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Tidal Asymmetry and Energy Variation Due to Sea-Level Rise in a Macro Tidal Bay

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ABSTRACT

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Multiple coastal constructions at shallow depths in macro tidal environments, have resulted in remarkable coastal hydrodynamic alteration resulting in tidal asymmetry, energy flux, and dissipation. Consequently, the temporal aspect of sedimentation has changed abruptly and can eventually cause long-term variations. These anthropogenic alterations should be precisely investigated in relation to sea-level rise (SLR) in order to mitigate unexpected consequences. To understand alteration of tidal asymmetry due to SLR, gamma parameters that combine the traditional tidal amplitude ratio of M_4/M_2 and phase-lag difference were evaluated using the ADvanced CIRCulation (ADCIRC) model under finely resolved complex coastal geometry. Moreover, tidal energy flux and dissipation changes, in relation to tidal-flat area, were examined in Gyeonggi Bay, South Korea. As a result of SLR, spatial change in tidal asymmetry would occur; moreover, gamma parameter intensity, which shows flood dominance, would attenuate. M_2 and M_4 tidal energy flux would be lessened by SLR. For the energy dissipation, slight change appeared in M_2, while lessening tidal flat area directly affected reduction in M_4 based on SLR scenarios. Because a small change in tidal asymmetry could yield long-term morphological changes in the macro tidal environment, these alterations should be treated as important. A numerical restoration test removal of Siwha Dike, which behaved as a tipping point on tidal asymmetry, revealed that even a SLR scenario did not have significant effect if the natural shoreline persists. Thus, future studies should be focused on the importance of long-term impact on tidal alteration induced by coastal construction.

ADDITIONAL INDEX WORDS: *Tidal flat, ADCIRC, artificial coast, anthropogenic, flood dominance.*

INTRODUCTION

Multiple coastal constructions in the macro tidal environment in Gyeonggi Bay (GGB) [west coast of Korea (WCK), a part of the Yellow Sea (YS)], have resulted in remarkable coastal hydrodynamic alteration involving tidal asymmetry, energy flux, and dissipation. The mean spring tidal ranges along the WCK from the south-west of the Korea Peninsula to GGB vary from 3.8 to 8.0 m, and the GGB is well known as one of the most remarkable macro tidal basins in the world. The tidal form factor, $F = (K_1+O_1) / (M_2+S_2)$ is less than 0.20 thus, the WCK belongs to a semi-diurnal dominant region.

The GGB has been influenced by the coastal anthropogenic activities of Korean and China (Song *et al*. 2013; Suh *et al*. 2014) in terms of the near- and far-field effects during the last several decades. Suh *et al*. (2014) revealed that completion of the Siwha Dike, among a series of coastal developments, has behaved as a tipping point in tidal hydrodynamic changes from ebb to flood dominance. Pelling *et al*. (2013) showed that land-reclamation construction caused significant changes in tidal amplitude throughout the Bohai Sea because of extensive natural and anthropogenic activities. Moreover, this tidal basin will be influenced by global environmental changes and human interference within and adjacent to it (Wang *et al*., 2015). Thus, the necessity of understanding tidal hydrodynamics is greatly increasing, if we are to figure out how tidal hydrodynamic change will continue or be altered by sea-level rise (SLR). SLR would alter tidal dynamics, morphological change, and possibly the associated ecosystem of the tidal basin over the long-term.

Lopes and Dias (2014) attempted to quantify changes in tidal patterns for a coastal lagoon, in response to the local mean sea level rise. They found tidal alteration due to variation of depth toward shallowness in the lagoon under mean SLR conditions. SLR alters tidal asymmetry and hence affects coastal or estuarine morphological environments. Chernetscky *et al*. (2010) revealed how tidal asymmetry due to the intensifying nonlinear effect could alter sediment equilibrium dynamics. Van Maanen *et al*. (2013) simulated the morphological evolution of a tidal embayment to explore its response to rising sea level for semi-circular idealized basin with a barrier, and found SLR affected the exchange of sediment between the different morphological elements. Besides the impacts on sedimentation, the tidal energy variations associated with SLR were deeply investigated (Clara *et al*., 2015) in a series of scenarios that

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represented the present and future conditions due to SLR.

It is difficult to distinguish natural and artificial changes in tidal hydrodynamics of GGB because there is insufficient historical data recorded from 1959 to now (2015). Moreover, long-period tidal fluctuation, such as the nodal factor arising every 18.6 years, was not clearly discerned earlier. Thus, in analysis of future tidal alteration, by perhaps 2100, special causative factors should be included. This is because a modulation factor for M_2 of 3.7% for a corresponding amplitude of 3 m could be a variation of at least 11 cm of water surface elevation (WSE). Haigh *et al*. (2011) depicted variations in high tides that arise because of the 18.61-yr lunar nodal cycle and the 8.85-yr cycle of lunar perigee. Hence, not only for assessment of tidal asymmetry but also for the purpose of preventing coastal disaster, the long-term decadal modulation should be considered in tidal hydrodynamic analysis, especially in a macro tidal bay like GGB.

In this paper, the trend of tidal asymmetry, energy flux, and dissipation in the GGB will be touched upon, as well as how those would respond with respect to SLR. In the analysis, ADCIRC (Luettich *et al*., 1992) was applied to provide several simulated scenarios corresponding to increments of SLR on finely resolved meshes considering inter-tidal flat variations and the impacts of artificial coastal structures that prevent overland flooding.

METHODS

According to the tidal asymmetry study along the WCK (Suh *et al.*, 2014), GGB in particular, showed abrupt change of tidal hydrodynamics from ebb to flood dominance. In this paper, the region of interest (ROI) is confined to the GGB to examine the tidal hydrodynamic alteration there. To analyze past changes in the tides, harmonic analysis and fast Fourier transformation have been applied to data from the recording period 1959–2015 at the Incheon tidal recording station shown in Figure 1.

SLR Scenarios and numerical parameters

For the future SLR, we followed IPCC RCP (IPCC, 2014) scenarios 4.5 and 8.5; thus, 0.64 and 0.82 m of mean SLR would be expected by 2100 in GGB (KMA, 2012). In addition, hypothetical SLR scenarios were incorporated to assess further possible rise, (*i.e.*, 1.0 and 2.0 m after Pelling *et al*. (2013), who added SLR of 1, 2, or 3 m in scenarios). Clara *et al*. (2015) considered even 10 m of SLR to get insight into potential future SLR. In addition, a nodal factor of 18.6 years was included in the analyses, and hypothetical cases involving removal of the Siwha Dike were tested to assess the potential for restoration, with or without consideration of potential SLR.

After setting up the grid, an unstructured circulation model, ADCIRC was applied with harmonic constants of eight major tidal constituents on open boundaries extracted from FES2004. The ADCIRC is a continuous-Galerkin finite element model that solves the generalized wave continuity equation, which is a modified form of the shallow water equations, and momentum equations on unstructured meshes in a Cartesian or spherical coordinate system. Solution in time can be performed using a semi-implicit or explicit time stepping algorithm. Subsequent improvements, details of code, manuals, and related utilites can be found at http://adcirc.org. Details of nodal intensity and other numerical parameters in modeling of ADCIRC can be found in a related article (Suh *et al*., 2014).

Because tidal modeling in shallow regions with inter-tidal flats is greatly dependent on bottom friction, precise resolving of coastal lines and bathymetry is necessary. To meet this requirement, the study domain was discretized with great care on this point. For the bottom friction, a quadratic formula was adopted and spatially varying coefficients of 0.02 to 0.03 were assigned to account for the frictional losses in a shallow coastal region. Moreover, a coefficient higher than 0.2 was assigned to represent a land canopy for area flooding due to sea-level rise, because energy dissipation in this area is directly affected by surface roughness coefficients (Pelling and Green, 2013).

Tidal asymmetry and energy flux

Tidal distortion can be determined by the relationship with the major lunar semidiurnal constituent and its overtide (*i.e.*, the asymmetry intensity) by taking the amplitude ratio of M_4/M_2 and phase difference of $2\varphi M_2 - \varphi M_4$. In addition, the gamma parameter expressed in Equation (1) was applied for the purpose of simplification (Song *et al*., 2013). In this paper, the strength of asymmetry was determined using the gamma parameter.

$$\gamma_{M_2/M_4} = \frac{\frac{3}{2} a_{M_2}^2 a_{M_4} \sin\left(2\varphi_{M_2} - \varphi_{M_4}\right)}{\left[\frac{1}{2}\left(a_{M_2}^2 + 4a_{M_4}^2\right)\right]^{\frac{3}{2}}} \tag{1}$$

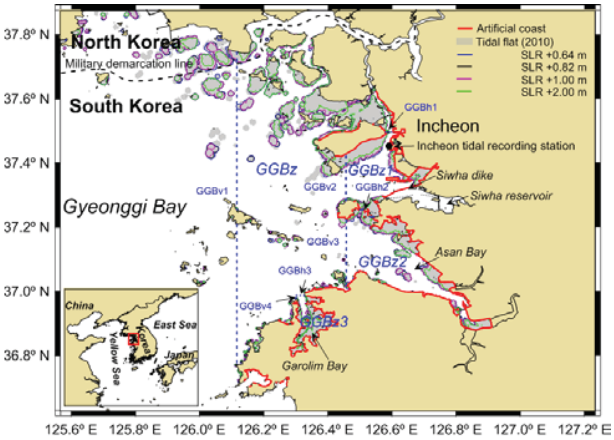

Figure 1. Map showing the study area, Gyeonggi Bay in Korea. Artificial coast (in red line) and tidal flat (in grey) retreats are depicted by color lines corresponding sea-level rise scenarios. Spatially divided zones with vertical and horizontal cross-sections are represented for the tidal energy flux comparison.

To understand precisely spatial tidal distortion, tidal energy flux, and dissipation, GGB was divided into sub zones as in Figure 1: main GGB zone, Incheon Harbor zone, Asan Bay zone, Garolim Bay zone. These were denoted GGBz, GGBz1, GGBz2, and GGBz3, respectively. The tidal-energy flux crossing sections for the sub zones were also shown as vertical and horizontal sections. Energy flux and dissipation averaged over a tidal cycle were computed using Equation (2) and Equation (3) (Pugh, 1987).

$$\text{Average energy flux} = \frac{1}{2}\rho g D H_0 U_0 \cos\left(g_{\zeta_0} + g_{U_0}\right) \qquad (2)$$

$$\text{Average energy dissipation} = \frac{4}{3\pi} C_D \rho U_0^3 \text{ per unit area} \qquad (3)$$

in which, ρ, g, and D are water density, gravitational acceleration, and water depth, respectively. H_0 and g_{ζ_0} (U_0 and g_{U_0}) represent the amplitude and phase of the surface elevation (current components), respectively. C_D is bottom friction.

Tidal asymmetry can be analyzed using tidal record data or by numerical modeling. The future SLR was predicted using the ADCIRC. Tidal amplitudes and phases of M_2 and its overtides M_4 and M_6, were extracted from simulated results for one year with SLR scenarios in year 2090 or 2100.

RESULTS

It would be meaningful to assess how alterations persist and how tidal asymmetry continues where anthropogenic impacts cause crossing of a tipping point. Among many construction projects over the last four decades in the GGB, clearly the most influential alteration would be the Siwha Dike and its tidal power plant. Among several future physical changes due to SLR, the foremost variation could be lessening of inter-tidal flat areas. Hence, we calculated the variations and found that sea level rise of 0.64, 0.82, 1.0, and 2.0 m would cause reductions of 19.2, 23.6, 28.0, and 47.1% of total inter-tidal area, respectively, in the GGB. This major reduction of shallow intertidal area (shown in Figure 1) acts as the primaryfactor slowing or intensifying of tidal distortion.

Simulation showed that the gamma parameters lessened gradually from 0.148 in 2010, to 0.122, 0.114, 0.108, and 0.084 for the corresponding SLR of 0.64, 0.82, 1.0, and 2.0 m, respectively, in 2100. Hence, the tidal asymmetry amplitude ratio M_4/M_2 would shrink from 0.045 to 0.038, 0.035, 0.033, and 0.021 (in the same order), though computed asymmetry showed somewhat higher value compared to the one observed in the present condition. However, phase differences $2\varphi M_2 - \varphi M_4$, show almost the same result, 129.0–130.2°, except for 112.7° for the 2.0 m SLR scenario.

To understand spatial tidal distortion distribution, gamma parameter tests were done and typically represented in the case of SLR +1.0 m (assigned as additional forthcoming anthropogenic rise effect based on SLR of 0.82 m in accordance with the IPCC RCP 8.5 scenario). Comparison of simulated results to present sea level condition is depicted in Figure 2. Most regions along coasts are flood dominant; however, the intensity gradually decreases with SLR. It is noted that sub-zone GGBz3 (Garolim Bay), will be slightly changed from flood to ebb dominance.

Tidal distortion might alter the tidal energy flux and/or dissipation variations. Under the present condition, strong flux of M_2 tidal energy occurs (on the order of 10^5–10^6 W/m) along channels surrounded by islands (Figure 3a). However, when sea level becomes 0.82 m higher, the tidal flux will be lessened by about 10^3–10^4 W/m in main channels, as seen in Figure 3b. The shrinking of tidal energy flux is due to de-amplification of M_2 caused by increasing mean depth, and to lessening of tidal flat area owing to SLR. On the other hand, M_2 energy did not dissipate regardless of changes in the area of tidal flats. Especially in GGBz3, tidal energy will be more dissipated than at present. This might be the result of ebb dominant change in the tidal characteristics. Besides tidal energy flux variations, SLR would cause reduction of the tidal power-generating capability at Siwha by 1.56, 1.92, 2.57, and 5.76%, corresponding with SLR of 0.64, 0.82, 1, and 2 m, respectively.

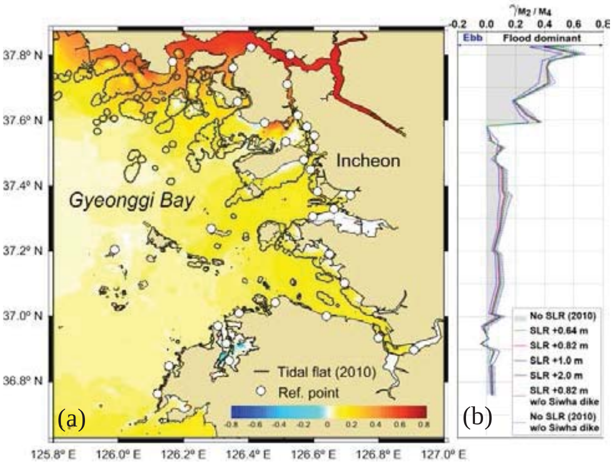

Figure 2. Tidal asymmetry: (a) Spatial distribution owing to a 1.0 m SLR scenario, (b) Temporal variations at coastal reference points for all scenarios in terms of γ_{M_2/M_4}.

However, results on shallow overtides showed lessening of M_4 energy influx through the main cross section of GGBv1. Even so, the magnitude of efflux dominant M_6 energy would be less due to SLR. M_4 energy would be dissipated mainly in GGBz and GGBz3 due to nonlinear energy dissipated by M_2 interaction and geometry. However, the M_6 component, which is more influenced by bottom friction, will lose energy only inGGBz. It is noted that there is strong correlation of M_4 energy flux and dissipation with tidal flat area variation as seen in Figure 4. This means that the non-linear shallow tidal energy and dissipation of M_4 in GGB, are directly affected by topology and hence would show a gradual decrease with SLR, owing to lessening of tidal flat area.

DISCUSSION

The morphological developments in estuaries and tidal basins are influenced by global environmental changes and human interference within and adjacent to them (Wang *et al.*, 2015). Owing to SLR, strengthening of tidal asymmetry might be attenuated in GGB, where critical change from ebb to flood dominance was recorded due to anthropogenic coastal construction (particularly the Siwha Dike, see Suh *et al*., 2014). Van Maanen *et al*. (2013) have shown that tidal asymmetry related to morphological change during SLR cannot be neglected. This aspect, as found in this paper, is important because small changes in tidal asymmetry can yield long-term morphological changes in strong tidal currents in macro tidal environments such as GGB (Choi and Jo, 2015).

In this paper, the impacts of artificial coast on future tidal hydrodynamic changes were evaluated, because it is getting familiar as a hard-treating methods for coastal hazards protection. Pelling and Green (2013) pointed out that if permanent flooding of land were allowed, the response of the tides to SLR is dramatically different because permanent flooding of new land significantly alters the tidal response. However, 54% of the total coast in the GGB has already been made into artificial coast, so permanent flooding due to SLR is only valid for a restricted natural region. Thus, analysis should be done with intense care with much finer grid resolution and selection of proper roughness coefficients corresponding to surface canopy conditions.

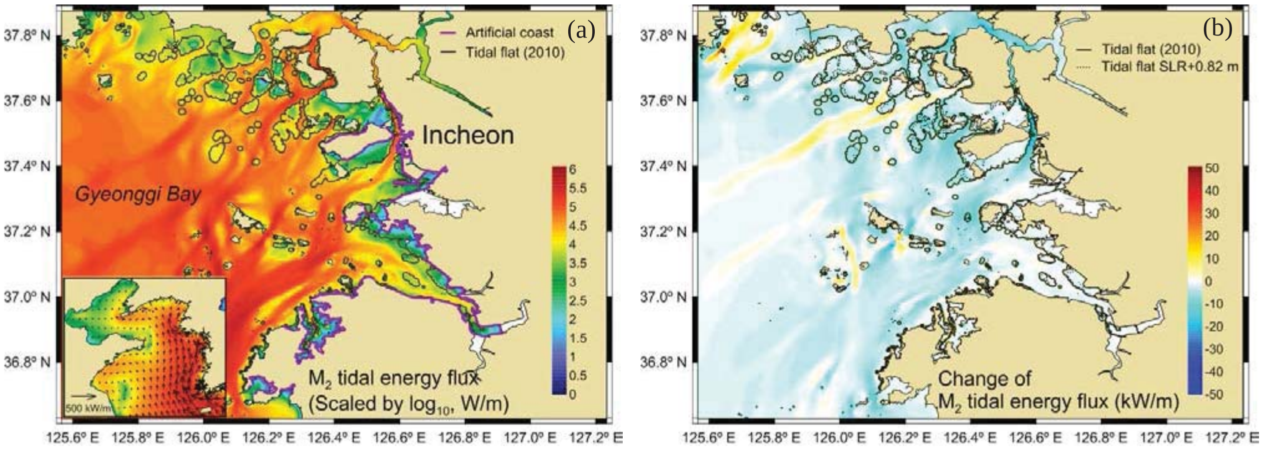

Figure 3. Tidal energy flux: (a) Distribution at present condition, (b) Differences due to SLR of 0.82 m by 2100.

Through recorded tidal data analyses, the 18.6-yr nodal factor variation was not clearly distinguishable because of the mixed effects of nearby large reclamation and dike construction. Although the length of the tidal record is about 65 yr long, inconsistency caused by re-installation or malfunctions reduced the record of reliable data by about 40 yr. Thus, careful attention is necessary in this analysis of tidal data as pointed by Houston and Dean (2011). It is manifest that the long-term period of constituents should be incorporated into the analysis of SLR (Haigh *et al*., 2011; Pelling *et al.*, 2013). However, it is still not accounted properly in extrapolation due to limitations or lack of records from past years. Thus, further study is clearly required.

The study area is a very shallow, macro tidal environment thus, the intertidal flat area behaves as the main source of tidal distortion. Simulated results for SLR very clearly indicate decreasing M_4 tidal energy and dissipation, with lessening of tidal flat area. Because tidal distortion is mainly produced within a tidal basin by a combination of frictional effects and the interaction of the tide with the bathymetry, this can describe how the M_4 tidal energy has strong correlation with the decreasing tidal flat area due to SLR. Furthermore, tidal distortion with respect to SLR could alter not only the existing tidal power generating capability at the Siwha plant, but also a considerable amount at Asan and Garolim Bay (Figure 1: GGBz2 and GGBz3, respectively).

To investigate the impact of an anthropogenic tidal barrier, removing the Siwha Dike was tested and assessed by means of hypothetical simulations. The hypothetical modeling might give some insight into indiscriminate dike construction in other coastal bays. Through the recorded tidal data analysis, we now better understand how completion of the dike acted as a flood-dominating tipping point in the GGB. Through this hypothetical analysis, we found there might not be big impacts on coastal tidal hydrodynamics even with SLR of 0.82 m, if the natural condition (*i.e.*, without Siwha Dike), persists or is restored by 2100. Thus, any anthropogenic activity should be investigated profoundly, because unwanted impacts could arise in the near-field as short-term effects but also basin-wide over the long term. In addition, ongoing and future coastal projects in China and Korea could continuously distort the YS tidal hydrodynamics. Such artificial effects will complicate predictions related to natural sea-level change on both sides of the YS. It is essential to discern the anthropogenic impacts by precise analyses.

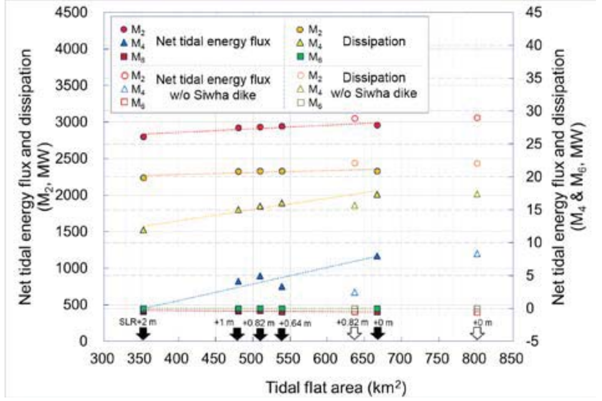

Figure 4. Tidal energy and tidal flat area correlations due to SLR scenarios for the GGB.

CONCLUSIONS

To understand the intensification of tidal asymmetry due to SLR, a gamma parameter that combines the traditional tidal amplitude ratio of M_2/M_4 and phase lag difference was evaluated using the ADCIRC model under finely resolved complex coastal geometry. Through this study, the author determined the trend in tidal asymmetry in the GGB, which has crossed a tipping point from ebb- to flood-dominance due to multiple coastal developments, which continue regardless of SLR and lessening of tidal flat area. Although the importance of the 18.6-yr periodic nodal factor under the condition of M_2 tidal amplitude of 3 m, could not be explicitly distinguished due to the mixture of anthropogenic coastal construction and relatively short period of observation (55 yr). Thus, inclusion of pure impact by the nodal factor should be accounted correctly in future research intended to account for sea-level variation. Model simulation results showed SLR, based on IPCC RCP scenarios with hypothetical cases, could lessen tidal asymmetry, and reduce tidal energy influx of M_4 by 50%, as a result of reduction of tidal flat area.

Through a numerical restoration test involving removal of the Siwha Dike, it is expected that even SLR of 0.82 m would not alter the tidal system of the bay greatly, if natural shoreline persists. Tidal hydrodynamic alterations could influence morphological change in estuaries and tidal basins as a result of global sea-level change and human interference. Thus, future studies should be focused on addressing the importance of any impact of tidal hydrodynamic alteration induced by coastal construction, using a well-designed numerical model. This is because anthropogenic land reclamation and/or tidal barriers have led to significant changes in semi-closed basins.

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LITERATURE CITED

Chernetscky, A.S.; Schuttelaars, H.M., and Talke, S.A., 2010. The effect of tidal asymmetry and temporal settling lag on sediment trapping in tidal estuaries. *Ocean Dynamic*s, 60, 1219-1241.

Choi, K. and Jo, J., 2015. Morphodynamics and stratigraphic architecture of compound dunes on the open-coast macrotidal flat in the northern Gyeonggi Bay, west coast of Korea. *Marine Geology*, 366, 34-48.

Clara, L.M.; Simionato, C.G.; D’Onofrio, E., and Moreira, D., 2015. Future sea level rise and changes on tides in the Patagonian Continental Shelf. Florida Coconut Creek (U.S.A.). *Journal of Coastal Research*, 31(3), 519–535.

Haigh, I. D.; Eliot, M., and Pattiaratchi, C., 2011. Global influences of the 18.61 year nodal cycle and 8.85 year cycle of lunar perigee on high tidal levels. *Journal of Geophysical Research*, 116, C06025.

Houston, J.R. and Dean, R.G., 2011. Accounting for the nodal tide to improve estimates of sea level acceleration. *Journal of Coastal Research*, 27(5), 801-807.

IPCC, 2014. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* IPCC, Geneva, Switzerland, 151p.

KMA, 2012. *Climate Change Forecast Report for Korean Peninsula.* Korea Meteorological Administration, 151p (in Korean).

Lopes, C.L. and Dias, J.M., 2014. Influence of mean sea level rise on tidal dynamics of the Ria de Aveiro lagoon, Portugal. *In:* Green, A.N. and Cooper, J.A.G. (eds.), *Proceedings 13th International Coastal Symposium (Durban, South Africa), Journal of Coastal Research*, SI 70, 574-579.

Luettich, R.A.; Westerink, J.J., and Scheffner, N.W., 1992. *ADCIRC: An Advanced Three-Dimensional Circulation Model for Shelves Coasts and Estuaries Report 1: Theory and Methodology of ADCIRC-2DDI and ADCIRC-3DL.* Vicksburg, MS: US Army Corps of Engineers Waterways Experiment Station, *Dredging Research Program Technical Report DRP-92-6*, 141p.

Pelling, H.E. and Green, J.A.M., 2013. Sea level rise and tidal power plants in the Gulf of Maine. *Journal of Geophysical Research: Oceans*, 118, 2863-2873.

Pelling, H.E.; Uehara, K., and Green, J.A.M., 2013. The impact of rapid coastline changes and sea level rise on the tides in the Bohai Sea, China. *Journal of Geophysical Research: Oceans*, 118, 3462-3472.

Pugh, D.T., 1987. *Tides, Surges and Mean Sea-Level*. New York: John Wiley & Sons, 472p.

Song, D.; Wang, X.H.; Zhu, X., and Bao, X., 2013. Modeling studies of the far-field effects of tidal flat reclamation on tidal dynamics in the East China Seas. *Estuarine, Coastal and Shelf Science*, 133, 147-160.

Suh, S.W.; Lee, H.Y., and Kim, H.J., 2014. Spatio-temporal variability of tidal asymmetry due to multiple coastal constructions along the west coast of Korea. *Estuarine, Coastal and Shelf Science*, 151, 336-346.

Van Maanen, B.; Coco, G.; Bryan, K.R., and Friedrichs, C.T., 2013. Modeling the morphodynamic response of tidal embayments to sea-level rise. *Ocean Dynamics*. 63(11), 1249-1262.

Wang, Z.B.; Van Maren, D.S.; Ding, P.X.; Yang, S.L.; Van Prooijen, B.C.; De Vet, P.L.M.; Winterwerp, J.C.; De Vriend, H.J.; Stive, M.J.F., and He, Q., 2015. Human impacts on morphodynamic thresholds in estuarine systems. *Continental Shelf Research,* CSR3681.