17th World Conference on Earthquake Engineering, 17WCEE

Sendai, Japan - September 13th to 18th 2020

DEVELOPMENT OF INTEGRATED VISUALIZATION SYSTEM FOR TSUNAMI FORECAST INFORMATION

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Abstract

Real-time forecasting of tsunamis is one of effective measures for mitigating damages and improving disaster response during tsunami disaster. Taking advantage of large-scale dense observation networks deployed both on land and seafloor such as MOWLAS (Monitoring of Waves on Land and Seafloor) by National Research Institute for Earth Science and Disaster Resilience (NIED), we automatically forecast or evaluate the tsunami effects by several different methods. These methods have their own advantages and make up for one another. An approach of conducting several promising methods simultaneously is one practical way to effectively and surely forecast tsunamis because it is difficult to establish a single all-around forecast method covering all the possible tsunami cases. It is, therefore, essential to grasp all the forecast results seamlessly and compare them easily. For this purpose, we develop an integrated visualization system that can display the various information output from several real-time tsunami forecast systems maintained by NIED on a unified interface.

The system provides Web interface that consists of timeline, cart, and map as main elements. Operation of the interface starts from the timeline that aligns the available information by time assigned for the tsunami event in rows grouped by forecast methods. If certain information is selected on the timeline, the information is added to the cart and is visualized on the map. The cart controls display or non-display of information on the map. The cart also controls creation of new windows to plot the waveforms and snapshots included in the information. Multiple pieces of information can be stored in the cart and can be displayed simultaneously. Thus, we can compare the forecast information estimated by the different methods or estimated for different tsunami events.

The current integrated visualization system can show coastal tsunami heights estimated by 1) database-based approach named multi-index method, and by forward simulations based on the initial tsunami heights estimated from 2) tsunami waveform inversion and from 3) CMT solutions. The system also displays the results associated with each method, such as initial tsunami heights, tsunami waveforms, tsunami travel time, etc. Methods 1) and 2) use tsunami data observed on the seafloor as water pressure change, which would lead to more accurate constraint on the affected areas and magnitude of tsunamis. Method 1) has an advantage of generating tsunami forecast information immediately after finding scenarios that match the observed data while method 2) takes longer computational time but has a flexibility to cope with heterogeneous initial tsunami height distribution. A new technique to reduce effects of noises in the seafloor pressure data is incorporated with method 2). Method 3) covers tsunamis due to earthquakes that occur in and around the Pacific Ocean based on CMT solutions. For far-field tsunamis or tsunamis in the regions without seafloor observation networks, this information is effective and useful. We also plan to include the tsunami forecast information based on amplification relationship between the seafloor observation data and the coastal tsunami heights.

Keywords: tsunami forecast; real-time system; seafloor observation data; MOWLAS

1. Introduction

As an island country surrounded by the sea and located in subduction zones, Japan has been hit and threatened by large tsunamis. To overcome the tsunami disaster, both structural and non-structural measures should be appropriately prepared. In the non-structural measures, a real-time tsunami forecast is one of effective approaches for mitigating damages and improving disaster response [1]. Many efforts have been made to realize accurate and effective tsunami forecast. In Japan, Japan Meteorological Agency (JMA) forecasts tsunamis along coasts all over Japan and issues an official tsunami warning. During the 2011 Tohoku-Oki earthquake (Fig. 1), the first tsunami warning based on the hypocenter information underestimated the tsunami heights for heavily damaged regions. Then, the forecast tsunami heights were upgraded using offshore observation data obtained by Global Positioning System buoys [2], suggesting the significance of the offshore observation data for accurate tsunami forecast [3]. After the Tohoku-Oki earthquake, two large-scale seafloor observation networks started in full operation in the offshore of Pacific coast of Japan (Fig. 1). One is S-net (Seafloor Observation Network for Earthquakes and Tsunamis along the Japan Trench), which covers the offshore regions from Kanto to Hokkaido [4, 5, 6], constructed by. National Research Institute for Earth Science and Disaster Resilience (NIED). The other is DONET (Dense Oceanfloor Network System for Earthquakes and Tsunamis) deployed in the offshore regions of Kii Peninsula and eastern Shikoku Island along the Nankai Trough [7, 8], constructed by Japan Agency for Marine-Earth Science and Technology (JAMSTEC). Now that DONET has been transferred to NIED, these two seafloor networks are maintained by NIED as a part of MOWLAS (Monitoring of Waves on Land and Seafloor). S-net and DONET can detect tsunamis in real time using pressure gauges in terms of water pressure changes. Taking full advantage of the real-time data and information generated by those data, NIED has developed real-time automated systems to forecast or evaluate the tsunami effects using several different approaches.

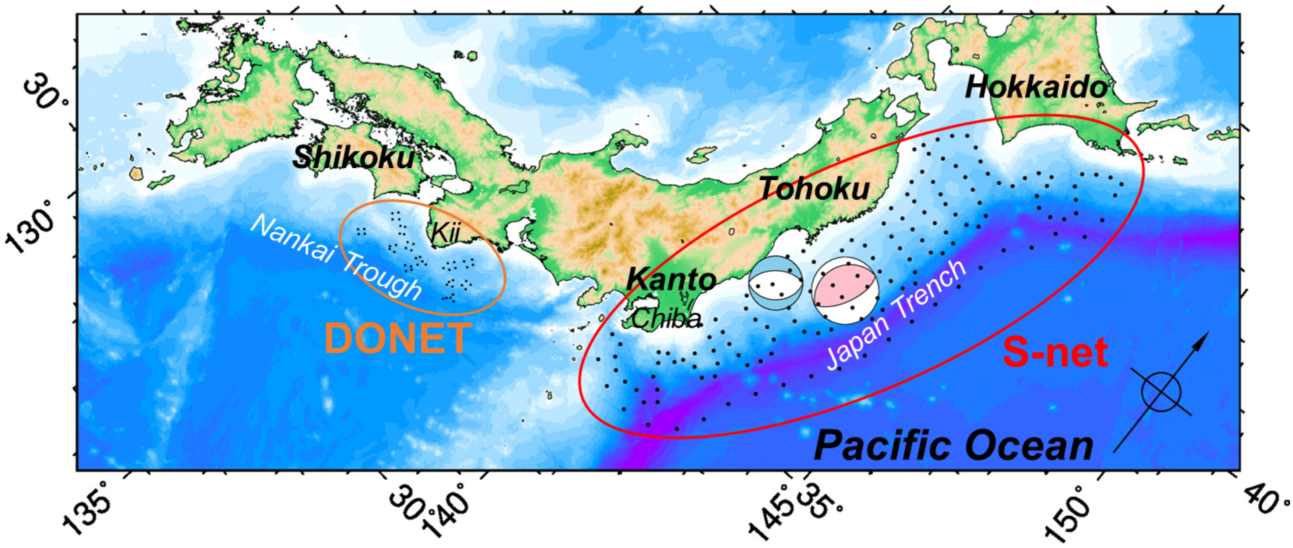

Fig. 1 – Two large-scale seafloor observation networks in the offshore of Japan (S-net and DONET) and regions mentioned in this paper. Pink and skyblue beachballs denote location and source mechanism of the 2011 Tohoku-Oki earthquake and the 2016 Fukushima-Oki earthquake, respectively

Several real-time tsunami forecast methods have been proposed to cope with the conditions, such as available data, required lead time or target phenomena. A database approach is one choice to immediately perform the tsunami forecast to wide regions and/or in detail that requires much computational time. The forecast information is made by selecting tsunami patterns in the database that match the source information or observed data. Another effective methodology is that the heterogeneous tsunami source model or initial tsunami height distribution is estimated, and then the resultant tsunami effects are evaluated by a forward simulation. This approach could overcome a problem originated from a heterogeneous source process of actual large earthquakes, which might make tsunami phenomena very complex but cannot be modeled by pre-calculated simple tsunami patterns. This has become feasible as the dense and real-time observation data are available as well as computer performance increases. Contrary, there is another demand for a simple but rapid forecast methodology. For this demand, an approach using a forward simulation based on fault models estimated from the seismic information is a realistic choice. Particularly for far-field tsunamis or tsunamis in the regions without seafloor observation networks, this methodology is effective and useful. These three approaches explained so far have been implemented to the real-time tsunami forecast systems operated in NIED.

The tsunami forecast systems in NIED have their advantages and make up for one another. An approach of conducting several promising methods simultaneously is one practical way to effectively and surely forecast tsunamis because tsunami disaster is so rare and various that it is difficult to establish a single all-around forecast method covering all the possible tsunami cases. It is, therefore, essential to grasp all the forecast results seamlessly and compare them easily. For this purpose, we have developed an integrated visualization system that can display the various information output from several real-time tsunami forecast systems maintained by NIED on a unified interface. In this article, we first describe the three tsunami forecast systems operated in NIED and then elaborate the integrated visualization system which incorporates the results from the three systems.

2. Tsunami Forecast Systems

2.1 Forecast System Based on Multi-index Method

The multi-index method takes a database approach with the aim of forecasting detailed coastal tsunamis and tsunami inundations based on the offshore tsunami data [9]. This method uses a database comprising tsunami scenarios, which are sets of simulation result at ocean bottom observation station, along the coast and on land. The resemblance of the offshore tsunami data between the observation and scenarios is evaluated using the three indices: two variance reductions and correlation coefficient. The two variance reductions are respectively sensitive to the overestimation and underestimation of amplitudes whereas the correlation coefficient is sensitive to the spatial distribution. Using these three indices, the method can propose the forecast information from plausible tsunami scenarios that fit the present observation.

The real-time tsunami forecast system implementing the multi-index algorithm to S-net data has been developed and operated for a few years [10]. Pacific coast of Chiba (Fig. 1), on the east of Tokyo, is a target region to forecast detailed tsunami inundation calculated using the non-linear long-wave equation with a 10-m mesh topography model in coastal areas. Rather rough forecast is also performed for wider region along the Pacific coasts from Kanto to Hokkaido through Tohoku regions (Fig. 1), using a 90-m mesh topography model. The database named tsunami scenario bank used for the system contains nearly ten thousand of tsunami scenarios mainly due to thrust earthquakes on the Pacific plate interface [11]. The S-net data are transmitted to the system and processed continuously in real time. If some scenarios meet the criterion in the multi-index evaluation, the system can make forecast information without any trigger by earthquake occurrence information.

Fig. 2 shows a Web interface of the forecast system designed for the Pacific coastal region of Chiba. The distribution of tsunami inundation depth can be confirmed on Web GIS (Geographic Information System). Since the interface is designed for the Pacific coastal region of Chiba, the maximum coastal tsunami height and the shortest time before tsunami arrival are listed in a table specialized for municipalities in the region. The coastal tsunami height distributions for scenarios that meet the multi-index criteria are drawn altogether to show the uncertainty of forecast information. A comparison between the observed and scenario offshore tsunami data of the S-net pressure gauges is also plotted to examine the validity of the selected scenarios.

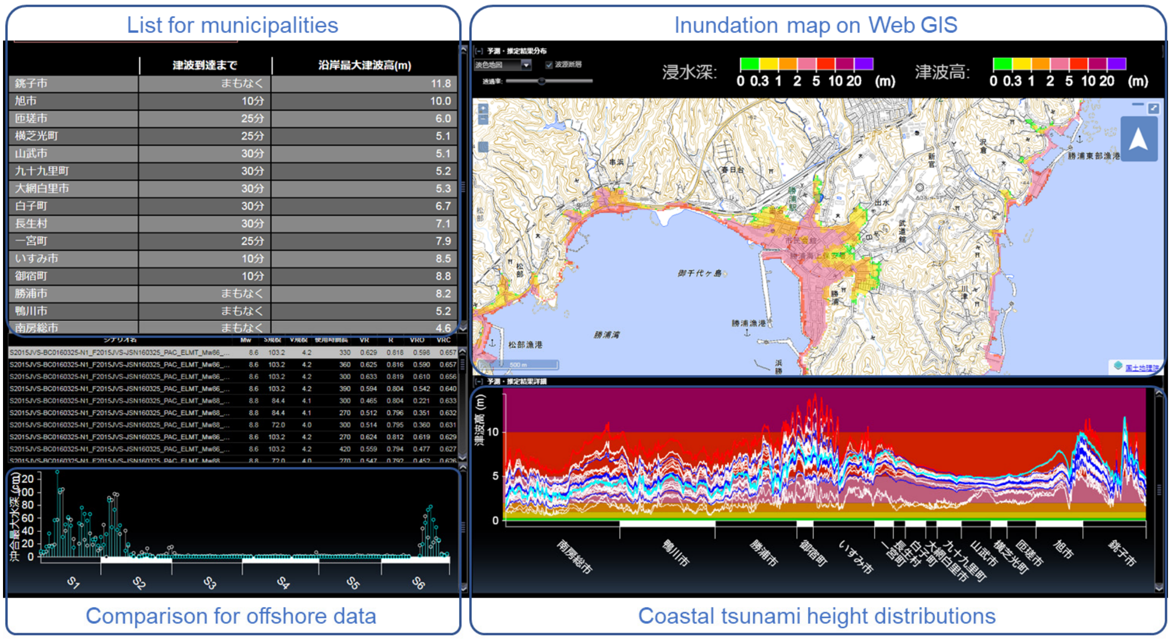

Fig. 2 – A Web interface of the tsunami forecast system based on the multi-index method designed for the Pacific coastal region of Chiba with notes on each item

2.2 Forecast System Based on Tsunami Source Inversion

Inspired by preceding researches showing the effectiveness of the tsunami source inversion for near field tsunami forecast [12,13], a real-time tsunami source inversion system including a forward tsunami simulation has been developed and in operation using the S-net data. In the system, an analysis is triggered by receiving a centroid moment tensor (CMT) solution estimated within the S-net deployed regions by AQUA system [14]. The CMT information is used not only for triggering the system but for determining spatial range of inversion; that is, element tsunami sources to be inverted are distributed over the areas in which some crustal deformation is expected based on the fault models assumed by the CMT solution. The uplift or subsidence at each element tsunami source is estimated by solving linear observation equation connecting the tsunami source and the offshore tsunami data via Green's functions [15]. In addition to the ordinary tsunami source inversion, the two new techniques are incorporated in the system for the purpose of obtaining results stably and quickly. One is an inversion method using the derivative of the offshore pressure data, which could reduce the effect of non-tsunami components involved in the pressure data [16]. The other is like a two-step inversion in which the initial tsunami source model (crustal deformation) is estimated from observed data other than tsunami data and then the source model is improved by inverting an observation equation comprising the difference between the observed pressure data and simulated ones based on the initial model [13]. We use the AQUA CMT solution to initially constrain the extent of the tsunami source rapidly after the earthquake.

The system provides tsunami inversion results by Web page and a report compiled as a PDF (Portable Document Format) file. Fig. 3 shows an example of a report derived for a hypothetical interplate earthquake in the offshore of Chiba with a moment magnitude (M_W) of 8.2. Red and blue color contours denote uplift and subsidence areas, respectively, in the bold polygon denoting the spatial range to be inverted. The result is derived using the offshore pressure data observed at S-net station (black curves in Fig. 3b) for twenty minutes after the earthquake occurrence, which are well reproduced by the estimated initial tsunami height distribution (red curves in Fig. 3b). The system also performs inversions using the observed data for five, ten, and fifteen minutes after the earthquake. In the case of the hypothetical earthquake, the earlier inversions also provide reasonable results.

(a) (b)

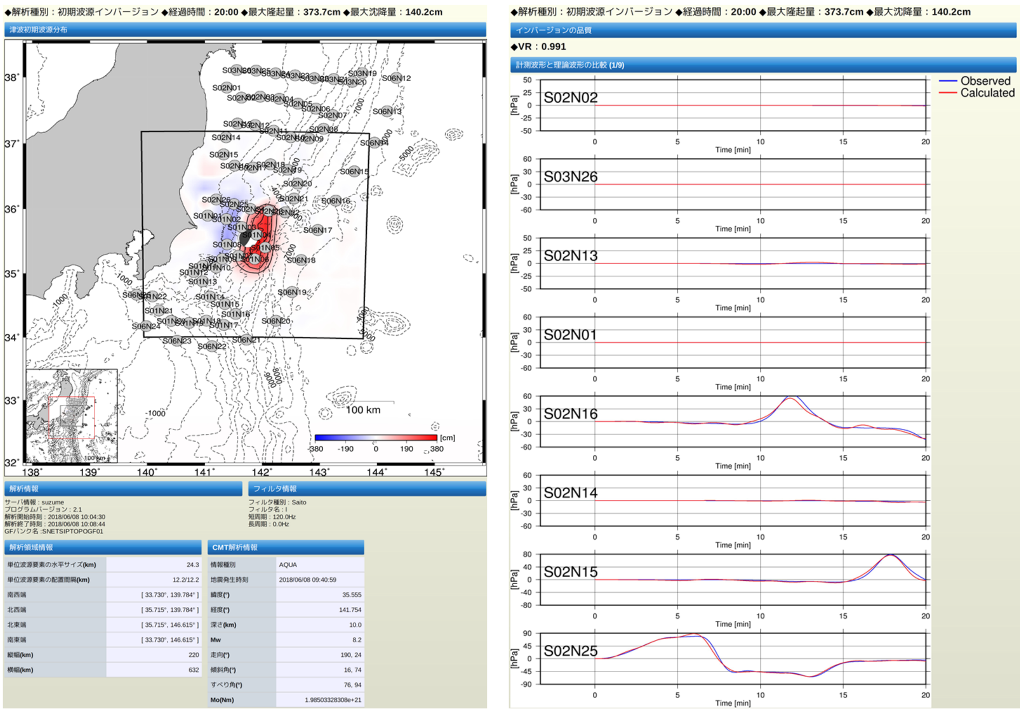

Fig. 3 – A PDF report of tsunami inversion result (a) initial tsunami height distribution (b) comparison between the observed and synthetic wavforms of pressure change

Based on the estimated initial tsunami height distribution, the system performs a forward tsunami simulation using a software package, TNS [17], on GPU (Graphical Processing Unit) device with the non-linear long-wave equation and a minimum 90-m grid topography model for the regions from Kanto to Hokkaido (Fig. 1). From the forward simulation, the system estimates the inundation depths, maximum coastal tsunami heights, tsunami arrival time and offshore tsunami heights at certain time interval (snapshots). Since these results are rather difficult to draw in the figures with fixed map ranges on the Web page and reports, they are visualized only on Web GIS of an integrated visualization system as explained later.

2.3 Forecast System Based on Seismic CMT solution

An automated system of tsunami propagation calculation using the CMT solution and fast calculation technique has been developed for earthquakes in and around the Pacific Ocean [18]. A selection of appropriate calculation areas according to earthquake locations and a parallel computing using linear long-wave equation enable to calculate the tsunami waveforms at coastal points and seafloor observation stations within 40 seconds after receiving the source information. The system is relatively easily portable; therefore, it was first developed in JAMSTEC and then ported to NIED. The forecast system is prompt enough even for earthquakes around Japan but does not miss far-field earthquakes by utilizing both regional CMT solutions (AQUA and F-net [19] determined by NIED) and global CMT solution (ERI_WPHASE provided by Earthquake Research Institute, University of Tokyo [20]) [21].

The system provides the forecast information via e-mail, to which a PDF report of the calculation results like Fig. 4 is attached. Fig. 4 shows the results for an M_W7.6 earthquake that occurred in Papua New Guinea on May 14, 2019. The report contains a map of the maximum tsunami height and arrival time distributions over the Pacific Ocean and around Japan, waveforms and maximum tsunami heights at coastal and offshore observation stations, and source information. The tsunami height distribution is drawn using four colors considering ISO 22324 (Societal security - Emergency management - Guidelines for colour-coded alerts). If tsunamis with certain amplitudes are forecast around Japan, the system sends the alert mail specialized for mobile phones.

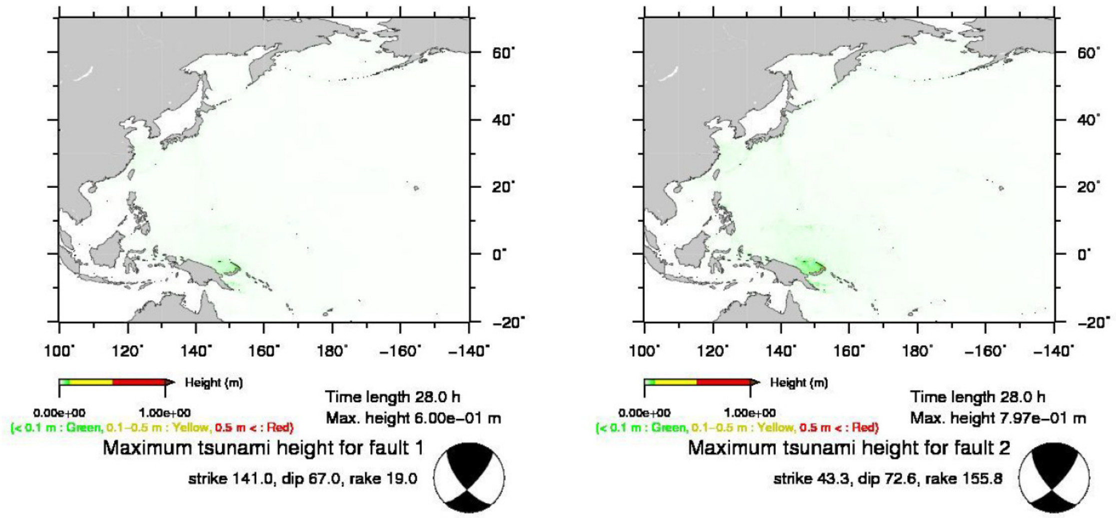

Fig. 4 – A PDF report of the forecast system based on the CMT solution using ERI_WPHASE data

3. Integrated Visualization System for Tsunami Forecast Information

As reviewed in section 2, we have several tsunami forecast systems, each of which has its own advantage. Since the results are provided and displayed in the different way, it is preferable to show those results in the same interface for the purpose of grasping plausible tsunami forecast information. Therefore, we develop an integrated visualization system that can display the various information output from the aforementioned real-time tsunami forecast systems on a unified interface. Fig. 5 shows the Web interface of the integrated visualization system, which consists of timeline, cart, and map as main elements. Operation of the interface starts from the timeline that aligns the available information according to the time of the tsunami event. The information is grouped by forecast method in row. If certain forecast information is selected on the timeline, the information is added to the cart and is visualized on the map. In the case of Fig. 5, the selected forecast information is the CMT solution of an M_W6.5 earthquake that occurred around Solomon Islands at 14:02 on January 27, 2020. The cart controls display or non-display of the information on the map.

Since the integrated visualization system uses Web GIS, the forecast information drawn on map can be flexibly confirmed as shown in Fig. 6 while the original forecast systems introduced in sections 2.2 and 2.3 only provide the figures with the fixed map range. In the transoceanic tsunami propagation forecast by the system based on the CMT solution, for example, we can zoom in on the region around Japan (Fig. 5) and zoom out to see the situation from the source to Japan (Fig. 6a). Fig. 6 also introduces the visualization on map of the results derived by the two other forecast systems. Fig. 6b draws the results derived by the tsunami source inversion system from a validation test using the seafloor pressure data observed during the M_W7.0 Fukushima-Oki earthquake on November 22, 2016 (Fig. 1). The items on map are the CMT solution used to constrain the inversion conditions, the estimated initial tsunami heights, the maximum coastal and offshore tsunami heights simulated based on the initial tsunami heights. Figs. 6c and 6d respectively show the zoom in and zoom out of the results derived based on the multi-index algorithm. In the map zoomed in to a certain municipality in Fig. 6c, the inundation depth distribution can be confirmed. The displayed inundation in Fig. 6c is rougher than that shown in Fig. 2 because the integrated visualization system incorporates the forecast information targeted for the wider regions using scenarios calculated using a 90-m grid topography model. The overview of the coastal tsunami heights from Chiba to the eastern end of Hokkaido is available if we zoom out the map (Fig. 6d).

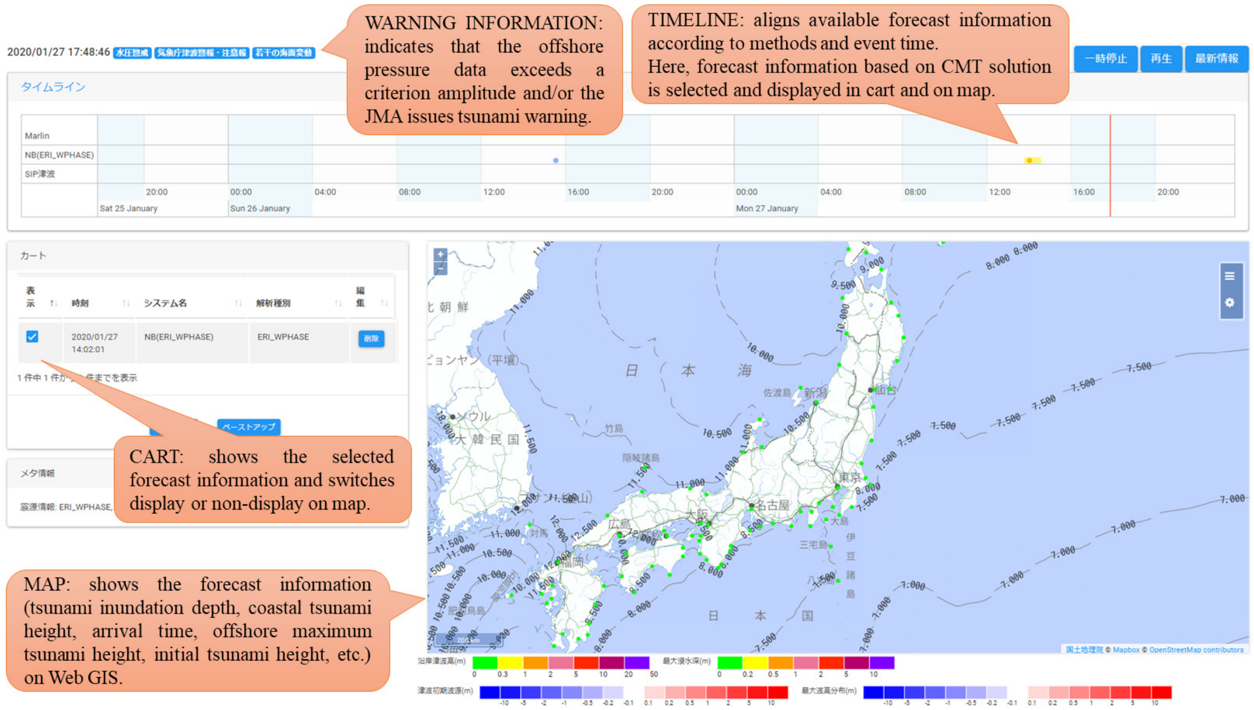

Fig. 5 – Web interface of the integrated visualization system for tsunami forecast information. Balloons explain the functions of each item

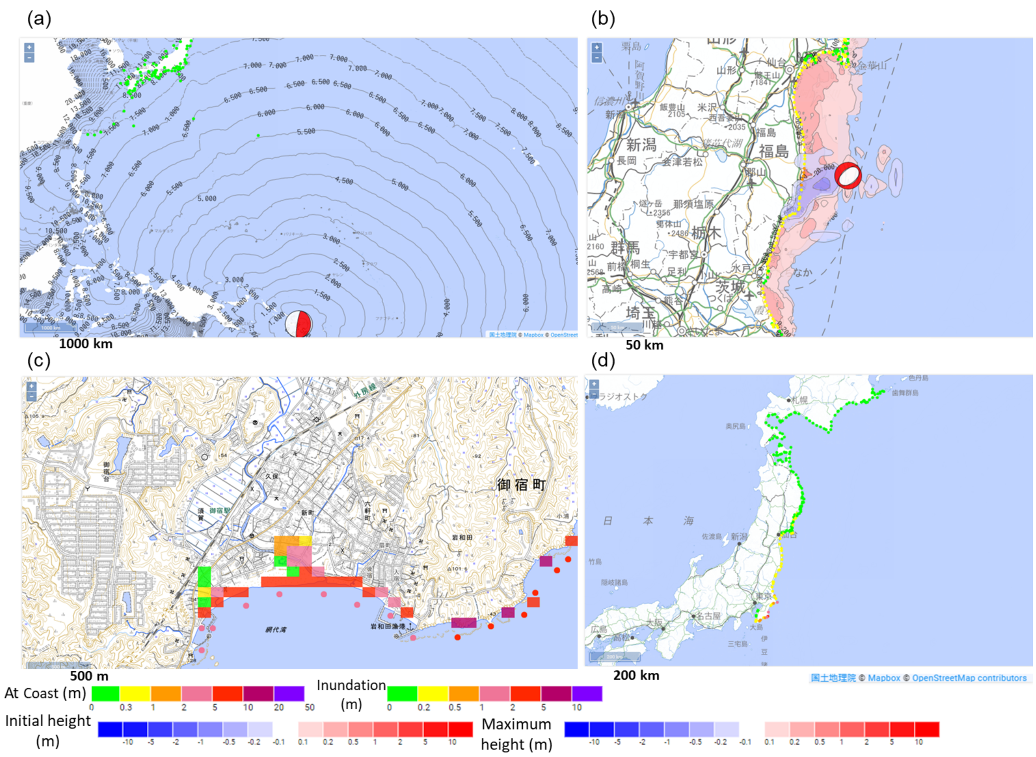

Fig. 6 – Map of the integrated visualization system showing (a) the tsunami propagation forecast based on the CMT solution (b) the results derived from the tsunami source inversion and forward simulation (c) inundation depth distribution forecast by the multi-index method (d) coastal tsunami height distribution forecast by the multi-index method

The visualization system provides functions to effectively investigate the forecast information and compare the forecast information estimated by the different methods or information for different tsunami events. Multiple pieces of information can be stored in the cart and displayed simultaneously. In some situations, it is more convenient to use two or more windows. The system therefore has a function to reproduce a map whose range is precisely the same as that of the map displayed in the different window. Background map can be switched among map service provided by Geospatial Authority of Japan. Location of offshore observation stations can be plotted.

Fig. 7 – Snapshots of the forecast tsunami propagation at an interval of 300 seconds shown by the integrated visualization system

The forecast system based on the tsunami source inversion outputs snapshots of the forward tsunami propagation simulation, which help grasp the characteristics of the forecast tsunami information better. The integrated visualization system can display the snapshot one by one on large map or display all the snapshot in one page. Fig. 7 shows the snapshots of the forward tsunami simulation results based on the tsunami inversion result for the 2016 Fukushima-Oki earthquake. The forecast information visualized in this page clearly shows a large secondary wave caused by the reflection along the coast near the source area [22].

4. Summary and Future Prospects

We have developed an integrated visualization system that can display the various information output from real-time tsunami forecast systems for the purpose of enabling to grasp all the forecast results seamlessly and compare them easily. The timeline shows the available forecast information in the intuitive way. All the spatial information is displayed on Web GIS and therefore can be flexibly confirmed according to the demands. The system is designed for easily comparing the information output from the different forecast systems or for different tsunami events on the one single map altogether or on the same maps of the duplicated windows.

The current integrated visualization system incorporates with the three forecast systems. Among these systems, the forecast systems based on the multi-index method and the tsunami source inversion use the S-net data, and then make forecast information along the coast of eastern Japan. Expanding the forecast regions to the western Japan using the DONET data is an upcoming task for the two forecast systems and the integrated visualization system. In addition, another real-time tsunami forecast system based on the amplification relation between the seafloor pressure data and the coastal tsunami heights has been developed and in operation using the DONET and S-net data [23]. The system has been implemented in the local government office [24]. We also plan to include this tsunami forecast information into the integrated visualization system toward covering all the promising forecast information.

5. Acknowledgements

We thank Hiroshi Tsuruoka for providing ERI_WPHASE CMT solutions.

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