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Agenda Item 4.3

REPORT OF

WG 2 Tsunami Detection, Warning and Dissemination

This document has been prepared by the Working Group, chaired by Bill Fry, New Zealand, on behalf of Working Group 2 and covering outcomes of TT chaired by Charles McCreery (USA), Adrienne Moseley (Australia), Tim Melbourne (USA), Vasily Titov (USA), Geoff Kilgour (New Zealand and and Mattias Sifon (Chile).

Intersessional activities of WG2 are comprised of the advances of four working groups: Task Team Tsunami Service Providers (TT TSP), Task Team Integrated Sensor Network (TTISN), Task Team Forecasting from Ocean Observations (TT FOO) and Task Team Tsunami Generated by Volcanoes (TTTGV).

This report summarises the outcomes and recommendations arising from the TT and additional matters considered by WG2.

Recommendations arising from each TT are compiled in a summary table at the end of this report.

Table of Contents

WG2, Tsunami Detection, Warning and Dissemination

1 Task Team Integrated Sensor Networks, TTISN (Co-Chairs Adrienne Moseley and Tim Melbourne)

1.1 Background

Recognizing 1) the proliferation of DART tsunamimeters, 2) the significant potential of SMART Cables to support tsunami monitoring, and 3) advances in the analysis of real-time geodetic data for earthquake monitoring, the 28th session of the ICG-PTWS established the Task Team for Integrated PTWS Sensor Networks for Tsunami Detection and Characterisation. Further recognizing advances in seafloor fibre-optic observations and the promising potential of GNSS technology to directly sample the ocean height, the 30th session of the ICG-PTWS expanded the scope of work to be undertaken by TTISN. The TTISN has completed the tasks contained within its terms of reference. However, we note that further work on this area is needed. Recognizing the alignment of TTISN with TTFOO, we recommend the closure of TTISN and expansion of the terms of reference of TTFOO to incorporate continued focus on integrated sensor networks.

TTISN Terms of Reference:

This expert Task Team will establish and document a methodology to test the sensitivity of the PTWS sensing networks, integrating new and emerging techniques and technologies by:

1. Developing a methodology for gap and sensitivity analysis that combines multiple sensing technologies for tsunami detection and characterisation.
2. Integrating emerging techniques and sensor technologies (e.g. better use of tide gauges; GNSS technology and processing; sensors on SMART Cables) with the existing sensing network to meet tsunami warning service requirements in support of UN ODTP goals.
3. Where possible, include cost-benefit analysis of the potential technologies being considered.
4. Undertake to establish direct collaboration between ICG/PTWS Member States and other expert groups (such as International Association of Geodesy (IAG), International GNSS Service (IGS)) for the purpose of collaborating on data sharing and research efforts that are adaptable to the tsunami warning systems and operations of the IOC-Tsunami Programme, and aligned to the 10-year Research, Development and Implementation Plan of the UN ODTP.
5. Assess the utility and limitations of emergent technologies and techniques, e. g. GNSS, ADDOSS and SMART Cable, that have potential to deliver ocean height in real-time.
6. Align efforts with the *Task Team on Tsunami Forecasting from Ocean Observations* to ensure that Task Team recommendations account for existing and likely future observation systems.
7. Align efforts with the *Task Team for TSPs* and NTWC operational needs, to ensure that the Task Team recommendations consider the current and potential operational feasibility of emergent technologies augmentation for TSPs and NTWCs.

1.2 **Developing a methodology for gap and sensitivity analysis**

A framework to quantify network sensitivity for deep ocean measurements (e.g. DARTs) and terrestrial (fixed location) GNSS observation sites was presented in the report of Working Group 2 to the ICG-PTWS XXX session (Appendix 4). Please see the WG2 report from ICGPTWS XXX for a full description of the framework. We build upon that framework and present summary results in Appendix 1. We note in our analysis, whether or not data is currently available from a given technology, we consider it to be either part of the class of observations that can readily be incorporated into existing forecasting algorithms, EXISTING (e.g. seismic, ocean-bottom pressure) or part of the class of observations that has yet to be incorporated into operational forecasting algorithms, NOVEL (e.g. GNSS TEC, fibre-optic interferometry) (figure x).

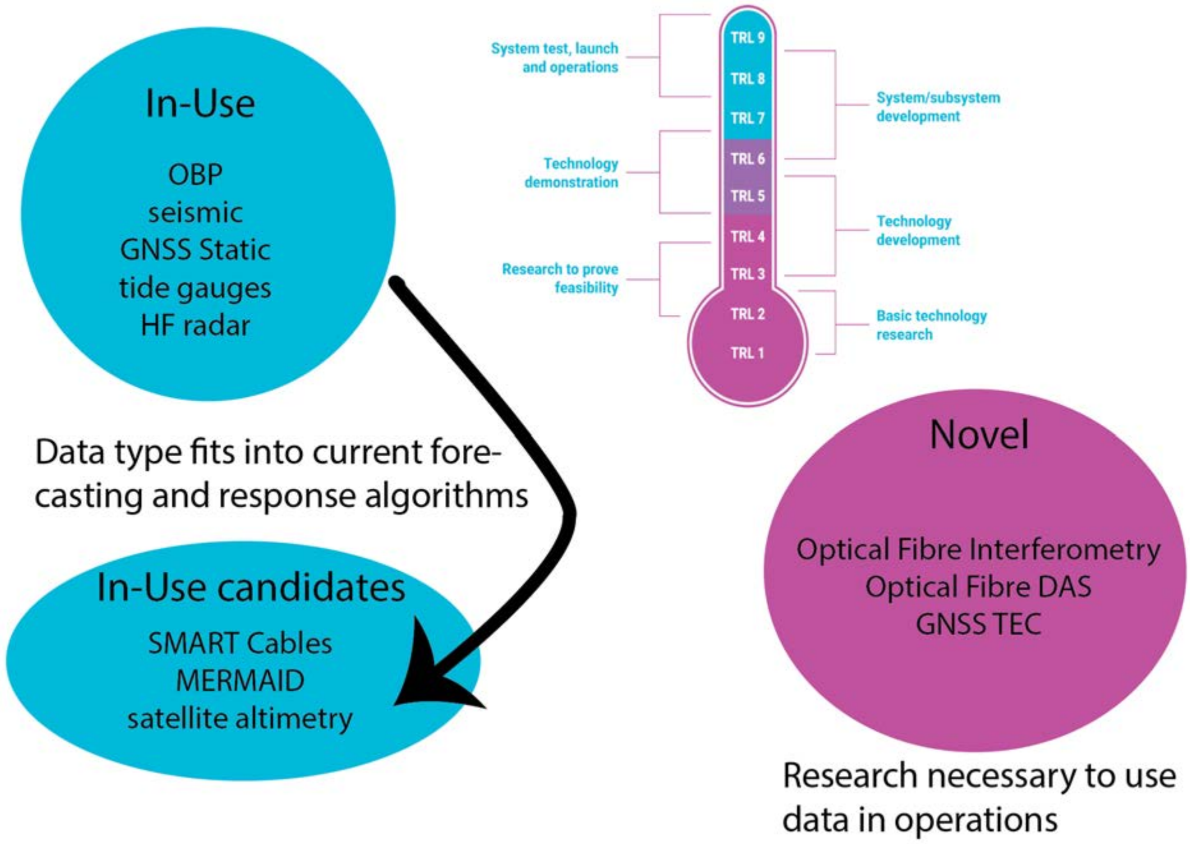


Figure 1. Data falling in Technology Readiness Levels 7-9 is classified as “in-use or in-use candidates”. Lower TRL data are described as “Novel”. Both classes are considered in our gap analysis.

In our gap analysis, we also consider the possibility of natural warning for events generated proximal to coastlines. To do this, we quantify the relative amount of sources that are within 100km of populated coasts. We chose 100km, as it represents the approximate distance from an earthquake in which ground motions are MMI 6, or will likely be felt as “strong”.

1.3 **Integrating Emerging Techniques and Sensor Technologies**

Different types of data have different sensitivities and as such, provide disparate but complementary information for operational forecasting through the entire tsunami threat lifecycle (figure x).

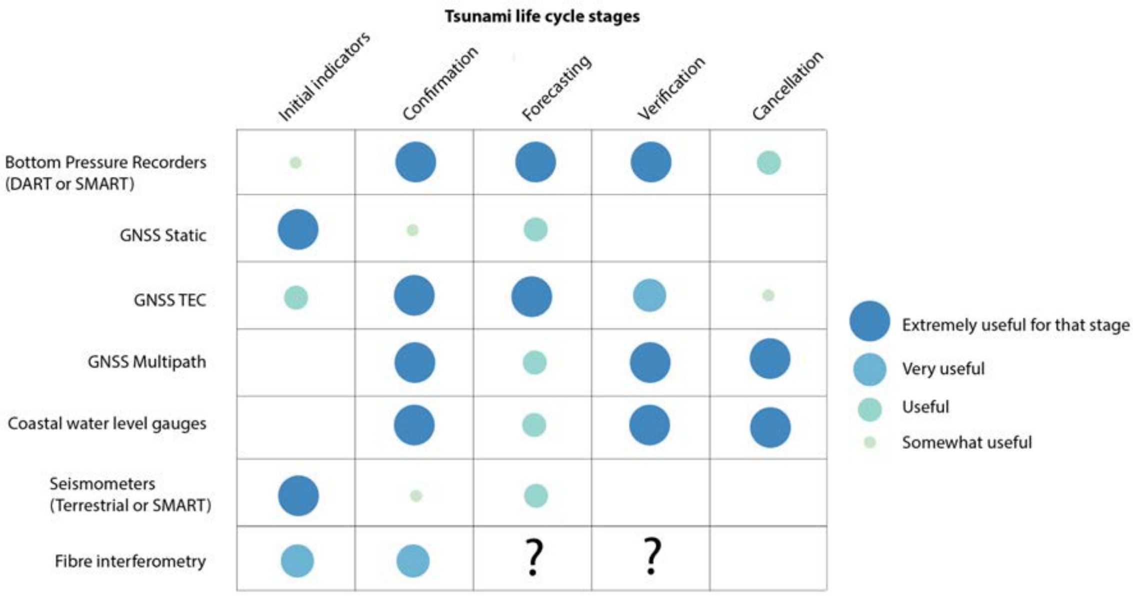


Figure 2. Table of complementary sensitivities of different data types within the operational "tsunami threat life cycle" spanning from initial indication that a tsunami might have been generated through understanding enough about the threat to provide an estimation of when the threat can be cancelled.

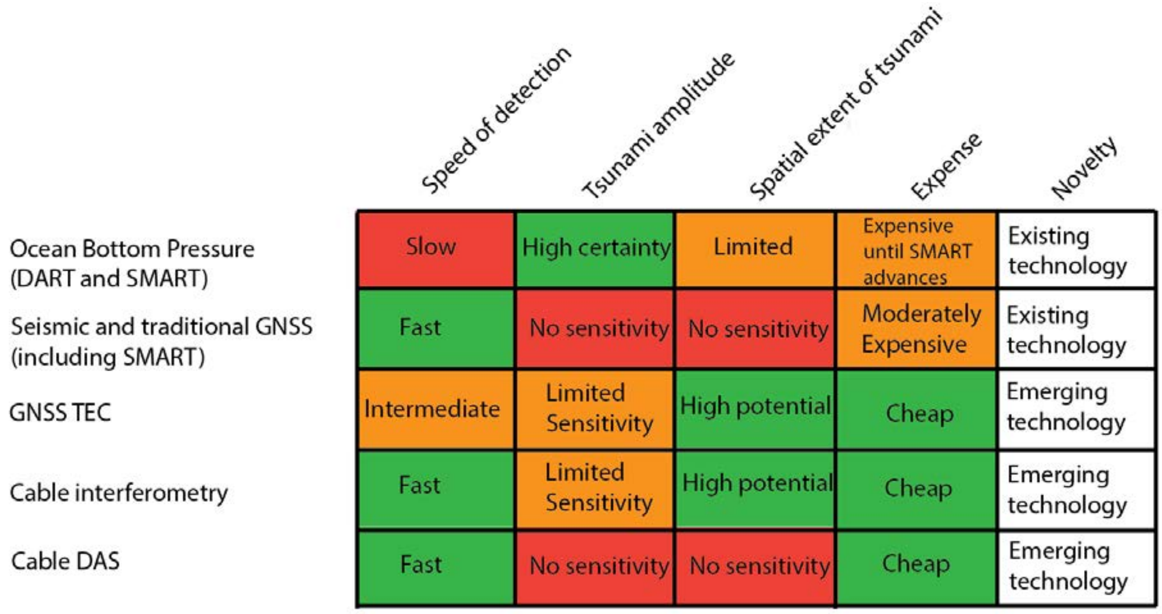
Our sensitivity analysis is based on the quantification of minimum tsunami and earthquake seismic wave travel times from the centre of discretised subduction zone earthquake sources to the available integrated sensor network including publicly accessible seismic, DART and GNSS stations. We further consider improvements from future SMART Cable observations between Vanuatu and New Caledonia (TamTam project). Lastly, we draw upon the promising advances in GNSS TEC (Total Electron Count of the ionosphere), which has been shown to be sensitive to tsunami passing below low-earth orbiting satellites, making it an enticing possibility to map the spatial extent of tsunami. We have engaged with the GNSS TEC community directly, through the IUGG and through the GeTEWS Oceania initiative to develop spatial metrics for our logic approach to gap analysis involving this emergent method.

In collaboration with the U.K. National Physical Laboratory (UKNPL), member state New Zealand has begun direct testing of monitoring with high-resolution laser interferometry on the Southern Cross NEXT ocean bottom cable stretching between Australia, New Zealand and Fiji (Figure X). The approach has thusfar provided useful observations of earthquakes (e.g. M7.2 Vanuatu earthquake of 17/12/24) but has not yet had the opportunity to be tested on a tsunami capable of generating marine threat (>30cm at the coast). Theoretical calculations suggest sensitivity should be capable of detecting >3cm deep ocean waves. Experimental monitoring of this cable will continue until at least December, 2025. Significantly, the technology can be retrofit in-situ to active or retired seafloor fibre-optic cables.

Figure 3. Approximate location of the Southern Cross NEXT cable. Thick red lines show extent of monitoring test.

1.4 Cost-benefit analysis

While the direct costing of densifying or deploying sensors is largely dependent on information outside the scope of TTISN, we have developed an approach to defining the benefit of sensor deployment (Appendix 2). We have also made qualitative estimates of cost (Figure X) that can be used by member states to make informed decisions on investments in monitoring when considered in conjunction with the risk-based products in Appendix 2. In this approach, we compare subduction-zone tsunami travel times to observational sensors (existing DART, future SMART) and approximate observational radii of GNSS stations to consider future advances of GNSS TEC. We then calculate the travel time of the tsunami to the coast and consider a difference of 20 minutes (observational travel time minus coastal impact time) to be sufficient to provide opportunity for instrumental forecasting. Note, this approach, necessitated by the advent of GNSS TEC and other near-coast technologies, encourages reconsideration of the forecasting paradigm. Rather than defining time to forecasting metrics, network investment can now consider pre-impact warning times as targets for instrumental forecasts.



	Speed of detection	Tsunami amplitude	Spatial extent of tsunami	Expense	Novelty
Ocean Bottom Pressure (DART and SMART)	Slow	High certainty	Limited	Expensive until SMART advances	Existing technology
Seismic and traditional GNSS (including SMART)	Fast	No sensitivity	No sensitivity	Moderately Expensive	Existing technology
GNSS TEC	Intermediate	Limited Sensitivity	High potential	Cheap	Emerging technology
Cable interferometry	Fast	Limited Sensitivity	High potential	Cheap	Emerging technology
Cable DAS	Fast	No sensitivity	No sensitivity	Cheap	Emerging technology

Figure 4. Qualitative analyses of the benefits and limitations of available data streams. Multidata approaches require at least one green box in each of the first 3 columns. We note that traditional GNSS and Cable DAS are largely limited to onshore monitoring and is not currently suited to offshore (tsunami) detection.

1.5 **Aligning with external bodies**

During the intersessional, we have worked closely with the IUGG (through the GeTEWS Oceania project) to align infrastructural GNSS improvements in the southwest Pacific with PTWS monitoring goals. We have also worked closely with the JTF-SMART Cable (through the TamTam project) to ensure that operational forecasting algorithms are prepared to ingest new data when they are available. By invitation, we presented our strategy to the Eighteenth Meeting of the International Committee on Global Navigation Satellite Systems (ICG-18) in October 2024.

1.6 **Utility and limitations of emergent technologies**

We have assessed the utility of emergent technology using the approaches decribed in 2.2, 2.3 and 2.4. Three emergent technologies present significant possibilities for helping to achieve ODTP decade forecasting goals (Figure 5).

Tsunami Source	**Initial indicators** (time after origin)	**Source partially constrained** (time after origin)	**Source fully constrained** (time after origin)
Earthquake	3min	10min	45 mins
Non-earthquake (known)	10mins	45mins	1hr
Non-earthquake (unknown)	45 mins	1hr	90mins

Figure 5. Target forecasting goals from the 10-year Research, Development and Implementation Plan of the UN ODTP.

These three emergent technologies include SMART Cable, GNSS TEC and high-resolution laser interferometry on fibre-optic cables. While we recognise these are not the only techniques that may augment the existing integrated sensor network, they currently appear either closest to realisation or most-likely to fill a critical gap in the ISN. SMART Cables remain a promising path to provide cost-effective tsunami amplitude measurements similar to those provided by DART technology. SMART data can be directly ingested into our existing forecasting strategies.

GNSS TEC and cable laser interferometry are more novel techniques that will require research and development of new algorithms for ingestion into operational forecasting. Both of these techniques are likely capable of mapping migrating tsunami either in the deep ocean (cable laser interferometry) or within about 1500km of the coast (GNSS TEC). However, questions remain about the ability of either technique to deliver absolute amplitude of detected tsunami.

1.7 SMART Cables

WG2 continues to view proliferation of SMART Cables as a clear path to improve tsunami early warning capabilities throughout the Pacific region. By formalizing relationships between the ICG/PTWS, National Tsunami Warning Centers, and the Joint Task Force SMART Cables, we anticipate more coordinated and effective deployment of this dual-purpose infrastructure. Over the next three to five years, this initiative has the potential to lead to the gradual adoption of SMART Cable technology as a standard component in new submarine telecommunications cable projects, particularly in high-risk seismic zones. The resulting expanded network of real-time ocean bottom pressure and seismic instruments has the potential to significantly enhance tsunami detection speed and accuracy by providing continuous, high-resolution data from previously unmonitored deep-ocean areas. Combined with advanced forecasting algorithms (TTFOO), this improved observational capacity has the potential to reduce warning times, decrease false alerts, and provide more precise inundation forecasts, directly contributing to the ODTP goal of 100% of at-risk communities having access to tsunami early warnings by 2030.

1.8 **Aligning with TTFOO**

We recognise the natural confluence of TTISN and TTFOO. The two groups are currently working closely together through key shared membership. Given the completion of the original terms of reference for TTISN, we request that the ICG incorporate TTISN into TTFOO with updated terms of reference to guide the expanded scope of work.

1.9 **Align efforts with TTTSP**

Recognition of TSP operational limitations has led to the classification of the In-Use and NOVEL classifications of data described in 1.2. It is recommeded that all TSP have a path to incorporate newly available in-use data, including that from SMART Cables, when available. Further, it is recommended that terms of reference for TTFOO be expanded to include consideration of TSP needs and capabilities to ensure that enduser needs are kept as a driving force for the operationalisation of ISN and FOO.

2 Task Team Forecasting from Ocean Observations, TTFOO (Co-Chairs Bill Fry and Vasily Titov)

2.1 Background

Recent events including the devastating tsunami resulting from the 2022 Hunga Tonga Hunga Ha'apai volcanic eruption and the 2018 Sulawesi strike-slip earthquake highlighted the inadequacies of the current operational forecasting paradigm that uses earthquake proxies for tsunami sources. Recognizing this and explicitly considering 1) the need to forecast tsunami from non-earthquake sources and 2) the inability of current operational systems to achieve ODTP forecasting goals (Figure 5), the 30th session of the ICG-PTWS established the Task Team for Forecasting from Ocean Observations (TTFOO).

TTFOO Terms of Reference:

This expert Task Team will establish and document a methodology to test the sensitivity of the PTWS sensing networks, integrating new and emerging techniques and technologies by:

1. Compare and document existing strategies for source-independent tsunami early warning and quantify and document their operational usefulness. Efforts will include consideration of both existing and emerging ocean observations technologies and techniques.
2. Connect with appropriate entities in the WMO and IOC Oceanographic communities to allow best-practice direct observation driven forecasting techniques to be assessed for their usefulness in Tsunami Forecasting from Ocean Observations.
3. Align efforts with the Task Team Integrated PTWS Sensor Networks to ensure that existing and likely future monitoring systems support TT recommendations.

2.2 Forecasting requirements

Tsunami forecast algorithms use tsunami measurement data from available (and emerging) sensor technologies, and transform those into forecast products that can be used for tsunami warning, evacuation and real-time tsunami hazard assessment. For the purpose of tsunami warning operations, tsunami forecast algorithms should project or extrapolate the measurement data in time and/or in space to provide assessment of tsunami hazard for locations of interest and time intervals beyond the coverage of the sensor data. The ODTP clearly provides targets for warning times (Figure 5) and we assess existing and emerging warning strategies against these goals.

Operationally important aspects of the products that are output by the forecast are: (1) the *accuracy* of the forecast and (2) the *speed* of obtaining the forecast products. These qualities depend on the combination of the algorithm and the data that the algorithm is using. It is, therefore, useful to classify the algorithms in relation to the data that are used to produce the forecast. Two large classes of the data that are used for tsunami warnings are (1) direct tsunami observations, (2) indirect observations that can be associated with tsunamis by non-trivial transfer functions and algorithms. The direct observations, in general, will lead to better accuracy of the forecast, since it doesn't have additional errors and uncertainties built into the transfer function of indirect data. On the other hand, indirect data often available earlier in the forecast process and can reduce the speed of the forecast. The following is the list available and emerging forecast algorithms that the WG2 is monitoring for improving the final forecast products and achieving ODTP forecasting goals.

2.3 Available and Emerging Forecasting Algorithms

We largely consider two classes of forecasting algorithms, the first is based on indirect observations, or observations of the physical phenomena that lead to the secondary peril of tsunami generation (e.g. earthquake, volcanic or landslide observations). The second class is based on direct tsunami observations. We note that algorithm classes could also be distinguished based on the way tsunami amplitudes are calculated. However, we choose to first consider algorithms based on the observational data or metadata they require to better align with TTISN, fulfilling terms of reference #3 of TTFOO.

2.3.1 Indirect Observation Forecasting

In practice, operational tsunami response forecasts are almost always driven by initial inversion of seismic data to provide basic earthquake source parameters that are then either used to select pre-calculated models of tsunami hazard or are used to create a tsunami source model providing initial conditions to calculate impacts in near real-time.

This type of forecasting, driven by seismic data analysis, is used in most tsunami warning operations. It is in use by all existing tsunami service providers (TSP). It is the fastest data assessment of a potential tsunami. The main drawback for these algorithms is limited accuracy that is bound by limitations of data at this initial stage of earthquake assessments. Uncertainties introduced by using proxy seismic measurements, rather than direct measurements of the tsunami, largely inhibit inundation and impact modelling.

Existing forecast algorithms in this class of approaches includes the calculation of tsunami travel times and tsunami coastal amplitudes. At a minimum, these require some type of locational information (e.g. earthquake epicenter or centroid) and magnitude. Many of these algorithms also require conversion of earthquake metadata through pre-defined regression analysis (scaling laws) to estimate the fault size and possible static deformation model to generate initial conditions for tsunami modelling.

Over the past decade, advances on these types of forecasts have included refined earthquake source models (i.e. finite fault models) based on either dynamic (seismic waveforms) or static (GNSS offsets) ground motion observations. In some cases, the refinement of proxy earthquake sources can bring commensurate improvements in tsunami forecasts. If the geometry of the source and observational network is fortunate, algorithms for real-time GNSS data inversion have the potential to provides better finite fault models, especially for large events and faster earthquake source fault distribution than the seismic data. With GNSS-base finite fault approaches, the rest of the forecast stream is like the forecast based on the seismic data. However, in cases in which the earthquake is more than about 75km from the observational network, theoretical and practical experiments have shown that uncertainties in the finite fault are significant, and it is uncertain if GNSS-based forecasts can improve upon traditional or more advanced seismic analysis. The operational readiness of GNSS methods is only recently being tested through prototype systems in at least the United States, Japan and New Zealand.

Tsunami Source	**Initial indicators** (time after origin)	**Source partially constrained** (time after origin)	**Source fully constrained** (time after origin)
Earthquake	3min	10min	45 mins
Non-earthquake (known)	10mins	45mins	1hr
Non-earthquake (unknown)	45 mins	1hr	90mins

Figure 6. Indirect observation forecasting largely addresses the two ODTP targets highlighted in blue above. Note, many operational centers do not currently meet the time targets show above and, in many cases, densification of observational data are required. In some select cases (when the source is within ~75km of the coastline), it can be argued that indirect observation forecasts based on inversion of static offset data from GNSS can achieve “Source fully constrained”, shown in green.

2.3.2 Ensemble Forecasting

A subset of indirect forecasting is ensemble forecasting. Improvement in computer speeds (especially use of GPU) to model tsunami, even to inundation has reduced the time needed for models to almost immediate assessment. Very fast computations create possibilities for better accuracy through improved resolution. Ensemble forecasts based on multiple model runs can also help provide better estimates of forecast uncertainties, especially in the case that uncertainties in indirect observations are known, for example, earthquake parameters including magnitude, location or geometry.

2.3.3 Hybrid Indirect Observation Forecasting augmented with Direct Observation

There exists a class of forecasts that combine advances in indirect observation forecasting with direct ocean observations. This approach was taken in response to the Hunga Tonga Hunga Ha'apai volcanic eruption and tsunami. In this case, early information was used to establish a source location for the event and ocean observations (DART data) were used to appropriately scale forecasts. Of course it is now known that in this case, the approach was complicated by the migrating tsunami source caused by the coupling of the airborne wave and the ocean. In practice, many operational NTWC use ad hoc direct observational scaling of forecasts based on indirect observations. In this way, hybrid forecasts can begin to address non-earthquake sources. If seeded by indirect observations, some data assimilation approaches could be considered hybrid approaches. However, hybrid assimilation approaches are dominantly sensitive to, and in some cases do not require indirect observations and are better considered as direct observation techniques.

Tsunami Source	**Initial indicators** (time after origin)	**Source partially constrained** (time after origin)	**Source fully constrained** (time after origin)
Earthquake	3min	10min	45 mins
Non-earthquake (known)	10mins	45mins	1hr
Non-earthquake (unknown)	45 mins	1hr	90mins

Figure 7. Hybrid Indirect observation forecasting augmented with direct observations can improve forecasts after sufficient time has allowed the waves to propagate over observational sites (typically deep ocean DARTs). Because of the time needed for direct observations to be obtained, they are largely useful for tsunamis with travel times over about 45 minutes and typically rely on indirect observations to define the source location. ODTP targets for which hybrid algorithms are most well suited are highlighted in orange above.

2.3.4 Forecasting from Direct Observation, existing methods

Forecasting from direct ocean observations is currently in use in many operational centres. Both the United States and New Zealand have inversion methods that utilize DART observations to solve for tsunami source. This source can then be used to rapidly simulate tsunami wave propagation. In these instances, it is assumed that the tsunami was generated by an earthquake. However, because the goal of operational forecasts is to provide the most accurate and timely prediction of the incoming tsunami hazard, and not to provide the most accurate model of the tsunami source, forecasts based on the inversion of DART or other deep ocean bottom pressure (BPR) data are now the best operational way to forecast tsunamis if sufficient data sampling the tsunami wavefield is rapidly available.

2.3.5 Forecasting from Direct Observation, aspirational algorithms

Many different methods exist in the scientific literature to assimilate BPR data to assess the tsunami source for tsunami models. These forecast methods usually provide high accuracy of tsunami amplitude forecast, however the time of the forecast depend on the proximity of BPR to the source.

Since these are mostly very sparse observation systems (with the exception of Japan and NZ coasts), the observations rarely come faster than 30 minutes after an event.

For dense observation networks, like in Japan and NZ, new inversion algorithms are actively being developed to accommodate large numbers of observations, to improve the timing and accuracy of the forecast. Many of these new algorithms use AI-assisted data assimilation. They can provide quicker assessment of the source for dense or sparse BPR networks without the a priori information about the source. This is active area of research and significant effort will be required for operationalization of any A.I. based technology. It is also likely that novel data technology will be required to support the implementation of these advanced analytical techniques in operational centres. Candidate techniques include cable-based observations (both SMART and cable interferometry) and GNSS TEC. GNSS TEC is particularly promising, as it provides one of the few currently feasible paths to forecasting near-regional events with ~45-120 minute travel times. However, much of the emergent data technology does not provide the same type of measurement that BPR do and deliberate strategies must be developed to utilize the strength of novel observational technologies and mitigate their weaknesses. Multi-data strategies are very well suited to do this. It is likely we can only fully achieve ODTP target forecast goals by using multi-data strategies to harness complementary sensitivities of all available sensing technologies.

Tsunami Source	**Initial indicators** (time after origin)	**Source partially constrained** (time after origin)	**Source fully constrained** (time after origin)
Earthquake	3min	10min	45 mins
Non-earthquake (known)	10mins	45mins	1hr
Non-earthquake (unknown)	45 mins	1hr	90mins

Figure 8. Direct observation forecasting can improve forecasts after sufficient time has allowed the waves to propagate over observational sites (typically deep ocean DARTs) or with emergent technology, over seafloor fibre-optic cables or under travelling constellations of low-earth orbiting satellites that support GNSS TEC observations. Because forecasts are based on direct observations of the tsunami, they are source agnostic. ODTP targets for which direct ocean observation forecasts are most well suited are highlighted in red above.

3 Task Team Tsunami Generated by Volcanoes, TTTGV (Co-Chairs Mattias Sifon and Geoff Kilgour)

3.1 Background

Following the Hunga Tonga Hunga Ha'apai volcanic eruption and tsunami, immediate ad hoc procedures to warn of the tsunami hazard were undertaken. To better prepare for future volcanically generated tsunami, WG2 developed interim guidelines based on simple scaling of forecasts with ocean observations (either tide gauge data or deep ocean BPR). Recognising the interim procedure was poorly suited to most future volcano tsunami, ICG-PTWS XXX created a Task Team for Tsunami Generated by Volcanoes (TTTGV).

TTTGV Terms of Reference

1) To confirm the list of volcanoes identified by the TGV as posing a potential threat to the Pacific (referred in Annex 4 Technical Series 183), to identify additional potential threat volcanoes, and continually review the list.
2) Among the volcanoes with potential tsunami threat, to identify those with implemented tsunami hazard assessment, monitoring, warning, and preparedness systems.
3) To establish direct collaboration between ICG/PTWS member states and IAVCEI to facilitate the contribution of PTWS tsunami expertise to the monitoring and warning capability of existing volcano monitoring centres or NTWCs, as appropriate
4) To identify potential volcanic partners in countries and international bodies, and recommend collaboration opportunities with them to improve tsunami early warning and to support the downstream decision makers affected by the volcanically-generated tsunami
5) To develop guidelines on SOPs to monitor, detect, warn, and prepare for any volcano-induced tsunami waves.
6) To develop guidelines on SOPs to monitor, detect, warn, and prepare for any volcano process that could induce tsunami waves.

3.2 Ongoing work

We have begun work on Terms of reference items 1, 2 and 3.

1) Volcano tsunami threat inventory: For the southwest Pacific, member state New Zealand has created an initial list of 28 regional volcanoes that pose a hazard of tsunamis (Figure 9a). To develop operational procedures for response purposes, tsunami generated by maximum credible sources represented by a simple characteristic Gaussian function with diameter=10km and maximum height=15m (figure 9b) were modelled (Gusman and Wang, 2024). Resulting threat level maps were created and are currently available for expert use in response.

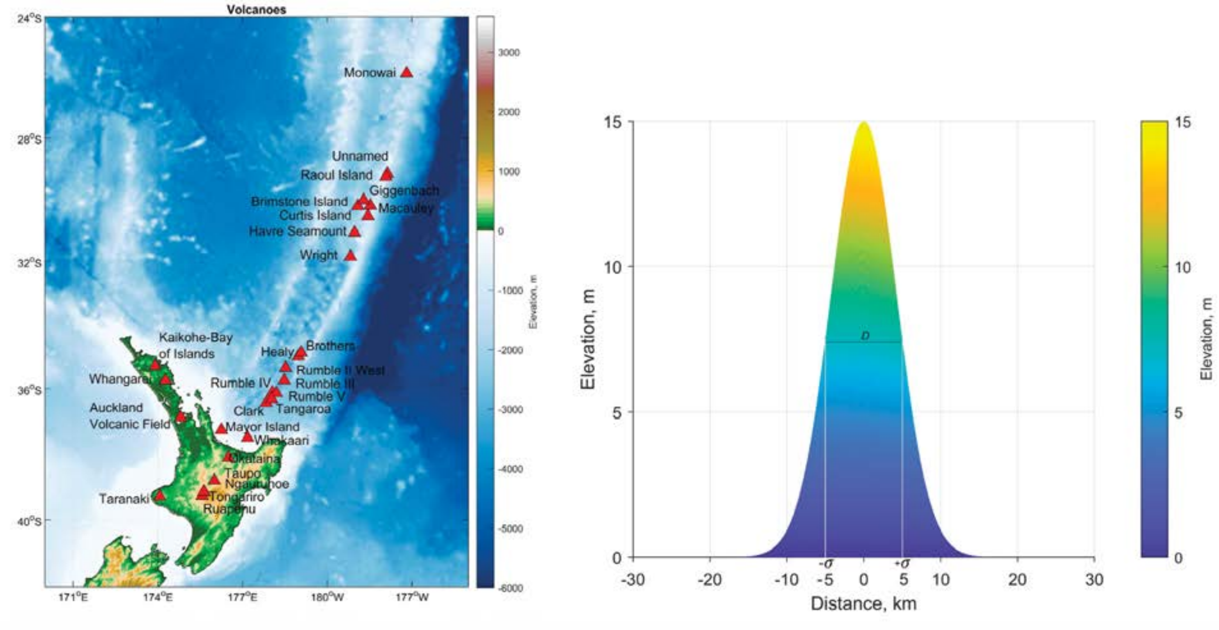


Figure 9. Left panel, map of 28 newly analysed active volcanoes capable of generating tsunamis. Right, simple Gaussian representation of maximum credible source used to model the events and create operational threat level maps for use by subject matter experts during response.

2) Cataloguing hazard and implemented warning protocol: In addition to the work presented above, Member State Australia has implemented procedures in the Joint Australian Tsunami Warning Centre to warn for volcano generated tsunamis. These procedures are largely based on calculating using Volcanic Ash Advisory Centre notifications and calculating tsunami travel times to exposed coastlines (Figure 10).

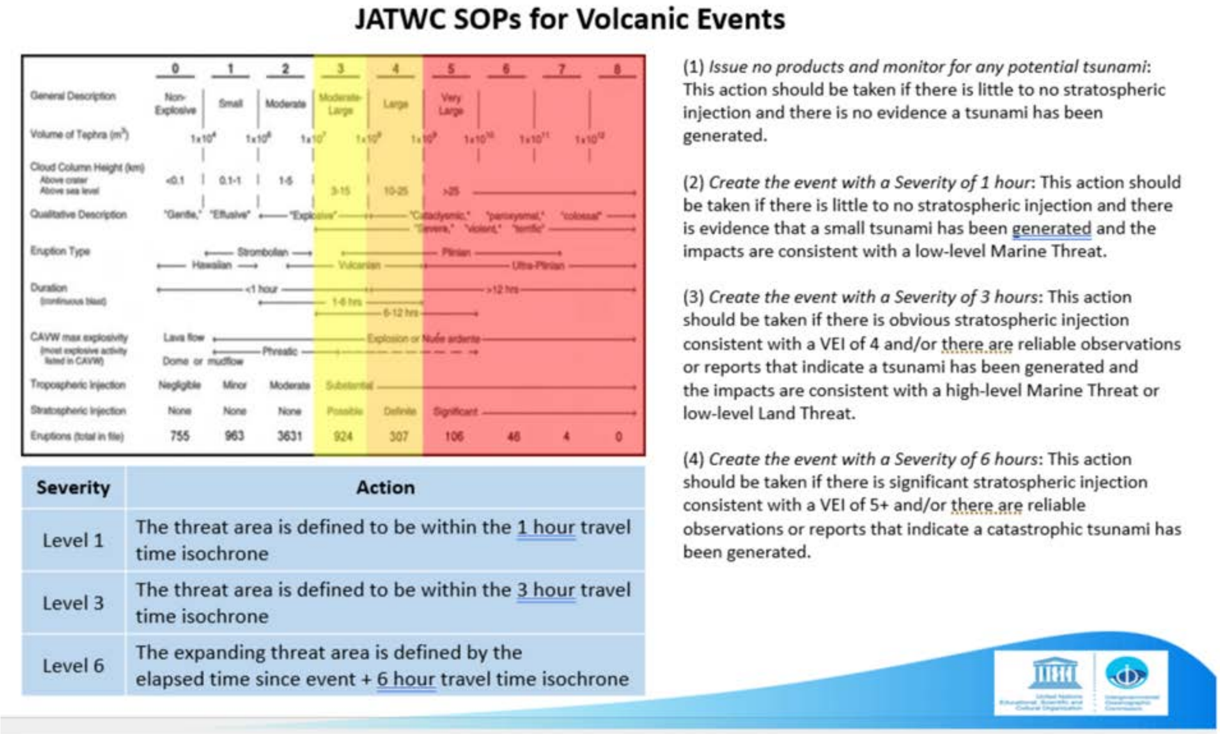


Figure 10. Volcanic tsunami SOP implemented by the Australian JATWC. The response framework draws upon volcanic eruption severity and tsunami travel times.

4 Task Team Tsunami Service Providers, TTTSP (Chair Charles McCreery)

The update from TTTSP will be presented in separate agenda items 4.6-4.8.

5 Update on NTWC Competency Framework

At the PTWS ICG XXX (Tonga), the National Tsunami Warning Centre (NTWC) Competency Framework was approved by Member States. The ICG further accepted the offer by the International Tsunami Information Centre (ITIC) to pilot the Framework by developing a Training Course. The ITIC is currently developing course modules in partnership with Member States with advanced tsunami warning centers to be available in 2025 - 2026. To date, the ITIC has engaged Australia's Bureau of Meteorology and Geoscience Australia, New Zealand's GNS Science and NEMA, and the USA Pacific Tsunami Warning Center (PTWC) and COMET MetEd online courses to use their materials. The course will be enabled as part of the IOC's OceanTeacher Global Academy, and will consist of a series of online and self-paced, hybrid, and in-person modules covering the approved minimum core competencies. Each module will build upon the previous, and the trainee will have to obtain a passing grade in order to proceed to the next module. The final module is planned to be a 3-4 week in-person training at the ITIC and PTWC that will enable trainees to engage in live and simulated PTWC event operations.

6 Event Reporting Standards

6.1 Background

Through joint discussions between WG2 and the IUGG Joint Tsunami Commission, It has been recognized that inconsistency in reporting tsunami and their impacts limits the knowledge gained and possible tsunami disaster risk reduction through event learnings. Historical databases including The Global Historical Tsunami Database (GTDB) maintained by the National Centers for Environmental Research (NCEI) in Boulder, Colorado, USA (https://www.ngdc.noaa.gov/hazard/tsu_db.shtml) and the Tsunami Laboratory of the ICMMG SD RAS in Novosibirsk, Russia (http://tsun.sscc.ru/gtdb/default.aspx) exist. These databases contain tsunami records covering the period from 2000BC to present comprising almost 2,750 historical tsunamigenic events and over 32,000 run-up and tide-gauge measurements. The collected sets of observational, instrumental and descriptive data are widely used globally in tsunami research directed to tsunami warning, hazard assessment and mitigation.

Under recommendation of the ITSU-XI/3 (ICG PTWS 11th session, 1987), a standardized database format was developed, and the first tsunami database was compiled based on the numerous bibliographical sources available in the ITIC library. This first version of the database, containing about 1800 events, and was distributed through the ITSU National Contacts (Pararas-Carayannis, 1991). The adopted structure divided all dataset into two main parts – source event data and run-up data and the format (set of the main parameters) of the tsunami database is still being used. On average, 14-15 recent tsunamigenic events per year are added to the catalogue and corrections to historical tsunamis based on newly discovered data and re-interpretion is ongoing.

However, the lack of internationally accepted system and standards for routine compilation of tide-gauge records is detrimental to this effort. This is especially true for weak tsunamis which don't generate damage and can only be detected in tide-gauge records. The lack of damage results in the lack of reported observational data available for these events. Some of these weak tsunamis were generated by strong submarine earthquake which were a subject to urgent real-time analysis in TWC, resulting in the issuance of warnings. The current version of the database contains about 10 shallow focus events with magnitude Mw above 7.5 since 1976. It is important to understand why these submarine earthquakes with magnitude well above the threshold for issuing a tsunami warning have not generated any significant tsunami. Unfortunately, the lack of standardized reporting of information related to them hinders this effort.

PTWS Members States are asked to provide information on "Tsunami Occurrences" in their respective National Reports to the ICG. Here we propose to provide a standard of reporting to member states to facilitate the collection and archiving of event data. In addition to the mandatory information on the structure of Tsunami Warning Systems, Standard Operating Procedures, etc. required by the present format of MS National Reports, an "Information on Tsunami Occurrence" section could include the observational source and wave-form data for tsunamigenic events that occur and are observed within the area of responsibility of reporting country/agency during the reporting period. The reporting standard should contain all principal parameters characterizing the event and its actual observations at the particular coastal location. It would highly desirable for all ICGs to adopt a section on "Information on Tsunami Occurrence" in their National Reports.

Station	Lat,,*) N	Long,*) E	First wave			Max wave			Period (min)	Comment**)
			Arrival time (UTC)	Travel Time	Amplitude (cm), sign	Wave amplitude (cm)	Wave height (cm)	Time (UTC)		
Sovetskaya Gavan	48.97	140.29	11:27	4h 17m	-2.7/+4.5	8.5	15.9	01:01*	65	
Uglegorsk	49.08	142.07	?	?	?	8.4	14.7	17:09	27, 15, 8	First arrival is undetactable
Sosunovo	46.53	138.33	09:40	2h 30m	+5.2	12.9	24.0	09:49	15, 5.5	
Rudnaya Pristan			08:47	1h 37m	+10.3	30.0	64.7	15:01	27, 12, 7.5	High noise level caused by wind waves
Kholmsk-T4			09:47	2h 37	+1.8	6.5	12.6	16:40	23, 10.5	Bottom pressure gauge outside the port
Kholmsk			09:43	2h 33m	+4.4	12.2	25.2	15:52	8.5	
Wakkanai			09:02	1h 52m	+4.5	14.0	26.6	00:27*	26, 7	Late maximum wave

Oshoro			08:39	1h 29m	+9.6	14.4	32.6	15:18	14, 6.5, 3.3	
Okushiri			08:14	1h 04m	+2.5	11.7	24.1	09:02	7.5, 4	
Fukaura			08:03#	0h 53m#	+7.2	34.5	73.3	09:04	20, 4	

Table 1. Populated Template (Example for the Noto Peninsula tsunami of 1 January 2024 recorded by tide gauges in the northern Sea of Japan)

In addition, WG2 requests member states to provide, in their National Reports, a list of tsunami-related papers and reports published within the reporting period, especially in languages other than English (since they cannot be easily accessible outside the country of origin) as well as the references to newly published tsunami catalogs or other compilations (tables, lists, websites) related to the tsunami data.

Imlementation of these recommendations will provide an increase in level of completeness, reliability and specificity of tsunami data incorporated into the Global Historical Tsunami Database and thus will contribute to further progress in internationally-wide tsunami research and mitigation.

7 Proposal

WG2 **commends** advances in SMART Cable initiatives in the Pacific and recommends the ICG/PTWS continue to work closely with the JTF for SMART Cables to utilise monitoring data from these efforts when they are available.

WG2 **commends** testing of laser interferometry on the Southern Cross NEXT fibre-optic cable in the southwest Pacific.

WG2 **commends** the Geodetic Tsunami Early Warning Systems Oceania (GaTEWS) initiative in the southwest and continues to follow their efforts.

WG2 **commends** Australia for continued support of instrumentation and data retrieval in the southwest Pacific, including installation and maintenance of seismic and geodetic infrastructure.

Noting the significant potential of SMART Cables to advance tsunami monitoring and forecasting

and **noting** the progress of SMART Cable initiatives in the SW Pacific

WG2 **recommends** the PTWS encourages Member States to incorporate SMART capability into new subsea telecom cable projects, prioritizing deployment in high-risk tsunami zones.

WG2 further **recommends** partnering with the JTF SMART Cables to develop protocols for real-time data access and integration from SMART Cables into the Pacific Tsunami Warning System (PTWS) and National Tsunami Warning Centers (NTWCs).

Recognising the opportunities to improve tsunami DRR through the standardisation of member state reporting of tsunamigenic events

WG2 **recommends** the ICG-PTWS to request member states to adopt standard event reporting within their National Reports to the ICG.

WG2 **commends** the IUGG JTC for leading the effort to standardise event reporting standards.

WG2 structural recommendations

Noting that the TT Integrated Sensor Network has completed the task contained within its terms of reference and

Noting that further work on integrated sensor networks, beyond the original terms of reference is needed and

Further **noting** the alignment of TTISN with TTFOO,

WG2 **recommend** the closure of TTISN and an expansion of the terms of reference of TTFOO to incorporate continued focus on integrated sensor networks within the context of forecasting strategies highlighted by TTFOO.

WG2 **recommends** that ICG/PTWS continue the Task Team on Forecasting from Ocean Observations and expands its terms of reference to include inclusion of integrated sensor networks.

WG2 recommends that ICG/PTWS continue the Task Team for Tsunami Generated by Volcanoes.

WG2 **requests** the ICG/PTWS solicit confirmation of current members of WG2 and nominations for additional representatives from Member States.

8 Appendix 1

In the following, we present results of a framework to quantify network sensitivity for deep ocean measurements (e.g. DARTs) and terrestrial (fixed location) GNSS observation sites. Our network analysis is capable of ingesting any new “in-use” data streams when they are available. This analysis framework is based on a time-to-detection. We highlight circum-pacific areas in which the disparate data streams can contribute to instrumental early warning. We attempt to analyse the cost-benefit potential of future technologies by first limiting network gap analysis to travel times > 45 minutes. For typical earthquake sources (M8+), 45-minute travel time is approximately the maximum distance that most tsunamigenic earthquakes will be widely and strongly felt, the distance at which an M7.5 earthquake is strongly felt is about 100km, but local variations in bathymetry and tsunami speed vary significantly, making travel time-based precluding of M7.5 events challenging.

8.1 TTISN analysis

To assess the effectiveness of the PTWS integrated sensing network, including emergent observational data such as SMART Cables, GNSS TEC and GNSS static displacement, we apply a series of logical filters to the currently available network and imminent TamTam SMART Cable. We consider existing and plausible warning systems. We then assess either 1) the amount of residual coastal population exposed to subduction zone unit sources that can’t be warned for and 2) the amount of residual subduction zone sources per coastal population zone that can’t be warned for.

8.2 Input Datasets

The spatial datasets used in the analysis include:

- The world coastline from Level 1 shoreline data at intermediate resolution derived from the GSHHG dataset used by Generic Mapping Tools (GMT), and provided by SOEST, University of Hawaii (https://www.soest.hawaii.edu/gmt/).
- The Global Digital Elevation Model (DEM) at 30 arc-seconds resolution (Minimum statistics) provided by USGS (https://topotools.cr.usgs.gov/gmted_viewer/gmted2010_global_grids.php).
- Population density and count at 30 arc-second resolution from Gridded Population of the World, Version 4 (GPWv4) provided by NASA (https://www.earthdata.nasa.gov/data/catalog/sedac-ciesin-sedac-gpwv4-popdens-r11-4.11).
- The subduction zone earthquake source locations from the propDB database.
- Publicly available seismic stations
- Pacific Deep-ocean Assessment and Reporting of Tsunami (DART) stations
- GNSS stations Continuous GNSS stations recording data at 30 seconds sampling rate and packaged in daily files. The list is obtained from the University of Nevada Geodetic Laboratory (https://geodesy.unr.edu/)
- Tsunami Travel Time grids obtained from NOAA National Centers for Environmental Information (NCEI): https://www.ngdc.noaa.gov/hazard/tsu_travel_time.shtml

8.3 Tsunami Travel Time (TTT)

Tsunami travel times from each source were required to estimate the time available for evacuation before tsunami impact for each vulnerable coastal population. We calculated the difference between tsunami travel time to the coastal population and to the ocean height observational locations (DARTs). Tsunami travel time grids for the propDB unit sources were provided by NOAA National Centers for Environmental Information (NCEI). They are available for each earthquake source analysed and cover only the tsunami propagation through water. As the extent of population grids is limited to land, population data were projected to the nearest offshore location to allow extraction of the tsunami travel times from the TTT grids (as explained in 1.2). We then use the same resolution to model the travel time to each observational point. The TTT grids used for forward propagation from the unit sources were at 0.5 degrees resolution. Their extent was limited to travel times less than 2 hours. The sources causing tsunamis with travel times greater than 2 hours to the nearest coast were not considered in this study.

8.4 Coastal Populations

Costal populations comprise the number of people living in the low-lying coastal areas that might be at risk from tsunami. Low-lying coastal areas were defined as areas within 10 km from the coastline and with elevation less than 50 m above Mean Sea Level (MSL).

We created grids of coastal population from the Gridded Population of the World which provided the count of people at 30 arc-second resolution. The coastline was buffered by 10 km and used to clip the initial population grid. The Global DEM was used to remove all population cells where the elevation was greater than 50 m above MSL. The resulting grid was aggregated to 5 arc-minutes resolution and exported to points with each point representing the number of people within 5 by 5 arc-minute area of the coastal region (~84 km^2). This point layer was used in further analysis.

To determine the tsunami travel times to each population point from the TTT grids that were limited to offshore areas, the points were projected to the nearest cell in the TTT grid. In this process, the number of people was further aggregated to the 0.5 degrees resolution, so the population counts could be shown on maps at a reasonable scale. That also matches the resolution of the TTT grids used in the analysis. The population points shown in the maps provide the count of people in 0.5 by 0.5 degrees area of the coast (~2,500 km^2).

8.5 Exposure (Number of people at risk for each earthquake source)

The coastal population and earthquake sources datasets were used to estimate the number of people at risk from tsunami for each earthquake source. In the first instance, the distance between sources and population was used to estimate the number of people affected which was presented in a map. It was assumed that people who were less than 100 km away from the source will have a natural warning (i.e. shaking) and these were excluded from analysis. People more than 800 km away from the source were also not considered. In the second iteration, the tsunami travel times between sources and the population were analysed and results presented in map books.

In the first analysis, the distance from each source to the coastline and to the population points was determined. For each source the population points between 100 and 800 km were identified, the population counts were summed and attached to the source point. The colour of source point symbols on the map was used to show the number of people affected. The sources closer than 100 km to the coast were depicted differently than those more than 100 km away using a different shape for the symbol.

In the second iteration, TTT grids were used to extract the tsunami travel times from a source to population points and the number of people affected was calculated for different time thresholds and attached to the source point. The analysis was done for 10, 20, 45, 90 and 120 min time frames. Here we only present the 20 minute maps. Also, the distance to the nearest population was used to differentiate between sources that are more or less than 100 km away from the vulnerable areas, compared with distance to the coast used initially. The results were presented in a series of maps books for each warning time threshold.

Two wphase solution criteria (10 and 20 min) were also used in the analysis represented with different area around an earthquake source within which the number and position of the seismic stations was analysed. The number of seismic stations within 4,000 (10 min) and 8,000 (20 min) km of each source were calculated using the Generate Near Table tool, trying to identify any source with less than 5 seismic stations within the search radius. This number of stations was assumed to be necessary for detecting a tsunami. All sources had more than 5 seismic stations within the search radius.

The azimuthal gap between stations relative to the source that satisfied above criterion was also calculated for each source using the NEAR_ANGLE output from the tool with a requirement that the maximum azimuthal gap is less than 180°. It was assumed that if the maximum azimuthal gap between stations was greater than 180°, these stations were not evenly positioned around the source and would not provide a reliable warning. Only one source for 8,000 km and eleven sources for 4,000 km search radius were identified as not satisfying above criteria. These stations were shown using coloured background symbols on the maps.

8.6 Tsunami early warning using GNSS finite fault inversion

A series of maps was created to show the possibility of early tsunami warning using the GNSS stations and finite-fault based forecasting strategies, and what improvement can be achieved by including the Vanuatu SMART cable into the warning system. The SMART cable was presented with a number of points that were treated the same as GNSS stations and BPR in the analysis.

The number of GNNS stations within 200 km of each source was calculated and maximum distance between the stations was determined. It was assumed that the early tsunami warning is possible if there are at least two stations within the search radius with maximum distance between them of more than 100 km. That indicates that the stations are spread enough in relation to the source location to provide a reliable source inversion. The sources for which the GNSS-based early warning was possible or not possible were presented with different symbols on the maps.

In the first instance, the number of people within 800 km radius from each source has been identified and depicted with the source symbol colour on the maps.

In the second iteration, a slightly different criteria were used to create a map book that shows the number of people within 45 minutes tsunami travel time from each source and for what sources the early warning would be possible using the GNSS stations streaming the real-time data at the time. TTT grids were used to identify number of people within 45 min tsunami travel time for each source. In this scenario it was assumed that at least 2 GNSS stations are required within 200 km radius from a source with maximum distance between the stations of more than 100 km.

8.7 Tsunami early warning using DART inversion

DART stations are used in recording tsunami by detecting the change in water pressure caused by tsunami waves. Early warning using DART stations is possible if the stations are close enough to the source so there is enough time from the moment a station records a tsunami to the time that that tsunami wave reaches the coastal population.

Use of the DART network for tsunami early warning was analysed by calculating the number of sources that could affect the coastal population and for which the DART-based warning would not be possible. This number of sources was attached to each population point along the coastline and presented in map books. Different warning times (10, 20 and 45 minutes) were considered, and it was investigated and presented on maps how changes to the DART network (e.g. high- or low-density network, some DART stations being out of function) might affect the early warning. An option with Vanuatu SMART cable sensors was also analysed, treating each SMART cable sensor as a DART station.

It was assumed that at least 2 DART stations were required for a reliable detection of a tsunami. Tsunami travel times from each source to vulnerable population and the DART station were extracted from the TTT grids and the difference between these times was compared with a required warning time. The furthest DART station in terms of travel time was used to calculate the time difference.

In most cases only the sources where natural warning was not possible were considered. This approach excluded all the sources less than 300 km from the coast or sources generating tsunamis with travel times to the coast of less than 45 minutes.

The symbols used for the population points on the maps were coloured based on the number of the earthquake sources for which the DART-based warning would not be possible (considering different warning times required) while the symbol size reflected the number of people that that point represents.

8.8 Tsunami early warning using DART and GNSS TEC

The possibility of early warning was assessed if DART and GNSS TEC observations were used together, assuming that warning should be received 20 min before the arrival of tsunami. In this scenario, it was assumed that only one DART station that provide enough warning time is required for a reliable warning together with two GNNS stations that are within 1,200 km from the earthquake source. The earthquakes that could provide a natural warning (i.e. shaking) were not considered so only sources further than 300 km from the closets populated coastal area were analysed.

The results were shown in the maps where each population point was coloured based on the number of the subduction zone sources affecting that population and where the DART and GNSS based warning could not be possible more than 20 min prior to the arrival of tsunami. The size of symbols was based on the number of people affected.

8.9 Other maps

Some additional maps were also created. These include:

Grids that show the number of GNSS stations within 1,000 km radius around each cell were created at two resolutions (0.5 and 1 degrees) and shown on maps together with location of the earthquake sources and coastal population.

- The coastal population within the areas that less than 3 km away from the coastline and with the elevation below 30 m above MSL was aggregated to grids at two resolutions (0.5 and 1 degrees) and shown on maps together with shallow earthquake source locations with magnitude greater than 7. The shallow earthquakes were defined as those less than 50 km deep, and they were symbolised based on the magnitude.

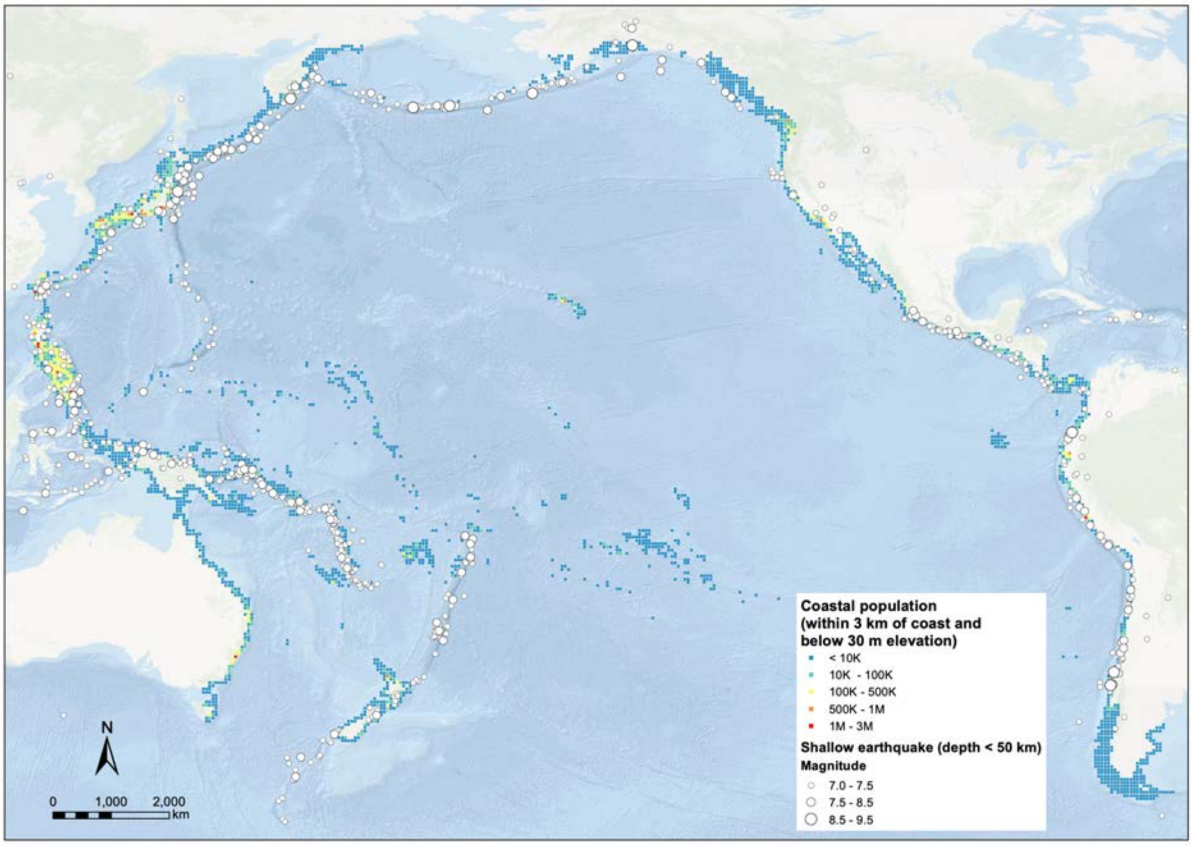


Figure A1. Database of exposed coastal population in 0.5 degree coastal bins. Exposed is defined as population within 3km of the coast and living below 30m elevation.

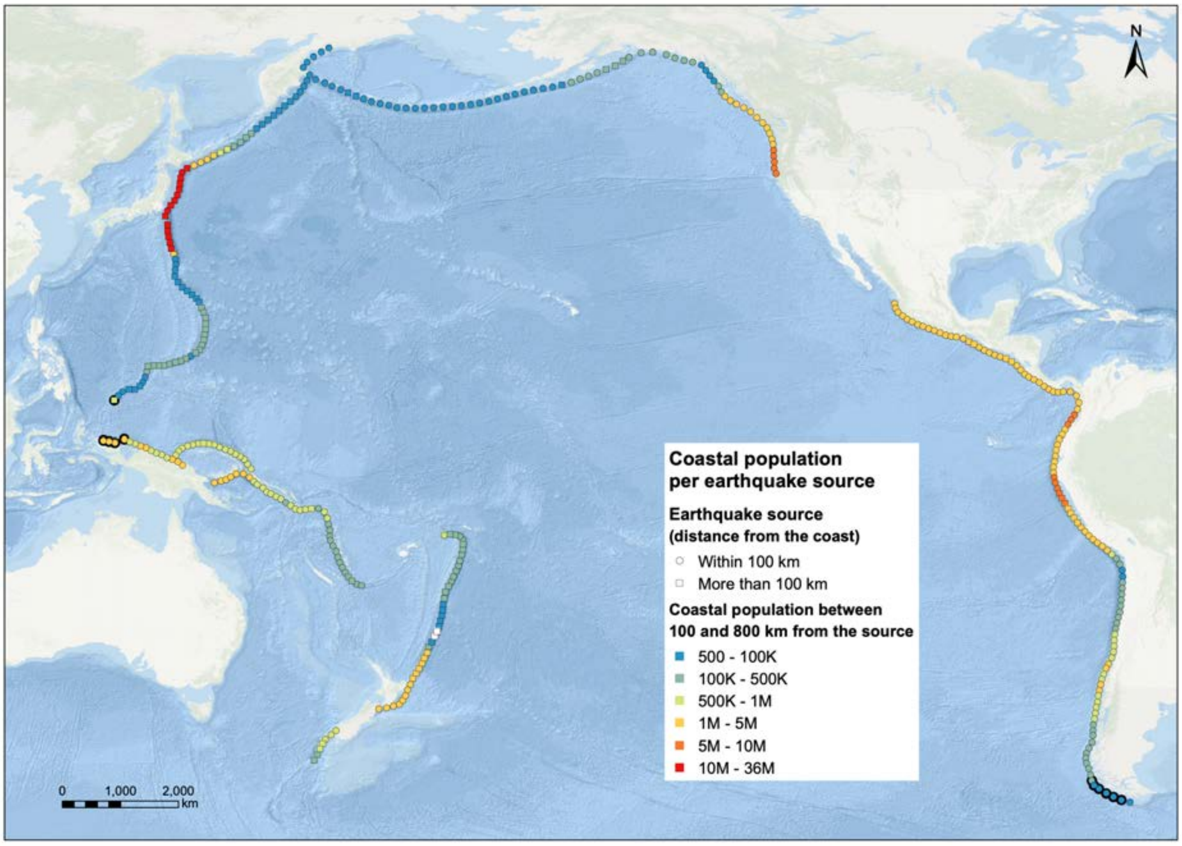


Figure A2. Figure showing the amount of coastal population (colour-scale) at near-regional distances to subduction zone tsunami sources (squares and circles). Circles represent sources that are within 100km of the nearest coastline, suggesting M7.5+ earthquakes will be strongly felt and trigger natural warning based evacuation, assuming sufficient education and outreach. Squares show events at distances greater than 100km, making natural warning based on earthquake shaking uncertain.

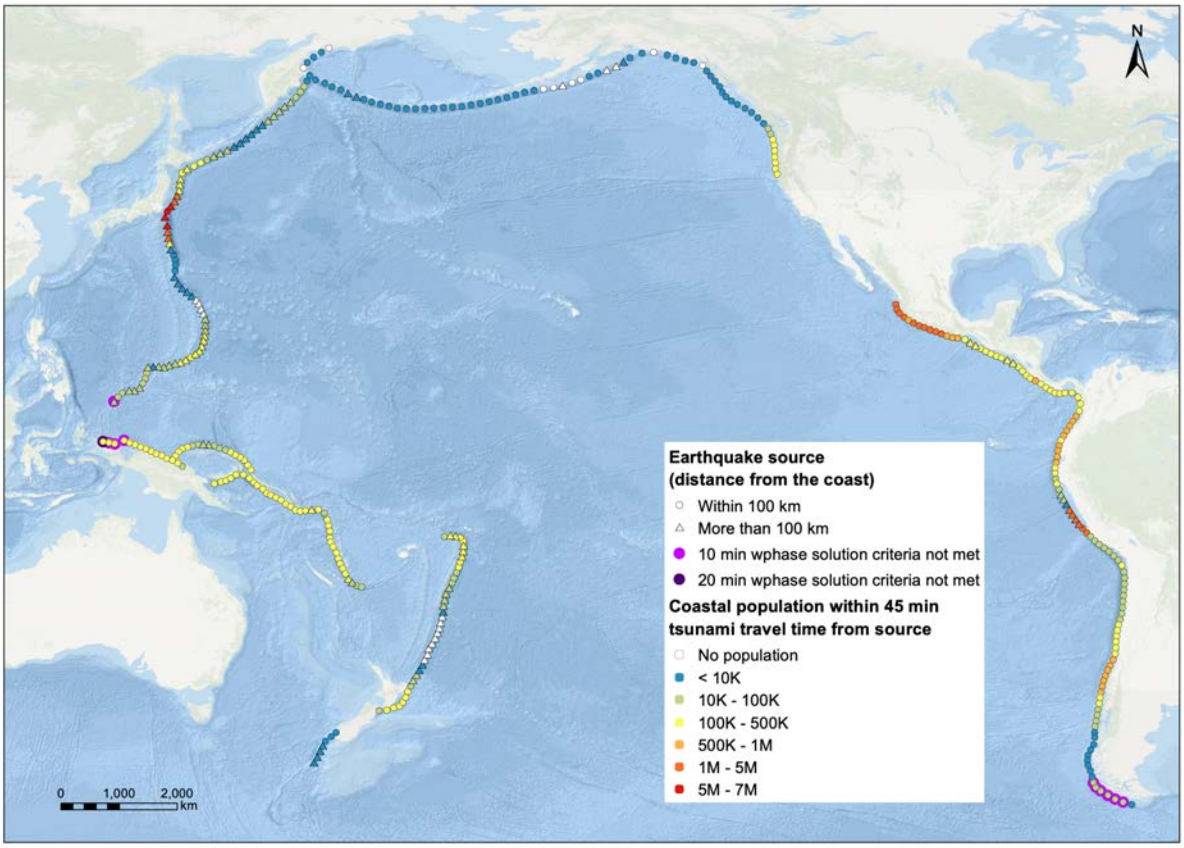


Figure A3. Subduction zone tsunami sources (dots) coloured by coastal population within 45 minute tsunami travel time. All dots without outer thick circle outline meet the seismic criteria for providing a centroid and Mww within 10 minutes. Dots with thick outlines (purple) show the relatively few sources for which the current seismic network does not provide adequate data for 10 minute solutions. Criteria include minimum of 10 high-grade stations with maximum azimuthal gap of 180 degrees.

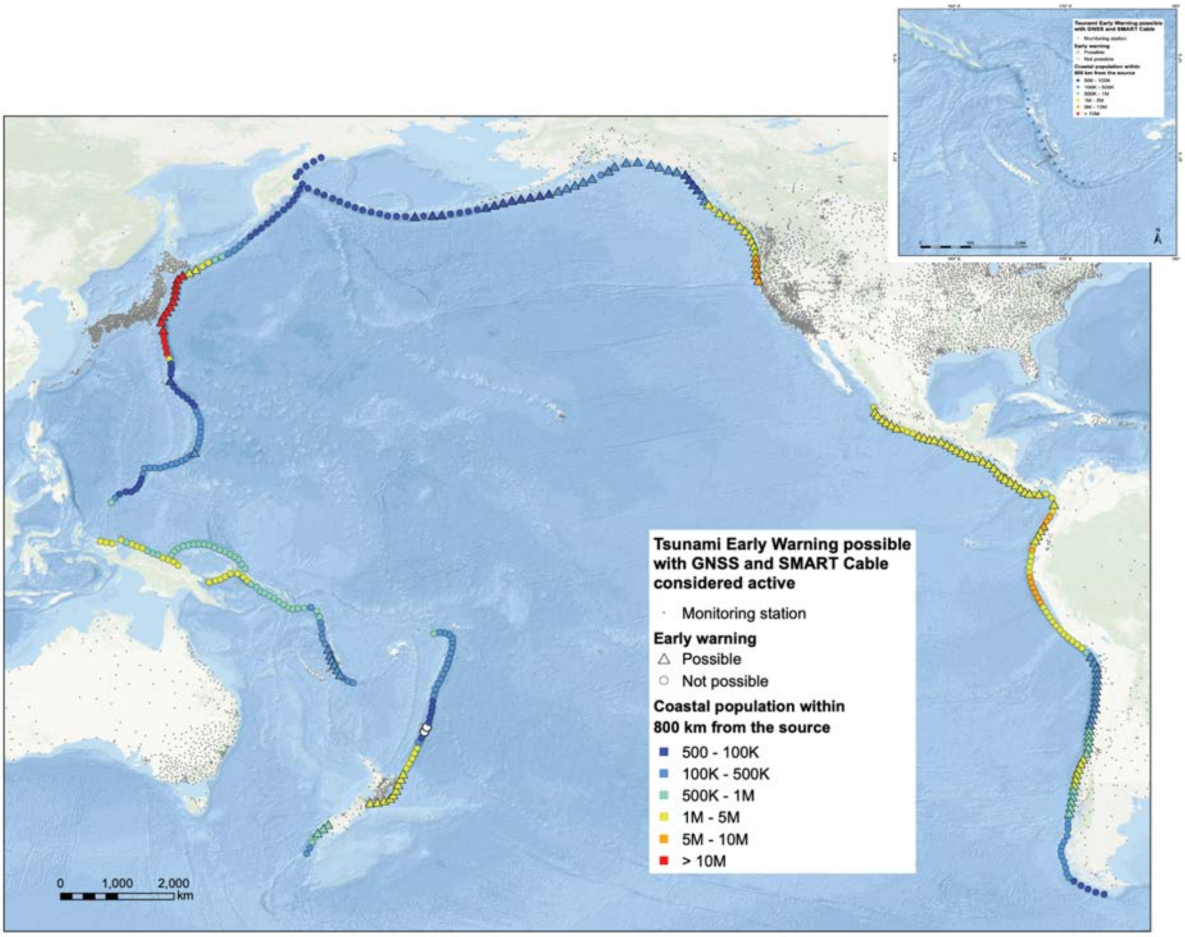


Figure A4. Analysis of integration of GNSS (static) and SMART Cable into the ISN. In this analysis, the ability to use displacement data to solve for earthquake source is assessed. We require at least 5 GNSS stations and/or SMART nodes to be located within at least 200km of the rupture to support forecasting. Further, we require the minimum aperture (maximum distance between points within 100km of the rupture) to be 100km. Estimation of active GNSS stations are shown in grey dots. Triangles show subduction zone sources that meet our logic criteria. Circles represent sources that do not meet the criteria. Colour coding of the sources represents coastal populations at near-regional travel times. Inset shows the effects of the TamTam SMART Cable on the analysis.

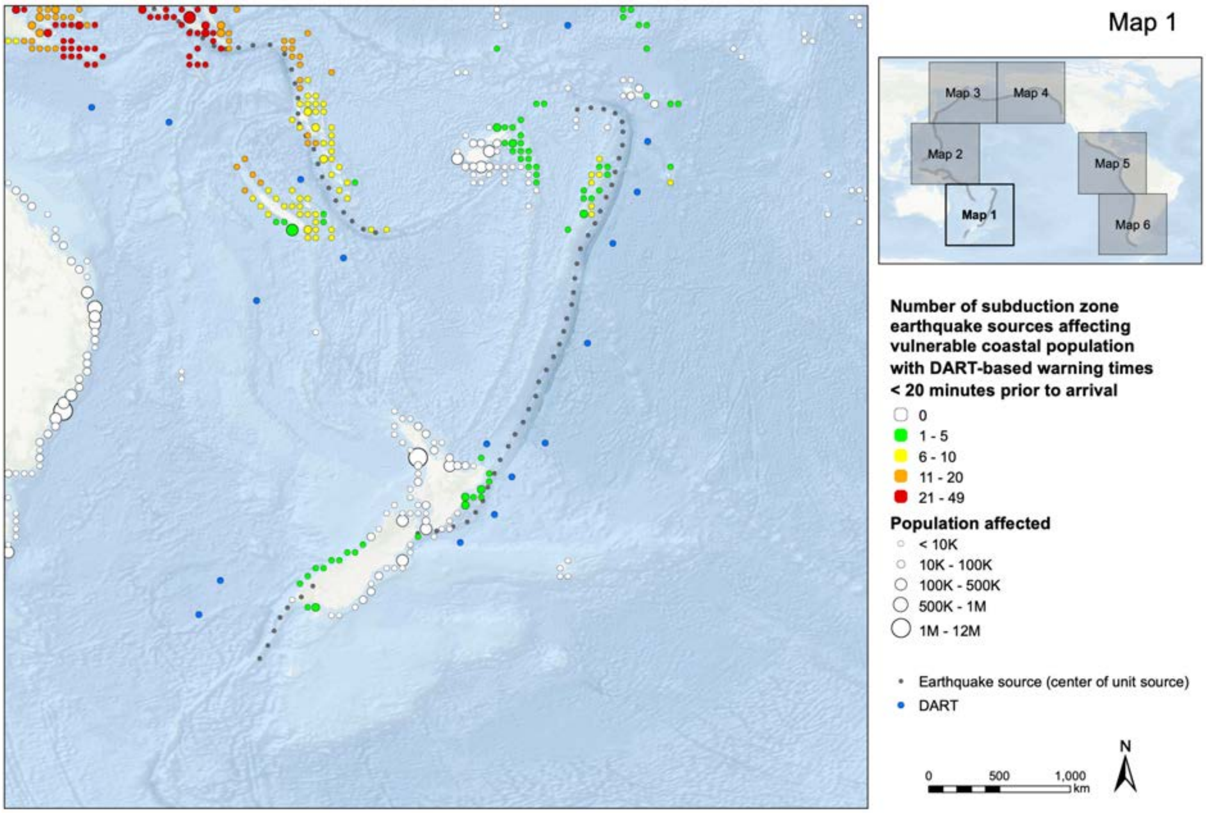


Figure A5. Graphical analysis of exposure of coastal population to regional subduction zone tsunamis for which the ISN cannot support at least 20 minutes of pre-impact warning through the analysis of 2 ocean height observations. Map 1.

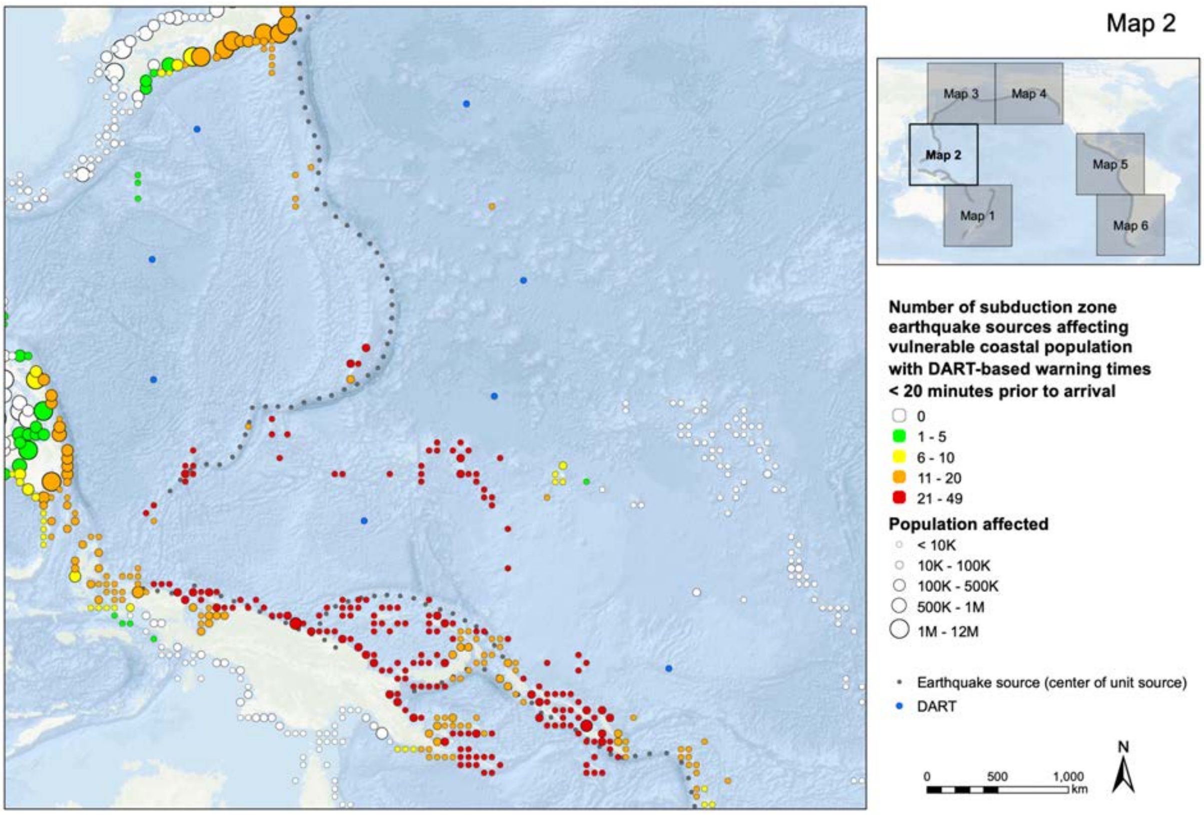


Figure A6. As Figure A5, but for Map 2.

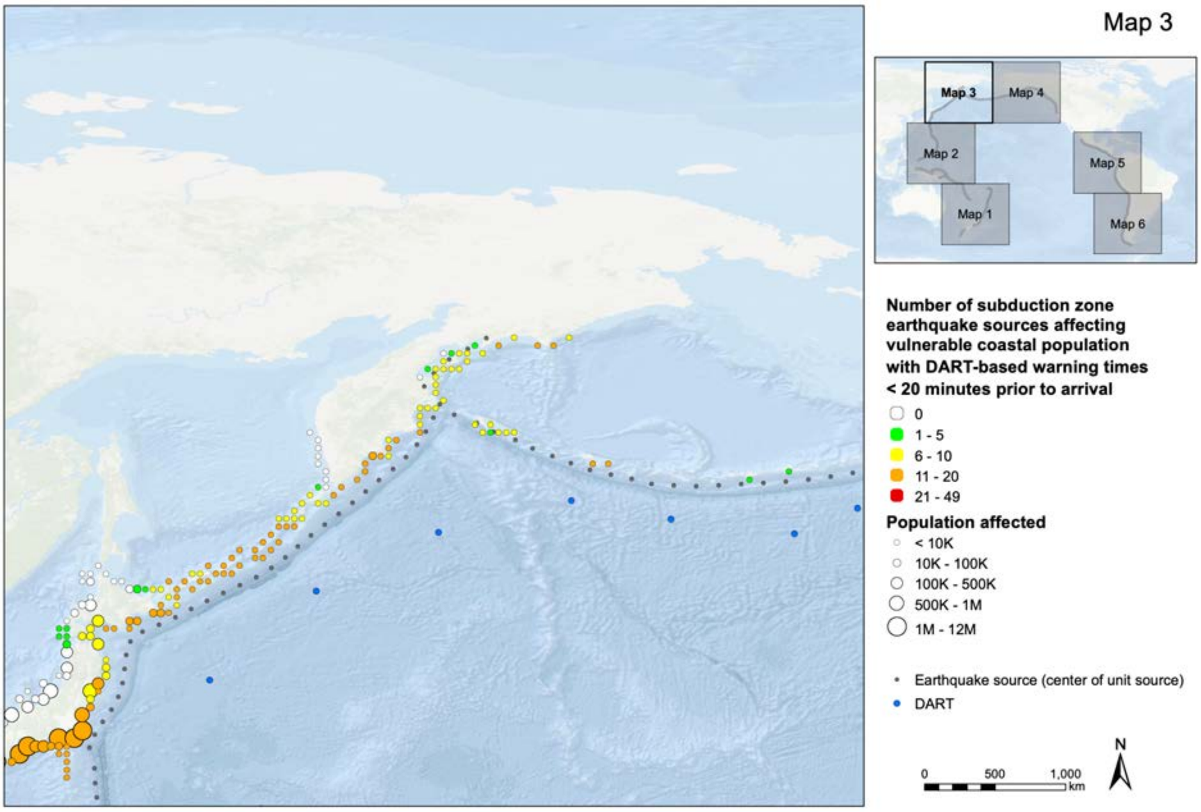


Figure A7. As Figure A5, but for Map 3.

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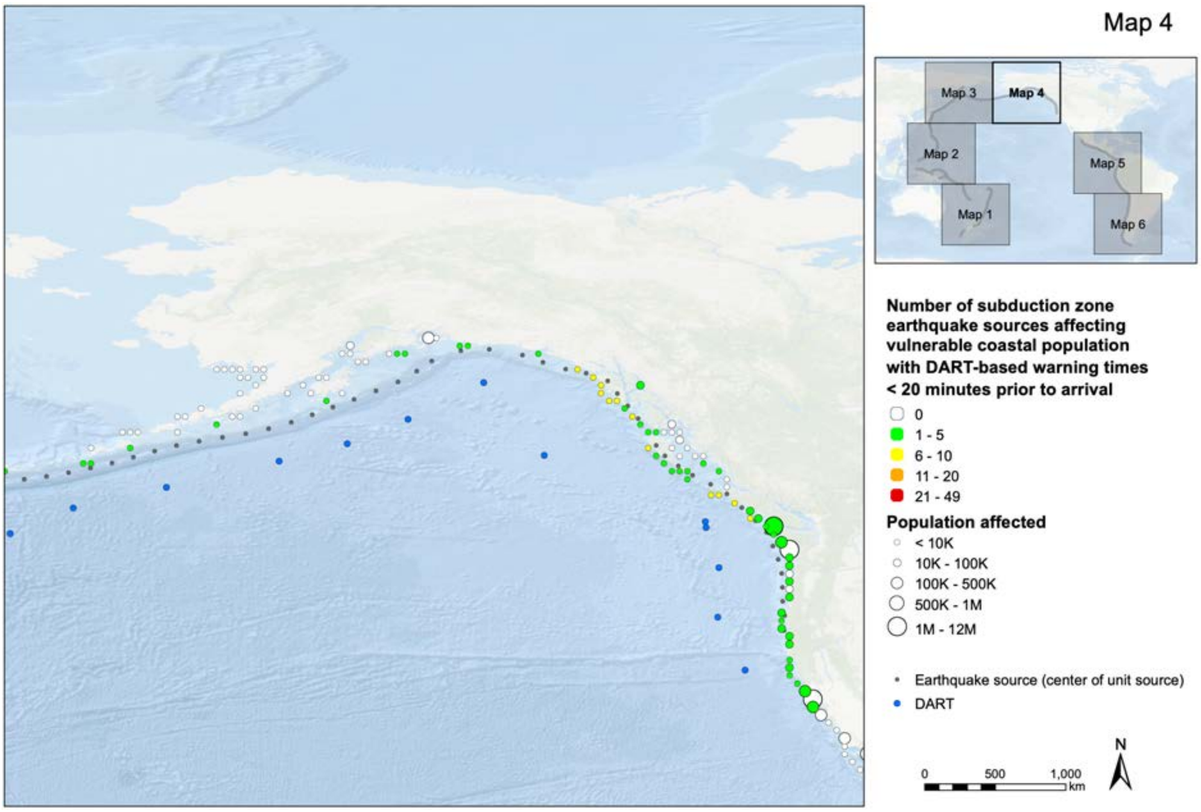

Figure A8. As Figure A5, but for Map 4.

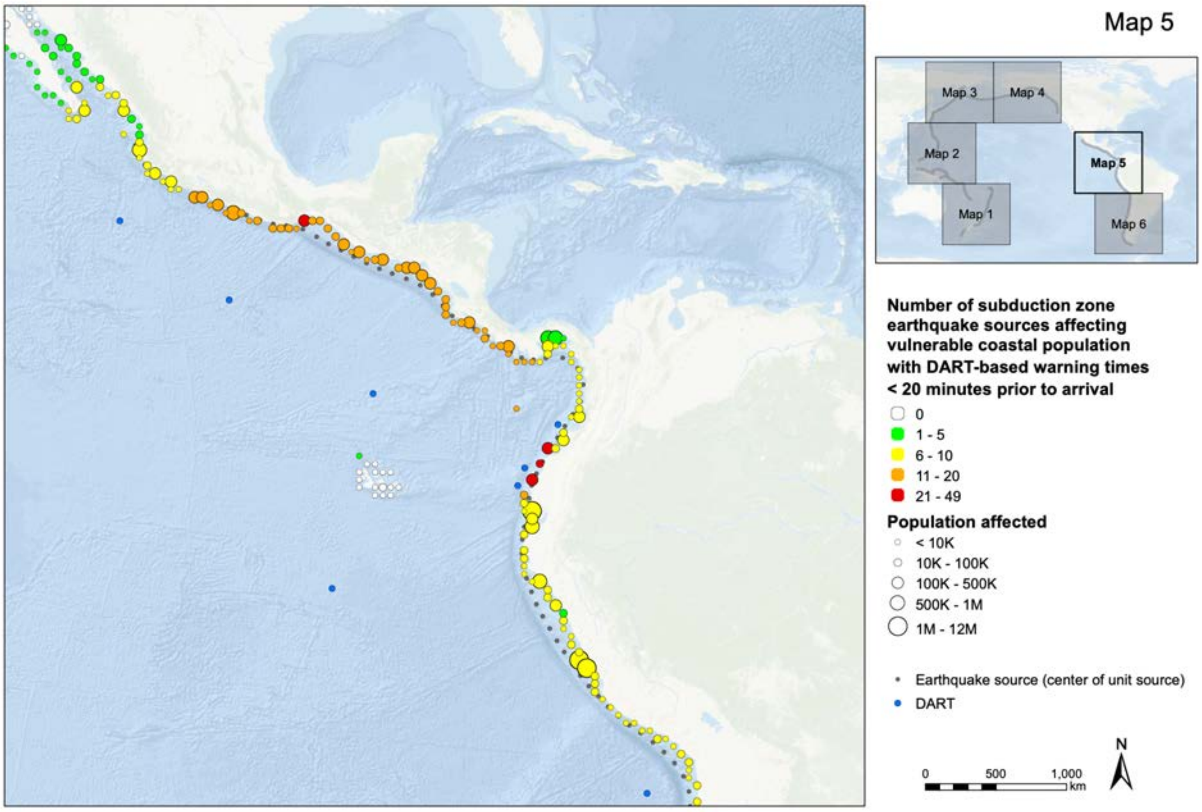

Figure A9. As Figure A5, but for Map 5.

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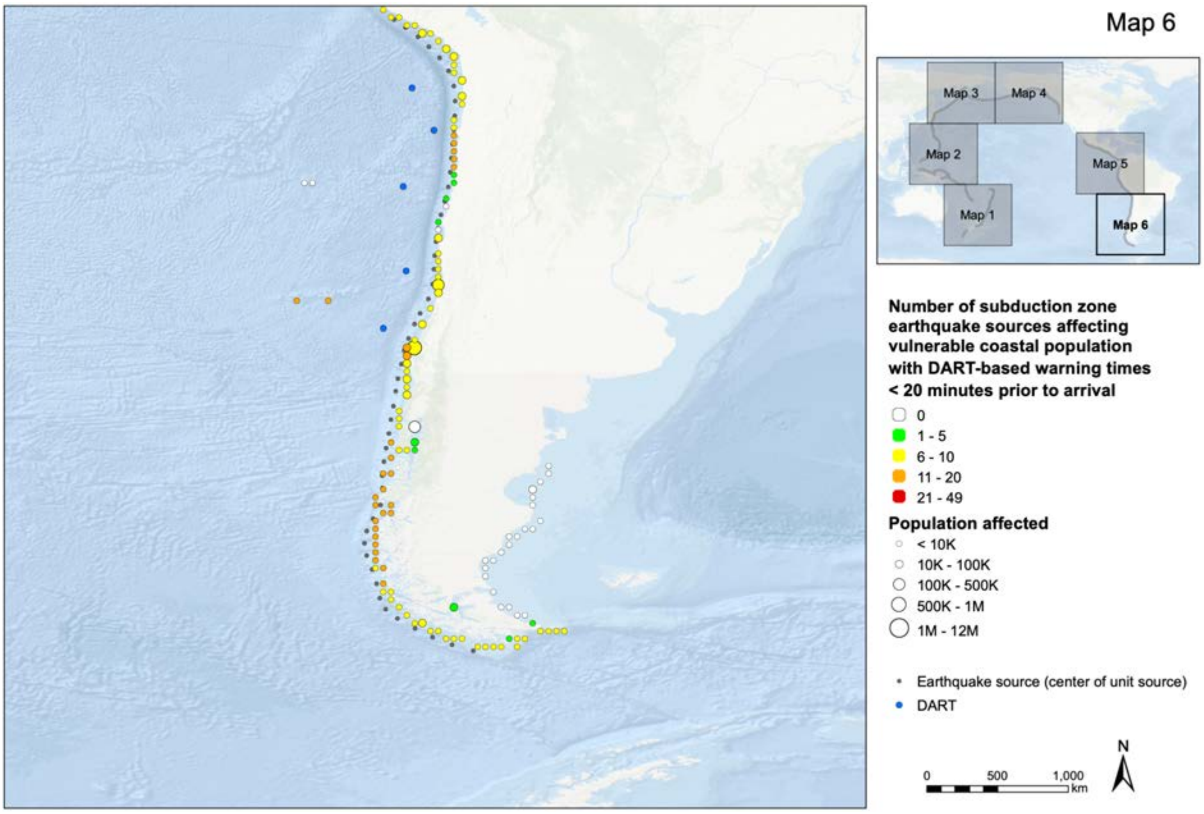


Figure A10. As Figure A5, but for Map 6.

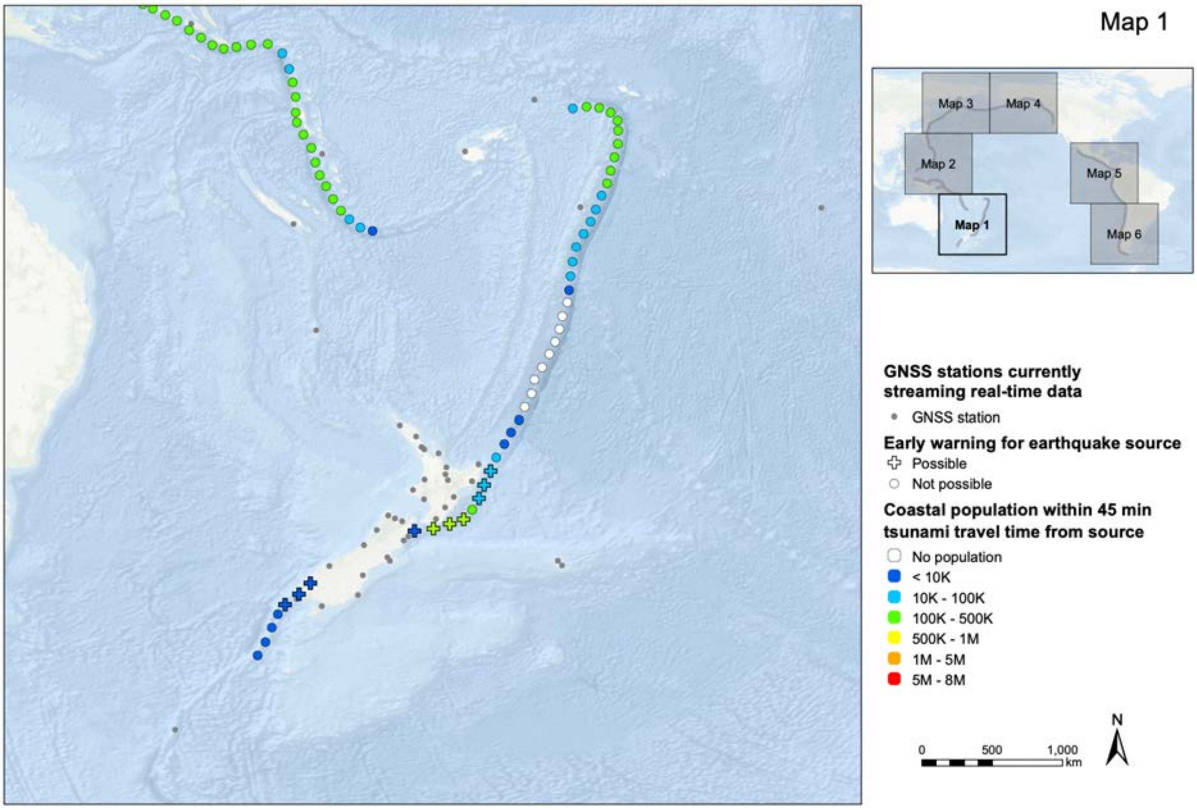


Figure A11. Graphical analysis of the ability of GNSS (static) to support TEW for local events. The GNSS network is deemed adequate if at least 5 active GNSS receivers exist within a 200km radius of the subduction zone tsunami source and the minimum aperture of the 5 stations is at least 100km. We note that this is a conservative estimates and likely overestimates the ability of the current network to underpin TEW.

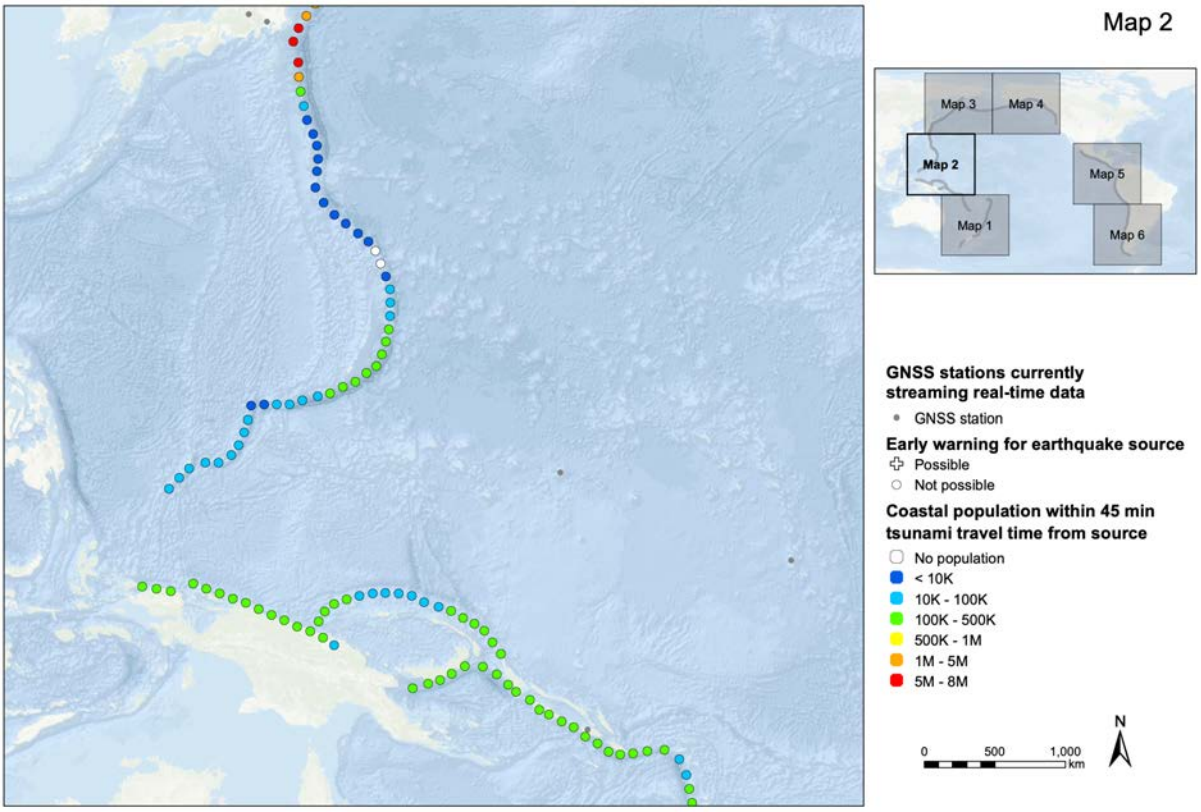


Figure A12. As Figure A11, but for Map 2.

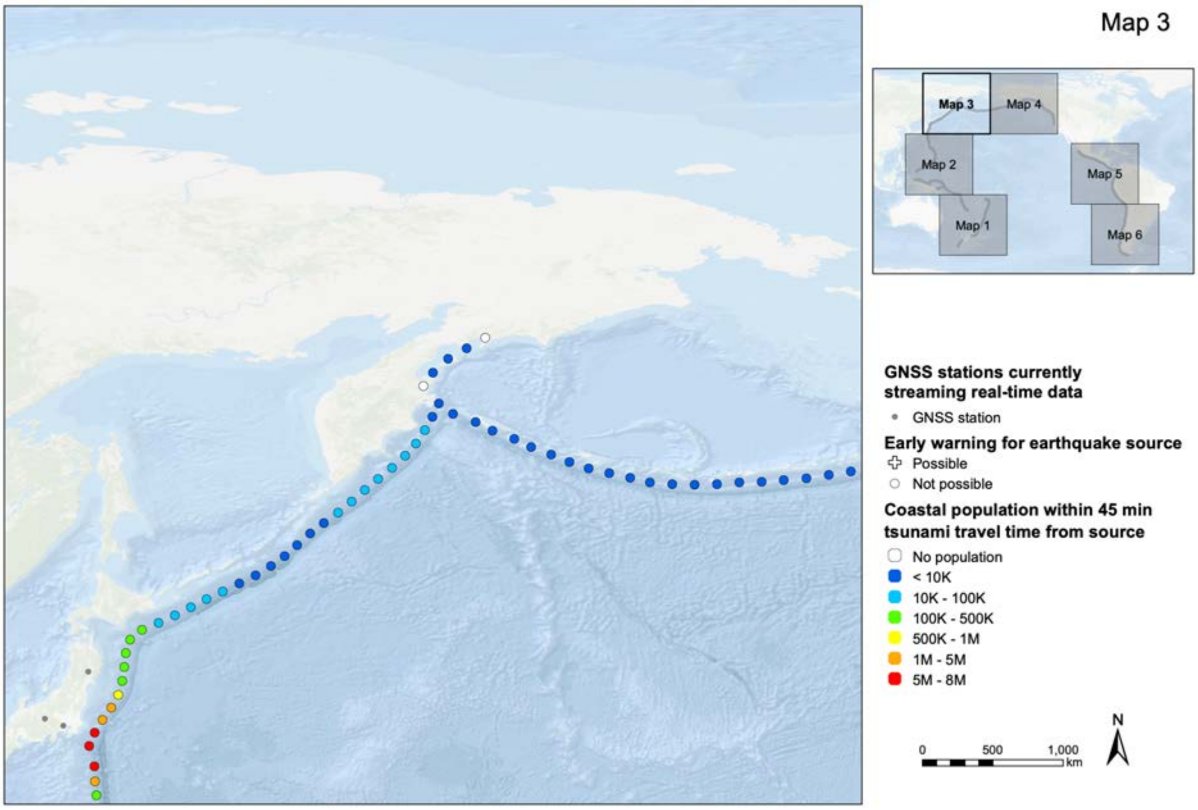


Figure A13. As Figure A11, but for Map 3.

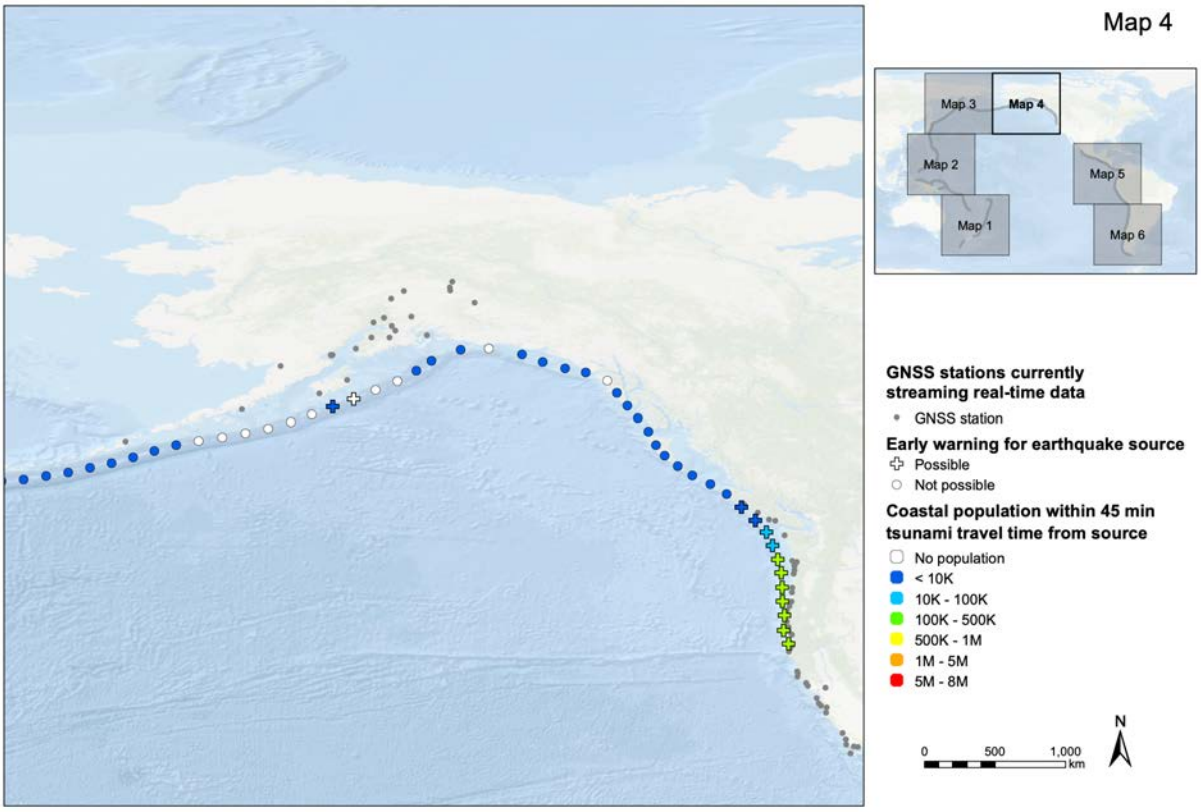


Figure A14. As Figure A11, but for Map 4.

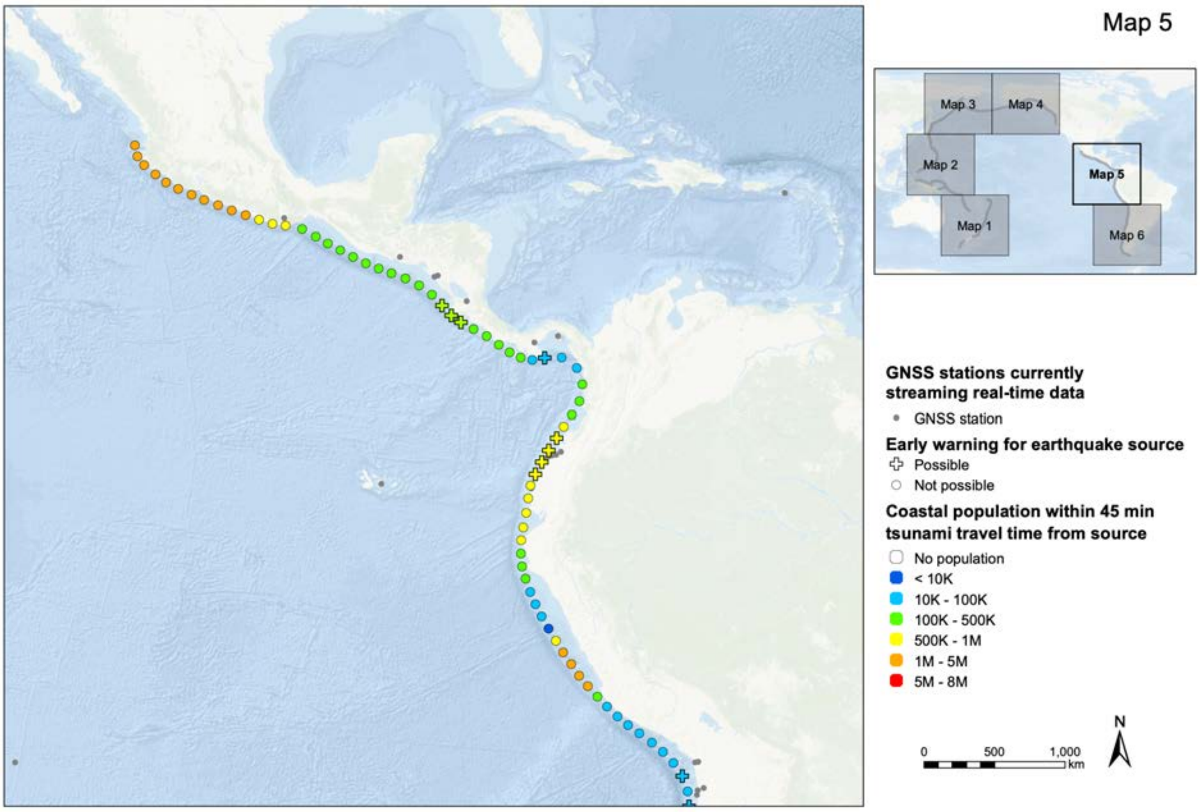


Figure A15. As Figure A11, but for Map 5.

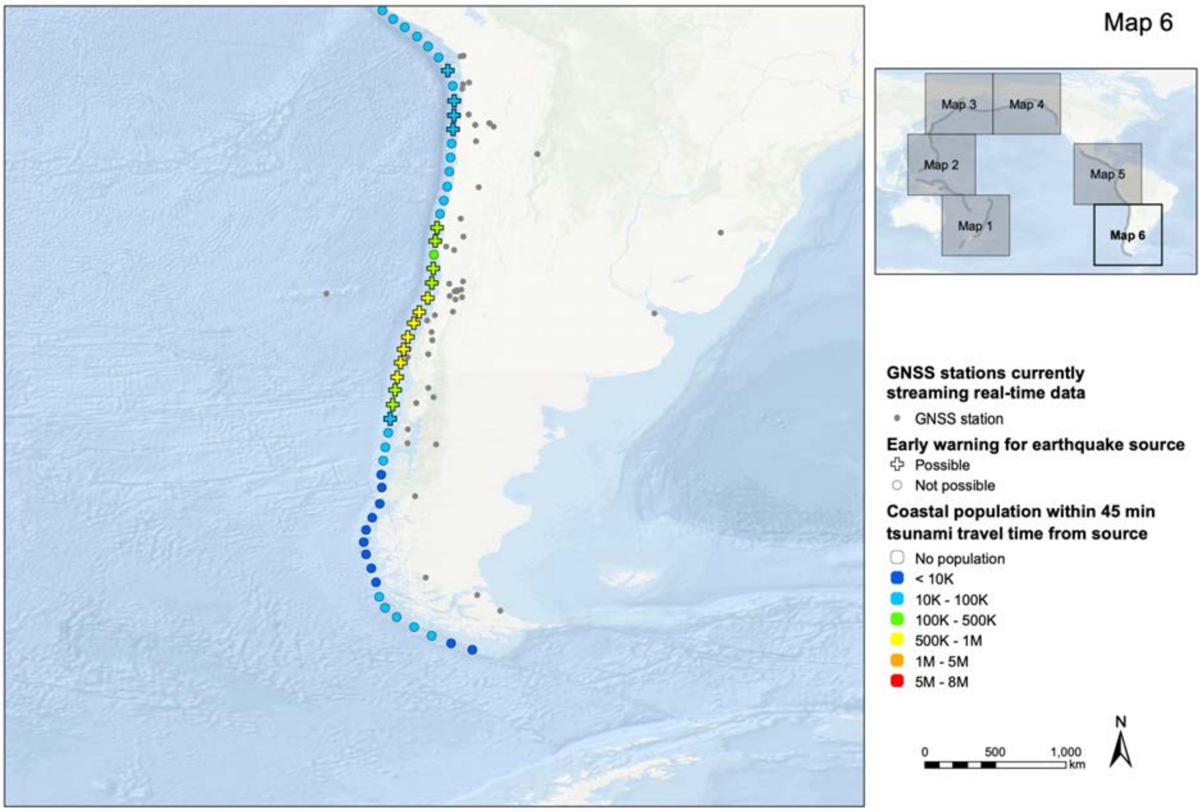
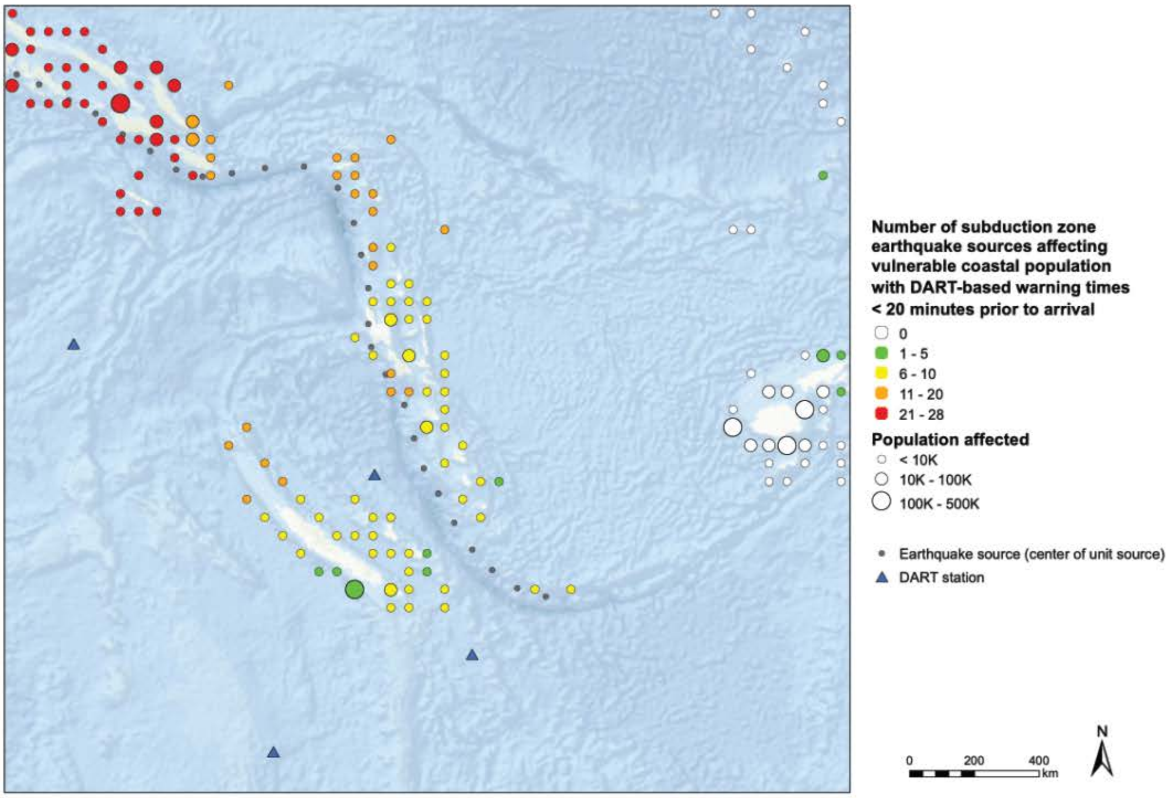


Figure A16. As Figure A11, but for Map 6.



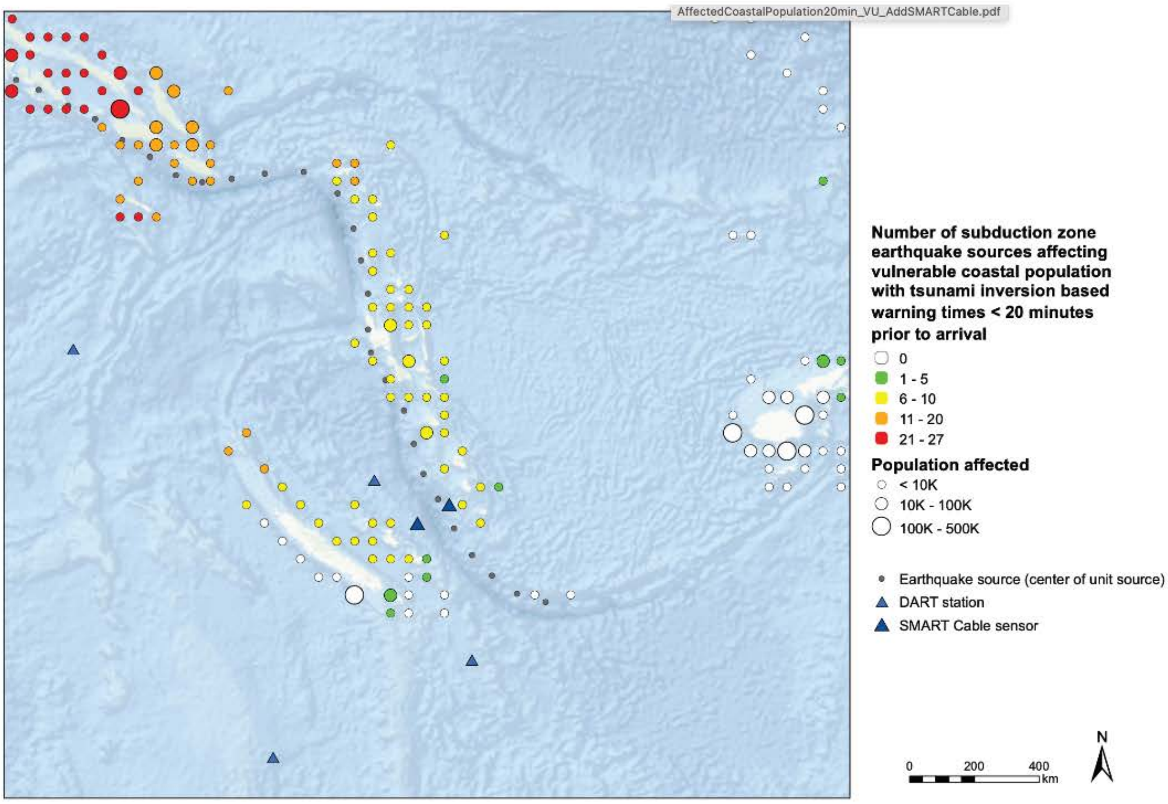


Figure A17. Top, ability to provide at least 20 minutes of pre-impact warning time with existing network. Bottom panel shows an increase in network effectivity with the addition of two nodes representing the TamTam deployment.

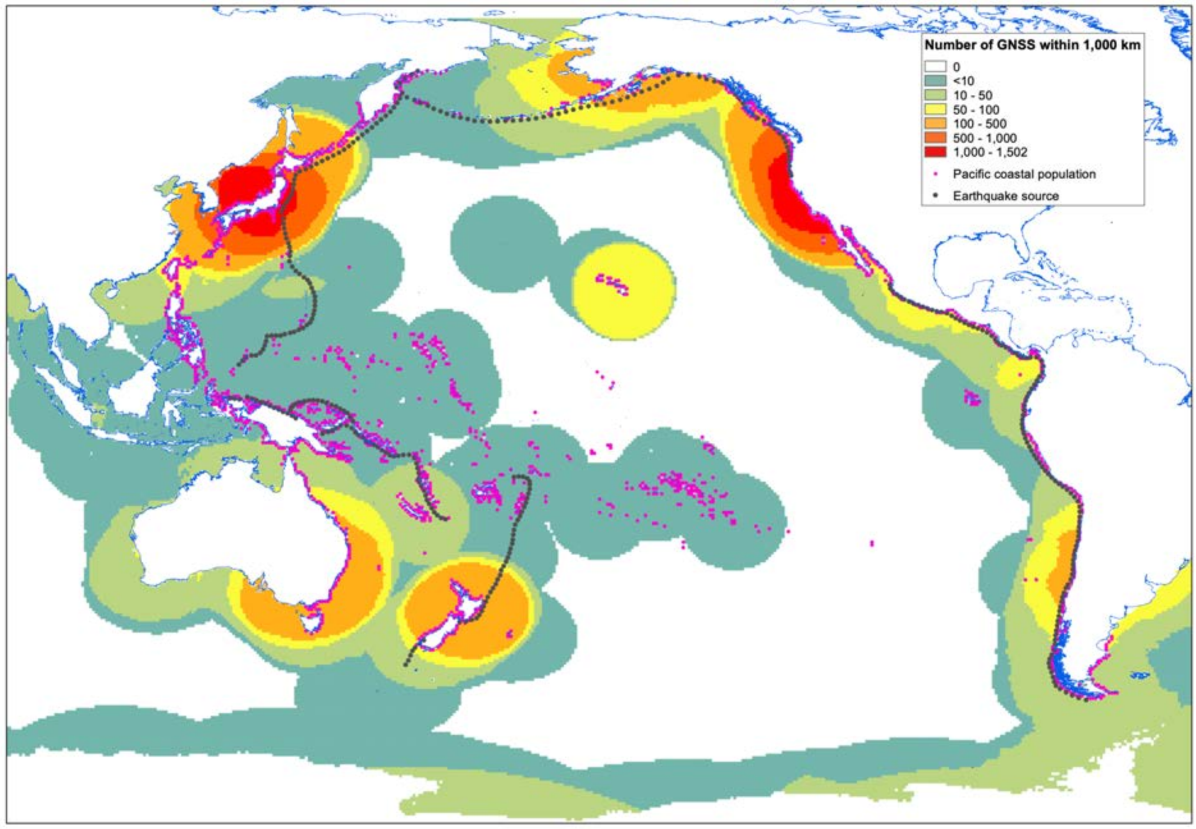


Figure A18. Spatial analysis of GNSS density. This analysis is useful to guide discussion of the power of GNSS TEC to augment ISN.

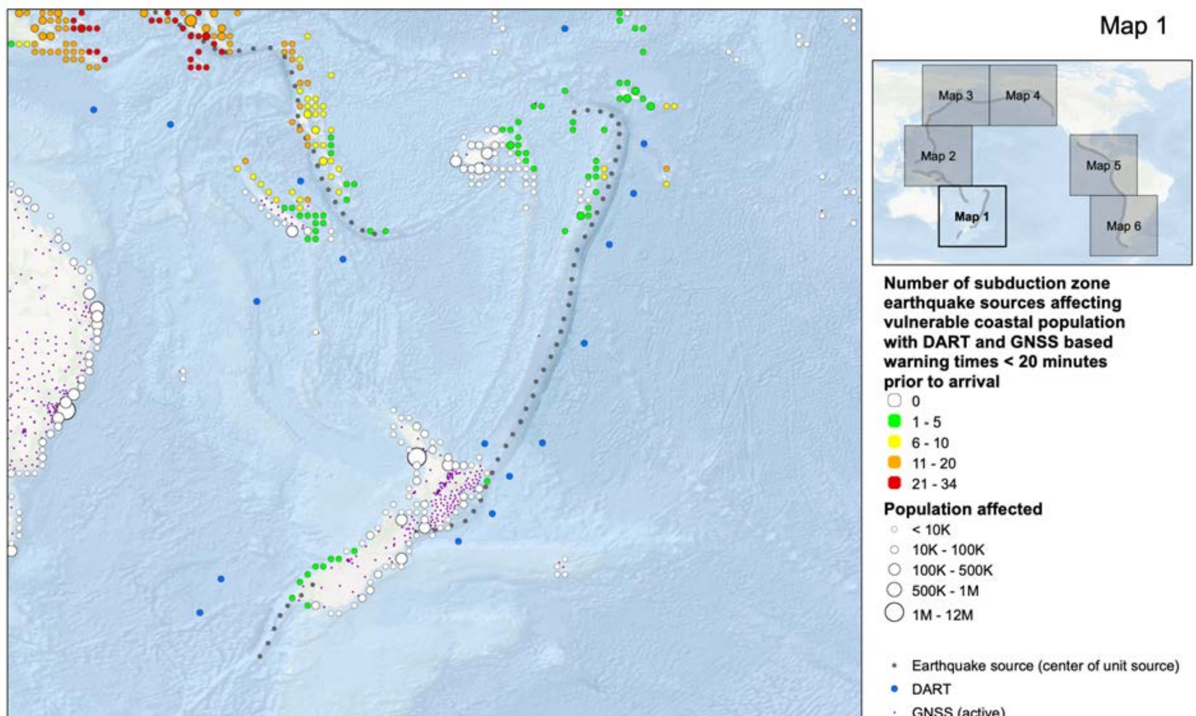


Figure A19. Hypothetical network effectiveness if GNSS TEC can be combined with DART. This analysis assumes a spatial coverage of GNSS TEC of 300-1200km from the GNSS station, sufficient satellite constellation density, and at least one DART measurement to provide absolute amplitude scaling of the tsunami.

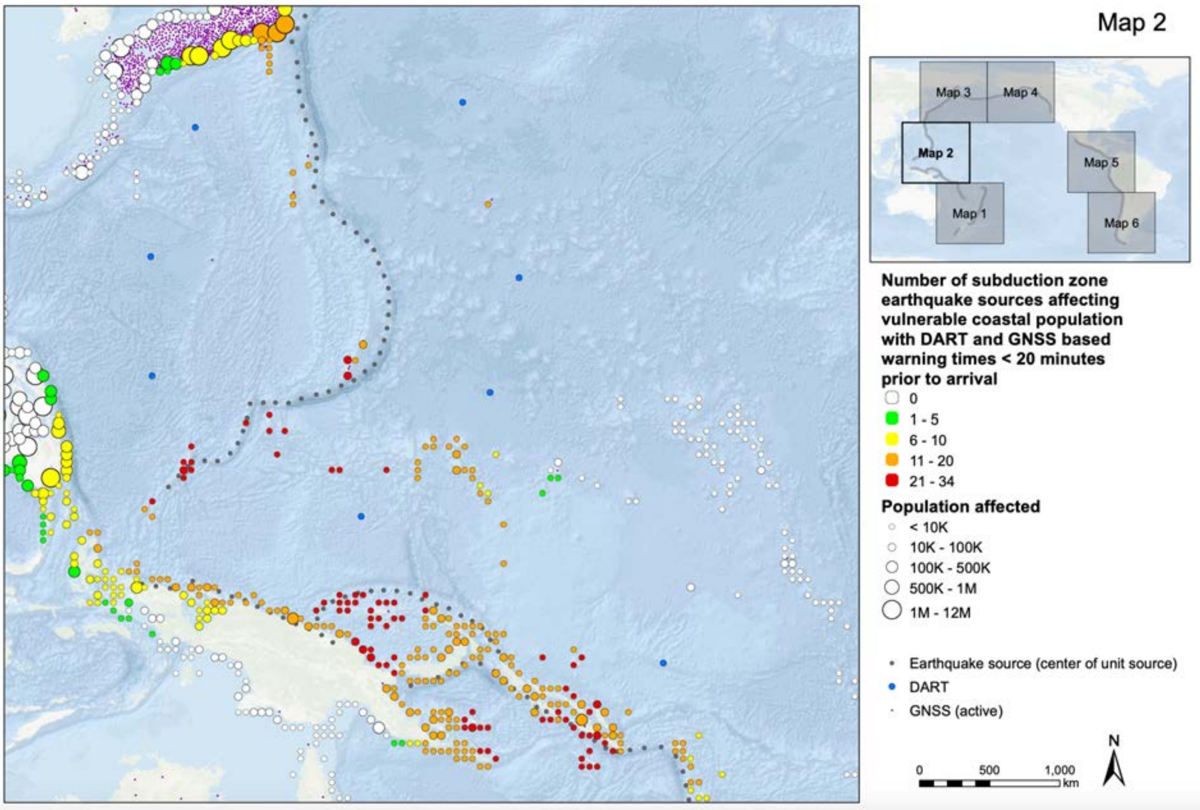


Figure A20. As per figure A19, but for Map 2.

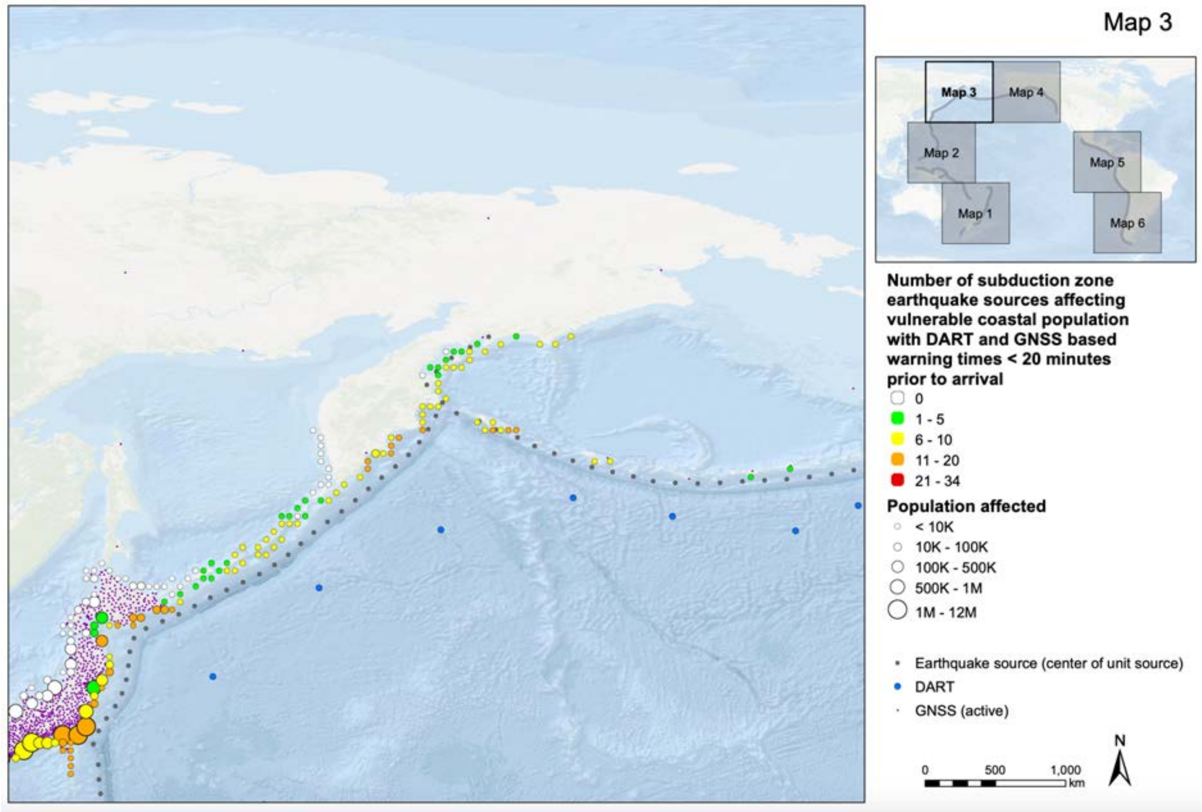


Figure A21. As per figure A19, but for Map 3.

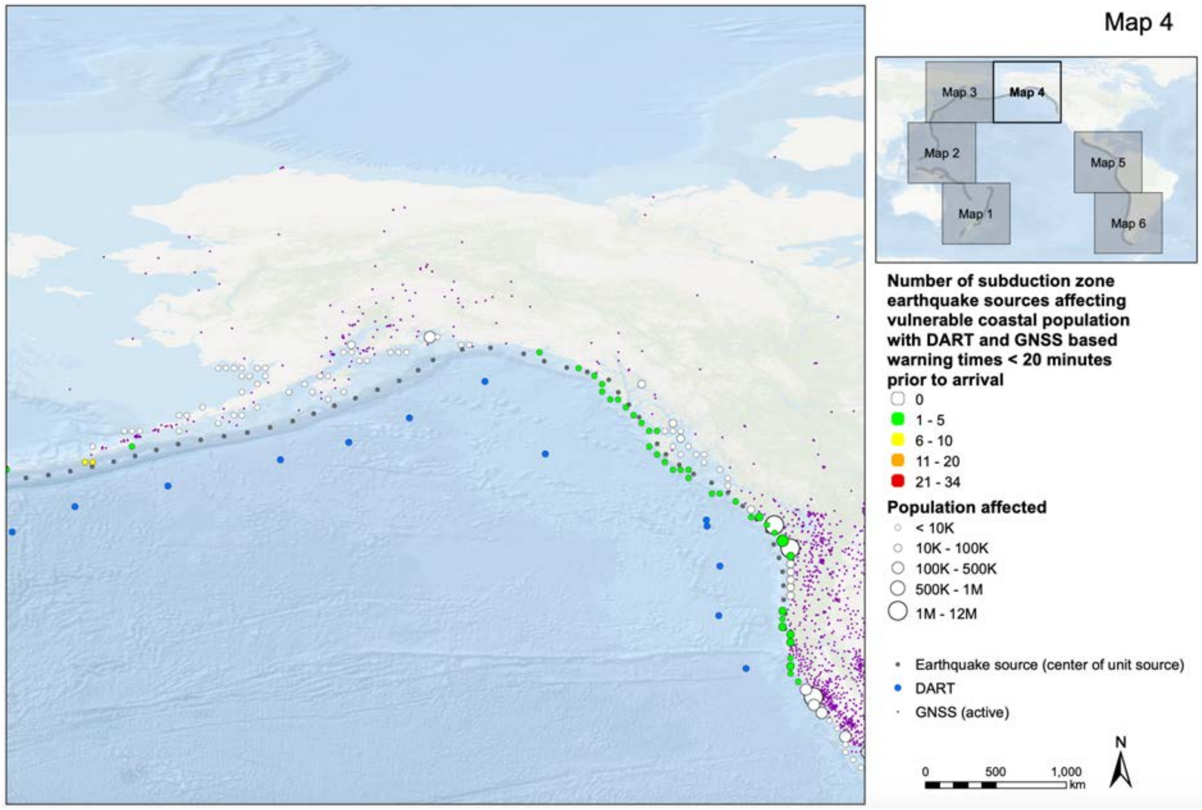


Figure A22. As per figure A19, but for Map 4.

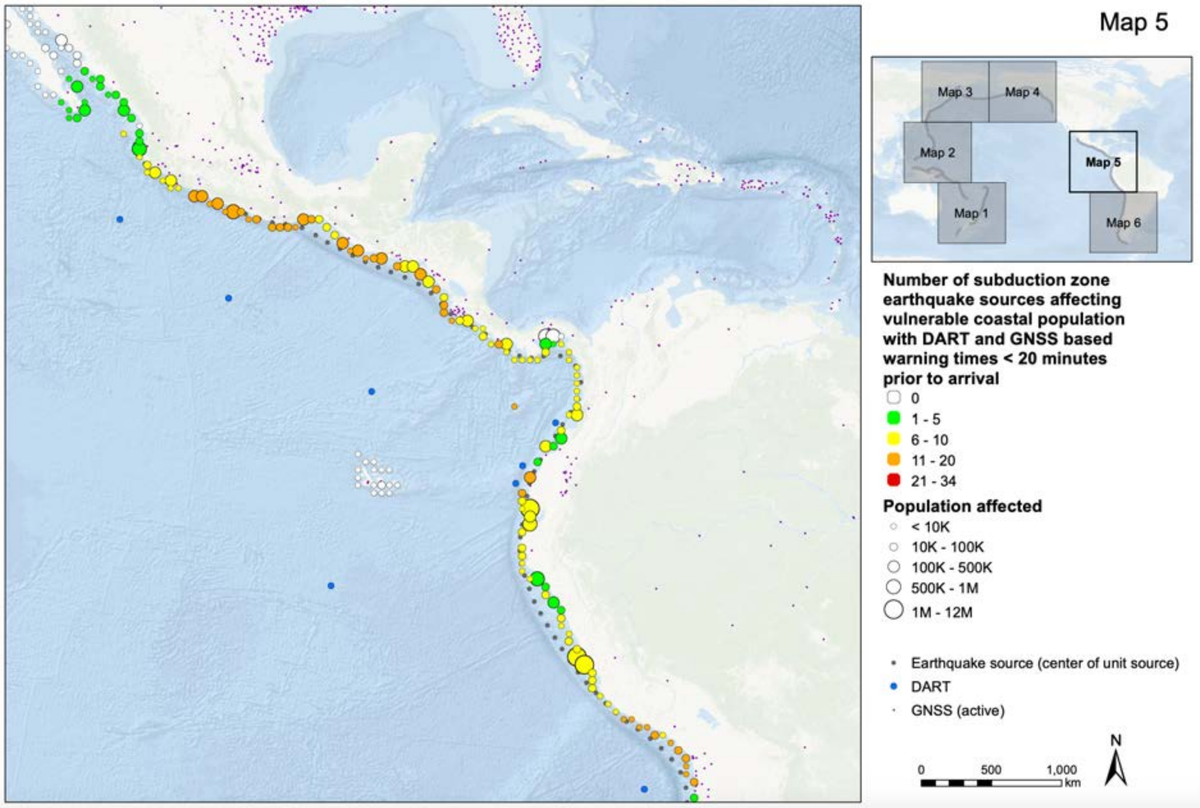


Figure A23. As per figure A19, but for Map 5.

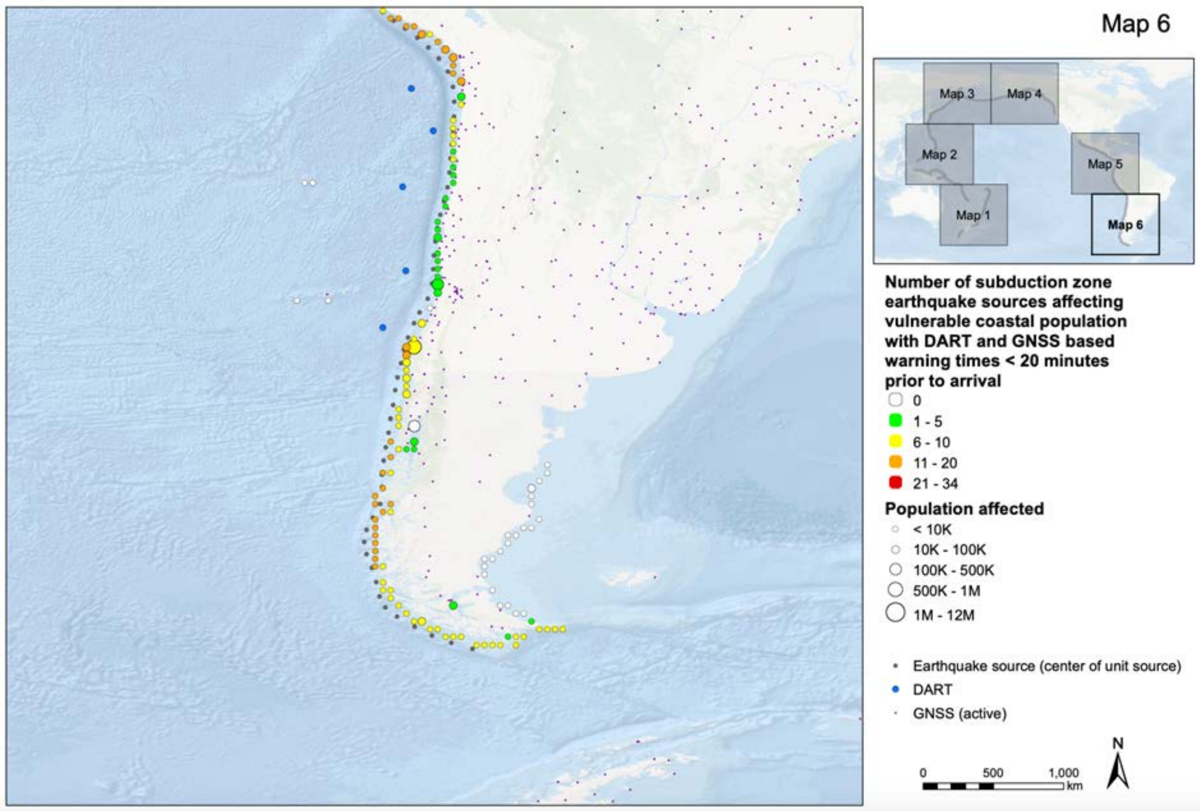


Figure A24. As per figure A19, but for Map 6.