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ARTICLE *in* KSCE JOURNAL OF CIVIL ENGINEERING · DECEMBER 2007

Impact Factor: 0.48 · DOI: 10.1007/s12205-008-8001-2

4 AUTHORS, INCLUDING:

Kyeong Ok Kim
Korean Institute of Ocean Science and Tec…

Han Soo Lee
Saitama University

KSCE Journal of Civil Engineering
Vol. 12, No. 1 / January 2008
pp. 1~8
DOI 10.1007/s12205-008-8001-2

Coastal and Harbor Engineering

Wave and Storm Surge Simulations for Hurricane Katrina using Coupled Process Based Models

By Kyeong Ok Kim*, Han Soo Lee**, Takao Yamashita***, and Byung Ho Choi****

Abstract

Coupled process based model incorporating the atmosphere-wave-ocean interactions has been developed to investigate wave and storm surge in the region of extremely shallow waters. An additional shear stress, due to wave energy dissipation using the roller concept within the surface boundary layer, is introduced in this system to consider the processes of energy transfer from wind to current through wave process. Hindcast simulation of storm surge for 2005 Hurricane Katrina in this study has demonstrated the importance of energy transfer path via whitecap dissipation of wind waves in the generation mechanism of mean current in the shallow waters. It is also shown that the atmosphere-wave-ocean coupling model system using designed coupler adopted in this study is a feasible system for understanding wave and storm surge dynamics.

Keywords: *storm surge, hurricane Katrina, Gulf of Mexico, atmosphere-wave-ocean interaction*

1. Introduction

In recent 100 years, mean air temperature of the earth rises 0.6 °C. Almost of the heat energy due to this warming are absorbed in the ocean. Also the sea surface elevation rises 3.1 cm in recent 10 years, and sea surface rise of the 50 cm is expected to 2100 (Intergovernmental Panel on Climate Change, IPCC Third Assessment Report, 2001). Especially, temperature distribution of the ocean is expected low at high latitude, and high at low latitude where the tropical cyclone occurs. From the numerical simulation result of climatic variation estimate, enlargement of scale is announced out from increase of the number of occurrences of the typhoon due to global warming.

Generally when the shallow water depths are continued, the occurrence ratio of wave dissipation and current flow increases. In addition, the circulation currents caused by typhoon or strong wind field are advanced in the ocean or in the wide bay, causing the sudden water level rise when it is blocked by the land. Because of this process, the bigger storm surge may occur even with the lower atmospheric pressure of identical scale in the continental shelf area with wide and shallow waters. The hurricane Katrina in 2005 was one of such phenomena.

Katrina formed over the Bahamas on August 23 during the 2005 Atlantic hurricane season and caused devastation along much of the north-central Gulf Coast. The most severe loss of life and property damage occurred in New Orleans, Louisiana, which flooded as the levee system catastrophically failed, in many hours after the storm had moved into the inland. The hurricane caused severe destruction across the entire Mississippi coast and into Alabama, as far as 160 km from the storm's center. Katrina was the eleventh tropical storm, fifth hurricane, third major hurricane, and second Category 5 hurricane of the 2005 Atlantic season. The detailed history, observations, casualty and damages of Hurricane Katrina were reported by National Hurricane Center (Knabb *et al.*, 2005). The National Oceanographic Partnership Program (NOPP) project provides operational forecasts of winds, waves and surge during the approach and landfall of tropical cyclones. The results of these forecasts would provide real-time information and predictions of the sea state and storm surge for several days in advance to the National Hurricane Center (Jensen *et al.*, 2006).

To assess the influence of air-sea interaction of the storm, the meso-scale modeling study was conducted the coupled hurricane simulation included atmosphere, wave and ocean numerical models covered the Gulf of Mexico using the Fifth-Generation NCAR/PSU (National Center for Atmospheric Research and

*Assistant Professor, Graduate School for International Development and Cooperation, Hiroshima University, Higashi-Hiroshima, Japan (E-mail: kokim@hiroshima-u.ac.jp)

**Ph.D., Graduate School for International Development and Cooperation, Hiroshima University, Higashi-Hiroshima, Japan (E-mail: hslee@hiroshima-u.ac.jp)

***Professor, Graduate School for International Development and Cooperation, Hiroshima University, Higashi-Hiroshima, Japan (E-mail: tkoyamashita@hiroshima-u.ac.jp)

****Member, Professor, Department of Civil and Environmental Engineering, Sungkyunkwan University, Suwon, Korea (Corresponding Author, E-mail: bhchoi@skku.edu)

Pennsylvania State University) Model (MM5) for atmosphere, Wave Watch III (WW3) of NCEP (National Centers for Environmental Prediction) for wind wave and the Princeton Ocean Model (POM) for ocean current. Subsequently the regional wave and storm surge simulation was computed considering the wave-current interaction using WW3 and SWAN (Simulating WAves Nearshore) for wind wave and POM for storm surge.

2. Modeling Organization

All numerical models, MM5 for atmosphere, WW3 and SWAN for wind wave, and POM for ocean current, are already parallelized by using the Single Program Multiple Data (SPMD) methods through MPI-library. The coupling program (Coupler) was designed in this study to collect and distribute the exchanging data within the MPI parallel system. Every models and Coupler are executed at the same time, and they calculate their own jobs and pass relevant data to other models. The essential function of the Coupler is to repeatedly transfer data, such as atmospheric pressure, wind speed etc., to other models that need these data as an external forcing over the interfacial boundary. The programming method of Multiple Program Multiple Data (MPMD) was performed to couple these models. The Coupler and each models are united the separated group, and they calculated by the group unit. Also they passed message when exchanging data within the system.

The Coupler and the master nodes of each model communicate the signal at each models time step and they exchange the data every the least common multiple time steps. We composed that the domain of POM and WW3, and the last nested domain of MM5 are identical, and time step of MM5 at the first domain, the internal mode time step of POM and the global time step of WW3 are equal. The designed coupler combines all modules, and exchanges the interaction variables throughout the whole computational time. This atmosphere-wave-ocean interaction modeling system including designed Coupler for hurricane simulation and the regional wave and storm surge simulation are shown in Fig. 1.

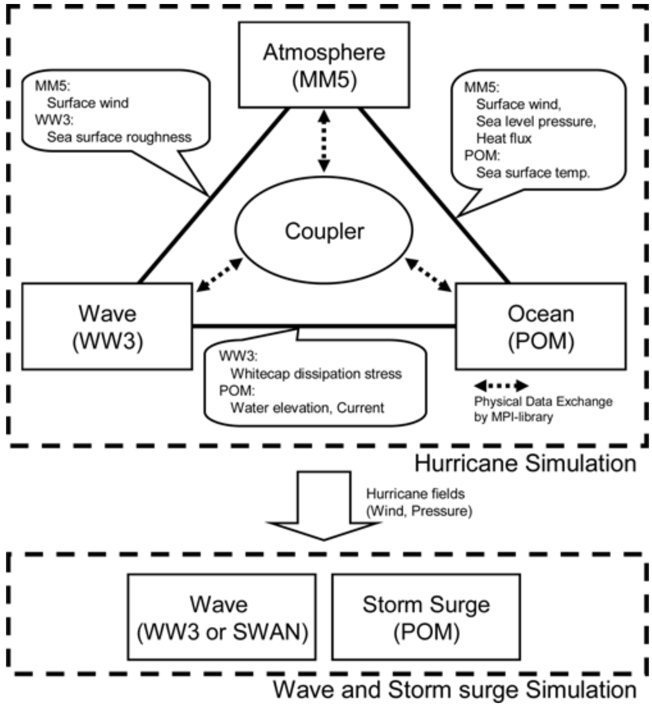

Fig. 1. Structures of Hurricane Simulation Using the Coupling Model Considering Atmosphere-Wave-Ocean Interaction, and Wave and Storm Surge Simulation

2.1 Atmospheric Dynamic Model: MM5

The Pennsylvania State University and National Center for Atmospheric Research have developed the Mesosclae Model (MM5) which is based on a non-hydrostatic, primitive equation model with a terrain-following coordinate for atmospheric simulation (Grell *et al.*, 1994). The initial and lateral boundary conditions for this simulation are imposed by the enhanced dataset (1 hour interval) by another MM5 simulation using NCEP Global Final Analyses (FNL) dataset. The historical records of typhoon data obtained from the Joint Typhoon Warning Center (Chu *et al.*, 2002) include position of hurricane center and the maximum 1-minute sustained wind speed every 6hour interval. A bogussed typhoon is applied in the first domain at an hourly interval, the location and minimum pressure of Hurricane Katrina interpolated by JTWC data. This scheme is designed to be robust and provide a significant enhancement of initial tropical storm strength and positioning relative to what is available in the background grid information obtained from models (Davis and Low-Nan, 2001). At first, tropical cyclone from the first-guess is detected and extracted. Then, bogus vortex and blending with a modified background field are computed.

The physical parameterization used in the study is the Reisner graupel explicit moisture scheme, which is based on the mixed-phase scheme plus additional graupel and ice number concentration prediction equations. The mixed-phase microphysics scheme (Reisner *et al.*, 1998) is applied for resolvable scale motions, in which five prognostic equations are used for water vapor, cloud water, rainwater, cloud ice and snow. The medium-range forecast (MRF) planetary boundary layer scheme is used for calculation of vertical fluxes of sensible heat, moisture and momentum. It is an efficient scheme based on Troen-Mahrt representation of counter-gradient term and K profile in the well mixed PBL, as implemented in the NCEP MRF model. (Hong and Pan, 1996) The nesting calculation and four-dimensional data assimilation (4DDA) were used. The nesting aims to refining mesh resolution. Additional domains with finer mesh resolution are placed inside the larger domain, and the boundary data of both domains are exchanged between domains during calculations. The 4DDA function is to nudge the numerical calculation to the objective analysis data or observational data. Since the simulation must be done as accurately as possible during event period, this method will be effective when a system has a function of acquiring observed and/or analysis data.

2.2 Spectral Ocean Wave Model: WW3 and SWAN

WAVE WATCH III (WW3) has been developed at the Marine Modeling and Analysis Branch of NCEP, USA. WW3 differs from its predecessors, such as WAM (WAMDIG, 1988), in all major aspects; i.e., governing equations, program structure, numerical and physical approaches. The source term package of Tolman and Chalikov (1996) consists of the input source term of Chalikov and Belevich (1993), and two dissipation constituents. Nonlinear wave-wave interactions can be modeled using the discrete interaction approximation (Hasselmann and Hasselmann, 1985). In shallow water additional processes have to be considered, most notably wave-bottom interactions. A simple parameterization of bottom friction is the empirical, linear JONSWAP parameterization (Hasselmann *et al.*, 1973), as used in the ocean wave model, WAM (WAMDIG, 1988).

SWAN (Simulating WAves Nearshore) is also a third generation spectral wave model and it uses the same formulation of source term with WAM model. However, SWAN incorporated some additional formulations, the dissipation by depth-induced breaking waves in shallow water. The main differences of SWAN from WW3 are the source term formulations for the wind input and dissipation terms. SWAN contains a depth induced wave breaking dissipation proposed by the bore-based model of Battjes and Janssen (1978).

2.3 Ocean Dynamic Model: POM

POM is a three-dimensional primitive sigma-coordinate ocean model incorporating a turbulence closure model to provide a realistic parameterization of the vertical mixing processes (Mellor, 1998). Full-nonlinear terms and the variable Coriolis parameter are considered in the momentum equations. Free surface elevation is prognostic variable with some sacrifice of computation time. The mode splitting technique eases the CPU-shortage, in which the vertically-integrated volume transport and the vertical velocity shear (profile) are separately computed.

2.4 Air-Sea Interaction

Various studies concentrating on wave-driven currents have been performed to storm surge modeling. Theory of wave-current interactions by radiation stress was introduced and developed by Longuet-Higgins and Stewart (1964). Radiation stress, based on momentum transfer from wave to current through the gradient of additional stresses, due to excess momentum flux of wave motion. This concept of radiation stress has been used in analyses of wave set-up or set-down, coastal current, rip current and wave-induced current. Weaver and Slinn (2004) showed the result of storm surge numerical model introducing the wave set-up caused by the radiation stress. However Mastenbroek *et al.* (1993) and Zhang and Li (1996) described that the gradient of stresses may not be detected in the coarser grid system, thus not so effective in surge modeling of extended area covered in this study.

Mastenbroek *et al.* (1993) investigated the wave-current interactions by studying the wave effects on the generation of storm surges with considering an additional surface roughness for wind turbulence due to existence of wind waves. They used a wave-dependent surface drag relation with the analytical approximation of sea surface stress for wave generation which was developed by Janssen (1991). This relation was introduced in the equation between sea surface aero-dynamical roughness z_0, and the friction velocity of wind u_*, which were solved by iterative procedure in the wave energy balance equations. The wave-dependent drag coefficient could be calculated by dividing wind speed in the friction velocity, and this wave-dependent drag coefficient was used to calculate the surface stress. They showed the effect of the wave-dependent drag coefficient on the generation of storm surges by exhibiting that the normal bulk law of sea surface stresses proposed by Smith and Banke (1975) underestimate the surge heights by 20% compared with those computed by wave-dependent drag coefficient. Zhang and Li (1996), Ozer *et al.* (2000), Choi *et al.* (2003) and Moon (2005) also used the quasi-linear theory of wave generation by Janssen (1991) to compute the wave-dependent stress which describe to equals the amount of momentum going to the waves due to wind. We noted that the above formulation of sea surface stress is derived for the wind wave generation, not for the mean current generation.

Deigaard and Fredsoe (1989) used the roller concept to formulate forcing terms within the surface boundary layer on applications in the current model wave forcing due to wave dissipation. The wave-induced shear stress, introduced by the surface roller, translated the momentum decay of the surface layer due to wave breaking to the lower layers and provides the boundary condition for the middle layer (Roelvink and Reniers, 1994). It is assumed that energy dissipation due to breaking changes to surface shear stress at the mean surface level. The principle of the roller model in this module is to convert wave energy dissipation by breaking into the shear stress and the turbulence production near the surface through the roller. The wave-induced shear stress on the mean water surface works as the driving force to generate the shear flow near the surface together with wind shear stress. Kato and Yamashita (2000) used time-averaged wave energy balance equation (Battjes and Janssen, 1978; Nairn *et al.*, 1990) to derive the wave field and to calculate the dissipation of surface roller energy due to wave breaking and wave-induced shear stress on coastal current. They observed the currents influenced by shallow water in coastal area and they showed the observation results about the increase of drag coefficient in shallow water (Fig. 2).

When we estimate the energy from wind waves to mean current to compute current field accompanied to storm surges, the wave energy dissipation rate in the wind wave energy balance equation should be evaluated because this part of wave energy changes into mean current. To take such effect into account, we define an additional wave-induced shear stress for mean current, τ_{br} [Eq. (1)], which is the shearing stress caused by surface roller of whitecap breaker, that is equivalent to the wave energy dissipation rate divided by the wave celerity in the energy

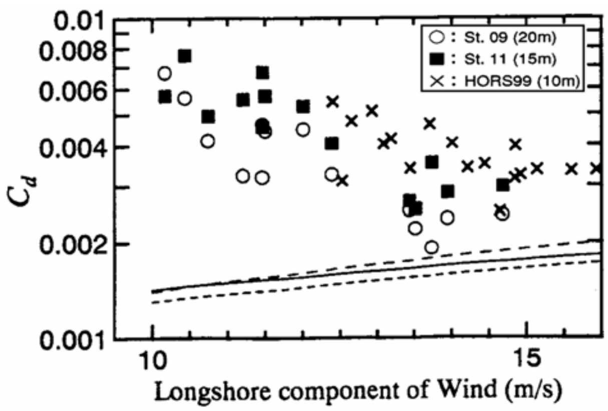

Fig. 2. Trends of Increase of Drag Coefficient by Shallow Water by Observations in Water Depth of 20 m, 15 m and 10 m, and the Predicted Drag Coefficients (Kato and Yamashita, 2000)

flux conservation. This stress may be evaluated by the wave energy dissipation rate $S_{ds}(f,\theta)$, divided by the wave celerity $C(f)$ of component of frequency, f, shown by the following equation;

$$\tau_{br} = \alpha\rho g \iint \frac{S_{ds}(f,\theta)}{C(f)} df d\theta \tag{1}$$

where, ρ is the density of water, g is the acceleration due to gravity, and α is the effective shear stress factor (empirically taken as 0.1 so far, Kim and Yamashita, 2005). This stress can be computed by wave dissipation term of the wave direction θ, in the wave energy balance equation. The total shear stress, τ_{total} [Eq. (2)], is expressed by the combination of wind-induced shear stress, $\tau_{surface}$ [Eq. (3)], and wave-induced shear stress, τ_{br}, as;

$$\tau_{total} = \tau_{surface} + \tau_{br} \tag{2}$$

$$\tau_{surface} = \rho_a C_D |U_{10}| U_{10} \tag{3}$$

where, ρ_a is the density of air, and the drag coefficient for wind-induced shear stress, C_D [Eq. (4)], is parameterized by Smith and Banke (1975) with the mean wind speed at 10m height from the sea level, U_{10}, as;

$$C_D = (0.066|U_{10}| + 0.63) \times 10^{-3} \tag{4}$$

With regard to the current effect to wave, depth-averaged currents may cause wave refraction and the water elevation may also affect wave celerity. Both of these were computed by ocean model forced by tidal boundary and surface boundary forced by wind and waves. In wave model, constant current velocities and water elevations are assumed and the refraction terms are computed in a preprocessing step. The coupling model re-computes the refraction terms and water depth after each time step of wave model, when new current velocities are available assuming slowly varying conditions with respect to the time scale (wave period) and the space scale (wavelength).

3. Huricane, Wave and Storm Surge Simulations

The coupled atmosphere-wave-ocean model composed by MM5, WW3 and POM is used for simulating hurricane Katrina. For atmosphere simulation, two-domain nesting system, the first domain (27 km horizontal distance) and the second domain (9km horizontal distance), is hired with 23 sigma layers in vertical coordinate. The grid systems of wave and ocean models have same horizontal coordinate with the first domain of atmosphere model in hurricane simulation. Initial and boundary condition of ocean model is provided from Levitus98 climatology data. Fig. 3 shows the computation domains and the track of hurricane

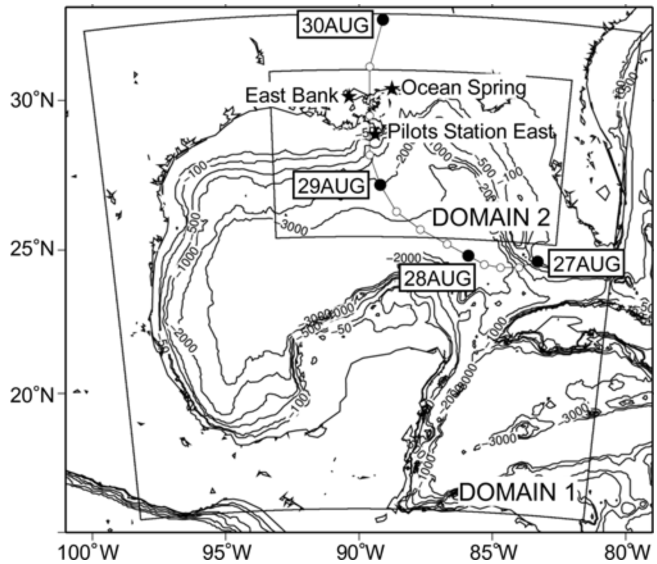

Fig. 3. Computation Domains for Meso-scale Hurricane Simulation and Track of Hurricane Katrina

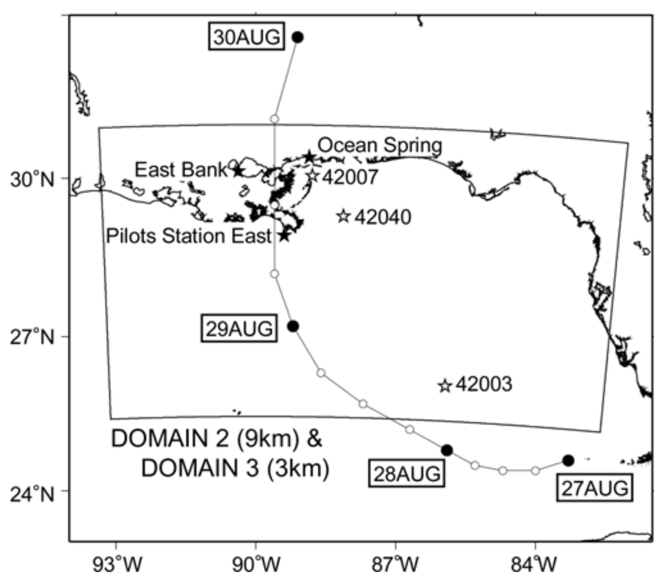

Fig. 4. 2nd Domain of Hurricane Simulation and Regional Domain for Wave and Storm Surge Simulation and Location of Wave Observation Buoys

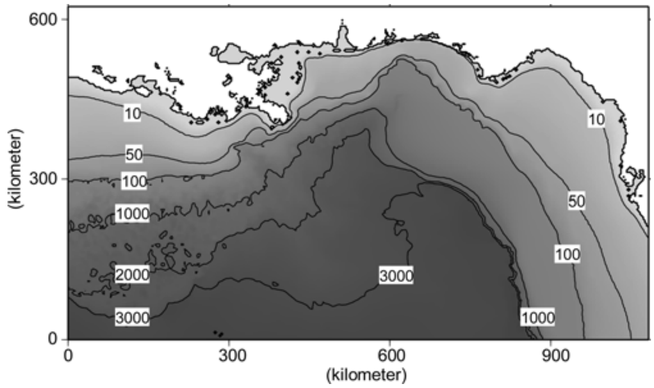

Fig. 5. Water Depths (in Meters) of Regional Wave and Storm Surge Simulation. Axes indicate Grid Lengths of Cartesian Coordinate in Kilometer

Katrina in 2005.

Storm surge and wave computation is simulated in the third domain which is same area with the nested second domain of atmosphere model in 3 km horizontal distance. The wind and pressure fields of the second domain in hurricane simulation interpolated to the grid system of the third domain for storm surge and wave simulation. Fig. 4 shows the regional wave and storm surge computation domains, and location of wave buoys of National Data Buoy Center, NOAA. Fig. 5 shows the water depths and finite-difference grid for the wave and storm surge model with a grid size of 3 km horizontal distance of the south of the Unite Stats, has a wide and shallow continental shelf. Wave, ocean and storm surge models used interpolated water depths from the GEBCO (The General Bathymetric Chart of the Oceans) 1-minute data.

4. Results and Discussions

4.1 Hurricane Katrina Simulation

Goni and Trinanes (2005) reported the surface ocean conditions before and after passage of Hurricane Katrina in the Gulf of Mexico (GOM). The cooling of the surface waters is observed by the decrease of the sea surface temperature values under the storm. The passage of the cyclone produces a strong mixing of surface waters and upwelling of deeper and cooler waters. Fig. 6 shows the Satellite-derived sea surface temperature (SST) in the

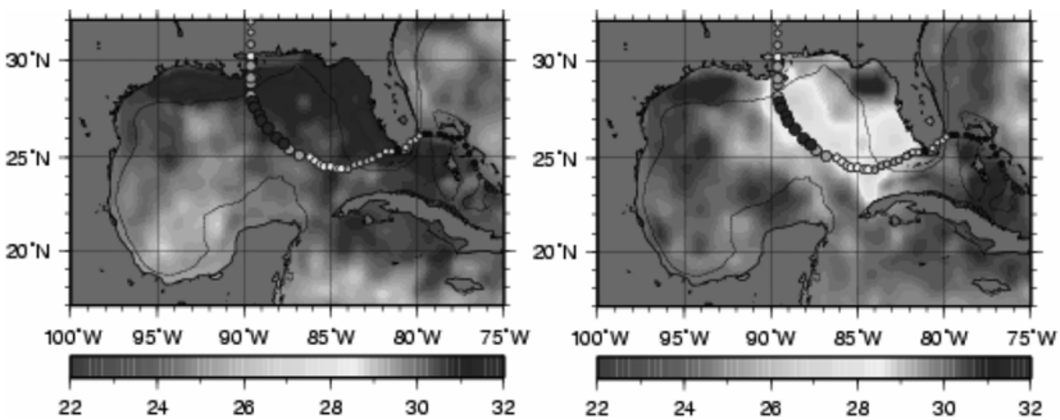

Fig. 6. Satellite-derived Sea Surface Temperature in the Gulf of Mexico on August 28 (Left), and SST after the Passage of Hurricane Katrina on August 31 (Right), (NOAA/AOML Altimetry Products, GOM Surface Dynamics Report)

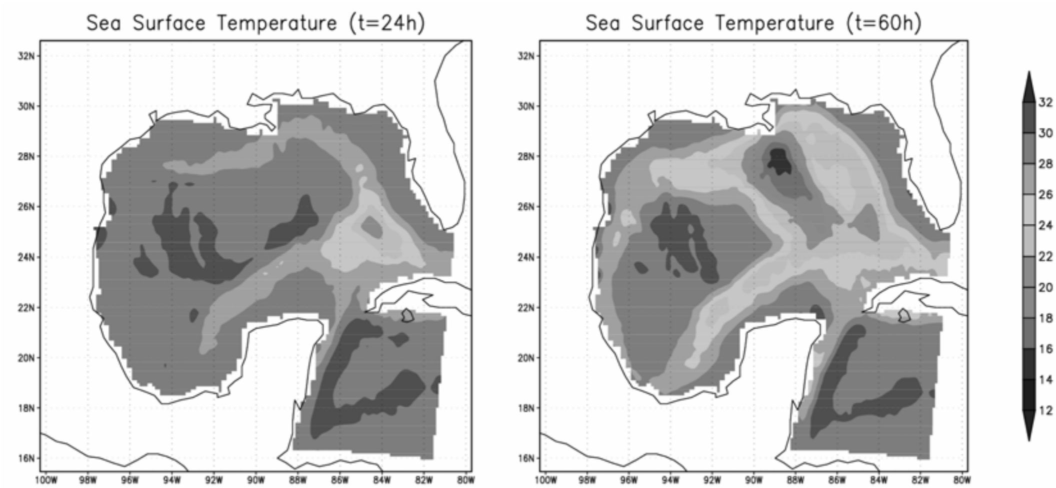

Fig. 7. Computed Sea Surface Temperature on August 28 (Left) and August 29, 12:00 (Right)

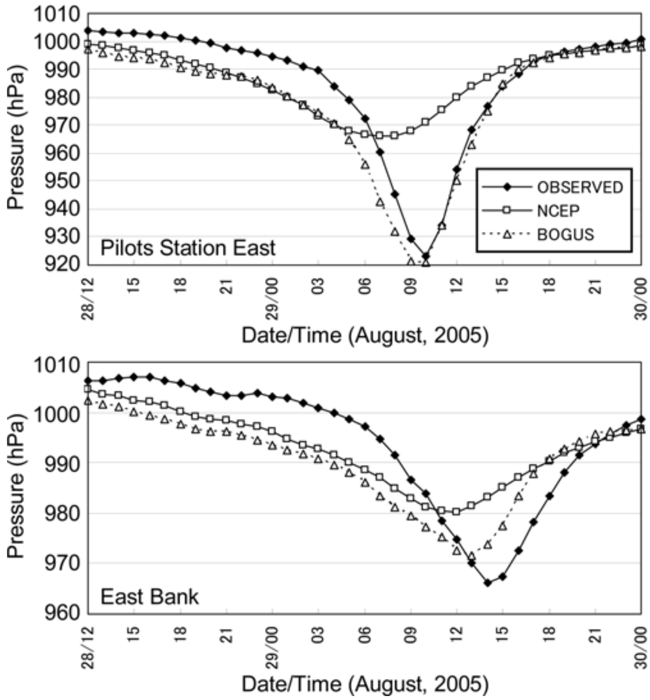

Fig. 8. Time Series of the Surface Atmospheric Pressures Observed (Closed Circle), Calculated with Typhoon Bogus (open triangle) and without Typhoon Bogus (Open Square) of Pilots Station East (Upper) and East Bank (Lower)

Gulf of Mexico on August 28, 2005, and SST after the passage of hurricane Katrina on August 31, 2005.

The result of atmosphere-wave-ocean coupling system of this study shows similar pattern. Computed sea surface temperature using atmosphere-wave-ocean coupling system is plotted in Fig. 7. The cooling effect to sea surface temperature is shown after hurricane passes.

The surface atmospheric pressures observed, calculated with typhoon bogus and without typhoon bogus of Pilots Station East and East Bank are plotted in Fig. 8. The influence of typhoon bogus is well indicated. As for this, it is thought that the radius of typhoon is too large in bogus step. The future study probably is needed to enhancement.

4.2 Wave Induced by Hurricane Katrina

WW3 is employed to compute high wave condition caused by hurricane Katrina in domain 3 which covers same area with domain 2 but less grid size (3 km). Computed and observed significant wave heights at the wave observation buoys of National Data Buoy Center, NOAA, indicated in Fig. 4, are shown in Fig. 9. The result of Simulating Waves Nearshore model (SWAN) also was compared together. The water depths of each buoy are 3233.0 m (42003), 443.6 m (42040) and 14.0 m (42007). In addition, data of Station 42003 was lost after 08/28/05Z because the buoy capsized. It is reported that this is first capsizing of a 10-meter buoy in the Gulf of Mexico in NDBC's 30-year history of operation. Station 42040 reported a significant wave height of 16.91 meters on 08/29/11Z. Although 42040 does not measure maximum wave heights, the maximum wave height may be statistically approximated by 1.9 times the significant wave height (World Meteorological Organization, 1998), which would be 32.1 meters. Station 42007 broke its mooring and went adrift after 08/29/05Z. SWAN has an enhancement of estimating wave status in the shallow area, but it seems that too much dissipation energy in the result of 42007. Fig. 10 shows the comparison between WW3 and SWAN. Possibly in shallow and

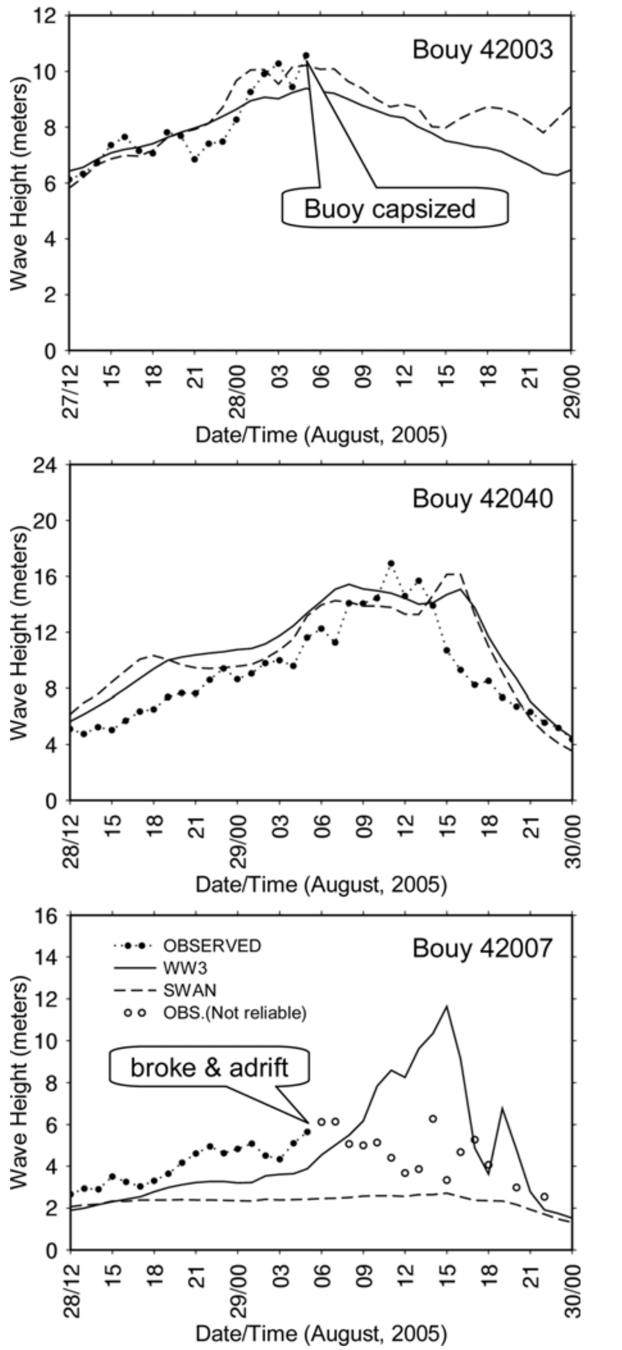

Fig. 9. Computed and Observed Significant Wave Heights at the Wave Observation Buoys of National Data Buoy Center, NOAA

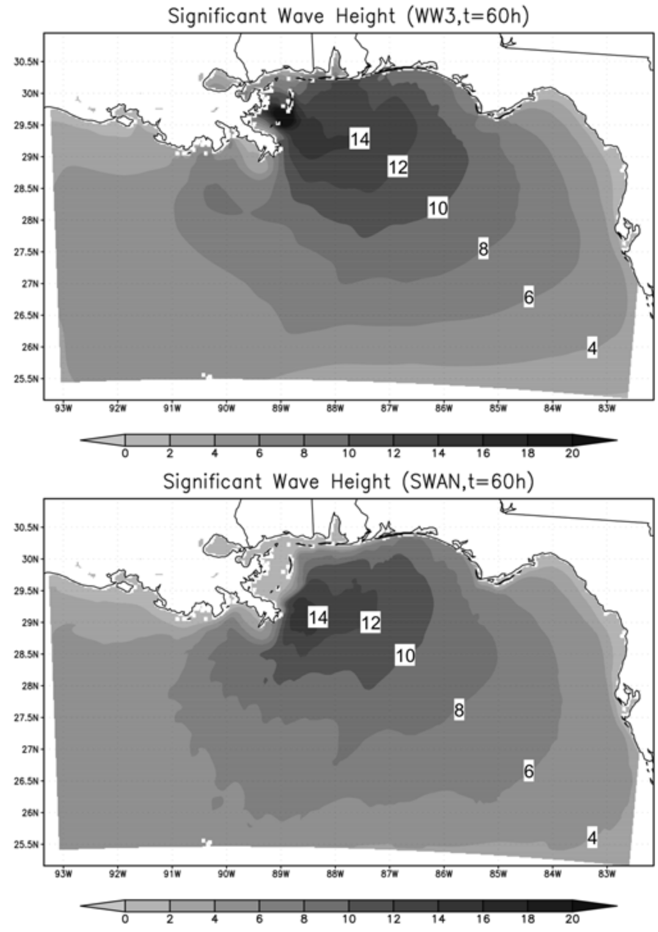

Fig. 10. Significant Wave Heights Computed by WW3 and SWAN on August 29, 12:00

blocked by island area, SWAN may not reproduce the wave strength reasonably well.

4.3 Storm Surge Induced by Hurricane Katrina

The storm surge computation considers the interaction wave-current interaction in domain 3. Fig. 11 show the computed surge elevations caused by wind, atmospheric pressure and wave, and observed surge elevations which excluded tidal components from observation sea level heights at Ocean Springs and Pilot Station East indicated in Fig. 4. The computed sea water level is 6.8 m in Ocean Springs. The station observation was stopped at 13:00, but 7.9 m of storm surge was observed at Biloxi near Ocean Springs in survey. At the Pilots Station East the maximum water level of 2.362 m was recorded but the simulated water levels not reached. The differences between the observed and simulated water levels may come from the incorrect bathymetry used for the study that could not resolve the low lying coastal region of the Pilots Station East. An additional shear stress for mean current which is the shearing stress caused by surface roller of whitecap breaker is defined to take the following two effects into account. Wave breaking energy dissipation rate in the wind wave energy balance equation can be used for evaluation of the total amount of wave energy changing into mean current. Enhancement effects of wave breaking dissipation of shoaling waves due to increasing of wave steepness.

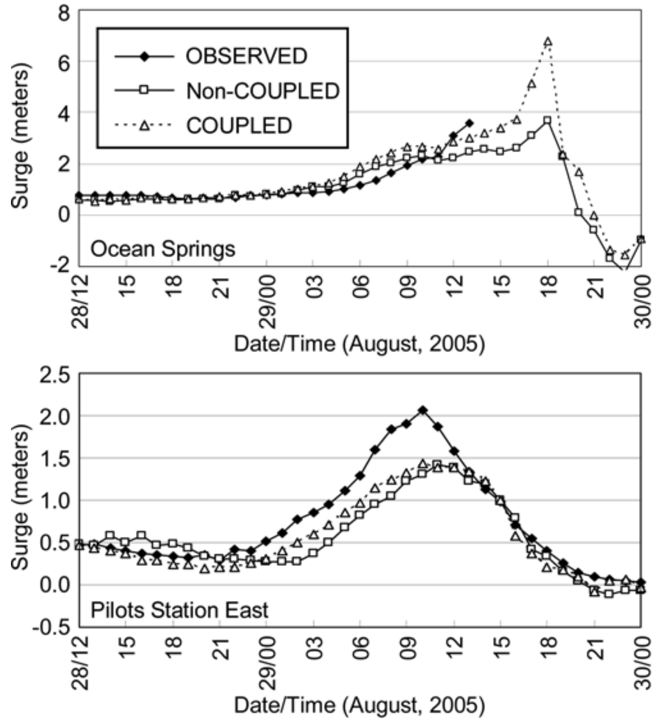

Fig. 11. Computed and Observed Surge Elevations at Ocean Springs (Top) and Pilot Station East (Bottom)

5. Summary and Conclusions

The combination of two systems, the mesoscale coupling simulation for hurricane and regional storm surge simulation, is tested to the 2005 Hurricane Katrina case which considers the expansion mechanism of the surge on the continental shelf. To enhancement typhoon bogus and 4DDA method introduced to compute hurricane in atmosphere model (MM5). The influence of typhoon bogus is demonstrated, but the more enhancement study is needed.

Two wave models are compared. SWAN has an enhancement of estimating wave status in the shallow area, but it seems that too much dissipation energy in this case. Especially in shallow and blocked by island area, SWAN may not reproduce the observed wave.

It appears that the model reproduced the wave heights and water levels during the event with reasonable accuracy. An additional sea surface shear stress, due to wave energy dissipation using the roller concept within the surface boundary layer, was introduced to consider the effects of energy transfer from wind to current through wave dissipation in the air-sea interaction system. Hindcast simulation of storm surge in this study showed the importance of energy transfer path via whitecap dissipation of wind waves in the generation mechanism of mean current in the extremely shallow water.

An additional shear stress for mean current which is the shearing stress caused by surface roller of whitecap breaker was defined to take the following two effects into account. (i) Wave energy dissipation rate in the wind wave energy balance equation can be used for evaluation of the total amount of wave energy changing into mean current. (ii) Enhancement effects of wave breaking dissipation of shoaling waves due to increasing of wave steepness.

References

Battjes, J.A. and Janssen, J.P.F.M. (1978). "Energy loss and set-up due to breaking in random waves." *Proceeding of the 16th International. Conference*, Coastal Engineering, pp. 569-587.

Chalikov, D.V. and Belevich, M.Y. (1993). "One-dimensional theory of the wave boundary layer." *Bound. Layer Meteor*, Vol. 63, pp. 65-96.

Choi, B.H., Eum, H.M., and Woo, S.B. (2003). "A synchronously coupled tide-wave-surge model of the Yellow Sea." *Coastal Engineering*, Vol. 47, pp. 381-398.

Chu, J., Sampson, C.R., Levine, A.S., and Fukada, E. (2002). The Joint Typhoon Warning Center Tropical Cyclone Best-Tracks, 1945-2000, *Joint Typhoon Warning Center, NRL Reference Number: NRL/MR/7540-02-16.*

Davis, C.A. and Low-Nam, S. (2001). The NCAR-AFWA tropical cyclone bogussing scheme, *A report prepared for the Air Force Weather Agency*, AFWA.

Deigaard, R. and Fredsoe, J. (1989). "Shear stress distribution in dissipative water waves." *Coastal Engineering*, Vol. 13, pp. 357-378.

Goni, G. and Trinanes, J. (2005). Gulf of Mexico surface dynamics reports, *NOAA Atl. Oceanogr. and Meteorol. Lab.*, Miami, Fla., 29 Aug. (Available at http://www.aoml.noaa.gov/phod/altimetry/katrina_v2.pdf)

Grell, G.A., Dudhia, J., and Stauffer, D.R. (1994). A description of the fifth-generation Penn State/NCAR Mesoscale Model (MM5). *NCAR Tech. Note NCAR/TN-398 + STR*.

Hasselmann, K., and Coauthors (1973). "Measurements of wind-wave growth and swell decay during the Joint North Sea Wave Project (JONSWAP)." *Dtsch. Hydrogr. Zeitschr.*, Vol. A8, No. 12, pp. 1-95.

Hasselmann, S. and Hasselmann, K. (1985). "Computations and parametrizations of the nonlinear energy transfer in a gravity wave spectrum. Part I: a new method for efficient computations of the exact nonlinear transfer integral." *Journal of Physical Oceanography*, Vol. 15, pp. 1369-1377.

Hong, S.Y. and Pan, H.L. (1996). "Nonlocal boundary layer vertical diffusion in a medium-range forecast model." *Monthly Weather Review*, Vol. 124, pp. 2322-2339.

Intergovernmental Panel on Climate Change (2001). *Climate Change 2001, IPCC Third Assessment Report*, Cambridge University Press.

Janssen, P.A.E.M. (1991). "Quasi-linear theory of wind wave generation applied to wave forecasting." *Journal of Physical Oceanography*, Vol. 21, pp. 1631-1642.

Jensen, R.E., Cox, A., Hagen, S., Graber, H.C. and Slinn, D. (2006). "Real Time Forecasting of Waves and Surge during Hurricane Katrina." *Eos Trans. Ocean Sciences Meet.* American Geophysical Union, Vol. 87, No. 36, Suppl., Abstract OS11K-02.

Kato, S. and Yamashita, T. (2000). "Three-dimensional model for wind, wave-induced coastal currents and its verification by ADCP observations in the nearshore zone." *Proc. 27th Int. Conf. On Coastal Eng.*, ASCE, pp. 3777-3790.

Kim, K.O. and Yamashita, T. (2005). "Wind-wave-surge coupled model: Application to storm surge simulation in the Bay of Bengal." *Proc. of Asian and Pacific Coasts 2005*, Jeju, Korea, pp. 603-606.

Knabb, R.D., Rhome, J.R., and Brown, D.P. (2005). Tropical cyclone report: Hurricane Katrina, *National Hurricane Center, NOAA*. (Available at http://www.nhc.noaa.gov/pdf/TCR-AL122005_Katrina.pdf).

Longuet-higgins, M.S. and Stewart, R.W. (1964). "Radiation stress in water waves, a physical discussion with application." *Deep-Sea Res.*, Vol. 11, pp. 529-563.

Masternbroek, C., Burgers, G., and Janssen, P.A.E.M. (1993). "The dynamical coupling of a wave model and a storm surge model through the atmospheric boundary layer." *Journal of Physical Oceanography*, Vol. 23, pp. 1856-1866.

Mellor, G. (1998). *A three-dimensional, primitive equation, numerical ocean model.* Program in Atmospheric and Oceanographic Sciences Report. Princeton University, Princeton.

Moon, I.J. (2005). "Impact of a coupled ocean wave-tide-circulation system on coastal modeling." *Ocean Modelling*. Vol. 8, pp. 203-236.

Nairn, R.B., Roelvink, J.A., and Southgate, H.N. (1990). Transition zone with and implications for modeling surfzone hydrodynamics, *Proc. 22nd Int. Conf. On Coastal Eng.*, ASCE, pp. 68-82.

Ozer, J., Padilla-Hernández, R., Monbaliu, J., Fanjul, E.A., Albiach, J.C.C., Osuna, P., Yu, J.C.S., and Wolf, J. (2000). "A coupling module for tides, surge and waves." *Coastal Engineering*, Vol. 41, pp. 95-124.

Reisner, J., Rasmussen, R.M., and Bruintjes, R.T. (1998). "Explicit forecasting of supercooled liquid water in winter storms using the MM5 mesoscale model." *Quarterly Journal of the Royal Meteorological Society*, Vol. 124, pp. 1071-1107.

Roelvink, J.A. and Reniers, A.J.H.M. (1994). Upgrading of a quasi-3D hydrodynamic model. Abstracts-in-depth, *MAST G8-M overall workshop*, Gregynog.

Smith, S.D. and Banke, E.G. (1975). "Variation of the sea surface drag coefficient with wind speed." *Quarterly Journal of the Royal Meteorological Society,* Vol. 101, pp. 665-673.

Tolman, H.L. and Chalikov, D.V. (1996). "Source terms in a third-generation wind-wave model." *Journal of Physical Oceanography*, Vol. 26, pp. 2497-2518.

WAMDIG (1988). "The WAM model - A third generation ocean wave prediction model." *Journal of Physical Oceanography*, Vol. 18, pp. 1775-1810.

Weaver, R.J. and Slinn, D.N. (2004). "Effect of wave forces on storm surge." *Coastal Engineering 2004*, World Scientific Publishing, pp. 1532-1538.

World Meteorological Organization (1998). *Guide to Wave Analysis and Forecasting*, WMO 702, Geneva.

Zhang, M.Y. and Li, Y.S. (1996). "The synchronous coupling of a third-generation wave model and a two-dimensional storm surge model." *Ocean Engineering*, Vol. 23, pp. 533-543.