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M9 returns – towards a probabilistic pan-Pacific Tsunami Risk Model

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ABSTRACT: Over the past decade, the awareness of tsunami hazard has returned to global prominence with several devastating events occurring. The quantification of this type of hazard and especially risk is still however very complex. So far the focus of these models was almost exclusively in the field of hazard or probabilistic vulnerability, with less effort spent on the risk in terms of socio-economic losses.

This study introduces a probabilistic tsunami risk model for the Pacific region. For tsunami sources, only earthquakes are considered, as the spatiotemporal aspects of mass movements and volcanic events with respect to tsunami generation are difficult to quantify for this region and require further study. The tsunami model uses a fast non-linear shallow water wave equation solver to determine peak coastal amplitudes for all major Pacific coast lines and thus provides return periods and the respective probabilities of wave height exceeding. The risk is calculated via an elevation based model of capital stock and population in coastal regions with respect to the expected wave heights. The run-up is hereby estimated from the peak coastal amplitude using an amplification factor per coastal segment. This preliminary version of the model can thus be considered a first step toward a uniform and comprehensive pan-Pacific tsunami risk model.

1 INTRODUCTION

Tsunamis are among the deadliest but also rarest reoccurring natural disasters around the world with 12% of all fatalities due to earthquakes since 1900 coming from tsunamis (Daniell et al., 2011). Especially after the disastrous events of 2004 Indian Ocean (Titov et al., 2005) and 2011 Tohoku (Lovholt et al., 2012), tsunamis returned to prominence in terms of research given the impacts seen across the world. Figure 1 shows a summary of tsunami hazard statistics globally using the NOAA tsunami database since 1500 (NOAA, 2015). It can be clearly seen, that earthquakes are the major source of tsunami events and that the Pacific generates by far the largest number of tsunamis as compared to other locations globally. Many countries with significantly long coastlines have developed tsunami hazard assessments to identify return periods of tsunami heights (e.g. (Power, 2013)). In contrast to earthquake hazard assessments, the source and the location of damage are often decoupled in the order of 1000s of kms. Tsunamis may also cause damage over a vast area, usually far away from their origin. Thus a tsunami hazard assessment has to take into account two kinds of sources; local sources which are more or less directly located close to the coastline impacted and distant sources, often located thousands of kilometres away. It is surprising that there has been very little comprehensive hazard assessments which have taken into account e.g. Pacific tsunami sources as a whole and analyse their impact on all Pacific coastlines. Considering the amount of data, this was so far considered unfeasible on a local computing scale. Nevertheless, detailed country-based tsunami hazard assessments have been undertaken for New Zealand, Japan or the United States (see Section 2).

The quantification of hazard is of course the first step to calculating the impact of tsunamis, but the need to identify the risk in terms of possible economic losses and fatalities is becoming more important with increasing population in coastal settings globally. This study introduces the first step towards an integrated and comprehensive tsunami risk assessment for all coastlines across the Pacific. It focuses on tsunamis originating from earthquake sources, since the majority of tsunami events originate from earthquakes (Geist and Lynett, 2014). Such a model is comprised of various aspects from a megathrust earthquake hazard assessment of all major subduction zones in the region to wave propagation modelling to an inundation estimation procedure to estimate local losses and fatalities. Inundation describes the actual flooded area, while run-up is the maximum height above sea-level reached by the wave when travelling inland. Each element is prone to uncertainties and is computationally expensive. A new computation framework was developed which combines all these aspects with regard to computation speed without the need for a supercomputer.

This study introduces the first results of the pan-Pacific risk assessment and the computation framework with which these results have been achieved. Section 2 reviews tsunami hazard and risk assessments of countries along the Pacific Rim. Section 3 briefly introduces the computation framework of each methodological aspect and how it has been implemented. Finally, section 4 presents the first results of the risk model for different countries around the Pacific.

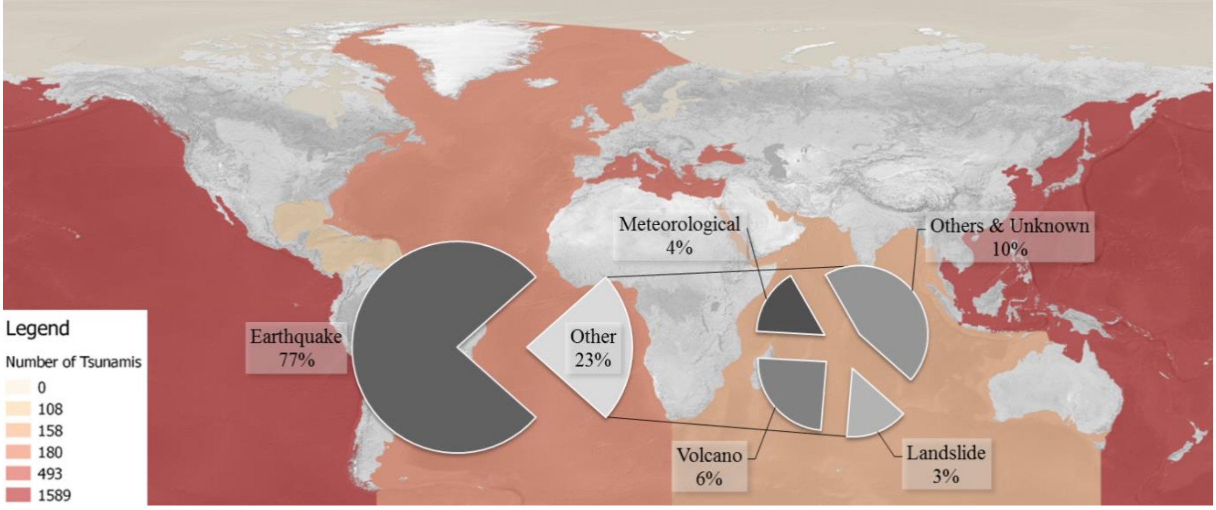

Figure 1: Worldwide distribution of tsunamis, colour-code represents the number of recorded events per world ocean and statistics of tsunamis source mechanisms. "Others and Unknown" include astronomical and tidal events. (Edited from the NOAA tsunami database, 2015).

2 PACIFIC TSUNAMI RISK MODELS

As the Pacific area is one of the most tsunami-prone areas in the world, it is reasonable that the majority of tsunami hazard and risk assessments have been undertaken here (Jelinek and Krausmann, 2008). Most of them focus exclusively on a country-based scale, e.g. just the Japanese or Canadian coastline, while other models focus on certain cities with more detailed modelling, while a small number assessed larger areas and groups of countries, which are in general too small to take out an assessment on their own, e.g. the Pacific Island nations.

Some studies have focused primarily on the most tsunami-prone coasts of a country, like (Burbidge et al., 2008), where the tsunami hazard in Western Australia is assessed for the Indonesian Trench offshore Java and Sumatra which poses the largest threat, but also distant sources like the Makran subduction zone offshore Pakistan indicate a significant hazard. While the number of local sources for Australia is rather limited, for New Zealand they are dominant. Various studies like (Power, Reyners and Wallace, 2008), (Power, 2013) or (Wallace et al., 2014) primarily examined sources to the North of New Zealand such as the Hikurangi and Kermadec subduction zones and the subduction along the Southern New Hebrides offshore Vanuatu and Fiji. These assessments were both probabilistic and deterministic and in some cases reviewed certain locations to quantify the tsunami impact of certain return periods. 15 Pacific Island nations have been assessed by Thomas and Burbidge (2009). They can be impacted severely by strong tsunamis from almost everywhere in the southern Pacific. Thus, in their model, sources in Chile have the same weight as sources offshore Tonga, while highly impacting local tsunami-genic earthquake sources often do not even exist, since most of the islands are located far away from any subducting plate boundary.

A number of large scale models have been looked at, including the tsunami hazard for Australia which was calculated by Burbidge et al. (2008), via the Geoscience Australia, using Pacific and Indian Ocean sources. NGI and Geoscience Australia (2014) is an example of modelling however, with a different goal of scenario modelling at 500 year return period, with a model undertaken globally at variable resolution. PCRAFI (2011) focussed on the probabilistic tsunami loss modelling of 15 small nations across the Pacific.

The tsunami hazard along the West Coast of North America is dominated by the Cascadia subduction zone for local scales, but also by distant events from the Aleutians, the Kuril-Kamchatka trench or the many subduction zones close to Japan (Leonard, Rogers and Mazzotti, 2012), (Gonzalez et al., 2009), for which also detailed assessments have been taken out (Sakai et al., 2006). In general, most of these approaches are pure hazard assessments, thus the actual risk and impact of tsunamis haven't been examined. But nevertheless, the methodology developed in all these studies leads to a substantially better understanding of tsunamis themselves, from source modelling to propagation to wave shoaling and the calculation of peak coastal amplitudes. The latter is the common parameter in estimating tsunami hazard. Since it is still computationally difficult and time-consuming to build probabilistic inundation maps, the modelling is purely focused on the wave height just before it hits dry land. With respect to this study, the focus is to reduce computation time and to streamline the methodology of tsunami hazard assessment and to give a first insight into a rapid risk modelling.

3 METHODOLOGY

3.1 Sources and Data

So far, more than 30 distinct earthquake source zones have been identified along the Pacific. They consist of large subduction zone areas as of the Mid-American trench to rather segmented areas as like the Hikurangi plate interface offshore New Zealand. The quantification of megathrust earthquake return periods is strongly linked to the quality of earthquake data available for each source segment. Thus, since better data is not yet available for this study, several of these sources have been combined to provide a more robust look into the general tsunami hazard. More detailed segmentation was undertaken by linking the results obtained from a probabilistic seismic hazard assessment of large magnitude earthquakes to a tectonic slip model which adds additional information for the return period of tsunami-genic earthquakes. Each source zone could be then split into segments of about 50 km length along the subduction front, representing individual elements of the subducting slab which may rupture independently. The source zones are defined using a simple vector approach which follows the subduction frontal zone. For each segment, a dip angle was computed based on the global centroid catalogue data of dip-slip earthquakes in the vicinity of each segment (Ekström et al., 2015). Assuming that the tsunami-genic region of earthquake generation along a subducting slab ends around 70 km depth (Astiz, Lay and Kanamori, 1988), the width is computed using the assigned dip angle until it reaches the assumed 70 km depth.

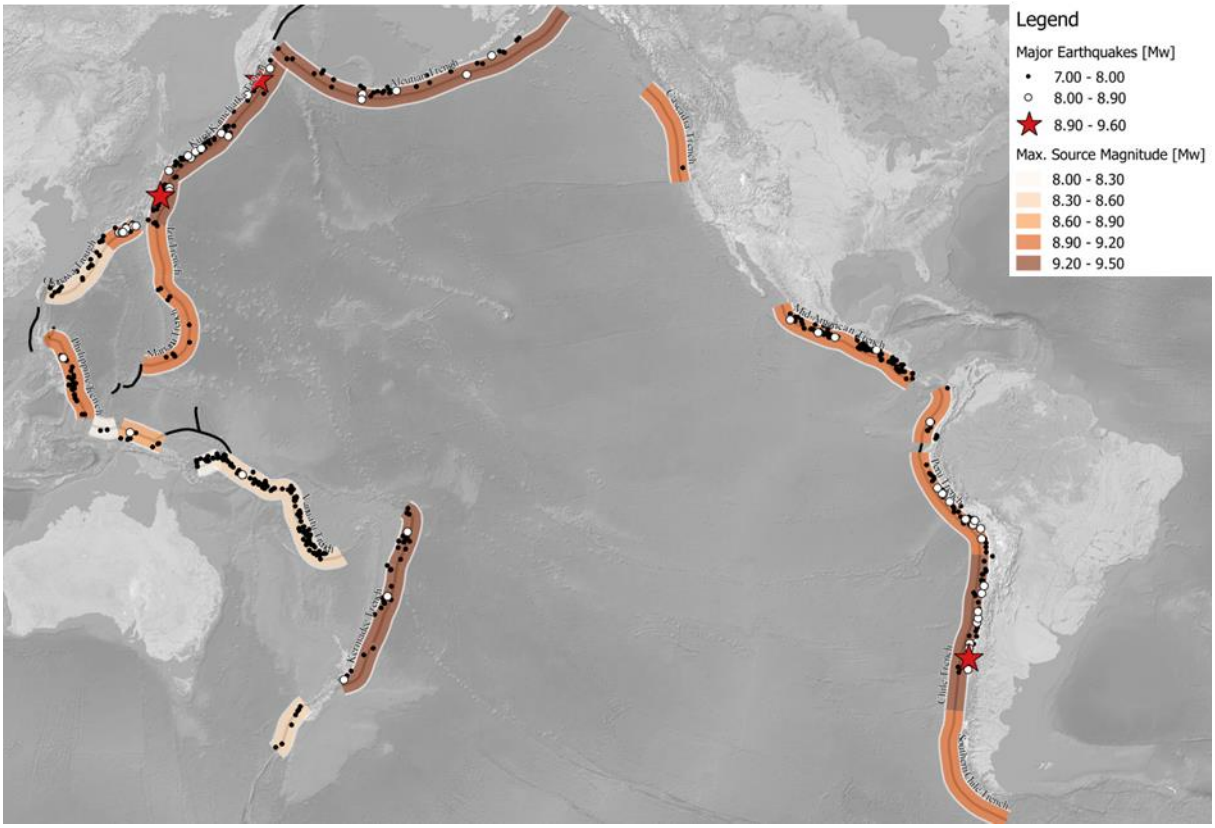

Figure 2: Map of the currently used tsunami source zones which correspond to the major subduction zones in the Pacific. Black dots represent smaller magnitude historic earthquakes (Mw 7-8), white dots are major historic earthquakes (Mw 8-8.9) and the red stars indicate the 3 major Pacific megathrust earthquakes of 1952, 1960 and 2011, Mw ≥ 8.9. Black lines indicate all probable sources for tsunami-genic earthquakes. Sources used in this study are indicated with a brown colormap buffer which indicates the associated possible maximum magnitude.

This study uses global earthquake catalogues from three sources. The Global Earthquake History catalogue (GEH) (GEM, 2014) for events pre-1900, the World Centennial Earthquake Catalogue for 1900 until 1965 (Engdahl, van der Hilst and Buland, 1998) and the ANSS earthquake database for post-1965 (NCEDC, 2014). A more detailed data collection will be undertaken in the future where each source will be reviewed in detail and also linked to the aforementioned tectonic slip models. Only earthquakes with a maximum depth of 70 km have been used. The return periods of earthquakes have been determined based on a Gutenberg-Richter calculation (Gutenberg and Richter, 1944) for each segment. Hereby, two spatial methodologies have been applied. First, b-values have been computed based on earthquakes which are directly within each source zone, while a second set of b-values has been computed for each segment, using all earthquakes in the dataset within 200 km around the centroid of the segment.

Figure 3 shows a Pacific-centred view of the currently used source zones, with their respective combinations also indicated. Table 1 gives an overview of all combined sources and also their assumed maximum magnitudes with respect to the size of the subduction zone and computed return periods of magnitude 9 earthquakes calculated using only earthquake statistics of the Gutenberg-Richter relations. As an example, the Cascadia subduction zone can be considered, which has not had a major earthquake since 1700, the Gutenberg-Richter relation indicates a significantly longer return period of about 2000 years for M9 events with respect to paleoseismic data and slip-rate data, where an average return period of about 500 years has been computed (Gonzalez et al, 2009). To estimate the surface deformation of the earthquake rupture, the method of Okada (1985) is applied using rupture geometries resolved from the equations of Wells and Coppersmith (1994).

Table 1: Overview of Tsunami Source Statistics, providing modelled maximum magnitudes, Gutenberg-Richter relations, historic events within the respective source zone of Mw ≥ 4 and rounded return periods for Mw ≥ 9 events.

Name	Max. Magnitude (Model)	b-value	a-value	Observed Events Mw≥4	Return-Period M9 [years]
Philippine Trench	9.0	1.12	6.87	4925	1500
New Guinea Trench West	8.0	1.05	5.75	407	5350
New Guinea Trench East	8.7	0.97	5.67	1669	1250
Solomon Trench	8.3	1.06	6.52	2609	950
East Solomon Trench	8.5	1.07	6.93	5008	500
Vanuatu Trench	8.5	1.09	7.01	5086	600
New Zealand Trench	8.5	1.00	5.63	744	2200
Mariana Trench	9.0	1.17	6.97	3553	3350
Okinawa Trough	8.5	1.13	6.69	2653	3300
Nankai Trough	9.0	0.78	3.91	249	1200
Izu Trench	9.0	1.25	7.12	2270	13000
Japan Trench	9.3	1.18	7.63	6535	950
Kuril-Kamchatka Trench	9.5	1.02	6.61	7208	400
Cascadia Trench	9.0	0.84	4.23	215	2050
Mid-American Trench	9.0	1.08	6.89	8915	700
Cambodia Trench	9.0	0.95	5.21	640	2050
Peru Trench	9.0	0.91	5.31	1016	725
Northern Chile Trench	9.0	1.01	5.89	1299	1450
Chile Trench	9.5	1.01	6.54	7333	350
Southern Chile Trench	9.0	0.94	4.46	58	9525
Tonga Trench	9.3	1.12	7.08	4585	950
Kermadec Trench	9.3	1.22	7.67	6120	1900
Aleutian Trench	9.5	0.99	6.41	6594	300

3.2 Propagation

The propagation modelling of each tsunami event is calculated using the non-linear shallow water equation (1-3), where U and V are the flow velocity components in longitude and latitude respectively, both averaged over the depth. η is the water surface deformation from the equilibrium, D being the total height of the water column and H the water depth at equilibrium. f and C_B are Coriolis and friction parameters.

$$\frac{\partial U}{\partial t}+U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial y}=-g\frac{\partial \eta}{\partial x}-\frac{C_B\sqrt{U^2+V^2}}{D}-fV \qquad (1)$$

$$\frac{\partial V}{\partial t}+U\frac{\partial V}{\partial x}+V\frac{\partial V}{\partial y}=-g\frac{\partial \eta}{\partial y}-\frac{C_B\sqrt{U^2+V^2}}{D}-fU \qquad (2)$$

$$\frac{\partial \eta}{\partial t}-\frac{\partial}{\partial x}(DU)+\frac{\partial}{\partial y}(DV)=0 \qquad (3)$$

$$U=\frac{1}{D}\int_{-H}^{\eta}u dz \qquad\qquad V=\frac{1}{D}\int_{-H}^{\eta}v dz$$

The above equations have been adopted for spherical coordinates and the Coriolis force has been neglected. The propagation is computed for a period of 24h after the tsunami was triggered. This time period is assumed to be appropriate to capture local and far-field effects of tsunamis in the Pacific. The propagation modelling does not apply wetting of dry cells and is simply undertaken until it reaches 50m deep water, where a reflective boundary is implemented. The actual wave height is then extrapolated using the Green's Law (eq.4) for 1m deep water along the shoreline. The Green's Law describes the wave height relation between the wave height in deep water to its shoaling in shallow water.

$$H=H_0\sqrt[4]{\frac{H_d}{H_s}} \qquad (4)$$

Here, H_0 is the wave height in water with a depth of H_d (deep) and H the wave height in water with depth H_s (shallow). Several studies have provided sufficient validation that the Green's law is a good estimate for wave tsunami wave heights when approaching the shore line (Kamigaichi, 2009), (Sorensen et al., 2012).

The computational framework is a new python toolkit called Tsukit, (with components developed as part of the lead author's PhD and before), which is currently under development and provides various analytical tools for tsunami risk analysis. The main focus is the robust computation of hazard and risk components on a moderate to high resolution using the computation capabilities of standard desktop computers. It applies GPU processing methods based on the NVIDIA CUDA (e.g. (Vanka, Shinn and Sahu, 2011)) to speed up the computation of wave propagation. If no compatible GPU is available, the calculation can also be undertaken on a CPU, but will be computationally expensive. The current version uses a 5x5 km grid for the greater Pacific area [105°E, 65°W], [60°S, 60°N] with about 9.1 million grid points ending up with computation times of about 75 seconds per event on a NVIDIA Geforce GTX970 GPU. The average speed up between GPUs and CPUs are currently about 5-250 times depending on the hardware setup.

3.3 The Pacific tsunami exposure database

Given the lack of a global high resolution coastal exposure dataset for tsunami modelling, the exposure model for the tsunami risk model consisted of a high resolution hybrid population and capital stock modelling effort within 10km of all coastlines across the Pacific. This included the creation and calibration of datasets for 46 countries and 3 entities with the USA being split into 3 parts (Hawaii, Alaska and West Coast). The population model built on the work of Daniell (2014) within CATDAT, with census information and global datasets such as GPWv4, CATDAT, WorldPop and SOPAC data, being calibrated and adjusted to the latest available data. A resolution of 100m was used for most small countries, with this being compatible with land use assumptions of SOPAC and WorldPop. Detailed splits were made where building specific and mesh block data were available from local census entities. Coastline data were used from the NOAA database of coastlines with minor adaptions where necessary to fit 100m vs. 1km data points. 1km resolution was used for countries where there was sparse data, or where the runtimes were too long such as China (although 100m was also created).

Each raster point over the 100m or 1km resolution was created using at latest 2010 data, in order to bring the population to June 2015 population totals. DEMs were used globally from the SRTM datasets at 90m and 250m resolution for the average height of the polygon centroid, with 500m being used for Kiribati (due to programming issues), and 300m being used for parts of Siberia and Alaska (given the lack of extent of SRTM data). In the future, this will be adapted to a split population mesh allowing for higher resolution. Capital stock modelling was undertaken for each country individually using the Perpetual Inventory Method, and gross capital stock estimates (replacement costs) as per the methodology within Daniell et al. (2012), except for Tonga where higher resolution modelling was undertaken. This was adapted to June 2015 using IMF and local financial department data. This capital stock value includes all buildings, infrastructure, transportation, machinery and equipment in 2015 USD for the 10km coastal band at the same resolution as population.

3.4 **Tsunami vulnerability and risk estimation module**

Many functions for economic loss and fatalities from tsunami were reviewed, as well as historic data from the NOAA and CATDAT databases. The building inventory data aggregated for each country from Daniell et al. (2012) in the Pacific region was used to collect the percentage of population and buildings in Adobe, Concrete, Wood, Steel and Masonry buildings for urban and rural settings. This was imposed on to the already created population and capital stock rasters. This was used as the basis for economic cost calculations.

Specific functions (usually a standardised normal distribution function or lognormal cdf) for different building typologies or aggregated stocks were produced from a number of historic events such as Japanese events (1896, 1933, 1978, 1993) by Koshimura et al. (2009a); the 2004 Indian Ocean event (Tinti et al., 2010, Koshimura et al., 2009b); the 2009 Samoan tsunami (Gokon et al., 2011; Reese et al., 2011); the Chile 2010 event (Mas et al., 2012a), (Mas et al., 2012b) and the 2011 Tohoku (various authors including Mas et al., 2012; Suppasri et al., 2012). In reality, vulnerabilities of building types will be different in each country, depending on historic tsunami, storm surge or cyclone activity – leading to very different damage rates. A simplified vulnerability has been undertaken where the same functions are used for each country with the adjustment for building typology used where no specific country data from events was seen. The only additional feature being a level of protection estimate based on historical influence of such events in order to cap small losses.

Given a lack of data in many of the countries which have not experienced damaging tsunamis, a simplification of tsunami fatality functions was made, with a hybrid version of Reese et al. (2011) based on Samoan data; and Koshimura (2006) for the Indian Ocean; being used with the addition of a tsunami inundation time where a certain percentage of the population being able to evacuate given a tsunami warning time (5% decrease per 5 mins up to a total of 75 mins). The inundation amplitude was used in conjunction with the DEM average height above sea level and tsunami hazard scenarios in order to derive a mean loss ratio and fatality estimate for each cell for each event. This was then aggregated into PML curves and AAL estimates. These functions represent a first estimate of tsunami losses and will be adapted in future studies.

4 RESULTS

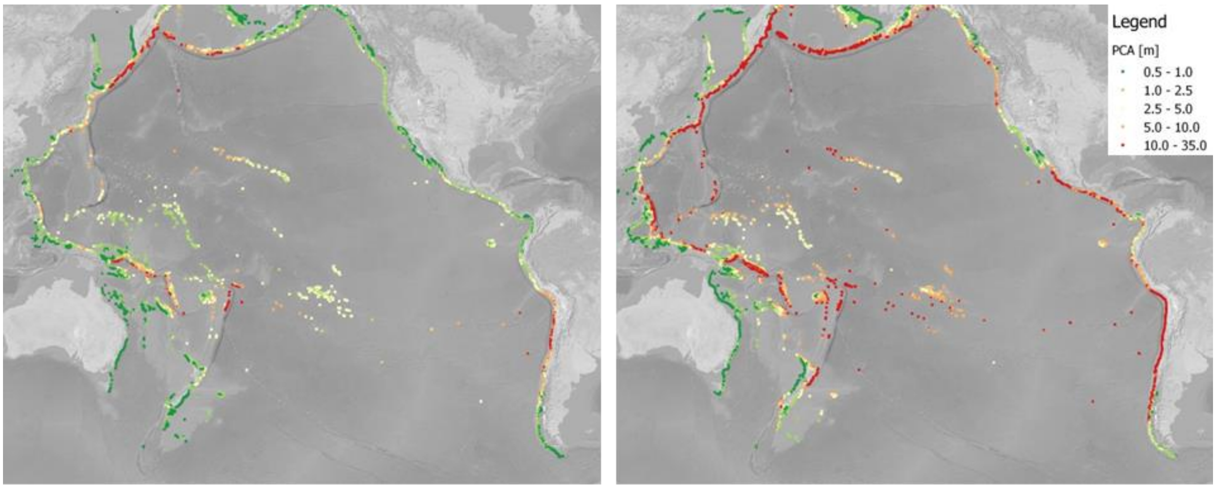

Figure 3: Peak Coastal Amplitude maps for a return period of 500 years (left) and 2500 years (right). Each dot represents a 5 km broad coastal segment with an average water depth of about 50 m. The onshore water wave height of the PCA has been extrapolated using Green's law.

In this paper, tsunami risk is defined through peak coastal amplitudes, which have been computed using a numerical propagation algorithm and then extrapolated onto a data grid of economic and human exposure to estimate inundation areas. Since the model is in the early phases of development, there are still a lot of uncertainties especially with respect to extreme events, but it provides a first insight into the tsunami hazard and subsequent risk for the Pacific as a whole. The general hazard is introduced using peak coastal amplitudes (PCA), wave height when reaching the shoreline, for return periods of 500 and 2500 years. The maximum value is capped to 35m for visualization purposes as it can be seen in figure 4.

A generalised loss and fatality model has been taken out for every major country in the Pacific and annual rates have been computed. When interpreting the results and comparing them with historic loss functions, it is apparent that the use of the protection factors, modelling or the resolution used, led to an overestimation of the population affected consistently across all countries. A factor of 0.333 was therefore applied in order to match better the empirical data. Similarly, the loss functions built for structures underestimate the total stock loss seen historically, and an adjustment factor was similarly needed for the final model. The final AAL and fatalities per year are shown in figure 5.

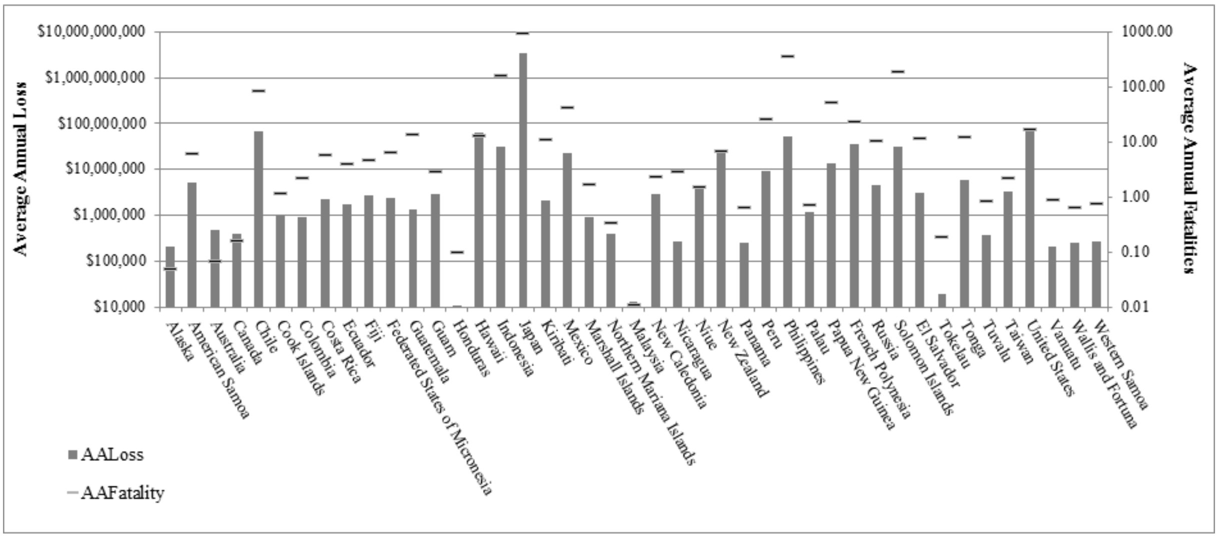

Figure 4: Overview of average annual losses and fatalities for countries around the Pacific due to earthquake-induced tsunami w.r.t. the source of figure 2.

The PCA values indicate the largest run-up along coastlines with a subduction zone directly offshore, such as Chile, Japan or Papua New Guinea. Distant frequently occurring tsunami sources are the general hazard for most of the Pacific Island nations and tend to produce smaller but more frequent run-ups. The impact on risk with regard to loss and fatalities is highly constrained with the coastal topography and offshore bathymetry. The steep coasts of Samoa, Fiji, Hawaii or Tahiti provide natural protection, while rather shallow coasts like in the Philippines or many harbour cities on the West Coast of the United States suffer from moderate event tsunami heights. Not surprisingly, the most famous nations for megathrust earthquakes, Chile and Japan face the largest risk impact, but many other nations have to be aware of an annual loss due to tsunamis of more than $1,000,000 – $10,000,000. However, for countries like the United States or even Mexico, these values are considerably small with respect to their exposed capital stock. For Ecuador, Micronesia and many other smaller nations, tsunamis have a significant impact in relative terms.

5 DISCUSSION

Modelling risk simply based on an estimate of peak coastal amplitudes is extremely challenging with various factors of uncertainty come into place. On the one hand, there are first order uncertainties arising from insufficient data or error in the source modelling itself. Resolution is thereby a crucial element. This current study has been taken out on a grid with a pixel resolution of 5 km, cutting off at a water depth of 50 m with Green's law applied. When taking a look at the actual results, this model works well in estimating the tsunami impact and inundation using a simple extrapolation method as long as the coastline is rather homogeneous like for coast lines of Central Chile or most parts of the Western United States. With increasing topographic and morphological complexity of the coastline, the larger the uncertainties become. These uncertainties are especially present when modelling water inflow into a bay and for coastlines with a large amount of barrier islands or an offshore continental shelf with an intermediate distance to the actual coast. In addition, small island nations like some islands as part of French Polynesia or the Pitcairn Islands may not be present in the gridding structure and the propagation impact of protecting coral reef formations offshore the islands is currently neglected. Thus the current model will most likely underestimates the risk in many places because of these resolution problems. Nevertheless, the current version provides a fast computation solution to estimate the risk within a very short time. Future versions will be able to incorporate such error sources and will contain correction elements to provide more advanced estimates. In addition, the general modelling of exposure and related vulnerability functions is also very important and will be linked to a tsunami vulnerability database. Estimating the time of day, when a tsunami arrives at the coast line, level of structural protection, sea barrier walls, tidal variations and evacuation time are further parameters which influence the risk itself.

6 CONCLUSION

This study provides a first glimpse into a pan-Pacific tsunami risk model. Considering the short time period we have observed and recorded so far, the long return periods of megathrust events are the dominating factor for tsunami impact. Countries around the Pacific can be briefly grouped into two sets. The first group comprises countries with local tsunami sources, e.g. offshore subduction zones within about 100 km of the coastline with these countries severely hit by massive megathrust earthquakes, reaching run-up heights of up to 15-30 m. The second group represents countries which are less severely hit by individual events, but receive moderate tsunami wave heights more frequently via distant sources, e.g. most of the Pacific Island states of Micronesia, French Polynesia or Hawaii. Many coastlines are naturally protected from massive tsunami waves due to local bathymetric and topographic effects like Australia or Canada or where volcanic orogeny produced sometimes steep coasts where waves do not travel as far inland such as Western Samoa.

A general problem so far is the model itself. As described in section 5, various sources of uncertainty influence the results and important factors like coastal protection, dynamic offshore friction (e.g. from coral reefs), direct inundation modelling and the influence of tides and the exposure impact of time of day will have to be accounted for, either by direct modelling or by sufficiently well-constrained assumptions. Future versions of the computation framework will take most of these factors into account to provide not only a Pacific risk model, but also a comprehensive and global tsunami risk model, which can be used for comparative risk assessments globally and locally.

REFERENCES:

Astiz, L., Lay, T. and Kanamori, H. (1988) 'Large intermediate-depth earthquake and the subduction process', *Physics of the Earth and Platenary Interiors*, vol. 53, pp. 80-166.

Burbidge, D., Cummins, P.R., Mleczko, R. and Thio, H.K. (2008) 'A Probabilistic Tsunami Hazard Assessment for Western Australia', *Pure Applied Geophysics*, vol. 165, pp. 2059-2088.

Burbidge, D., Mleczko, R., Thomas, C., Cummins, P., Nielsen, O. and Dhu, T. (2008). 'A Probabilistic Tsunami Hazard Assessment for Australia.' Geoscience Australia Professional Opinion. No.2008/04.

Center for International Earth Science Information Network - CIESIN - Columbia University. 2014. Gridded Population of the World, Version 4 (GPWv4), Preliminary Release 2 (2010). Palisades, NY. http://www.ciesin.columbia.edu/data/gpw-v4.

Daniell, J. E., Khazai, B., Wenzel, F., and Vervaeck, A. (2011). ‚The CATDAT damaging earthquakes database.' *Natural Hazards and Earth System Science*, 11(8), 2235-2251.

Daniell, J.E., Wenzel, F. and Vervaeck, A. (2012) 'The Normalisation of socio-economic losses from historic worldwide earthquakes from 1900 to 2012', 15th WCEE, Lisbon, Portugal, Paper No. 2027.

Daniell, J.E. (2014) 'Development of socio-economic fragility functions for use in worldwide rapid earthquake loss estimation procedures', Doctoral Thesis, Karlsruhe Institute of Technology, Karlsruhe, Germany.

Ekström, G., M. Nettles, and A. M. Dziewonski, The global CMT project 2004-2010: Centroid-moment tensors for 13,017 earthquakes, *Phys. Earth Planet. Inter.*, 200-201, 1-9, 2012. doi:10.1016/j.pepi.2012.04.002Engdahl, E.R., van der Hilst, R. and Buland, R. (1998) 'Global teleseismic earthquake relocation with improved travel times and procedures for depth determination', *Bulletin of the Seismological Society of America*, vol. 88, pp. 722-743.

Geist, E.L. and Lynett, P.J. (2014) 'Source processes for the probabilistic assessment of tsunami hazard', *Oceanography*, vol. 27, no. 2, pp. 86-96.

GEM, GEH (2014) *Global Historical Earthquake Archive*, 25Dec, [Online], Available: http://www.emidius.eu/GEH/download/GEM-GHEC-v1.txt [1 Jun 2015].

Gonzalez, F.I., Geist, E.L., Jaffe, B., Kanoglu, U., Mofjeld, H., Synolakis, C.E., Titov, V.V., Arcas, D., Bellomo, D., Calrton, D., Horning, T., Johnson, J., Newman, J., Parsons, T., Peters, R., Peterson, C., Priest, G., Venturato, A., Weber, J., Wong, F. et al. (2009) 'Probabilistic tsunami hazard assessment at Seaside, Oregon, for near- and far-field seismic sources', *Journal of Geophysical Research*, vol. 114, no. C11023, p. 19.

Gokon, H., Koshimura, S. & Matsuoka, M. (2011): Developing tsunami fragility curves for structural destruction in American Samoa. *Journal of Japan Society of Civil Engineering* ,67(2), pp.1321-1325.

Gutenberg, B. and Richter, C.F. (1944) 'Frequency of earthquakes in California', *Bulletin of Seismological Society of America*, vol. 34, pp. 185-188.

Jarvis, A., Reuter, H. I., Nelson, A., & Guevara, E. (2008). 'Hole-filled seamless SRTM data V4', International Centre for tropical Agriculture (CIAT).

Jelinek, R. and Krausmann, E. (2008) 'Approaches to Tsunami Risk Assessment', *JRC Scientific and Technical Reports*, vol. 48713.

Kamigaichi, O. (2009) 'Tsunami Forecasting and Warning', in Meyers, R.A. (ed.) *Encyclopedia of Complexity and Systems Science*, Berlin, Heidelberg: Springer-Verlag.

Koshimura, S., Katada, T., Mofjeld, H. O. & Kawata, Y. (2006) 'A method for estimating casualties due to the tsunami inundation flow' *Natural Hazards* 39, 265–274

Koshimura, S., Oie, T., Yanagisawa, H. & Imamura, F. (2009) 'Developing fragility functions for tsunami damage estimation using numerical model and post-tsunami data from Banda Aceh, Indonesia.' *Coastal Engineering Journal*, 51(3), pp.243-273.

Koshimura, S., Namegaya, Y., Yanagisawa, H. (2009) ‘Tsunami Fragility – A New Measure to Identify Tsunami Damage ’ *Journal of Disaster Research*, 4(6), pp. 479-488.

Leonard, L.J., Rogers, G.C. and Mazzotti, S. (2012) 'A Preliminary Tsunami Hazard Assessment of the Canadian Coastline', *Geological Survey of Canada Open File*, vol. 7201, p. 126.

Lovholt, F., Kaiser, G., Glimsdal, S., Scheele, L., Harbitz, C.B. and Pedersen, G. (2012) 'Modelling propagation and inundation of teh 11 March 2011 Tohoku tsunami', Natural Hazards and Earth System Science, vol. 12, pp. 1017-1028.

Mas, E., S. Koshimura, A. Suppasri, M. Matsuoka, M. Matsuyama, T. Yoshii, C. Jimenez, F. Yamazaki, and F. Imamura. "Developing Tsunami fragility curves using remote sensing and survey data of the 2010 Chilean Tsunami in Dichato." Natural Hazards and Earth System Science 12, no. 8 (2012a): 2689-2697.

Mas, E., Suppasri, A., Imamura, F., & Koshimura, S. (2012b). Agent-based simulation of the 2011 great east japan earthquake/tsunami evacuation: An integrated model of tsunami inundation and evacuation. Journal of Natural Disaster Science, 34(1), 41-57.

NCEDC, N.C.E.D.C. (2014) 'UC Berkeley Seismological Laboratory - Dataset'.

Norwegian Geolotechnical Institute (NGI) and Geoscience Australia (GA) (2014). “Tsunami Methodology and Result Overview.” Global Assessment Report White Paper.

NOAA *National Geophysical Data Center / World Data Service (NGDC/WDS): Global Historical Tsunami Database. National Geophysical Data Center*, [Online], Available: HYPERLINK "https://www.ngdc.noaa.gov/hazard/tsu_db.shtml" https://www.ngdc.noaa.gov/hazard/tsu_db.shtml [15 Jul 2015].

NOAA National Geophysical Data Center, WVS 17/07/2015 http://www.ngdc.noaa.gov/mgg/shorelines/shorelines.html.

Okada, Y. (1985) 'Surface Deformation due to Shear and Tensile Faults in a Half-Space', *Bulletin of the Seismological Society of America*, vol. 75, no. 4, August, pp. 1135-1154.

Pacific Catastrophe Risk Assessment and Financing Initiative (PCRAFI) Component 2 (AIR Worldwide, 2011).

Power, W. (2013) 'Review of Tsunami Hazard in New Zealand (2013 Update)', GNS Science Consultancy Report.

Power, W., Reyners, N. and Wallace, L. (2008) 'Tsunami hazard posed by earthquakes on the Hikurangi subduction zone interface', GNS Science Consultancy Report 40.

Reese, S., Bailey, B.A., Bind, J., Smart, G., Power, W. & Sturman, J. (2011): Empirical building fragilities from observed damage in the 2009 South Pacific tsunami. *Earth-Science Reviews*, 107, pp.156-173.

Sakai, T., Takeda, T., Soraoka, H., Yanagisawa, K. and Annaka, T. (2006) 'Development of a probabilistic Tsunami Hazard Analysis in Japan', *Preceedings of ICONE14*, International Conference on Nuclear Engineering, Miami, Florida, 7.

Sorensen, M.B., Spada, M., Babeyko, A., Wiemer, S. and Grünthal, G. (2012) 'Probabilistic tsunami hazard in the Mediterranean Sea', *Journal of Geophysical Research*, vol. 117, no. B01305.

Suppasri, A., Mas, E., Koshimura, S., Imai, K., Harada, K. & Imamura, F.(2012). ‚Developing tsunami fragility curves from the surveyed data of the 2011 Great East Japan tsunami in Sendai and Ishinomaki plains.’ *Coastal Engineering Journal*, 54(1).

Thomas, C. and Burbidge, D. (2009) 'A Probabilistic Tsunami Hazard Assessment of the Southwest Pacific Nations', *Geoscience Australia Professional Opinion. No. 2009/02*.

Titov, V., Rabinovich, A.B., Mofjeld, H.O., Thomson, R.E. and Gonzalez, F.I. (2005) 'The global reach of the 26 December 2004 Sumatra tsunami', *Science*, vol. 309, pp. 2045-2048.

Vanka, P.S., Shinn, A.F. and Sahu, K.C. (2011) 'COMPUTATIONAL FLUID DYNAMICS USING GRAPHICS PROCESSING UNITS: CHALLENGES AND OPPORTUNITIES', ASME 2011

International Mechanical Engineering Congress & Exposition, Nov. 11-17, Denver, Colorado, USA.

Wallace, L.M., Cochran, U.A., Power, W.L. and Clark, K.J. (2014) 'Earthquake and tsunami potential of the Hikurangi subduction thrust, New Zealand: Insights from paleoseismology ', *Oceanography*, vol. 27, no. 2, pp. 104-117.

Wells, D.L. and Coppersmith, K.J. (1994) 'New Empirical Relationships among Magnitude, Rupture Length, Rupture Width, Rupture Area, and Surface Displacement ', *Bulletin of the Seismological Society of America*, vol. 84, no. 4, August, pp. 974-1002.