Climate Change and Anthropogenic Impact Around the Korean Coastal Ecosystems: Korean Long-term Marine Ecological Research (K-LTMER)

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Background

The East-Asian Marginal Seas (EAMS), including the Yellow Sea, the East China Sea, and the East Sea (Fig. 1), are regarded as one of the hot spots where rapid warming of seawater occurs. During the period from 1982 to 2006, sea surface temperature (SST) of the EAMS increased 0.67–1.09 °C, which is the highest among the 18 large marine ecosystems (LME) in the world (Belkin 2009), and is 2–4 times higher than the global SST warming rate of 0.13 °C per decade (IPCC 2007). The climate change-induced variations in physical oceanographic conditions have greatly altered the composition, abundance, and metabolic activities of lower trophic levels (i.e., heterotrophic bacteria, phytoplankton, and zooplankton) as well as the seasonal peak abundance of phytoplankton in the East Sea and Yellow Sea (Chiba and Saino 2003; Chiba et al. 2012; Jahan et al. 2013; Jahan and Choi

2014; Joo et al. 2014; Lee et al. 2014; Jung et al. 2017; Kim et al. 2017b; Kim et al. 2019a; Park et al. 2019f). In addition to climatic change, intense anthropogenic activities, including reclamation of coastal wetlands, construction of artificial dikes along the coasts and at the river mouth, and intense aquaculture operation, have exerted profound effects on the physico-chemical and biological conditions in this region (Jahan et al. 2013; Sin et al. 2013, 2015; Kim et al. 2017c; An et al. 2019; Choi et al. 2020).

Coastal upwelling is one of the unique physical oceanographic properties along the southeast Korean peninsula and is largely responsible for the high primary production of the Ulleung Basin (UB) in the East Sea (Hyun et al. 2009; Yoo and Park 2009). However, the strength of southwesterly wind stimulating the upwelling has decreased by up to 34% in the 2000s compared with the 1960s (KORDI 2010), and the SST has increased 1.09 °C during the period of 1982–2006 in the East Sea including the UB (Belkin 2009). The weakened wind strength and warming of seawater may induce a relatively stronger stratification (i.e., pycnocline) at the surface mixed layer, which ultimately lower upward flux of major nutrients (Sarmiento et al. 1998). Nutrient depletion in the mixed layer of the UB resulted in a shift of phytoplankton size distribution from large diatoms to smaller flagellates, and consequently annual primary production has decreased ~17% (approximately 50 g C m⁻² year⁻¹) since 2006 (Joo et al. 2014). Since small phytoplankton have lower sinking rates than large phytoplankton (Legendre and Le Fèvre 1995; Winder and Sommer 2012; Siegel et al. 2014), a higher contribution of small phytoplankton can cause lower export production in the UB (Kim et al. 2017b).

In the Gyeonggi Bay of the Yellow Sea, due to the early winter warming, the spring diatom blooms observed in the 1990s moved forward to winter blooms in the 2000s (Jahan and Choi 2014). In addition, as the wind stress weakens in

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Fig. 1 Major research sites for Korean Long-Term Marine Research (K-LTMR) program around the Korean peninsula

winter, turbulent water mixing has decreased in this shallow coastal bay, and *Thalassiosira nordenskioeldii* (planktonic diatom) has become the only dominant species during winter blooms since 1998, while *Paralia sulcata* (tychopelagic or benthic diatom) was the most dominant species during 1981–1982 (Jahan et al. 2013). These climate-driven changes in the phytoplankton community may have cascading ecosystem effects, thereby affecting the composition, abundance, and community structures of the higher trophic levels in the EAMS (Joo et al. 2017; Jung et al. 2017).

As a result of the warmer SST, *Halophila nipponica* (seagrass), which is reported generally in warm temperate Japanese waters (Kuo et al. 2006), has been observed in the southern coastal waters of Korea (Kim et al. 2009; Kim et al. 2012; Kim et al. 2017a) where cold affinity *Zostera marina* is typically the dominant native seagrass species (Lee and Lee 2003; Lee et al. 2005). Similarly, recent appearance of the *Spartina* spp. (saltmarsh plant) in the intertidal sediments of the Yellow Sea where *Suaeda japonica* is the dominating native salt marsh plant (An et al. 2020) was largely ascribed to climate change-induced warming. Inhabitation of these invasive plants significantly modify the biogeochemical cycles of C, N, P, Fe, and S and microbial communities in the sediments (Kim et al. 2017a; An et al. 2020).

An enhanced anthropogenic carbon input is to be largely responsible for both $p\text{CO}_2$ increase and ocean acidification in the East Sea. During the period from 1995 to 2009, studies in the East Sea reported increasing $f\text{CO}_2$ in surface sea water ($2.7 \pm 1.1 \mu\text{atm year}^{-1}$) and pH levels (-0.03 ± 0.02 pH units per decade) that were higher than observations at most other ocean time-series sites during the same period (Kim et al.

2014b). Similarly, increasing anthropogenic N deposition was ascribed to the enhanced reactive N in the surface mixed layer of the EAMS (Kim et al. 2011; Kim et al. 2014a), implying an ecological transition from N-limited to P-limited condition.

Coastal wetlands protect coastal regions from storms and sea-level rise, transform organic matter, metals and nutrients, and provide nursery grounds that support commercial fisheries (Barbier et al. 2011; Kirwan and Megonigal 2013; Mok et al. 2019; Neubauer and Verhoeven 2019). Tidal marsh ecosystems are considered the most efficient natural organic carbon sinks on earth, and thus coastal reclamation to expand land use could result in increased emissions of greenhouse gases (CO_2 , CH_4 , and N_2O), which further affects local/global carbon cycles (Li et al. 2014; Ewers Lewis et al. 2019). Remote-sensing analysis along the Yellow Sea coastline, including China, North Korea, and South Korea, revealed that 28% of tidal flats existing in the 1980s had disappeared by the late 2000s (1.2% annually) (Murray et al. 2014). Yim et al. (2018) also reported that the area of tidal flats in the Yellow Sea had been reduced by 36% in the 2010s ($\sim 6670 \text{ km}^2$) compared with the 1980s ($\sim 10,500 \text{ km}^2$). The area of coastal reclamation in South Korea during this period was 2360 km^2 (Yim et al. 2018).

Large-scale coastal reclamation and land-use projects in South Korea were inevitably accompanied by the construction of enormous artificial seawalls, such as the Yeongsan River Dike (4.35 km long), Shihwa Dike (12.7 km long), and Saemangeum Dike (33.9 km long), which is the longest seawall in the world (Choi 2014; Yim et al. 2018). Construction of the dike in the Yeongsan River estuary led to a marked

increase in the tidal amplitude and a decrease in the current velocity (Kang 1999), which ultimately resulted in the accumulation of organic matter in the sediments near the dikes (Kim et al. 2017c; An et al. 2019). A similar situation associated with the massive accumulation of organic material on coastal sediment applies to the aquaculture activities in coastal environments (Dempster and Holmer 2009). Aquaculture production in Korea was ranked 7th among the world's top 25 aquaculture countries in 2014 (FAO 2018) and accounted for 62% of total seafood production (3.72 million tonnes) in 2017 (KOSIS 2018). In organic-rich coastal sediments, O_2 is rapidly depleted within a few millimeters depth of the surface sediment, and most organic carbon oxidation is carried out by anaerobic respiration processes, mostly by sulfate reduction due to high abundance of SO_4^{2-} in seawater (Canfield et al. 2005; Jørgensen 2006). Major environmental concerns associated with the dominance of organic carbon oxidation by sulfate reduction include the accumulation of highly toxic and reactive hydrogen sulfide (H_2S) (Holmer et al. 2005; Hyun et al. 2013; Kim et al. 2017c).

In the estuarine sediments near the Yeongsan River Dike, sulfate reduction accounted for 73% of organic carbon oxidation and was responsible for strikingly high concentrations of the H_2S (487 μM) in the pore water (Kim et al. 2017c). Similarly, sulfate reduction accounted for 48–99% (average 70%) of the total organic carbon oxidation in the sediment of an oyster farm (Hyun et al. 2013). The H_2S produced from the sulfate reduction reacts quickly with iron oxides to form iron sulfides, which ultimately releases the P bound to Fe(III) into the pore water, thereby enhancing the benthic P flux near the dike (An et al. 2019). Finally, the enhanced benthic nutrient flux may contribute to coastal eutrophication, which may stimulate primary production in the water column via benthic-pelagic coupling in shallow coastal ecosystems. Recently, Choi et al. (2020) estimated that the benthic nutrient release from fish farm sediment accounted for 52–837% and 926–1048%, respectively, of the N and P demand for phytoplankton production in the southern coast of Korea. Similarly, Kim et al. (2017c) also reported that the benthic nutrient flux at the sediment near the Yeongsan River Dike accounted for 200% of N and P, respectively, required for primary production in the water column.

The enhanced nutrient conditions (i.e., eutrophication) resulting from the anthropogenic activities in the coastal ecosystem are also responsible for the incidence of harmful algal blooms (HABs) that have been increasing continuously for decades around the world (Hallegraeff 1993; Heisler et al. 2008). In Korea, *Cochlodinium polykrikoides* is the dominant species causing major economic losses such as massive mortality of aquaculture and wild fishes or shellfishes (Lee et al. 2013). The economic loss by the *C. polykrikoides* bloom in Korea reached USD \$7 million in 1993, USD \$60 million in 1995, and ranged from 4 to USD \$19 million per year from

2000 to 2012 (see Shin et al. 2017). The eutrophication and resulting algal bloom make environmental conditions even worse by developing a hypoxia ($DO \leq 2 \text{ mg L}^{-1}$) that is responsible for the unexpected changes in biogeochemical element cycles and ecosystem structures (Conley et al. 2002, 2009; Diaz and Rosenberg 2008; Middelburg and Levin 2009; Rabalais et al. 2010). In Korea, intense anthropogenic activities such as reclamation, construction of artificial structures (i.e., dikes), and aquaculture activities, have been mostly responsible for the continuously growing incidence of coastal eutrophication and hypoxia (Lee and Kim 2008; Lim et al. 2012; Kim et al. 2015; see Lee et al. 2018).

Scope and Objectives of the K-LTMER

These climatic changes and anthropogenic activities have resulted in a series of interrelated environmental issues, which ultimately alter the ecological and biogeochemical processes of the estuarine and coastal ecosystems of Korea. Therefore, understanding the current status of ecosystem structure and elucidating cause–effect relationships to changes in major ecological and biogeochemical processes become imperative not only to evaluate/predict the ecosystem changes associated with climatic changes and anthropogenic activities, but also to provide relevant scientific information that should be considered by decision makers for maintenance of sustainable estuarine and coastal environments.

In this respect, the Korean Long-Term Marine Ecological Research (K-LTMER) program under the auspices of Korean Ministry of Oceans and Fisheries has been carrying out ecological and biogeochemical process studies for the last 10 years since 2010:

1. To obtain environmental baseline information including monitoring of indicator organisms and their physico-chemical controls under current status;
2. To diagnose/evaluate short-term response in ecological processes to the recent climatic regime shift in late 1990s and catastrophic anthropogenic events occurred in the last 10–20 years;
3. To predict long-term changes and response of marine ecosystems associated with large-scale anthropogenic activities and rapidly changing climatic conditions around the Korean peninsula.

Ecological monitoring studies on various indicator biological communities include prokaryotes, eukaryotic microplankton, macrofauna, seagrasses and fishes, and the measurements of physico-chemical and geochemical parameters that ultimately determine the shape and shift of the biological communities. Ecological and biogeochemical process studies include metabolic rate measurements such as phytoplankton

primary production, bacteria secondary production, microbial respiration, and benthic mineralization of organic matter coupled with functional analysis of biological communities using metagenomic and metatranscriptomic approaches. The study area was divided into four coastal regions that represent the unique environmental features around the Korean peninsula (Fig. 1b):

1. Estuarine and coastal waters in the Gwangyang Bay along the riverine–estuarine–coastal marine continuum in the southern part of the Korean peninsula;
2. Intertidal wetlands and coastal waters in the Garolim-Gyeonggi Bay in the eastern part of the Yellow Sea (i.e., western part of the Korean peninsula);
3. Subtropical coastal ecosystem in Jeju Island near the East China Sea; and,
4. Coastal upwelling ecosystem in the Ulleung Basin of the East Sea.

Overview of the Special Issue

Whereas another previous special issue of the K-LTMER mostly dealt with the current status of the East Sea in changing environmental conditions earlier (Lee et al. 2017), in this special issue, we present 16 papers that address a broad range of topics covered mostly in the estuarine and coastal ecosystems of the four major K-LTMER sites and the Yeongsan River estuary where a large artificial dike (i.e., Yeongsan River Dike) has exerted a profound impact on coastal and estuarine ecosystems (Kim et al. 2017c; An et al. 2019; Sin and Jeong 2019; Park et al. 2019b; Fig. 1).

The greater part of this special issue features ecological and biogeochemical baseline studies that will provide relevant information to evaluate and predict the variations of ecosystems in response to the long-term climate changes and anthropogenic impacts.

Qin et al. (2019) investigated the reproductive phenology and sexual reproduction of *Zostera marina* in two seagrass sites to elucidate the response of native cold affinity seagrass (*Z. marina*) to warming of seawater. They demonstrated that cold water upwelling in the east coast provided a relatively long period of optimal water temperature for production of *Z. marina*, leading to a prolonged flowering period and enhanced seed production. By contrast, high summer water temperature appeared to shorten the flowering period and reduce sexual reproduction of *Z. marina* in the south coast sites. Kim et al. (2019c) also found that the growth of *Z. marina* under anomalously elevated water temperature conditions was significantly declined, whereas the plant growth was maintained or slightly increased under suddenly decreased water temperature conditions. The results suggested that intensified sea

surface water temperature anomalies induced by global climate change will alter the growth and distribution of temperate seagrasses, thereby affecting the long-term stability and maintenance of seagrass meadows.

In contrast to the clear response of *Zostera* to warming (Kim et al. 2019c; Qin et al. 2019), Park et al. (2019e) found that the small SST difference between 20 and 25 °C in Jeju Island had no significant influence on reproductive physiology of *Alveopora japonica* and *Oulastrea crispata*, the two high-latitude corals. The results suggest that although recent expansion and explosion of the *A. japonica* population from the south into the north of the Island might be linked to the increase in SST in the East China Sea, this needs to be substantiated through long-term monitoring of patterns of coral reproduction and population dynamics. As a part of the environmental baseline study in the Jeju Island site, Kwon et al. (2018) elucidated that southern coastal waters (SCW) off Jeju were characterized by higher nutrients and humic-like fluorescent dissolved organic matter (FDOM_H), while those in the western coastal waters off Jeju (WCW) showed no trend. Based on a significant negative correlation of salinity against ²²²Rn activities, the main source of nutrients and FDOM_H is found to be from fresh groundwater in the SCW. However, depleted ²²²Rn activities in the fresh surface waters of the WCW indicate that those in the WCW originate mainly from the remote Changjiang diluted water. The results suggested that high nutrient concentrations in the SCW provide favorable conditions for the growth of seaweeds, while relatively low nutrient concentrations and high FDOM_H concentrations in the WCW provide favorable conditions for survival of corals.

Kim et al. (2019b), using a data from the C and N stable isotope analysis, conducted ecological baseline studies on the trophic links of macrobenthic food web in diverse wetland habitats along the riverine–estuarine–coastal marine continuum in low turbidity Gwangyang Bay. They revealed that *Phragmites*-derived organic matter contributed considerably to the nutrition in the estuarine channel, whereas microphytobenthos and *Zostera* provided trophic subsidies to the deep bay and offshore communities. On the other hand, Kwak and Cho (2019) revealed that mean residence time in Gwangyang Bay is more than 20 days in winter due to its large volume, but less than 5 days in summer due to increased gravitational circulation driven by large volumes of river discharge and a horizontal density gradient. Both results of Kim et al. (2019b) and Kwan and Cho (2019) imply that food web structure of the benthic macrofauna in the Gwangyang Bay is susceptible to anthropogenic activity-induced topographic changes in the future. Kwak and Cho (2019) additionally reported that the mean residence time of Jinju Bay is less than 5 days in winter and summer due to its small volume and shallow depth, suggesting that the Jinju Bay is likely to remain free from anthropogenic eutrophication

caused by nutrient inputs from aquaculture throughout the year. As a part of physical oceanographic baseline study, Cho et al. (2019) further measured the circulation pattern of the Sumjin River estuary in the Gwangyang Bay to evaluate the net exchange potential of material in the estuary. They elucidated that the most important factor affecting exchange flow is the horizontal salinity gradient which increases up to 7 times during the spring tide compared with the neap tide. Finally, Kim et al. (2019a) investigated phytoplankton primary production, heterotrophic bacterial production and respiration to evaluate the changes in ecological processes in response to the recent climatic regime shift in late 1990s in Gyeonggi Bay (GB). In comparison with the early 1990s, they found that warming in GB intensified the carbon flux through the microbial loop, which may reduce the efficiency of energy transfer to higher trophic levels.

In addition to the papers providing ecological and environmental baseline information, from the four K-LTMER sites, we invited additional papers dealing with the environmental impacts of large-scale artificial dike in the Yeongsan River estuary (Fig. 1b) and Shihwa Dike in the Gyeonggi Bay (Sin and Jeong 2019; Park et al. 2019b; Kim and Kim 2018), benthic biogeochemistry associated with finfish and shellfish aquaculture (Kim et al. 2019d), and recovery of Manila clam from the catastrophic oil spill off western part of Korea (Park et al. 2019a).

Sin and Jeong (2019) explored semidiurnal and fortnight tidal variations of phytoplankton community (size and taxonomic groups) in the macrotidal Yeongsan River estuary that receives freshwater regulated by the Yeongsan River Dike. Their results revealed that taxonomic variation is associated with freshwater discharge and was explained principally by water temperature and salinity, rather than tidal height. The results imply that episodic anthropogenic freshwater discharge events disturb predictable macrotidal effects on water column processes, thereby enhancing the ecological complexity of estuaries. Tidal interactions with regulated freshwater discharge into estuaries would provide fundamental information on the dynamics of phytoplankton in estuarine ecosystems that are affected by the artificial dikes. Park et al. (2019b) also investigated the modification of carbon flow by a dike construction in estuarine system by making comparisons of the $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of subtidal macrobenthic consumers in the Yeongsan River estuary affected by the Yeongsan River Dike and the Gwangyang Bay without a dike. They found that the consumer $\delta^{13}\text{C}$ values recorded non-significant spatial differences among sites in the diked estuary, and the isotopic niche widths were much narrower than those in the dike-free estuary. Moreover, the indices of community-wide metrics were smaller in the diked estuary than in the dike-free estuary. These comparisons provide evidence that dike construction and subsequent alteration of hydrologic and circulation processes may lead to

modification of the trophic structure of estuarine macrobenthic communities.

Kim and Kim (2018) measured the fluorescence intensity of humic-like fluorescent dissolved organic matter (FDOM_H) in brackish Lake Shihwa, the impounded water by the Shihwa Dike. Based on the significantly positive relationship between the fluorescent intensity of FDOM_H and nutrients (NH_4^+ and PO_4^{3-}) together with the low DO level, they concluded that the enhanced FDOM_H is released from the anoxic pore water of the sediment. The results indicate that the contribution of FDOM_H from reducing environments is comparable with that from stream water that is known to be a major source in coastal regions.

Kim et al. (2019d), using an in situ benthic chamber, measured sediment oxygen demand (SOD) and benthic nutrient fluxes to assess the impact of finfish and shellfish (oyster) aquaculture on coastal ecosystems. They consistently found that the SODs at the finfish and oyster farm were more than twice those of the control site. The benthic fluxes of ammonium and phosphate at the finfish and oyster farm were up to 10 times and 7 times, respectively, higher than those of the control site. The results confirm previous reports that the discharge of organic matter from both the commercial finfish and oyster farms enhanced benthic metabolism, locally altering the cycling of organic matter and nutrients in the coastal environments (Hyun et al. 2013; Choi et al. 2020).

Park et al. (2019a) addressed the impact of the Hebei Spirit oil spill, that spread 40 km to the northeast and 50 km to the southeast from the collision spot, 10 km off Taean in the west coast of Korea, on the phenology of Manila clam (*Ruditapes philippinarum*). Eighteen months after the oil spill, no clear seasonal fluctuations were detected in the biometric components of the clams at the oil-damaged beach, compared with the pronounced seasonal dynamics at the undamaged beach. However, the lack of energy reserves in the clams in the damaged area likely resulted in a failure of gametogenic development because the gross egg weight was much higher at the control than at the damaged site during June–July, emphasizing a 1-month lag in the major spawning pulse at the damaged site. The results suggest that the oil spill may interfere with the clam phenology at Malipo Beach within 2–3 years after the incident.

Finally, the remaining three papers address the dynamics of fish communities in the east coast (Park et al. 2019f) and short-term and long-term variations in phytoplankton distribution using satellite images in the East Sea (Park et al. 2019c, d).

Park et al. (2019f), based on the community composition and stable carbon and nitrogen isotope ratios, reported the temporal variability in the trophic structure of a fish community and the trophic levels of dominant fish species off the eastern coast of Korea. Major findings were that (1) fish assemblages were mainly dominated by resident benthic and

benthopelagic fish, (2) resident species showed no seasonal differences in their isotopic signatures, whereas pelagic species showed temporal variability in $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values, and (3) the isotopic niche of fish assemblages showed distinctly different patterns between spring–summer and winter–fall with the seasonal changes in the fish community. These patterns might be associated with seasonal variation in fish communities affected by seasonal changes in environmental conditions (e.g., hydrographic parameters and food availability). Park et al. (2019c) produced level-3 chlorophyll-a (chl-a) monthly map in the East Sea from 2003 to 2015. They found a strong contrast in spatial amplitude between the eastern and western areas of the East Sea in March or April, and prominently strong variability in the eastern area along the Japanese coast. The annual peak appeared mainly in March recently, which is 1 month earlier than in the past. The spring bloom of chl-a preferred strong wind as precondition in the early spring. Increasing long-term trend of chl-a concentration had positive relation with shoaling upper layer affected by global warming. Park et al. (2019d) also presented short-term biological responses to sea surface wind field over mesoscale eddies using GOCI (Geostationary Ocean Color Imager) chl-a concentration in the East Sea. In this study, wind field modification over the warm eddies was observed and Ekman pumping (EKP) velocity field was derived from the scatterometer wind data. Their results demonstrated that the biological response to the eddy-/wind-induced EKP arouses very quickly on an hourly base. They also revealed that the SST-induced EKP played a significant role in total EKP by air–sea interaction because of a subpolar front in the central East Sea over the anticyclonic eddies.

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