

2.6 GNSS データ等を用いた津波波源の即時推定 (2)

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(Tsushima, H. and Y. Ohta, 2014: Review on near-field tsunami forecasting from offshore tsunami data and onshore GNSS data for tsunami early warning, *J. Disaster Res.*, **9**, 339-357)

Review:

Review on Near-Field Tsunami Forecasting from Offshore Tsunami Data and Onshore GNSS Data for Tsunami Early Warning

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[Received February 3, 2014; accepted April 10, 2014]

This paper reviews recent studies on methods of real-time forecasting for near-field tsunamis that use either offshore tsunami data or onshore global navigation satellite system (GNSS) data. Tsunami early warning systems for near-field coastal communities are vital because evacuation time before tsunami arrival is usually very short. We focus on forecasting between the occurrence of a tsunamigenic earthquake and the arrival of the first tsunami at a near-field coast – typically a few tens of minutes or less after the earthquake. Offshore tsunami measurement that provides coastal communities with direct information on impending tsunamis is very effective in providing reliable tsunami predictions. Crustal deformation due to coseismic slips at an earthquake fault detected by real-time GNSS analysis is quite useful in estimating fault expansion and the amount of slip, which in turn contributes to timely tsunami warnings, e.g., within 10 minutes, even for huge interplate earthquakes. Our review encompasses methods on the leading edge of research and those already in the process of being applied practically. We also discuss an effective combination of methods developed for mitigating tsunami disasters.

Keywords: offshore tsunami observation, real-time GNSS (GPS), near-field tsunamis, tsunami early warning system, combination use

1. Introduction

The huge major earthquake that struck northeastern Japan's Pacific Ocean on March 11, 2011, was named the 2011 off the Pacific coast of Tohoku Earthquake by the Japan Meteorological Agency (JMA) (hereafter, 2011 Tohoku earthquake). The earthquake's moment magnitude (M_w) was 9.0, and it triggered a massive tsunami that devastated an 850 km swath of coastal Japan, took more than 15,880 lives, and set off a nuclear plant disaster in Fukushima.

The JMA first estimated the earthquake to be JMA magnitude (Katsumata, 2004 [1]) (M_{jma}) 7.9 based on rapid analysis of short-period seismic waves (Tatehata, 1997 [2]). Three minutes after the earthquake, the JMA issued the first tsunami warning for coastal Japan based on this estimated magnitude (Ozaki, 2011 [3]), e.g., a 3-6 m tsunami (larger in some locations) would affect coastal regions near to the tsunami source. An offshore Global Positioning System (GPS) buoy (Kato et al., 2000 [4]) deployed off northeastern Japan then recorded a steep rise in sea level and the JMA updated the tsunami warning 28 minutes after the main shock (Ozaki, 2011 [3]) at heights upgraded to 6-10 m or more. The spilling wave of the tsunami, which was over 10 m in height, struck the most exposed coastal region ~30 minutes after the main shock. The first warning was clearly underestimated given the actual tsunami height because the estimated magnitude of 7.9 was much smaller than the true magnitude of 9.0, i.e., the underestimation of the true scale led to an underestimation in the height of the resulting tsunami. The update based on the GPS-buoy measurement demonstrates that tsunami height observed offshore is very effective in rapid, reliable updating of tsunami warnings. The 2011 Tohoku earthquake and its associated tsunami clearly reaffirm the need for an accurate tsunami early warning system, the importance of rapid reliable determination of earthquake magnitude, and the reliability of tsunami prediction based on offshore tsunami observation.

In this review, we focus on recent studies in methods for the real-time forecasting of near-field tsunamis using either offshore tsunami data or onshore global navigation satellite system (GNSS) data. The time window we discuss is from when an earthquake and tsunami occur to when the tsunami arrives at the near-field coast – typically 0 minutes to 30 minutes. We first review recent progress in real-time tsunami forecasting based on offshore tsunami measurement and onshore GNSS data. We then briefly describe current efforts designed to improve

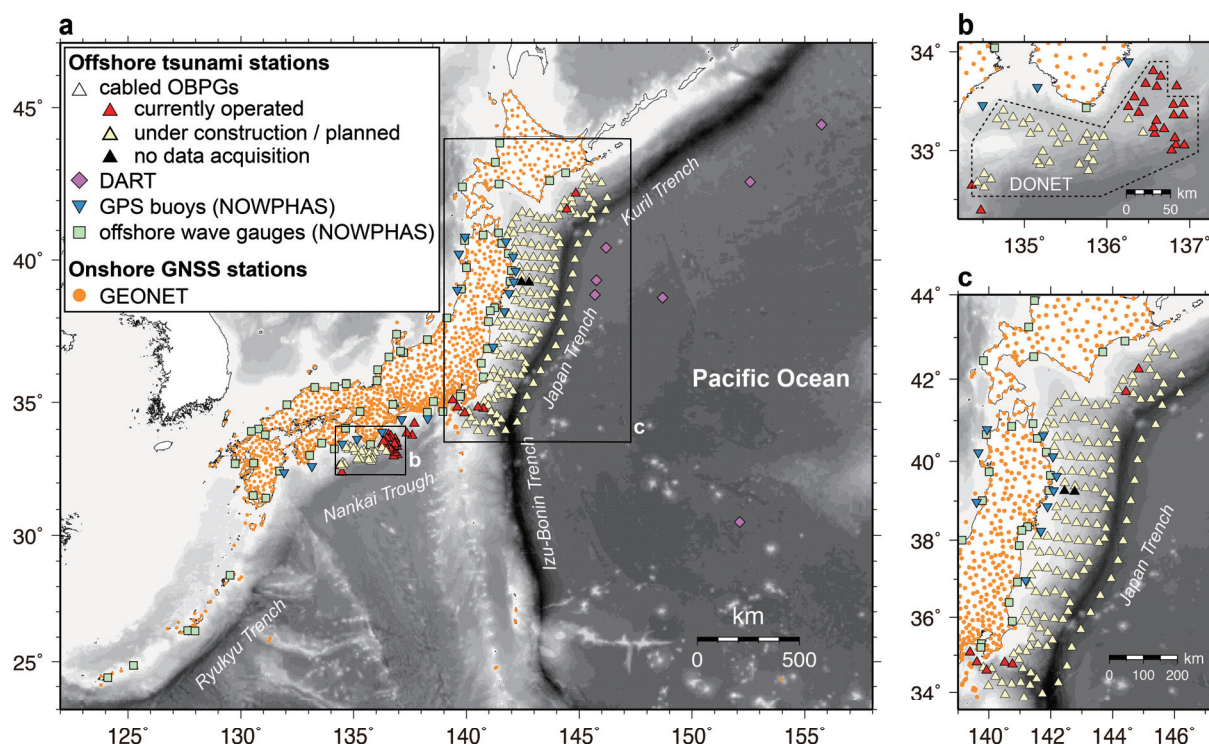


Fig. 1. Map of stations for offshore tsunami and onshore GNSS observations around the Japan Islands. (a) shows an overall view; (b) and (c) show enlarged views focusing on DONET and the Japan-Trench cable network, respectively.

the tsunami early warning system in Japan following the 2011 Tohoku earthquake. We also discuss recommendations how existing multiple sensors could be used to improve the tsunami early warning system for dealing with large-scale events.

2. Real-Time Tsunami Forecasting Based on Offshore Tsunami Data

2.1. Offshore Tsunami Observation System

Observation of water waves plays an important role in tsunami forecasting because such observations may detect tsunamis. Directly measuring tsunamis provides reliable information aiding in tsunami forecasting, both for tsunamis generated by regular tsunamigenic earthquakes and for those caused by tsunami earthquakes, i.e., earthquakes followed by tsunamis that are much larger than predictions based on seismic data analysis alone (Kanamori, 1972 [5]), and nonseismic events such as landslides (e.g., Miller, 1960 [6]). Specifically, offshore tsunami observations are very effective in early tsunami forecasting because they provide measurement of a tsunami before its arrival at the near-field coast. In this section, we introduce offshore tsunami observation systems and tsunami studies using offshore data, focusing on the Japanese case.

Over the last 30 years, dozens of offshore tsunami observation systems have been deployed in deep-ocean areas, i.e., water depth > 1 km. One such deep-ocean system is the cabled ocean-bottom earthquake and tsunami

observation system (triangles in **Fig. 1**). The system consists of ocean-bottom pressure gauges (OBPGs) for monitoring tsunamis. These OBPGs are pressure sensors that utilize quartz oscillators (e.g., Takahashi, 1981 [7]). The resonant frequencies of quartz crystals that are changed by an amount proportional to both pressure and temperature are measured. By applying temperature compensation that is valid under thermal equilibrium conditions, measured frequencies are converted to bottom pressure. Then, under hydrostatic equilibrium conditions, pressure is converted to water depth or relative sea level. In 2013, eight cabled systems were installed off Japan (Meteorological Research Institute, 1980 [8]; Fujisawa et al., 1986 [9]; Kanazawa and Hasegawa, 1997 [10]; Momma et al., 1997 [11]; Eguchi et al., 1998 [12]; Hirata et al., 2002 [13]; Saito, 2007 [14]; Kaneda et al., 2009 [15]). The northeastern cable system is no longer operational, however, because its land-based station was destroyed by the 2011 Tohoku earthquake tsunami, i.e., the two OBPG stations shown by black triangles in **Fig. 1**. These systems are operated by the JMA, University of Tokyo, National Research Institute for Earth Science and Disaster Prevention (NIED), and Japan Agency for Marine-Earth Science and Technology (JAMSTEC). Each cable system consists of 2-3 OBPGs (**Fig. 1(a)**), except for the Dense Oceanfloor Network System for Earthquakes and Tsunamis (DONET, now called DONET1), which has 20 (Kaneda et al., 2009 [15]) (**Fig. 1(b)**). Observed pressure data sampled at a frequency greater than 1 Hz are transmitted in real time to land-based stations through submarine cables. These Japanese cabled observatories are deployed on landward slopes of trenches where sub-

duction earthquakes often occur (**Fig. 1**), so they measure pressure variations caused both by propagating tsunamis and by deformation of the permanent seafloor just below OBPG locations, such as the 2003 Tokachi-Oki earthquake ($M_w 8.3$) (Mikada et al., 2006 [16]; Tsushima et al., 2012a [17]) and the 2011 Tohoku earthquake ($M_w 9.0$) (e.g., Maeda et al., 2011 [18]; Tsushima et al., 2011 [19]). Seafloor deformation indicates the height of tsunamis generated at OBPG locations, so it also provides important geodetic data on target tsunamis (Ito et al., 2011 [20]; Saito et al., 2011 [21]; Tsushima et al., 2011 [18]). Another system in use is the Deep-ocean Assessment and Reporting of Tsunamis (DART) (González et al., 2005 [22]), which is a worldwide network of offshore tsunami observatories developed by the Pacific Marine Environmental Laboratory (PMEL) of the National Oceanic Atmospheric Administration (NOAA) (Titov et al., 2005 [23]). DARTs around Japan are shown by purple diamonds in **Fig. 1(a)**. DART also consists of OBPGs for measuring offshore tsunamis, as well as the Japanese cabled system, but data transmission differs from that in cabled systems, i.e., observed data are transmitted to data centers via moored buoys and communication satellites (González et al., 2005 [22]). Currently, more than 45 DARTs have been deployed worldwide by NOAA and other countries, and the data they record are made available via the Internet by the National Data Buoy Center¹. DART has two reporting modes – standard mode and event mode (Meinig et al., 2005 [24]). In standard mode, the sampling rate of transmitted data is 15 minutes to observe oceanic tides. Once an automatic tsunami-detection algorithm (Mofjeld, 1997 [25]) is triggered, reporting mode switches to event mode. The typical sampling rate during event mode is one minute, which is constrained mainly by the satellite communications baud rate. DART stations are deployed outside regions of potential permanent seafloor deformation due to subduction earthquakes (Spillane et al., 2008 [26]) (**Fig. 1(a)**).

Many tsunamis generated by moderate to great earthquakes have been detected by cabled and DART OBPGs, even though amplitudes of tsunamis at station sites may have been only a few centimeters or less (Hino et al., 2001 [27]; Hirata et al., 2003 [28]; Titov et al., 2005 [23]). The tsunami waveform observed at an OBPG is simpler than that observed at a coastal tide-gauge station and provides a tsunami source signature free of distortion due to complex coastal topography (e.g., González et al., 1991 [29]). Since 2000, much tsunami data has been used to investigate earthquake source parameters by comparison with results of numerical tsunami simulation. Hino et al. (2001) [27] and Hirata et al. (2003) [28] analyzed cabled-OBPG tsunami waveforms from $M_w 6$ -7 earthquakes and demonstrated that using offshore data is effective in constraining source-fault parameters. Other studies have used inversion analysis of OBPG data to estimate tsunami sources, i.e., coseismic fault slips, and/or initial sea-surface distribution of tsunami events such as

the 2003 Tokachi-Oki earthquake ($M_w 8.3$) (Tanioka et al., 2004 [30]), the 2006 and 2007 Kuril earthquakes ($M_w 8.3$ and $M_w 8.1$), (Fujii and Satake, 2008 [31]), the 2010 Chile earthquake ($M_w 8.8$) (Fujii and Satake, 2013 [32]), and the 2011 Tohoku earthquake ($M_w 9.0$) (discussed later).

GPS-buoy systems also observe offshore tsunamis (Kato et al., 2000 [4]) (blue reverse triangles in **Fig. 1**). In such systems, a moored buoy with a GPS antenna detects the arrival of tsunamis as a change in wave height using real-time kinematic baseline GPS (or GNSS). GPS buoys are operated by the Ministry of Land, Infrastructure, Transport and Tourism and the Port and Airport Research Institute as wave stations that are part of the Nationwide Ocean Wave information network for Ports and HarborS (NOWPHAS) (Nagai, 1998 [33]). Sea-level observations at a sampling interval of one second (Kawai et al., 2010 [34]) are transmitted in real time by radio waves to land stations. These systems are deployed offshore within 20 km of the coastline (**Fig. 1**), which is constrained mainly by radio wave broadcast limits. Water at deployment sites is shallower (100-400 m) than for deep-ocean OBPGs. A tsunami generated by the 2004 Kii-Peninsula earthquake ($M_w 7.4$) was detected at a GPS buoy deployed off Muroto about eight minutes earlier than at the nearby coast (Kato et al., 2005 [35]). The GPS-buoy event data were used together with the cabled-OBPG data in the tsunami-source inversion studies by Baba et al. (2005) [36], Satake et al. (2005) [37], and Saito et al. (2010) [38]. Later, many GPS buoys were installed off Japan's coast. The large tsunami generated by the 2010 Chilean earthquake ($M_w 8.8$) was the first such event detected by the GPS-buoy array (11 buoys) (Kawai et al., 2010 [34]). Offshore wave stations of NOWPHAS, which were operating before GPS-buoy deployment, are within several kilometers of the coast and have recorded many tsunamis (e.g., Takayama et al., 1994 [39]) (green squares in **Fig. 1**). These stations also detect tsunamis before their arrival at nearby coasts (e.g., Nagai and Ogawa, 2004 [40]).

These various offshore stations clearly detected the huge tsunami generated by the 2011 Tohoku earthquake ($M_w 9.0$). Specifically, at near-field stations such as cabled OBPG and GPS-buoy stations, the tsunami was detected 5-10 minutes before it reached coastal tide-gauge stations nearest to the tsunami source (Tsushima et al., 2011 [19]). The tsunami waveforms thus obtained show remarkable characteristics (e.g., Maeda et al., 2011 [18]; Tsushima et al., 2011 [19]; Kawai et al., 2011 [41]), i.e., an initial gradual sea-level increase followed by an impulsive tsunami, i.e., a large-amplitude short-period tsunami, for which total sea-level elevation was 5 m or more. Such offshore data reflecting a significant source signature have been used by many source-estimation studies in back-propagation analysis for detecting the source extent (Hayashi et al., 2011a [42]), trial-and-error forward tsunami modeling for obtaining slip distribution (Maeda et al., 2011 [18]), and tsunami inversion for determining the final distribution of coseismic fault slips (Fujii et al., 2011 [43]; Gusman et al., 2012 [44]) and initial

1. <http://www.ndbc.noaa.gov/dart.shtml>

sea-surface displacement (Saito et al., 2011 [21]). These studies obtained a source image that having two major features – a huge-extent source that should generate long-period tsunamis and a small-extent, largely elevated source east of the epicenter near the trench that should produce an impulsive tsunami. By exploiting high-quality high-sampling-rate (HSR) tsunami data (< 1 minute) within or near the source, multiple time windows were inverted to determine the spatiotemporal evolution of the coseismic fault rupture (Satake et al., 2013 [45]) and initial sea-surface displacement (Takagawa and Tomita, 2012a [46], 2012b [47]). Results demonstrated that the generation of the delayed rupture or sea-surface displacement occurred in the near-trench area north of the epicenter. Note that Takagawa and Tomita (2012b) [47] modified a tsunami-inversion scheme in which coseismic permanent deformation was estimated from tsunami data both at observing points and at different points, for example, using GPS-buoy data, so that the coseismic step at a nearby land station of each GPS buoy could be obtained. Coseismic vertical deformation at the land station appears as an apparent sea-level variation in GPS-buoy data, i.e., a baseline shift in a sea-level time series, producing a source-image artifact. They demonstrated the effectiveness of their scheme for reducing source artifacts and the applicability to real-time inversion for tsunami forecasting.

As mentioned, various tsunami sizes have been measured by offshore tsunami stations, and several examples exist in which offshore sensors have detected tsunamis before they reached the coast. Another benefit is that obtained tsunami data provided substantial information on impending tsunamis. In the next section, we review studies on near-field tsunami forecasting based on these offshore tsunami data.

2.2. Real-Time Tsunami Forecasting Based on Offshore Tsunami Data

Various methods have been proposed for using offshore tsunami data to forecast near-field tsunamis. In the calculation of tsunami behavior near to and on land, i.e., inundation, nonlinear effects such as bottom friction should be taken into account, but calculation is costly and takes time even though rapid forecasting is important, especially with near-field tsunamis. To reduce calculation time, several studies have used linear assumption for forecasting calculation. Under linear assumption, a predicted tsunami waveform is expressed by a linear superposition of pre-calculated tsunami waveforms, i.e., Green's functions. Other studies have calculated nonlinear tsunami behavior quickly using high-performance systems effectively. Here, we review these methods and their retrospective applications to the 2011 Tohoku earthquake, focusing mainly on those of Japanese research groups.

Several studies have proposed tsunami forecasting based on source estimation using offshore tsunami data exploiting the abundant source information such data contain. PMEL developed Short-term Inundation Forecast

for Tsunamis (SIFT), based on DART data inversion, for modeling coseismic fault-slips to forecast inundation in real time for coastal sites (Titov et al., 2005 [23]). Preceding an earthquake, they calculate tsunami propagation using pre-defined subfaults at shallow parts of worldwide subduction zones using the "Method Of Splitting Tsunami" (MOST) numerical model (Titov and González, 1997 [48]). This generates a propagation database storing time series information on water height and flow velocity (Gica et al., 2008 [49]). After an earthquake, DART measurement is inverted to determine slip distribution on pre-defined subfaults using Green's function extracted from the database. Once the source is obtained, the linear combination of the pre-calculated time series of water heights and velocities from subfaults is applied. Results are then used as dynamic boundary conditions for real-time nonlinear calculation to forecast inundation at coastal sites of interest. The inundation model is optimized so that several hours of inundation modeling are done in minutes on a single processor (Tang et al., 2008 [50]). SIFT has been applied to many tsunami events (e.g., Tang et al., 2008 [50]; Wei et al., 2008 [51]). The 2011 Tohoku earthquake ($M_w 9.0$) was the first event for which near-field data were recorded by multiple DART systems with good station coverage (Tang et al., 2012 [52]). Tang et al. (2012) [52] showed that the SIFT algorithm identified a 300-400 km long 100 km wide source area from the first tsunami waves recorded at the two closest DARTs within 1.5 hours of the main shock. The source model was used to investigate the tsunami impact on near-field Japanese coasts by Wei et al. (2013) [53], and it agreed very well with post-tsunami survey data (Mori et al., 2011 [54]), modeling the run-up height, spatial pattern, and extent of inundation with an accuracy of 85.5%. PMEL recently added subfaults to the outer-trench region and tested it with the 2012 Japanese tsunami event (Bernard et al., 2013 [55]).

In contrast to PMEL's approach, several other studies inverted offshore tsunami data to determine the distribution of initial sea-surface displacement to forecast coastal tsunamis. This approach is advantageous in forecasting tsunamis both due to interplate earthquakes and due to other types of tsunami events, such as splay faulting (e.g., Fukao, 1979 [56]), the geometry of which is difficult to estimate in real time. Since 2000, several researchers have devoted their efforts to developing such a method.

Tsushima et al. (2007 [57], 2009 [58]) proposed a tsunami-forecasting algorithm called "tsunami Forecasting based on Inversion for initial sea-Surface Height" (tFISH) that inverted cabled-OBPG tsunami waveform data to determine initial sea-surface displacement distribution (seafloor deformation in Tsushima et al., 2007 [57]) and then synthesized tsunami waveforms at near-field coastal sites by linearly combining pre-calculated Green's functions. In tFISH analysis, the origin time and epicenter location of an earthquake based on seismic-wave analysis are used but not requiring information about earthquake magnitude and fault geometry. In addition to the spatial smoothness constraint, the epi-

center location is incorporated as a damping constraint to stabilize the solution of the inversion. Successive calculation of forecasting is done within a few minutes. To improve forecasting reliability, OBPG data are updated at short time intervals to repeat forecast calculation. To calculate Green's functions from unitary displacement of small sea-surface segments, they calculated finite difference approximation of linear long-wave equations (Satake, 1995 [59]) to construct a Green's function database. Tsushima et al. (2007 [57], 2009 [58]) tested the algorithm in its application to "observations" simulated numerically from the source model of the 1896 Sanriku tsunami earthquake (Tanioka and Satake, 1996 [60]). Results showed that the tFISH algorithm provides accurate coastal predictions of arrival times and amplitudes of the first tsunamis, obtaining these more than 20 minutes before the first wave reached its maximum at the coastal site nearest to the source. They retrospectively applied it to real data from a small tsunami generated by a local earthquake (M_w 6.8) and forecast the tsunami at coastal tide-gauge stations. Tsushima et al. (2009) [58] showed that forecasting accuracy was affected by spatial relationships between the tsunami source and offshore observation stations. They suggested a possible solution, i.e., deploying additional offshore stations with spacing comparable to the trench-parallel length of the target tsunami source. Tsushima et al. (2012a) [17] improved their Green's function so that the tFISH algorithm was applicable to data from an OBPG inside the source area. OBPG records at the source contain pressure variation due to deformation of the permanent seafloor, which is geodetic data important for constraining a source effectively. They applied the tFISH algorithm with improved Green's functions to real data obtained by four OBPGs during the 2003 M_w 8.3 Tokachi-Oki earthquake, two of which were within the source area, thus demonstrating its good performance in both source estimation and near-field tsunami forecasting.

Yasuda et al. (2007) [61] and Yasuda and Mase (2013) [62] developed a method of near-field tsunami forecasting based on the inversion of offshore GPS-buoy data. They considered source areas of Nankai Trough earthquakes, such as the huge earthquake that simultaneously ruptures all the source areas of the Tokai, Tonankai, and Nankai earthquakes (Central Disaster Management Council., 2003 [63]) to perform numerical tsunami forecasting experiments. Results demonstrated preferable performance in forecasting tsunami waveforms at nearby coastal sites and the effectiveness of additional GPS buoys for rapid forecasting. Tatsumi and Tomita (2008) [64] incorporated information on epicenter location into the inversion of GPS-buoy data. Its effectiveness in improving source estimation and tsunami forecasting was shown in its application to observation data simulated from historical Nankai Trough earthquakes. To forecast real-time inundation, Tatsumi and Tomita (2009) [65] newly combined source inversion, estimation of the volume of water overflowing into coastal sites, and the level-fill method. Tatsumi and Tomita (2013) [66] also developed other real-time inundation forecasting by jointly applying their in-

version scheme and nonlinear tsunami inundation calculation accelerated by graphics processing unit computing. Numerical simulation results based on the 1946 M 8.0 Nankai earthquake showed that the method provided reliable estimates of inundation within five minutes of first-peak tsunami amplitudes being observed at offshore stations near the coast of interest.

These forecasting methods based on inversion for initial sea-surface displacement have been applied retrospectively to the 2011 M_w 9.0 Tohoku earthquake. Tsushima et al. (2011) [19] used offshore tsunami data from four cabled-OBPGs and five GPS-buoy stations off northeastern Japan for applying the tFISH algorithm. Results of forecasting, done 20 minutes after earthquake occurrence, demonstrated with a lead time of more than 5 minutes that tsunamis with heights greater than 5-10 m were predicted at tide-gauge stations nearest to the source. Yasuda et al. (2012) [67] performed detailed analyses by varying combinations of GPS buoys used in inversion and comparing predicted tsunami waveforms and inundation height data measured by the Tsunami Joint Survey Group (Mori et al., 2011 [54]). They obtained several important findings, e.g., tsunami prediction based on data from three GPS buoys with nonbiased station density were more accurate than from five buoys with biased density. Tatsumi and Tomita (2013) [66] forecast real-time inundation retrospectively and demonstrated that their method provided predictions of arrival time, height, and inundation with $\sim 50\%$ error about five minutes before the first tsunami reached its maximum height at the site. Their inundation modeling is incorporated in real-time tsunami hazard mapping developed by Takagawa et al. (2013) [68], improving speed and enhancing accuracy. The system also incorporates tsunami inversion with spatiotemporal rupture effects (Takagawa and Tomita, 2012b [47]) and thus provided inundation mapping soon after acquisition of offshore tsunami measurements. Time for successive calculation was about two minutes.

Another useful approach to forecasting coastal tsunami height in real time is the law of tsunami amplification. The height of a tsunami is amplified during its propagation from offshore to the coast because water depth is reduced. This effect is based on the energy-conservation law, known as Green's law (Green, 1837 [69]). If an accurate amplification factor can be prepared in advance, its real-time application to tsunami height observed offshore could immediately provide its predicted height at a coastal point of interest. Several studies have investigated the tsunami-amplification factor using past tsunami data and/or numerical tsunami simulation. To estimate maximum tsunami height at a coastal tide gauge using data from offshore OBPGs, Baba et al. (2004) [70] modified Green's law by assuming that tsunami wave height is doubled by reflection at a coastline, i.e., total reflection. Note that water depth at a coastal station was assumed implicitly to be 1 m. The proposal showed good performance in far-field tsunami events but could not be verified for near-field events because there were no appropriate data at that time. Takayama (2008) [71] extended amplification

factors of Baba et al. (2004) [70] by taking into account water depth at the coastal station and then discussed the effects of other parameters such as epicenter distance on amplification factors. His statistical analysis showed that corrections related to offshore tsunami amplitude and/or epicenter distance improve the performance of amplification factors, depending on how the offshore OBP and coastal tide gauge are paired. Hayashi (2010a) [72] derived amplification factors for first-wave height and maximum-wave amplitude between NOWPHAS stations, i.e., offshore wave gauges and GPS buoys, and coastal tide gauges using both near-field and far-field tsunami measurement. In addition to water depth at a coastal site, he empirically incorporated the effects of a tsunami wave reflected from the coastline, both on coastal tsunami height and on offshore tsunami height. This is because offshore stations in NOWPHAS are located < 20 km from the coastline and a reflection wave might return to an offshore station before the first-wave height reached its peak there. Prediction error using his method is within 30% of observations. Hayashi (2010b) [73] proposed using amplification factors practically in a tsunami warning system. Baba et al. (2013) [74] conducted Monte Carlo tsunami simulation to investigate the empirical relationship between DONET pressure measurements and coastal tsunami height for near-field tsunamigenic earthquakes. More than 3,400 fault models were assumed and resulting tsunami propagation was calculated by parallelized tsunami simulation code, called “JAMSTEC improved former code developed by Geoscience Australia and URS Corporation (Jakeman et al., 2010 [75]) which uses Satake (2002) [76]’s kernel” (JAGURS) (Baba et al., 2014 [77]). By analyzing simulation results, they developed an amplification-factor in which the average waveform of the absolute value of hydrostatic pressure change at all DONET stations is used as offshore data for predicting coastal tsunami height. Because DONET stations are deployed where the sea is deep, the obtained tsunami-amplification factor and DONET data enable rapid prediction of coastal tsunami height. The accuracy of estimation is comparable to that using GPS-buoy data acquired near the coast.

In addition to these developments, an approach was designed using a pre-calculated tsunami-scenario database. Abe and Imamura (2010) [78] proposed a strategy for real-time inundation forecasting of near-field tsunamis in which numerous tsunami-inundation scenarios were calculated before earthquakes occurred. Then, following an earthquake, the number of possible scenarios was narrowed down from pre-calculated inundation scenarios by referring to information available in real time, such as seismic source parameters and tsunami height observation. This reduced real-time calculation time. To evaluate its performance, Abe and Imamura (2012) [79] applied the method retrospectively to the 2011 Tohoku earthquake. Results indicated that prediction for Sendai agreed with observed inundation, but that for Ishinomaki was an underestimation. That could be mitigated by adding inundation scenarios of $M8.6$ - 9.0 earthquakes to the database

(original: $M < 8.4$) and using GPS-buoy data nearest the city. Estimated lead times for these two cities would be 25-30 minutes.

Seto et al. (2013) [80] proposed an effective, convenient procedure for evaluating and helping prevent underestimations in tsunami warnings using offshore GPS-buoy measurement. Their evaluation model is a simple equation expressing the relationship between moment magnitude and initial or maximum tsunami height measured by a GPS buoy. Preceding an earthquake, evaluation equations are derived using results of numerical tsunami simulation for various fault models. Following an earthquake, the first evaluation is made by comparing initial tsunami heights from GPS-buoy measurement and those estimated by their model. Heights predicted by the model are obtained by applying the rapid magnitude used for the previously issued tsunami warning to their equations. A second evaluation is based on maximum tsunami height measured at GPS buoys in the same way. These convenient evaluations are very easy and done in real time.

As shown, significant efforts have been made to improve tsunami forecasting based on offshore data. Given the effectiveness of offshore tsunami data, such improvements should be continued in the future.

3. Real-Time Tsunami Forecasting Based on Onshore GNSS Data

3.1. High-Rate GNSS Data Processing for Seismology

Recently, HSR (typically used 1-Hz-sampled) GNSS data have been used to create GNSS seismograms. GNSS data directly measure ground displacement, unlike broadband seismometers that measure velocity or acceleration, and they must be mathematically integrated once or twice to obtain displacement data that may, however, be potentially degraded by iteration (e.g., Miyazaki et al., 2004 [81]). HSR GNSS data are a basic technology for real-time tsunami forecasting based on onshore GNSS data, so we briefly introduce studies on HSR GNSS data processing and its applications below.

Conventionally, GNSS data – usually GPS – were used to estimate “daily” coordinates to determine the seismological nature of crustal deformation in seismological and geodesic applications. The difference between coordinates from the day before and the day after an earthquake, for example, is strongly indicative of coseismic displacement. Similarly, steady and slow displacement trends caused by plate motion and subduction are important information for estimating strain accumulation before an earthquake. In this context, most GNSS data processing software packages used for scientific purposes estimate these daily coordinates precisely, e.g., Bernese GNSS software (Dach et al., 2007 [82]), GIPSY-OASIS II (Lichten and Border, 1987 [83]), and GAMIT/GLOBK (Herring et al., 2006 [84]). For the estimation of the daily coordinates, the unknown parameters are limited. Bernese

GNSS software, for example, thus applies standard least squares adjustment when estimating unknown parameters with *a priori* information. The standard least squares method is typical and robust in estimating daily GNSS coordinates. Least squares estimation is, however, clearly unsuitable for more frequent coordinate estimation, i.e., with a one-second sampling interval, because of the large number of unknown parameters to be solved at any one time. In this situation, processing time will be longer than realistic calculation time. Standard least square estimation is also unsuitable for real-time processing because of all of the epochs necessary for each calculation. Kalman-filter-based (KF) processing, in contrast, is useful for estimating such unknown time-dependent parameters. The KF forms the basis of most state estimation algorithms used in navigation systems and uses all of the measurement information available instead of just the most recent set of measurements (Groves, 2013 [85]). Many examples of precise positioning software use the KF approach, e.g., GIPSY-OASIS II and RTKLIB (Takasu, 2010 [86]).

The potential of HSR GPS data for use in seismology was first discussed by Hirahara et al. (1994) [87], Miyazaki et al. (1998) [88], Ge (1999) [89], and Ge et al. (2000) [90], who focused on very short baselines for detecting large displacement based on short-time-interval analysis. Based on these studies, Larson et al. (2003) [91] found good agreement between ground displacement integrated from records of strong seismic motion and long baseline 1-Hz-sampled GPS position estimates collected several hundred kilometers from the 2002 Denali earthquake epicenter and based on GIPSY-OASIS II processing. Bock et al. (2004) [92] also detected a large surface wave caused by the Denali earthquake using the dense network of 1-Hz GPS stations of the Southern California integrated GPS network (Hudnut and Nancy, 2001 [93]). In their analysis, displacements were derived using independent 1 Hz instantaneous positioning proposed by Bock et al. (2000) [94]. Ohta et al. (2006) [95] analyzed kinematic GPS records of the 2004 Sumatra-Andaman earthquake using very long baselines of over several thousand kilometers and demonstrated good agreement between GPS time series and integrated broadband seismic displacement records. Ohta et al. (2008) [96] extracted “pure” coseismic displacements for the 2008 Iwate-Miyagi inland earthquake deduced from kinematic precise point positioning (PPP). Bilich et al. (2008) [97] showed GPS seismology capabilities specifically with regard to the relative strengths of GPS and seismic datasets based on the 2002 Denali earthquake. Most of these previous studies estimated coordinate values relative to the reference site(s) and required precise information on GPS satellite orbits. Some efforts have been directed, however, toward estimating only short-term variations in GPS stations with no other reference sites. Issiki et al. (2000) [98], for example, proposed point-precise variance detection (PVD) to estimate only short-term variations at GPS stations based on multiple GPS satellite carrier-phase data and GPS almanac data with a stand-alone dual-frequency GPS re-

ceiver. They suggested that because PVD only requires small calculational loads, it would allow quasi real-time rapid measurement of components with high-frequency variations. Colosimo et al. (2011) [99] presented a similar approach using what they called the variometric approach for displacement analysis stand-alone engine. This approach estimated the time series of three-dimensional “velocity” and integrated the estimated velocity into “displacement” over the interval. Biases in estimated velocities accumulating over time, however, appeared as drift in estimated time series, thus limiting the integration interval to a few minutes (Branzanti et al., 2013 [100]). Li et al. (2013) [101] proposed capturing coseismic displacements quickly in real time using a single GNSS receiver, assuming that if the receiver position before an earthquake was determined accurately enough, phase ambiguity between GNSS stations and satellites could be fixed in subsequent epochs. They indicated that this assumption could overcome the convergence problem of kinematic PPP and avoid the integration of the variometric approach (e.g., Colosimo et al., 2011 [99]). These many efforts mainly described the detection of displacement caused by coseismic and passage of seismic waves such as surface waves. HSR GPS time series are also useful for modeling seismic ruptures on fault planes. Several studies investigated the rupture process of large earthquakes (e.g., Miyazaki et al. (2004) [81]; Yokota et al., (2009) [102]) based on HSR GPS time series. The advantage of HSR GPS time series is the sensitivity of cumulative slip distribution compared to that of a seismometer.

Larson (2009) [103] reviewed “GPS seismology” and suggested that the future of GPS seismology should focus on using GPS as a strong-motion instrument. Strong-motion seismometers measure acceleration, whereas GPS seismology contributes to accurately estimating displacement. The seismometer is band-limited because it is an inertial system consisting of a spring and weight. The GPS (GNSS) seismometer is also inertial between the earth and GNSS satellites, but the system is larger than the seismometer and, in principle, has no band limit.

Based on developments in GPS (GNSS) seismology, several researchers have attempted to use real-time GNSS analysis results in earthquake and tsunami warning systems. In the section that follows, we review the role of real-time GPS (GNSS) seismology in tsunami disaster mitigation.

3.2. Rapid Earthquake-Size Determination and Tsunami Forecasting Based on GNSS Data

Following the 2004 Sumatra-Andaman earthquake, Blewitt et al. (2006) [104] proposed that true earthquake magnitude and tsunamigenic potential could be obtained from inland GPS data within a short period – less than 15 minutes – of the main shock. In September 2007, a workshop entitled “Real-Time GPS Science Requirements” was held in Leavenworth, Washington, USA, at which many geodesy and seismology scientists and engineers, including one of this paper’s authors, worked to-

gether to determine the requirements of a GPS network for disaster prevention. Based on workshop discussions, Blewitt et al. (2009) [105] identified a potentially important design for a GNSS or GPS system that could contribute to real-time earthquake source determination and tsunami warning. They suggested that 10 mm real-time full GNSS – that is, not limited to GPS – displacement accuracy is required to prevent false tsunami warnings. Similarly, Sobolev et al. (2007) [106] proposed a GPS shield concept that used special near-field GPS arrays to reliably predict tsunami wave heights. Based on numerical experiments of earthquake and tsunami scenario for Padang, Sumatra, they suggested that a GPS shield measuring both horizontal and vertical displacements could resolve higher order features of slip distribution on the plate interface. Based on numerical experiments, they showed that tsunami waves could be predicted reliably and issued in less than 10 minutes of an earthquake's occurrence. Song (2007) [107] proposed a unique approach in which he estimated seafloor displacement that was projected or extrapolated from near-field GPS measurements. Seafloor displacement along the cross-shelf section were modeled using an empirical trench profile. Once seafloor displacement was estimated, initial tsunami height and propagation could be calculated immediately. He replicated three historical tsunamis – the 2004 Sumatra-Andaman earthquake, the 1964 Alaska earthquake, and the 2005 Nias earthquake – based on real and/or simulated GPS data and succeeded in reproducing coastal tsunami heights recorded by tide gauges. He also indicated that these steps were achievable within a few minutes of the trigger event. The Geospatial Information Authority of Japan (GSI) developed a rapid earthquake fault model estimation algorithm and Nishimura et al. (2010) [108] a corresponding procedure using real-time 1 Hz GPS data. They tried estimating rectangular fault model using multiple approaches. In one, they assumed a focal mechanism – fault strike, dip, and rake angle – for each pre-defined rectangular area determined experimentally based on previous large earthquakes. Based on this focal mechanism, they estimated a single coseismic fault model using inversion analysis with *a priori* information.

The $M_w 9.0$ 2011 Tohoku earthquake occurred after these pioneering efforts. As mentioned in the introduction, the JMA tsunami warning system clearly underestimated actual tsunami height. Effort to rapidly determine earthquake size based on real-time GNSS data progressed following the 2011 Tohoku earthquake. Allen and Ziv (2011) [109] extracted static offset shortly after S-wave arrival was detected using a simple algorithm based on the short-term average (STA) versus the long-term average (LTA) trigger algorithm (Allen, 1978 [110]). Melgar et al. (2012) [111] proposed and called fastCMT to determine the moment tensor and centroid location for large earthquakes based on real-time high-rate GPS data. They applied their algorithm to two large earthquakes replayed in simulated real-time mode: the 2003 $M_w 8.3$ Tokachi-Oki and the 2010 $M_w 7.2$ El Mayor-Cucapah earthquakes. They demonstrated that an accurate centroid moment ten-

sor (CMT) solution could be obtained within two to three minutes after rupture initiation without any need for *a priori* information. The fastCMT algorithm uses a pre-defined arbitrary grid to invert the CMT solution, so the earthquake location is limited in CMT inversion both on the subducting plate interface, and at other locations, such as intraslab, outer rise, and inland earthquakes. This is a great advantage in actual monitoring because large earthquakes occur in areas other than on the subducting plate interface. The fastCMT algorithm assumes a point source, which is reasonable in a situation where an inland GNSS site is located far enough from the centroid. For larger magnitude events, this clearly increases because the fault plane also expands with increasing magnitude. For reliable, accurate early tsunami warnings, information on both finite fault size and slip amount is important.

Ohta et al. (2012) [112] developed an algorithm to detect/estimate static ground displacement due to earthquake faulting from real-time kinematic GPS (RTK-GPS) time series, called the RAPiD algorithm. This algorithm has three main steps to the algorithm. The first is displacement detection, where the value from the STA and LTA based on 1 Hz RTK-GPS data is calculated. When this value is larger than a previously defined threshold, the algorithm registers static displacement occurrence. In the second step, once an occurrence is registered, the amount of displacement is estimated. Finally, this estimated displacement is used to create a fault model of one rectangular plane with homogeneous slip. To assess its performance, they applied the RAPiD algorithm to data obtained in the 2011 Tohoku earthquake. Based on the quasi real-time fault determination, they found that estimated moment release reached $M_w 8.7$ five minutes after the origin, which is relatively close to the actual earthquake size of $M_w 9.0$ compared to the first JMA magnitude estimation. They simulated a tsunami based on the estimated fault plane using pre-computed tsunami Green's functions. The estimated tsunami arrival time and height agreed well with actual tide-gauge data. It is noteworthy that their algorithm detected an event realized by the real-time GPS time series only. In other words, their algorithm needs no other information, for example, from the JMA's earthquake early warning (EEW) system. In their developed algorithm, however, the estimated moment release of $M_w 8.7$ was clearly underestimated compared to the actual $M_w 9.0$, which may have been due to the heterogeneity of fault slip distribution along the plate interface.

To determine earthquake size and expansion more reliably, Crowell et al. (2012) [113] investigated two different methods for rapidly inverting heterogeneous finite earthquake slip distribution using real-time GPS time series. One method used pre-defined fault planes, such as the plate interface, and the other used the fastCMT solution proposed by Melgar et al. (2012) [111] to initially estimate the ruptured fault plane. They applied their two methods to the 2003 $M_w 8.3$ Tokachi-Oki earthquake and the 2010 $M_w 7.2$ El Mayor-Cucapah earthquake in northern Baja California. Based on the two methods, they concluded that the fastCMT method performed well for both

earthquakes with the added benefit of requiring no *a priori* information on fault geometry. The estimated earthquake size (M_w) was the almost same as the actual one for both methods. These results were reasonable because they estimated heterogeneous slip distribution on the fault plane. In a similar approach, Colombelli et al. (2013) [114] developed an inversion algorithm for slip distribution on the fault plane. Their strategy does not require restrictive *a priori* assumptions about the ongoing earthquake and it is a “self-adapting” strategy. The initial fault plane used for slip inversion is built using preliminary estimation of magnitude and the model is then upgraded as new values for magnitude are determined. Hoechner et al. (2013) [115] applied the GPS shield concept proposed by Sobolev et al. (2007) [106] to the 2011 Tohoku earthquake. They also estimated tsunami height along Japan’s coastline based on estimated slip distribution on the plate interface. The estimated tsunami height exceeded 10 m around central Tohoku – a height consistent with actual tsunami height based on field surveys compiled by Mori et al. (2012) [116]. Melgar et al. (2013) [117] modified the fastCMT algorithm through extension to a linear geometry by superposing point sources. It was modified mainly for the huge earthquake ($M_w > 8.5$) because the point source assumption is clearly unsuitable for such a huge event. They inverted several moment tensors (MTs) along pre-defined points, after which they calculated the weighted average of all individual MTs to obtain a single CMT estimation. For a posteriori analysis of the 2011 Tohoku earthquake, they estimated a moment magnitude of 9.0 and its mechanism. This modified fastCMT algorithm is very useful for estimating both the earthquake mechanism and magnitude for large interplate earthquakes and other types of event. After information on the earthquake mechanism and centroid is received from modified fastCMT analysis, they inverted for static slip using the same coseismic offsets as those used for CMT modeling.

These previous studies mostly used baseline analysis for processing real-time GNSS (GPS) data. Baseline analysis has been used in many precise positioning applications such as geodetic surveys. Baseline analysis in real time yields cm-level accuracy with few difficulties by processing carrier-phase observables of GNSS (GPS) signals at both user and reference receivers. In real-time baseline analysis, the reference site(s) must be used for processing. Ohta et al. (2012) [112] highlighted the effect of ground shaking on real-time baseline GPS analysis due to the passage of the long period seismic wave. Shaking at the reference site could cause incorrect estimation of coseismic permanent displacement that could, in turn, cause unstable estimation of the coseismic fault model or slip distribution on the plate interface. From this perspective, they indicated that PPP is another way to monitor real-time crustal deformation. PPP uses data such as precise ephemerides and GNSS (GPS) satellite clock corrections provided by various analysis centers to estimate site coordinates without the need for data from reference sites. PPP is advantageous in light of the problem of the shaking of the reference site. Wright et al. (2012) [118] applied

the PPP strategy to GPS data processing for the 2011 Tohoku earthquake for rapid coseismic fault slip determination; inevitably, their result was not affected by the reference site shaking. Real-time PPP, however, is slightly lacking in precision, accuracy, and stability compared to conventional real-time baseline analysis. This is mainly due to the quality of GNSS (GPS) satellite real-time orbits and clock corrections. With future improvements of those products, the PPP approach should play a leading role in real-time crustal deformation monitoring.

In this and earlier sections, we have reviewed many works on near-field tsunami warning systems based on offshore tsunami measurement and onshore GNSS data. In the sections that follow, we briefly review progress in implementing many of these strategies by governmental agencies in Japan.

4. Progress in Implementing Near-Field Tsunami Warning Systems Based on Offshore Tsunami Data and Onshore GNSS Data in Japan

4.1. Offshore Tsunami Data

Here we briefly introduce progress made in implementing tsunami forecasting using offshore tsunami data for tsunami early warning systems in Japan.

After the 2011 Tohoku earthquake and tsunami, the JMA investigated the contents of tsunami warning bulletins and the timing of their issue (Hoshiba and Ozaki, 2012 [119]; Japan Meteorological Agency, 2013 [120]). The investigation pinpointed several problems, such as the underestimation of earthquake magnitude based on rapid analysis of seismic waves soon after the earthquake occurred that resulted in the underestimation of tsunami height. Improvements required to overcome some of the problems in basic policies and technical strategies were also indicated. After the investigation, certain activities were performed to overcome these problems. Katsumata et al. (2013) [121], for example, developed a procedure for avoiding underestimating earthquake magnitude. Thereafter, in many great efforts for implementing these improvements, the JMA introduced a new tsunami warning system on March 7, 2013 (Japan Meteorological Agency, 2012 [122]; Japan Meteorological Agency, 2013 [120]).

One of the problems identified related to the tsunami warning for the 2011 Tohoku earthquake was that the data recorded by cabled OBPGs located further offshore than the GPS buoys were not used for updating the warning (Hoshiba and Ozaki, 2012 [119]). This was because the operating procedures for updating warnings using OBPG data had not yet been established at the time. The JMA therefore started to use cabled OBPG data for updating tsunami warnings on March 9, 2012. The measurement of tsunami height at an OBPG is converted to the height predicted on the coast by applying an empirically obtained tsunami amplification factor. In 2012 and 2013, the JMA

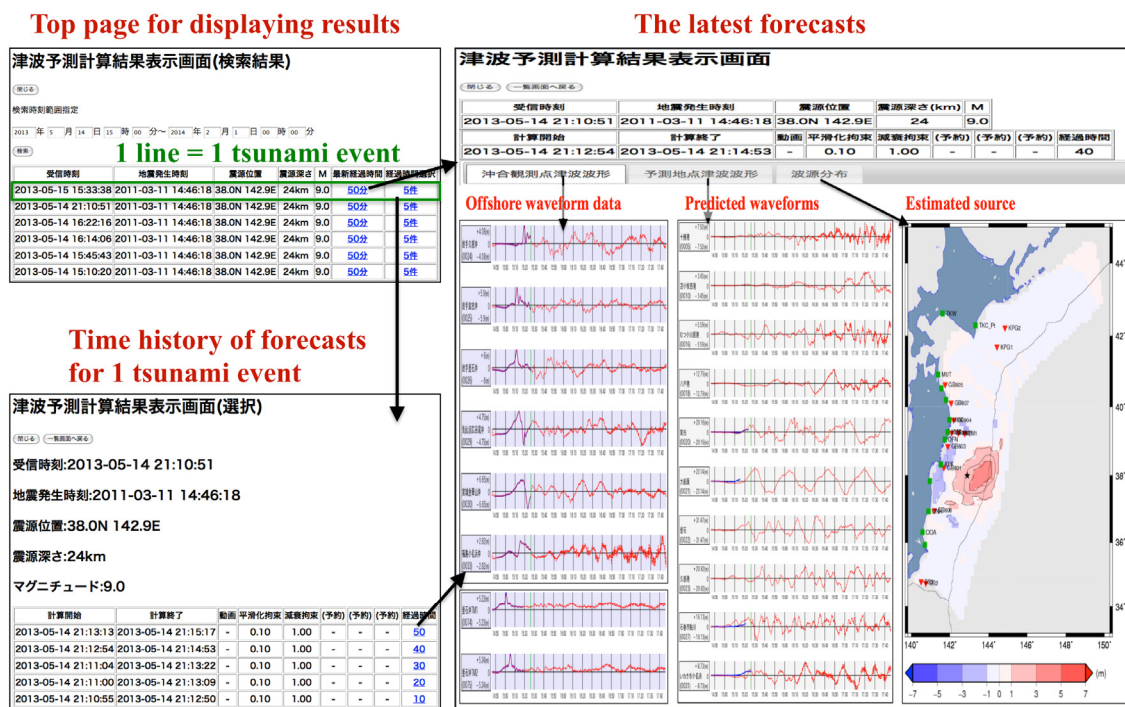


Fig. 2. Example of results provided by the prototype system for real-time tsunami forecasting developed by the Meteorological Research Institute.

deployed DART buoys in the outer regions of the Japan Trench to enhance offshore tsunami monitoring capabilities – these now account for three DART buoys been deployed in total (**Fig. 1(a)**). On December 25, 2012, these deep-ocean pressure measurements started being used for updating tsunami warnings based on the amplification factor approach.

Further improvement is presently being promoted. As mentioned in Section 2.2, source inversion is one of the most effective techniques for real-time tsunami prediction from offshore tsunami measurements, especially those recorded by cabled OBPGs and DART buoys, because these data contain substantial information about the source. In an effort to implement such forecasting procedures into a tsunami warning system, the Meteorological Research Institute of the JMA developed a prototype system in 2012 for predicting near-field tsunami based on source inversion (Tsushima et al., 2013 [123]). Here, we briefly introduce the functions of the system and its performance for applications in real-time analysis. The major part of the system is based on the tFISH algorithm (Tsushima et al., 2009 [58], 2012a [17]) in which the distribution of initial sea-surface displacements inverted from offshore tsunami data is used for forecasting tsunami waveforms at target sites. In this system, offshore points near coastal sites are chosen as the target site. The predicted tsunami height at the target site is then amplified to obtain the heights at coastal sites using the amplification factors developed by Hayashi (2010b) [73]. What triggers the real-time forecasting analysis is the earthquake magnitude fed into the system. Once the given magnitude exceeds a pre-defined threshold, forecasting calculation

is started automatically and is carried out repeatedly at short intervals by renewing offshore tsunami waveform data. The figures for the obtained results are produced automatically, i.e., the offshore tsunami waveforms, estimated source model, and predicted tsunami waveforms (**Fig. 2**). These are viewed with a web browser and operators can therefore obtain the latest forecasting results promptly. The software used for real-time analysis is installed on hardware that is designed specifically for the operation of software. The database of Green's functions for the tsunami has been developed for two oceanic areas around Japan, i.e., the Kuril-Japan Trench and the Nankai Trough seismogenic regions. A simulated test run was performed using offshore tsunami data from the 2011 Tohoku earthquake (Tsushima et al., 2013 [123]). Forecasting calculations were performed in 10 to 50 minutes after the main shock at intervals of 10 minutes. Successive calculations were then undertaken without error despite the lack of data on offshore measurements, and the forecasting calculation was accomplished within about two minutes. This shows that the system will deliver good performance for real-time analysis.

In future, many applications that may be developed for this prototype system using real data from past tsunami events and those using simulated data from assumed tsunamigenic earthquakes of various sizes and in various locations will be required for determining the detailed performance of the system. A performance test in which offshore data without tsunami signals are used will be very important for verifying the capability of the system to avoid false alarms. The knowledge accumulated from test runs such as these will help bring the prototype system

closer to practical operation.

Studies on enhancing the procedures for reducing real-time noise will be very important in practical operations of tsunami early warning systems, both for improving tsunami forecasting accuracy and for avoiding false alarms due to noise contamination in offshore measurements. Specifically, a procedure for treating OBPG data should be prioritized for development for the large OBPG network that is currently under construction around Japan as detailed in Section 5. In addition to the effects of tsunamis, OBPG data include the effects of ocean tides, atmospheric and oceanographic disturbances, vertical deformation of the seafloor, seismic waves, and elastic oscillations of water columns (Kajiura, 1970 [124]; Nosov and Kolesov, 2007 [125]; Matsumoto et al., 2012 [126]). It should be noted that false pressure variations with substantial amplitudes due to temperature changes around OBPGs are sometimes recorded by an OBPG (Takahashi, 1981 [7]; Hirata and Baba, 2006 [127]; Baba et al., 2006 [128]; Inazu and Hino, 2011 [129]). Preexisting procedures have been applied for reducing such noise components (Saito, 1978 [130]; Ishiguro et al., 1984 [131]; Matsumoto et al., 2000 [132]), and studies on the analysis of noise properties and the development of procedures to reduce individual noise components have been implemented (Hirata and Baba, 2006 [127]; Baba et al., 2006 [128]; Tolkova, 2009 [133]; Inazu and Hino, 2011 [129]; Matsumoto et al., 2012 [126]). Continuous improvements in noise reduction methods promise to deliver more reliable tsunami warnings in the future.

4.2. Onshore Real-Time GNSS Data

In this section, we briefly introduce steps in the progress of the implementation of real-time GNSS processing for tsunami early warning systems in Japan.

The GSI operates a network of more than 1,200 continuous GNSS stations – the GNSS Earth Observation Network System, called GEONET – across the entire area of Japan (**Fig. 1**). Most GEONET stations record and transmit dual-frequency phase data once each second (1 Hz), and these have been used primarily as reference point data for public surveys since before the 2011 Tohoku earthquake struck. Following the 2011 Tohoku earthquake, the policy board of the Headquarters for Earthquake Research Promotion in Japan commented about the future of high-precision tsunami early warning systems based on the underestimation of the predicted tsunami height for the 2011 Tohoku earthquake. The policy board suggested that the structural reinforcement of tsunami early warning systems required for the mitigation of the tsunami hazard. They also highlighted the requirement for real-time crustal deformation monitoring by the onshore pre-existing GEONET. The Central Disaster Management Council of the Cabinet Office of the Japanese government also pointed out the requirement for more precise, more rapid tsunami forecasting techniques that should be based on a comprehensive approach. Following these governmental statements, the GSI decided from 2011 on the de-

velopment of monitoring crustal deformation in real time using GEONET real-time streaming data.

The GSI has been performing routine daily analyses of GEONET data since 1996, and so it revised its analysis strategies for routine daily analysis to achieve higher precision and greater accuracy. The version of the routine analysis strategy currently used is version 4. This daily routine analysis solution is called the “F3” solution. The latency of the F3 solution is two weeks because of the delay in the release of final precise orbital information from the International GNSS Service. The GSI also estimates coordinates for all of the GEONET sites every three hours (data length is six hours, latency of the processing result is five hours), which is called the Q3 solution, based on the ultra-rapid orbital information from the International GNSS Service. Previously, the GSI did not estimate the coordinates in real time except for a limited number of stations – a maximum of 30 sites – for experimental purposes (Nishimura et al., 2010 [108]). At around this same time, Tohoku University started its preliminary analysis for real-time GNSS data processing for rapid earthquake size determination and its practical use in tsunami early warning systems, which started before the 2011 Tohoku earthquake (Ohta et al., 2010 [134]; Kobayashi et al., 2010 [135]). The GSI and Tohoku University subsequently jointly developed a new real-time analysis system using the GEONET for quasi real-time M_w estimation, which has been in operation since September 2012.

The GSI launched the prototype of the real-time GNSS (GPS) analysis system in 2012 with 146 GEONET stations mainly covering the Tohoku district, and this is planned for being expanded to cover all of Japan. This prototype system consists of three major components: (1) real-time GNSS data processing, (2) the automated extraction of displacement fields resulting from large earthquakes, and (3) the automated estimation of M_w by an approximated single rectangular fault model. For event detection, the RAPiD or EEW issued by the JMA has been adopted. This entire process is performed within a few minutes at most and estimated results are announced immediately to GSI personnel via email. The GSI is currently assessing the stability, precision, and accuracy of the real-time GNSS time series based on the prototype system composing the 146 GEONET sites. Under the test operation of the prototype, the GSI has reported many false positives in crustal deformation using the RAPiD algorithm and caused mainly by the instability of the real-time GNSS time series. Kobayashi et al. (2012) [136] improved the RAPiD algorithm to mitigate these false positives of crustal deformation. Under the improved algorithm, an earthquake occurrence is defined as having occurred only when the target GNSS site and all of its neighboring GNSS sites have detected a displacement. They suggested that the improved algorithm would reduce the occurrence of false positives dramatically. A group from Tohoku University has also developed a visualization tool for monitoring the real-time GNSS time series (Demachi et al., 2013 [137]). **Fig. 3** shows an example of the real-time GNSS time series for the 1126 station of GEONET

GEONET RTK-GPS(GNSS) time-series

1126 (TOSASHIMIZU3) w.r.t. 0252 (HEGURAJIMA) (baseline= 675.5km)

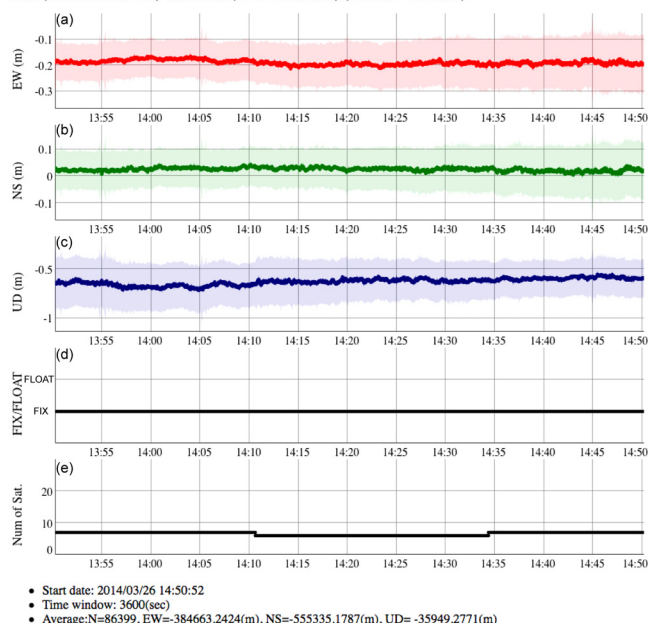


Fig. 3. Example of real-time GNSS time series visualization developed by Demachi et al. (2013) [137]. Real-time streaming data were analyzed at Tohoku University. (a), (b), and (c) show east-west, north-south, and up-down components; (d) shows the status of the phase ambiguity resolution of the GNSS data processing. FIX and FLOAT define whether phase ambiguity resolution is successful or unsuccessful; (e) shows the number of GNSS satellites used for processing. Note that this example is of a period in which nothing related to our subjects of interest has happened.

(Tosashimizu) relative to the 0252 station of GEONET (Hegurajima). The length of the baseline between the two sites is 676 km. The developed tool is used to plot the time series in real time and provide interactive operation. The tool is also used for zooming in on the time series interactively, which is an extremely important visualization function used in the actual monitoring of all GEONET sites. The GSI will thereby implement their visualization tool for real-time GNSS time series monitoring during 2014.

Based on these efforts, the GSI will expand real-time GNSS processing to Japan nationwide in 2014. Under current plans, the GSI intends to share information on earthquake size based on GNSS with the JMA.

5. Discussion and Concluding Remarks

In this section, we discuss projected developments for the introduction of a more reliable early warning system for near-field tsunamis. In Section 3, we have reviewed recent progress in near-field tsunami forecasting based on offshore tsunami measurements and onshore GNSS time series data. In this section, we will start by discussing the properties of each type of measurement.

Figure 4 shows the coverage of individual types of

sensors used in near-field tsunami prediction. The rapid analysis of short-period seismic wave data, for example, M_{jma} or EEW, by the JMA will provide the first information on the size and location of an earthquake. This is extremely important information in the first issuance of tsunami warnings.

Real-time GNSS data have an advantage compared with the seismometer in the robust estimation of the coseismic fault dimension and location because the spatial pattern of permanent coseismic displacement from the GNSS measurements is strongly affected by these source parameters. Many other approaches exist, of course, for rapid determining the size of an earthquake and the mechanism underlying it based on seismograms. W-phase analysis, for example (Kanamori, 1993 [138]; Kanamori and Rivera, 2008 [139]), is one way of estimating the magnitude of a huge earthquake within a very short time. Duputel et al. (2011) [140] demonstrated the use of rapid W-phase analysis based on F-net broadband seismic network data obtained by the NIED for the 2011 Tohoku earthquake. These analyses are based on a point-source assumption, but finite-source parameters such as heterogeneous slip distribution (Geist, 2002 [141]) and spatial extent greatly influence the resulting tsunami height distribution regarding near-field coastal areas. The estimated point source can be translated to the finite fault model experimentally by applying the scaling law between fault dimension and magnitude (e.g., Kanamori and Anderson, 1975 [142]). In the case of a huge earthquake, however, coseismic fault expansion and its aspect ratio may be extremely diverse because the width and length of the seismogenic zone differ between subduction zones. Benavente and Cummins (2013) [143] explored the applicability of W-phase waveform inversions for recovering the first-order coseismic slip distribution for a large earthquake. They initially estimated the point source based on W-phase inversion, then they used a simple linear multiple time window method to account for changes in rupture velocity using smoothing and moment minimization constraints to infer the slip and rake variations over the fault. They also identified one of the problems involved in their approach, which is the question of how fault dimensions are to be determined. Seen from this perspective, real-time GNSS data have a distinct advantage in tsunami early warning.

In Section 3.2, we have reviewed the many efforts based on real-time GNSS data for the rapid determination of earthquake size. Most studies identified that the entire process of earthquake size determination could be accomplished within a few minutes at most, which is almost same as with the source time function of the target event. As mentioned earlier, the GNSS is not band-limited, at least in principle. Real-time GNSS data are therefore expected to be useful in updating initial tsunami warnings based on short-period seismic data (**Fig. 4**). The use of onshore GNSS data alone, however, has limitations with regard to precise tsunami warnings because huge interplate earthquakes frequently occur far offshore. In fact, the maximum slip portion of the 2011 Tohoku earth-

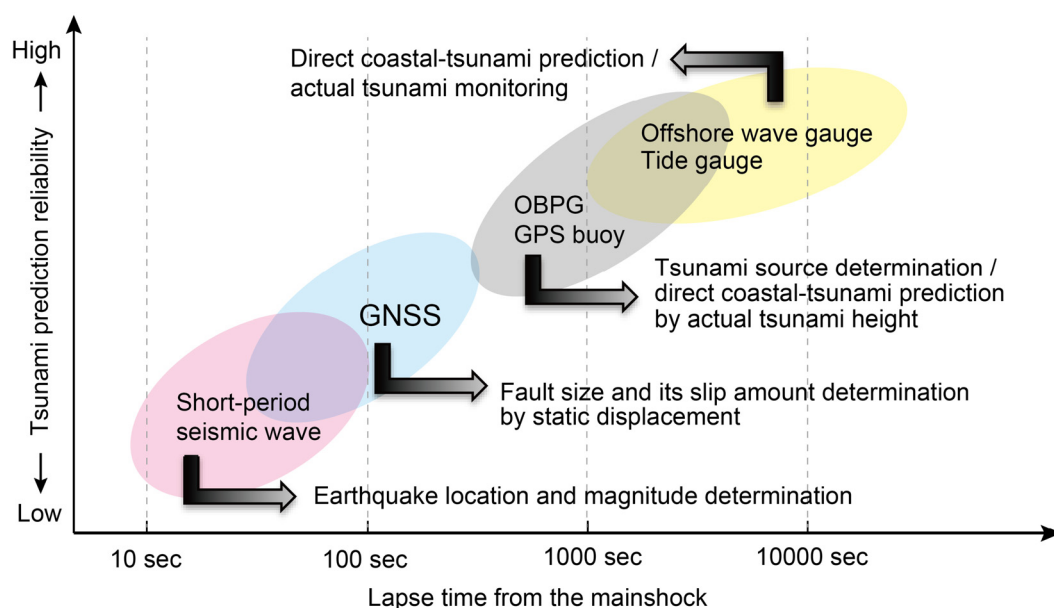


Fig. 4. Individual sensor coverage for near-field tsunami early warnings. The horizontal axis shows the lapse time after the main shock. The vertical axis shows the reliability of predicted tsunami results.

quake was concentrated mainly in the up-dip portion of the subducting plate interface (e.g., Ide et al., 2011 [144]; Iinuma et al., 2012 [145]; Satake et al., 2013 [45]). In the 2011 event, localized large slip in the shallower portion of the subducting plate generated an impulsive large tsunami (e.g., Maeda et al., 2011 [18]). Tsunami forecasting based on the estimated earthquake size and its expansion determined by using onshore data is also an indirect estimation and thus it is expected that the combined use of both onshore and offshore data will provide more reliable tsunami forecasting. Melgar and Bock (2013) [146], for example, developed a tsunami-forecasting algorithm based on the joint inversion of onshore GPS, strong motion, and offshore and coastal tsunami data for a fault-slip model. They demonstrated that rapid ingestion of offshore shallow-water (100-1000 m) wave-gauge data, including the cabled-OBPG data, substantially improves the earthquake source and tsunami forecasts for the 2011 Tohoku earthquake.

From this point of view, the actual measurement of tsunami height in the offshore region also is important for revising tsunami warnings. It also takes longer, however, to obtain tsunami signals from offshore tsunami observations than would be taken by measuring seismic waves and crustal deformation by using seismograph and GNSS because the tsunami propagates more slowly than elastic deformation. The time for detection depends strongly on the density and distribution of offshore sensors. In southwestern Japan, the DONET2 network, which consists of 31 OBPG stations (yellow triangles in **Fig. 1(b)**), is under now development around the Nankai seismogenic zone to complement the existing DONET1 (Kaneda, 2013 [147]). Along the Japan Trench region, a cabled ocean-bottom observation network of a large scale and with high density is now being constructed by the NIED (Uehira et al.,

2012 [148]; Kanazawa, 2013 [149]; Saito, 2013 [150]) (yellow triangles in **Fig. 1(c)**). With this network, 150 stations consisting of seismometer and pressure gauges is to be deployed at intervals of 30 to 60 km. This large-scale high-density OBPG network should prove to be very effective in improving the accuracy of tsunami forecasting very quickly, as shown by numerical simulations based on source-inversion techniques (Tsushima et al., 2012b [151]) and on data-assimilation approaches without an earthquake and tsunami source (Maeda et al., 2013 [152]), although this deployment is proving to be very expensive.

Coastal tide gauges provide on-site tsunami information that can be used in upgrading tsunami warnings for other coastal areas that have not been directly affected by the tsunami. Monitoring the tsunami decay process (Hayashi et al., 2009 [153], 2011b [154]; Hayashi, 2012 [155]; Saito et al., 2013 [156]) from tide-gauge data is also useful for the timely cancellation of warnings concerning both near- and far-field tsunamis (Hayashi et al., 2010 [157], 2012 [158]) because tsunami heights at tide gauges are linked directly to information on the loss of life.

Individual types of sensors, as indicated previously, have both advantages and disadvantages, which means that multiple sensors should be used in combination to bring out the advantages of individual data sources. We have already reviewed Melgar and Bock's approach in this section (Melgar and Bock, 2013 [146]), in which they demonstrated that the rapid ingestion of offshore shallow-water (100-1000 m) wave-gauge data substantially improved earthquake source and tsunami forecasts for the 2011 Tohoku earthquake. This is a very good example for the combination use of multiple types of sensors. We are also developing a different combination approach us-

ing onshore GNSS data and offshore tsunami measurement (Tsushima et al., 2012c [159]). Briefly, our algorithm combines the RAPiD algorithm with onshore GNSS data and the tFISH algorithm with offshore tsunami measurements. In the use of this algorithm, an initial sea-surface height distribution estimated from rapid GNSS data is used to incorporate robust information about the finite source size into the inversion of offshore tsunami data to obtain reliable tsunami predictions along near-field coasts. For more reliable, accurate tsunami forecasting, these combination approaches are expected to prove promising in overcoming the disadvantages of individual sensor types.

In Section 4, we have reviewed current progress in the real-time prediction of near-field tsunamis using offshore tsunami data by the Meteorological Research Institute and onshore rapid earthquake size determination based on the real-time GNSS data processing system of the GSI. It is hoped that government agencies will implement these approaches as soon as possible with a view toward mitigating the effects of disasters triggered by earthquakes and tsunamis. These systems should address many of the known problems under actual operational conditions, such as false positives. The EEW of the JMA started in 2007 could contribute greatly to disaster mitigation in Japan but not as long as EEW false positives continue to appear. Such was the case on August 8, 2012, in which a magnitude 2.3 earthquake struck Wakayama Prefecture in western Japan. The EEW predicted a maximum seismic intensity level of 4-7 for this event across wide areas of southwestern Japan. This false alarm was caused mainly by the large electric noise in the cabled ocean bottom seismometer. Every such failure becomes a stepping stone to success, however, and thus new approaches for a near-field tsunami early warning system such as onshore GNSS and offshore tsunami measurements are needed for performance testing in actual data-gathering environments.

In this paper, we have focused on developments in recent studies of real-time forecasting of near-field tsunamis using both offshore tsunami data and onshore GNSS data. Many other sensor types that exist could also be useful in the future for use in tsunami early warning systems. The many new approaches for the detection of tsunamis such as the observation of ionospheric disturbances due to tsunamigenic gravity waves (e.g., Rolland et al., 2010 [160]; Tsugawa et al., 2011 [161]; Galvan et al., 2011 [162], 2012 [163]; Komjathy et al., 2012 [164]), geomagnetic observations (e.g., Toh et al., 2011 [165]; Utada et al., 2011 [166]; Minami and Toh, 2013 [167]; Sugioka et al., 2014 [168]), and ocean radar measurement (e.g., Barrick, 1979 [169]; Lipa et al., 2006 [170]; Fuji et al., 2013 [171]). A review of these sensors is beyond the scope of this paper but, as mentioned above, the inventive combined use of multiple sensor types could lead to more robust, precise, and accurate tsunami forecasting systems for major earthquakes in the future and could contribute greatly to advances in tsunami disaster mitigation.

Acknowledgements

The authors thank Prof. Naoshi Hirata and Dr. Aitaro Kato for their invitation to take part in this special issue. We thank the University of Tokyo, JAMSTEC, JMA, the Ministry of Land, Infrastructure, Transport and Tourism, and the Port and Airport Research Institute for providing offshore and coastal tsunami data. We also thank Drs. Kenji Uehira and Toshihiko Kanazawa of NIED for providing information on Japan-Trench Cable Network OBPG stations. We thank GSI for providing real-time GPS data under a cooperative research agreement between GSI and Tohoku University. We are also grateful to the International GNSS Service for providing high-quality precise ephemerides as well as real-time observation data from tracking stations. This study was also supported by the MEXT project, Japan, "Observation and Research Program for the Prediction of Earthquakes" and supported in part by the Science and Technology Research Partnership for Sustainable Development (SATREPS). Careful reading of the manuscript and the contribution of constructive comments by reviewers were most valuable and helpful. Figures in this paper were prepared using Generic Mapping Tools (GMT) (Wessel and Smith, 1998 [172]).

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