Earth

wtwco.com

Earth Risk: No hazard is an island

When a natural disaster occurs, a casual observer will all too often see it as an isolated incident. But if you look a little deeper, beyond the news headlines, you see that most of these hazards are interconnected.

Tsunamis are a prime example; although a destructive and devastating hazard on their own, this mass movement of water can be caused by large magnitude earthquakes (such as the 2004 Boxing Day tsunami), powerful volcanic eruptions (seen recently during the 2022 Tonga eruption), and even large landslides (the largest of which, 1958 in Lituya Bay, caused a mega-tsunami with a maximum wave height of 524 metres) that all come with their own effects on the surrounding environment and population. Links can be seen between a variety of other natural hazards, such as extreme weather events and wildfires influencing landslide hazard, and interactions between volcanism and weather conditions such as El Nino, and even potential influences of extreme rainfall on the triggering of volcanic eruptions (though this theory is not universally accepted, as discussed in our recent our recent Insight Piece, ‘Exploring the links between climate change and volcanic hazards’).

These links are becoming ever more important in the worlds of risk analysis, resilience and insurance, as the effects of climate change become more prevalent and weather patterns across the globe become more unpredictable and erratic. Extreme temperatures, extreme rainfall, drought and storm events are becoming more frequent, and have the potential to trigger or otherwise worsen the effects of a number of geological hazards in the coming years and decades. For geoscientists, used to dealing with depositional environments formed over millions of years and events that can sometimes take hundreds of years between reoccurrence, these changes could be thought of as very sudden. But new and evolving technologies such as remote earth observation, machine learning and high-performance computer modelling are helping to better understand the interplay between these hazards and their effects.

The WTW Research Network is continuing to support academics and industry scientists working with the earth hazards, risk and exposure, with new and improved modelling software development that is being shared across wider WTW teams, and recommendations on how existing analytics tools can be improved to more accurately account for hazards which may change in the face of climate uncertainty.

The WTW Research Network is continuing to support academics and industry scientists working with the earth hazards, risk and exposure, with new and improved modelling software development that is being shared across wider WTW teams, and recommendations on how existing analytics tools can be improved to more accurately account for hazards which may change in the face of climate uncertainty.

James Dalziel
Head of Earth Risk

Tsunami risk assessment: the quest for more reliable models

In a changing and dynamic natural world, with increasing populations exposed to coastal risks, these have caught the attention of the insurance industry.

An urgent need for investment in preparedness and establishing plans to mitigate effects on lives, critical facilities, and ultimately, economic growth is clear. Particularly, tsunami phenomena have been raising interest due to their impacts on large areas. While the frequency of large tsunamis are rare, these events can be destructive and several tsunamis over the last decade have provided insights on the complexity of forecasting impacts along the coast. This is not only due to the physical aspects and inherent variability of triggering phenomena such as earthquakes, submarine or subaerial landslides, volcanic eruptions or their cascading effects, but also because of the lack of information about the built environment.

Tsunami hazard and risk assessment has been evolving, owing to advances in numerical modelling and the computational power needed to simulate flow evolution and impact. Tsunami inundation is dependent on the tsunamigenic source's characteristics, although other associated processes such as bay resonance may influence wave heights that could differently affect points along a coastline. This could be analogous to local effects known in seismic hazard assessment, where resonant processes may amplify the response of buildings to shaking, influencing effects on the built environment and casualties.

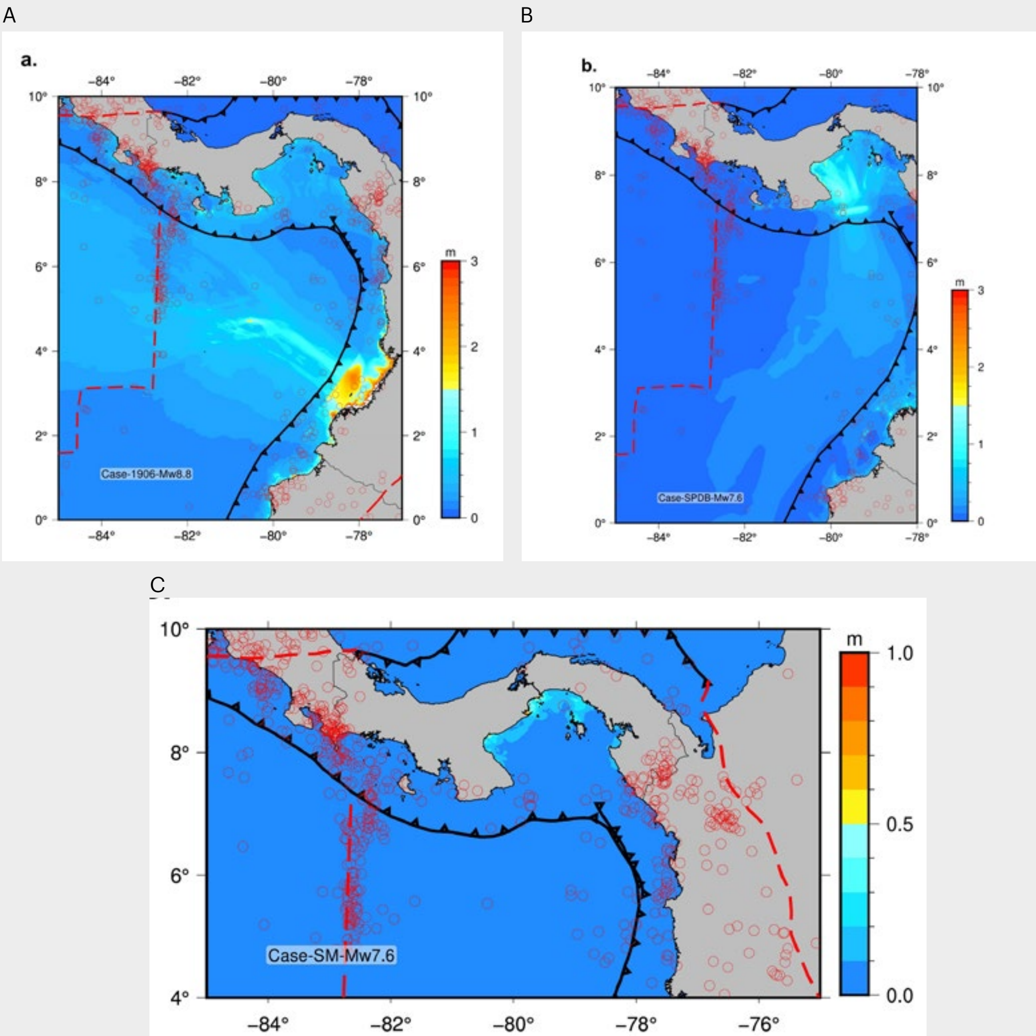
Risk analysts have been dealing with these aspects to account for a whole range of uncertainties. In estimating the hazard, for example, characterization of seismic ruptures or submarine landslides could lead to different tsunami magnitudes. Multi-hazard assessment is also a crucial aspect of hazard estimation not always considered in urban planning[1]. The main sources of uncertainty for tsunami research are limitations or availability of some datasets to simulate tsunamis (e.g. topo-bathymetry) and a lack of information on the built environment that adds more caveats for the hazard and therefore risk assessment.

The most common approaches to assess tsunami hazard are through deterministic and probabilistic analyses. The reason to choose one or the other may be justified by the application of resulting hazard estimates. Tsunami hazard maps based on one or few seismic scenarios have been commonly used for evacuation purposes or inundation maps in worst-case scenarios; using historical data or geological interpretation as source inputs for the maximum credible hazard.

[1]Grezio, A., Cinti, F.R., Costa, A., Faenza, L., Perfetti, P., Pierdominici, S., Pondrelli, S., Sandri, L., Tierz, P., Tonini, R. and Selva, J. (2020). Multisource bayesian probabilistic tsunami hazard analysis for the Gulf of Naples (Italy). Journal of Geophysical Research: Oceans, 125(2), DOI:10.1029/2019JC015373.

Here, we show some case study scenarios taken into consideration that may affect Panamá. Wave heights are shown along the coast for the Mw 8.8, 1906 Colombia-Ecuador earthquake (Fig. 1, top-left panel), a scenario triggered by a Mw 7.6 earthquake (Fig. 1, top-right panel), and a scenario based on local faults near the Panamá canal with no associated return period (Fig. 1, bottom panel). These examples are selected among several numerical simulations, corresponding to local and regional sources. These scenarios may be used for restricted purposes to assess impacts with almost no treatment of uncertainties.

Fig. 1: **Numerical simulations for a.) 1906 Colombia-Ecuador Mw 8.8 earthquake, b.) Southern Panama Deformation Belt Mw 7.6 earthquake, and c.) Potential Mw 7.6 earthquake scenario along the San Miguel Fault near the Panama Canal. Numerical simulations conducted with easyWave[2]**



Source: [2]https://git.gfz-potsdam.de/id2/geoperil/easyWave

On the contrary, probabilities are needed for integrating uncertainties into a decision-making problem of any type[3]. Since the 2004 Sumatra earthquake, methodologies such as the probabilistic approach have been more commonly used for engineering purposes aiming to reduce the large uncertainties related to a lack of tsunami observations, or due to the aleatory nature of the system[4].

In general, this approach has been widely used in weather or seismic hazard forecasting among other applications, and particularly for tsunami probabilistic hazard assessment as this is grounded in seismic hazard assessment as proposed by Cornell[5]. The hazard can be seen as the input to be considered in the vulnerability, exposure and loss estimates for a particular site.

[3] Rougier, J., & Beven, K. (2013). Model and data limitations: The sources and implications of epistemic uncertainty. In J. Rougier, S. Sparks, & L. Hill (Eds.), Risk and Uncertainty Assessment for Natural Hazards (pp. 40-63). Cambridge: Cambridge University Press. doi:10.1017/CBO9781139047562.004

[4] Grezio, A., Babeyko, A., Baptista, M. A., Behrens, J., Costa, A., Davies, G., et al. (2017). Probabilistic tsunami hazard analysis: Multiple sources and global applications. Reviews of Geophys., 55, 1158–1198. https://doi.org/10.1002/2017RG000579

[5] Cornell, A. (1968) Engineering Seismic Risk Analysis. Bulletin of the Seismological Society of America, 58, 1583-1606.

Workflows used in catastrophe models

Most of the workflows used in tsunami risk assessment, as in other natural phenomena, are composed of modules (Fig. 2). This modular approach is used in different ways, many times oversimplified due to data limitations or spatial scale of the study area. Most commonly the modules that composed a catastrophe model have inherent uncertainties, mostly due to the lack of data and limitations for forecasting recurrence rates that may lead to underestimation. For a particular study in Panamá, the deterministic use of scenarios and the different characteristics of the hazard may impact losses by almost 50%. The risk is also sensitive to the assumptions of fragility curves and scale of the built environment, which lead to misestimation of the risk.

A comparison between models used as input data to the loss module indicates that more granular and comprehensive data should be used to construct each module. While improvements for workflows lie in the propagation of uncertainties, assuming that the limits to good quality data can be overcome, adding confidence intervals and enhancement in the visualization will also benefit risk estimates, stakeholders and ultimately, risk mitigation.

Fig.2: **General workflow to study the risk component**[6]

Modules	Characteristics	Data
Hazard	• Integration of one or several scenarios (ideally multi source) • Probabilistic or deterministic scheme depending on data and aims of the project	• Bathymetry • Source characterization • Source rates
Exposure	• Distribution of built environment • Elements at risk • Economic value • Polulation density	• Building type • Density • Coastal critical facilities • Census
Vulnerability	• Physical, social, economical, type of elements at risk • Material • Resilience	• Economic value • Fragility curves
Losses	• Impacty to the economic addets • Impact to critical facilities • Impact to livelihood	• Census • Different thresholds
	Risk results from modules integration	

Source: [6]Goda K. Multi-hazard parametric catastrophe bond trigger design for subduction earthquakes and tsunamis. Earthquake Spectra. 2021;37(3):1827-1848. doi:10.1177/8755293020981974

Availability of high-resolution bathymetry data, as well as an understanding of the effects of poor incorporation of uncertainties are key aspects to generating more reliable risk models. Generally, workflows are not necessarily performed to assess joint losses (e.g. earthquakes and tsunamis), although by assessing damage related to tsunami or earthquake and how buildings can respond to both phenomena using data from previous studies, this could help determine how buildings respond to cascading events. These improvements could then be used to supplement hazard assessment and modelling tools within the insurance industry.

About the BSC

The Barcelona Supercomputing Center - Centro Nacional de Supercomputación (BSC-CNS) specializes in high performance computing (HPC) and manage MareNostrum, one of the most powerful supercomputers in Europe. Over their well-established collaboration with the WTW Research Network, our colleagues at the Barcelona Supercomputing Center have provided a reflection on how improvements to tsunami hazard modelling approaches and the role of uncertainties could lead to more accurate risk models. Past projects have modelled volcanic eruptions and forecasted the impacts of volcanic ash clouds on air traffic.

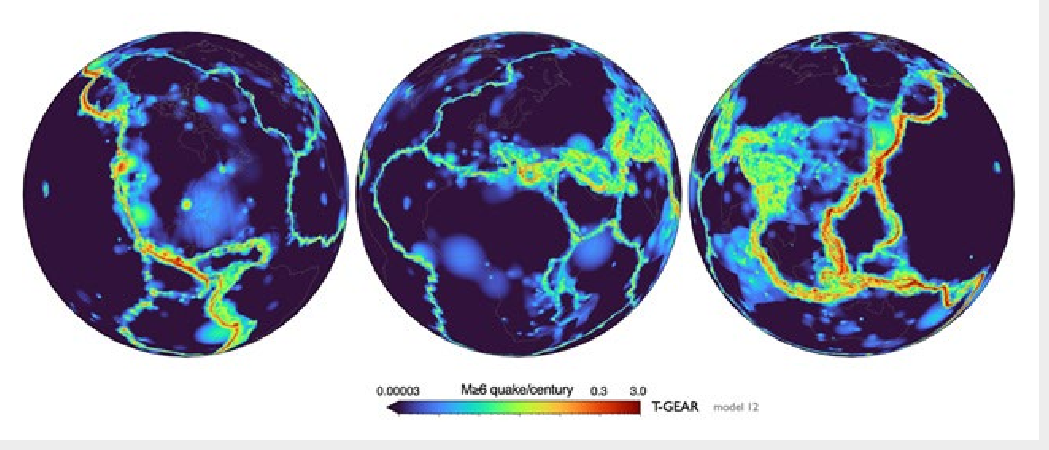
Creating a globally consistent stochastic event set for earthquake modelling

The product of more than a year of work by the Temblor team under the WTW Research Network, and with the close evaluation of WTW and GallagherRe scientists, EVENTSET is the only independently-tested, globally-consistent stochastic event set.

What is 'EVENTSET', and why does it differ from standard practice?

EVENTSET2 is Temblor's worldwide 60,000-year stochastic event set. The set comprises 30 million M≥5.0 events worldwide (with magnitude, location and depth), in which M≥7.0 earthquakes represented by extended sources. EVENTSET2023 accounts for the role of recent large earthquakes in altering the quake rate, with areas of enhanced and suppressed seismicity via Temblor's Realtime Risk technology. Affected countries include Japan (2011 M9.0 Tohoku and 2016 M7.0 Kumamoto shocks), New Zealand (2010-2011 M6.3-7.0 Canterbury and 2016 M7.8 Kaikoura shocks), Chile (2010 M8.8 Maule and 2015 M8.3 Illapel quakes), and Mexico (2017 M8.1 Tehauntepec and M7.0 Puebla shocks).

Fig.1: **Temblor's Global Earthquake Activity Rate (T-GEAR) model and EVENTSET 2.1**



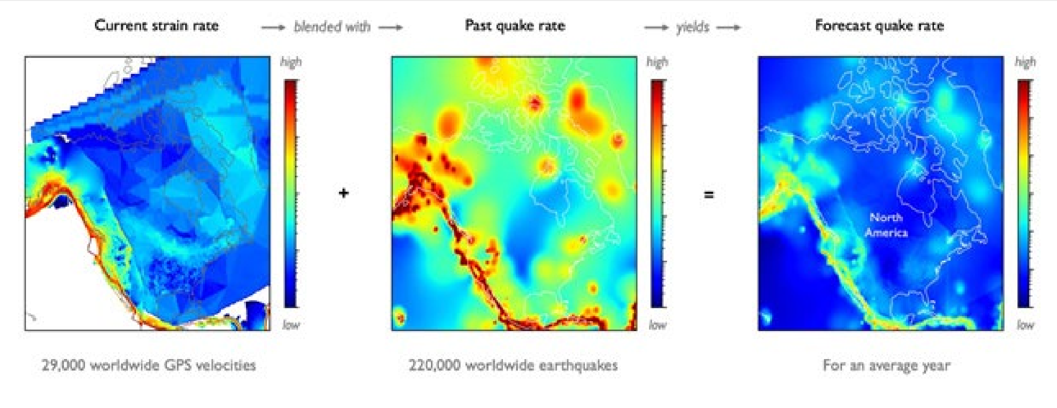
Active seismic zones and continental interiors captured fully and consistently - everywhere on Earth

Source: Temblor

Typically, modelers use fault traces to draw rectangles, and then assign maximum earthquake magnitudes to those rectangles, and return times for quakes in those rectangles based on fault slip rates, with magnitudes and rates between faults ("areas sources") estimated.

The problem with this approach is that the global inventory of active faults is woefully inadequate, fault slip rates are rarely known, and earthquakes can rupture multiple fault sections and so exceed the maximum magnitude. Recent examples of failures of such "fault-based characteristic earthquake models" include the 2011 M9.0 Tohoku, 2016 M7.8 Kaikoura, and 1993 M7.3 Landers, California earthquakes, which were 10 times larger than in models. In addition, large damaging quakes have struck where no faults were mapped at all in Japan (M6.9 Iwate-Miyagi), California (2019 M7.1 Ridgecrest) and New Zealand (2011 M7.1 Darfield). And these are the three best mapped countries in the world.

Fig.2: **Components of T-GEAR**



Source: Temblor

Temblor's advance

PolyCat provides an analysis tool for EVENTSET. One can examine any polygon, shape file, or country boundary file, buffered by any distance (since quakes just outside the boundary can contribute to hazard inside), to extract the event set over any magnitude and depth range of interest. PolyCat also furnishes the return time for any magnitude and depth range, and the return time uncertainty.

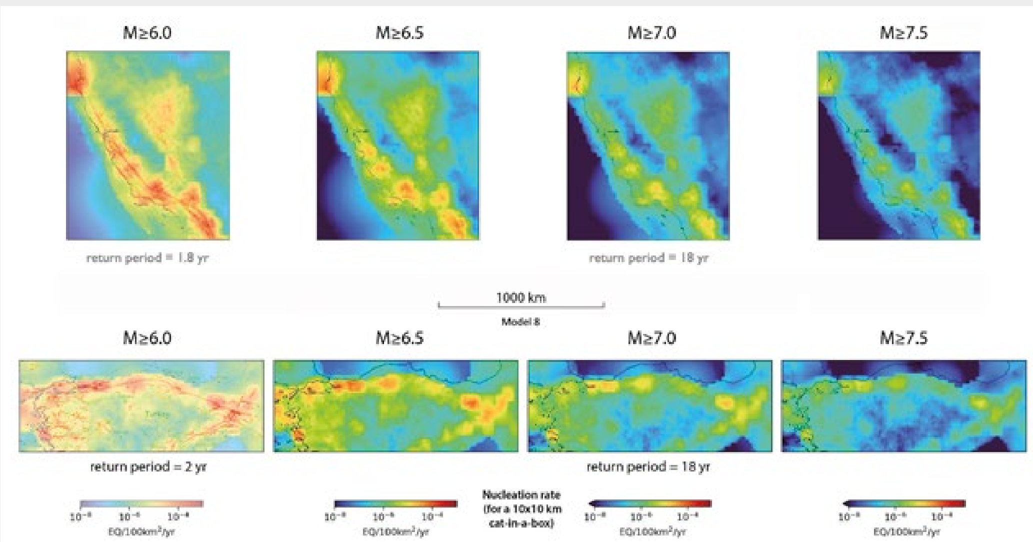
Temblor blends GPS strain rate as a proxy for the forces that load faults, with past earthquakes, which unload those forces. In contrast to faults, GPS is measured in the same manner by similar instruments worldwide. Temblor's earthquake catalog spans 117 years. This means that the quake intensity and frequency anywhere in the world are strictly inter-comparable. For example, when one compares the San Andreas Fault system (California) with the North Anatolia Fault system (Turkey), in which the two faults have the same slip rate and length, the earthquake return times are nearly identical, a strong test of EVENTSET's accuracy. In contrast, most vendor models are built by different scientists in different areas, and so are unable to assure they are self-consistent.

temblor

Temblor, Inc.

Temblor is a Silicon Valley tech company providing personal, immediate, and credible sources of seismic risk solutions. Their free mobile and web app and daily blog have gained 900,000 users worldwide in under 16 months, and their enterprise projects for insurance and financial clients has given them an understanding of key unmet needs. Temblor's CEO Ross Stein, CTO Volkan Sevilgen, and collaborator Shinji Toda from IRIDeS of Tohoku University, are the world pioneers in Coulomb stress transfer.

Fig.3: **California and Turkey (with faults of same slip rate and length) give similar return times in T-GEAR**



Source: Temblor

Rigorous testing

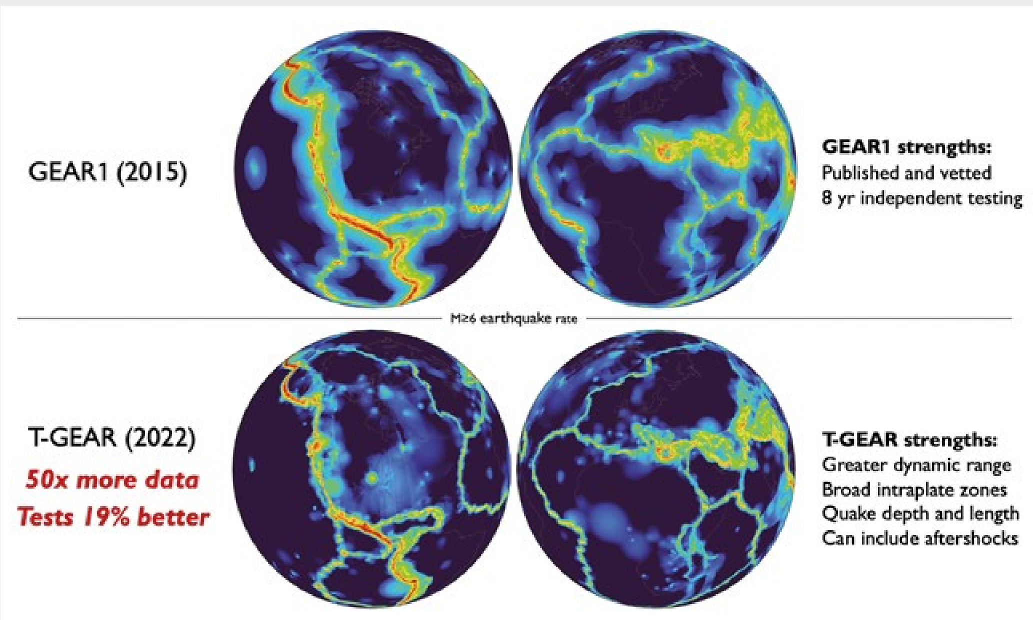
T-GEAR (for Temblor's Global Earthquake Activity Rate model) is the basis for EVENTSET. Random draws of this underlying quake rate model are used to generate EVENTSET. T-GEAR includes 200 million earthquake rates in 0.15M (magnitude) increments on a 0.1° x 0.1° spherical grid.

T-GEAR's predecessor, GEAR1, was published in 2015 (Bird et al., BSSA 2015) and has been under test by the international seismic testing agency, CSEP (Collaboratory for the Study of Earthquake Predictability) for 8 years, where it has outperformed its academic competitors in every year. It was the subject of a test publication (Strader et al., SRL 2018). No other commercial or foundation has submitted its event set for independent testing. In retrospective tests, T-GEAR outperformed GEAR1 during 2019-2021 by 23% (based on the Kagan I1 information score), in part because T-GEAR includes 50 times the data as GEAR1.

Benefits

For reinsurers, EVENTSET enables disparate population centers, such as Los Angeles, Tokyo, Santiago, and Istanbul, to be rigorously inter-compared. For primary insurers, they have the confidence that the event set in Indonesia, the Philippines, or Ecuador is just as accurate and complete as it is for California or Italy. For Insurance Linked Security companies, any parametric cat bond or private placement can be independently analyzed.

Fig.4: **Comparisons between Temblor's 'GEAR1' and the new 'T-GEAR' models.**



Source: Temblor

Estimating population displacement following disasters

Global disasters displaced 265 million people between 2008 and 2018[1].

The number of people displaced annually is likely to increase under ongoing trends, driven by poorly managed urban growth in hazard-prone areas[2] and potentially exacerbated by climate change[3]. Despite the scale of the human impact from disaster-induced displacement, efforts to model population displacement from disasters are in their infancy, and limited information exists on the drivers and extent of protracted displacement.

Investigating displacement duration using past events

Most statistics regarding population displacement following a disaster event provide single values representing a snapshot in time, often indicating the peak estimate. However, the duration of displacement is an essential component for understanding the human impact of disastrous events. For example, large-scale displacement in the form of evacuations before a storm can save lives and be followed by mass return shortly thereafter.

In contrast, a devastating event such as an earthquake could damage or destroy a significant proportion of the residential building stock, causing occupants to seek temporary shelter or accommodation for months to years. Not only does this type of protracted displacement pose a significant disruption to the livelihoods of affected households, but it also disrupts the economic production of the overall community[4].

PhD candidate Nicole Paul, Prof Carmine Galasso at UCL, and Prof Jack Baker at Stanford University are simulating recent past events to compare existing simplified models of displacement (i.e., solely based on housing damage) to reported displacement values. A particular focus is on events where time-varying displacement data is available to differentiate between immediate displacement and protracted displacement. This benchmarking study will evaluate the uncertainty range of simplified displacement models and attempt to identify the factors driving protracted displacement. As an outcome, this research will propose a framework to estimate both immediate and protracted displacement.

[1] Internal Displacement Monitoring Centre (2019). Disaster Displacement: A global review, 2008-2018.

[2] Internal Displacement Monitoring Centre (2017). Global Disaster Displacement Risk: A baseline for future work.

[3] IPCC (2012). Summary for Policymakers. In: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation

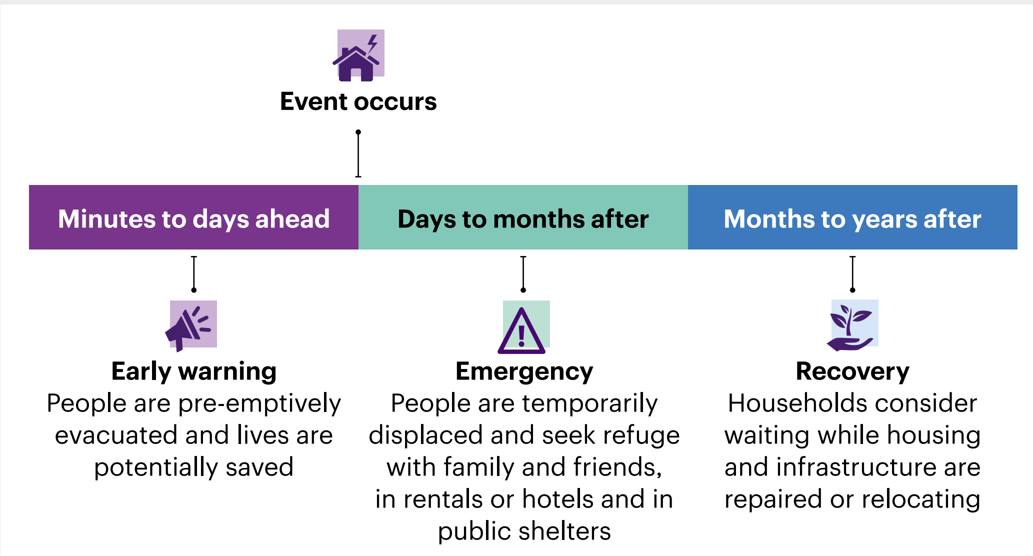
[4] Internal Displacement Monitoring Centre (2018). Assessing the Economic Impacts of Internal Displacement: Conceptual Framework. In: The ripple effect: economic impacts of internal displacement.

Identifying hotspots of disaster-induced displacement risk

With a framework to quantify population displacement from disasters in place, existing datasets will be leveraged to estimate urban disaster-induced displacement risk globally. In collaboration with the Global Earthquake Model (GEM) Foundation, models covering seismic hazard, the exposure of buildings and population, and fragility relationships relating earthquake-induced ground shaking to damage levels are available for this study. As derived from the earlier case studies, a displacement consequence model will be applied to estimate displacement risk globally.

A few modifications to GEM Global Exposure Model are planned to highlight the current and future displacement risk of urban areas. Earth Observation (EO) datasets will inform a spatial disaggregation of the exposure and a projection of built areas into the future decades. Through open datasets such as WorldPop and the Global Human Settlement Layer (GHSL), the distribution of buildings and people can be reflected in a realistic manner that aids disaster risk assessment for multiple hazard types (e.g., earthquakes, floods). Additionally, data from GHSL regarding built-up areas across different epochs can be combined with data covering man-made features (e.g., roads, existing towns) and natural features (e.g., topography) to predict future built-up areas via geographically weighted regression[5]. Following this approach, this research will project the baseline (i.e., current year) exposure to 2050 to understand how displacement risk will likely evolve under ongoing trends and under hazards such as floods that will be affected by climate change.

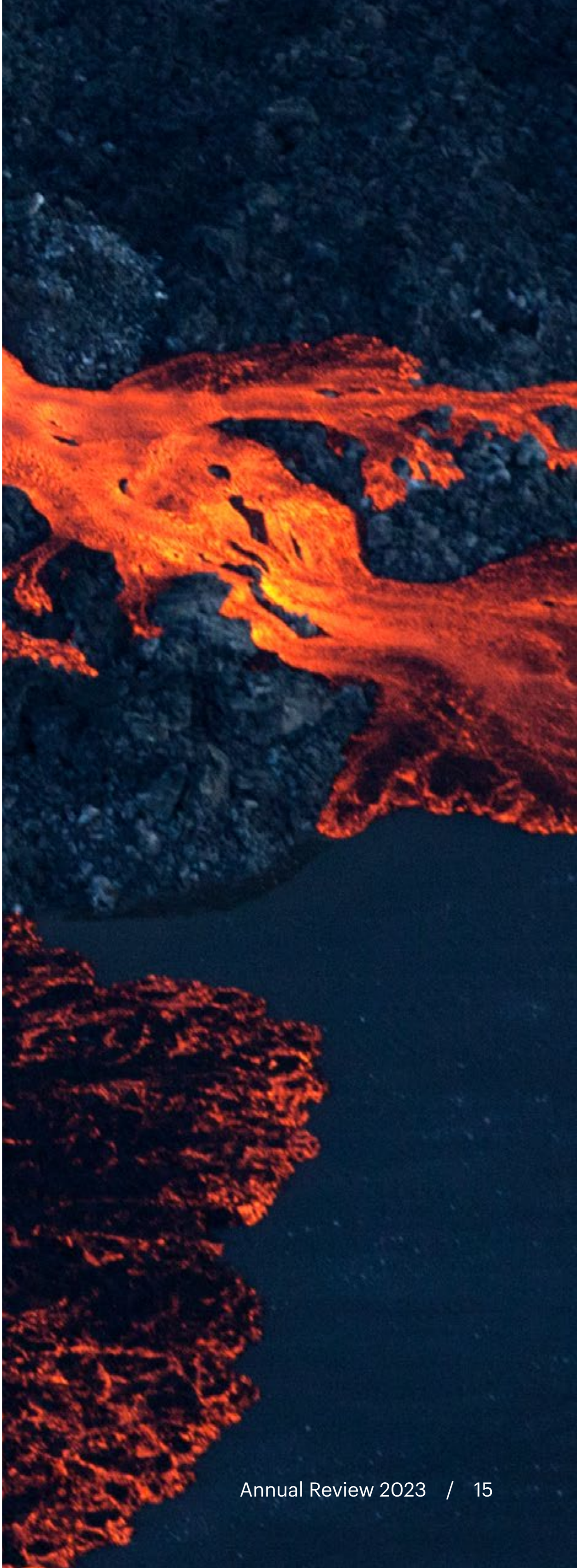
Fig.1: **A timeline representing displacement duration alongside key phases of disaster management and recovery.**



[5] Calderón, Alejandro, and Vitor Silva (2021). "Exposure forecasting for seismic risk estimation: Application to Costa Rica." Earthquake Spectra 37, no. 3.

University College London

UCL Civil, Environmental and Geomatic Engineering (CEGE) is a multidisciplinary department renowned for excellence in research and teaching. It currently holds a substantial UK Research and Innovation (UKRI) research portfolio in civil engineering. Home to world-leading research projects, groups and centers, CEGE reflects a broad, enquiring and human-centered view of the engineering world. Strong links to industry and research are embedded throughout a diverse range of programs. These links are enhanced by CEGE's proximity to both significant infrastructure projects and leading firms, thanks to its central London location. Within CEGE, Prof Galasso's and Dr Cremen's research focuses on developing and applying probabilistic and statistical methods and tools for catastrophe risk modeling and disaster risk reduction. They investigate risks to building portfolios and infrastructure exposed to multiple natural hazards, including earthquakes, strong wind, and flooding, with special emphasis on developing countries.'



Impact of a giant megathrust earthquake in Chile today

Southern Chile is home to the largest historical earthquake ever recorded, the Giant May 22, 1960 M9.5 Valdivia megathrust event.

The rupture zone reached more than 1,000 km along the Chilean coastline, with an estimated extent of peak ground accelerations (PGAs) shown in **Figure 1**. The shaking from the Valdivia earthquake and the subsequent tsunami resulted in more than 1,600 fatalities and 3,000 injured, rendered more than 2 million people homeless, and caused $550 million (adjusted for inflation, ~$5 billion today) in damage in Chile. Due to the extensive tsunami generated by the earthquake, additional deaths were recorded in Japan, Hawaii and the Philippines.

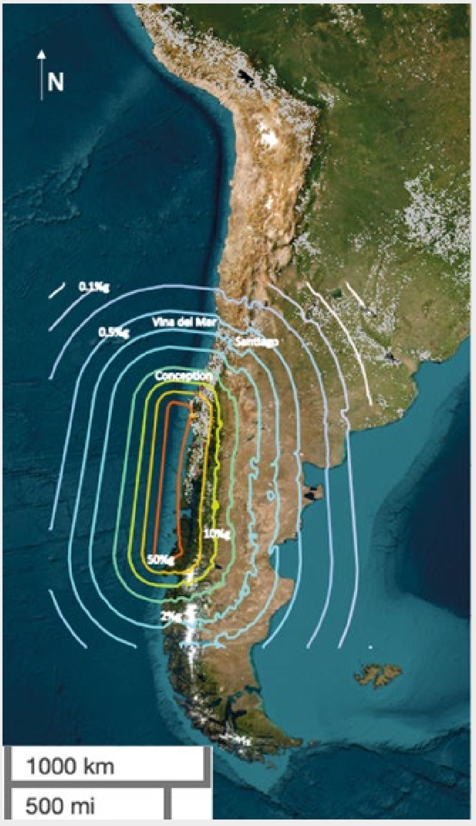
One reason why the number of fatalities from the Valdivia event was relatively modest considering its large magnitude is that the rupture occurred south of many of the population centers. For example, if the Giant earthquake had ruptured a stretch of the trench 500-1,000 km further north, at the latitude of Santiago (~2 million people in 1960, ~8 million today) and coastal resort cities such as Vina del Mar, the outcome would likely have been very different.

While prediction of the timing of the next M9.0+ earthquake along the Chilean coast is impossible, these Giant events do appear to follow a time-dependent strain accumulation pattern, with a ~2.2% probability of a 1960-like event between 1960 and 2017[1]. Despite the rather low probability, the effects of such large earthquake must be considered to ensure that premiums accurately reflect expected losses.

Loss estimating in Catastrophe models conventionally relies on regression of empirical ground motion recordings (Ground Motion Prediction Equations, or GMPEs) from historical earthquakes. However, GMPEs by construction produce large uncertainty due to the inherent smoothing, and potential bias in the estimated ground motions. Furthermore, since seismic instrumentation in 1960 was insufficient to capture the ground motions from the Valdivia event, and no other historical earthquake of this magnitude has occurred, GMPEs are mostly unconstrained for such large-magnitude events. The smooth PGA contours that generally decay uniformly with distance from the rupture zone in the scenario ShakeMap in **Figure 1** hint at the limitations of GMPE-based ground motion predictions.

[1] Moernaut, J., M. Van Daele, K. Fontijn, K. Heirman, P. Kempf, M. Pino, G. Valdebenito, R. Urrutia, M. Strasser, and M. de Batist (2018). Larger earthquakes recur more periodically: New insights in the megathrust earthquake cycle from lacustrine turbidite records in south-central Chile, Earth and Planetary Sciences 481, 9-19.

Fig.1: **US Geological Survey PGA Shakemap for the 1960 Valdivia earthquake[2]. Modified from** https://earthquake.usgs.gov/earthquakes/eventpage/official19600522191120_30/shakemap/pga

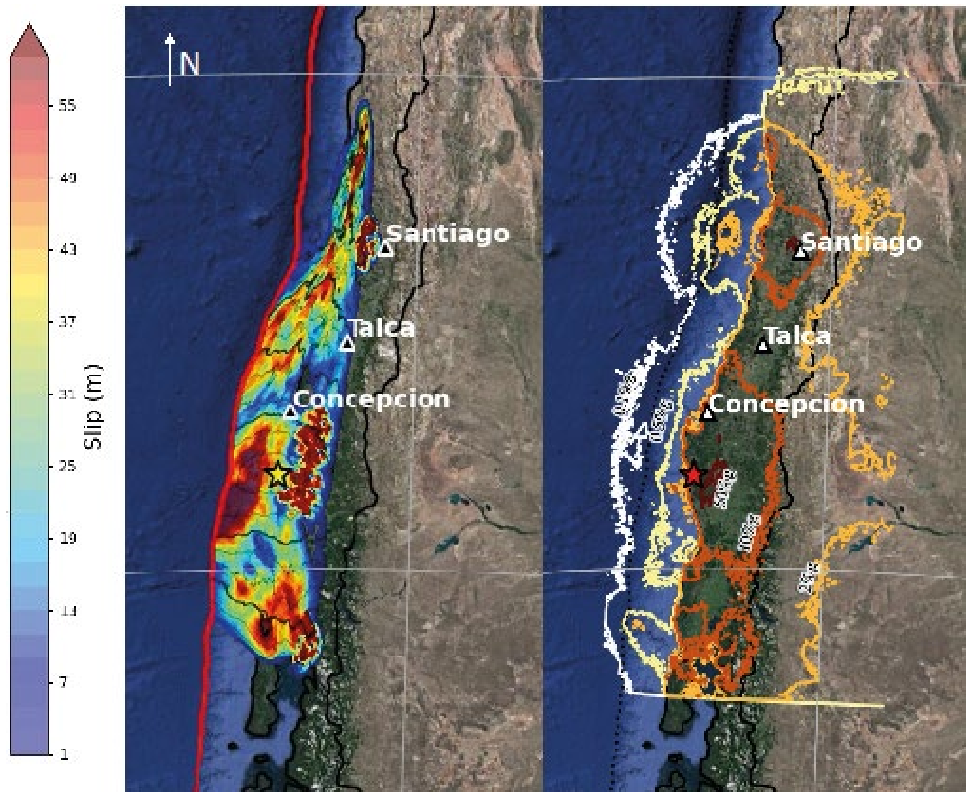


Source: [2]Larger earthquakes recur more periodically: New insights in the megathrust earthquake cycle from lacustrine turbidite records in south-central Chile, Earth and Planetary Sciences 481, 9-19.

A viable alternative to using GMPEs to predict ground motions and resulting losses from a future Valdivia-type event is to use wave propagation simulations in state-of-the-art 3D earth models. Since 2017, the WRN has been working with researchers from San Diego State University (SDSU) exploring how physics-based 3D ground motion simulations can improve the accuracy of catastrophe modeling. SDSU scientists Prof. Kim Olsen and his research team pioneered the first large-scale wave propagation simulations more than 2 decades ago, demonstrating how 3D effects of sedimentary basins can strongly affect the resulting ground motion predictions.

The ongoing research collaboration between WTW and SDSU aims to estimate the seismic risks along the south American west coast for megathrust earthquakes, including Giant, Valdivia-type events. **Figure 2** shows a rupture model and simulated PGAs for a realization of a 'worst-case' Valdivia-type earthquake scenario, rupturing further to the north compared to the 1960 event, close to metropolitans of Santiago and coastal resort towns. Notice the irregular PGA contours for the predicted PGAs, as opposed to the much smoother contours in Figure 1, caused by basin amplification, directional effects, and wave focusing, that are insufficiently covered by the GMPEs. Specifically, PGAs in the Santiago area and nearby coastal areas can exceed 50%g in this scenario, more than 5 times larger than the values from the 1960 Valdivia earthquake.

Fig.2: **(left) Rupture model and (right) resulting PGAs for a M9.54 megathrust earthquake scenario off the coast of central Chile. The star depicts the epicenter, the color shading is the slip distribution in meters, and the contours show the rupture initiation times.**



Source: Larger earthquakes recur more periodically: New insights in the megathrust earthquake cycle from lacustrine turbidite records in south-central Chile, Earth and Planetary Sciences 481, 9-19.

The improved ground motion estimates from 3D models come with an added cost – they require use of thousands of processing units on today's largest supercomputers for hours. However, 3D physics-based simulations include potentially significant basin amplification that are not typically captured in conventional loss estimation. Moreover, the losses resulting from 3D ground motion simulations are characterized by a much lower volatility than in catastrophe models, thus allowing a more accurate and less uncertain loss estimation, as an input to decision making. 3D earthquake simulations have progressively presented themselves as alternatives to a dearth of strong motion data records in the near field and for large magnitude earthquakes, and we are at the point where synthetic seismograms produced by 3D models are making their way into decision making for society.

San Diego State University

San Diego State University (SDSU) has been a member of WRN since 2017. Prof. Kim Olsen is the primary developer of the Anelastic Wave Propagation (AWP) code used to generate physics-based ground motion predictions for future catastrophic earthquakes in regions with high exposure. The simulations are taking into account the three-dimensional structure of the sedimentary basins, the ocean water layer, realistic variation in the rupture pattern, and the amplification and nonlinear effects of the near-surface low-velocity layers.

Exploring the links between climate change and volcanic hazards

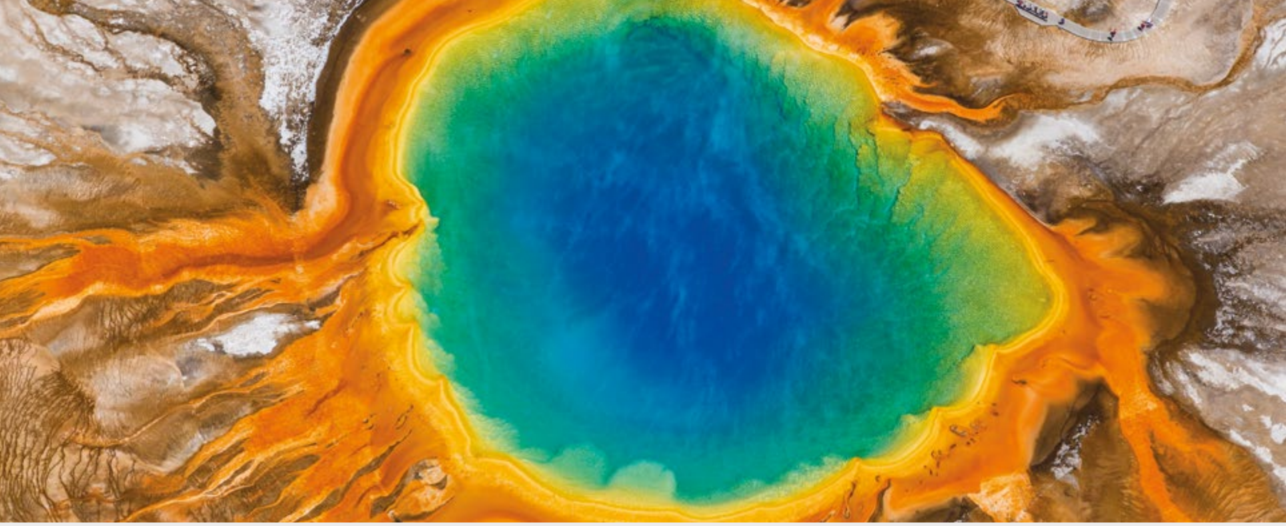
The ongoing climate emergency has proved to be a far-reaching point of discussion in recent years, with the effects of rising temperatures, melting ice caps, changing seasons and more intense storms having the potential to affect aspects of our everyday lives across the globe.

In the world of geohazards, the most discussed consequences are how changing weather patterns can influence landslides, slope stability and coastal erosion. But another potentially significant link, and in some cases the topic of intense debate, is that between climate variability and the triggering of volcanic activity.

One area of study where climate influence on volcanism is better understood and broadly accepted is that of glacial melting and the subsequent unloading of underlying magma chambers.

Work done by Albino et al.[1] looked at how surface load variations around Icelandic volcanoes act on their shallow magma chambers. Findings showed that in line with model predictions, the last nine historical eruptions at Katla volcano occurred during the summer season when snow cover was at its smallest. The 2004 Grímsvötn eruption was also noted to have been immediately preceded by a 'jökulhlaup', or glacial outburst flood, which may have triggered the event if the magmatic system was already close to failure. Another paper from Sigmundsson et al.[2] supports these findings, stating that pressure can influence both magma production as well as the failure of magmatic systems and making the wider claim that a current reduction in ice load on subglacial volcanoes, due to climate change, is modifying pressure conditions in magmatic systems. More recent work by Praetorius et al.[3] and Rawson et al.[4] finds evidence for a similar link during deglacial transitions in Alaska and Chile respectively, suggesting this is not a phenomenon limited to certain geographies or volcanic settings. These findings suggest that not only are the failure conditions of magmatic systems altered by melting snow and ice, but an increased rate of magma production threatens more voluminous eruptive activity from subglacial volcanoes as well as potentially greater frequency.

[1] Albino, F., Virginie Pinel, and F. Sigmundsson. "Influence of surface load variations on eruption likelihood: application to two Icelandic subglacial volcanoes, Grímsvötn and Katla." Geophysical journal international 181.3 (2010): 1510-1524.



Another potential link between the effects of a changing climate and volcanism comes in the form of sea level change at island arc volcanoes.

A paper by Coussens et al.[5] uses evidence in the rock record to find a connection between periods of rapid sea level rise and flank collapse at Soufrière Hills, Montserrat, and periods of heightened volcanic activity over the past million years. Satow et al.[6] also identifies a link between sea level change and eruption frequency at Santorini, however these results show the opposite to Coussens et al. with periods of sea level fall triggering dyke injection and feeding eruption over the past 360,000 years. This could indicate that the effect sea level has on volcanism is dependent on geography or tectonic setting, but in either case the work shows that rapid sea level rise from climate change will have an effect on volcanoes around the world.

Fighting back: How volcanoes can affect our climate

The relationship between volcanoes and our climate can work in both directions. Some climate change sceptics claim that volcanoes, rather than people, are responsible for current global warming trends. Looking back through history, we can see that the opposite is true. In addition to lava and ash, sulphur dioxide (SO2) is a major output from volcanic eruptions. If

[2] Sigmundsson, Freysteinn, et al. "Climate effects on volcanism: influence on magmatic systems of loading and unloading from ice mass variations, with examples from Iceland." Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 368.1919 (2010): 2519-2534.

[3] Praetorius, Summer, et al. "Interaction between climate, volcanism, and isostatic rebound in Southeast Alaska during the last deglaciation." Earth and Planetary Science Letters 452 (2016): 79-89.

[4] Rawson, Harriet, et al. "The magmatic and eruptive response of arc volcanoes to deglaciation: Insights from southern Chile." Geology 44.4 (2016): 251-254.

[5] Coussens, Maya, et al. "The relationship between eruptive activity, flank collapse, and sea level at volcanic islands: A long-term (> 1 Ma) record offshore Montserrat, Lesser Antilles." Geochemistry, Geophysics, Geosystems 17.7 (2016): 2591-2611.

[6] Satow, Chris, et al. "Eruptive activity of the Santorini Volcano controlled by sea-level rise and fall." Nature Geoscience 14.8 (2021): 586-592.

propelled high enough into the atmosphere in sufficient concentrations, this gas can reflect solar radiation and have a cooling effect on the Earth. There are records of these 'volcanic winter' events occurring throughout history, with a notable entry being the 1815 eruption of Mount Tambora resulting in the 'year without a summer' and credited as helping contribute to Mary Shelley's writing of "Frankenstein". Similarly, many historical records of famines can be linked to volcanic eruption events, such as the 1783 Laki eruption in Iceland. More recently, the eruption of Mount Pinatubo in 1991 caused ~15 million tonnes of SO2 to be propelled into the stratosphere, resulting in a 0.5°C drop in average global temperature for the next 2-3 years.

So could a potential increase in the frequency of eruptions, as a result of climate change, result in enough SO2 being released into the atmosphere to in fact cool the Earth and solve the problem? Although not impossible, this eventuality is extremely unlikely. There have been records showing periods of heightened volcanic activity triggering 'little ice ages' of regional cooling, but the size of eruptions needed to cause this are significant.

For reference, the recent eruption of the submarine Hunga Tonga-Hunga Ha'apai volcano had effects felt across the globe (as discussed in our recent insight piece), but even this only produced a volcanic cloud containing ~50x less SO2 than the Mount Pinatubo eruption, and is reported to have had negligible effects on the climate.

When it rains, it pours lava: Links between rainfall and volcanism

An area where the links between climate variability and volcanism are somewhat less well-defined is regarding the influence of rainfall. A paper published in Nature[7] discusses the theory that anomalously high rainfall and a subsequent increase in pore pressure may have influenced the weakening and mechanical failure of the volcanic edifice at Kīlauea Volcano, Hawai'i in 2018, contributing to the triggering of a subsequent eruption in May of that year. This connection raises an important question in the worlds of hazard and risk assessment; could more frequent intense rainfall events, driven by climate change, also influence the frequency of volcanic activity in a similar way to glacial melting and sea level change?

At this stage the answer seems to be that further study is required. Farquharson & Amelung's findings are not universally accepted, and have been the subject of some fervent academic debate in recent years. Scientists at the USGS led by Dr. Mike Poland have responded to the article casting doubts on the links between rainfall and the 2018 Kīlauea eruption[8], questioning the rain gauge data used, the GPS measurements signalling pressurisation of the magma chamber prior to eruption, and the significance of the relatively small pore pressure changes (~0.1 kPa) reported by Farquharson & Amelung. This in turn has been rebutted by the paper's original authors in February 2022[9], responding to the questions raised and holding to their theory. They also point out in their response that the USGS themselves found links between anomalous rainfall and volcanic eruptions,

[7] Farquharson, Jamie I., and Falk Amelung. "Extreme rainfall triggered the 2018 rift eruption at Kīlauea Volcano." Nature 580.7804 (2020): 491-495.
[8] Poland, Michael P., et al. "Rainfall an unlikely factor in Kīlauea's 2018 rift eruption." Nature 602.7895 (2022): E7-E10.

discussed in a paper by Fred Klein[10], but this was dismissed at the time because it was "difficult to imagine a physical triggering mechanism of rainfall on eruptions". Other past work has been done in this area, including a paper by Barclay et al.[11] linking increased rainfall to heightened probability of primary volcanic activity (pyroclastic flows, dome collapses and explosions) at Soufrière Hills Volcano, Montserrat between 1998 and 2003, and calling for integration of meteorological data into volcano monitoring.

The controversy surrounding this research suggests that more work will need to be undertaken, in order to determine how robust the links are between intense rainfall events and volcanic activity and their worldwide applicability.

If evidence suggests that this is a global phenomenon, with high-quality data that reinforces the theories put forward and satisfies those with doubts, the implications would be profound. Not only would it mean that weather data and forecasts could provide another means of helping to predict volcanic hazards, but also that the continuing effects of climate change may mean activity such as dome explosions and flank collapses occur more frequently as intense rainfall occurs more often at active volcanoes. Another paper by Farquharson & Amelung[12] widens the scope to examine what links between heavy rainfall and both eruptive and non-eruptive volcanic hazards may mean for subaerial volcanic regions globally in the face of rapid climate change. How this conversation develops will be of great interest, not only to those in the academic community, but also those involved with volcanic hazard assessment such as the WTW Research Network and its partners.

Working together to assess the risks

Overall, the links between climate and volcanism are definitive, but the how, when and where of climate change affecting the occurrence of volcanic activity is an area still under investigation. Even if claims that extreme rainfall can directly contribute to triggering of eruptions are considered unlikely, the combined findings of these papers prove that numerous aspects of climate variability have been seen to promote volcanic activity in the past, and that the continuing results of rapid climate change may have the potential to reshape the volcanic risk landscape around the globe.

[9] Farquharson, Jamie I., and Falk Amelung. "Reply to: Rainfall an unlikely factor in Kīlauea's 2018 rift eruption." Nature 602.7895 (2022): E11-E14.

[10] Klein, Fred W. "Eruption forecasting at Kilauea volcano, Hawaii." Journal of Geophysical Research: Solid Earth 89.B5 (1984): 3059-3073.

[11] Barclay, Jenni, Jade E. Johnstone, and Adrian J. Matthews. "Meteorological monitoring of an active volcano: implications for eruption prediction." Journal of volcanology and geothermal research 150.4 (2006): 339-358.

[12] Farquharson, Jamie I. and Amelung, Falk (2022). "Volcanic hazard exacerbated by future global warming-driven increase in heavy rainfall." R. Soc. open sci.9: 220275.

An upcoming special issue in the Bulletin of Volcanology looks at progress made over the past twenty years and future challenges in the field, and includes a perspective paper by Aubry et al. discussing climate-volcano impacts[13]. Given how this could affect those at risk from volcanic hazards, further exploration of these impacts is a potential focus point for the WTW Research Network in the future. Together with other teams in WTW such as the Climate & Resilience Hub, we have formed an Earth Risk Working Group to bring earth scientists, hazard analysts and stakeholders together and discuss what areas of research could most benefit everyone.

The climate emergency is one issue at the top of our agenda, and these sort of links with other geohazards are an area we shall all be watching with great interest.

[13] Aubry, T.J., Farquharson, J.I., Rowell, C.R. et al. (2022). “Impact of climate change on volcanic processes: current understanding and future challenges.” Bull. Volcanol. 84, 58.

Parametric insurance solutions for volcanic ash disruption

Background and the problem to be addressed

Of the plethora of volcanic hazards, volcanic ash is the furthest reaching. Small particles of solidified lava are dispersed by wind and the clouds and can easily travel for hundreds of kilometres. Just 1 mm of ash fallout can significantly affect crucial aspects of infrastructure and agricultural activity, and 1 cm of ash can damage buildings[1]. Since the Eyjafjallajökull eruption in 2010, it is well-known that the aviation sector is particularly vulnerable to volcanic eruptions. The industry suffered a total loss of US$2bn due to delays, rerouting and cancelations associated with that single, moderately sized eruption[2]. On the ground, hangars, airports and grounded planes are at risk, but the main concern is in the atmosphere. Amongst several safety hazards, airborne ash can remelt in turbines causing flame-out, and thus airplanes generally are advised by the International Civil Aviation Organization (ICAO) to avoid ash clouds[2,3].

However, there are few adequate insurance products available on the market for risks associated with volcanic eruptions and the resulting losses are predominantly uninsured[4,5]. The protection gap for recent eruptions was between 50 and 100%[2,5]. This gap is mainly attributed to:

1 Limitations of traditional insurance:

Traditional insurance cover can be expensive for volcanic eruptions, and the processing of claims is often complicated and long.

2 No proper catastrophe models:

Volcanic ash is a poorly and/or unmodelled risk in the (re)insurance and aviation sectors and, therefore, most insurance policies do not cover it.

3 Limited scale:

Available insurance products are focused on specific areas (e.g., lava flow insurance for homeowners in Hawaii).

[1] Jenkins, S.F., Wilson, T.M., Magill, C.R., Miller, V., Stewart, C., Marzocchi, W. and Boulton, M. (2015) Volcanic ash fall hazard and risk: Technical Background Paper for the UNISDR 2015 Global Assessment Report on Disaster Risk Reduction. Global Volcano Model and IAVCEI. https://www.preventionweb.net/english/hyogo/gar/atlas/. DOI: 10.1017/CBO9781316276273.005

[2] Prata, F., and Rose, B. (2015) Chapter 52: Volcanic ash hazards to aviation. In Sigurdsson, H. (Ed.), The Encyclopedia of Volcanoes (Second Edition) (pp. 911-934), Academic Press. DOI: 10.1016/B978-0-12-385938-9.00052-3

[3] ICAO (2012) Doc 9974, Flight Safety and Volcanic Ash. https://www.icao.int/publications/documents/9974_en.pdf

[4] https://www.swissre.com/dam/jcr:02550b19-f9a2-45f2-9288-377d25952b5b/Swiss+Re_Volcano_PR_en.pdf

[5] Smolka, A., and Käser, M. (2015) Chapter 12 - Volcanic Risks and Insurance. In Shroder, J.F., and Papale, P. (Eds.), Volcanic Hazards, Risks and Disasters (pp. 301-314), in Hazards and Disasters Series, Elsevier. DOI: 10.1016/B978-0-12-396453-3.00012-5

Developing solutions through collaboration

One possible way to address the protection gap for risks associated with volcanic ash dispersion is the use of alternative risk transfer mechanisms based on robust catastrophe modelling. Mitiga Solutions and WTW have partnered to face this challenge, under the framework of the Eurostars project "Volarisk" since 2019.

Mitiga Solutions leverage their founder's accumulated 20+ years of experience developing and using FALL3D[6], one of the most renowned ash dispersal models to create bridges between volcanology, aviation and the insurance markets. They are building the next generation of the crisis management tool of Eurocontrol, the European Organisation for the Safety of Air Navigation. In addition, together with Replexus and the Howden Foundation, Mitiga developed the first humanitarian volcano cat bond that was released to the market in 2021. Issued by the Danish Red Cross, the bond covers losses due to eruptions from 10 volcanoes worldwide. It is based on a sophisticated cat model for ash fallout on the ground. Pay-out in the bond is triggered by eruption column height (Fig. 1) and then further based on wind directions.

The goal of Volarisk is to develop a parametric insurance solution for volcanic ash-inflicted losses to assets in the aviation sector, i.e. airports, hangars, runways, and in particular flights between city pairs. This insurance solution is based on a fully probabilistic global volcanic ash catastrophe model. Parametric insurance structures are widely used in catastrophe (cat) bonds; an example of insurance securitization in which the risk is transferred to the capital markets via a so-called special purpose vehicle or SPV[7]. Parametric insurance solutions thus require reliable cat models that form the base for proper risk assessment and financial structuring.

For more than 100 volcanoes worldwide, Mitiga developed a catastrophe model for ash fallout that provides loss estimates to a client's portfolio in order to quantify the risk at various return periods.

[6] Folch, A., Mingari, L., Gutierrez, N., Hanzich, M., Macedonio, G., and Costa, A. (2020) FALL3D-8.0. a computational model for atmospheric transport and deposition of particles, aerosols and radionuclides – Part 1: Model physics and numerics. Geosci. Model Dev., 13, 1431-1458. DOI: 10.5194/gmd-13-1431-2020

[7] Cummins, J.D., and Trainar, P. (2009) Securitization, Insurance, and Reinsurance. The Journal of Risk and Insurance, 76:3, 463-492. DOI: 10.1111/j.1539-6975.2009.01319.x

[8] Macedonio, G., Costa, A., and Longo, A. (2005) A computer model for volcanic ash fallout and assessment of subsequent hazard. Computers & Geosciences, 31, 837-845. DOI: 10.1016/j.cageo.2005.01.013

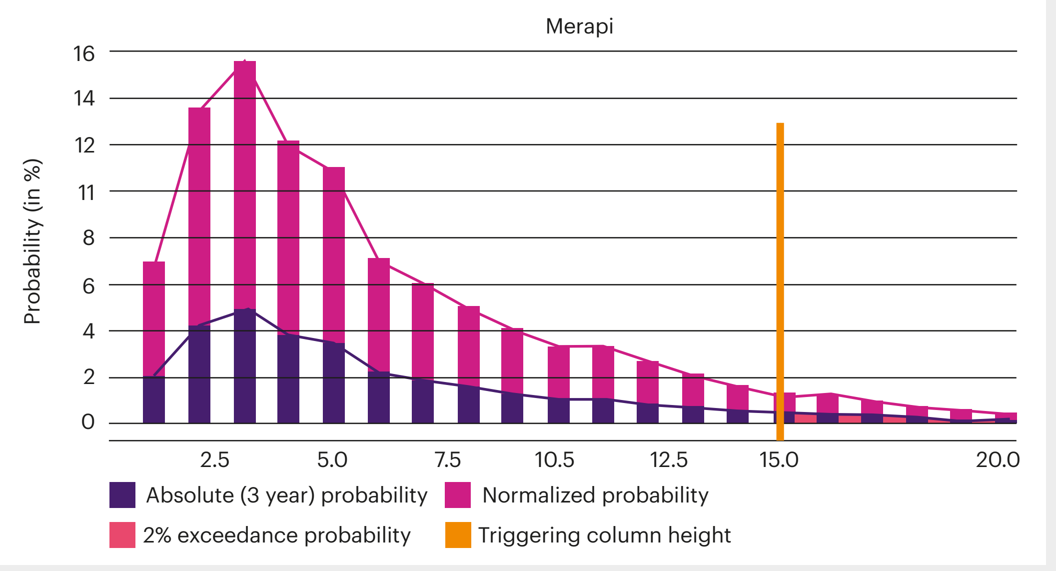
Eruption recurrence times and probability distributions for event intensities are derived from the eruption catalogues in a first step (Fig. 1). Together with historical wind data, these serve as the input for more than 10,000 footprint simulations per volcano. These simulations are performed with the ash dispersion model HAZMAP[8] and result in hazard maps for ash load on the ground (Fig. 2). Finally, these data are translated into a stochastic event catalogue. The final cat model is run on the OASIS platform that combines the event catalogue with vulnerability functions and client exposure datasets. The cat model has passed initial validation with historical loss data.

In order to develop the parametric insurance solutions for flights between city pairs, the cat model needs to be adapted for airborne ash. This requires simulations with the more sophisticated and computationally expensive model FALL3D, as HAZMAP is limited to ash deposition on the ground and does not simulate ash concentrations in the atmosphere. Mitiga has developed a novel methodology to address the computational demands of FALL3D for producing a robust stochastic event catalogue.

The final cat model is the base for parametric insurance solutions that will be developed together with WTW. The next steps will be proof-of-concept and validation studies in close collaboration between Mitiga, WTW and potential clients from the aviation sector.

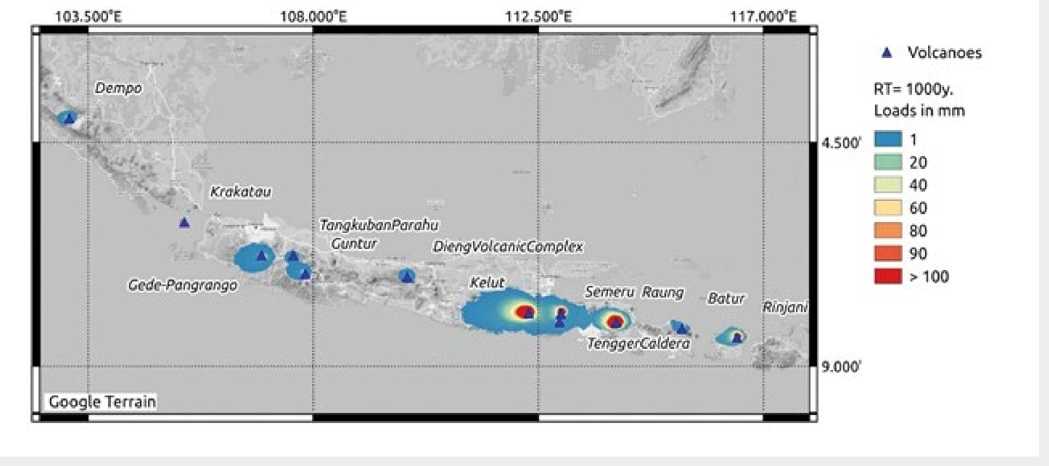
Figures

Fig.1: **Normalized and absolute probability distribution for eruption column height (≈ event intensity) of Merapi volcano. Green bars show the relative probability density function (PDF) discretized in 1 km bins (column heights in km above vent). The area below the relative PDF sums to 100%. Red bars give the absolute 3-year PDFs. The area below the absolute PDFs gives the 3-year probability of eruption, corresponding to 31.58% in the case of Merapi. The cat bond trigger is determined by finding the column height for which the area to the right (blue shaded region below the red curve) equals 2%, which for the particular case of Merapi yields 12.5 km above the vent for 3-years.**



Source: Mitiga Solutions

Fig.2: **1000y return period map of ash fallout in Indonesia**



Source: Mitiga Solutions

Mitiga

Mitiga Solutions

Mitiga Solutions is an offshoot of the Barcelona Supercomputing Center which specializes in high-performance computing. It is certified by Eurocontrol, and Mitiga Fall3d is the dispersion model currently in use by the Darwin and Buenos Aires Volcanic Ash Advisory Centers. The Barcelona Supercomputing Center is also the official provider for the sand and dust storm warnings of the World Meteorological Organization. Learn more at: mitigasolutions.com

About WTW

At WTW (NASDAQ: WTW), we provide data-driven, insight-led solutions in the areas of people, risk and capital. Leveraging the global view and local expertise of our colleagues serving 140 countries and markets, we help you sharpen your strategy, enhance organisational resilience, motivate your workforce and maximise performance. Working shoulder to shoulder with you, we uncover opportunities for sustainable success — and provide perspective that moves you. Learn more at wtwco.com.

wtwco.com/social-media

WTW-83951 02/23

wtwco.com