Tsunami hazard potential for the atolls of Tokelau

Prepared for the Villages Emergency Committee of Tokelau

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Executive summary

Awareness of the potential consequences of tsunami for low-lying islands and coastal regions has heightened since the disastrous events of Sumatra in 2004, Tonga-Samoa in 2009 and Tohoku (Japan) in 2011. Information on tsunami hazard for the Tokelau Islands has been prepared for the Villages Emergency Committee of Tokelau and the New Zealand Government Ministry of Civil Defence and Emergency Management "Pacific Tsunami Risk Management Project". The tsunami inundation assessment was based on applying a tsunami source-propagation-inundation model to assess whether there is potential for tsunami flooding on any of the village motus from a range of fourteen earthquake sources in terms of magnitude, orientation, and distance from the Tokelau Islands. For each tsunami source the maximum potential tsunami was simulated and earthquake source location and moment magnitude were linked to tsunami wave heights and tsunami flood depths. Where potential tsunami flooding was identified, recommended evacuation heights above local sea level were compiled, with particular attention paid to variations in tsunami flood depth around the nukus.

Wave fields are channelled by the bathymetry of the Pacific basin in such a way that many of the largest wave heights tend to miss the Tokelau Islands. But a great earthquake from the Kuril Trench poses the greatest inundation threat to Tokelau in our simulations, and may last a few hours and include several wave trains. Other sources can impact particular regions of the atolls, particularly from regional sources to the south, and northern and eastern distant sources.

This study shows that dry areas remain around the villages in nearly all our tsunami simulations of the Tokelau Islands, consistent with the oral history of little or no tsunami threat. In particular, simulations of the recent Tohoku earthquake shows some flooding but that much of the land remains dry. We provide evacuation advice in term of tabulated values of tsunami runup and safe heights, and arrival times and event duration. But complex wave behaviours around the nukus, islets, tidal channels and within the lagoons were observed in our simulations. Unusual wave interactions are inferred for the lagoons and strong currents may occur on shoals and in tidal channels.

1 Introduction

1.1 Study background

Awareness of the potential consequences of tsunami for low-lying islands and coastal regions has heightened since the disastrous events of Sumatra in 2004, Tonga-Samoa in 2009 and Tohoku (Japan) in 2011. The widespread damage to towns and infrastructure and the many casualties that occurred has received global media coverage, raising public awareness of the dangers of tsunami. But these events also demonstrated the lack of community understanding of tsunami hazard risk, appropriate response plans and the broader societal impacts.

Tokelau is located just south of the equator, and consists of three relatively small atolls (nukus) that span approximately 160 km along a southeast-northwest axis, covering a total land area of approximately 12.25 km^2 within an EEZ of 290,000 km^2. The islands are located between 8º33'S 172º30'W (Atafu) and 9º21'S 171º12'W (Fakaofo), with Nukunonu approximately midway (Figure 1.1). Tokelau is located some 480 km north of Samoa. All three nukus have a lagoon surrounded by a continuous fringing reef with the landmass, on the reef flat, made up of a series of islets (motus). These are typically not more than a few hundred metres wide, and less than 3 to 5 m above mean sea level. The tidal range in the Tokelau region is around 0.7 m. Cyclones and droughts are the two most common natural hazards affecting Tokelau. Cyclones (strong winds and storm tide and wave-related inundation) predominantly occur during El Niño conditions (e.g. Cyclone Percy in February 2005), with drought conditions more common during periods of La Niña (e.g. 2011).

Tokelau's population is currently just below 1500, split between the three nuku. On Atafu and Nukunonu there is a single village, whereas on Fakaofo the population is split between two motus (Fale and Fenua Fala). The villages are all located on the leeward (western or northwestern) side of the nuku.

As far as we are aware there is no recorded or oral history of any distant or regional tsunami events causing inundation damage on any of the nuku of Tokelau (or indeed on any mid-ocean plate atolls in the Pacific region). Another potential source for tsunami is local submarine landslides on the reef-edge, but landslides big enough to cause any significant tsunami flooding will be very rare and infrequent.

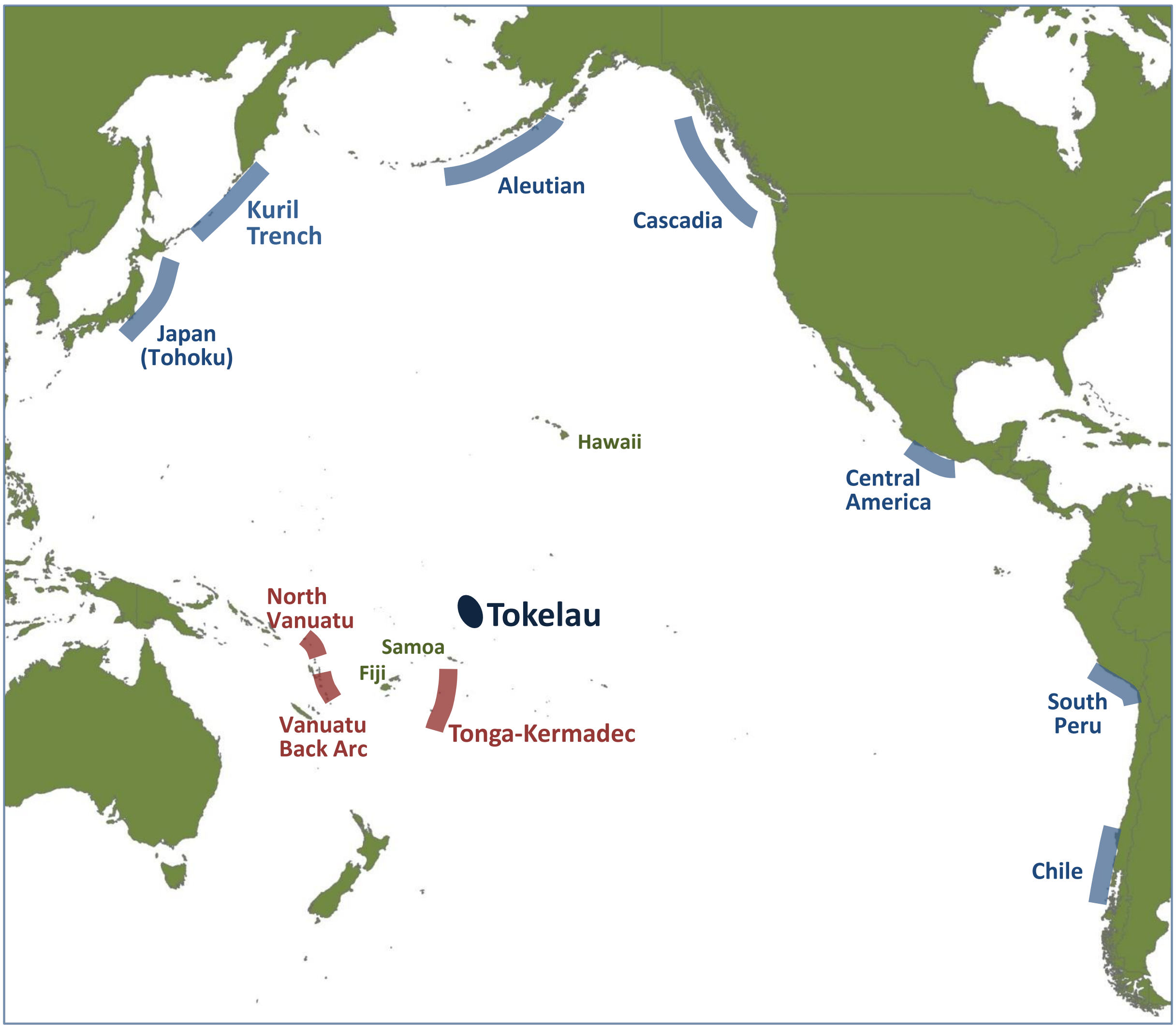

Figure 1-1: Location of Tokelau with known regional (pink lines) and distant (blue) earthquake sources indicated around the Pacific.

1.2 Project overview and purpose

Tokelau is also one of five Pacific Island nations being supported under the New Zealand Government's Ministry for Civil Defence and Emergency Management (MCDEM) Pacific Tsunami Risk Management Project which focuses on implementing key country disaster management priorities, early warning systems, public education and national exercises. Associated with the Disaster Risk Reduction Plan is the development of individual nuku response plans for specific disaster events (including tsunami). These will capture hazard event thresholds and emergency management arrangements specific to each nuku.

Through discussions between MCDEM, the Government of Tokelau and NIWA, NIWA was contracted to carry out an initial assessment of tsunami inundation hazard for Tokelau. The assessment aims to inform the Disaster Risk Reduction by exploring whether tsunami from distant or regional earthquakes sources is capable of causing tsunami inundation on Tokelau.

The primary purpose of this project is to provide advice to the MCDEM, the Tokelau Apia Liaison Office (TALO) and associated National Emergency Committee (who have overall responsibility for disaster management) and the Village Emergency Committee on each nuku, on:

1. Whether there is a tsunami inundation risk to any of the villages on the three nukus from potential regional or distant tsunami sources?

2. If there is tsunami inundation risk, what are the potential thresholds (e.g. Source location, moment magnitude, measurements at DART Buoys and other sea-level stations) that would require each nuku to respond to a tsunami warning (to ensure responses are efficient and any evacuations are not undertaken unnecessarily)?

The information is intended to help each Village Emergency Committee form their specific pre-determined response to tsunami warnings disseminated from the Pacific Tsunami Warning Centre in Hawaii via the General Manager of the Office of the Ongoing Government of Tokelau and the Director of Transport and Support Services within TALO. This will help ensure that emergency responses to tsunami warnings are efficient and any evacuations are not undertaken unnecessarily.

1.3 Scope of the project and limitations

A number of studies have assessed deep water tsunami hazard around the Pacific Islands and southwest Pacific, for example the first-generation tsunami scenario database developed for the Australian region by CSIRO as part of the Joint Australian Tsunami Warning Centre (JATWC) (Greenslade et al., 2009). However, deep-water tsunami models alone are not sufficient to develop an understanding of whether there is a potential tsunami inundation risk, particularly on atolls such as Tokelau where the seabed rises very steeply from depths of between 2000-3000 m to the edge of the fringing reef.

To understand whether tsunamis do pose a threat to any of the communities on the three nuku required modelling assessment of the potential for tsunami flooding. Limited information exists for bathymetry and topography for any of the nuku on Tokelau, which in turn limits the current scope of the project:

1. The modelling has been based on an integrated representation of the nearshore bathymetry and topography drawn from available data sources from Land Information New Zealand (LINZ), New Zealand Defence Force (NZDF), satellite images and other published sources.

2. Modelling tsunamis has been limited to distant and regional sources, where typically a warning would be provided by the Pacific Tsunami Warning Center.

3. No assessment has been conducted of potential tsunami inundation from a submarine landslide off any of the flanks of the nuku.

4. The focus was on the potential for inundation of the four village motus with lesser attention placed on the uninhabited motus.

5. The lack of high resolution topography means that tsunami inundation extent or tsunami-flood depth maps cannot be produced accurately for each village motu. Inundation results should thus be seen as indicative and more weight should be given to water levels.

2 Assessing tsunami inundation risk for Tokelau

2.1 Modelling objectives

The tsunami inundation assessment was based on applying a tsunami source-propagation-inundation model to assess whether there is potential for inundation on any of the village motus from a range of potential distant and regional tsunami sources:

- For each potential tsunami source the maximum potential tsunami was simulated, based on the largest earthquakes and published estimated fault displacements.
- Source location and moment magnitude were linked to tsunami-wave heights (H_{max}) and tsunami-flood depths (H_{in}).
- Source regions that pose a greater hazard were identified and reported separately from other compiled sources.
- Where potential tsunami flooding was identified, recommended evacuation heights above local sea level were compiled, with particular attention paid to variations in tsunami flood depth around the nukus.

2.2 Earthquake and tsunami hazard

In this report only earthquakes that can generate tsunami by a sudden displacement of the seafloor are considered. The Moment Magnitude (M_w) and physical parameters of the rupturing fault that generate the earthquake are critically important for tsunami generation, as these govern the amount of seafloor displacement that occurs during fault rupture, and hence the characteristics of the tsunami.

The tsunami-generating earthquake sources can be classified into two basic scenarios based on event records: (1) regional sources that would have limited warning (a few hours) and require a timely response; and (2) distant sources that cause Pacific Ocean-wide events and would allow time for verification that a tsunami has occurred and appropriate warnings to be given.

The list of historic sources used in the current study is summarized in Table 2-1 (for a full list of world historical earthquake see earthquake.usgs.gov/earthquakes/world/historical.php).

Date	Latitude	Longitude	M_W	Comment
22/05/1960	-38.29	-73.05	9.5	Chile
28/03/1964	61.02	-147.65	9.2	Prince William Sound, Alaska
4/11/1952	52.76	160.06	9	Kamchatka, Russia
11/03/2011	38.322	142.369	9	Tohuku, near the east coast of Honshu, Japan
31/01/1906	1	-81.5	8.8	Colombia-Ecuador
27/02/2010	-35.846	-72.719	8.8	Offshore Maule, Chile
4/02/1965	51.21	-178.5	8.7	Rat Islands, Alaska
9/03/1957	51.56	-175.39	8.6	Andreanof Islands, Alaska
3/02/1923	54	161	8.5	Kamchatka

Date	Latitude	Longitude	M_W	Comment
13/10/1963	44.9	149.6	8.5	Kuril Islands
23/06/2001	-16.264	-73.641	8.4	near the coast of south Peru
6/11/1958	44.329	148.623	8.3	Kuril Islands
19/08/1977	-11.085	118.464	8.3	South of Sumbawa, Indonesia
4/10/1994	43.773	147.321	8.3	Kuril Islands
25/09/2003	41.815	143.91	8.3	Hokkaido, Japan region
15/11/2006	46.592	153.226	8.3	Kuril Islands
4/05/1959	53.351	159.645	8.2	near the east coast of Kamchatka
16/05/1968	40.903	143.346	8.2	off the east coast of Honshu, Japan
11/08/1969	43.478	147.815	8.2	Kuril Islands
17/02/1996	-0.891	136.952	8.2	Irian Jaya region, Indonesia
4/03/1952	42.5	143	8.1	Hokkaido, Japan region
17/10/1966	-10.807	-78.684	8.1	near the coast of central Peru
10/01/1971	-3.132	139.697	8.1	Papua, Indonesia
3/10/1974	-12.254	-77.524	8.1	near the coast of central Peru
22/06/1977	-22.878	-175.9	8.1	Tonga region
12/12/1979	1.598	-79.358	8.1	near the coast of Ecuador
13/01/2007	46.243	154.524	8.1	East of the Kuril Islands
1/04/2007	-8.466	157.043	8.1	Solomon Islands
29/09/2009	-15.489	-172.095	8.1	Samoa Islands region

Table 2-1: Largest Pacific earthquakes since 1900 and Pacific earthquake of M_w>8.1 since 1950. Data from USGS (http://earthquake.usgs.gov/earthquakes).

2.3 Paleo-tsunami and earthquake-model scenarios

Paleo-tsunami research is conducted through investigation of geological evidence of past tsunami. Tsunami deposits are highly variable but are generally composed of material that is not from the immediate geological environment in which they are observed (e.g. the presence of coral blocks on a volcanic surface). A compilation of tsunami sources compiled from prehistoric evidence is presented in Figure 2-1.

The earthquake scenarios selected cover a range of possible tsunami sources and are considered the "most likely" sources of tsunami that may impact the Tokelau Islands. To be capable of generating a tsunami large enough to reach Tokelau and other southwest Pacific Islands, ocean-wide or regional earthquakes would typically have to be of magnitude greater than M_w8.0.

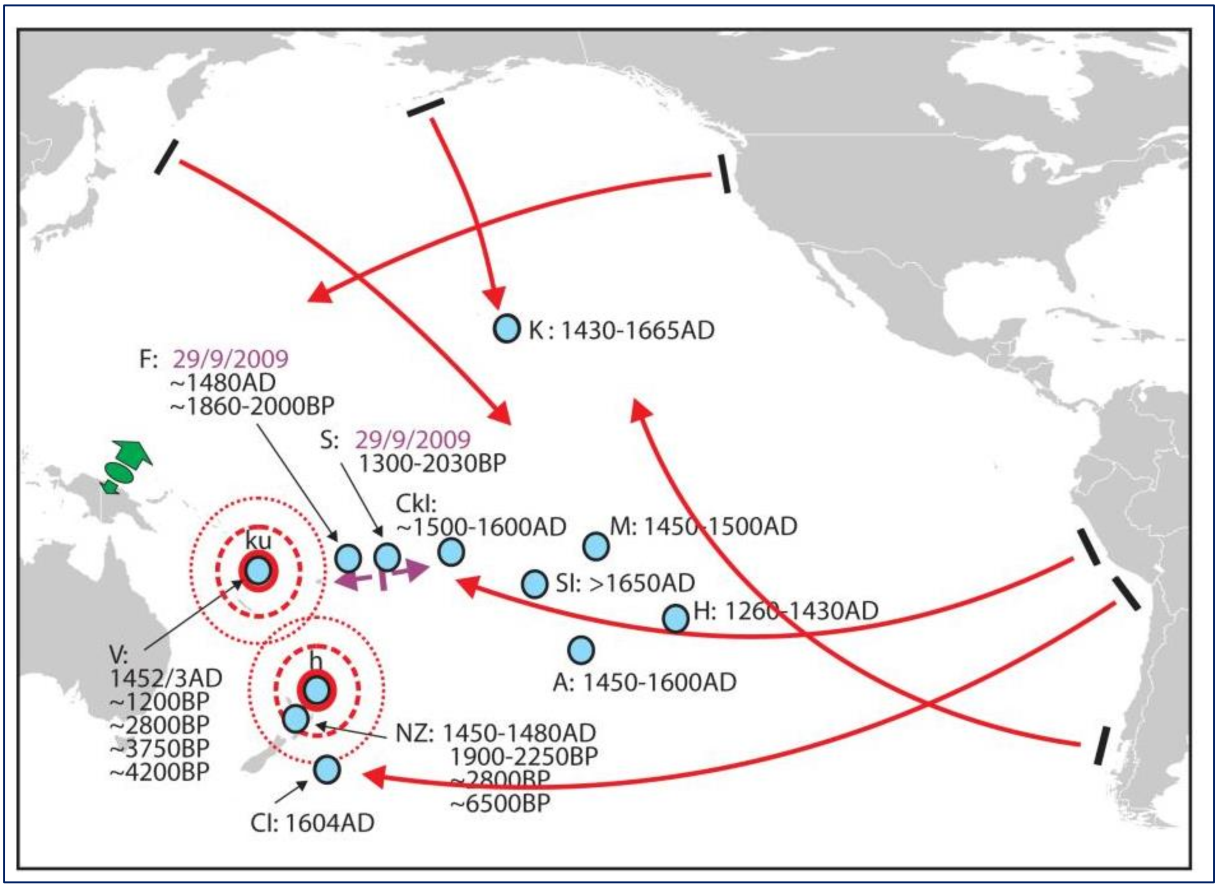

Figure 2-1: Earthquake sources identified from paleo-tsunami research in the southwestern Pacific. A-Austral Islands, CI - Chatham Island, CkI - Cook Islands, F - Futuna, H - Henderson Island. Figure modified after Goff et al. (2011a).

2.4 Datasets and methods

Tsunami propagation is controlled by seafloor topography and water depth along the tsunami path, while inundation is controlled by the coastal bathymetry, topography above the shore line and human modification. Key physical parameters of the earthquake sources influence the amplitude of the tsunami at transoceanic distances, including focal depth and total slip and slip area. The final amplitude at a receiving shore is also strongly affected by focusing and defocusing effects, due to variations in bathymetry along the path of the tsunami.

The results of tsunami numerical modelling are strongly dependant on the quality of seafloor topographic (bathymetric) data and the land topographic data for the area of inundation. Regional bathymetry from the General Bathymetric Chart of the Oceans datasets (GEBCO; www.gebco.net) were used to create the generalised bathymetry. High-resolution multibeam bathymetric data of the nuku slopes, approaches and channels, acquired by the Royal New Zealand Navy Littoral Warfare Support Group in Tokelau for the Ministry of Foreign Affairs and Trade during Exercise Tropic Twilight in July 2011 (Jensen, 2011) were incorporated into the bathymetric grid. We used remotely-sensed depth information from colour satellite images to compliment these bathymetric data and to better parameterise the lagoons and reef flats and aprons. Hand-editing was required with iterative model runs to ensure sensible bathymetric profiles were achieved.

Elevation information for the nukus, motus and emergent reefs were generated from a range of data sources, all of which required careful filtering (Figures 2-3 to 2-6). Vector data (generated from radar) and feature catalogue information from the Multinational Geospatial Co-Production Programme (MGCP, New Zealand Defence Force) are at a 30-m grid spacing and were incorporated where applicable. But given the very low elevation of the nuku, extensive and careful hand-editing of the elevation spot-heights was essential to ensure sensible elevations were incorporated into the topographic grid surface. Tree-tops were regularly listed as the land elevation and the spot-height density was often too low to create the grid resolution required to ensure useful model results.

Due to the low-data density around the villages, these elevation data were complimented by manual input of spot heights estimated from satellite images, following known natural bathymetric features such as beach-rock, reef flats or the beach face, along with man-made features such as sea-walls where elevations could be estimated from field photographs. A schematic depiction of the sea-level elevations and inundation terminology used in the tsunami model simulations is shown in Figure 2-2.

The fringing-reef edge was assigned a height of 0 m, approximating a model mean sea-level datum (MSL), both on the seaward and the lagoon sides of the nuku. This assumption appears compatible with the small number of available cross-sections of the village motus from McLean (1993). Wave height and runup inundation depths cannot be extrapolated linearly from any given sea-level because of the complex behaviour of the wave and interactions with the nuku as it shoals. Hence, a second run of simulations were undertaken to represent a "worst-case scenario", with the model sea level datum now set at +1 m to simulate a tsunami arriving at Mean High Water Spring tide (MHWS), with a strandline that approximates the base of the beach rise. A measure of the tsunami-wave runup over the emergent land (a proxy for inundation) is termed "H_{in}".This differs from the max wave height, "H_{max}", above a given sea-level. We anticipate that the two complete sets of simulations herein capture the range of realistic model outcomes and a more broad understanding of the likely tsunami behaviour and risks.

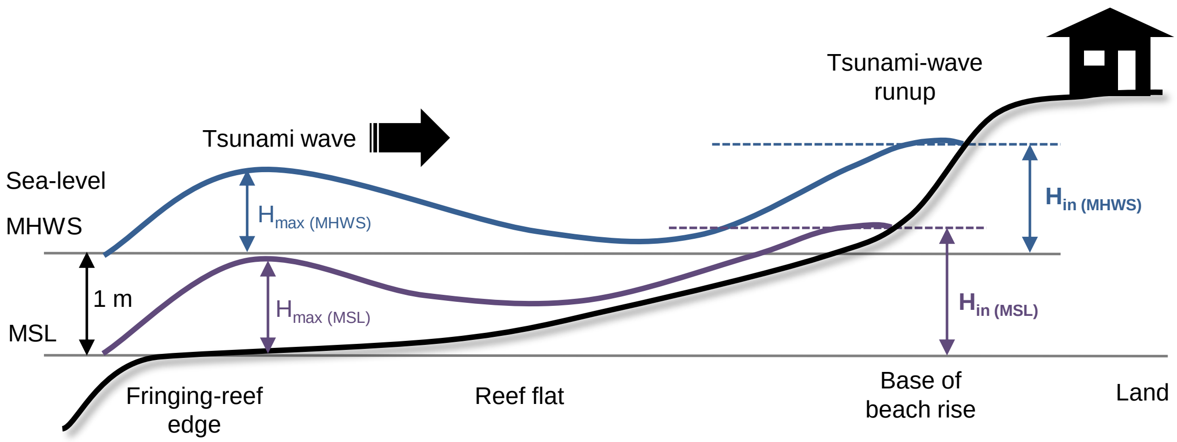

Figure 2-2: Schematic depiction of model sea-levels used in the tsunami simulations and terminology used to quantify tsunami-wave inundation. The horizontal and vertical dimensions are not to scale.

2.5 Earthquake fault parameterisation

Earthquake parameters were obtained from the literature (summarised in Table 2-2 and using globally accepted empirical relationships to derive the earthquake moment magnitude from the geological fault parameters and knowledge of regional tectonics and geodynamics (e.g. Johnson and Satake, 1993; Johnson et al., 1996; Lamarche et al., 2010; Goff et al., 2011, 2012).

Earthquake fault parameters for distant sources were based on historical earthquakes readily available from the United States Geological Survey database (http://earthquake.usgs.gov). Note that there are inherent complexities when modelling large earthquakes in excess of M_w9.2. As highlighted by Greenslade et al. (2009), linear scaling becomes unreliable beyond M_w9.2 and results in unrealistic earthquake rupture lengths and slips because peak slips occur only over a small area. Such an assertion is consistent with the measured M_w9.5 for the 1960 Chile earthquake but field evidence of variable slip rupture. As such, our simulation has been modelling using M_w9.29.

The regional sources were South Vanuatu Trench, central Vanuatu back-arc, North Vanuatu Trench, and the Tonga Trench. For the Tonga Trench specifically, four scenarios were developed: (i) rupture of the entire Tonga Trench; (ii) rupture of the entire Tonga Trench with an arbitrary +1 m water height at the time of tsunami initiation to simulate potential climate – induced sea-level rise or storm-related set-up; (iii) north Tonga Trench only; and, (iv) central Tonga Trench only (as for the Sep 2009 earthquake).

In all cases we purposefully selected parameters that generated the largest plausible earthquake in the region based on the data available. Unless otherwise stated, in most cases these earthquakes have not happened in historical time, but are created to represent potential “worst case scenarios".

2.6 Tsunami model parameterisation

The tsunami modelling was achieved using *Gerris Flow Solver* (Popinet, 2003). The depth-averaged equations used for numerical tsunami simulations have been integrated into *Gerris*, with details of the solution method and application summarised in Popinet (2011) and, Popinet 2012), respectively. In the time-dependent tsunami simulations, the adaptive grid generated in *Gerris* evolves (refines and coarsens) to select the appropriate grid resolution to capture the tsunami wave as it shoals and subsequently passes the islands. When running the model, there is a balance between accuracy around the islands, and the need to complete the runs in a timely fashion (weeks rather than months of computation). For the scenarios used herein, the regional simulations have been run with spatial grid scales spanning 62,500 m down to a minimum of 31 m, while the distant simulations span grid scales of 208,498 m down to a minimum of 25 m. Here, the minimum grid size was limited by the resolution afforded by the elevation data for each of the nukus, which in most cases has significant uncertainty. A smaller grid size would yield meaningful results only if high resolution data existed of sufficient density and accuracy, such as remotely-sensed laser-light elevations (LIDAR). As noted above, the current radar-derived vector data were not sufficient in this regard.

Name	Based on[1]	M_w[2]	L[3] (m)	W[4] (m)	Slip[5] (m)
North Vanuatu Trench	worst case	8.39	400	40	10
Vanuatu - back arc	worst case	7.96	200	30	6
South Vanuatu Trench	worst case	8.24	300	40	8
Tonga Trench	worst case	9.06	1000	80	20
Tonga 2009	29 Sep 2009	8.1	200	342.5	61
Tonga Trench + 1m	worst case	9.06	1000	80	20
North Tonga Trench	worst case	8.16	300	40	6
Central Tonga Trench	worst case	8.57	600	50	10
Japan (Tohoku)	11 Mar 2011	9.0	700	?	81
Chile	22 May 1960	9.29	920	120	32
Peru	13 Aug-1868	9.0	900	150	15
Aleutian Arc	9 Mar 1957	8.6	850	150	10
Cascadia	worst case	9.1	1050	70	17.5
Kuril Trench	worst case	9.28	1000	200	17

Table 2-2: 1: date of earthquake used as reference; 2: magnitude used for the model, likely to differ from that of the reference earthquake; 3: fault length; 4: fault width; and, 5: length of slip along fault plane. See http://earthquake.usgs.gov/earthquakes/eqinthenews/2009/us2009mdbi/finite_fault.php and Figure (see Annexe C).

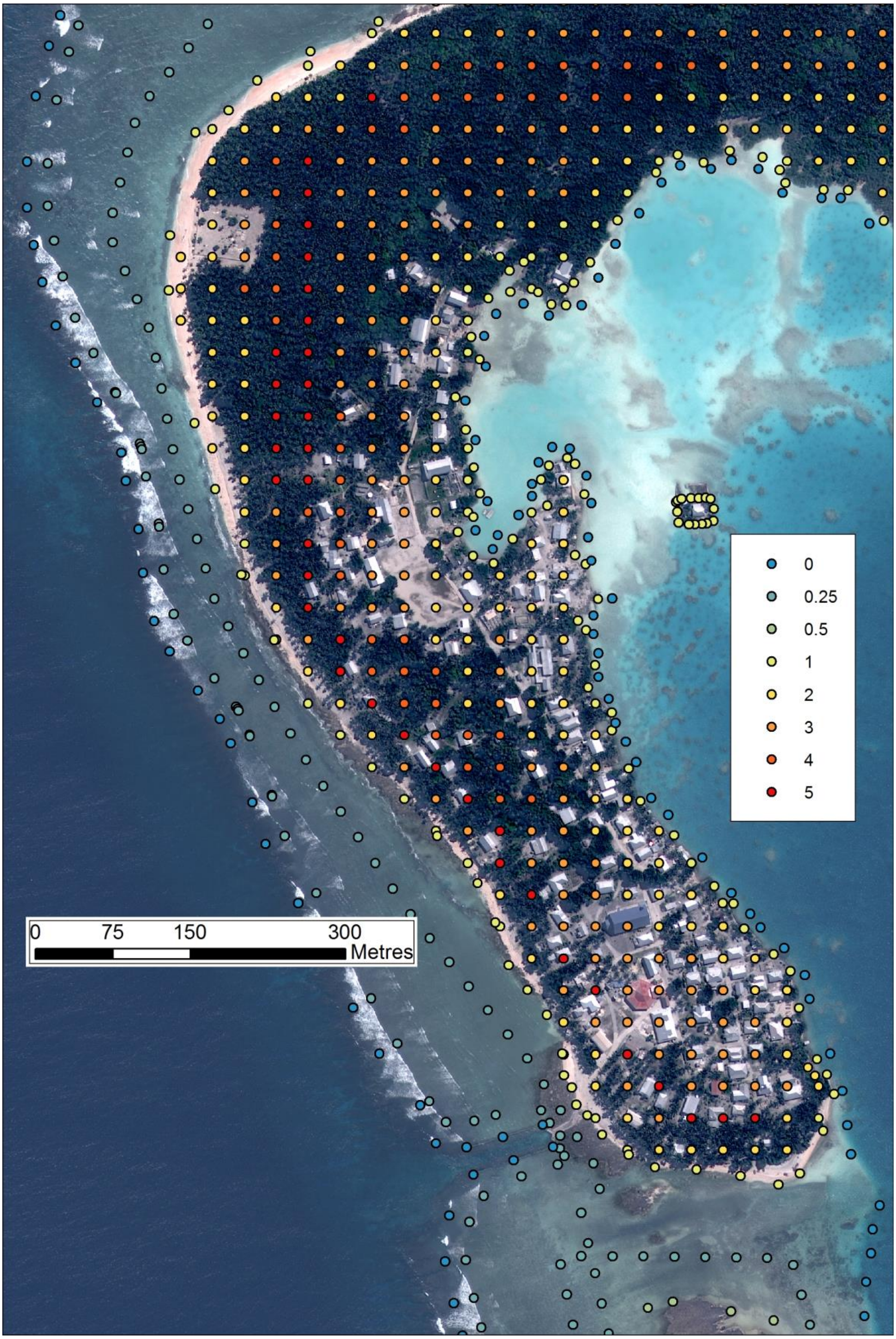

Figure 2-3: Derived spot-height data with a grid spacing of ~30 m for the area around Atafu village.

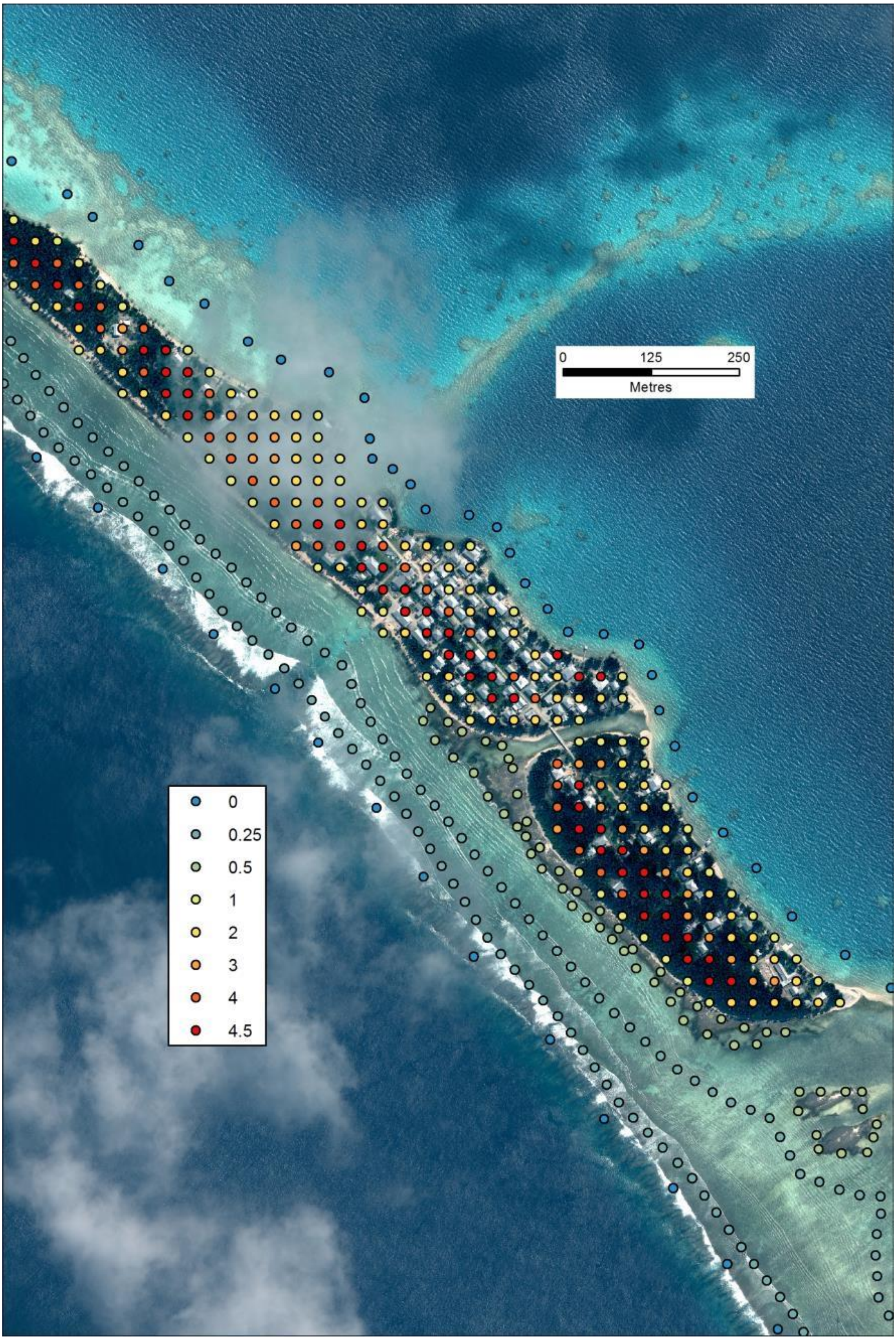

Figure 2-4: Derived spot-height data with a grid spacing of ~30 m for the area around Nukunonu village.

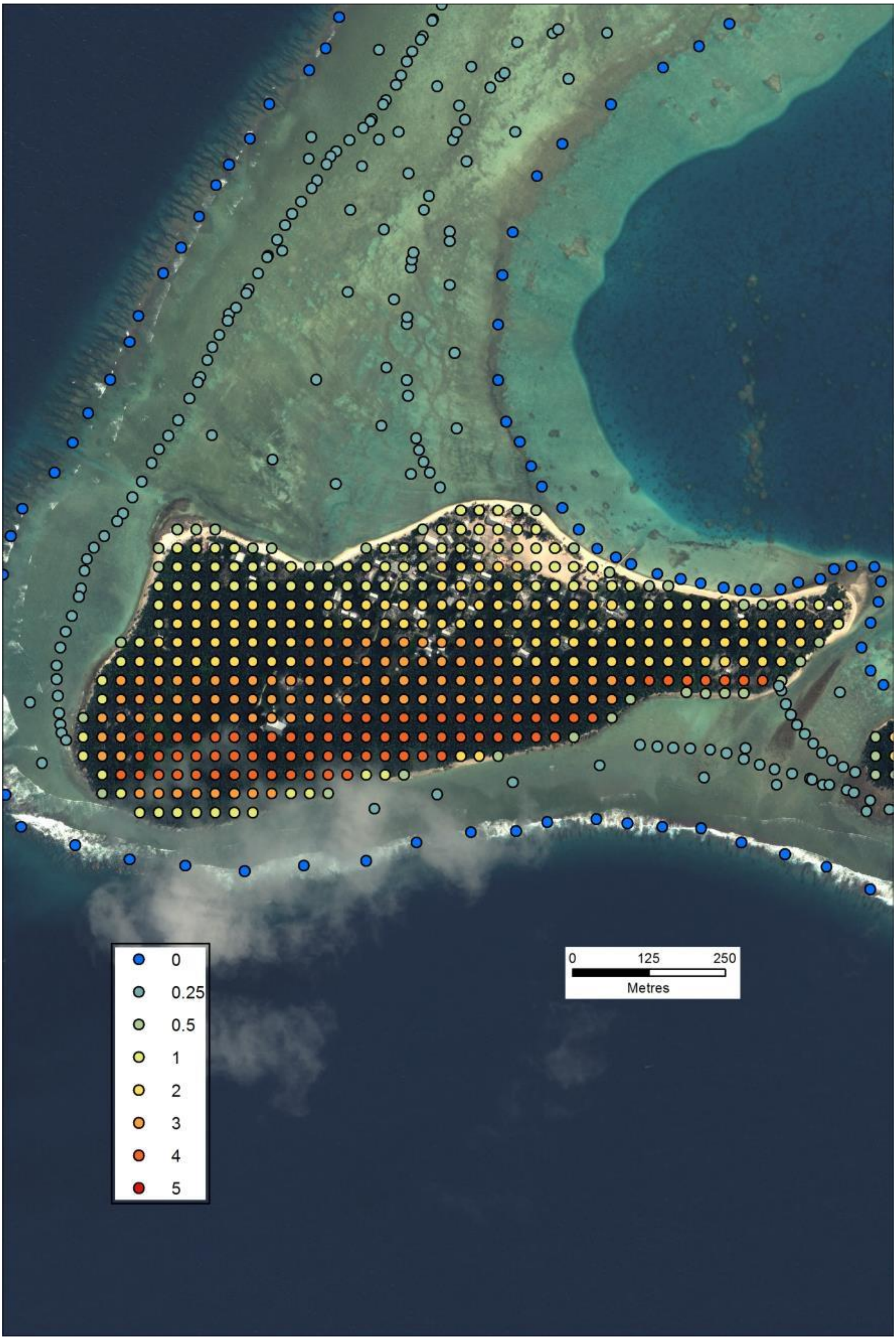

Figure 2-5: Derived spot-height data with a grid spacing of ~30 m for the area around Fenua Fala village, Fakaofo.

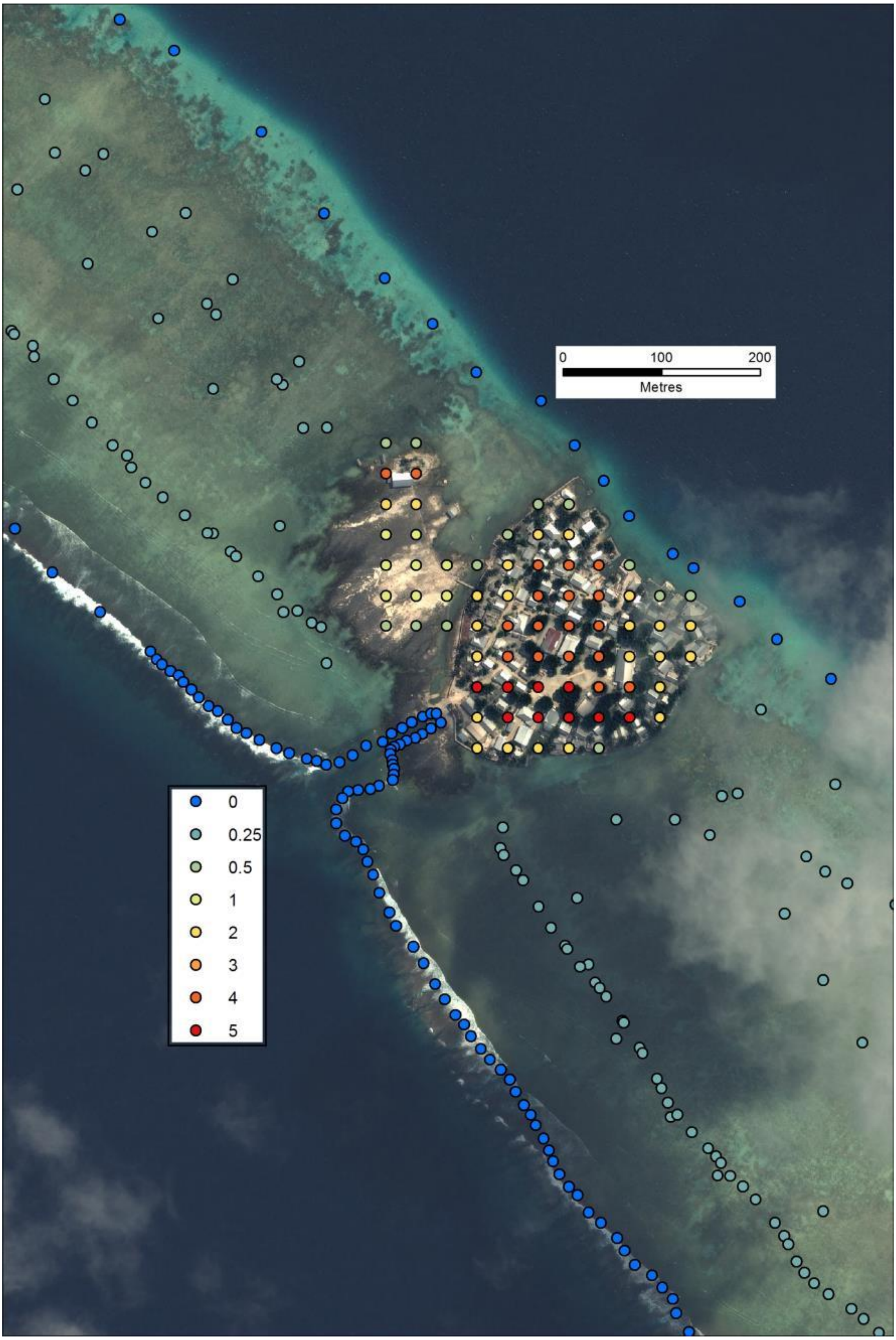

Figure 2-6: Derived spot-height data with a grid spacing of ~30 m estimated for the area around Fale village, Fakaofo.

3 Results from tsunami model simulations

3.1 Distant-earthquake sources

Figures 3-1 to 3-8 show the results for the distant sources listed in Table 2-1. Figure 3-1 combines the resultant maximum tsunami-wave height above sea level (H_{max}) of each simulation, over the time of each simulation. The height is plotted on a logarithmic scale to adequately capture the wide range of wave amplitudes (0.125 m in dark blue to over 7.9 m in red). The top frame provides a regional focus, with the Tokelau Islands outlined in white. The lower frame provides a wider view of the Pacific Ocean and the distant tsunami source regions, with the Tokelau Islands outlined in black. The largest earthquake sources can be seen from the elongated red streaks of high waves around the Pacific basin. The tsunami waves do not simply radiate out from a source location. As the wave travels from the source region, it encounters topography in the form of sea floor bathymetry, seamounts, seamount chains, and other islands and larger land masses; each of these can accelerate, slow, and scatter the incident wave field, transforming the original single coherent wave, into a train of waves.

Figure 3-2 replicates Figure 3-1, except that the worst case Kuril-earthquake event has been excluded from the compilation of maximum tsunami sources. The abrupt squared-off ends to some of the colour swathes mark the end of the model simulations: when the data indicated that the tsunami wave had long since passed through Tokelau, there was minimal risk of significant wave reflections, and there is no additional benefit to continue the simulations.

In comparing the upper frames in Figures 3-1 and 3-2 it is noticeable that the worst case Kuril event generates a response at the Tokelau Islands substantially larger than that of all the other simulations. This is not simply a reflection of the relative initial earthquake magnitude of the Kuril event. The wider view frames highlight how the wave fields are channelled by the bathymetry of the Pacific basin in such a way that the largest wave heights miss the Tokelau Islands. Similarly, for the M_w 9.1 Cascadia event the propagation is such that no significant wave heights are registered at Tokelau. Importantly for hazard assessment, these simulations reinforce that earthquake event magnitude is not the only factor when determining the likelihood of significant waves at Tokelau. Here, orientation of the wave front and the propagation direction across the seafloor are also significantly influential. The regional earthquake-source simulations show similar behaviour.

At the broad scales of Figures 3-1 and 3-2, the tsunami wave height in the vicinity of the Islands is around 50 cm excluding the Kuril event, but the wave height is potentially over 1 m with a Kuril event included.

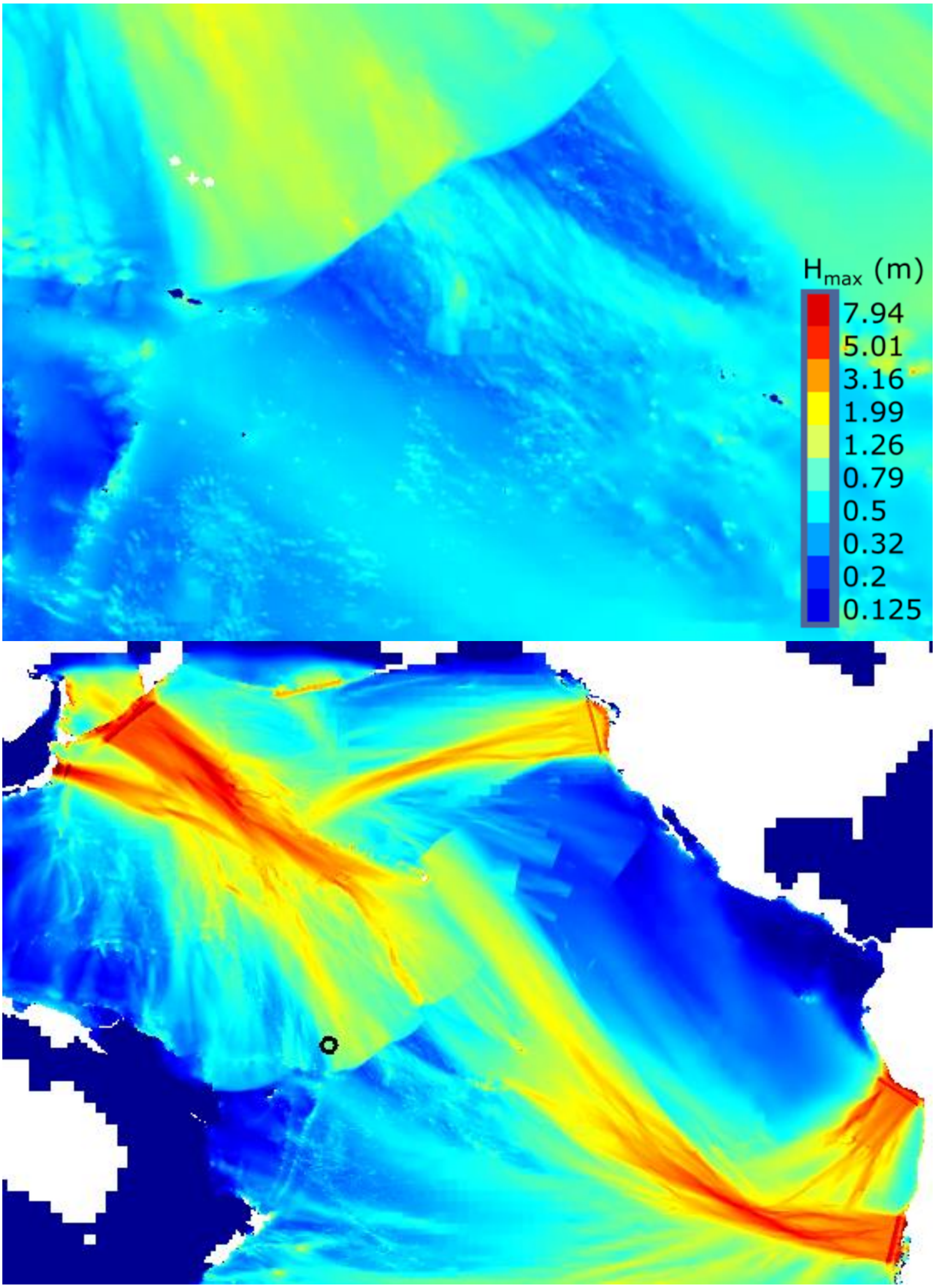

Figure 3-1: Summary of maximum wave heights for all distant sources *including* Kuril; regional view above (the Tokelau Islands are indicated by the white circles upper left), wider view of the Pacific Ocean below (the location of Tokelau is indicated by the black circle). Note that simulations stop after the majority of the tsunami wave train has passed Tokelau.

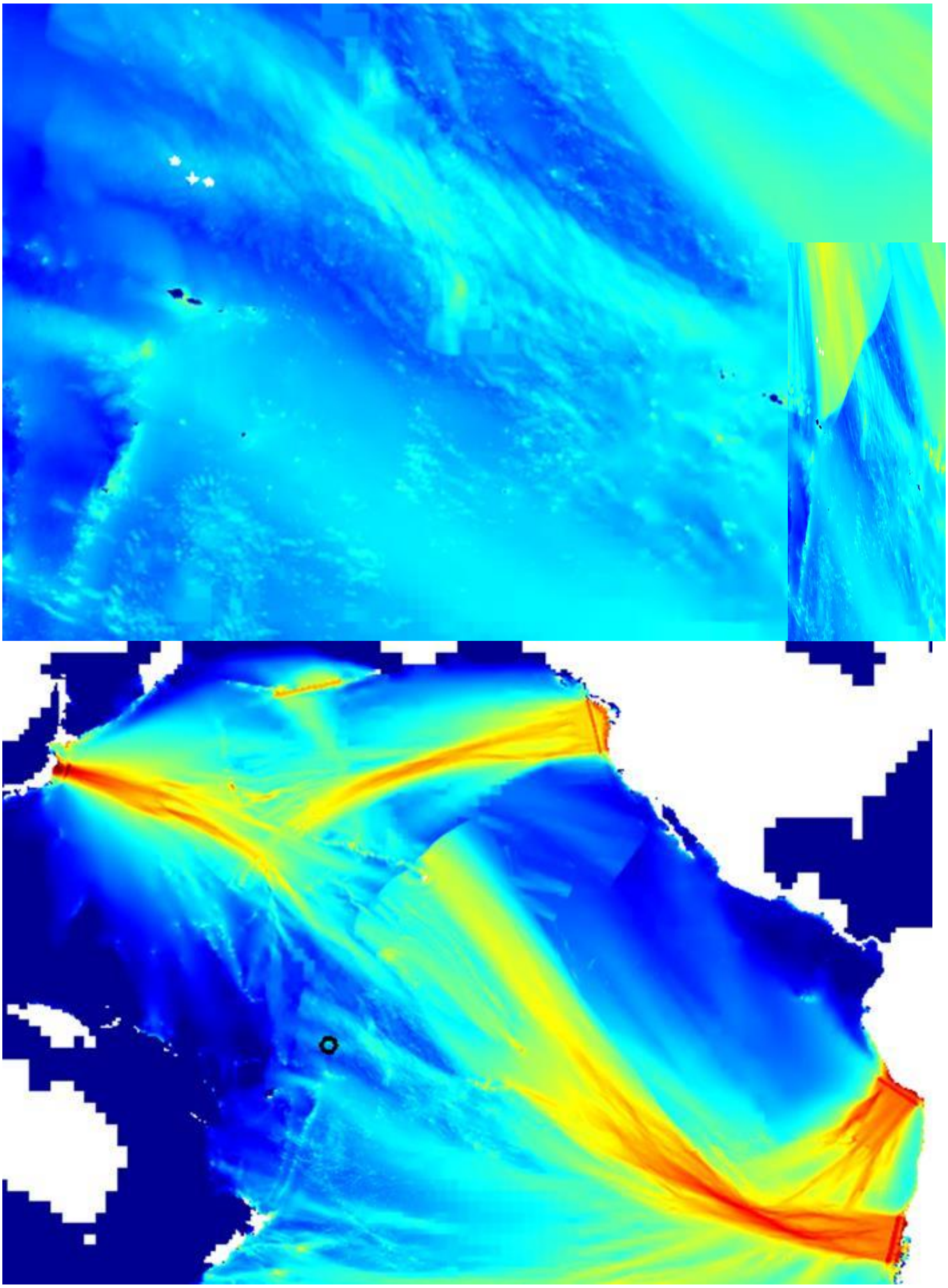

Figure 3-2: Summary of maximum wave heights for all distant sources *excluding* Kuril: regional view above (the Tokelau Islands are indicated by the white circles upper left), wider view of the Pacific Ocean below (the location of Tokelau is indicated by the black circle). Note that simulations stop after the majority of the tsunami wave train has passed Tokelau.

Figures 3-3 to 3-8 represent modelled maximum inundation estimates for the Islands using the maximum estimates from all distant-source simulations The colour bar legend shows the maximum tsunami-flood inundation depth (in centimetres) above land, H_{in}. The uncoloured areas, where the underlying satellite image of the nuku and moku can be seen, are emergent land areas that remain dry during the modelled tsunami flooding events. The lagoon and fringing reef are not considered land and are low-lying so have no colour, but because these areas are so shallow on occasion one or two grid squares of colour might occur away from the known areas of land.

Of the three nuku, the villages on Nukunonu and Fakaofo have more potential risk of inundation along their margins during the largest events because of their low and narrow land area (Figures 3-4, 3-6 and 3-8). The modelling suggests that the Tohoku event did result in some inundation; nonetheless, much of the land surrounding the villages remained dry. Further validation of this modelled result could be yielded from observations after the Tohoku event in 2011, and Kuril earthquakes over recent decades and incorporating these with information on the tidal state when the waves arrived. To the best of our knowledge there is no historical legacy of "unusual tides or surges" or other phenomena that could be linked with such events.

Figures 3-3 to 3-8 give a static impression of maximum wave heights and nuku inundation, integrating the time history into just a single image. However, each event is generally not characterized by the rapid passage of a simple, single wave front before returning to rest. A tsunami could persist for 2 to 3 hours, during which time the wave field may remain at levels capable of generating potential inundation (Table 3-1). The wave train may persist across the Pacific for days, but model simulations were stopped when the risk for further significant flooding was considered low.

For the distant-earthquake simulations Table 3-1 shows that the arrival times are in excess of 8 hours for sources in the western part of the Pacific basin, and in excess of 13 hours for Chile and Peru in the eastern part of the Pacific. Hence, warning times are relatively long..

Distant Source	Magnitude (M_w)	Atafu	Nukununu	Fakaofo	Approximate Duration
Aleutian	8.6	8h 15m	8h 25m	8h 30m	~ 2h
Chile	9.29	13h 40m	13h 30m	13h 30m	> 3h
Kuril	9.28	8h 20m	8h 25m	8h 35m	> 3h
Peru	9.0	15h 15m	15h 10m	15h 00m	> 2h
Tohuku	9.0	8h 55m	8h 55m	8h 55m	> 3h

Table 3-1: Arrival times in hours (h) and minutes (m) for waves from distant-earthquake simulations with heights greater than 10 cm, and approximate event duration.

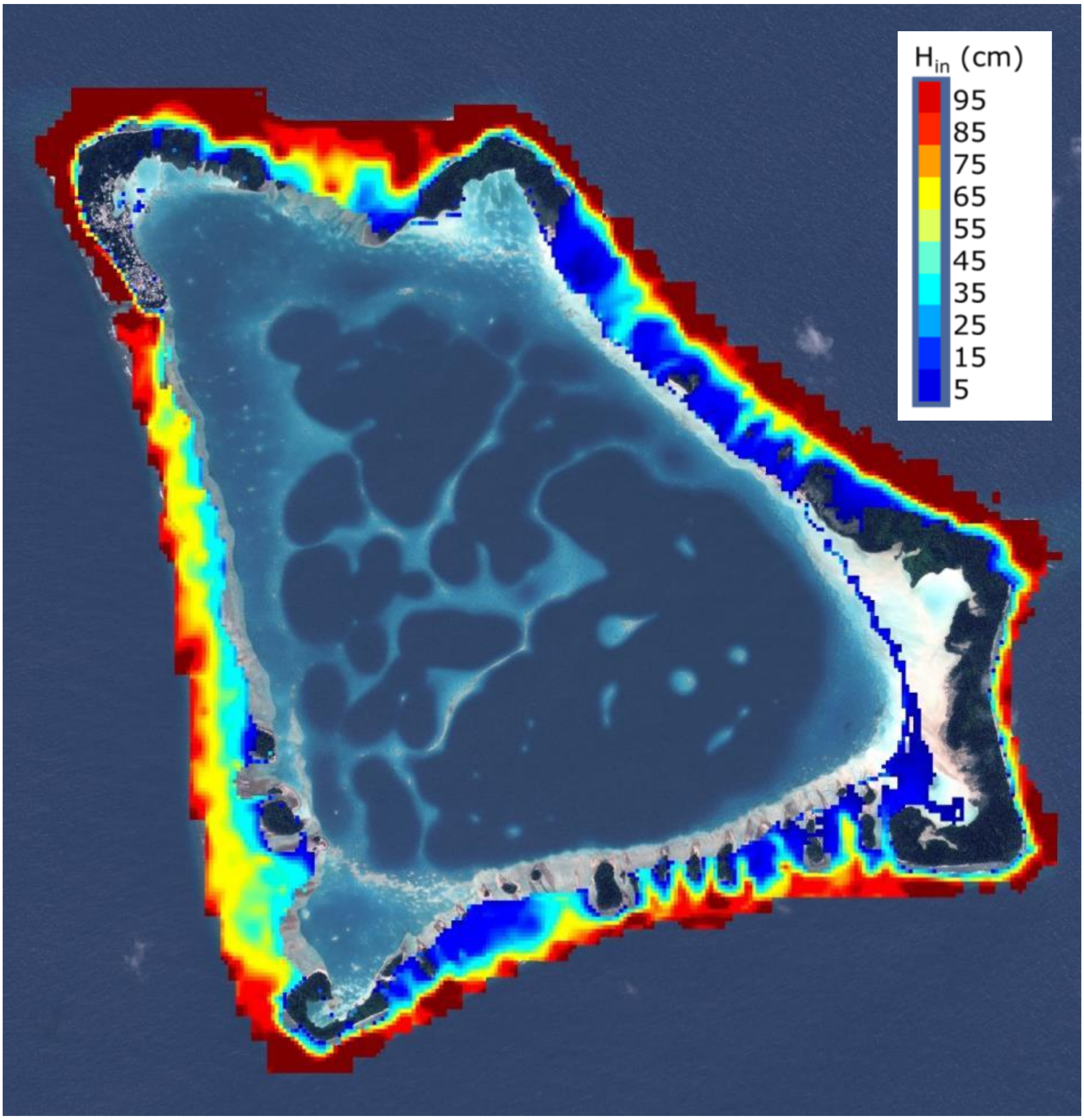

Figure 3-3: Modelled tsunami-flood inundation depths (above MSL) on Atafu from all distant-earthquake sources.

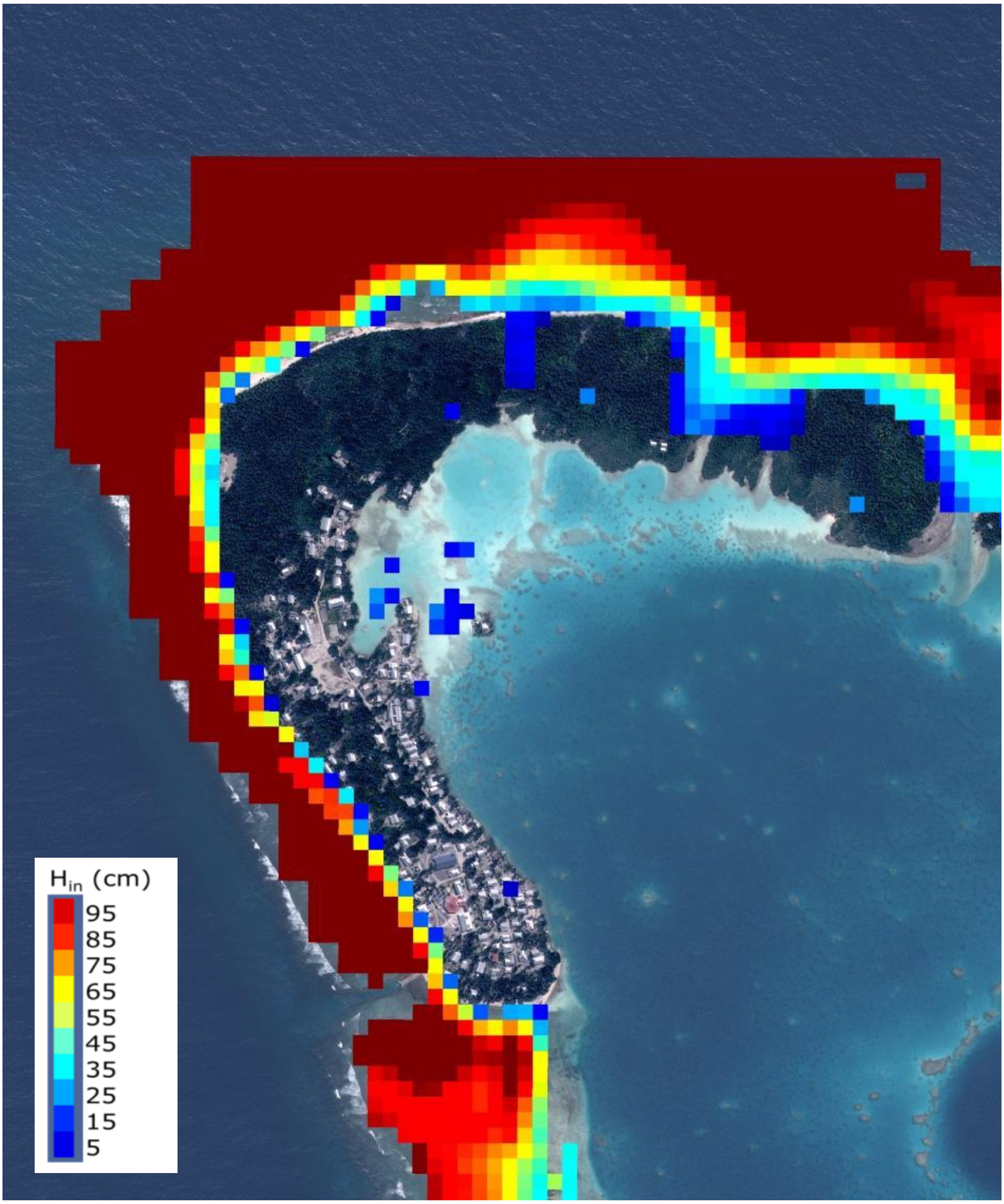

Figure 3-4: Modelled tsunami-flood inundation depths (above MSL) for the village on Afatu from all distant-earthquake sources.

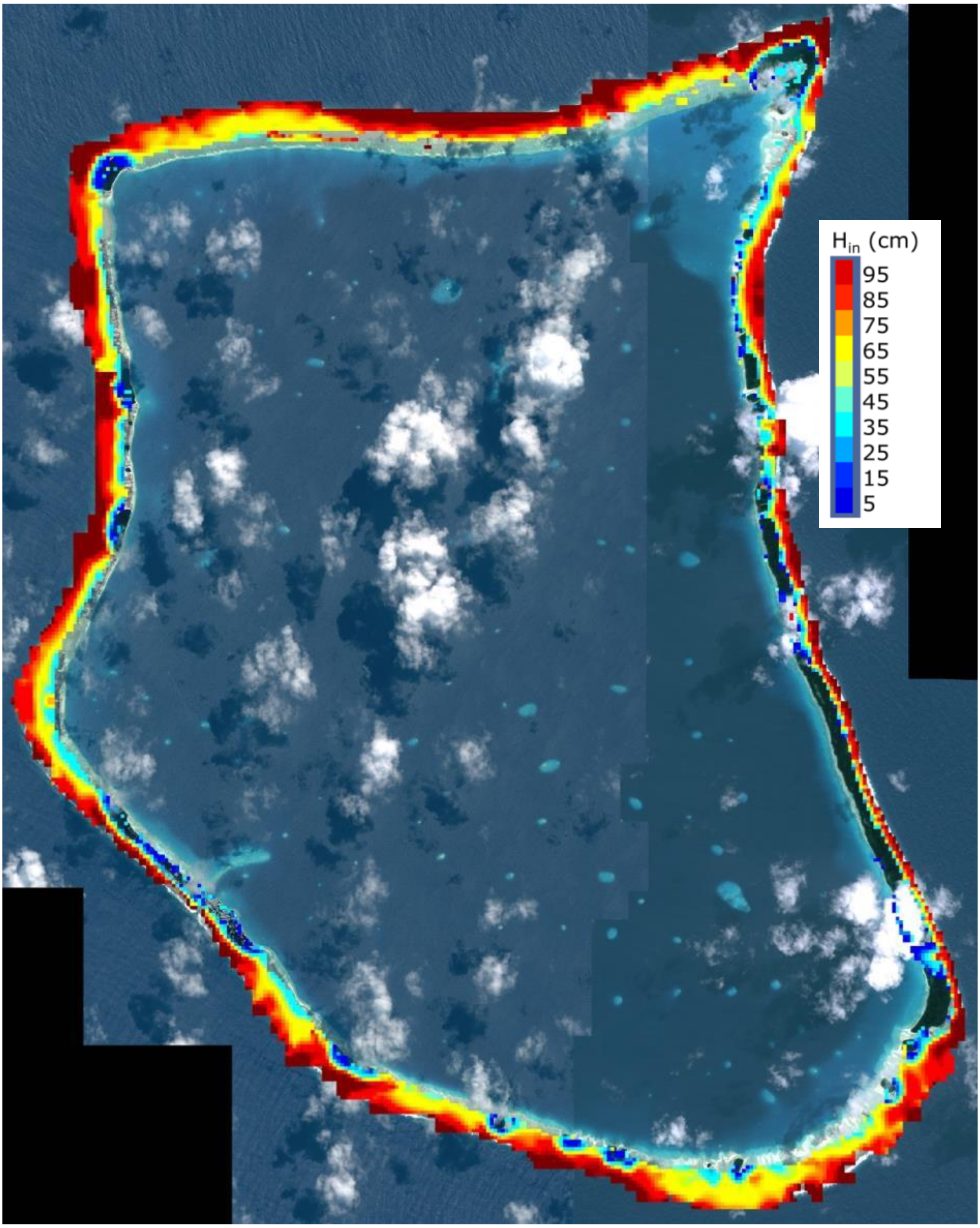

Figure 3-5: Modelled tsunami-flood inundation depths (above MSL) on Nukumonu for all distant-earthquake sources.

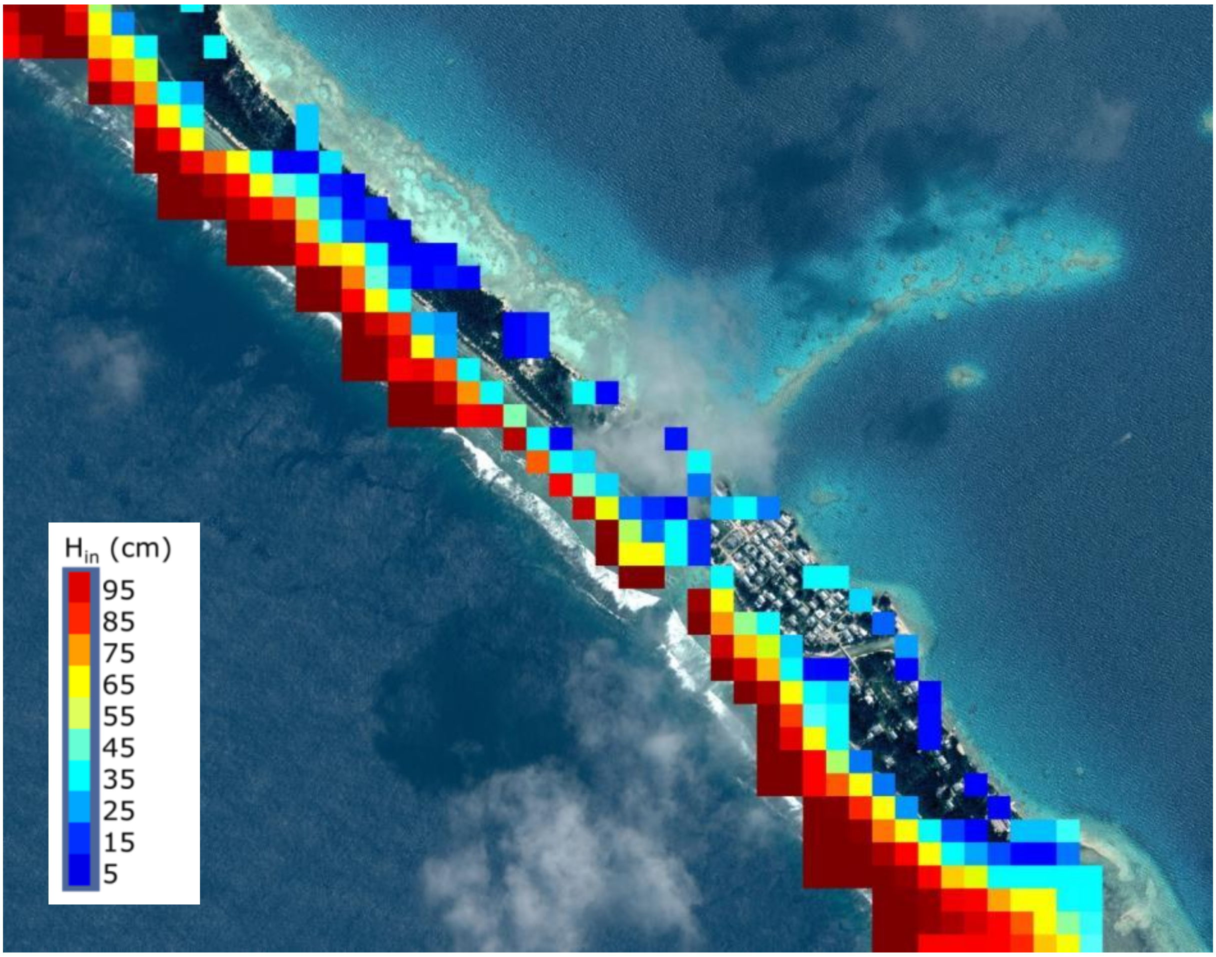

Figure 3-6: Modelled tsunami-flood inundation depths (above MSL) for the village on Nukunonu from all distant-earthquake sources.

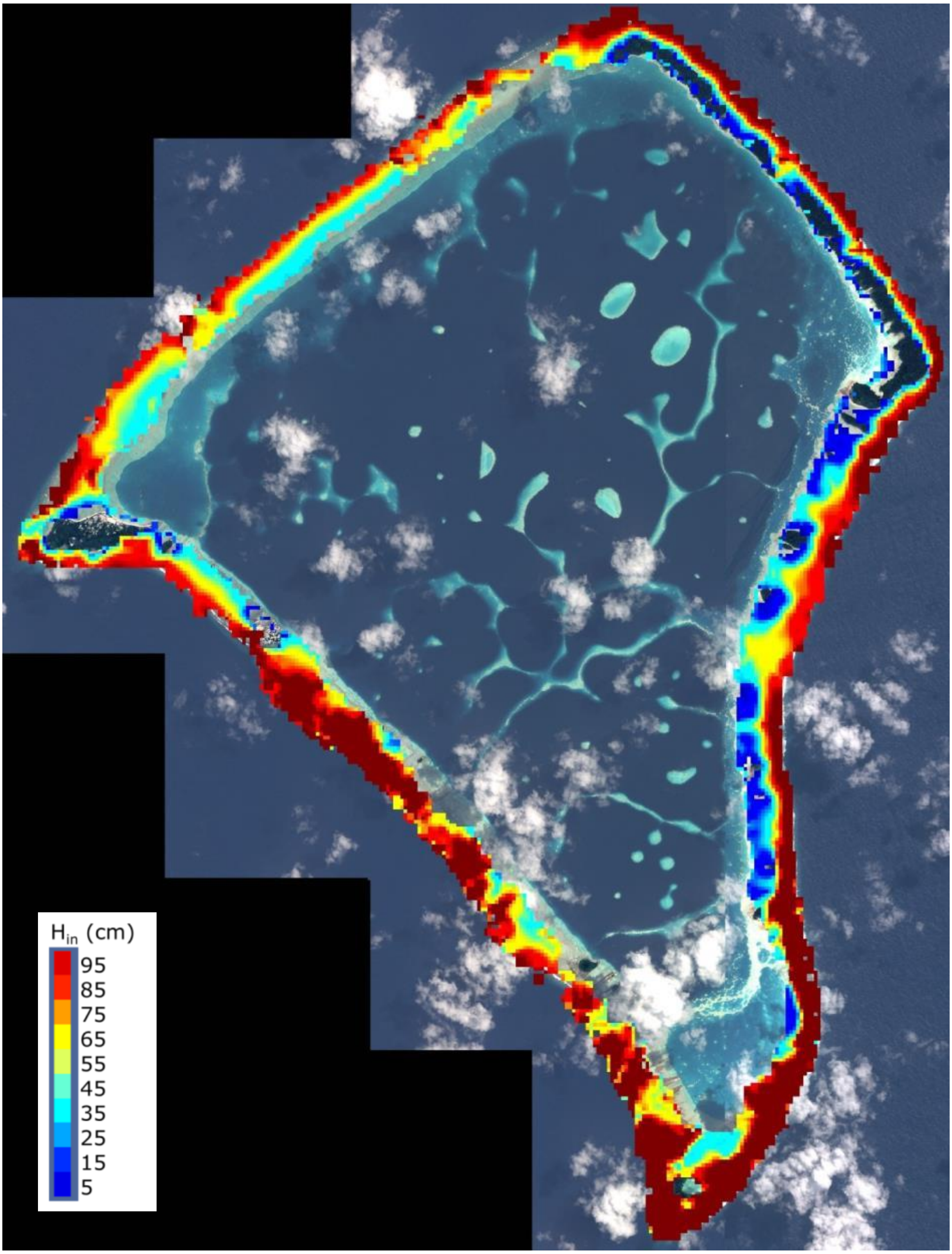

Figure 3-7: Modelled tsunami-flood inundation depths (above MSL) on Fakaofo from all distant-earthquake sources.

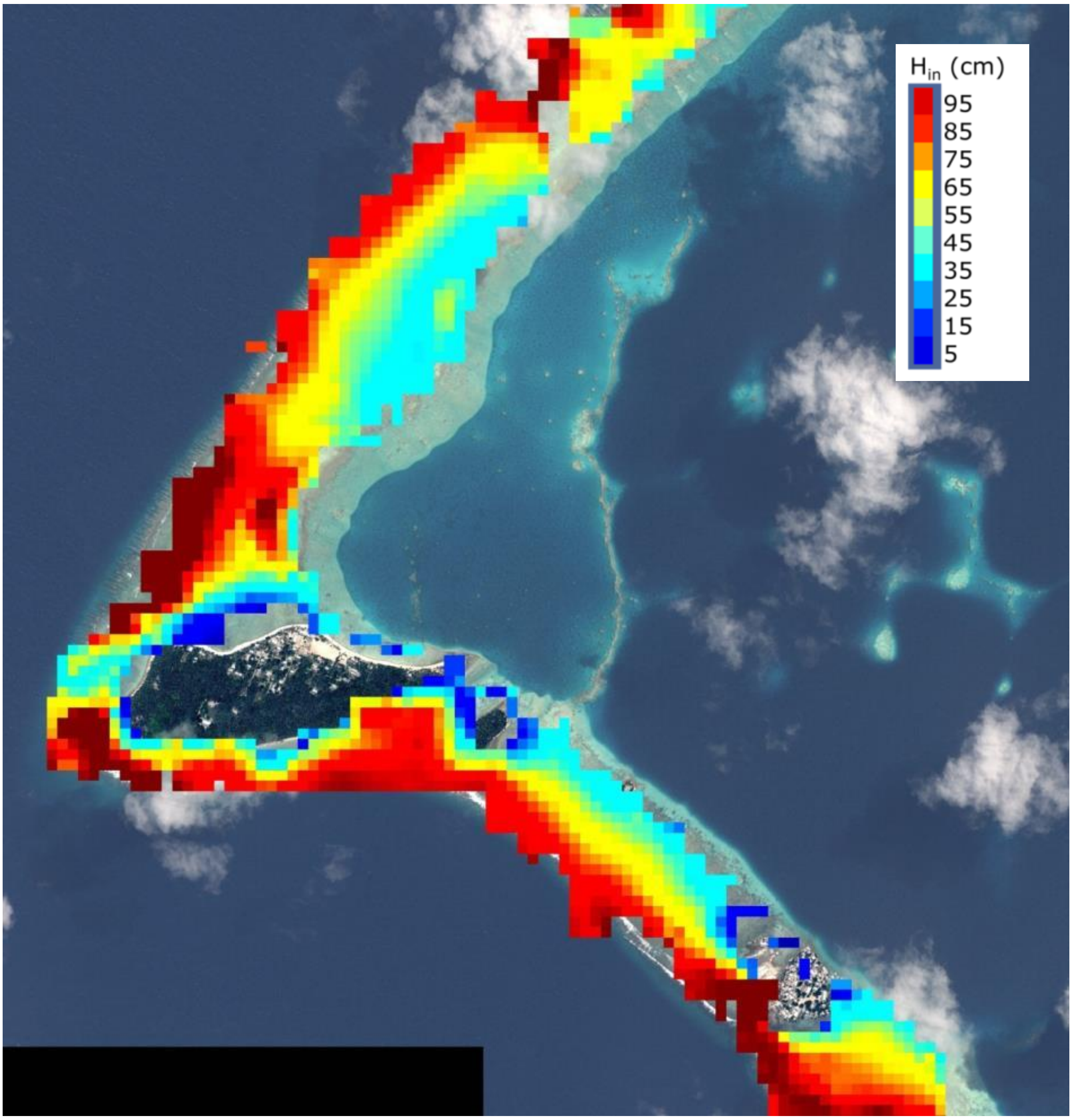

Figure 3-8: Modelled tsunami-flood depths (above MSL) for the villages of Fenua Fala and Fale on Fakaofo from all distant-earthquake sources.

3.2 Regional-earthquake sources

Seven regional scenarios were modelled, but only two (Northern Tip Tonga and Tonga Trench) resulted in wave heights over 10 cm at the Tokelau Islands. Fig. 3-9 shows the maximum wave heights for all the regional simulations; around the Tokelau Islands (shown by the white outline) H_{max} is typically less than 30 cm. The regional sources used in this study are generally located to the south or south west of the Tokelau Islands and, when combined with the fault orientation and bathymetry in this region, it seems that the Tokelau Islands are relatively “sheltered” (particularly by the Samoa Island chain) such that wave heights exceeding 0.5 m are predicted to occur further west and east of the Tokelau Islands, but do not impact Tokelau.

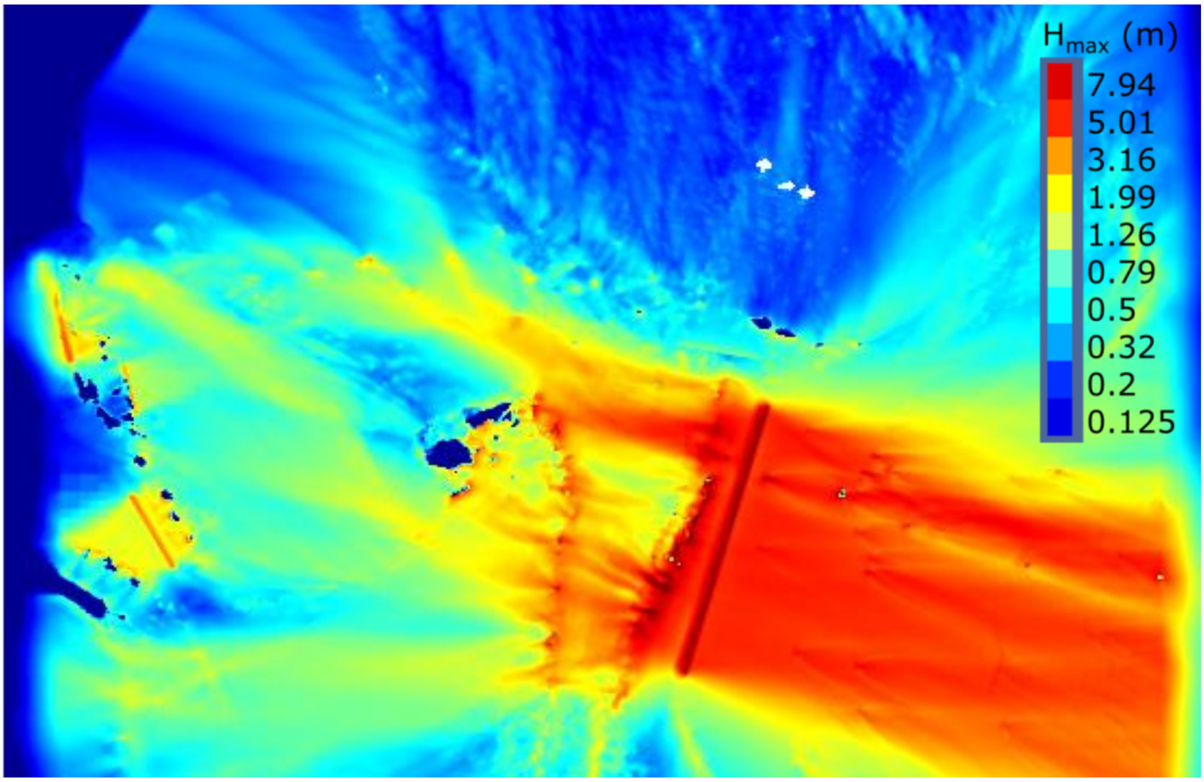

Figure 3-9: Maximum wave heights (above MSL) for the compilation of maximum-regional source simulations (0.125 m in dark blue to 7+m in red). Tokelau is indicated in white, upper right.

Summary plots of maximum tsunami inundation depth show some inundation on each of the islands resulting from the maximum-regional source simulations, but significant areas of land remain dry (Figures 3-10 to 3-15). The amplitudes and patterns of inundation are comparable to the distant events *excluding* Kuril (Figure 3-2), and reflect the consistent factor of each island's topography in the model simulations. Hence, the same land areas identified as dry for the distant earthquake sources are also predicted to stay dry for regional sources.

The significant point of difference for the regional- versus the distant-earthquake source simulations is the arrival times of the first significant tsunami waves; a function of travel distance. Arrival times of 45 minutes (Northern Tip Tonga) to around 60 minutes (Tonga Trench) are to be expected, with event durations of between 1 and 3 hours can occur (Table 3-2). This lead time for implementing any emergency plan is short for a regionally-generated event.

	Magnitude (M_w)	Atafu (mins)	Nukununu (mins)	Fakaofo (mins)	Approximate Duration (mins)
Northern Tip Tonga	8.16	50	50	50	>70
Tonga Trench	9.06	70	65	60	>180

Table 3-2: The occurrences of waves greater than 10 cm height (H_{max}) are used to define initial arrival times to Tokelau and quantify tsunami duration (in minutes) for regional earthquake sources.

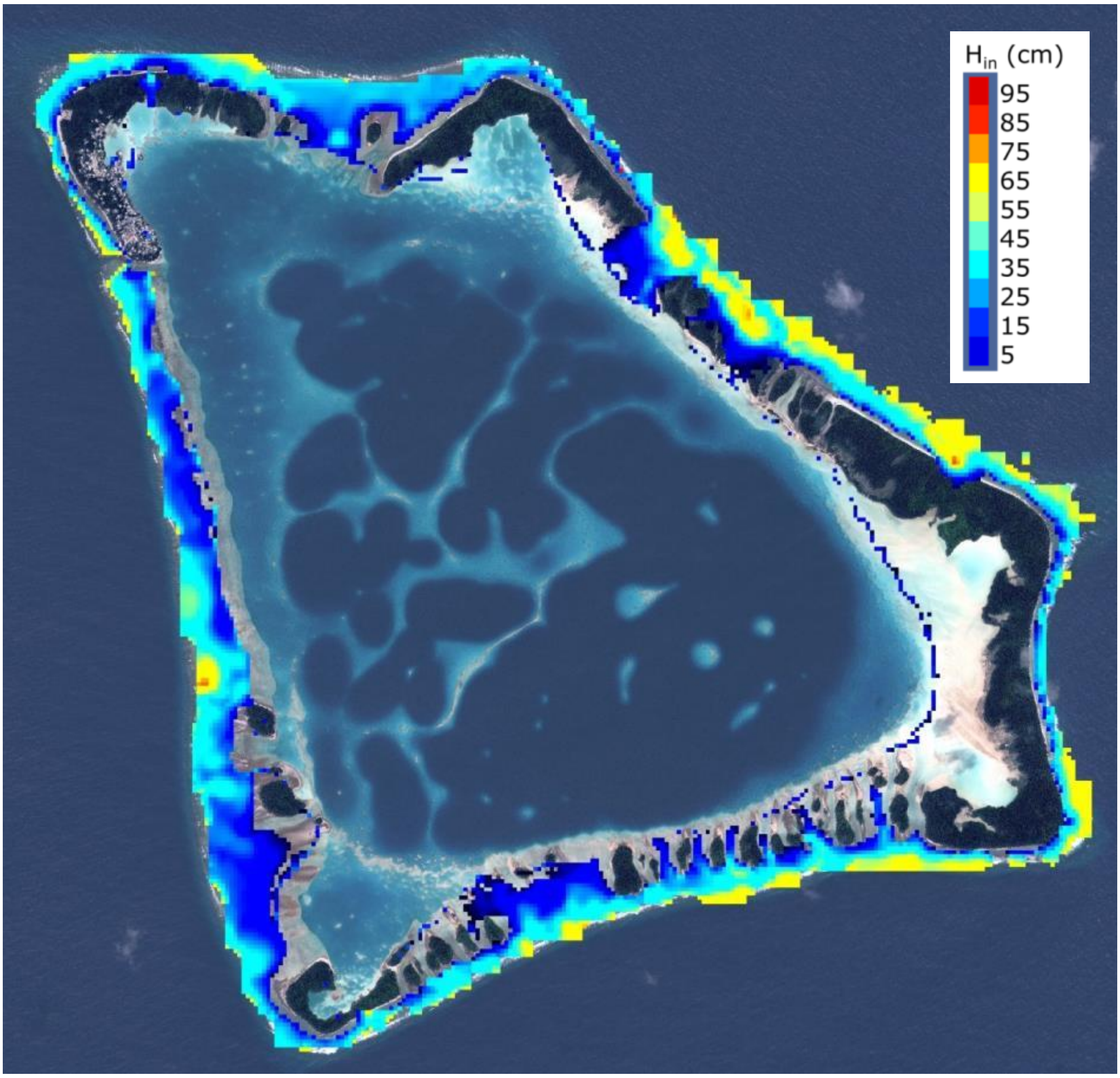

Figure 3-10:Modelled tsunami-flood inundation depths (above MSL) on Atafu from all regional-earthquake sources.

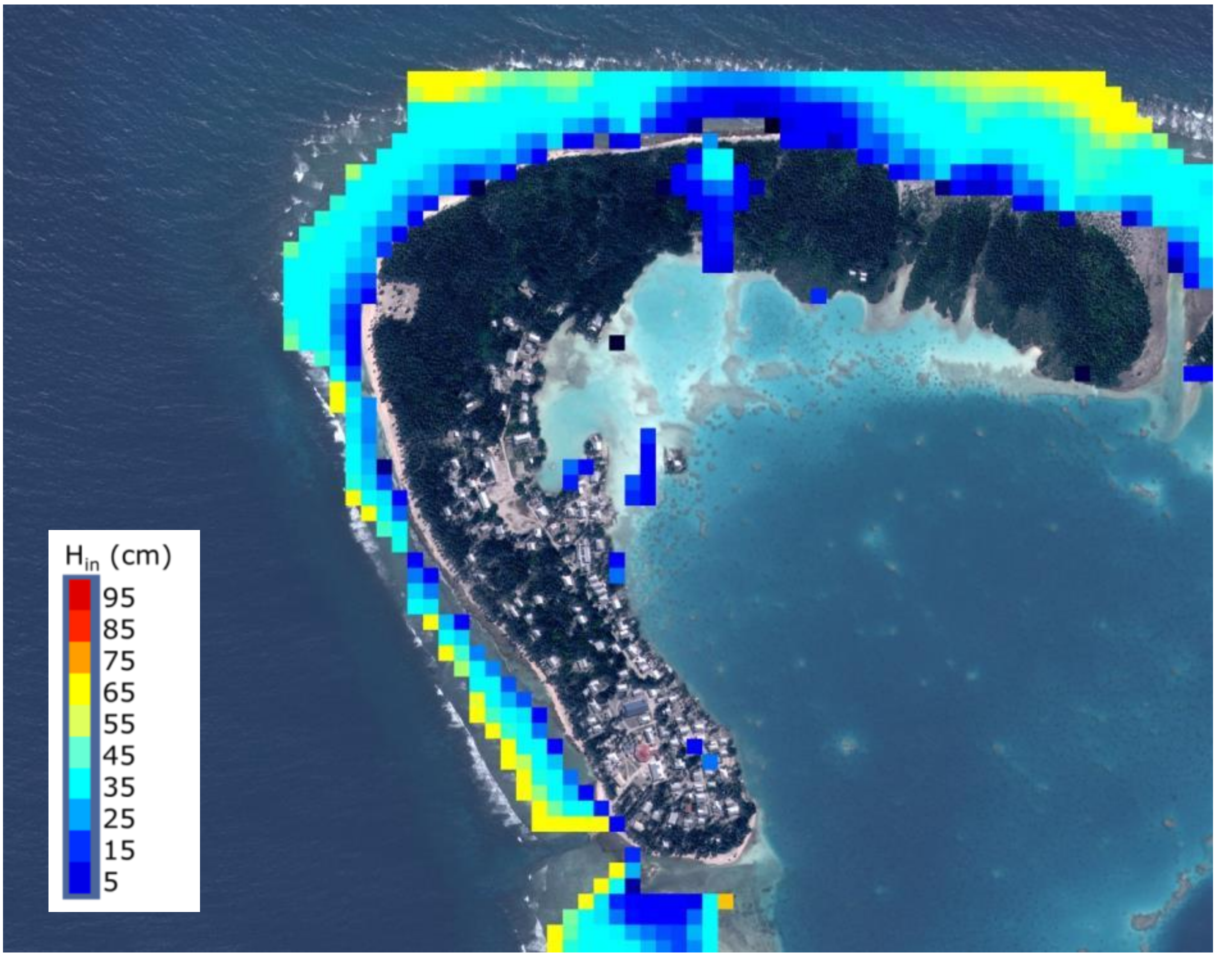

Figure 3-11:Modelled tsunami-flood inundation depths (above MSL) for the village on Atafu from all regional-earthquake sources.

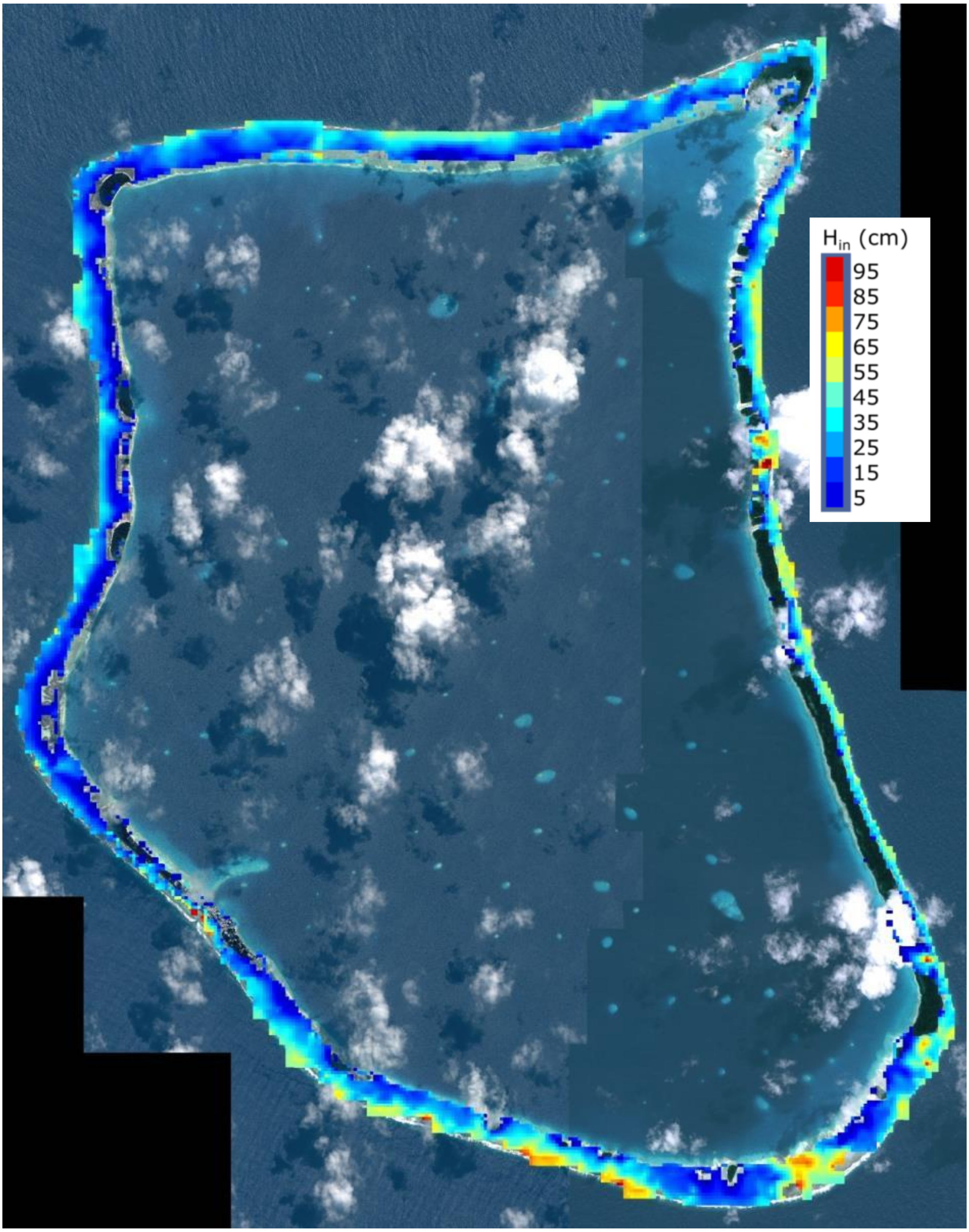

Figure 3-12:Modelled tsunami-flood inundation depths (above MSL) on Nukunonu from all regional-earthquake sources.

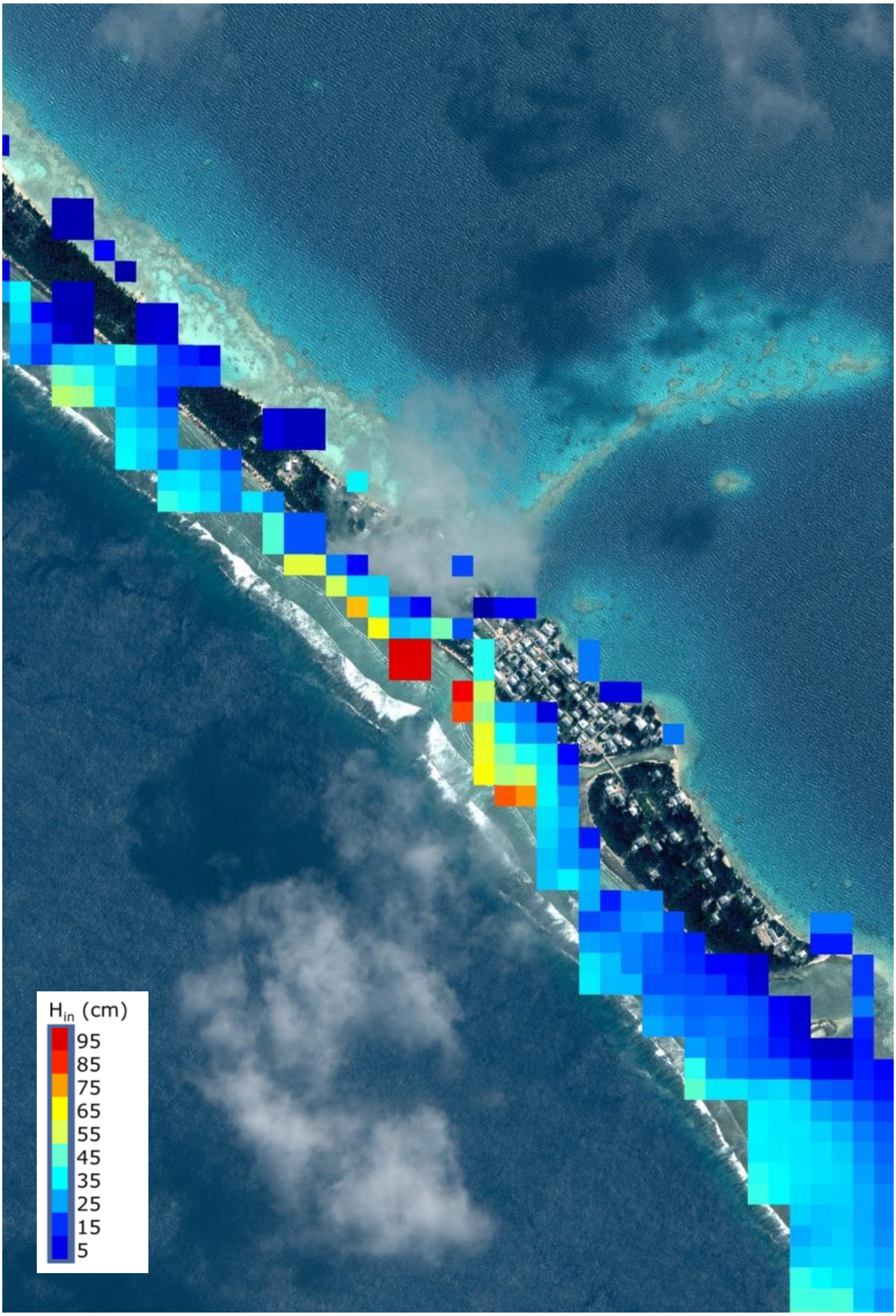

Figure 3-13:Modelled tsunami-flood inundation depths (above MSL) for the village on Nukunonu from all regional-earthquake sources.

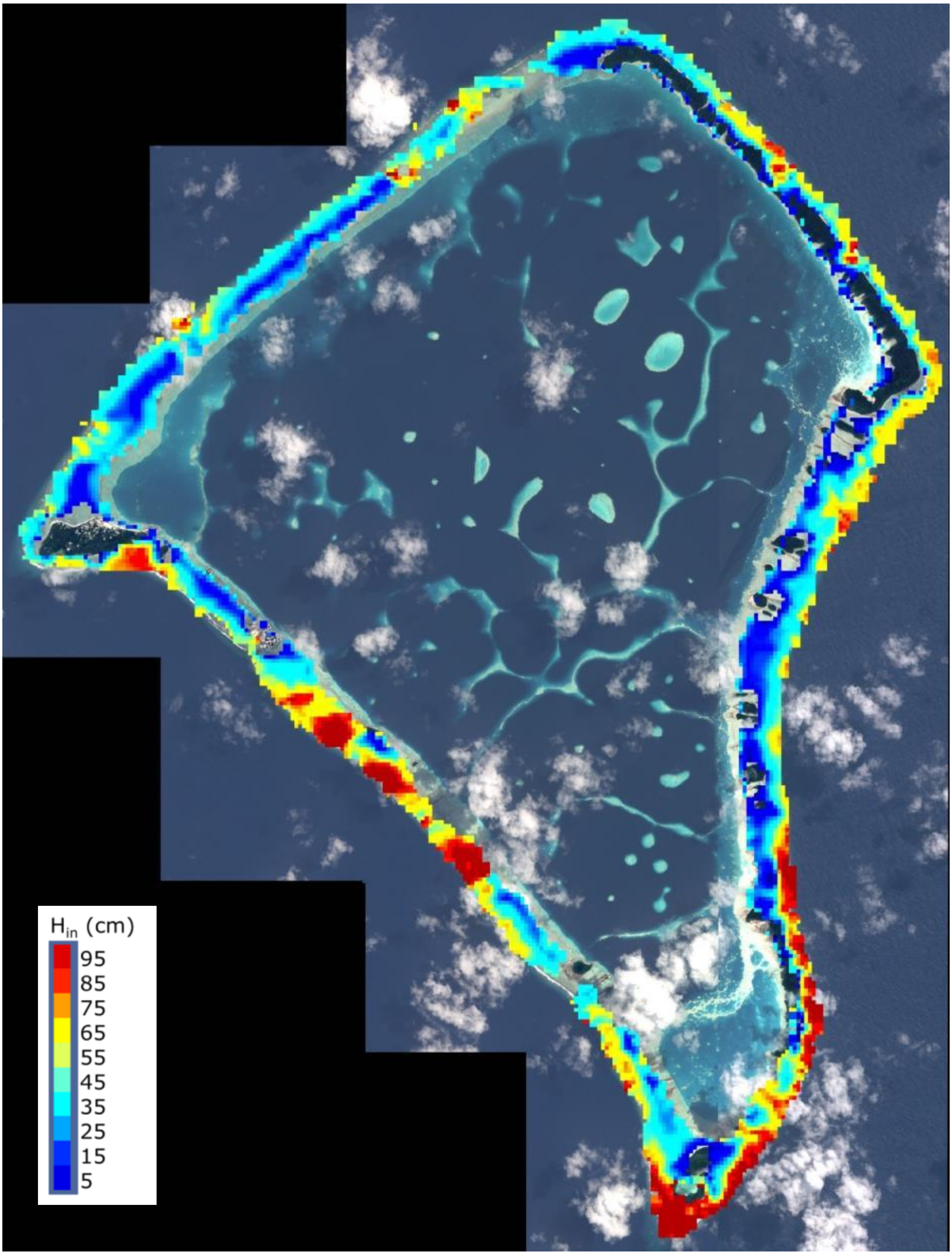

Figure 3-14:Modelled tsunami-flood inundation depths (above MSL) for Fakaofo from all regional-earthquake sources.

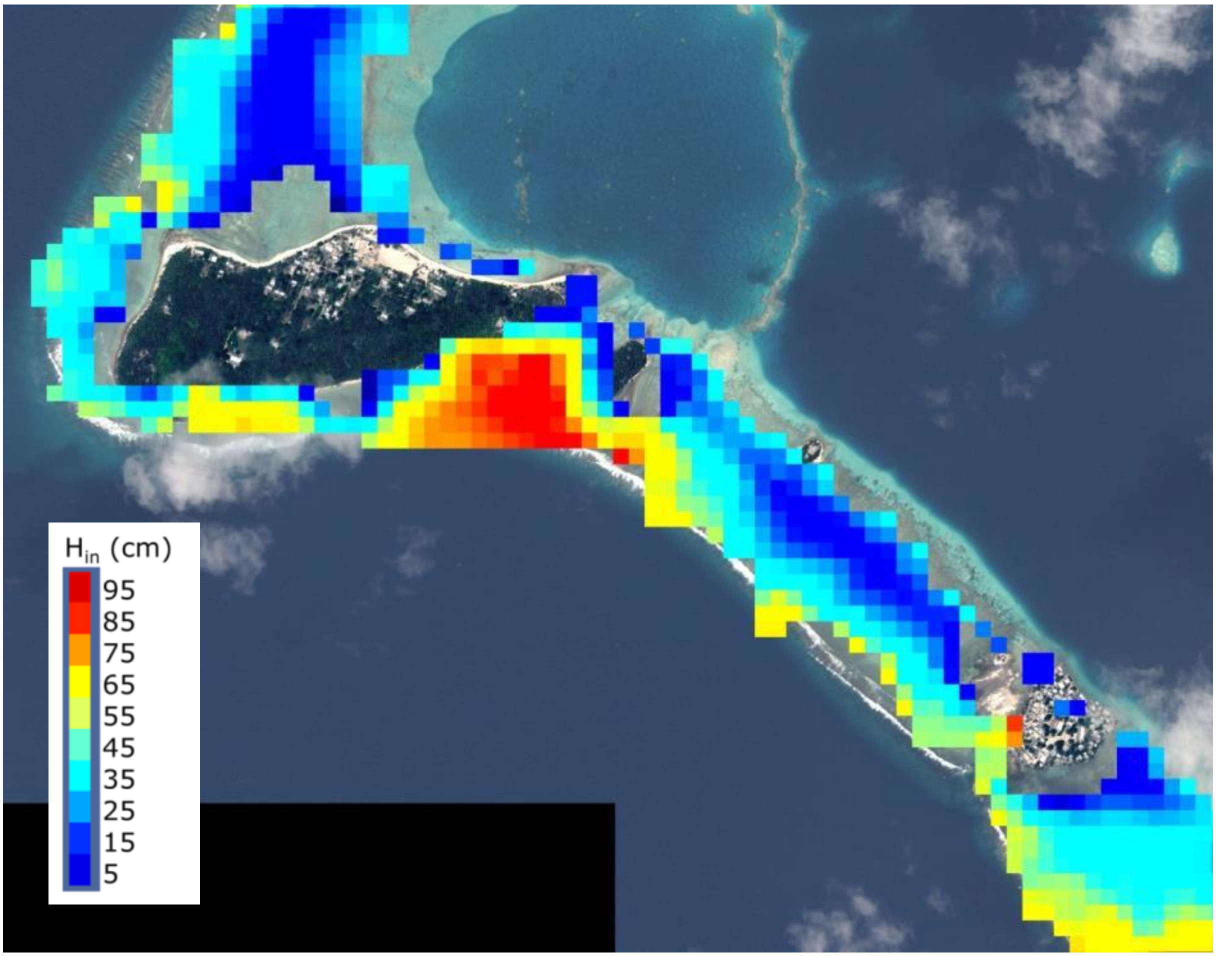

Figure 3-15:Modelled tsunami-flood inundation depths (above MSL) for the villages of Fenua Fala and Fale on Fakaofo from all regional-earthquake sources.

3.3 Summary of results

From the 14 potential distant and regional tsunami sources investigated in this hazard assessment the Tokelau Islands nearly all have land areas within the villages that will remain dry. The scenarios sample a range of earthquake sources in terms of magnitude, orientation, and distance from the Tokelau Islands. The outcome that none of the modelled tsunami waves over-wash any of the nukus is probably consistent with the oral history of little or no tsunami threat perceived by the Tokelau Islanders themselves.

The static images used in this report represent a snap-shot of a tsunami-event scenario as the tsunami wave interacts with each of the nuku. However, other wave behaviour is evident when the complete wave passage is viewed as a movie, emphasising wave dynamics and refraction effects around the nuku, islets, tidal channels and within the lagoons. Deep channels through the fringing-reef matrix in particular can allow for the propagation of far more tsunami energy than shoals protected by the reef or motus. The simulations run at MHWS reinforce that during the largest events runup is possible from the lagoon side of the nuku, as the reef flat does not provide a significant barrier to wave propagation.

4 Tsunami evacuation advisory for the Tokelau Islands

In order to provide some kind of summary advisory for emergency planning for the Tokelau Islands in the event of a major tsunami, the combined maximum tsunami-flooding results from the numerical modelling have been used to inform evacuation strategies. The results are presented in terms of the tsunami wave "runup": the maximum elevation on land above the initial sea level to which the sea inundates as a result of the tsunami event. For each island the highest runup from three cases is recorded. Two cases are based on the largest distant-sources; one with, and one without, the Kuril simulation. A third case records the highest runup simulated from the combined maximum regional sources.

For each nuku, compass quadrants provide a geographically practical means to assess the impact of the tsunami simulations on specific sections of the nuku (depicted as the red lines in Figures 4-1 to 4-3) and the main village(s) (depicted as the white circles in Figures 4-1 to 4-3). For each geographic region, the maximum runup height (in metres) is given above the specified local sea level. For each nuku two tables are provided: the top table records runup values when the arrival of the tsunami is simulated to coincide with mean sea level (MSL); and the lower table records runup values at our reconstruction of Mean High Water Spring (MHWS), +1 m above MSL (refer to Figure 2-2).

In some cases, runup heights for simulations with sea-level at MHWS are lower than the equivalent earthquake sources run at MSL. At first glance this seems counterintuitive and the reverse of what might be expected. The terrain gradient initially encountered by an incoming tsunami wave at MHWS can be quite different relative to the same wave simulated at MSL. The barrier-island matrix is much more open and penetrable when sea level is raised. Similarly, restrictive emergent barrier motus or coral cays may encourage greater runup. Consistent with other complex tsunami behaviour observed in this study, runup did not appear to be as linear as initially expected.

Each geographical region recorded in Tables 4-1 to 4-3 show an elevation considered to be the minimum “SAFE" evacuation height in the event of a major tsunami. In some regions the result is flagged as “NOT SAFE”; these are regions that are particularly low lying, or where the tsunami inundation is large. In such cases the advisory is to evacuate completely.

The particular earthquake-source simulations responsible for the maximum runup are identified in the Tables 4-1 to 4-3, and annotated accordingly as Chile (C), Kuril (K), Peru (P), and Tohoku (T). These tabulated results highlight that the largest magnitude earthquakes are not always responsible for the highest predicted runup around the nuku. The direction from which the tsunami wave arrives is critical to the runup height. But importantly, regardless of the earthquake source, the simulations predict that some areas of dry land would be preserved. Note that regional-earthquake sources generally result in lower tsunami runup compared to distant sources, except for the southern quadrant of Atafu as regionally-sourced tsunami waves are typically arriving from southern latitudes.

For the simulation of Atafu, with the sea-level set at MHWS, the higher initial water level covers most of the western geographical quadrant of the atoll and is deemed to be unsafe (Table 4-1). With the Kuril event specifically, there are still safe areas around the main village, and to the south and the east. But compared to the simulation with sea-level at MSL, the northern quadrant is not considered safe. Without Kuril the runups are lower, and all areas for potential evacuation except the western quadrant.

The results for Nukununu show that Kuril and Chile earthquake sources dominate the maximum runups from distant sources. Again, safe evacuation heights for these sources can be found in each geographic quadrant of the Island for the simulation with sea-level at MSL. Regional sources result in typically lower runups, except around the main village, where the propogation direction of the regional sources from southern latitudes results in relatively higher runup at this southward-facing location.

In comparison to Atafu, for the simulation with the sea-level at MHWS, the relatively low terrain of Nukununu enhances reef passages between the open ocean and the lagoon. The result is that many geographical regions of Nukununu are typically not safe and the main village itself is potentially liable to be completely inundated from a Kuril or regionally sourced earthquake (Table 4-2). For the distant sources not including Kuril (but including the recent Tohoku event), the main village remains largely dry.

Like Nukununu, Fakaofo is relatively low lying with many areas open to the ocean at the highest tides. For all simulations the southern and northwestern quadrants are typically not safe, as is the eastern quadrant for simulations at MHWS (Table 4-3). But importantly, for all simulations (including Kuril), the main village and Fale on Fakaofo are expected to retain safe dry areas.

The Tohoku tsunami is a recent historical event of significant relevance. For the simulation with the sea-level at MSL runups are <1 m, nonetheless the lowest lying area on the northwest of Fakaofo would not be safe. In comparison to the simulation with the sea-level at MHWS, the runup for the main village on Atafu increases to around 1.6 metres but dry land remains around the village. All the simulations suggest that there would have been some observable runup resulting from the Tohoku tsunami, but on a much smaller scale than predicted for a Chile or Peru worst-case event, and significantly smaller compared to the Kuril event.

Figure 4-1: Geographical regions (red lines) and main village (white circle) for Atafu. The labels correspond to those in the Table 4-1.

Atafu (sea-level at MSL)	Main village	N	S	E	W
Source including Kuril	2.5 (K)	2.6 (K)	1.8 (K)	2.3 (K)	1.5 (K)
Distant Source excluding Kuril	2.0 (C)	1.1 (C)	1.5 (C)	2.3 (C)	1.3 (C)
Regional Sources	1.5	0.7	2.0	1.3	0.8
Atafu (sea-level at MWHS)					
Source including Kuril	2.5 (K)	NOT SAFE	1.8 (K)	2.3 (K)	NOT SAFE
Distant Source excluding Kuril	1.6 (T)	1.2 (P)	1.5 (P)	1.2 (P)	NOT SAFE
Regional Sources	1.6	1.0	1.1	1.2	NOT SAFE

Table 4-1: Recommended evacuation heights above local sea level (metres) for Atafu for combined distant sources. Labels refer to the distant sources of Chile (C), Kuril (K), Peru (P), and Tohoku (T), as the source for the maximum runup. The geographical regions are those shown in Figure 4-1.

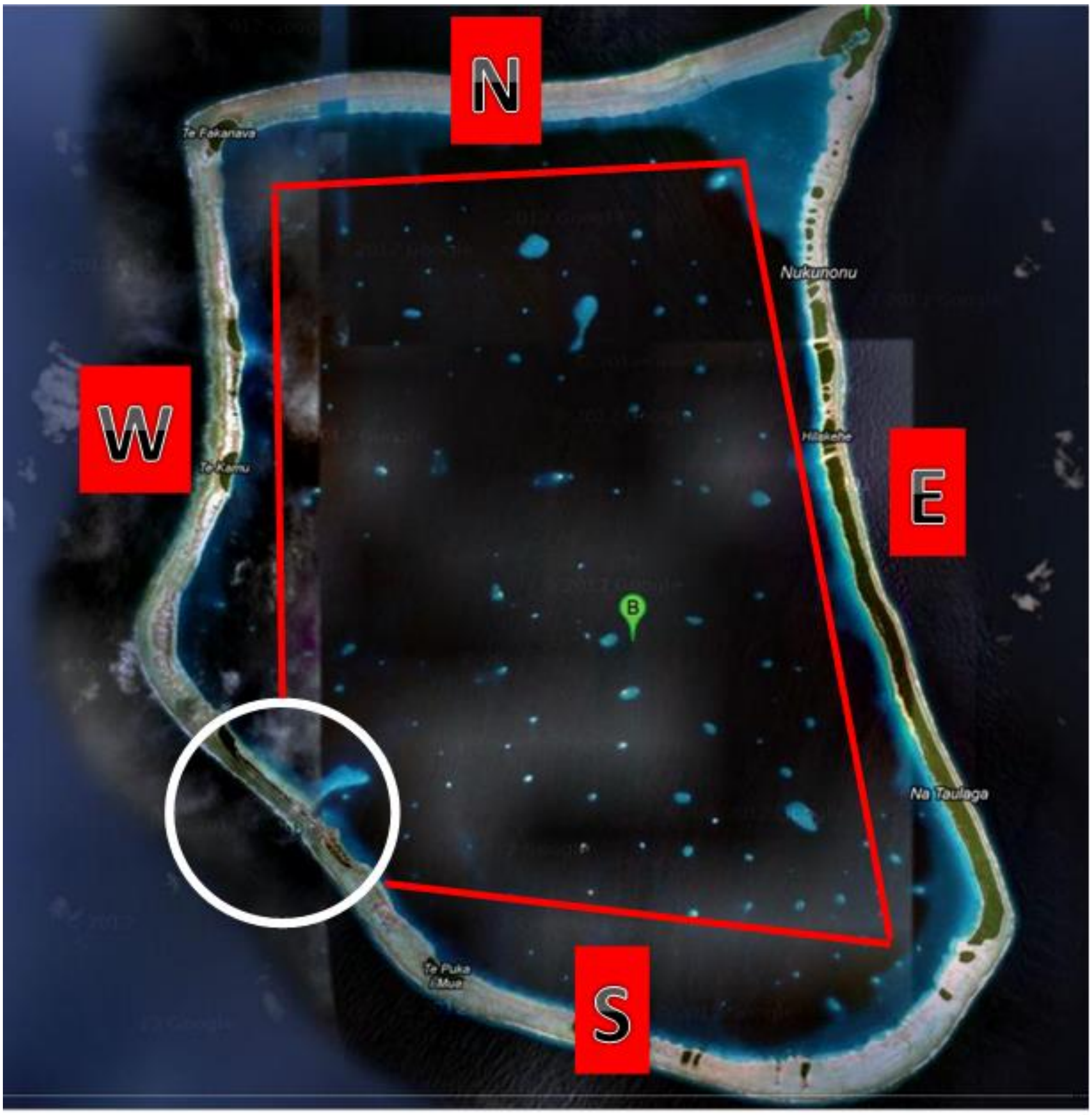

Figure 4-2: Geographical regions (red lines) and main village (white circle) for Nukunonu. The labels correspond to those in Table 4-2.

Nukununu (sea-level at MSL)	Main village	N	S	E	W
Distant Source including Kuril	1.8 (K)	2.0 (K)	1.5 (C)	2.8 (C)	2.0 (K)
Distant Source excluding Kuril	1.8 (C)	1.2 (C)	1.5 (C)	2.8 (C)	1.0 (C)
Regional Sources	2.0	0.7	1.3	1.5	1.5
Nukununu (sea-level at MWHS)					
Distant Source including Kuril	NOT SAFE	1.8 (K)	NOT SAFE	1.4 (C, K)	NOT SAFE
Distant Source excluding Kuril	1.4 (C, P)	1.1 (P)	NOT SAFE	1.4 (C)	1.0 (C)
Regional Sources	NOT SAFE	1.1	NOT SAFE	1.1	1.5

Table 4-2: Recommended evacuation heights above local sea level (metres) for Nukonunu for combined distant sources. Labels refer to the distant sources of Chile (C), Kuril (K), Peru (P), and Tohoku (T), as the source for the maximum runup. The geographical regions are those shown in Figure 4-2.

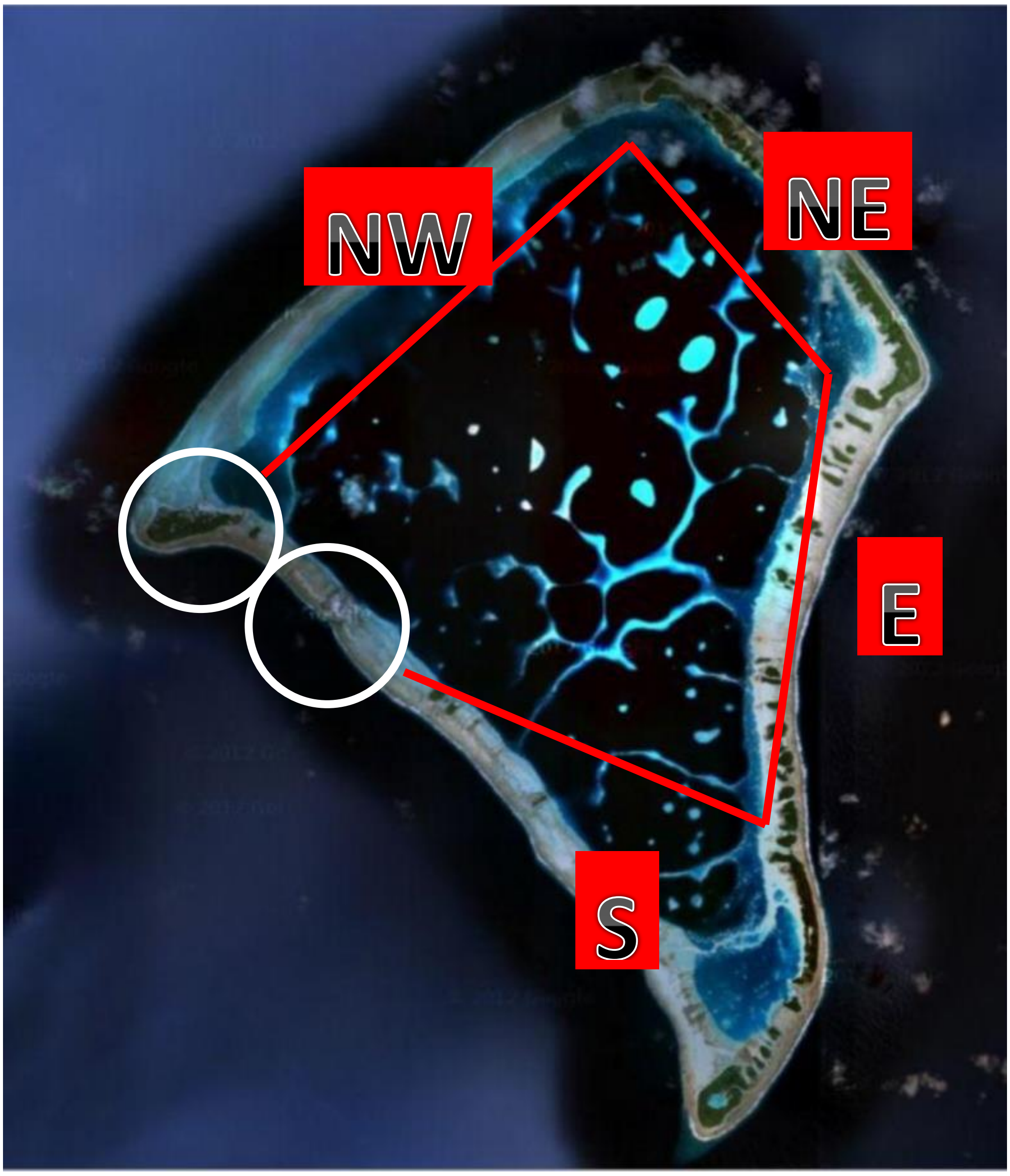

Figure 4-3: Geographical regions (red lines) and main village (northernmost white circle) and Fale (southern circle) for Fakaofo. The labels correspond to those in Table 4-3.

Fakaofo (sea-level at MSL)	Main village	Fale	NE	S	E	NW
Distant Source including Kuril	2.9 (K)	1.7 (P)	2.3 (C)	NOT SAFE	1.6 (C)	NOT SAFE
Distant Source excluding Kuril	2.2 (C)	1.7 (P)	2.3 (C)	NOT SAFE	1.6 (C)	NOT SAFE
Regional Sources	1.5	1.3	0.8	1.8	1.1	NOT SAFE
Fakaofo (sea-level at MHWS)						
Distant Source including Kuril	2.4 (P)	2.0 (P)	1.7 (P)	NOT SAFE	NOT SAFE	NOT SAFE
Distant Source excluding Kuril	2.4 (P)	2.0 (P)	1.7 (P)	NOT SAFE	NOT SAFE	NOT SAFE
Regional Sources	1.5	1.6	1.0	0.9	NOT SAFE	NOT SAFE

Table 4-3: Recommended evacuation heights above local sea level (metres) for Fakaofo for combined distant sources. Labels refer to the distant sources of Chile (C), Kuril (K), Peru (P), and Tohoku (T), as the source for the maximum runup. The geographical regions are those shown in Figure 4-3.

5 Conclusions

- This study shows that dry areas remain around the villages in nearly all our tsunami simulations of the Tokelau Islands.
- A great earthquake from the Kuril Trench poses the greatest inundation threat to the Tokelau Islands but other sources can impact particular regions of the atolls.
- A tsunami wave event may last a few hours and include several wave trains.
- Tsunami wave direction has an impact on inundation risk, particularly from regional sources to the south, and northern and eastern distant sources.
- The lagoon and deep passages through the fringing-reef matrix can also propagate significant tsunami wave energy, particularly if tides are high.

6 Acknowledgements

NIWA kindly acknowledges the provision of data and support provided by the Geospatial Intelligence Organisation of the New Zealand Defence Force, and the New Zealand Hydrographic Authority of Land Information New Zealand.

7 References

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Popinet, S. (2003). Gerris: a tree-based adaptive solver for the incompressible Euler equations in complex geometries. Journal of Computational Physics. 190: 572–600.

8 Websites of interest

Natural Hazards Data, Images and Education, National Geophysical Centre, National Oceanic and Atmospheric Administration (NOAA)

http://tsunami.noaa.gov/

http://www.ngdc.noaa.gov/hazard/

http://www.ngdc.noaa.gov/hazard/tsu_travel_time.shtml

UNESCO information about tsunami

http://www.ioc-tsunami.org/

http://itic.ioc-unesco.org/index.php

http://itic.ioc-unesco.org/index.php?option=com_content&view=article&id=1328&Itemid=1142&lang=en

http://itic.ioc-unesco.org/index.php?option=com_content&view=category&layout=blog&id=2000&Itemid=2000&lang=en

Information about historical earthquakes

http://earthquake.usgs.gov/earthquakes

Tsunami warning and alert for the Pacific.

http://ptwc.weather.gov/?region=1 ;

Appendix A Model Topography

Figures A-1 to A-3 show the model-generated topography of the islands at a regular spatial resolution of 15 m. In the time dependent tsunami runs, the adaptive grid in *Gerris* will evolve and select the appropriate grid dimensions consistent with the tsunami wave as it approaches and subsequently passes the islands. The solid black contours on each locate the initial sea level (MSL or MHWS). These particular model representations have been generated by forcing the model to use a regular spatial resolution of 15 m. These contours overlaid on satellite images of the islands show the average landward topographic extent; the challenge has been to generate data points on the land that the model can adequately interpolate between on the seaward and lagoon sides of each island. The vertical land heights span a relatively limited range of 0.25 m up to around 5 m. In contrast the surrounding ocean ranges from around zero at the reef edge to thousands of metres water depth within a short distance from the nuku shoreline, making topographic interpolation problematic if data density is low. The lagoons likely have inferred depth ranges spanning many tens of metres (no verified measured depths were available).

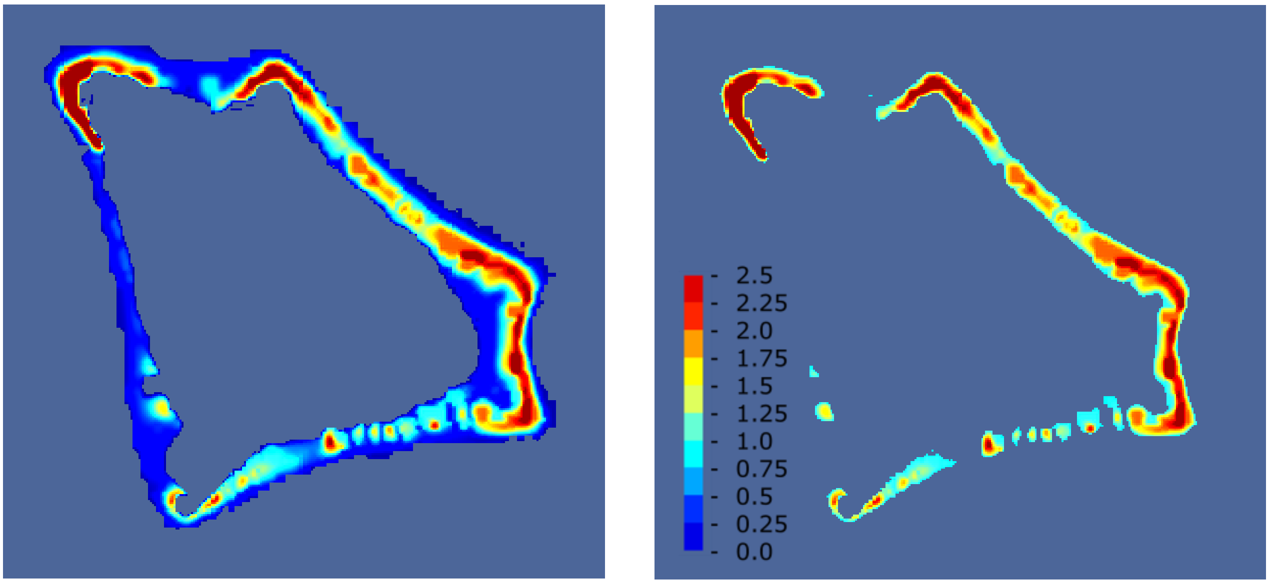


Figure A-1: Land topography in metres above mean sea level (MSL) (left) and mean high water spring (MHWS) (right) for Atafu.

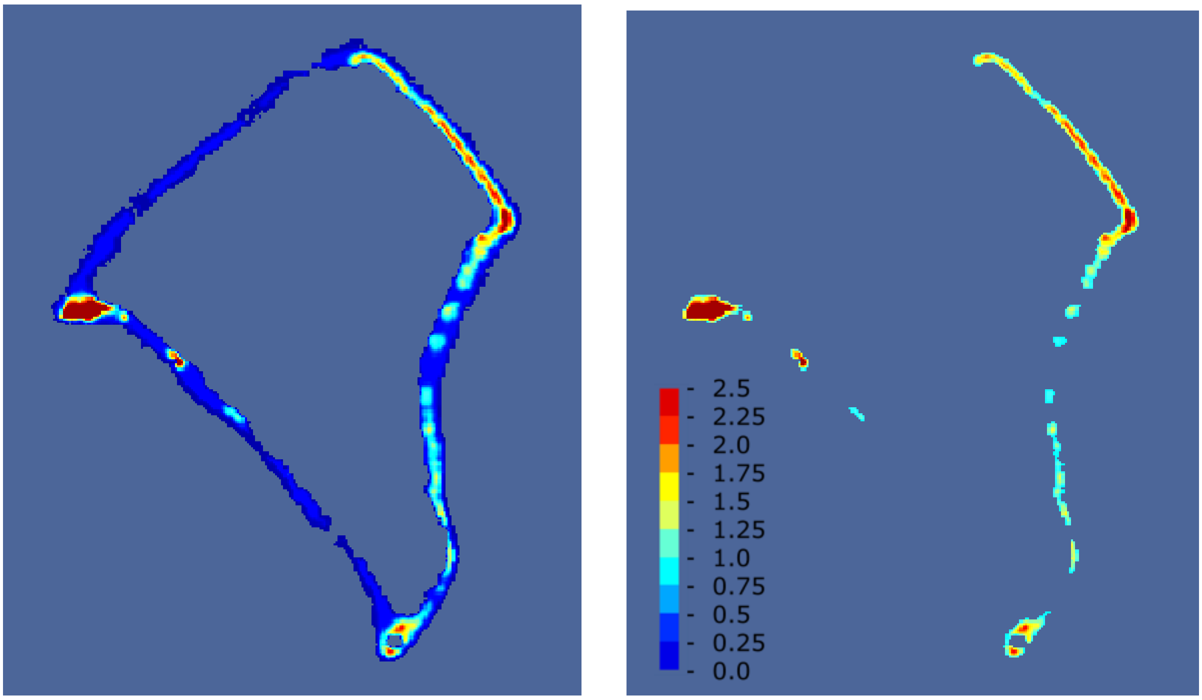


Figure A-2: Land topography in metres above mean sea level (MSL) (left) and mean high water spring (MHWS) (right) for Fakaofo.

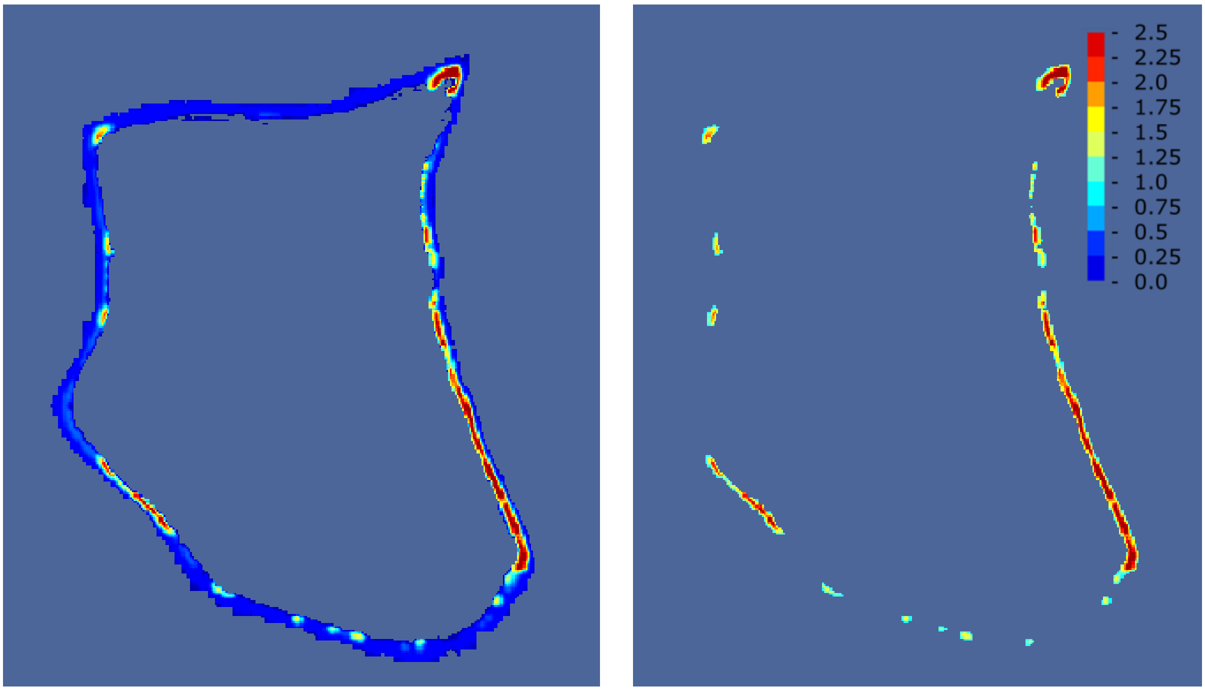


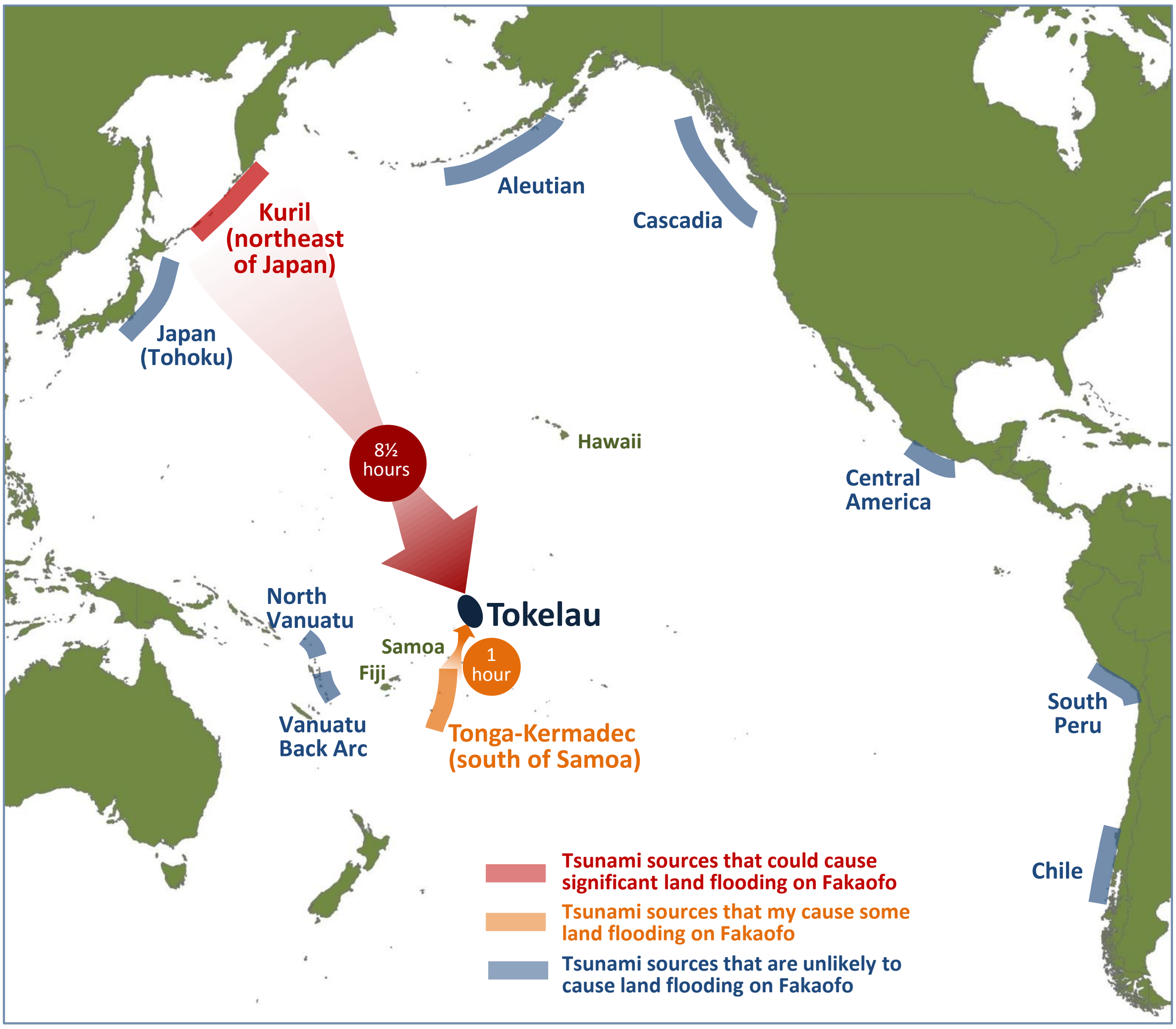
Figure A-3: Land topography in metres above mean sea level (MSL) (left) and mean high water spring (MHWS) (right) for Nukununu.

NIWA
Taihoro Nukurangi

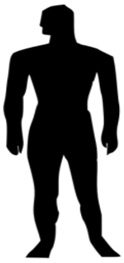
Tsunami Hazard: Fakaofo

Could the villages on Fakaofo experience damage from a tsunami?

- There is a small risk of a tsunami causing flooding in Tokelau, generated by an earthquake greater than 8.1 from either the **Kuril Trench (northeast of Japan)**, or the **Tonga-Kermadec Trench (south of Samoa)**.
- A tsunami from the **Kuril Trench** will take **8 ½ hours to reach Tokelau**, could cause **waist-deep flooding** and **last for 5 hours** after the predicted arrival time.
- A tsunami from the **Tonga-Kermadec Trench** will take **1 hour to reach Tokelau**, could cause **knee deep flooding**, and **last for 3 hours** after the predicted arrival time.



How deep could tsunami flooding be in the villages?



◄ **A tsunami from the Kuril Trench (northeast of Japan) could cause fast flowing water in parts of the villages up to waist height.**

◄ **A tsunami from the Tonga-Kermadec Trench (south of Samoa) could cause fast flowing water in parts of the villages up to knee height.**

If there is a warning of a strong earthquake (> Mw 8.1) or tsunami from the Kuril Trench or Tonga-Kermadec Trench:

- **Evacuate everyone to the identified safe buildings.**
- **Stay in the safe buildings until the all clear is given or:**
  - **Kuril Trench: for 5 hours after predicted arrival time.**
  - **Tonga-Kermadec Trench: for 3 hours after predicted arrival time.**

If there is a warning of any tsunami generated in the Pacific:

- **Get on to land and away from the shoreline, or stay out at sea.**
- **Stay away from seawalls, beaches, reef flats and boat channels, and the lagoon.**
- **Be aware; tsunami flooding might last for many hours with multiple water surges and retreats.**

Be aware:

- **The lagoon shoreline will be just as dangerous as the ocean shoreline.**
- **The lagoon could experience unusual waves, varying in size and direction.**
- **The tsunami might cause very strong currents over reef flats, in boat channels, and in channels between motu.**

This information has been prepared by NIWA for the Villages Emergency Committee of Tokelau, and New Zealand Ministry of Civil Defence and Emergency Management. It is based on modelling of 29 earthquakes from 13 potential tsunami sources in the Pacific.

Further information is available in: Orpin, A.; Rickard, G.; Gerring, P.; Bind, J. (2013). Tsunami hazard potential for the atolls of Tokelau. Unpublished NIWA Client report WLG2013-29.

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