Recent progress in storm surge forecasting

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RECENT PROGRESS IN STORM SURGE FORECASTING

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ABSTRACT

This report briefly summarizes recent progress in storm surge forecasts, one of topics discussed during the fourth International Workshop on Tropical Cyclone Landfall Process (IWTCLP 4) held during 5-8 December, 2017. In the workshop, improvement of storm surge forecasting system was mainly discussed with relevance to the problem of estimating the impacts of tropical cyclone landfall.

To deal with storm surges, accurate TC condition (predictions and forecasts) as input, reasonable storm surge predictions (with forecasting systems), and effective advisories/warnings (i.e. useful information products) are necessary. Therefore, we need to improve storm surge related matters systematically: input, prediction system, and effective information.

This report tries to highlight recent progress in the field of storm surges in relation to three key points: improvement in storm surge forecasting models/system, TC conditions as input for storm surge predictions, and informative products for end users.

Keywords: storm surges, tropical cyclone, forecast system, warning, landfall

1. Introduction

Storm surges are generated by atmospheric storm forcing, such as tropical cyclones, developed mid-latitude lows and so on. Storm surges are phenomena occurring in coastal regions and heavy inundations associated with storm surge have led to severe damage in history (Dube et al, 2009; Needham et al, 2015). Severe disasters by storm surges still occur worldwide as listed in Table 1. Considering the number of cases, it is clear that major storm surge disasters happen infrequently, but once they occur, the impact can be very serious.

In 2017, a number of such storm surge disasters occurred: Hurricane Harvey in the USA, Typhoon Hato in Hong Kong and Macau China, and Hurricane Irma caused severe damages in Caribbean countries. Although those disasters did not come only from storm surges, storm surges caused huge economic damages in those regions. Fortunately, total death tolls in most recent storm surge cases were not as high as previous historical cases which killed thousands of people or more. While storm surge warning systems apparently worked well in recent cases, we need to keep in mind that storm surges are capable of causing high death tolls and may kill many people in the future as populations in coastal regions are growing. Storm surge is surely one of the key topics in disaster risk reduction, despite their relatively infrequent occurrence.

Presently, storm surge forecasts are mainly created by numerical storm surge models. Storm surge model numerics were developed in many years ago, and there has been little recent improvement in physical processes. The improvement is mainly carried out in dynamical aspect such as grid resolution or coordinates. Other improvements are related to model coupling. When we talk about a risk of storm surges, it means rather inundation risk which is also affected simultaneously by many factors: astronomical tides, waves, river flows or precipitations and so on. Wave and atmospheric models are becoming increasingly reliable and useful, so coupled models can consider interacting processes and make integrated predictions based on the total water level envelope (TWLE).

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Table 1. Major storm surge disasters in recent years

TC name	Year	Max. Intensity (10-min wind)	Economic loss* (billion)	Fatalities*	Typical storm surge
Katrina	2005	902hPa 135kt	$108	1,833	4-7m
Sidr	2007	944hPa 120kt	$1.7	~15,000	3-6m
Nargis	2008	962hPa 100kt	$12.9	138,366	3-5m
Sandy	2012	940hPa 95kt	$68	233	3-4m
Haiyan	2013	895hPa 125kt	$2.86	6,329+1,074	5-7m
Winston	2016	884hPa 155kt	$1.4	44	3m
Hato	2017	965hPa 76kt	$6.82	24	3.5-4m
Irma	2017	914hPa 123kt	>$64.76	66+80	3-4.5m

*Total (not only by storm surges)

In the next section, progresses in storm surge models and systems are discussed. Section 3 and 4 focus on improvement in TC conditions for storm surge forecast input and effective information, and section 5 summarizes the discussion.

2. Progress in storm surge forecasting models/systems

Numerical storm surge models have become very reliable over recent decades and the basic model numerics have changed little. In a sense, physical understandings of storm surges and prediction models have matured; there have been no breakthrough in this field in recent years. However, model dynamical frameworks have been improved; unstructured methods such as Finite Element Method (FEM) or Finite Volume Method (FVM) are becoming popular.

In operational fields, storm surge forecasting systems are applied in many countries and their predictions are issued in real-time. In addition, global scale storm surge forecasts are also available now.

Another area of progress is the inclusion of other physical effects. Storm surge risk should be interpreted not solely based on storm surges, but with other factors such as tides and waves. Such integrated forecasting systems have been developed in the research field, and they are gradually transitioning into operations.

a. Progress in numerical models/systems

Recently, many unstructured storm surge models have been developed. The merits of unstructured models are freedom of model bathymetry setting. The model can set grids freely to fit with complicated coast lines and to set the grid resolution to be fine at the coast and coarse in offshore regions. The coarse model grid resolution offshore, where storm surges are not an important issue, saves computation resources while fine mesh nearshore provides an ability to resolve detailed storm surge behaviors there. There are several models commonly used for storm surge predictions, such as FVCOM (Chen et al., 2006), ADCIRC (Luettich and Westerink, 2004), SELFE (Zhang and Baptista, 2008), and Delft3D (DELTARES).Those models support the widespread use of unstructured storm surge models.

Nowadays ocean wave models are also available and recent trend is to develop a surge - (tide) - wave coupled system. Wave setup is a rather small scale phenomenon but high resolution models are skillful in simulating that effect accurately.

b. Operational storm surge prediction

Many National Met/Hydro Services (NMHSs) have come to use storm surge models in operation and issue warnings or advisories based on the predictions. This is one of the achievements of occasional international activities to develop storm surge modeling and forecasting, such as a series of workshop on storm surge and wave forecasting organized by WMO/IOC Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM) and WMO Tropical Cyclone Programme (TCP).

Those operational models are rather simple. Sophisticated storm surge models require huge computer resources, but ease-of-use and robustness is most important in operational work. Besides, accuracy of those straightforward storm surge models may not significantly different from more sophisticated models. Since storm surge forecast errors arise mainly from TC forecast errors (input for storm surge model), not from the lack of skill in storm surge models, even simple storm surge models work well in operational fields. There are several countries where computer resources are not sufficient for operating a complicated storm surge model but storm surge information is nonetheless required. Simple storm surge models are very useful for those countries.

c. Global scale storm surge information

Although storm surges are rather localized phenomena, severe storm surge disasters are usually devastating and monitoring and risk analysis needs to be carried out globally to cover all regions. One of those activities is the regional Storm Surge Watch Scheme (SSWS) of the World Meteorological Organization (WMO).

WMO Storm Surge Watch Scheme (SSWS)

Severe storm surge disasters happened worldwide in the late 2000s. In particular, the Cyclone Nargis disaster in Myanmar in 2008 was the trigger for the establishment of a global range storm surge watch scheme. At the 60th WMO Executive Council held in June 2008, a request to facilitate development of a storm surge watch scheme was put to the WMO Secretary General. The schematic image is shown in Figure 1. Establishment of such a scheme was encouraged in all tropical cyclone regions, and each Regional Specialized Meteorological Center (RSMC) for tropical cyclones is expected to provide storm surge information.

In the North Indian Ocean, the Panel on Tropical Cyclones and RSMC-Delhi (Indian Meteorological Department IMD) firstly developed SSWS in the Region, and RSMC-Delhi started issuing storm surge graphical advisories in 2009. In the Western North Pacific where tropical cyclone (typhoon) activity is most active, RSMC-Tokyo (Japan Meteorological Agency JMA) developed a regional storm surge forecasting system and issues real-time storm predictions to Typhoon Committee members. The operation started in June 2011 and products are gradually enhanced (Hasegawa et al., 2017). The current products are horizontal distribution maps, time series charts at 78 stations, and possible maximum storm surge map. RSMC La Reunion (Meteo-France) created a "cyclone surge atlas" for all coasts in the south Indian Ocean in 2013. Those atlases are the results of huge storm surge simulations with various assumed cyclonic conditions. The storm surge impacts are indicated in the atlases with classification of TC intensity. RSMC Nadi (Fiji Meteorological Service, FMS) is going to issue real time storm surge guidance to NMHSs in the South Pacific region soon. Some product examples are shown in Figure 2.

d. Integration of related factors

Although the storm surge model itself is not so changed, there are now numerous approaches to integrate related factors or to develop coupled models. Strictly speaking, a storm surge is defined as an anomaly from "regular sea level". Such an anomaly indicates the magnitude of response to meteorological forcing, e.g. strong wind and pressure depression. It is a good indicator for evaluating the magnitude of the phenomena. However, it does not necessarily indicate the real risk of storm surge.

A disaster due to storm surge actually means coastal inundation. Inundation occurrence can be interpreted by total sea level which is determined by not only storm surges but also by astronomical tides and so on. Storm surge as anomaly is not sufficient for risk assessment, but total wa-

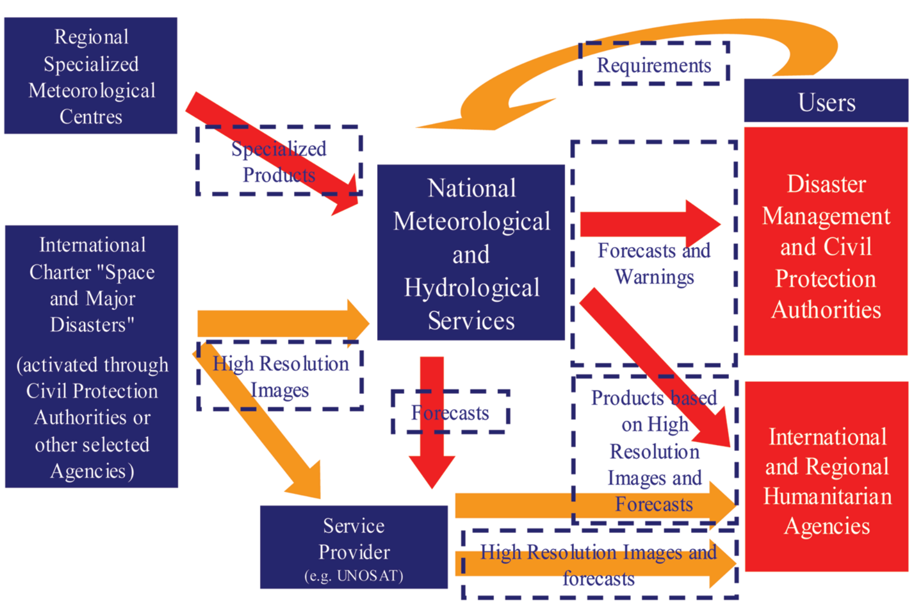

FIG. 1. The schematic image of Storm Surge Watch Scheme (SSWS)

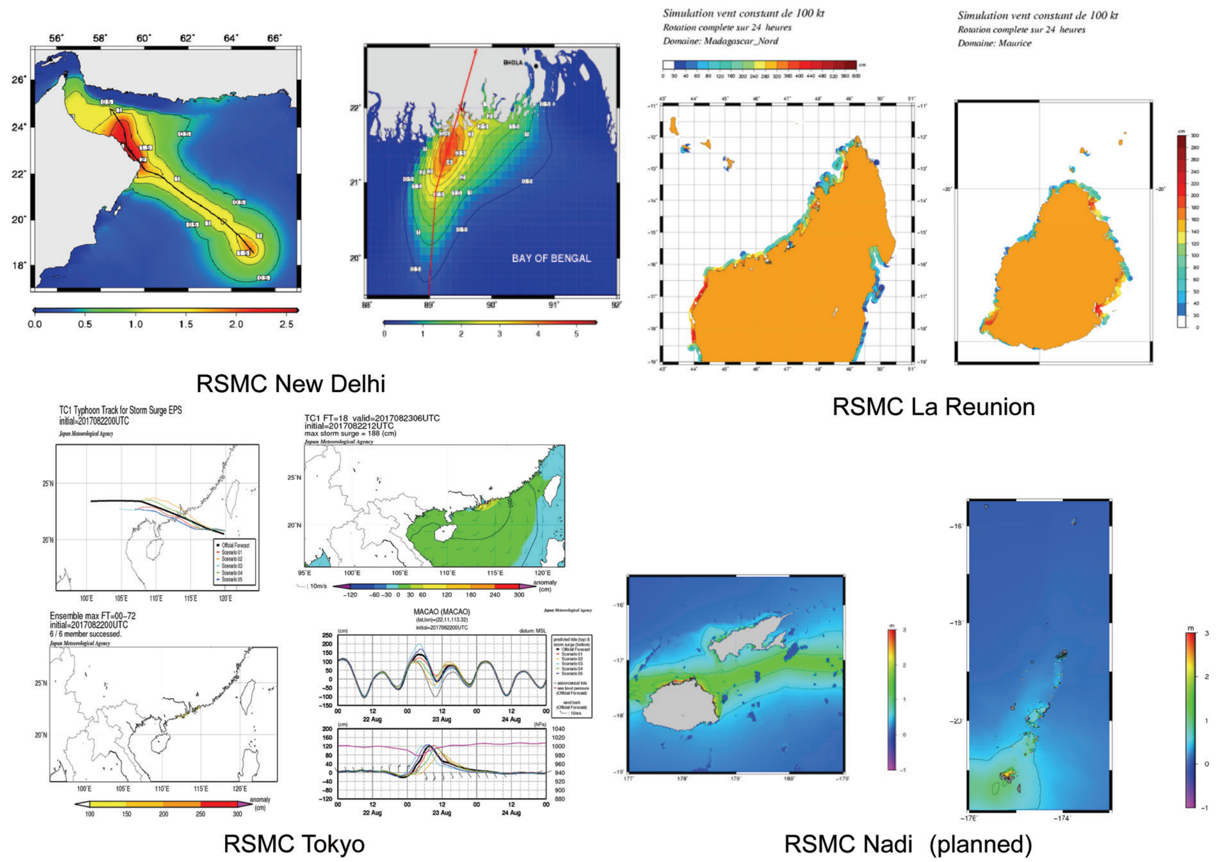

Fig. 2. SSWS Product samples issued by RSMCs

ter level is required. Therefore, we need to consider all of possible factors which may alter sea level.

Recently, various kinds of numerical models have been developed and are available for estimating other effects. There are several tide models, for example, FES 2014 (Carrere et al., 2015), TPXO.8 (Egbert et al., 1994; Egbert and Erofeeva, 2002), and GTSM (Kernkamp et al., 2011) calculate astronomical tides over the globe, and give reasonable tide values. Those models give tidal constituents which can be included with storm surge predictions.

Numerical wave models are widely used in many NHMSs. Recent operational wave models give very reasonable wave predictions. However, even though significant wave heights in offshore are accurate, wave setup, which is the key effect of waves in relation to storm surges, is not well resolved. It needs quite fine grid resolution (namely around 50 m) for models to accurately estimate wave setup (Sasaki and Iizuka, 2007), which may be acceptable in research models but is not always feasible in operational ones. Therefore, there are several attempts to develop a way for estimating wave setups in operational use. A simple formula for the coasts of Australia was developed for the Bureau of Meteorology's operational storm surge system (O'Grady et al., 2015). Wave setup along the Australian coasts was first calculated with a fine mesh wave model and a regression equation was derived from the results. A similar approach was carried out in Environment Canada (Telford, 2015). JMA are developing a simple wave setup estimation model, which estimates wave modification in the shallow water zone. In the USA, National Center for Environmental Prediction (NCEP) is trying to develop a wave-surge coupled system in which a simple wave model, namely the second generation wave model is used (Westhuysen et al., 2015). The second generation wave model requires fewer computation resources than the third generation wave models, and such a coupled model can be used in operational environment.

It is widely accepted that wave setup is important for storm surges, especially for solitary islands or area of steep bathymetry where wind setup is less important. Figure 3 indicates the importance of wave setup at such a coast. When typhoon Haiyan hit the Philippines in 2013, wave setup had an effect comparable to storm surge and could have contributed to the total water level in Guiuan, which faces the deep and the Philippine Trench. In Tacloban, large storm surges were generated by the typhoon, but wave setup was

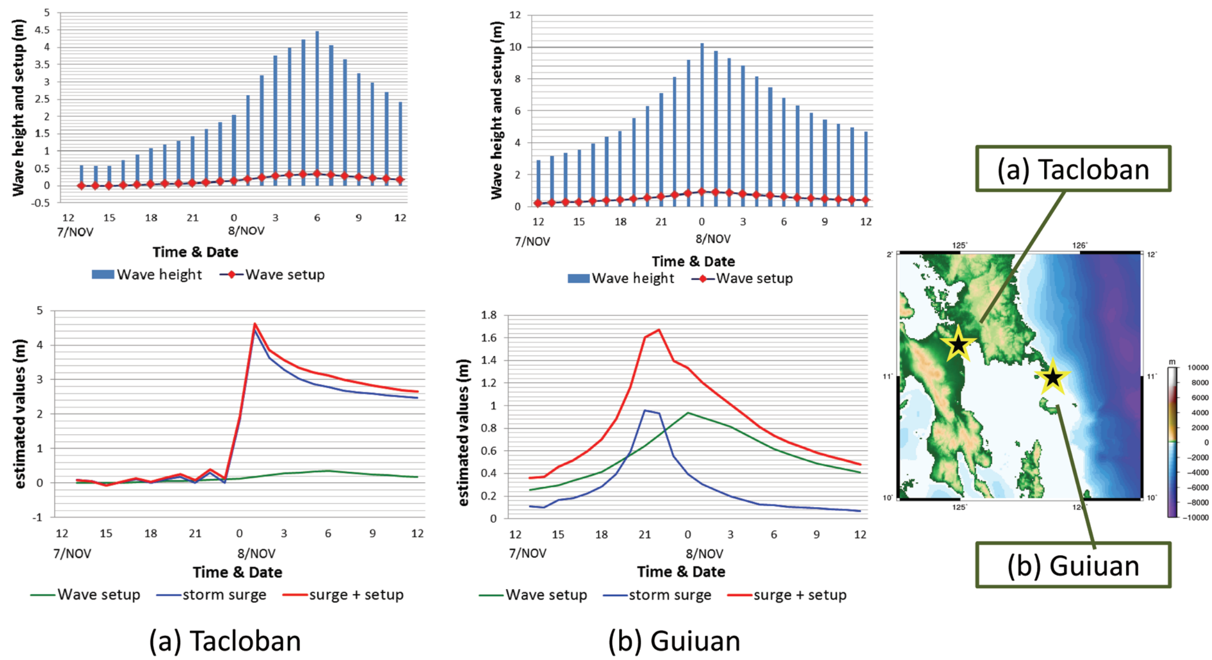

FIG. 3. Simulated wave heights, wave setup, and storm surges for the case of typhoon Haiyan (1430). The values are at (a) Tacloban and (b) Guiuan, in the Philippines.

not so large because the city is located in the inner part of Leyte Gulf. Developments of a method of estimating wave setup are ongoing, but they are not yet completed and further developments are expected.

Nowadays, many sophisticated hydrological models were developed that can provide river flow or flood information. The coupling with those models to storm surge models are not yet common, but it may also become popular eventually. There is such a project promoted by WMO.

WMO Coastal Inundation Forecast Demonstration Project (CIFDP)

JCOMMis leading the implementation of the WMO Coastal Inundation Forecasting Demonstration Project (CIFDP), jointly with WMO Technical Commission for Hydrology (CHy), to demonstrate how integrated coastal inundation forecasting and warnings can be improved and effectively coordinated by the NMHSs (WMO, 2013). CIFDP is aiming to develop an integrated system for inundation forecasts, which can be used in operational environment. The project deals with coordination of effective information and its flow to end users too. This is a demonstration project and it is intended to focus on demonstrating operational forecasting capabilities for integrated coastal inundation. Five sub-projects of CIFDP are implemented in Bangladesh, Dominican Republic, Fiji, Indonesia and Shanghai/China, and the Bangladesh sub-project was successfully completed in 2017.

The Bangladesh Meteorological Department (BMD) and related authority stakeholders in the country worked together to develop an integrated warning system for coastal flooding. The system considered storm surges, tide, wave setup, and river floods and those effects are integrated by Delft-FEWS. An example is shown in Figure 4. The performance of the system was evaluated in the three most recent cyclones and its usefulness was verified. The system is now used in BMD as an operational system.

3. TC conditions for storm surge prediction inputs

TC conditions are indispensable for storm surge simulations. Reasonable storm surge predictions cannot be expected without accurate TC forecasts. Storm surges generated by TCs tend to have large anomalies and those behaviors are highly dependent on TC location and intensity. The accuracy of storm surge prediction is determined by surface wind and pressure fields in addition to bathymetry.

TC forecast skill has been continuously improving and now is fairly accurate, but currently is often insufficient for storm surge predictions. Many NHMSs operationally analyze and issue TC forecasts, such as location, intensity, strong wind areas etc. For storm surge predictions TC location and intensity are most important.

Conventionally, many storm surge models use wind fields derived from parametric models. Sea level pressures (SLPs) in the region of the TC are expressed by some empirical pressure profile such as Holland (1980), Schloemer (1954), or Fujita (1952). From the derived SLPs, wind fields are calculated by utilizing the gradient wind relation. An asym-

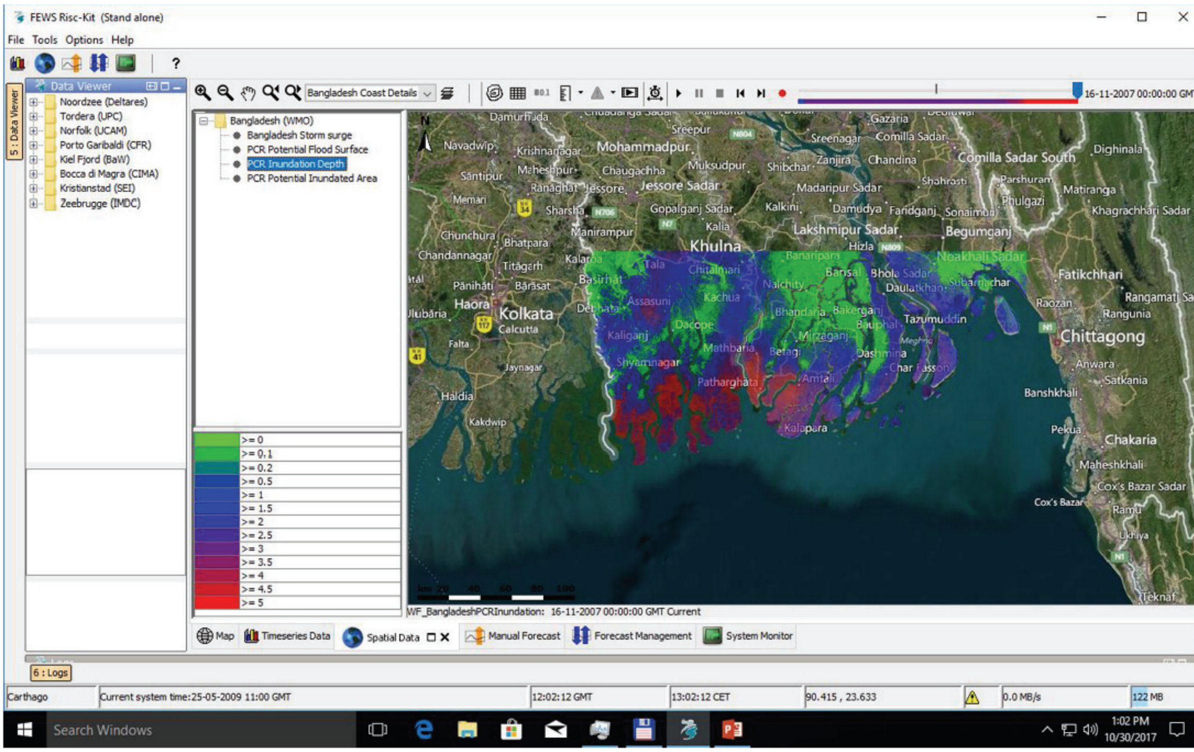

Fig. 4. Example of an inundation map of the CIFDP Bangladesh system.

metric wind component related with TC movement may be added too. This input condition may look very simplistic, it works well and gives reasonable storm surge values. In general, NWP models do not adequately resolve TC intensity, and parametric models with analyzed TC intensity may give better wind and pressure inputs. Besides, the TC track can be easily set in a parametric model, so as to adjust to official forecast or slightly shifted tracks. Therefore parametric models remain useful and will be continue to be utilized.

Parametric models also require the radius of maximum wind, which is a very important parameter for describing the storm extent. However, the parameter is determined empirically and contains large uncertainty. Several formulae for the radius exist, but there is still some room for improvement.

a. NWP products for storm surge input

Recently numerical weather prediction (NWP) models have been improved progressively and have fair skill in resolving tropical cyclone conditions. Track forecasts for short ranges have been improved and 24- hours forecast error is within about several tens of kilometers. The problem is that storm surges are critically dependent on landfall point, even a 10km error in the location may lead to large errors in storm surge predictions. Wind direction becomes opposite (onshore / offshore) around TC center, and a large gap may be generated in storm surge values there. Moreover, the intensity from NWP models is generally underpredicted, which is typical when a TC is very strong or its size is small. Those predictions are not yet satisfactory for storm surge inputs and thus parametric models are still popular.

However, some recent results using high resolution nonhydrostatic models reasonably predict TC intensity, if initial conditions are well assimilated with observed data, or techniques of appropriate bogus vortex initialization are used. NWP models can provide detailed TC structure and wind fields because modulations by environmental pressure patterns or orographic effects are considered. The wind fields dynamically calculated by NWP models are much accurate in the cases when TC structures vary from the standardized forms used in parametric models. Figure 5 indicates that typhoon Kalmaegi (1415) was highly influenced by large–scale pressure patterns and the wind peak was located behind the typhoon center. The NWP model skillfully predicted the wind structure and led to better storm surge predictions. Such situations may often happen in extratropical transition stage too. When a typhoon hits a bay surrounded by mountainous lands, wind fields are modulated by orographic effects. The NWP model gave better wind fields than a simple parametric model, which led to more accurate storm surge predictions as shown in Figure 6.

Perhaps, NWP predictions will be used in storm surge

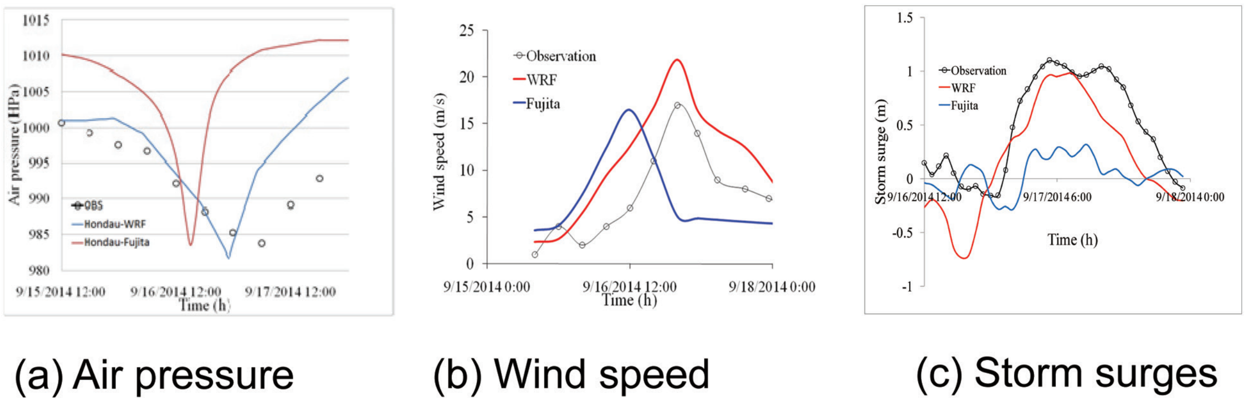

FIG. 5. Calculated and observed values at Hon Dau station for typhoon Kalmaegi in 2014. The graphs indicate (a) air pressures, (b) wind speeds, and (c) storm surges, respectively. The NWP was WRF model and Fujita's formula was used for the parametric model. (Thuy el al, 2014)

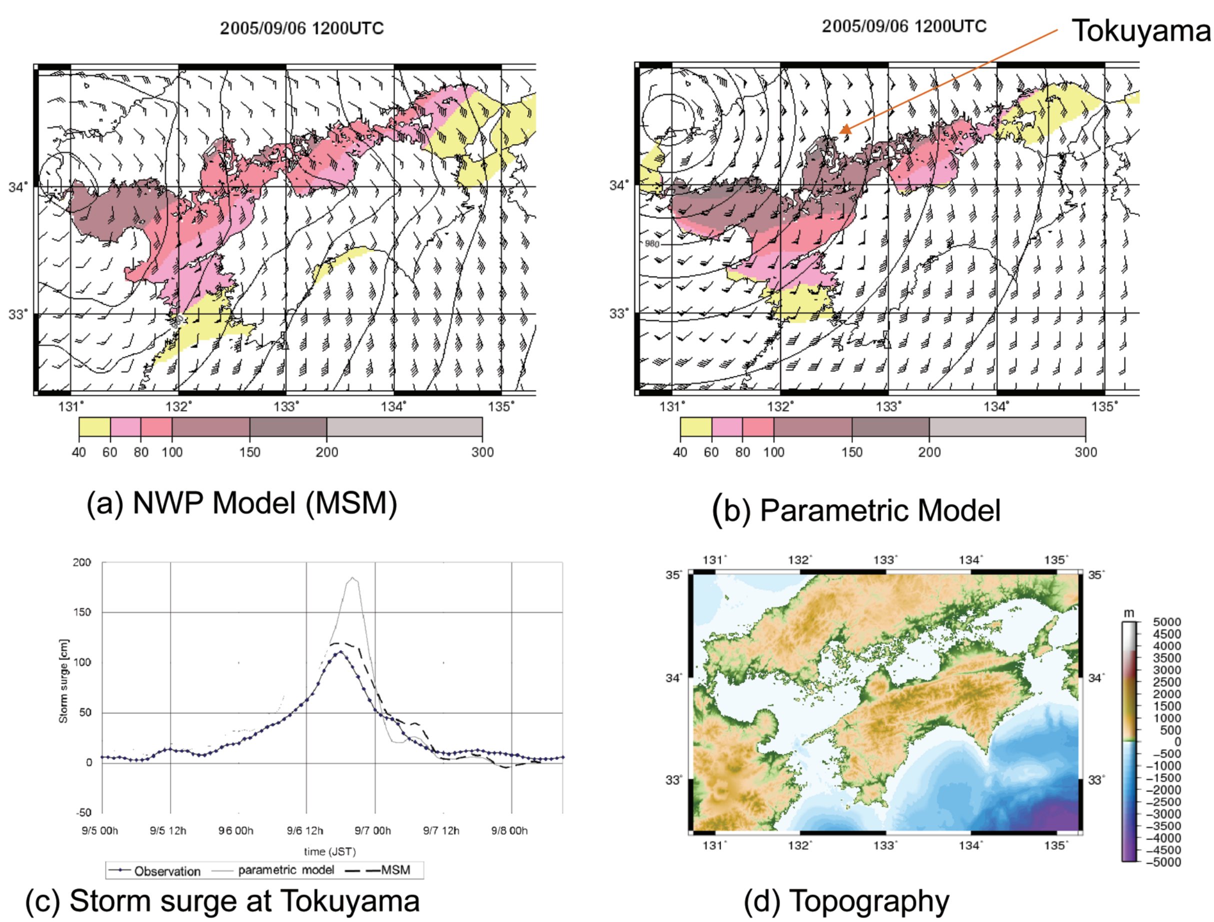

FIG. 6. Comparison of pressures, winds, and storm surges calculated by NWP model and parametric model. Calculated (a) NWP model MSM and (b) parametric model, for the case of typhoon Nabi in 2005. Calculated storm surges at Tokuyama and topography are also shown in (c) and (d) respectively.

predictions more and more in the future. The problem would be that NWP models do not always predict the exact same track or intensity as official forecasts. Some combination of NWP model and parametric model will still be necessary.

b. Ensemble forecast

We cannot entirely remove TC forecast errors, although the errors may become small. We need to consider a realistic amount of TC forecast error and incorporate this information into our storm surge forecasts. In such a condition, a single deterministic forecast is too uncertain to rely on, and thus probabilistic forecasts with multi-scenario (ensemble) predictions should be introduced.

There are several merits to ensemble forecasts. First, several kinds of storm surge values as mean (possible), maximum (worst) and minimum (optimum) are given. Ensemble forecasts also give spread information which helps interpret the reliability and range of predicted values. Besides, predicted ensemble mean (consensus) generally shows more stable and reliable conditions than a single forecast. In ensemble forecasts, the reliability becomes higher as the number of forecast member becomes larger but it requires more computer resources. Therefore, a simple and fast storm surge model is desirable for a forecasting system with large number of ensemble members.

Ensemble products become very useful as forecast time is extended as 2 to 3 days when the TC track forecast error becomes larger. For storm surges, earlier warning is required for taking longer lead time, so that end-users can prepare or evacuate before the dangerous situation. For that purpose, ensemble storm surge forecasts will be necessary.

Storm surge forecasts with many ensemble members or multi-scenarios are gradually becoming more common in operational environment. NHC creates storm surge forecasts, considering the change of various kinds of parameters, location, intensity and size etc. All of those parameters are shifted around the official forecast, considering an error range. The storm surge values are statistically determined by the results. The Australian Bureau of Meteorology (BoM) has developed an ensemble storm surge system (Greenslade et al, 2017). Based on an official TC forecast track, 1000 possible tracks are produced by the method of DeMaria et al. (2009). Storm surge model runs are made with 200 ensemble members that are randomly chosen from these possible tracks. Some examples of the

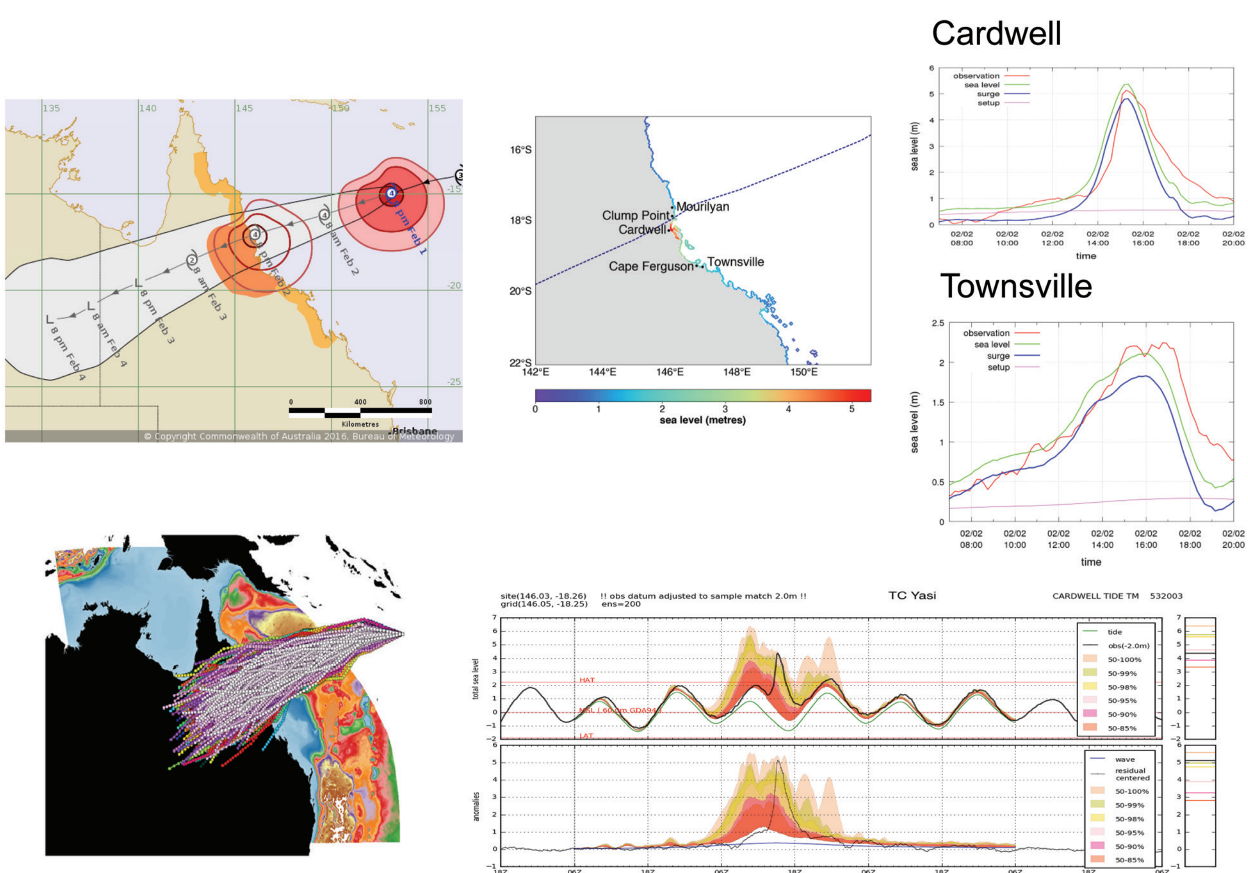

Fig. 7. Example of a storm surge ensemble forecast from the Bureau of Meteorology for TC Yasi in 2011. (Greenslade et al., 2017)

ensemble tracks and resulting forecasts for TC Yasi in 2011 are shown in Figure 7.

In storm surge ensemble forecasts, TC tracks are artificially created considering its forecast error range etc. There is another approach to make use of ensemble weather predictions. Weather models can predict possible TC tracks and spreads. They are determined with dynamical processes and environmental conditions. Basically, spreads of TC track forecasts are not the same among TCs and the values become narrow or broad. Such a dynamically calculated spread can be used in storm surge ensemble predictions. JMA started multi-scenario storm surge predictions with six typical typhoon tracks extracted using cluster analysis from an ensemble weather prediction system (Hasegawa et al., 2017).

Meteo-France in Reunion Island has developed an original method to generate ensemble scenarios around the RSMC's official track forecast in the SPICy project (Bonnardot et al., 2016). The method allows modulation of both tracks and intensity of the cyclone and is based on both climatological errors and the dispersion of the ECMWF EPS ensemble. A distinct probability is attributed to each scenario. Given this ensemble of meteorological forecasts, wind and pressure fields are generated through meso-scale modeling (Meso-NH model) for each individual scenario using a bogusing method. This high resolution ensemble of wind fields can finally be used for forcing a wave model and produce probabilistic forecast of oceanic and coastal conditions.

4. Informative products

Storm surges are possibly one of the least known phenomena to public. Even some NHMS forecasters are not so familiar with this phenomenon. This may be because people who are living in land are not overly concerned about oceanographic phenomena. However, there may be other reasons.

The first reason is that large storm surge disasters seldom happen, compared with heavy rain or strong wind, and people tend to disregard storm surge risk. Even though they might have suffered from storm surges, people tend to forget and lose their sensitivity to storm surges if they occur rarely. There is a popular phrase in Japan by Torahiko Terada who was a researcher on earthquakes and a writer: "天災は忘れた頃にやって来る", which means that *"A natural disaster strikes when people lose their memory of the previous one"*. It is a good thing that storm surge disasters do not happen frequently, but it also makes people tend to ignore the disaster. The public may forget about storm surge cases, NHMS staff must maintain memories of historical cases and knowledge on storm surges. In addition, education to the public and communication with stakeholders or residents are necessary for capacity building of storm surge risk management.

The second matter is that storm surge risk is not easily understood by the public. This is mainly because people do not know about storm surges but also because storm surges do not directly lead to disaster. As a matter of fact, small or moderate storm surges often happen but they seldom lead to disasters. What is storm surge disaster? It is coastal inundation, which is determined by total water level and land height as shown in Figure 8. When people talk about the risk of "storm surges", the main issue of concern is "coastal inundation".

"Storm surges" is a technical term for expressing the phenomenon of abnormal sea level rise by meteorological

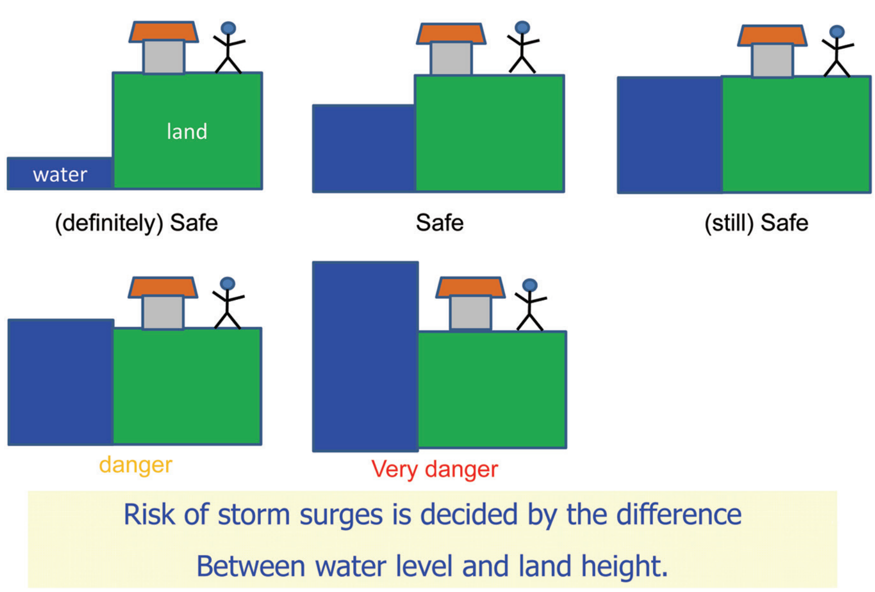

FIG. 8. Schematic image of Storm Surge Risk

forcing. By definition, storm surges refer only to anomaly from usual sea level and do not contain astronomical tides. The general public tends to use "storm surges" for expressing highly risen water levels or just mentioning the phenomenon, which is rather imprecise usage. Storm surge risk should be evaluated in regards of total sea level, considering of possibility of coastal inundation. There are several technical terms related with inundation as shown in Figure 9. Those terms are useful in the scientific world, but are very complicated to the public. Besides, total sea levels are decided by not only storm surges but also tide, waves, river flows etc. Those other effects must be included in discussing inundation risk.

Forecasting staff must understand those mechanisms and evaluate their contributions to total water levels as technical experts. However, the public does not need to know nor care about those mechanisms; they are just concerned about whether inundation may occur or not. This means some translation would be necessary for informing actual risk by storm surges to the public. This is quite different from other phenomena such as rain, because people can understand the meaning of rainfall amount. Storm surge risk should be communicated in a simple and user-friendly way. An example is the recent products issued from National Hurricane Center (NHC) of the USA.

National Storm Surge Hazard Map of NHC

NHC has made considerable efforts to improve storm surge information, based on experiences of storm surge cases by strong hurricanes. NHC tried to develop integrated information based on total water level in which surge, tides, waves, and fresh water and background anomaly are included. In addition, predicted water levels are converted to inundation guidance and issued as graphical images by utilizing a GIS tool. In the development of the product, they also engaged with experts in social science. The new graphical images are plain and people can understand the risk much easier than text message warnings. The new product became operational in the 2017 hurricane season. The first official risk maps, shown in Figure 10, were issued for hurricane Harvey in 2017.

5. Summary

Recent progress in the field of storm surges is briefly summarized. To repeat, it is necessary for improvement in storm surges to integrate various topics, improvement in TC forecasts and their usages, user-friendly and communicative information, as well as knowledge on storm surge physics and development of storm surge forecasting systems. Storm surge models consist of rather simple physics and numerics, which is relatively well-understood and mature. However, there are strong requirements for detailed forecasts with fine mesh models or integrating other related factors to calculate total sea level. It is mainly because other numerical models, such as tide models, wave models, and hydrological models have been developed and are reliable, and thus, nowadays coupled systems become increasingly feasible. Those coupled systems will be main-stream in future, and many processes will be coupled eventually.

Improvement of TC information (analyses and forecasts) is very important issue itself, but is also crucial for storm surge forecasts, and thus, accurate TC forecasts are eagerly expected. Recent NWP models come to have ability for resolving fair TC intensity. NWP models dynamically estimate TC structure, more specifically pressure and wind fields. Those conditions can simulate more realistic storm surge behaviors than ideal parametric model input, and direct use of those predicted grid point values for storm surge forecasts will be spreading.

The other trend is probabilistic forecasting with ensemble systems. We cannot entirely remove TC forecast errors, and ensemble techniques provide would be practical way for

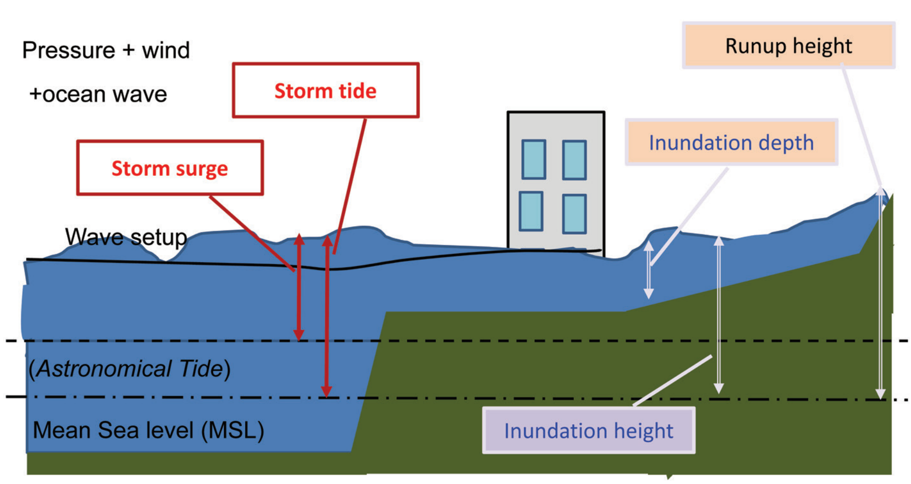

Fig. 9. Terms related with storm surges and inundation

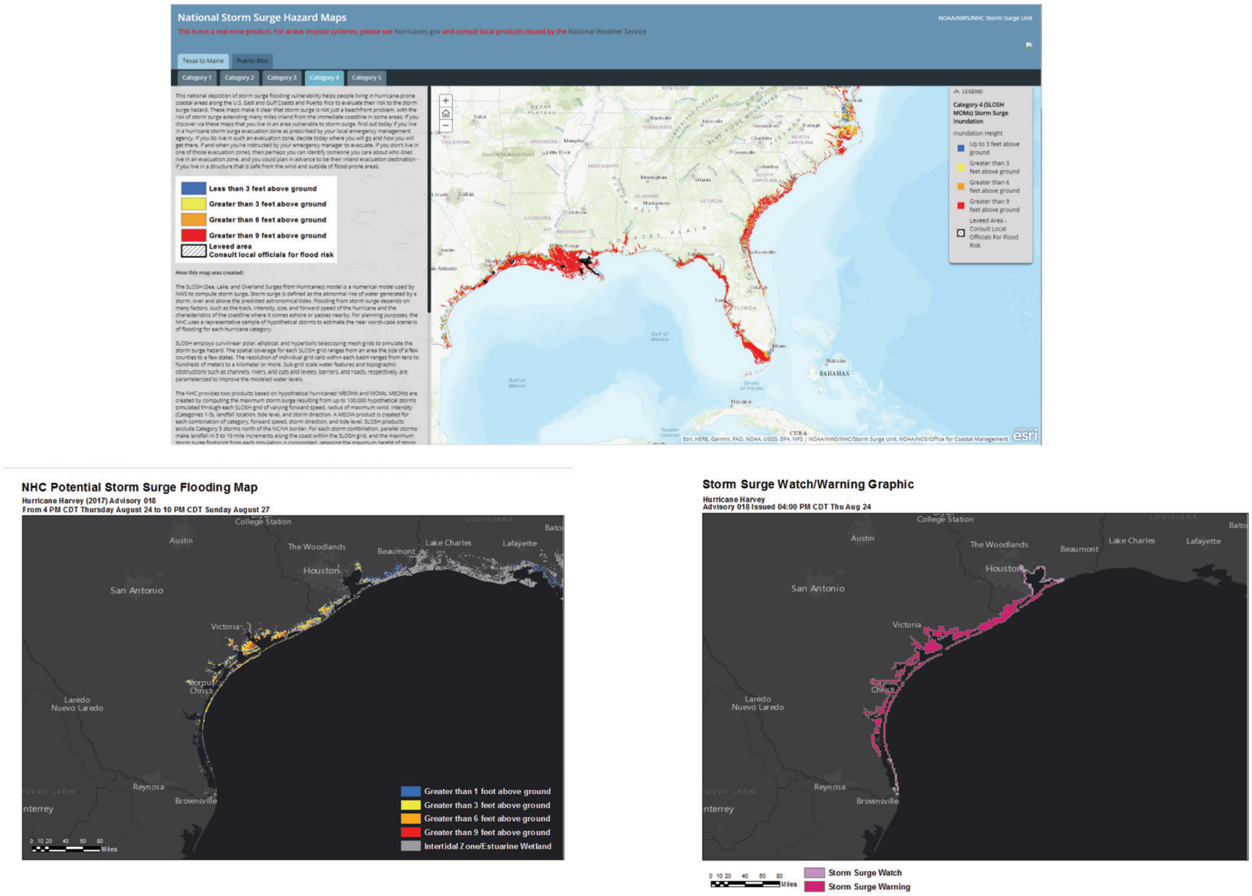

FIG. 10. Example of storm surge hazard map of NOAA NHC and NWS. The first operational risk map issued for Hurricane Harvey in 2017.

estimation of possible storm surges, including uncertainty and probability. Ensemble weather prediction systems are now widely used in many NHMSs and those predictions will give very useful storm surge predictions. However, the grid resolutions of EPS models are generally coarser than deterministic models and there is a concern that TC intensity would not fairly be resolved in EPS models. Improvement of EPS TC forecasting skill is also expected.

Even if storm surge forecasts are accurate, it is in vain if the risk is not well understood to the end user. People do not have much knowledge on storm surge characteristics, and they may forget because storm surges seldom happen. Education for the public, and communication with stakeholders and residents is necessary. Simple information which public people can easily understand is very important in disaster risk managements (DRM). Especially, storm surge is not a widely understood phenomenon by the general public, it is quite difficult to appropriately inform end users of the potential hazard. Since storm surge disaster means coastal inundation, the risk should be issued in relation to water level above ground (inundation), instead of just mentioning a phenomenon such as anomaly (storm surge). Recent development of forecasting models may enable the estimation of total sea level, and thus inundation heights. However, people usually do not know their elevation heights and we may further convert inundation heights (from mean sea level) to inundation depths above their local land height. To estimate inundation depth, we also need high mesh land elevation data may not be available in multiple countries. Inundation depth information may be not an easy task but remains a goal for the future.

Finally, we would like to stress the importance of observations, which was not so much discussed in the workshop. Storm surges are mainly observed by tide gauges. Much observed data are now shared under the Global Sea Level Observing System (GLOSS); however the number of tide stations is far from satisfactory, especially in developing countries where storm surges happen. A more dense observation network is desired, but it is not an easy task to install and maintain many tide stations along whole coast lines because of cost.

Recently remote sensing with micro-wave sensors of satellites becomes a popular way to obtain ocean observations. One of the many challenges associated with this data is that those satellites other than altimeters cannot directly observe storm surges because storm surges are limited in coastal area where satellite sensors are unable to measure. In addition, polar orbiting satellites will infrequently observe TC area and the storm surge might be missed. Various communities need to collaborate for constructing tide observing networks. Tide observations are used for not only storm surge monitoring but also for tsunami, so a dense tide observing network is useful for multi-purposes.

In regards of observations, we may expect indirect merits. If data from coastal weather radars or space-borne satellites can be assimilated to correct TC intensity or structure, the modified TC condition surely lead to better storm surge forecast. Better observations should be expected to contribute to storm surge forecast improvements, even though it does not directly measure storm surges.

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