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Storm surge prediction: present status and future challenges

Jiachun Li[a,b,]*, Bingchuan Nie[c]

[a]Key Laboratory for Mechanics in Fluid Solid Coupling Systems, Institute of Mechanics, Chinese Academy of Sciences, Beijing, 100190, China.
[b]School of Engineering Science, University of Chinese Academy of Sciences, Beijing 100049, China.
[c]School of Civil Engineering, Beijing Jiaotong University, Beijing 100044, China.

Abstract

In the current review, the most pessimistic events of the globe in history are addressed when we present severe impacts caused by storm surges. During previous decades, great progresses in storm surge modeling have been made. As a result, people have developed a number of numerical software such as SPLASH, SLOSH etc. and implemented routine operational forecast by virtue of powerful supercomputers with the help of meteorological satellites and sensors as verification tools. However, storm surge as a killer from the sea is still threatening human being and exerting enormous impacts on human society due to economic growth, population increase and fast urbanization. To mitigate the effects of storm surge hazards, integrated research on disaster risk (IRDR) as an ICSU program is put on agenda. The most challenging issues concerned such as abrupt variation in TC's track and intensity, comprehensive study on the consequences of storm surge and the effects of climate change on risk estimation are emphasized. In addition, it is of paramount importance for coastal developing countries to set up forecast and warning system and reduce vulnerability of affected areas.

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Keywords: Storm surge, Tropical cyclone; Extratropical cyclone; SPLASH, SLOSH; Risk analysis; IRDR

1. Introduction

Storm surge, an extraordinary sea surface elevation induced by atmospheric disturbance (wind and atmospheric pressure), is regarded as a most catastrophic natural disaster. According to long term statistical analysis, total death toll amounted to 1.5 million and property losses exceeded hundred billions USD globally since 1875[1]. They could

* Corresponding author. Tel.: +86-010-8254-4203; fax: +86-010-6256-0914
E-mail address: jcli05@imech.ac.cn

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be caused by extratropical cyclone (front or cold air outbreak) in winter and spring and tropical cyclone in summer and autumn. Generally speaking, the latter tends to be more severe and changeable.

In the globe, Northwest Pacific (NWP), Caribbean region/Mexico Bay/NW Atlantic, North Sea, Indian Ocean/NW Australia coast and Adriatic Sea are all storm surge prone areas. For a storm surge in Yishi Bay, Japan on Sep. 26 of 1959, the wind-induced water elevation of Nagoya coast was as high as 3.45 m with death toll more than five thousand. The most serious hazard occurred in Bangladesh on Nov. 13 of 1970. Low-lying land around Heng River delta was drowned and more than 300 thousand people lost lives.

With long coastline and frequent invasion of tropical cyclone (TC), China is heavily subjected to storm surge hazards in history. Total 576 years of grave storm surges from 18 B.C. to 1946 were recorded. Yet, there were some historical records as below:

- Lai Zhou Gulf in 1782: *On Aug. 5 in the fall, wind and storm rose all of a sudden. The areas even hundreds km far from the sea were indulged, a great many people and cattle were drowned.*
- Da Gu in 1895: *On Apr. 28, storm almost ruined all the buildings, the area became a vast expanse of water, more than 2000 people died.*
- Shan Tou in 1922: *At three o'clock on Aug. 2, wind grew stronger and stronger so that mountain was shocked, trees uprooted and buildings collapsed. Water was as deep as 3 meters due to heavy rain and tide, many villages disappeared in the flood. Number of dead inhabitants reached ten thousand.*

Even up to 1950s-1960s in the last century, still there were a number of serious events causing heavy casualties due to storm surge such as in Xiangshan on Aug. 2 of 1956, Nandu on Jul. 15 of 1965 and Shantou on Jul. 18 of 1969[2]. China's forecast of storm surge started in 1970s. Since then the death toll was considerably reduced to hundreds, even tens in the last decades (see Fig.1). However, the economic losses were still shocking due to industrial development and urbanization. And a few individual years claiming abnormally massive lives such as 1994 and 2006 still existed (see Fig.1).

Hence, storm surges are ranked among the most threatening calamities, the impacts can be comparable to earthquake and tsunami. Thus the theoretical prediction and operational forecast have always been put at priority of disaster mitigation.

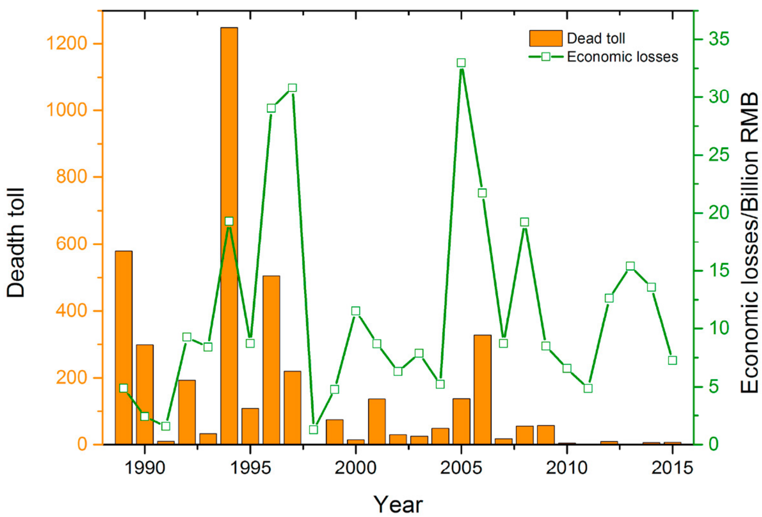

Fig. 1. Economic losses and death toll in China due to storm surge disasters since 1989.

2. Prediction and forecast--present status

Accurate prediction and forecast of storm surge hazards are heavily dependent on the following factors.

2.1. Tropical cyclone models

A TC including Typhoon in NWP and Hurricane in Atlantic Ocean is a vast warm and humid vortex containing large amount of vapor generated at the tropical sea surface beyond latitude of 5 degree with SST higher than 26℃. They are moving northwest with strong wind and heavy precipitation. The major parameters of a TC are genesis site, trajectory, central low pressure, maximal wind speed and its radius. During previous decades, people have advanced from empirical, statistical to numerical forecasts. We can list the models employed by meteorologist administrations of major countries and regions.

Cangialosi & Franklin[3] have provided a NHC comprehensive overview on TC's track, intensity and genesis forecasts in Atlantic and North Eastern Pacific Basins given by various models with error estimation (compared to baseline forecast such as CLIPPER 5). They include OFCL, GFDL, HWRF, AEMN models, which can be global or regional, single/multi-layered or interpolated dynamic, statistical or consensus/corrected consensus ensemble models. A few models such as UKM, EGRR of UKMO, EMX, EEMN of ECWMF and CMC of Canada out of US are also concerned with. Chen et al.[4] primarily compared TC tracks and intensity in NWP and South China Sea by 6 global or regional forecast models (4 official and 2 satellite) implemented by meteorology administrations of ambient countries such as GFS of JTWC, GDAPS of KMA, GRAPS of CMA, Beijing and Japan satellites.

Generally speaking, normal TC can be accurately predicted based on the following reasons: 1) Basically TC's track follows background steering flows; 2) Meteorological satellites and ground-based radars probing are very helpful for TC's cloud monitoring when approaching coastal areas within a few days ahead; 3) There are various numerical simulation techniques such as bogus initial field, nested and adaptive grid generation, 4D data-assimilation, parameterization improvement for HPC using advanced supercomputers available. Therefore, routine operational forecast becomes feasible since the beginning of this century with ever-growing accuracy. The diagrams in Figs. 2 & 3 demonstrate the average forecast accuracy of TC's track by NHC and that of intensity by five meteorologist administrations, respectively. We can find that the track errors of 24h validity time interval have been exhilaratingly reduced to 100 nautical miles or even around 50 nautical miles. In contrast, intensity forecast errors of 24h validity time interval are around 5 m/s, which almost rest on the same level of 1990s[3].

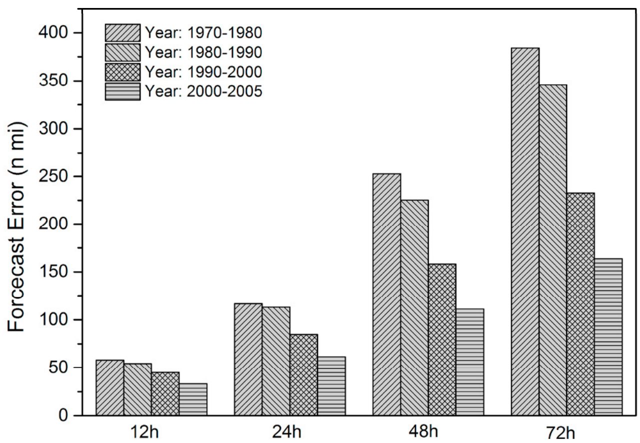

Fig. 2. NHC official track errors for Atlantic Basin tropical storms and hurricanes by decade[3].

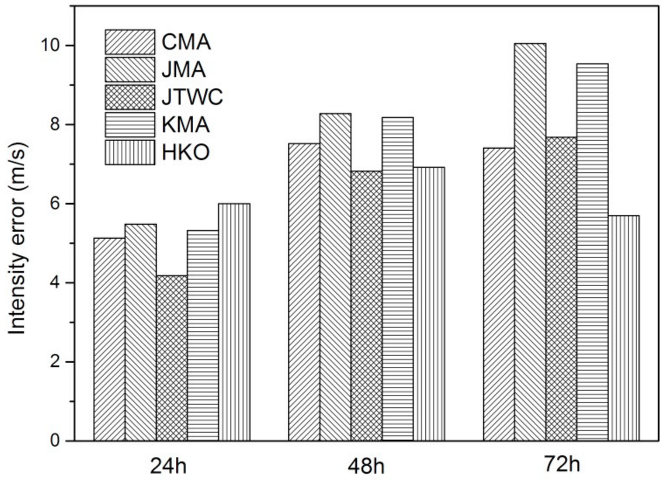

Fig. 3. Intensity forecast errors of subjective method in 2014 for Western North Pacific Basin TC. The five forecast models are China Meteorological Agency (CMA), Japan Meteorological Agency (JMA), Joint Typhoon Warning Center (JTWC), Korea Meteorological Agency (KMA) and Hong Kong Observatory (HKO) [4].

2.2. Storm surge prediction

The forecast of storm surge started in 1950s. Based on the nomograph method, Jelesanski[5] further developed SPLASH (Special Program to List Amplitude of Surge from Hurricanes), which was an influential and efficient approach to estimate peak surge of a storm for coastal protection engineering design. And now SLOSH model[6] (Sea, Land, Overland Surge from Hurricane) becomes a more popular tool in the operational forecast of temporal and spatial surge fields. As a matter of fact, SLOSH is a storm surge forecast model by NWS to implement a) real-time operational b) imaginary (for evacuation planning) c) historical (for validation purpose) d) probable and e) extratropical storm surge simulations. SLOSH and other numerical models need to solve a horizontal transport equation system obtained by vertical integration of incompressible N-S equation over the entire depth of water column. Numerical scheme is a 2-D explicit FDM formulated on a staggered ARAKAWA grid. Under the driving of wind stress, atmospheric pressure and Coriolis force, updated surge elevations at each grid can be obtained[7]. In contrast, FBM, CTS, CES of NMEFC employ spherical coordinate system and semi-implicit FDM scheme to simulate evolution of surge in China's 5 overlapped regions or more refined grids along the coastal line[2]. RMCS Tokyo-Typhoon Center reported the activities of 2015 in the simulation and verification of storm surge based on JMA's TEPS (Typhoon Ensemble Prediction System) [8]. Similar storm surge models are SEA model of UK, HYPSE for Adriatic Sea[9] and ADCIRC for Bangel Bay[10].

It should be noted at present that atmospheric simulation by GCM is still beyond the capability to provide accurate wind field at sea surface as major driving force to transport water body ashore and induce surge elevation. Therefore, people usually propose some kind of formulae in terms of central atmospheric pressure and maximal wind speed at a given radius such as Fujita and Takahashi expressions[2].

The verification of SLOSH models were carried out by comparing the simulation to the observation from NOAA tidal gauges at 13 gauge stations, 60 USGS Storm Surge Sensors (SSSs) and 268 USGS High Water Marks (HWMs) during Hurricane Sandy close to NY Basin on Oct. 28 of 2012. The results (see Fig. 4) showed that elevation errors of 80% SSS are less than 0.5m whereas relative errors of 92% sensors are less than 30% in regard to gauge sensors. In the meantime, the proportions of HWMs are 34%, 71% and 89% for relative errors less than 10%, 20% and 30%, respectively[7].

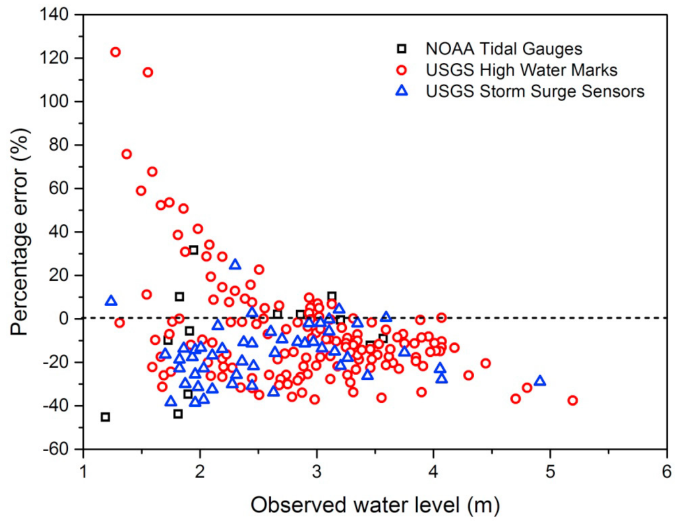

Fig. 4. Comparison of observed water level at NOAA tidal gauges, USGS storm surge sensors and USGS High Water Marks vs. those simulated by SLOSH [7].

3. Challenging issues

It was reported that the frequency of recorded disasters affecting communities significantly rose from about 100 per decade in the period 1900-1940 to 650 per decade in the 1960s，2000 per decade in the 1980s, and reached almost 2800 per decade in the 1990s[11]. Climate change further aggravates the affected degree in various aspects. Similarly, storm surges are still threatening human society and even cause more enormous losses due to economic growth, dense population and fast urbanization despite of progresses in storm surge forecast. Under these circumstances, the planning group on Natural and Human-induced Environment Hazard and Disaster of ICSU delivered a report on science plan of IRDR (Integrated Research on Disaster Risk) to mitigate disaster more effectively based on scientific risk analysis[11]. The so-called risk analysis is a methodology to estimate probable total losses in a hazard. In the frame of IRDR, such research should be across disasters and interdisciplinary. At the same time, return period and relevant statistical methods are used since the consequences of stochastic natural disasters are often random or even fuzzy[2,12]. In this regard, the challenging issues in the study for future storm surge mitigation are suggested as follows.

3.1. Abrupt variation of TC in track and intensity

The primary sources of forecast error come from variability of weather system. Namely, TC's track and intensity can change all of a sudden so that accurate surge elevation with long validity time interval is impossible. As a result, people of affected area are often rendered in unpreparedness and subjected to a peril state. Therefore, it is the first and foremost task to elucidate the mechanism of these variations and incorporated them into the forecast system to enhance forecast accuracy and extend validity time interval. Generally speaking, such abnormal tracks can be attributed to Beta effect, underlying surface condition, interaction with other weather systems, existence of binary TC system when environmental steering flow is weak enough. As for intensity variations, they are closely associated with air-sea interaction when TC is travelling over a warm water body. When SST is higher, the mixing layer thicker or interaction duration longer, TC will be strengthened shortly owing to more heat absorbed[13]. As an example, people found the asymmetric inner structure may lead to meandering in typhoon's track. Based on Rankine vortex model and contour dynamics (CD), we simulated the interaction of one major and two minor vortices inside as a model of Typhoon 9012. When Yancy was moving through Taibei and landed in Fujian, its stagnant and looping trajectory were reproduced[14].

3.2. Comprehensive study on hydrometeorologic disasters.

Since the impacts of a storm surge are caused by a great many factors such as strong wind, severe flood due to heavy rain and high tide/surge elevation, salty invasion, estuarine and harbor blockage. Consequently, the comprehensive research across disasters and disciplines is necessary in order to accurately estimate probable losses in a storm surge. As a paradigm, IUTAM/WMO/CAS Symposium on Tropical Disasters was convened in 1992 in Beijing, during which the scientists from meteorology, oceanography, hydrology and mechanics communities gathered for discussion and collaboration[15]. Actually, SLOSH is a powerful simulation software product capable of computing inundation by suitably dealing with wet/dry boundaries based on geographic database. Similarly, both SLOSH+TIDE and ADCIRC+SWAN are able to calculate surge/tide interaction and set up of sea level. Based on sediment settling and incipient models, Zhou & Li[16] simulated sediment transport and bathymetry variation in a harbor during Typhoon along different tracks. The mechanism of concave temporal variations in wind speed, water speed and sediment concentration induced by passing typhoons was elucidated. In addition, the database of population, agriculture, industry, enterprises and buildings in the probable inundated areas should be collected as vulnerability factor to estimate possible losses in risk analysis.

3.3. Climate change effects

It is evident that we need consider the effects of climate change in long term study of risk analysis. AR5[17] issued by IPCC in 2013 concluded that the global warming is attributed to human's activities with more than 95% confidence coefficient. Although people have come to agreement in Paris in 2015 for taking common actions in the reduction of carbon dioxygen emission, continuous rising in air temperature is inevitable due to greenhouse gases available in atmosphere. The influences of climate change on the storm surge impacts are twofold. On the one hand, the frequency and intensity of Typhoon are increasing during previous 70 years. On the other hand, the sea level is gradually rising owing to retreated glaciers, melt ice in arctic region and also volume expansion of water itself. According to the records available, the rise of sea surface level on average in the 20th century was 1.9mm/y though, however, the number became 2.0 mm/y in 1971-2010 and 3.2 mm/y in 1993-2010. It is estimated that sea surface rises up to 2100 could be 26-82 cm, for different RCPs (Representative Concentration Pathway) depending on human's energy consumption scenarios. More quantitatively, a nonstationary model is established to estimate extreme wind speeds of different return periods. Around 4.1-4.4% increase shall induce more grievous calamities during a storm hazard[18].

4. Concluding remarks

Storm surges belong to a most catastrophic natural hazard, which were and are still threatening human being with enormous property losses and even peoples' lives in history and at present days if we treat them slightly. With deepening knowledge and advanced observational/computational instruments, we are now able to carry out routine operational forecast using various numerical models. Furthermore, the forecast accuracy has been enhanced to the level of 50 nautical miles in track and 5 m/s in intensity within 24h validity time. The surge elevation can be within 50 cm and 12h of validity time interval on average.

There are still challenging issues in storm surge forecast. To cope with variability of TC in track and intensity, fundamental research in their abrupt variation is necessary. And then the implied mechanism should be incorporated in the prediction models to avoid pessimistic event occurrence again. An integrated research on TC, ocean waves, heavy precipitation, inundation, estuarine block and salty invasion is needed for overall risk estimation. The climate change effects should be taken into account in the long-term risk analysis.

Finally, we would emphasize again that the first and foremost task of surge mitigation for coastal developing countries is to establish warning system and reduce vulnerability against storm surge disasters.

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