

Article

Development of an Operational Storm Surge Prediction System for the Korean Coast

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Abstract : Performance of the Korea Ocean Research and Development Institute (KORDI) operational storm surge prediction system for the Korean coast is presented here. Results for storm surge hindcasts and forecasts calculations were analyzed. The KORDI storm surge system consists of two important components. The first component is atmospheric models, based on US Army Corps of Engineers (CE) wind model and the Weather Research and Forecasting (WRF) model, and the second components is the KORDI-storm surge model (KORDI-S). The atmospheric inputs are calculated by the CE wind model for typhoon period and by the WRF model for non-typhoon period. The KORDI-S calculates the storm surges using the atmospheric inputs and has 3-step nesting grids with the smallest horizontal resolution of ~300 m. The system runs twice daily for a 72-hour storm surge prediction. It successfully reproduced storm surge signals around the Korean Peninsula for a selection of four major typhoons, which recorded the maximum storm surge heights ranging from 104 to 212 cm. The operational capability of this system was tested for forecasts of Typhoon Nari in 2007 and a low-pressure event on August 27, 2009. This system responded correctly to the given typhoon information for Typhoon Nari. In particular, for the low-pressure event the system warned of storm surge occurrence approximately 68 hours ahead.

Key words : storm surge, operational system, CE wind model, WRF, KORDI-S

1. Introduction

Currently, operational storm surge forecasts are carried out by various governmental, meteorological and oceanographic agencies (Buch and She 2005; Verlaan et al. 2005; Bajo et al. 2007; Brassington et al. 2007; Lane et al. 2009; You and Seo 2009). Decadal efforts on storm surge research and forecasting are yielding new information such as inundation prediction incorporated into operational surge forecasts, and extending prediction domain to consider the practical importance and relevance of such forecasts (Murty et al. 2009).

In Korea, storm surges often cause severe damage to the many coastal developments, including land reclamation projects, which have been in operation along the peninsula over the past half century. Information on possible

damages of typhoons in terms of inundation zone and expected disaster area are important factors in mitigation of losses to coastal development along the Korean Peninsula. Storm surges in Korea are currently predicted every 3 hours, for a 48-hour in advance, by National Institute of Meteorological Research (NIMR) of the Korea Meteorological Administration (KMA). The Regional Tide/Storm Surge Model (RTSM) based on the Princeton Ocean Model (POM) is operated to forecast storm surges with 1/12 degree (~8-9 km) resolution using atmospheric forcing from the KMA's numerical weather model.

However, an operational storm surge prediction system in this study treats the atmospheric inputs by separating typhoon and non-typhoon periods using different approaches. The objective of the article is to check the capability of developed operational storm surge system. We describe recent efforts to develop KORDI operational storm surge prediction system along the Korean coast (Fig. 1). This

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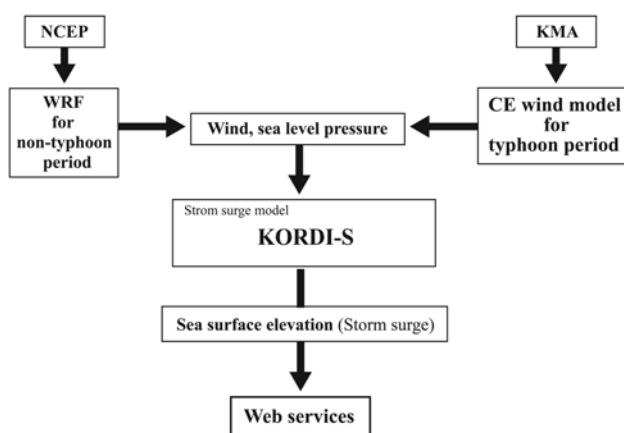


Fig. 1. Schematic diagram of the KORDI operational storm surge prediction system.

system consists of three parts. The first part concerns calculations of meteorological inputs such as sea level pressure and sea surface winds. This information is used as forcing in the second part, the storm surge model, which predicts sea surface elevation along the Korean Peninsula. The last part is dissemination through an Internet service, which provides usable information to decision makers and the public.

Below we focus on the first two parts only. Section 2 describes KORDI operational storm surge prediction system. Section 3 presents the results of hindcasts and forecasts by this system. Finally, we reflect on the overall findings by providing a summary of the results in section 4.

2. The KORDI operational storm surge prediction system

Atmospheric models

One of the most problematic challenges in operational storm surge prediction systems is the ability to acquire and provide precise atmospheric inputs such as sea winds and surface pressure data. Two numerical models are used for atmospheric inputs; the US Army Corps of Engineers (CE) wind model for typhoon period and the Weather Research and Forecasting (WRF) model for non-typhoon period. For storm surge calculations during typhoon period, we experienced that the typhoon parameter model such as CE wind model is superior to the state-of-the-art numerical weather model like WRF.

WRF (Weather Research and Forecasting)

For non-typhoon period the Advanced Research WRF (ARW) modeling system has been used in our storm surge

prediction. The WRF is designed to be a flexible, state-of-the-art atmospheric simulation system that is portable and efficient on available parallel computing platforms, and is in the public domain for community use (National Center for Atmospheric Research 2009).

Nested grids were applied, in which larger (smaller) domain covered 104.6–150.4°E, 14.9–52.5°N (121.1–133.6°E, 29.9–39.6°N) with 20 (4) km horizontal resolution, respectively. The WRF version 3.0 with NCEP Final Analysis was used for initial and boundary conditions. The WRF model is run on the Linux cluster system (32 cpus) twice daily (0100 and 1300 Local Standard Time, hereafter referred to as LST) for 72 hours. It takes about 30 minutes to download initial and boundary conditions while the computing time consumes about 3.5 hours.

The validation of WRF results was carried out by cross referencing with Yellow Sea Buoy in terms of checking sea winds and sea level pressure data during a 5-month period. The results (Figs. 2–3 and Table 1) showed reliable agreements though bias and standard deviation increased with forecasting time.

Typhoon model (CE wind model)

One of the challenges in storm surge forecasting is obtaining precise information on tropical cyclones (e.g., position, central pressure, and wind fields) at high spatial

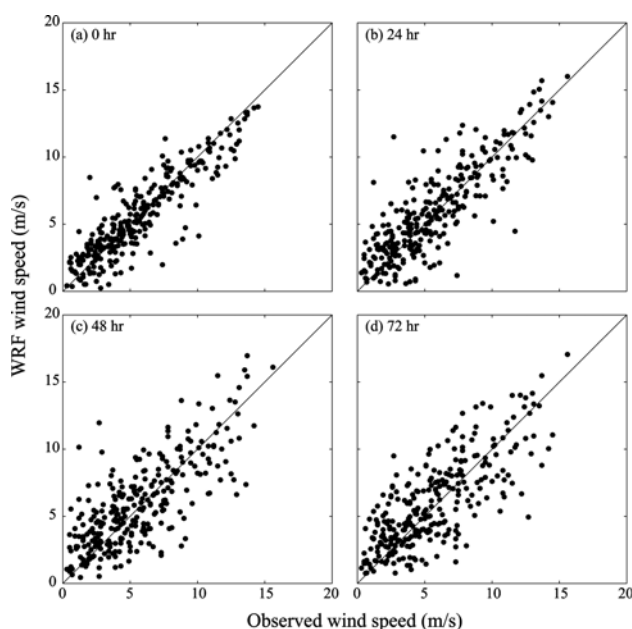


Fig. 2. Scatter plots of wind speed between WRF calculated and Yellow Sea Buoy data from July 7, 2009 to November 30, 2009. Predicted wind speed with forecasting time (a) 0 hour, (b) 24 hours, (c) 48 hours, and (d) 72 hours.

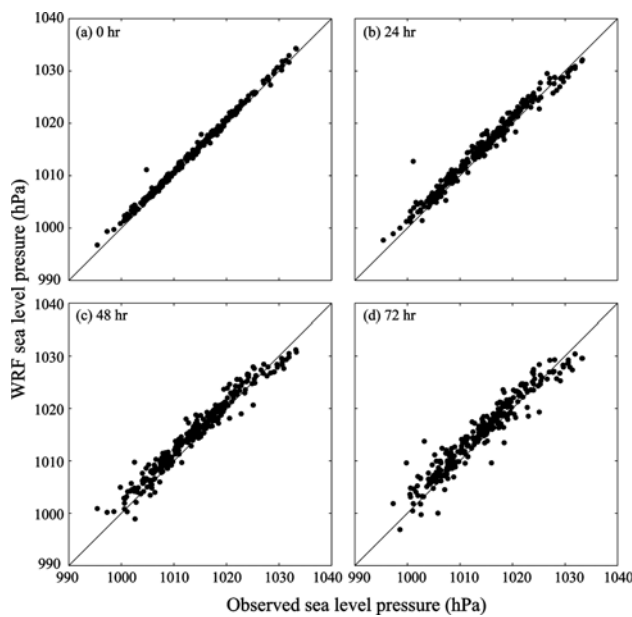


Fig. 3. Scatter plots of sea level pressure between WRF calculated and Yellow Sea Buoy data from July 7, 2009 to November 30, 2009. Predicted sea level pressure with forecasting time (a) 0 hour, (b) 24 hours, (c) 48 hours, and (d) 72 hours.

Table 1. Statistical results of WRF verification using Yellow Sea Buoy data from July 7, 2009 to November 30, 2009

	Forecasting time (hour)	Bias	Standard deviation
Sea wind (m/s)	0	-0.03	1.54
	24	0.3	1.91
	48	0.33	2.33
	72	0.32	2.29
Sea level pressure (hPa)	0	0.73	0.57
	24	1.01	1.24
	48	1.28	1.59
	72	1.28	2.09

and temporal resolutions. Consequently, predicting the path and strength of tropical cyclones remains a large obstacle for operational storm surge prediction systems. In this study, we applied the Holland-type pressure fields (Holland 1980). Once the pressure field was calculated, the sea surface wind field was estimated using the CE wind model (Cardone et al. 1994; Thompson and Cardone 1996; Vickery et al. 2000; Kwon et al. 2008).

The CE wind model requires input parameters such as the typhoon position, the central pressure of the typhoon, and the radius of the maximum wind speed. To calculate these parameters, we used all available data, including

typhoon information (e.g. track data) provided by the KMA, satellite-derived cloud-top temperatures to estimate the radius of the maximum wind speed, TOPography EXperiment (TOPEX) satellite data, and synoptic surface data from ground stations in Korea, China, and Japan. Once all necessary parameters were acquired, the CE wind model calculated sea surface wind fields once every hour.

The performance of the CE wind model has been verified with data in seas around Korea (Kang et al. 2002; Kwon et al. 2008). For example, comparisons with wind data obtained by buoys belonging to the Japan Meteorological Agency and by Korea's Jeodo Ocean Research Station were generally accurate.

Storm surge model (KORDI-S)

The KORDI-storm surge model (KORDI-S) is based on depth-averaged momentum equations and the continuity equation (Lee et al. 2008). KORDI-S includes a staggered grid and a fully implicit scheme. The model uses a one-way multi-nesting scheme to resolve complicated coastal areas and uncertain open boundary conditions. In total, 26 tidal stations around the Korean coast were used to validate tidal calibration (M2, S2, K1

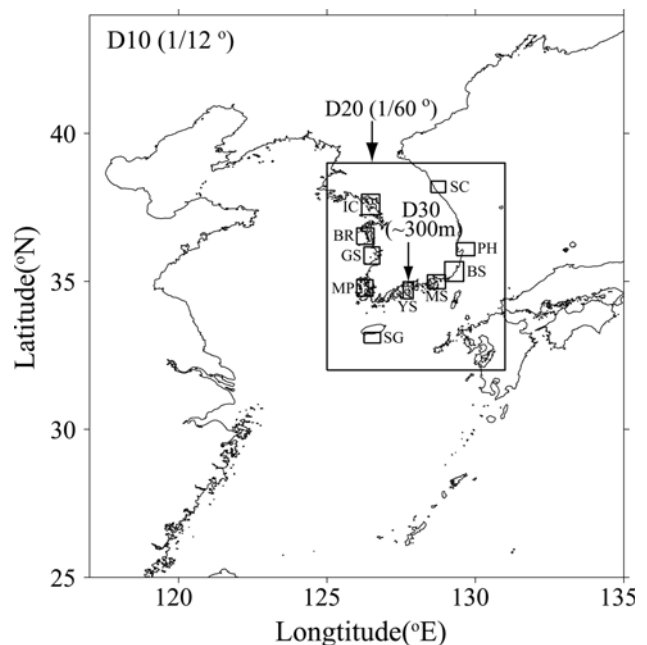


Fig. 4. Model domains: (1) 1/12 degree resolution (D10), (2) 1/60 degree resolution (D20), and (3) approximately 300-m resolution (D30, IC: Incheon, BR: Boryeong, GS: Gunsan, MP: Mokpo, SG: Seogwipo, YS: Yeosu, MS: Masan, BS: Busan, PH: Pohang, SC: Sokcho).

and O1), and the results showed reasonable agreements (Lee et al. 2008). KORDI-S was verified storm surge performances throughout a series of simulations for Typhoon Maemi (Kwon et al. 2008; Lee et al. 2008).

The model domain was 25–44°N, 117–135°E (Fig. 4). Three different sub-domains were used: (1) 1/12 degree resolution in the entire model domain (D10), (2) 1/60 degree resolution (D20), and approximately 300-m resolution (D30). There are ten D30 regions along the Korean coast for precise localized prediction. Atmospheric forcing from the CE wind model or the WRF model was applied at sea surface, while four tidal constituents (M2, S2, K1, and O1) were applied at open boundaries with an inverse barometric pressure. The four major tidal constituents may not be sufficient to predict sea surface elevation especially the western coast of the Korean Peninsula. However, it is still adequate to consider tide-surge interaction.

3. Results

The observed data were recorded in 1-minute intervals since 2003 by Korea Hydrographic and Oceanographic Administration. Therefore, 1-minute observed data since 2003 and 1-hour observed data prior to 2003 were used. Results from the D20 grid were analyzed to cover the entire Korean Peninsula, although the finer grid with nesting scheme provided better results on Typhoon Maemi (Lee et al. 2008). For example, the calculated

maximum surge height (MSH) at Masan was close to the observed maximum surge height as horizontal resolution increased (Fig. 5).

Hindcasting (typhoons)

Four typhoons were examined to verify the KORDI storm surge prediction system; typhoons Faye (9503), Saomai (0014), Rusa (0215), and Maemi (0314), all of which recorded more than 100 cm of MSH. In Fig. 6 observed MSHs are placed at the tidal stations with absolute errors (figures in parenthesis). The absolute error is the absolute value of the difference between observed and calculated MSH. For instance, the observed MSH at Masan was 212 cm and the absolute error was 8 cm during Typhoon Maemi's passage (see Fig. 6d). For the above four typhoons, the calculated MSHs generally matched the observations. There were relatively large errors when the observed MSHs were less than 50 cm away from the typhoon path. But the calculated MSHs near the typhoon track were closer to observed MSHs and absolute errors decreased when the observed MSH was higher.

Typhoon Ewinar (0603), which landed on the southwest coast of Korea with a central pressure of approximately 980 hPa, was explored for time series comparison with the 1-minute-interval data. Fig. 7 shows the typhoon track and comparisons of surge height at the three selected tidal stations. The differences in MSH and peak time lags were approximately 10 cm and less than 40 minutes, respectively. In terms of surge shape the predictions were slightly broader than observations.

Forecasting

Forecasting results were examined for Typhoon Nari (0711) and one low-pressure event (0530 on August 27, 2009) to check the capability of the KORDI operational storm surge system.

Typhoon Nari (0711)

Typhoon Nari (0711) landed on the Goheung Peninsula in southwestern Korea at 1815 on September 16, 2007, and subsequently became an extratropical cyclone over the middle of the Korean Peninsula. Fig. 8a shows three selected tracks (8th, 14th, and 18th release). The recorded minimum pressure and maximum wind were approximately 940 hPa and 45 m/s, respectively. The observed MSHs were 106 cm at Yeosu and 60 cm at Tongyeong (Fig. 8b, 8c).

The KMA releases typhoon information (TI) whenever

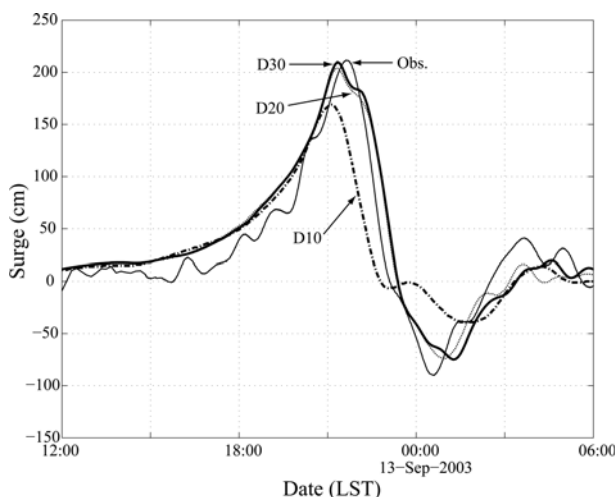


Fig. 5. Influence of grid resolutions on surge heights at Masan for Typhoon Maemi. Observed (thin solid line) and calculated storm surges from D10 (dash-dot line), D20 (thin dotted line), and D30 (thick solid line) are presented.

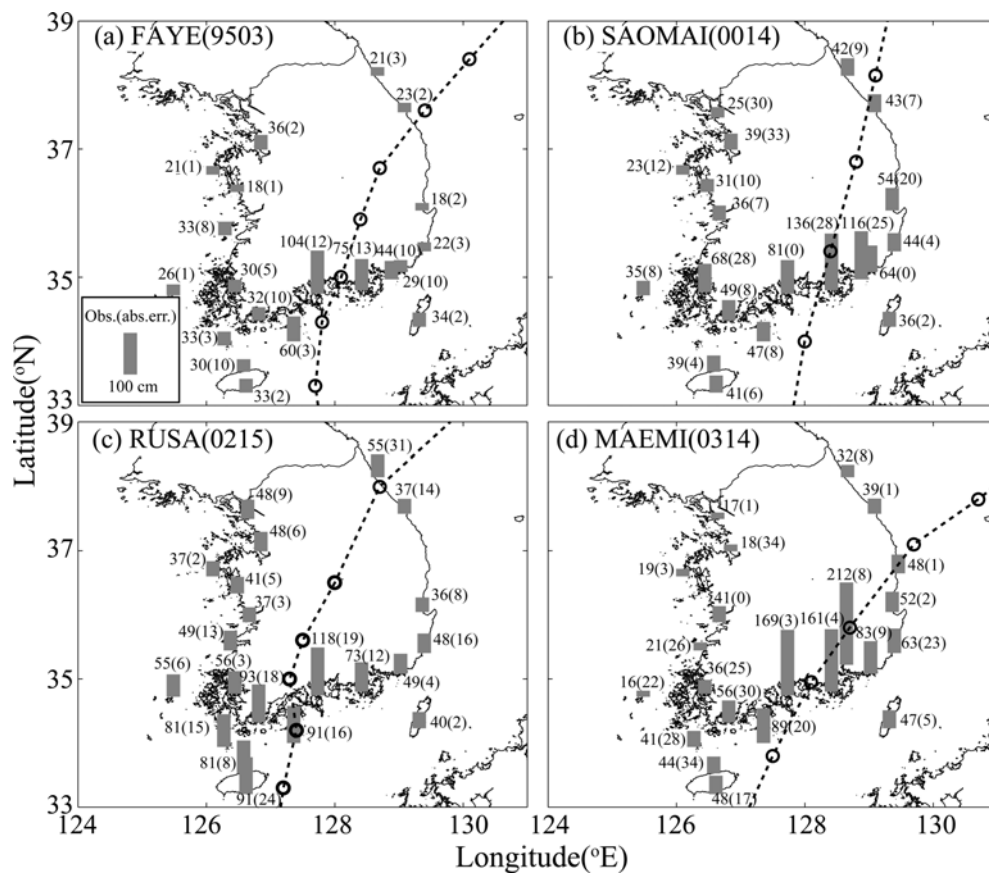


Fig. 6. Typhoon paths and observed maximum storm surge heights (in cm) with absolute errors (figures in parenthesis). (a) Typhoon Faye (9503), (b) Typhoon Saomai (0014), (c) Typhoon Rusa (0215), and (d) Typhoon Maemi (0314).

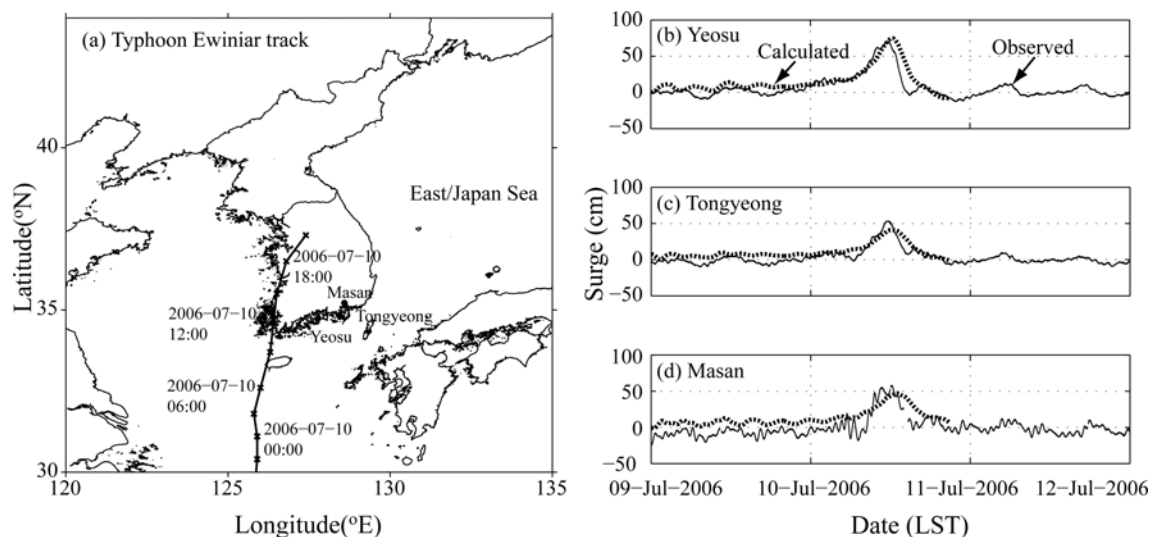


Fig. 7. (a) Typhoon Ewinar (0603) track and locations of the three tidal stations. The observed (solid line) and calculated (dotted line) storm surge of Typhoon Ewinar (0603) at (b) Yeosu, (c) Tongyeong, and (d) Masan tidal stations.

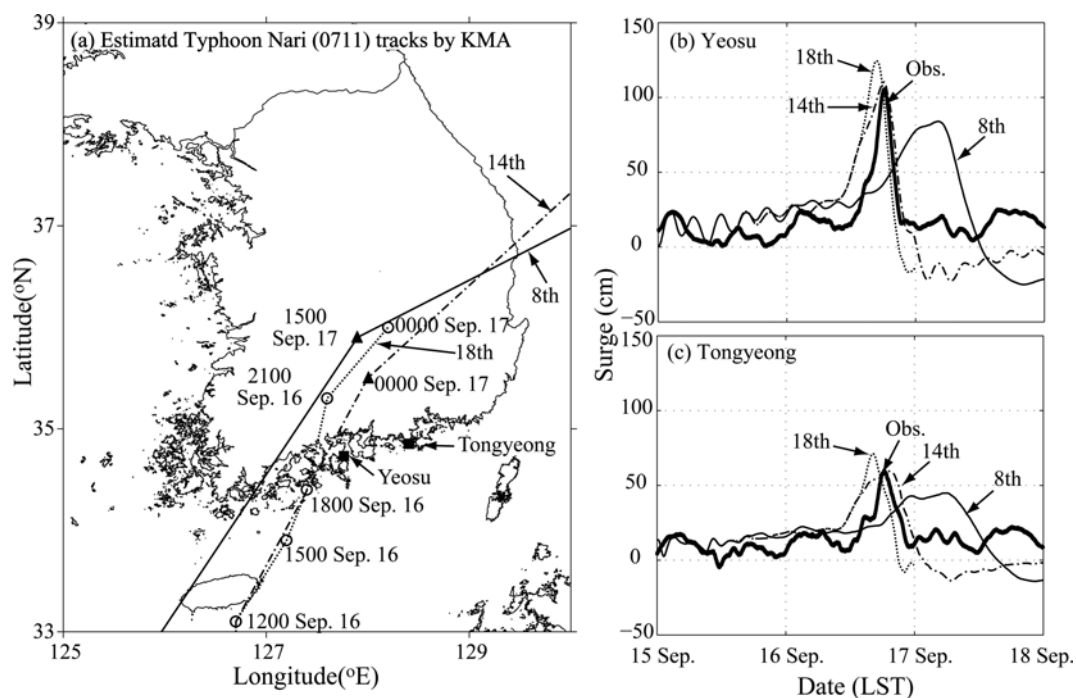


Fig. 8. (a) Three Typhoon Nari (0711) tracks (from KMA TI releases 8, 14, and 18) and locations of two tidal stations. The triangle marks and open circle marks represent the estimated and verified typhoon center location, respectively. The thick solid lines show the observed storm surges at (b) Yeosu and (c) Tongyeong. The predicted storm surges were based on TI releases 8 (thin solid line), 14 (thin dash-dot line), and 18 (thin dotted line), respectively.

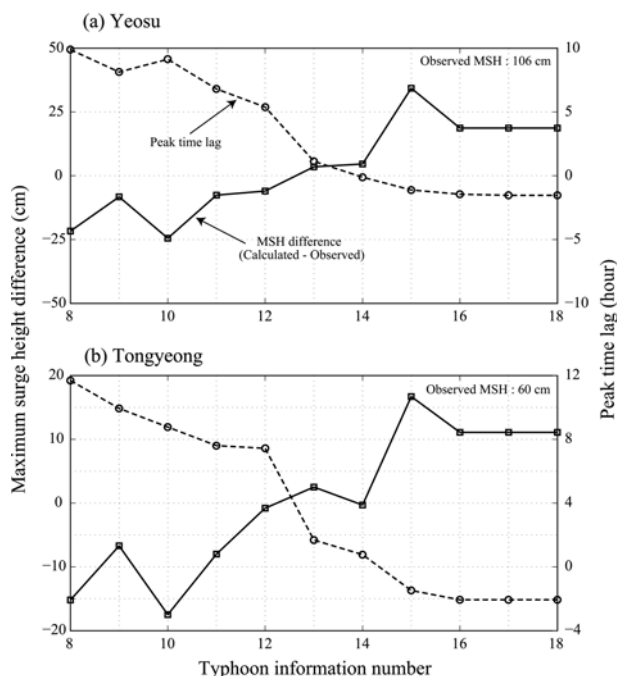


Fig. 9. The maximum surge height difference (solid line with squares) and the peak time lag (dotted line with circles) based on the TI issued by the KMA at (a) Yeosu and (b) Tongyeong during Typhoon Nari in 2007.

a typhoon occurs in the Northwest Pacific. TI includes the center location, central pressure, maximum wind speed, radius of strong wind, typhoon intensity, and movement speed. TIs are uploaded to the KMA's website (www.kma.go.kr) at intervals of 1 day (far from the Korean Peninsula) to 3 hours (close to the Korean Peninsula). Storm surge prediction for Typhoon Nari was made from the eighth to eighteenth releases because the estimated typhoon center had not reached the Korean Peninsula up to the seventh release. Note that TI issued by the KMA contained the verified position and predicted locations. Therefore, the later TI gave a more precise typhoon positions. In Fig. 8a, the center positions of 8th TI are predictions, but those of 18th TI are verified locations.

The operational storm surge system predicted 84 cm at Yeosu and 45 cm at Tongyeong with 8th TI. The predicted storm surges occurred relatively later, with a relatively large deviation, compared to the observed surges. This was because the 8th track was biased westward compared with the 18th track. According to the new TI, the predicted storm surges agreed more closely with the observed values. However, the predicted storm surges using the 14th TI gave better agreement than those using the 18th TI (Fig. 9). Possible reason for this might be

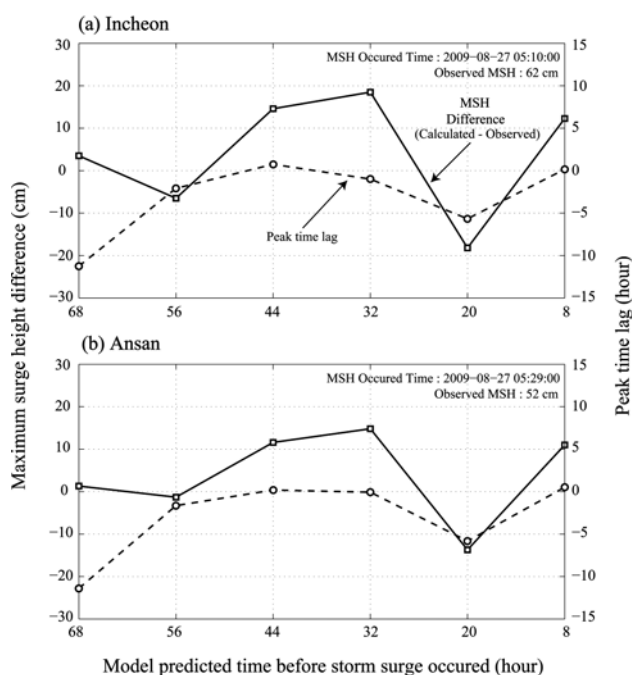


Fig. 11. The maximum surge height difference (solid line with squares) and the peak time lag (dotted line with circles) predicted by storm surge system at (a) Incheon and (b) Ansan during a low pressure event on August 27, 2009.

4. Summary and conclusions

An operational fine-mesh storm surge prediction system for coastal areas of Korea, developed by KORDI, was examined in order to assess its capability in terms of operational use throughout hindcasts and forecasts. In this system, the atmospheric inputs (winds and sea level pressure) are calculated using a typhoon parameter model (CE wind model) for typhoon period and the WRF model for non-typhoon period. We believe that the numerical weather models for storm surge calculations cannot adequately cover the wind field for typhoons. The storm surge model (KORDI-S) has 3-step nesting grids with the smallest horizontal resolution of ~300 m. The KORDI operational system predicted storm surges twice a day for 72 hours.

In five hindcasted typhoon cases, most of the highest MSHs were closely reproduced. For forecasts, Typhoon Nari (0711) and a low-pressure event were explored. This operational system can reproduce accurate MSH with precise typhoon information. Tidal records can be used to judge the best typhoon information as shown in Typhoon Nari. For a low pressure case (0530 on August 27, 2009), this system detected the occurrence of MSHs (just over 50

cm) approximately 68 hours ahead.

The results of hindcasts and forecasts indicate that this operational storm surge system is promising for storm surge forecasting along the Korean coast. However, more verifications of the system with surge records are required to improve its accuracy.

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