Tsunami inundation forecast development and usage for NOAA Tsunami Warning System

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Tsunamis are coastal disasters that in many cases allow only minutes of warning before initial impact. Since the 2004 Boxing Day tsunami, there had been significant advancements in tsunami forecast methodology, pre-disaster preparedness and basic understanding of tsunami physics. Yet, the destruction resulted from the 2011 Japan tsunami underscored the difficulties of implementing the advances in tsunami science into practical applications. The capability of tsunami inundation forecast has immence potential for increasing coastal resilience and reduce loss of lives during the tsunami. However, realization of such potential requires new standards of robustness and accuracy for practical application of such capability. The presentation describes methodologies of the real-time tsunami flooding forecast, its testing and implementation for the U.S. Tsunami Warning System and lessons learned from initial use.

S-net Utilization for Real-Time Tsunami Inundation Forecast System

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NIED is constructing S-net (Seafloor Observation Network for Earthquakes and Tsunamis along the Japan Trench) that consists of about 150 ocean bottom observation stations and covers wide area of the offshore Kanto, Tohoku, and Hokkaido. S-net successfully observed the 2016 Fukushima-oki earthquake and tsunami propagation from the offshore toward the land. Such records are useful for obtaining additional lead time for earthquake and tsunami early warning. Recently NIED developed a new methodology of realtime tsunami inundation forecast system using S-net, which will provide flow depth in addition to the tsunami arrival time and heights. In the system, the Tsunami Scenario Bank (TSB) that contains offshore tsunami pre-calculated waveforms, coastal tsunami heights, flow depth maps, and others is constructed in advance along the Pacific coast of Chiba prefecture in the Kanto region. When a tsunami is generated with an earthquake, several appropriate tsunami scenarios that can explain offshore tsunami observations are quickly selected from the TSB. The tsunami inundations are estimated explicitly without any source information, which may contain large estimation error. The system is evaluated and improved through the demonstration experiments with local governments. The performance of the system is validated for the simulated data of the 1677 historical Boso earthquake as well as the observed data of the 2016 Fukushima-oki earthquake.

キーワード：津波遡上予測、即時予測、S-net
Keywords: tsunami inundation forecast, realtime forecast, S-net

Synthesis of Tsunami Waveforms Including Dynamic and Static Pressure Change: Practical tests of tFISH

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Most tsunami studies neglected the effects of seismic waves in synthesizing tsunami waveforms. This is not a serious problem when using coastal tide-gauges and sensors deployed far from the tsunami source. However, when the records obtained inside or near the source are used, this becomes a significant problem because seismic waves contaminate tsunami signals. Therefore, in order to correctly evaluate the performance of tsunami forecasting methods, it is necessary to take into account the effects of seismic waves in addition to tsunami. In this study, we propose a synthesis method for ocean-bottom pressure records including both seismic waves and tsunami (Saito and Tsushima 2016 JGR). The method conducts seismic-wave and tsunami simulations in synthesizing the pressure records. First, a linear seismic-wave simulation is conducted with a kinematic earthquake fault model. Then, a nonlinear tsunami simulation is conducted using the sea-bottom motion calculated in the seismic-wave simulation. By using these simulation results, we synthesize realistic ocean-bottom pressure records including both seismic wave and tsunami. We synthesized the ocean-bottom pressure records of S-net for a simplified Tohoku-Oki earthquake fault model. Then, the performance of a tsunami source estimation method of tFISH was examined. Even though the synthesized records contain large dynamic pressure change, which is not considered in the algorithm, tFISH successfully worked with expected performance: tFISH correctly estimated the tsunami source when 5 min elapsed after the earthquake occurred. The pressure records synthesized in this study, including both seismic wave and tsunami, are more practical for evaluating the performance of our tsunami monitoring ability, whereas past tsunami studies usually neglected the seismic wave contribution.

キーワード：津波、 理論、シミュレーション
Keywords: Tsunami, Theory, Simulation

Improvement of tsunami-forecasting method based on tsunami inversion: small-size and large-amplitude tsunamis

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Since 2000, real-time tsunami forecasting methods based on inversion of offshore tsunami data have been proposed for tsunami disaster mitigation (e.g., Titov et al., 2005; Tsushima et al., 2009). In the previous studies, we developed a tsunami-forecasting method based on inversion for initial sea-surface height distribution, named tFISH (Tsushima et al., 2009, 2012). In the tFISH algorithm, tsunami source that is initial sea-surface height distribution is expressed by a linear superposition of elementary tsunami sources. The size of elemental sources is about 20 km that can well express tsunami sources of moderate to large interplate earthquakes. However, tsunamis that affect coastal communities are sometimes generated by a spatially small-size source. For example, a Mw 6.9 intraplate normal-faulting earthquake occurred off Fukushima prefecture, northeastern Japan, on 22 November 2016, and the 1.4-m-height tsunami was observed at coastal tide gauge. The area of the source is comparable or smaller than that of elemental source, and thus the tFISH may not resolve the source and decrease accuracy of tsunami forecasting. Considering that the tsunami height at the coast was large (> 1 m) enough to cause the disaster, the accurate forecasting for this event is important. In this study, we try to improve the tFISH algorithm for accurate forecasting of small-size and large-amplitude tsunamis.

I performed numerical simulation of tsunami forecasting assuming the 2016 Nov. off Fukushima earthquake. An earthquake faulting of the 2016 earthquake is assumed by referring the aftershock distribution, and then the resultant tsunami was calculated numerically to obtain tsunami waveforms at offshore and coastal tsunami observing points. The obtained waveforms are regarded as observation data and used in the tFISH inversion.

Firstly, to know the tFISH performance for the event, the tFISH was applied to the synthetic data. Tsunami waveform data at S-net and GPS buoys from the origin time to 30 min of the earthquake were fed into the tFISH inversion. As a result, the estimate of initial tsunami height distribution did not resemble to the assumed one (i.e. true source in the simulation): long-axis of the estimated source is north-south direction, although the true one is northeast-southwest direction. The difference of the long-axis direction directly leads to the difference of tsunami-energy directivity, resulting in degrading tsunami-height prediction along the coast. The cause of the source misestimation is that the spatial size of the elemental source is too large to express the true source. Actually, short-period tsunami waveforms observed at S-net are less modeled in the inversion.

Then, to solve the problem, a two-steps inversion is proposed in this study: at the first step, the conventional tFISH inversion is performed. Then, we consider that if the estimated source is expressed by extremely small number of elemental sources (e.g., one source only), the true source may be smaller than the elemental one. When this criterion is satisfied, we go to the next step. At the second step, we perform tsunami-waveform inversion with elemental sources whose sizes are much smaller than the original ones (here, 4 km size, the one-fifth of the original). In the inversion, the small-size elemental sources are distributed to sea area where tsunami source is imaged in the first-step inversion, in order to reduce the number of unknown parameters. After that, we decide whether or not the source model at the second step is chosen as the final solution by using the following criterion: the comparison between observed tsunami waveforms and the calculations in the inversion shows the better agreement than in the first-step inversion. We used tentative values for two criteria in the new approach and applied this algorithm to synthetic data from the 2016 Nov. off Fukushima earthquake and succeeded in avoiding the misestimation of long-axis of the source that is critical for tsunami directivity.

キーワード：津波、即時予測、逆問題
Keywords: Tsunami, Real-time forecasting, Inverse problem

巨大津波の早期検知に向けた航空機レーダーによる海面高度観測
Observations of sea surface heights using an airborne radar altimeter for great tsunamis early detection

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多くの津波予測システムは地震規模の推定結果に依存しているが、地震の規模が大きく振動が長時間続くようなケースでは地震・津波規模を過小評価してしまう傾向にある。一方、衛星レーダーを使って津波を直接的に検知する試みも行われている。衛星レーダーにより津波を検知した報告もなされているが（J. Gower 2007など）、衛星レーダーによって高い観測密度を確保することは難しく、リアルタイム検知は困難な状況にある。そこで我々は航空機に取り付けたレーダーを用いた海面高度観測による津波の直接検知を提案する。

今回我々は航空機胴体下部に取り付けたFrequency Modulated Continuous Wave (FMCW)レーダーによって直下点観測を行った。レーダー観測技術自体は現在衛星による海面高度観測で用いられているものと同様である。気流による揺れの影響が大きい航空機観測の場合、機体の位置を(Global Navigation Satellite System) GNSS観測により正確に捕捉することも重要となる。今回キネマティック基線解析により位置と高度を推定した。本研究では、レーダーによる海面距離観測およびGNSSによる高度推定により平均海面高さの時空間変化を算出した。

観測は2016年の6月に1回、12月に2回行った。精度検証のため、海面高度観測衛星Jason-2及びJason-3と同日同軌道上を数回往復する形で海面高度を計測し比較した。ジオイド高および潮位変化の補正を行った結果、誤差は10cm以下であり、巨大地震が引き起こす津波を沖合で捉えることが十分に可能であることを確かめた。将来的に複数の旅客機にレーダーを搭載することにより、より安価で密度の高い観測網を形成し、津波規模を直接かつ即時に検知できるとことが期待される。

キーワード：津波予測、航空機観測、レーダー高度計、GNSS
Keywords: tsunami forecast, airborne observations, radar altimeter, GNSS

Temporal variability of tsunami detection distance revealed by virtual tsunami observation experiments using HF radar

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We statistically examined the tsunami detection distance based on virtual tsunami observation experiments by using receiving signals of the Nagano Japan Radio Co., Ltd. (NJRC) HF radar during February 2014 installed on the Mihama coast, Japan and numerically simulated velocities induced by a M_w 9.0 Nankai Trough earthquake (Japan Cabinet Office's fault model case 3). In the experiments, the Doppler frequencies associated with the simulated tsunami velocities were superimposed on the receiving signals of the radar by the method developed by Gurgel et al. (2011), and the radial velocities were calculated from the synthesized signals by the fast Fourier transform. Tsunami arrival was then detected based on the temporal change in the cross correlation of the radial velocities, before and after tsunami arrival, between two range cells 3 km apart along beam 04. Combinations of HF radar systems and tsunami detection methods should be assessed as the onshore-offshore distribution of tsunami detection probability, because the detectability of tsunami wave will be affected by the signal-to-noise ratio and the tsunami magnitude in addition to the radar system specifications. We found that the detectability with a combination of NJRC radar system and our detection method primarily depends on the kinetic energy ratio between tsunami- and shorter-period background current- (BGC) velocities. In the onshore-offshore direction, the monthly average detection probability is over 90% when the energy ratio exceeds 5 (offshore distance: 9 km L 36 km and water depth: 50 m $< h <$ 600 m) and is about 50% when the energy ratio is approximately 1 (L = 42 km, h = 1,200 m). The probability reduced over the continental shelf slope with decreasing tsunami-induced velocities. For a certain range cell on the radar beam, the energy ratio temporally varied in accordance with the variations of ocean surface wave height, ionospheric electron density and also with the shorter-period BGC physics. The energy ratio significantly decreased when the extremely large wave height exceeded 5 m and/or the ionospheric electron density became greater. From statistical analyses of the Wakayama-Nanseioki GPS wave gauge, significant wave heights are smaller from spring to summer, that is to say, the receiving signals would be more intense in this season. Meanwhile, the ionospheric electron density of the F2 layer generally becomes greater in the season, which would lead to greater receiving noise in the daytime. In addition, the energy ratio also varies depending on the tsunami magnitude. When a weaker (greater) tsunami occurs, the energy ratio becomes small (large) and the maximum detection distance is thus expected to become shorter (longer). In the experiments, the tsunami detection distance found to be dependent on the energy ratio between tsunami- and shorter-period BGC velocities and sea surface state as well as receiving noise. This demonstrates that the virtual tsunami observation experiments for other seasons and/or for another coastal regions with varying tsunami magnitude are required to understand the tsunami detection performance of HF radars comprehensively. This study is the first step towards a comprehensive understanding of variability of the maximum tsunami detection distance and development of real-time detection methods.

キーワード：HFレーダ、津波検知、検知確率、仮想津波観測実験、エネルギー比、SN比
Keywords: HF radar, Tsunami arrival detection, Detection probability, Virtual tsunami observation experiment, Energy ratio, Signal-to-noise ratio

A global assessment of tsunami hazards over the last 400 years

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This work is our contribution towards World Tsunami Awareness Day, which was proposed by the United Nations (UN) in 2015. We conducted a global tsunami hazard assessment for local regions, including low tsunami risk areas, based on a 400-year database which allows insight on potential future tsunamis based on the seismic gap. The resulting tsunami hazard could be displayed on a global map and enable us to easily observe the local effects of tsunamis. Two criterions were selected to represent the past 100 major earthquake generated tsunamis: first, the earthquakes must be larger than magnitude 7.5 and secondly, occurred after the year 1600. Based on the results of the simulation, the locations of modern tsunamis (from the periods of 1970 to 2016) greater than 2 meters in height, are limited to areas affected by the 2004 Indian Ocean Tsunami, and the 2011 Great East Japan Tsunami. Regardless, damaging tsunamis have been witnessed everywhere in the world, especially along the Pacific Rim. This observation shows the importance of assessing or knowing the hazards based on historical events beyond our memory. Comparisons between tsunami height and wave force show that only using the tsunami height might underestimate the building damage. We wish that as a part of the World Tsunami Awareness Day related activities, our results and findings will increase tsunami awareness at the global scale, especially in comparatively low tsunami risk areas, and reduce human loss from future tsunamis.

キーワード：津波ハザード評価、グローバルスケール、世界津波の日
Keywords: Tsunami hazard assessment, Global scale, World tsunami awareness day

Tsunami inversion for sea surface displacement from far-field data of the 2011 Tohoku tsunami

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We investigate the initial tsunami sea surface displacement of the 2011 Tohoku earthquake by performing the tsunami waveform inversion with the data of far-field stations. Tsunami travel time difference up to 15 min and polarity reversal of initial phase between observed and synthetic waveforms have been pointed out for the stations with travel time larger than 3 hours (noted as “far-field”). The differences were mostly explained by the phase correction method (Watada et al., 2014, JGR), which accounts for the dispersion effects of tsunami loadings on the Earth, seawater compression, and gravitational potential change. By applying the phase correction method, we can convert synthetic waveforms of linear long wave into dispersive waveforms.
In this study, we attempt to improve the phase correction method by including the effect of ocean density stratification and calculating the realistic tsunami ray path, not along the great circle, which minimizes the tsunami travel time from the source to the station. The characteristic ocean depth 4 km is replaced by the corresponding depths along each path. We apply the improved phase correction method to waveforms of near-field stations (travel time < 3 hours, including wave gauges, GPS stations, and OBP-type stations) and far-field stations (only DART stations) in the single and multiple time window inversions. Our results show that ocean density stratification accounts for travel time delay up to 2 minutes. In addition, replacing the great circle distance and 4 km reference depth by the non-great-circle ray path length and corresponding depth account for up to 0.8 minutes in travel time.
The inversion result of only far-field data shows a long wavelength sea surface displacement in the source area with a crest of ~6.1 meters located at the midpoint of the epicenter and the trench. Inversion with only near-field data leads to a detailed result which locates a peak displacement of ~6.4 meters near the trench. In the result of both near- and far-field data, a compact ~6.9-meter-high peak displacement appears at the midpoint of the epicenter and the trench. An improved detailed result is obtained by combining near-field stations with far-field stations. The accurate calculation of far-field stations is essential for utilizing them in tsunami source studies and trans-ocean tsunami warnings.

Keywords: tsunami inversion, far-field, phase correction, 2011 Tohoku earthquake, trans-ocean tsunami

Frontal Pop-up Structures and Tsunami Earthquakes

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Tsunami earthquakes are special class of rare earthquakes that produce exceptionally large tsunamis from relatively small earthquakes (e.g., Kanamori, 1972; Polet and Kanamori, 2000; Okal, 1988; Lay and Bileck, 2007). These earthquakes are suggested to propagate up to the subduction front with low rupture velocities and stress drops, but it is not possible to produce large tsunamis from a slip on shallow dipping megathrust. Using recently acquired high-resolution seismic reflection, bathymetry and reflectivity data here we report the presence pop-up structures, bounded by steeply dipping thrusts, near the subduction front and fresh traces of seafloor ruptures in the 2010 Mentawai tsunami earthquake rupture zone (Hill et al., 2012; Singh et al., 2011; Lay et al, 2011; Newman et al., 2011; Bilek et al., 2011), indicating that the rupture reached to the seafloor. Using tsunami modelling study, we show that the co-seismic slip on these steeply dipping conjugate thrusts can uplift the water-column, produce a large localised tsunami, and can explain the observed tsunami on the neighbouring islands. These results suggest that the pop-up structures at the subduction front might be the main cause of tsunami during tsunamigenic earthquakes, and can be used for tsunami mitigation study.

Keywords: tsunami earthquake, surface rupture, pop-up structures

徳島県宍喰に襲来した1512年永正津波の波源に関する考察
A possible source model of the 1512 Eisho tsunami described in an ancient document

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南海トラフなどの沈み込み帯では海溝型地震が繰り返し発生する．過去の事象の解明は将来の予測に直結するが，近代的な地震津波観測が始まったのはおよそ100年前であり，それよりも古い地震については史料や地質調査に頼らざるを得ない．徳島県には「震潮記」という史料が存在する．これには1512年永正地震，1605年慶長地震，1707年宝永地震，1854安政南海地震の徳島県宍喰地域の被災状況が記録されている．宍喰は四国の南東部にある海岸沿いの集落であり津波による被害が甚大である．特に1512年永正地震では津波により3700人あまりが死亡したと震潮記にあり，大津波の発生を推察させる．ところが1605年慶長地震，1707年宝永地震，1854安政南海地震の記録は震潮記以外にも多数の記録が存在し，それらの津波は西南日本の太平洋沿岸部を広く襲ったと解釈できるが，1512年永正地震に関する史料は震潮記を除いて存在せずこの地震の真偽は定かではない．本研究では1512年永正津波が局所的な津波であったと仮定してその波源について考察する．局所的な津波の例としては，たとえば1998年のパプアニューギニア地震津波のような海底地すべりによる津波が挙げられる．

海底地形図を用いて海底地形を調査し，宍喰の南東約24km沖合の水深約800mの海底に幅約6km，高さ約400mの滑落崖を確認した．さらに学術研究船「白鳳丸」KH-16-5次航海において無人探査機NSSの深海曳航式サブボトムプロファイラを用いて調査したところ，比較的最近起こったとみられる地すべりの詳細な内部構造が捉えられ，それによる地層の垂直変位は約50mであった．これらの情報を基に海底地すべりをモデル化しWatts et al.（2005）の式を用いて津波の初期水位を求めた．ここで地すべり土塊の移動量は不明であるため，地すべり土塊の移動量を800mから3000ｍまで変更させて複数回計算を行った．津波シミュレーションでは非線形浅水波式を差分法で解いた．ネスティング手法を用いて宍喰地域の空間分解能を向上させた．宍喰地域の陸上地形データは現況の地形から堤防など人工構造物を取り除くとともに，古地形図などを用いて可能な限り当時の地形に近づけた．津波解析の結果，地すべり移動量1400ｍ～2400mで震潮記に記載された宍喰の浸水状況を再現できることがわかった．この場合の宍喰での最大津波高は6m～9ｍで，一方対岸の紀伊半島沿岸では最大で津波高3mとなった．

キーワード：歴史地震、津波、海底地すべり
Keywords: Historical earthquake, Tsunami, Submarine land slide

アップスケーリングによる市街地粗度パラメタリゼーションを用いた津波遡上モデルに関する研究
Numerical modeling of tsunami inundation using upscaled surface roughness parameterization

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2011年の東日本大震災における津波による壊滅的な被害や，南海トラフ地震をはじめとする大規模な地震への危惧のため，高精度の津波遡上モデルの必要性が大きくなってきている．本研究では，現在の市街地粗度パラメタリゼーションよりも正確に建物の効果を算定し，かつ，計算負荷を抑えつつ正確な計算結果を得るため，1) 合成等価粗度モデルと2) 建物抗力モデルという2種類の異なるアップスケーリングによる市街地粗度のパラメタリゼーションを行った．これら2種類のパラメタリゼーションを用いた津波浸水計算の結果を，沿岸市街地模型を用いた津波浸水実験の結果を真値として，最大浸水深，浸水範囲，津波到達時刻の観点で比較した．合成等価粗度モデル，建物抗力モデルの両モデルとも概ね実験結果と合致したが，建物が密集しているところでは合成等価粗度モデルが優れていた．一方で，浸水範囲の端（高台の上にある病院等）では建物抗力モデルの方が優れていた．これは，建物抗力モデルでは流れの向きの効果を再現することができるためである．しかし，両モデルとも粗度パラメータを計算する計算メッシュの大きさに計算結果が左右されるという課題と，一般的建物群に対して，抗力係数の評価が正確にできていないという課題を明らかにした．

キーワード：津波、高潮、底面粗度、Manning、アップスケーリング
Keywords: Tsunami, Storm surge, Bottom surface roughness, Manning, Upscaling

Tsunami Preparedness: **Is Zero Casualties Possible?**

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An important element of tsunami preparedness is the method to evacuate people from the flooding dangers of tsunamis before the tsunami arrives. The most common evacuation method is horizontal evacuation where threatened people escape to a safe area outside the tsunami hazard zone aided by well marked evacuation routes. In situations where there is insufficient time to evacuate to a safe area, some communities have established vertical evacuation procedures where evacuees seek shelter in structures that allow evacuees to rise above the flooding depth of the tsunami. These structures take several forms, including reinforced concrete building, specialized evacuation towers, or high elevation topography. Horizontal and vertical evacuation methods were put to the test during the 2011 Japanese tsunami. In general, these two methods saved about 95% of the threatened population. In order to achieve the goal of “Zero Casualties”, a third method of shelter in place option will be presented that will save the lives of people who are unable (i.e. elderly, disabled, small children) or unwilling (i.e. don’t trust the warnings, don’t want to go to an evacuation shelter with many people) to evacuate either horizontally or vertically. The shelter in place option takes the form of a survival capsule, a metal protective shell exclusively designed to survive the hostile tsunami environment.

Keywords: Tsunami Preparedness, Shelter in Place , Survival Capsule

