HANDLING UNCERTAINTY IN TSUNAMI EARLY WARNING: INTERACTION BETWEEN DECISION SUPPORT AND MULTI-SENSOR SIMULATION SYSTEM

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ABSTRACT: The new InaTEWS/GITEWS tsunami early warning system has been designed to work reliably and quickly in the special case of near-field tsunamis with extremely short warning times. In order to avoid false warnings this system is equipped with a multi-sensor simulation system which can evaluate multiple online measurement values simultaneously. With this system, within short time a reliable small number of scenarios can be selected to serve as an early situation assessment. However, in order to support a decision maker for issuing warning products, a thorough analysis of the simulation results and a blending with additional geographic and socio-economic information is necessary. In this paper the interplay between decision support system and simulation system is illustrated.

1. INTRODUCTION

After the devastating Tsunami of 26 December 2004, the Federal Ministry of Research and Education (BMBF) in Germany and the Ministry of Research (RISTEK) in Indonesia agreed on a joint research and development project to establish an early warning system for tsunamis in the Indian Ocean region (German Indonesian Tsunami Early Warning System, GITEWS). The challenge of this project was that most events along the Indian Ocean coasts of Indonesia are caused by subduction zone tsunamis along the Sunda Trench. Therefore, most of the events are near-field events with warning and arrival times well below one hour. Additionally, it is anticipated that false warnings can quickly lead to ignornance of warning messages in the Indonesian public. Thus, existing early warning systems could give only limited guidance in the design of a new tsunami early warning system (TEWS) for Indonesia.

Several observations led to the conclusion that only multiple simultaneous evaluations of different tsunami related measurements can give a more reliable base for near-field tsunami warning in Indonesia:

1. For larger earthquakes causing tsunamis along the Sunda Trench, the epicenter is generally not located near the center of the rupture area.
2. The effects of near-field tsunamis are very sensitive on the exact location and extend of the rupture area
3. Earth crust deformation (measured by online GPS sensors) can give reasonably reliable information on the rupture area
4. Deep ocean wave gauges (buoys) can give quick and reliable wave arrival time information as well as wave height information.
5. Simulation results represent a physically consistent system, thus different types of parameters represent different perspectives of one and the same event and can be compared to measurements.

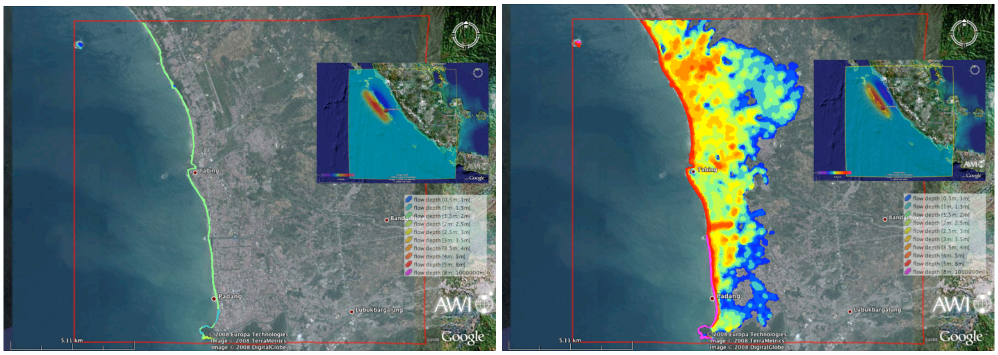

Figure 1. Two possible rupture areas related to the same earthquake location and magnitude. One (right) causes devastating destruction in Padang, the other (left) leaves Padang basically undisturbed. The initial uplift is shown in the small embedded figure for each of the cases.

From the above observations, the GITEWS near field tsunami early warning system derived the multi-sensor method to assess the situation in case of an under-sea earthquake. The simulation system (SIM) compares different types of incoming sensor data to pre-computed scenario values by a tuned weighted sum selection algorithm. It allows for uncertainty in this comparison and returns a list of probable scenarios matching the sensor observations. Each entry in the list of scenarios features additional information on its reliability and matching accuracy (skill), which can then be used in the decision support system (DSS) for further analysis. With this advanced information basis, the DSS can finally support a human decision maker (the chief officer on duty, COOD) to make an informed and qualified decision and diseminate quantitative and timely warning products.

In the following sections we will introduce the selection procedure of the SIM and the derivation of uncertainty measures therein (section 2). The DSS functionality is then described (section 3) together with the technical interaction of SIM and DSS (section 4). Final conclusions summarize the findings of our research and development project.

2. MULTI-SENSOR SIMULATION SYSTEM

2.1 Traditional Matrix-Based vs. Multi-Sensor Scenario Selection

Most existing TEWSs rely on seismic monitoring as a main source of information on tsunamogenic events. Based on the seismic parameters, a decision matrix is processed, which takes into account the location (unter or close to sea bed), strength (moment magnitude above a certain threshold), and depth of an earthquake. Based on these parameters, a certain number of pre-computed tsunami-scenarios is consulted in order to derive a coarse assessment of the expected wave height and inundation situation. Further wave gauge measurements are then used to validate and/or modify the assessment (see e.g. Furomoto et al., 1999). This approach works well in the far field, where enough time allows for thorough manual situation assessment. It can also work with a disciplined public and a well established communication infrastructure, which allows to inform the public about cancellation and updates. However, due to the uncertainty in seismic parameters in relation to tsunami generation, this approach does not allow to give qualified warnings in short time.

As an example for the misbehavior of the traditional approach we derive a synthetic earthquake with magnitude 8.5 close to the Mentawai Islands. Let the epicenter be at location (100°E, 2.4°S) and the depth after short evaluation time be estimated to approx. 30 km. Then the corresponding rupture areas as depicted in figure 1 could be caused by this earthquake. Note that the earthquake parameters have been derived from an early assessment after only a few minutes with a large uncertainty in depth and no aftershock information available. These two different ruptures cause very distinct inundation events. In case 1, there occurs hardly any inundation, because the largest portion of tsunamogenic uplift affects watermasses in the open Indian Ocean. Case 2, however, causes massive inundation in

Padang, because water masses between the Mentawai Island chain and the West Sumatra mainland are penetrated.

It is the aim of the new German-Indonesian TEWS to be able to distinguish between such cases within short time. Therefore, we utilize the ability to evaluate diverse measurements simultaneously and derive more accurate information on the rupture rather than the earthquake. With the following observation we start our multi-sensor selection:

A tsunami event consists of a physically consistent situation where the earth crust deformation, the earthquake and the water mass movement forms a wholistic picture of the situation. This can be represented by a (simplified) model, which also represents a physically consistent complete situation (including earth crust deformation, water mass movement, etc.) When we compare the two consistent situations – the true one, represented by sensor measurements, and the simulated one, represented by scenario data – we obtain a much more reliable situation assessment than by comparing only fractions (like the earthquake parameters) of the situation.

Thus, information about the earth crust deformation will complement the information about the energy release (magnitude) of the corresponding earthquake to give a more accurate short term assessment of the rupture area. Additionally, the sea surface elevation information complements the earthcrust deformation information, in case of non-typical tsunami events.

2.2 A Brief Introduction to the Multi-Sensor Scenario Selection

In order to perform a multi-sensor selection, we need to perform several steps to relate the given measurements to pre-computed scenario data. The task is – mathematically spoken – to define a norm in which the distance of a given data set to a scenario is represented in such a way, that the scenario corresponds to the real situation when the distance is zero. We will call this norm the *mismatch*. In order to derive the mismatch we need to

1. Define individual norms for each type of measurement data (location of epicenter, magnitude, depth, earth crust deformation vectors, sea level elevation time series, wave arrival times);
2. Take uncertainty into consideration in each individual norm;
3. Scale each individual norm to give comparable values in the unit interval range;
4. Combine the individual norms to a general aggregated norm.

Step 1. is performed by chosing generic distance measures (for the details see Behrens et al., 2008). To give an example: the epicenter location's norm is just the geographic distance (in mathematical terms the two-norm). Step 2. is also achieved by a generic approach, i.e. by defining an uncertainty radius, in which the norm is reduced to zero. In step 3. a scaling function is used that projects a given data range into the unit interval and at the same time emphasizes small differences. Therefore, closely matching values are distinguished sensitively, while non-matching values are treated rather indifferently. Finally, in step 4. we use a weighted sum approach to combine the scaled individual sensor norms. Since each scaled distance metric is normalized, the overal sum is normalized, once the weights are normalized. Therefore, a combined aggregated norm value (mismatch) close to 0 means a perfect match of a scenario to given data (considering the uncertainty).

Since there might be a number of indistinguishable scenarios, a list of matching scenarios might be the result of the selection procedure. For larger events, the uncertainty radius for the epicenter location might be quite large. Note that the uncertainty is not derived from an uncertainty in estimating the exact location from seismograph-picking, but from the possible number of rupture areas that could correspond to a given epicenter location.

2.3 Deriving Uncertainty Measures

In the last paragraph uncertainty radii where mentioned, which are considered in the matching process. In this paragraph the main aim is to derive uncertainty measures, which give information about the reliability of the matching procedure rather than the individual data.

The assumption here is: the more sensor data items available in the matching, the more reliable the results. This is backed by the following thought: If all sensor data were available in order to perform the matching, then there is no room for uncertainty any more. Of course the data might be uncertain in itself, but this cannot be overcome. Therefore, the greatest possible base for the assessment is available. On the otherhand, if only one or two sensor values (out of a larger number, say 20) are available then only 5 to 10 % of the theoretically complete set of information can be used for the matching. We define the ratio of available data to the number of stations as being the *reliability index* of a given situation. The reliability index (short: *R*) lies in the range of zero (no values), in which case a matching would be worthless, and one (all sensor data available), which will hardly ever be fulfilled.

The reliability index is a value related to the situation. It indicates the uncertainty of the given situation in terms of available sensor data. It does not take into consideration the number of actually used data. So even if the situation supports a number of available sensor data, if they cannot be matched with the scenario, they are worthless. This situation could arise, when either the sensor values are not supported (GPS data might not be available for all types of scenarios) or if the computational domain of the scenarios does not cover all sensor locations.

We will define the *skill* of a scenario (*S*) the ratio of available to actually used data items. Again, S can vary in the range of zero (in which case no data can be compared) to one (in which all available data are used for the matching).

To summarize, we have three different values to guide a chief officer on duty (COOD) in evaluating the situation assessment: the mismatch (or norm), which tells us how good a selected scenario corresponds to measurements. The reliability gives information about the data situation and is related to measurements. The skill gives information on the suitability of a scenario in the matching procedure and is related to each individual scenario. A scenario may have a very good mismatch, however if the skill is poor this mismatch value is relatively meaningless.

3. DECISION SUPPORT SYSTEM

3.1 A Brief Introduction to the Decision Support System

In order to support the COOD as key decision maker in the tsunami early warning process, the following tasks are required:

- Aggregation of all available information (real time sensor information and a-priori compiled baseline and scenario data), also called information fusion or sensor fusion;
- Generation and permanent update of Situation Awareness (this process is also called situation assessment);
- Generation and permanent update of Decision Proposals (assignment of warning levels, dissemination of warning messages, activation of sensors, recommendation whether to act or wait for further observations, etc.);
- Generation of products (e.g. warning messages) and initiation of product dissemination.

These are the tasks of the GITEWS DSS, which is designed and optimized to provide decision support in an 24/7 environment with high availability especially taking into account the immanent uncertainty and time pressure of the main tsunami early warning process.

shows the DSS as a central component in the Early Warning and Mitigation System concept of GITEWS. The DSS receives sensor observations of the different available sensor systems via a central

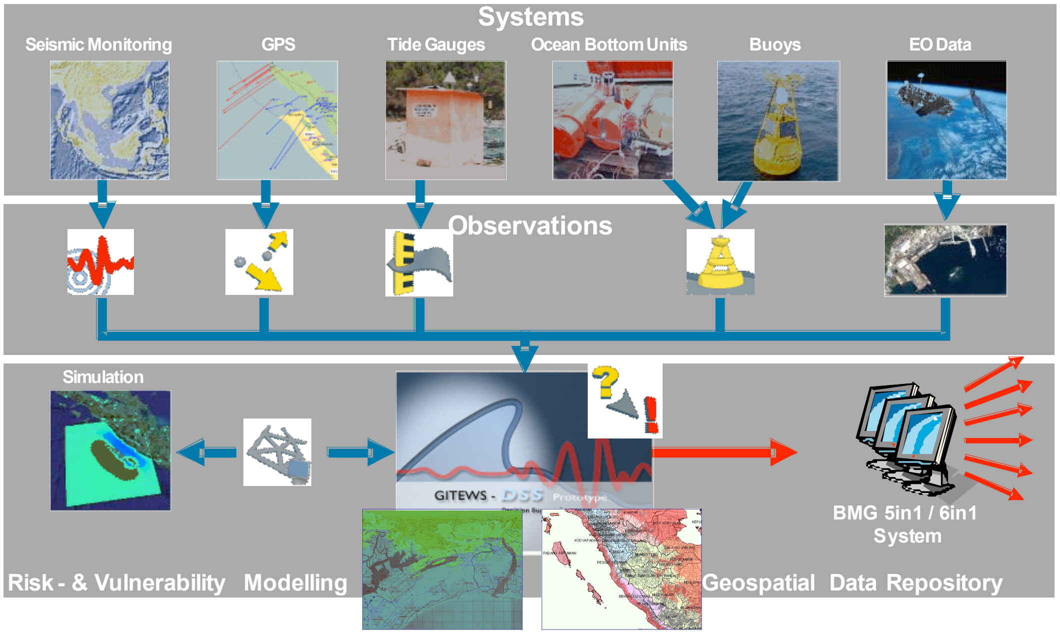

Figure 2. The Early Warning and Mitigation System Concept

sensor integration platform called Tsunami Service Bus (TSB) and interacts with the SIM in order to achieve the best and most sensible tsunami scenario selection based on available sensor observations. Products generated by the DSS are sent to the connected dissemination systems for further distribution.

To fulfill the tasks mentioned above, the DSS executes a core decision support loop (see

), which is iterated each time new sensor observations are available or deadlines have been reached. The core decision support loop consists of two major components:

- *Situational Awareness*
- *Decide and Act*

Situation awareness in turn comprises the steps:

- *perception* (gather information)
- *comprehension* (judge information)
- *projection* (effect estimation / projection)

In the perception step the DSS receives sensor input, including results from the simulation system. Following this step, the sensor input will be processed and analyzed. In the comprehension step there is further analyzing of sensor input across sensor types. The projection step comprises the projection of the current situation into the future. The following steps derive decision proposals based on the current situation awareness and helps implementing decisions, e.g. by automatic generation of required warning messages.
The user interface and process workflows of the DSS have been designed for decision making under uncertainty and time pressure. Based on the large body of research literature on this topic and the results of an eye-tracking based study regarding a first DSS GUI version, it is now available in an improved and optimized version (see **Fehler! Verweisquelle konnte nicht gefunden werden.**).

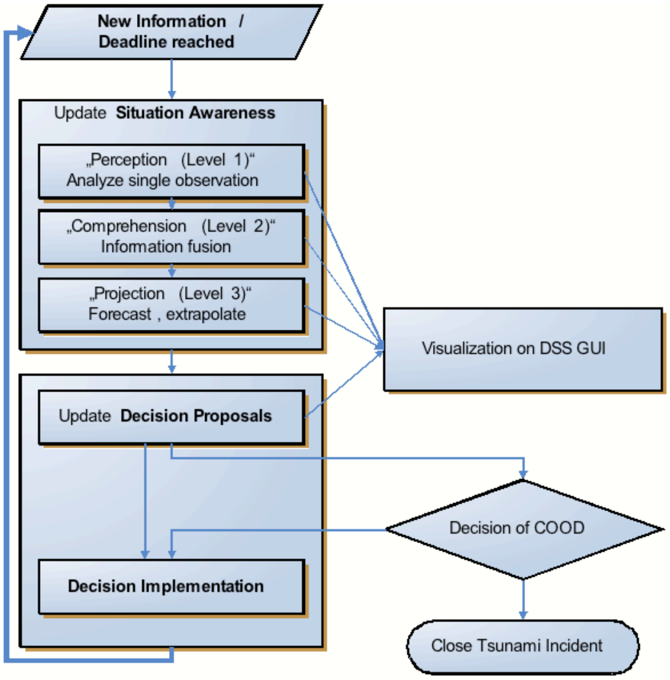

Figure 3. Core Decision Support Loop

The GUI consists of four displays (called *perspectives*) shown simultaneously to the COOD.

4. AUTOMATIC INTERACTION OF DSS AND SIM

4.1 Getting to know the scenarios: the Ingestion Process

Due to computational complexity and limitations of today's hardware, tsunami scenarios need to be calculated in advance. Available scenarios are then added to a central Tsunami Scenario Repository (TSR).

Before new scenarios can be used in the multi-sensor selection process of the SIM or the situation assessment process of the DSS, both systems must first learn about the new scenario. This process is called "ingestion" and includes

- The extraction of core parameters into an index database of the SIM, and
- The extraction of information essential for the DSS, e.g. information about the estimated time of arrival (ETA) and the estimated wave height (EWH) at sensor and coastal locations, inundation areas, isochrones.

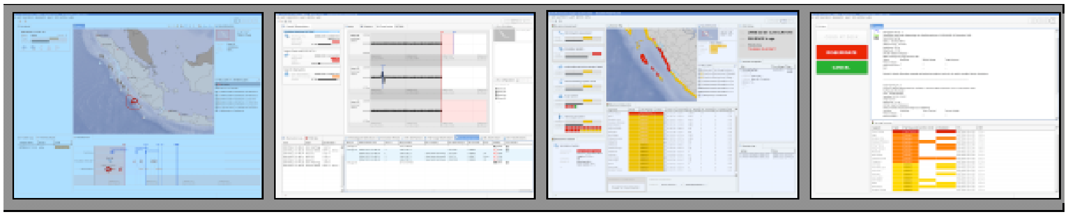

Figure 4. The DSS Graphical User Interface

After the ingestion process has completed successfully for the new scenario, it can be referenced by its scenario ID, used for the selection process and be part of a SIM result list which the DSS is prepared to interpret.

4.2 Requesting a Scenario Selection

When the DSS requires a tsunami scenario selection, it first compiles a list of sensor observations to be used in the multi-sensor selection process of the SIM. While some sensor observations complement previous observations, others replace them (e.g. in the case of a refined seismic observation which replaces the previous solution). After the DSS has selected the observations to be matched against, it submits this selection to the SIM and requests a scenario selection.

Beyond the request for tsunami scenario selection given the most current set of sensor observations, the DSS might trigger the SIM for other purposes, including sensitivity analysis, error detection, and ambiguity reduction.

4.3 The Scenario Selection Result

As a result of the scenario selection process, the SIM transmits a sorted list of possible tsunami scenario IDs, together with a set of quality and error parameters:

- The *reliability* index (*R*) as described above in section 2.3;
- For each of the scenarios in the result list:
    - Matching values for each of the observations used in the selection process (individual norms);
    - The *mismatch*; this is the overall mismatch of the scenario and the main sorting criteria for the result list;
    - The *aggregated mismatch* which describes the raw result of the analysis of data and is used as secondary sorting criteria for the result list;
    - The *skill* (*S*) as a quantification of the data situation in the scenario (see section 2.3).

The length of the result list is determined dynamically by the SIM, depending on the overall result of the individual selection process. Main criteria here is the relative difference of the mismatch value of neigbouring scenarios in the unshortened result list. The first almost indistinguishable scenarios are collected in the list. Therefore, the list length gives an additional indication on the uncertainty of the data situation.

4.4 Result analysis

The DSS uses all of the above mentioned q As result of the situation awareness step in the DSS core decision support loop, the DSS generates a description of the assumed tsunami, taking into account all available information. The SIM result list is the major building block of this process.

The DSS uses all of the above mentioned quality parameters to analyze the result list according to a set of criteria. Among the criteria considered are:

- Selectivity: can a single best scenario be identified or is it hard to differentiate between a number of scenarios?
- Ambiguity: what do the scenarios on top of the result list tell us? Are they describing similar arrival times and wave heights at sensor locations and points on the coastline?
- Aggregation: do we have to aggregate several scenarios in order to account for uncertainties? Which scenarios on the result list should be aggregated? How to aggregate?
- Sensitivity: how much does the result depend on few or single sensor observations?

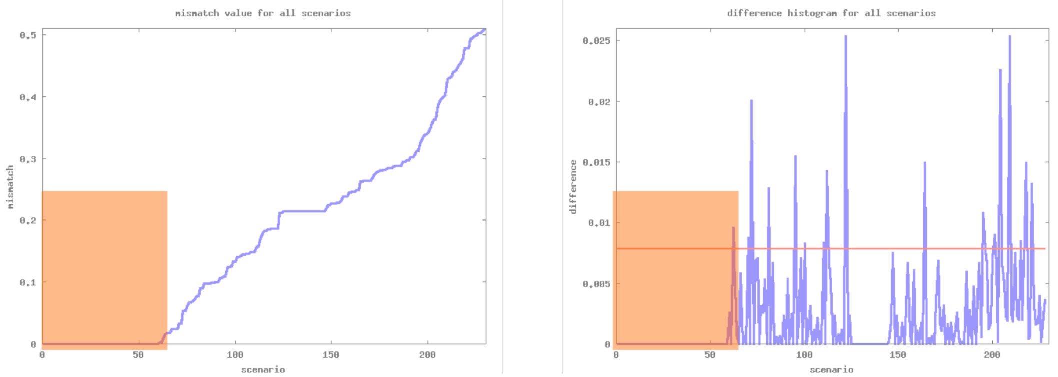

Figure 5. Example result list based on seismic observation only

A lot of scenarios with (nearly) equal mismatch values would require the DSS to consider them all; a closer look at the aggregated mismatch and skill parameters will in most cases allow to reduce the number of scenario candidates. An ambiguity analysis might reveal that the set of scenarios with equal mismatch values all predict similar consequences. If a scenario aggregation is considered necessary, the number of scenarios to be aggregated must not exceed a certain number due to performance reasons.

The finetuning of the large number of parameters in this overall analysis process will be done in the test and commissioning phase of the GITEWS project in 2009 and, as part of a permanent learning and optimization activity, beyond.

5. EXAMPLE

The following example shows how additional sensor observations improve the scenario selection result in terms of matching quality, number of potential scenarios, and increased certainty.

Figure 5 shows a result list example based on a single seismic observation: the left diagram depicts the increasing mismatch values of the scenarios in the result list, and the right diagram shows the according relative mismatch differences between neighbouring result list entries. The coloured block shows the part of the overall result list which has been selected for transmission to the DSS (72 scenarios in this example).

Figure 6 shows the waveform forecasts of the scenarios in the example result list for two tide gauge stations (Padang and Bengkulu). The black line shows the “true” (but unknown) signal, the red line is the best-fit scenario (No. 1 in the result list), and blue are the next best matches (fading from dark to light blue).

Figure 7 shows the same example, but now an additional oceanographic sensor observation is

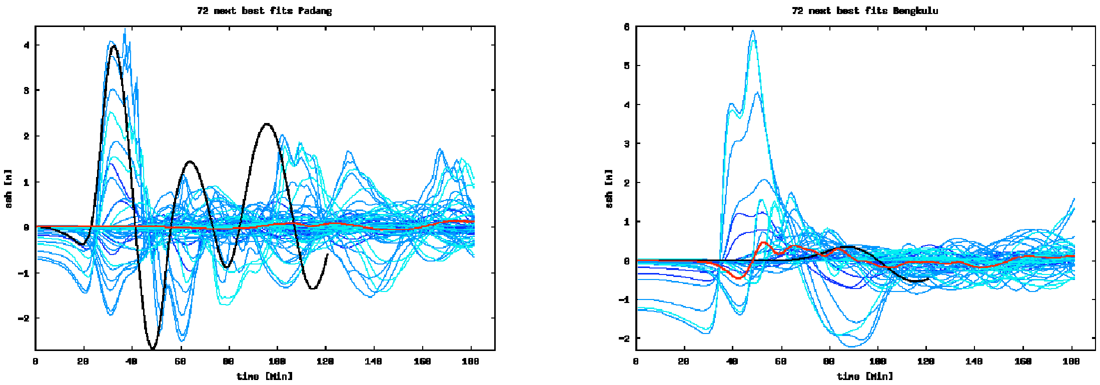

Figure 6. Example set of possible wave forms at two tide gauges

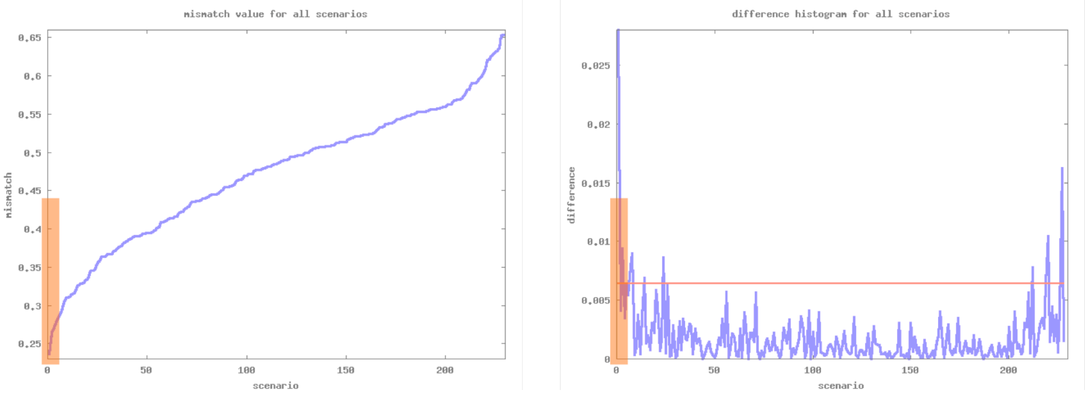

Figure 7. Example result list based on seismic and oceanographic observations

available for scenario selection. The improvements in the selection quality are obvious and show the power of the multi-sensor selection process: the left diagram depicts a steeper mismatch curve; both diagrams show that the result list is much shorter now and selectivity is increased drastically, now resulting in only 5 scenarios on the SIM result list.

Compared to Figure 6, Figure 8 shows that the waveform forecasts are much more precise and, if we would only take the best-fit scenario, it would fit quite well already. Additional available sensor observations improve the matching quality in a similar manner.

In this example, the list length gives a first indication on the reliability of the matching result. Additionally, the reliability index *R* has increased with additional sensor information, giving the COOD an immediate information about the situation assessment quality. In this example all scenarios are assumed to have the same skill.

6. CONCLUSIONS

In this article we presented the complex interplay between the DSS and the SIM within the GITEWS early warning system. A key feature of the system is its capability to deal with uncertainty in measurement data within the first few minutes of a tsunami event. By evaluating different types of data and using information derived from the comparison of simulated data with measurements, the uncertainty in the situation can be reduced drastically.

Since the system is intended to support decision processes, all interaction is performed automatically. Open interfaces support seamless operation. A close interplay is necessary in order to be able to interpret the added value of statistical analysis performed during the matching process.

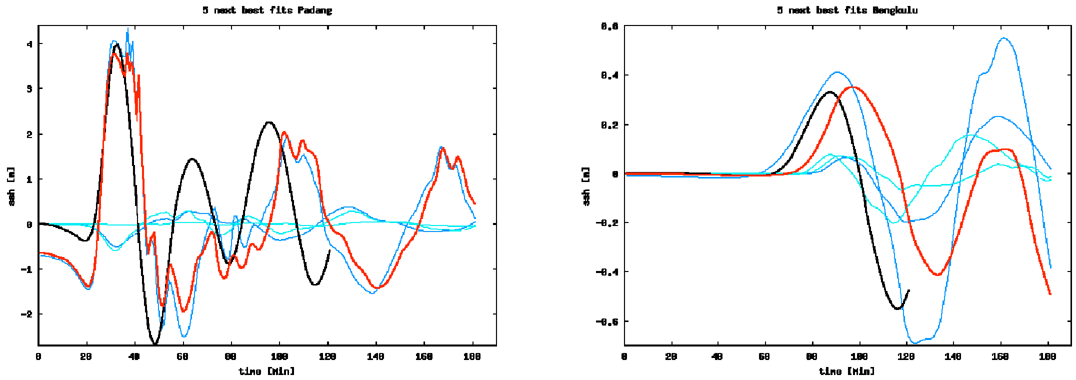

Figure 8. Example set of possible wave forms at two tide gauges

7. ACKNOWLEDGMENTS

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