account Balance (% of GDP)	1	1	1	1	1	-1
	Government Balance (% of GDP)	-1	-1	-1	-1	-1	-1
	Government Debt (% of GDP)	1	1	1	1	1	1
Finance related	CPI Inflation	1	-1	-1	-1	-1	1
	CB Policy Rate	1	1	1	1	0	1
	Bond Yields	1	1	1	-1	1	1
	Equity Prices	-1	-1	-1	-1	-1	-1
	Effective Exchange Rate (EER)	1	1	1	1	1	1
World related	World Oil Price	-1	-1	-1	-1	-1	1
	Non-Oil Commodity Prices	-1	-1	-1	-1	-1	-1
	World Trade	-1	-1	-1	-1	-1	-1

[24] The weighted average of a country's currency relative to an index or basket of other major currencies

[25] The interest rate differential across countries results in exchange rate adjustments between the currency pairs

[26] The exchange rate between two currencies adjusts to reflect change in price levels between these countries

Domestic Impacts

The trends for both financial and macroeconomic variables is the same across all scenarios for the domestic economy, i.e., to the country where the shock originates. However, for the sake of convenience we illustrate the following explanations with the use of a representative scenario, the Los Angeles earthquake (EQ-LA).

Financial markets

The shock event (*earthquake*) in the country (*US*) reduces the goods production capacity of firms in the local economy, reduces domestic consumption due to lower demand and affects the ports by curtailing its working capacity and operations. For instance, the earthquake in LA disrupts the seaport services until further reparation and reconstruction of the port facilities. Furthermore, there would be disruptions to services and production facilities. These factors jointly result in a decrease in both exports and imports, specifically through production disruptions and reduction in demand respectively. This leads to poor macroeconomic output that is evident from the lower GDP after the event.

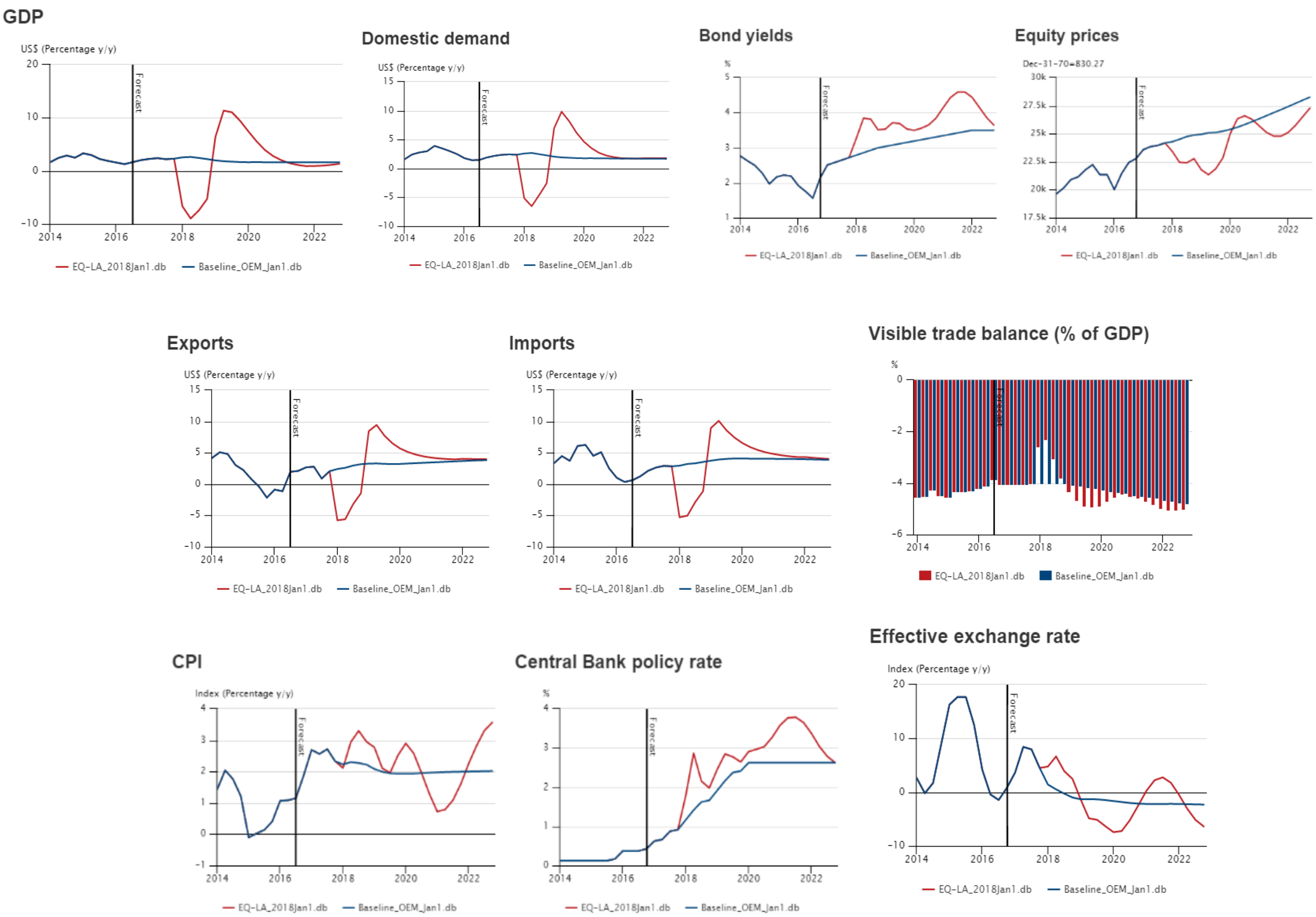

Figure 21: Impact of EQ-LA scenario on key macroeconomic variables

Due to deteriorating economic conditions immediately following the shock, the price level of goods in the economy declines resulting in a deflationary pressure immediately following the shock. However, the inflation increases subsequently due to an increase in the price level as the supply of goods decreases in comparison to the rise in demand in the short run. As a consequence of the rise in price levels, characterized by inflation, the central bank raises their short-term policy rate (also referred to as the *interest rate* in this section). They influence the interest rates by adjusting the money supply in the economy. Consumers anticipate a future increase in inflation thereby adjusting their immediate consumption; inflation rates adjust in conjunction with this adaptive behaviour.

The response of the capital markets to the change in policy rate will be discussed in terms of the government bond[27] yields and the equity price index. Firstly, as the inflation rate rises, the investors in government bonds demand higher yields to compensate for inflation risk. The increase in interest rates by the central bank, which leads to a rise in expected inflation by the investors, reinforces this behaviour further. Secondly, the equity prices drop because of this increase in interest rate due to increases in borrowing costs for firms. Since the prevailing interest rates are high, it may be profitable for companies to deposit their money in the bank instead of investing in new projects that might otherwise add more value to the company. As a result of lower returns, their stock prices dip resulting in a concomitant decline in the stock price index of the country. Notably, depending on the extent of this stock market decline, a substitution effect towards high-quality assets[28], such as government bonds, may be observed. Consequently, this might drive the increased demand for such bonds thereby pushing the bond prices up (and thus depressing bond yields[29]) in a competing manner.

In case of higher bond yields, there may be an upsurge in the foreign investment inflows in the government bond market which would depress the bond yields. These inflows cause an increase in the money supply in the domestic economy that would drive price levels higher in the short-term, leading to inflation and, therefore, reinforcing the interest rate adjustments loop. In case of stock price rally, there would be an increase in demand for equities, resulting in higher stock prices. However, this would also result in the same macroeconomic effects of higher inflation due to larger capital influx from foreign investors and their associated knock-on effects, as discussed above. For instance, one effect of increase in cash inflows due to a rise in interest rates (while interest rates of other countries remain unchanged) would be to appreciate the exchange rate due to the Uncovered Interest Rate Parity (UIP) effect.

The reduction in exports and imports because of the shock would also result in a change in trade balance. The extent of this parity between imports and exports depends primarily on the consumer behaviour (or its anticipation by firms) in the immediate term. In case of deteriorating trade balance, where decrease in exports are more than the decrease in imports, the effective exchange rate (EER) therefore depreciates. This is so because, reduction in trade balance is associated with a decrease in demand for the local currency[30], which leads to this depreciating currency trend. As a result of this depreciation, exports become more favourable. On the other hand, in the short-term, an increase in the interest rate attracts more foreign investments and increases the demand for the local currency (USD). This then leads to a net appreciation of the effective exchange rate of the local currency. It is to be noted that if this inflation is sustained over a longer period *(ceteris paribus)*, it would ultimately lead to a degree of currency depreciation.[31]

This natural disaster event also triggers a shock to investor confidence both locally and globally, causing a lower demand for financial assets and depreciating certain assets. This trigger could then feed into any of the other price adjustment mechanisms eventually necessitating appropriate policy actions by the monetary authority of the country.

The impact of confidence shocks on investment portfolios is outlined in Appendix 3, along with data on macroeconomic impact for an analysis *without* confidence shocks.

Comparison between trends in the 'with confidence shocks' and 'without confidence shocks' models

The import of services seems to exhibit a phase-transition like behaviour wherein its demand is unaffected by confidence shocks in most cases and changes in cases when the intensity of transmitted shock is above a "tipping point" threshold. The trends in current account balance (measured as a % of GDP) for international spill-overs for non-volcano scenarios with US-origin shocks are different for Germany than the other countries**.** This is perhaps due to the difference in the levels of relative decrease in GDP with respect to their current account balance (in absolute values).

With respect to international spill-overs, the *without confidence shocks* model has lower macroeconomic impacts

[27] 10-year Treasury bonds are the most commonly used asset for this purpose

[28] In finance literature, this behaviour is denoted by the "flight-to-quality" effect

[29] Bond yields and bond prices are inversely related to each other

[30] Assuming producer currency pricing, where all goods are assumed to be contracted in the currency of the producer country

[31] This is due to the Purchasing Power Parity (PPP) effect which is a longer term effect unlike the Interest Rate Parity (IRP) which has more immediate impacts on exchange rates

USA

	IMPULSE RESPONSE TRENDS	EQ-LA C	EQ-LA NC	EQ-TKY C	EQ-TKY NC	HU-FL C	HU-FL NC	HU-NJ C	HU-NJ NC	VO-MA C	VO-MA NC	VO-RA C	VO-RA NC
GDP related	GDP	↓	↓	↓	–	↓	↓	↓	↓	↓	↓↓	↓	–
	Consumer Spending	↓	↓	↑	–	↓	↓	↓	↓	↓	↓↓	↓	–
	Fixed Investment	–	–	↓	–	–	–	–	–	↓	–	–	↓
	Government Consumption	–	–	–	–	–	–	–	–	–	–	–	–
	Domestic Demand	↓	↓	↓	–	↓	↓	↓	↓	↓	↓↓	↓	–
	Exports	↓	↓	↓↓	↓	↓	↓	↓	↓	↓	↓↓	↓↓	↓
	Imports	↓	↓	↓	↓↓	↓	↓	↓	↓	↓	↓↓	↓↓	↓
Labour related	Average Earnings	↓↓	↓	↓	–	↓↓	↓	↓↓	↓	↓	↓↓	↓	–
	Real Earnings	↓	↓↓	↑	–	↓	↓↓	↓	↓↓	↓	↓↓	↓↓	↓
	Productivity	↓	↓	↓	–	↓	↓	↓	↓	↓	↓↓	↓	–
	Unit Labour Costs	↑	↑	↓	–	↑	↑	↑	↑	↑	↑↑	↑	–
	Total employment	↓	↓	↓	–	↓	↓	↓	↓	↓	↓↓	↓	–
	Labour Supply	↓	↓	↑	–	↓	↓	↓	↓	↓	↓↓	↓	–
	Unemployment Rate	↑	↑	↑	–	↑	↑	↑	↑	↑	↑↑	↑	–
Trade related	Exports of Goods	↓	↓	↓↓	↓	↓	↓	↓	↓	↓	↓↓	↓↓	↓
	Imports of Goods	↓	↓	↓	↓↓	↓	↓	↓	↓	↓	↓↓	↓↓	↓
	Exports of Services	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓
	Imports of Services	↓	↓	↓↓	↓	↓	↓	↓	↓	↓	↓↓	↓	–
	Visible Trade Balance (% of GDP)	↑	↑	↓	↓↓	↑	↑	↑	↑	↓	↑	↑	↓
	Current Account Balance (% of GDP)	↑	↑	↓	↓	↑	↑	↑	↑	↓	↑	↑	↓
	Government Balance (% of GDP)	↓	↓	↓	–	↓	↓	↓	↓	↓	↓↓	↓	–
	Government Debt (% of GDP)	↑	↑	↑	–	↑	↑	↑	↑	↑	↑↑	↑	–
Finance related	CPI Inflation	↑	↑↑	↓	–	↑	↑↑	↑	↑↑	↑	↑↑	↑↑	↑
	CB Policy Rate	↑	↑↑	↓	–	↑	↑↑	↑	↑↑	↓	↑	↑	↓
	Bond Yields	↑	↑↑	↓	–	↑	↑↑	↑	↑↑	↓	↑	↑↑	↑
	Equity Prices	↓↓	↓	↓	–	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓
	Effective Exchange Rate (EER)	↑↑	↑	↓	↓↓	↑↑	↑	↑↑	↑	↑	↑↑	↑	↓
World related	World Oil Price	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↑	↑	↑	↑
	Non-Oil Commodity Prices	↓↓	↓	↓	↑	↓↓	↓	↓↓	↓	↓	↑	↓	↑
	World Trade	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓

UK

	IMPULSE RESPONSE TRENDS	EQ-LA C	EQ-LA NC	EQ-TKY C	EQ-TKY NC	HU-FL C	HU-FL NC	HU-NJ C	HU-NJ NC	VO-MA C	VO-MA NC	VO-RA C	VO-RA NC
GDP related	GDP	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓
	Consumer Spending	↓↓	↓	↓	–	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓
	Fixed Investment	↓↓	↓	↓	–	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓
	Government Consumption	–	–	–	–	–	–	–	–	–	–	–	–
	Domestic Demand	↓↓	↓	↓	–	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓
	Exports	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓
	Imports	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓
Labour related	Average Earnings	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓
	Real Earnings	↓	↓↓	↑	↓	↓	↓↓	↓	↓↓	↓	↓↓	↓↓	↓
	Productivity	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓
	Unit Labour Costs	↓↓	↓	↓↓	↓	↑↑	↑	↑↑	↑	↑	↑↑	↑	–
	Total employment	↓↓	↓	↓	–	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓
	Labour Supply	–	–	–	–	–	–	–	–	–	–	–	–
	Unemployment Rate	↑↑	↑	↑↑	↑	↑↑	↑	↑↑	↑	↑	↑↑	↑↑	↑
Trade related	Exports of Goods	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓
	Imports of Goods	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓
	Exports of Services	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓↓	↓↓	↓
	Imports of Services	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓↓	↓	–
	Visible Trade Balance (% of GDP)	↓	↓↓	↑	↓	↓	↓↓	↓	↓↓	↓	↓↓	↓↓	↓
	Current Account Balance (% of GDP)	↓	↓↓	↑	↓	↓	↓↓	↓	↓↓	↓	↓↓	↓↓	↓
	Government Balance (% of GDP)	↑	↑↑	↑	–	↑	↑↑	↑	↑↑	↓	↑	↓	–
	Government Debt (% of GDP)	↑↑	↑	↑↑	↑	↑↑	↑	↑↑	↑	↑	↑↑	↑↑	↑
Finance related	CPI Inflation	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↑	↑↑	↑↑	↑
	CB Policy Rate	↓↓	↓	↓↓	↓	↓	↓	↓	↓	↓	↓	↓↓	↓
	Bond Yields	↑	↑↑	↓	–	↑	↑↑	↑	↑↑	↓	↑	↑	↓
	Equity Prices	↓↓	↓	↓	–	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓
	Effective Exchange Rate (EER)	↓	↓	–	↓	–	–	–	–	–	–	↓	–
World related	World Oil Price	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↑	↑	↑	↑
	Non-Oil Commodity Prices	↓↓	↓	↓	↑	↓↓	↓	↓↓	↓	↓	↑	↓	↑
	World Trade	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓

JAPAN

	IMPULSE RESPONSE TRENDS	EQ-LA C	EQ-LA NC	EQ-TKY C	EQ-TKY NC	HU-FL C	HU-FL NC	HU-NJ C	HU-NJ NC	VO-MA C	VO-MA NC	VO-RA C	VO-RA NC
GDP related	GDP	↓↓	↓	↓	↓	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓
	Consumer Spending	–	–	↓	↓	–	–	↓	–	↓↓	↓	↓↓	↓
	Fixed Investment	↓↓	↓	–	–	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓
	Government Consumption	–	–	–	–	–	–	–	–	–	–	–	–
	Domestic Demand	↓↓	↓	↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓
	Exports	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓↓	↓↓	↓
	Imports	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓↓	↓↓	↓
Labour related	Average Earnings	↓↓	↓	↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓
	Real Earnings	↑	↓	↓	↓	↓↓	↓	↑	↓	↓	↓↓	↓↓	↓
	Productivity	↓↓	↓	↓	↓	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓
	Unit Labour Costs	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑↑	↑↑	↑
	Total employment	↓↓	↓	↓	↓	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓
	Labour Supply	–	–	↓	↓	–	–	–	–	↓	↓↓	↓↓	↓
	Unemployment Rate	↑↑	↑	↑	↑	↑↑	↑	↑↑	↑	↑	↑↑	↑↑	↑
Trade related	Exports of Goods	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓↓	↓↓	↓
	Imports of Goods	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓↓	↓↓	↓
	Exports of Services	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓↓	↓	–
	Imports of Services	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓↓	↓	–
	Visible Trade Balance (% of GDP)	↓	↓↓	↑	↑	↓	↓↓	↓	↓↓	↓	↓↓	↓↓	↓
	Current Account Balance (% of GDP)	↓	↓↓	↓	↓	↓	↓↓	↓	↓↓	↓	↓↓	↓↓	↓
	Government Balance (% of GDP)	↓	↓	↓	↓	↓↓	↓	↓↓	↓	↓	↑	↓↓	↓
	Government Debt (% of GDP)	↑	↑	↑	↑	↑↑	↑	↑↑	↑	↑↑	↑	↑↑	↑
Finance related	CPI Inflation	↓↓	↓	↑	↑↑	↓↓	↓	↓	↑	↑	↑↑	↑↑	↑
	CB Policy Rate	↓↓	↓	↑	↑	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓
	Bond Yields	↑	↑↑	↑	↑↑	↑	↑↑	↑	↑↑	↓	↑	↑	↓
	Equity Prices	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓	↓↓	↓	↑
	Effective Exchange Rate (EER)	↓	↓	↑	↑	↓	↓	↓	↓	–	↓	↓	–
World related	World Oil Price	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↑	↑	↑	↑
	Non-Oil Commodity Prices	↓↓	↓	↓	↑	↓↓	↓	↓↓	↓	↓	↑	↓	↑
	World Trade	↓	↓	↓↓	↓	↓	↓	↓	↓	↓	↓↓	↓↓	↓

IMPULSE RESPONSE TRENDS		GERMANY												EUROZONE											
		EQ-LA		EQ-TKY		HU-FL		HU-NJ		VO-MA		VO-RA		EQ-LA		EQ-TKY		HU-FL		HU-NJ		VO-MA		VO-RA	
		C	NC	C	NC	C	NC	C	NC	C	NC	C	NC	C	NC	C	NC	C	NC	C	NC	C	NC	C	NC
GDP related	GDP	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓
	Consumer Spending	↓↓	↓	↑	—	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓
	Fixed Investment	↓↓	↓	↓	—	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓
	Government Consumption	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	Domestic Demand	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓
	Exports	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓
	Imports	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓
Labour related	Average Earnings	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓	↓↓	↓	↓	—	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓
	Real Earnings	↑	↓	↑	—	↑	↓	↑	↓	↓	↓↓	↓↓	↓	↑	↓	↑	↓	↑	↓	↑	↓	↓	↓↓	↓↓	↓
	Productivity	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓
	Unit Labour Costs	↑↑	↑	↑↑	↑	↑↑	↑	↑↑	↑	↑	↑↑	↑↑	↑	—	—	—	—	—	—	—	—	—	—	—	—
	Total employment	↓↓	↓	↓	—	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓
	Labour Supply	—	—	—	—	—	—	—	—	—	—	↓↓	↓	↓	↓	—	—	↓	↓	↓	↓	↓	↓↓	↓↓	↓
	Unemployment Rate	↑↑	↑	↑↑	↑	↑↑	↑	↑↑	↑	↑	↑↑	↑↑	↑	↑↑	↑	↑↑	↑	↑↑	↑	↑↑	↑	↑	↑↑	↑↑	↑
Trade related	Exports of Goods	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓
	Imports of Goods	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓
	Exports of Services	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓	—	—	—	—	—	—	—	—	—	—	—	—
	Imports of Services	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓↓	↓↓	↓	—	—	—	—	—	—	—	—	—	—	—	—
	Visible Trade Balance (% of GDP)	↑↑	↑	↑↑	↑	↑↑	↑	↑↑	↑	↓	↓↓	↓↓	↓	↑↑	↑	↑↑	↑	↑↑	↑	↑↑	↑	↓	↓↓	↓↓	↓
	Current Account Balance (% of GDP)	↑	↓	↑↑	↑	↑	↓	↑	↓	↓	↓↓	↓↓	↓	↓	↓↓	↑↑	↑	↓	↓↓	↓	↓↓	↓	↓↓	↓↓	↓
	Government Balance (% of GDP)	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓
	Government Debt (% of GDP)	↑↑	↑	↑↑	↑	↑↑	↑	↑↑	↑	↑	↑↑	↑↑	↑	—	—	—	—	—	—	—	—	—	—	—	—
Finance related	CPI Inflation	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↑	↑↑	↑↑	↑	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↑	↑↑	↑↑	↑
	CB Policy Rate	—	—	—	↑	—	—	—	—	—	—	—	—	—	—	—	↑	—	—	—	—	—	—	—	—
	Bond Yields	↑	↑↑	↓	↑	↑	↑↑	↑	↑↑	↓	↑	↑↑	↑	↑	↑↑	↓	↑	↑	↑↑	↑	↑↑	↑	↑↑	↑↑	↑
	Equity Prices	↓↓	↓	↓	—	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓	↓↓	↓	↓	—	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓
	Effective Exchange Rate (EER)	↓	↓	↓	↓	↓	↓	↓	↓	—	↓	↓	—	↓	↓	↓	↓	↓	↓	↓	↓	—	↓	↓	—
World related	World Oil Price	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↑	↑	↑	↑	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↑	↑	↑	↑
	Non-Oil Commodity Prices	↓↓	↓	↓	↑	↓↓	↓	↓↓	↓	↓	↑	↓	↑	↓↓	↓	↓	↑	↓↓	↓	↓↓	↓	↓	↑	↓	↑
	World Trade	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓↓	↓	↓	↓↓	↓↓	↓

across all scenarios (except VO-MA) for most variables. This is consistent with the fact that in the absence of confidence shocks, the intensity of international spill-over effects would be attenuated due to relatively higher confidence in the economies across the world.

The non-oil commodity prices in EQ-TKY and the volcano scenarios increase in comparison to the baseline in the *without confidence shocks* model, whereas it decreases in the other model. This is probably because confidence shocks depress the demand for non-oil commodities thereby supressing their prices**.** On the other hand, the increase in labour costs in the absence of confidence shocks possibly (i.e., in a less depressed economy) drives the aggregate price level of non-oil commodity prices higher than it would have been otherwise. Notably, the world oil prices are controlled largely by the OPEC and therefore are less sensitive to labour costs in local economies.

Furthermore, the international spill-over effects of EQ-TKY to US affects the imports of goods more than the exports of goods in the *no confidence shock* model and the vice-versa in the other model. This indicates the import dependence of Japan on US goods and the export independence of US goods to Japan, both relative to their respective trade partners. This reflects the asymmetry in trade relations between the two countries. More specifically, our calculations using UCTAD data shows that Japan exports roughly 20% of its total share of exports to the US, whereas US exports only about 3% of its total share to Japan. Similarly, for imports these numbers are 10% and 5% respectively.

In the same scenario, for the effects of EQ-TKY on US in the presence of confidence shocks, we note that labour costs go down which may be explained by the increase in labour supply as real earnings go up. This increase in labour supply could be explained with increase in consumer spending driving the domestic demand up. However, in the absence of confidence shock, these effects vanish as there is no significant macroeconomic impact on the US economy because of a shock in Japan, except in the case of trade related factors as noted earlier.

In the VO-MA scenario, the international spill-over trends imply a comparatively worse state of economy across all countries in the absence of confidence shocks, than in the presence of confidence shocks. The inflation levels and the commodity prices all over the world are high while the macro-economic outlook is bleak, implying a state of the economy that can be likened to stagflation[32]. This could possibly be attributed to the substitution effects that are more prominent in the presence of world confidence shocks, where the larger economies with a more reliable government backstop are likely to be preferred for trade over other economies and therefore appear to perform well in comparison to the case when confidence shocks were included. Similarly, the spill-over effects on the real economic variables such as domestic demand, average earnings, fixed investment and consumer spending in Japan due to VO-MA seem to be more severe in terms of declining trend in the *with confidence shock* model. However, the opposite trend is observed for trade-related and other labour-related variables. This is probably also due to the substitution effect wherein the demand for goods shift towards Japanese products and services in the presence of confidence shocks.

In the HU-NJ scenario, the effect of the absence of confidence shock on the CPI inflation in Japan, due to the international spill-over effects, is opposite to when the confidence shock is included. More specifically, in the absence of confidence shock Japan's economy is under inflationary pressure indicating favourable growth outlook. This is perhaps because, in the absence of confidence shocks, the spill-over effects of this US-origin shock are not adequate to negatively affect the macroeconomic prospects in the Japanese economy. However, this effect becomes significant once confidence shocks are considered.

In the USA, the trends in central bank (FED) action on interest rates for each of the volcano scenarios are in the opposite direction when these trends are compared across the two models. For instance, when interest rates are increased in the *with confidence shocks* model, they are decreased in the other**.** This can be explained by comparing the levels of CPI inflation across both volcano scenarios and across both the models. Whenever the inflation is very high, the central bank raises its interest rates to target the rising inflationary pressure. When the inflation is only moderately high, the central bank responds by loosening its monetary policy, which is achieved by lowering interest rates thereby allowing the economy to recover instead of targeting inflation, thereby revealing their priorities among their macroeconomic objectives.

[32] The state of the economy when aggregate supply is lower due to regulation costs or other factors, thereby driving prices levels whilst hampering economic growth. For more details, see stagflation of the 1970s in the US where Keynesian models gave way to new schools of economic thinking

With respect to bond yields in non-Eurozone economies for international spill-overs for non-volcano scenarios, two different trends are observed. In cases with small interest rate reductions, the yields go up by a larger amount in contrast to cases where the interest rates were significantly reduced, in what seems counter-intuitive at first. It is to be noted that the former trend was observed mostly in model with no confidence shock. These trends are most likely due to the combination of very low interest rates prevailing in the economy and the effects of confidence shocks. In conditions where the interest rates are reduced by relatively little in an already low interest rate environment, investors would short (sell) most of their asset holdings including much of their perceived safe government bonds due to the policy signals denoting the deteriorating state of economy. They would prefer to take their investments elsewhere or hold other commodities such as gold to hedge their consumption risk. On the other hand, when the interest rates are reduced significantly (in the presence of confidence shocks), investors would not find alternative lucrative investment prospects elsewhere due to the world confidence shocks and therefore may choose to short only a part of their safe asset holdings including government bonds to invest in a hedging asset class to diversify away some of the default risks of their holdings. Therefore, the bond yields go up only by a little in comparison to the case without confidence shocks, wherein it rises significantly due to lower demand for government-backed assets such as sovereign bonds, in comparison.

- In the model with confidence shocks, the domestic impact trends and the international spill-overs are mostly consistent across all scenarios, independent of the origin of shock (country)
- The two models lead to very similar short-term trends on my variables implying that the general direction of the impact remains the same in both cases
- There are some points of differences between these trends across the two models, of which some are more easily explainable than the others keeping in line with the model assumptions and consistent with economic theory
- Linkages between countries due to trade, exchange rates and monetary policy coordination are more pronounced while comparing the two models and can explain away most of the differences in trends. Some of those which remain unexplained could be attributed to modelling artefacts
- The medium and long-term trends are very difficult to explain primarily due to the interplay of large number of macroeconomic variables which result in complications such as varying persistence of the shock, lagged effects, trend reversals/overshoot among others

Section 7: **Conclusions**

The six example scenarios in this report demonstrate that natural catastrophes can produce losses on a scale that are likely to disrupt market returns from high quality investment portfolios. We argue that when a loss exceeds a certain threshold – typically a loss of a trillion dollars or more – this affects the macroeconomy and disturbs investment returns. The examples result in significant impairments to balance sheet that will concern insurers and regulators, but even more severe losses could be possible.

One of the reasons that destruction of capital stock is increasingly able to perturb the markets is because of the growing interconnectedness of the global economy and the ripple effects that rapidly pass across multiple markets of the world. Capital flows move more quickly and events that attract capital – such as major reconstruction needs – pull capital from other investment opportunities and cause market distortions, impacting interest rates, inflation, and other economic factors. Historical experience of past capital stock destruction and precedents from several decades ago may underestimate the interconnectivity effects of the modern global financial system.

Extreme events with shocks that exceed the apparent tipping point can display non-linear dynamics due to the complexities arising from interplay of multiple variables and the adaptive responses by economic agents with time. We have observed several features of complex systems in the model outputs, particularly in terms of non-linear dynamics and phase-transitions. There is a lack of consensus in academic literature regarding the upper limit of impacts on markets from natural catastrophes.

The immediate and delayed macroeconomic impacts resulting from the most disruptive and destructive of these catastrophe scenarios are significant. Bond ratings and stock markets move differently as a result of these large capital loss shocks, and these effects are different to those seen in financial crises, such as liquidity and credit crises.

In cases of large capital loss shocks of this type, there may be a greater need to liquidate asset holdings by institutions and/or private investors, which would have a significant impact on prices. As a result, asset fire sales may occur and this may cause contagion through the capital markets at a greater rate than during financial crises of other types. Beyond the tipping point, correlations become more pronounced.

In summary, highly destructive natural catastrophe events certainly have the potential to cause market fluctuations in the domestic as well as international markets. These risks are still less than the man-made risks of asset bubbles, interbank lending and liquidity shortages, credit crunches, and other causes of financial crisis, but they remain an important threat to economic and market stability.

This study challenges the commonly-accepted assumption that market risk has a very low correlation with underwriting risk. It suggests that beyond the threshold of around a trillion dollars of property destruction, markets will respond and effects will be felt on multiple investment asset classes, even impacting high quality and well-structured investment portfolios.

We believe that this effect will increase with even higher levels of capital stock loss shock, and that market impacts will be felt very much strongly, and non-linearly, with incremental property damage cost increases. We have described candidate scenarios for higher levels of loss, and ways that losses could potentially be amplified from the examples studied. A worthwhile further extension of this research would be to define the market response to scenarios of much higher levels of destructive loss, and to explore the frequency and severity of the levels of investment portfolio losses that would result from the continuum scale of multi-trillion dollar destructive events.

The frequency of occurrence of these destructive losses that can cause market loss is an important issue. The six scenarios that we have identified and used as illustrative examples each have low probabilities of occurrence, and yet collectively they illustrate that one of these market impacting natural catastrophe losses could be experienced at around a 200 year return period, potentially sufficiently frequently to influence regulatory levels of capital requirement. However these six scenarios are not the only candidates for large destructive events. Depending on how many there are, and their relative likelihoods, the complete picture of potential for market risk to correlate with large scale underwriting risk may impact at shorter return periods than previously assumed.

The use of scenarios derived from catastrophe science and events for which probabilities can be estimated is a tractable method for assessing the correlation between market risk and underwriting risk. A scenario-based method could potentially offer a higher confidence assessment for correlation assumptions that could inform or replace conventional methods, such as copula modelling.

Reports like this one and models of scenario events can be used to improve tail correlation assumptions between market risk and underwriting risk.

Section 8: **References**

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