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The Northward Habitat Expansion of the Korean Top Shell *Turbo sazae* (Gastropoda: Vetigastropoda: Turbinidae) in the Korean Peninsula: Effects of Increasing Water Temperature

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Abstract: Recent global climate change often leads to poleward expansions of habitat range of marine organisms in response to increasing water temperature at high latitude. This study investigated latitudinal distribution patterns of *Turbo sazae* from 2009 to 2018 along the southern and eastern coasts of Korea to verify whether gradual increases in seawater temperature in the East Sea/Sea of Japan (hereafter East/Japan Sea) accelerate changes in the geographic distribution of *T. sazae*. Between 2009 and 2018, underwater SCUBA surveys were conducted at 19 subtidal rocky shore habitats from the southern and eastern coast of the Korean Peninsula, including Jeju Island. Additionally, long-term seawater temperature records over the last 40 years (between 1980s and 2010s) from the East/Japan Sea were analyzed to verify how changes of water temperature corresponded to geographical distributions of *T. sazae*. The habitat range of *T. sazae* was found to have extended from latitude 34°02' N to latitude 37°06' N from 2009 to 2018. Although seawater temperature has gradually increased since the 1990s in the East/Japan Sea, habitat expansion was particularly evident during the rapid rise of coastal seawater temperature in the 2010s. Because the strong northward expansion of the Tsushima Current can accelerate the rise of seawater temperature in the East/Japan Sea, studies of the effects of climate change on marine ecosystems of the Korean Peninsula should include data from monitoring the dynamics of the Tsushima Current.

Keywords: *Turbo sazae*; marine benthos; habitat expansion; biogeography; climate change; East/Japan Sea; Tsushima current

1. Introduction

Since the mid-1970s, awareness of global climate change has increased, especially the impact of worldwide increase in seawater temperatures on ecological functions of marine species [1–3]. Increase in water temperature strongly influences the distribution of marine organisms, causing range

expansions or contractions, as well as local extinctions [4–6]. Understanding the dynamics of changes in geographic range are fundamental for biogeography and defining ecological niche [7]. Among various physicochemical factors influencing spatial distributing of marine organisms, water temperature is the most critical in determining such changes [8–11].

Shifts in the distribution of marine organisms, mediated by climate change, have been well established, especially in the Northern hemisphere [12–17]. Such shifts have been mostly in the form of poleward expansion in response to ocean warming throughout marine ecosystem globally [18–24]. Mieszkowska et al. reported that southern trochid gastropod *Phorcus lineatus* has shown shift in biogeographic distribution along a latitudinal gradient from low towards high latitude regions with synchronous increasing in abundance throughout several decades in Northern Ireland, North Wales and English Channel. The gastropod *P. sauciatus* has been newly colonized at northern shore habitats, along the north-west Iberian Peninsula, in relation to increasing sea surface temperature [25]. Expansions and contractions of species are common in both marine and terrestrial systems, yet are challenging to test [26,27]. Species' shifts in distribution, however, are likely strongly influenced by abiotic factors, especially water temperature, in conjunction with biotic causes, such as interactions among sympatric species [5,28].

The seas around the Korean Peninsula are some of the most vulnerable to climate change, as they currently show a rapid increase in seawater temperature [29]. Because Korean marine ecosystems extend from sub-tropical to sub-arctic zones, a variety of marine organisms have likely shifted their geographical distribution poleward in that country due to the recent global climate changes [30]. In particular, during the past half century, increases of nearly 1.7°C in mean water temperature have been reported in the East/Japan Sea, 1.4°C in the Korea Strait and 0.3°C in the Yellow Sea [31]. These increases were especially distinct during winter in the East/Japan sea [32]. Thus, biological and ecological responses of marine organisms are expected to be substantial among marine ecosystems in Korea.

The Korean top shell (*Turbo sazae*, Trochidae, H. Fukuda, 2017) is a sub-tropical marine gastropod inhabiting rocky subtidal habitats of water temperature ranging from 20 to 25 °C, occurring along the Kuroshio–Tsushima current regions of the northwestern Pacific [23,33–35]. *Turbo sazae* has long been included as *Turbo cornutus* (Lightfoot, 1786). Fukuda [36] recently observed that *T. cornutus* should be restricted to the species endemic to southern China and Taiwan, while the Japanese/Korean *Turbo* should be a new species, *T. sazae* (H. Pukuda, 2017 nom. nov.) Historically, the distribution of *T. sazae* in Korean waters was restricted mainly to the Jeju coast and secondarily to the Busan coast [37]. Recent oceanographic changes from shifts in climate, however, may have triggered a distributional shift, as also shown by a majority of warm water species inhabiting temperate seas elsewhere. Most studies have been focusing on Atlantic and tropical marine species, but only a few studies have documented marine species inhabiting the northwestern Pacific [38].

In studies on distribution patterns of marine organisms in relation to global climate change it is primarily assumed that, (1) the species is easily detectable in the water column, (2) the range of expansion is relatively small during a generation and (3) the distributions are consistently poleward, due to a global warming effect [19,20]. Second, assumptions for marine organisms may include, (1) the range of study area connected by one oceanic current, (2) there is no anthropogenic interference on distribution and (3) distributions occur within obviously detectable spatial ranges (generally within a latitude of 5°).

The purpose of this study was to access the poleward habitat expansion of *T. sazae* due to climate change, after observation of successful settlement in the temperate waters of the East/Japan Sea. Our specific objectives were grounded on: (1) the water temperature in the East/Japan Sea has gradually increased in parallel with recent climate change observations [31]; (2) the habitats of *T. sazae* are exposed to the Tsushima oceanic current transporting marine organisms from Jeju Island, Korea, to the East/Japan Sea [39]; and (3) *T. sazae* have a great potential for colonization of new habitats, due to dispersal of their planktonic larvae [40]. To support our objectives, this study analyzed occurrence

patterns from long-term surveys of *T. sazae* throughout subtidal habitats in various locations along the path of the Tsushima Current.

2. Materials and Methods

2.1. Data Collection

The presence/absence data on the latitudinal position of *T. sazae* was collected from the surveys conducted during spring (May) and summer (August) from 2009 to 2018 (excluding 2011, 2013 and 2014). The occurrence of *T. sazae* was recorded at rocky subtidal habitats from 19 stations from SCUBA dives between Jeju Island and the middle eastern coast of Korea (Figure 1). Two or three divers moved in a zigzag pattern at 0.5 to 1 m above the bottom (depth between 3 and 20 m depending on depths of study stations), recorded appearances of *T. sazae* on a plate, took photographs and collected some individuals for wet laboratory analyses. Diving time per single observation was approximately 30 min and the survey area at each station covered ca. 90 m². If three or more specimens of *T. sazae* were recorded in each survey occasion, it was regarded as an established settlement for the species. Individuals that could be misidentified due to their uncommon appearance were closely looked, especially at their appressorium shapes. The results of two surveys per year were aggregated to reflect occurrence by year (Table 1). Because *T. sazae* has been reported from a number of previous works at Jeju Island, observations reported in this study served only the purpose of confirming the ability of detecting that organism employing the methods herein.

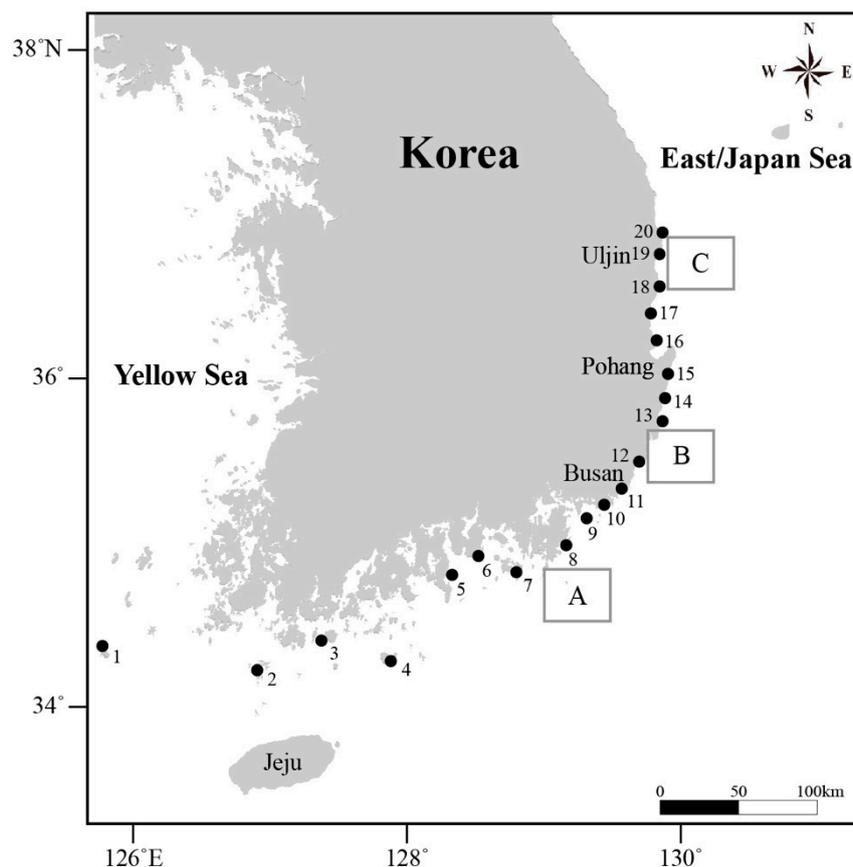


Figure 1. Study stations confirming occurrence of *Turbo sazae* with SCUBA observations (numbers and black dots), and long-term water temperature monitoring areas (gray boxed regions); regions were the southeastern coast of southern sea (A), and southern coast (B) and middle coast (C) of the East/Japan Sea.

Table 1. Station number and name, and occurrences of *Turbo sazae* recorded at each station between 2009 and 2018. Station numbering within the study area increase with their northward location.

Station		Year						
No.	Name	2009	2010	2012	2015	2016	2017	2018
1	Gageodo	•			•		•	
2	Chujado				•		•	•
3	Cheongsando			•	•		•	
4	Geomundo				•		•	
5	Geumodo							•
6	Mijodo					•		
7	Maemuldo					•		•
8	Jisimdo					•		•
9	Namuseom		•					•
10	Dongseom					•		•
11	Moondong					•		•
12	Jeongjadong			•				
13	Oryu					•	•	•
14	Samjeong			•				
15	Bangeo					•		•
16	Chuksan					•		•
17	Geoil						•	•
18	Jukbyeon					•		•
19	Nagok							•

2.2. Seawater Temperature

Coastal water temperature in the Korean Peninsula has been continuously analyzed by the OSTIA (Operational Sea Surface Temperature and Sea Ice Analysis) since 1985 [41]. OSTIA provides daily global scale of sea surface temperature and sea ice data in 0.05° lattice, which is reanalyzed for public consumption from field observation of ICOADS (International Comprehensive Ocean-Atmosphere Data Set; Worley et al., 2005), AVHRR (Advanced Very High Resolution Radiometer) data (<http://www.nodc.noaa.gov/SatelliteData/>), and ATSR (Along-track Scanning Radiometer) data (<http://neodc.nerc.ac.uk/>). The data from OSTIA between 1985 and 2018 have been used in this study to verify spatial and temporal patterns of sea surface temperature.

Because *T. sazae* mainly inhabits depths around 10 m [42], deeper isobath temperatures were obtained from field observations gathered by the National Institute of Fisheries Science and provided by the KODC (Korea Oceanography Data Center). Isobath data were used to confirm that long-term sea surface temperature changes reflected temperature changes at deeper depths, where the target species occurred. The relationships between sea surface temperatures and temperatures at the 10 m isobath were analyzed seasonally by region (Figure 1) for each decade from 1985 to 2018, represented as 1980s, 1990s, 2000s and 2010s. The trends of seawater temperature were summarized over four seasons, i.e., winter (January–March), spring (April–June), summer (July–September) and autumn (October–December), according to general seasonal classification in Korean seas [43].

Due to heteroschedasticity of water temperature data, non-parametric tests were chosen for analysis of temperature variation. The latitudinal variations of the 12 °C isothermal line in winter and the 22 °C isothermal line in summer were analyzed, because those temperature lines were typical isothermal lines showing considerable latitudinal fluctuations within the East/Japan Sea in each season. A Kruskal–Wallis (K–W) test was used to examine the effects of shifts in the mean latitudinal position of each 12 °C and the 22 °C isothermal line over four decades. Decade was considered a fixed factor and mean latitude was a continuous variable. The values for the isothermal lines were chosen based on characteristic seasonal sea surface temperatures for the study region. The 12 °C/winter and 22 °C/summer combination was used as the categorical factors for the analysis. If the K–W test revealed a significant difference between the four decades, the Mann–Whitney U test with a Bonferroni

adjustment was subsequently used to assess which pairs were responsible for the difference [44]. A significance level of 0.05 was used for K–W tests and 0.0083 (0.05/6 pair-wise groups) for Bonferroni pair-wise comparisons. Data exploration and analyses were carried out using SYSTAT software (Systat version 18. SPSS Inc., USA).

3. Results

3.1. Occurrence and Geographical Distribution of Turbo Sazae

The spatial occurrence patterns of *T. sazae* at 19 stations (except Jeju area) were different among years (Table 1, Figure 2). During the first survey in 2009, *T. sazae* occurred only at station 1, with their northern distribution boundary at 34°02' N. As soon as next year, the distribution expanded 104 km poleward reaching the Busan Coast (station 9, 34°58' N). During both years, the occurrence of *T. sazae* continued to be recorded around the Jeju Coast. In 2012, the distribution pushed northward to 36°00' N (station 14). Following that year, the northern limit of *T. sazae* gradually extended to the Uljin Coast (station 18, 37°02' N) until 2016, summing a linear distance of 116 km poleward since 2012. Since 2016, new occurrences of *T. sazae* were recorded at the northernmost stations of this study (station between 15 and 19). In total, northward expansion of *T. sazae* during this study was of 3°04' latitude, 342 km (Table 1, Figure 2).

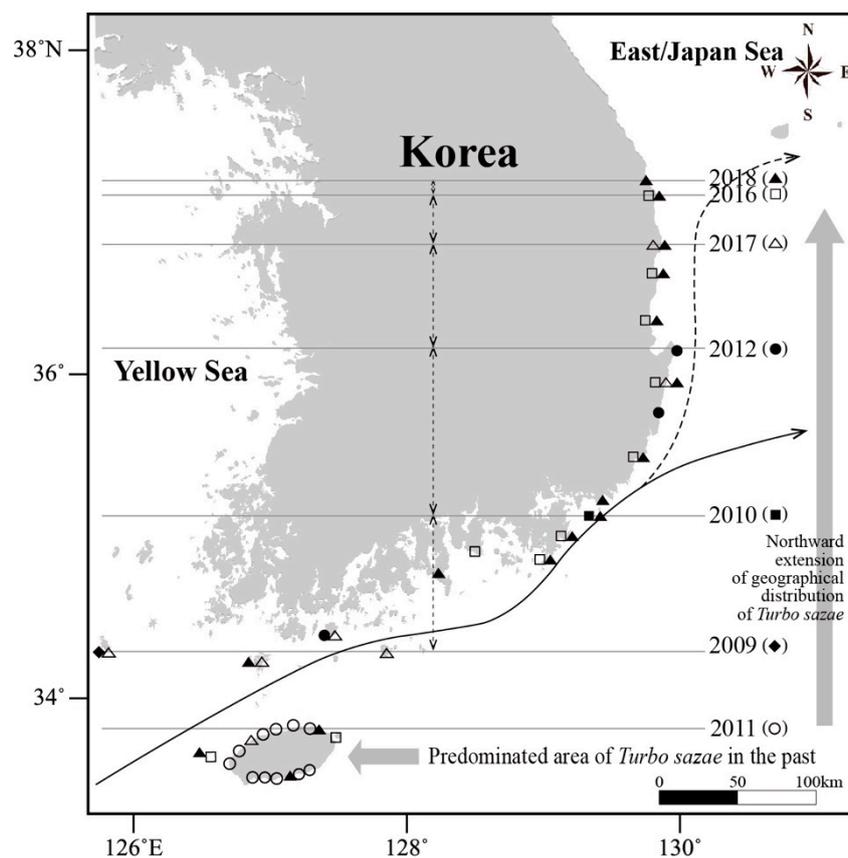


Figure 2. Spatial and temporal variations in occurrence of *Turbo sazae* from 2009 to 2018 (◆, 2009; ■, 2010; ○, 2011; ●, 2012; □, 2016; △, 2017; ▲, 2018) in the southern and eastern coasts of Korea; solid and dotted lines represent two northward main paths of Tsushima warm currents to the East/Japan Sea, and the vertical gray arrow indicates direction of habitat expansion.

3.2. Variations of Seawater Temperatures

Correlation analysis between water temperature of sea surface and that of 10 m deep showed significant relationships in winter, spring and autumn across each four decades at all three regions ($R^2 > 0.9$, $p < 0.05$; Figure 3), indicating strong tracing between sea surface temperature and temperatures at the 10 m bathocline for the study area. Correlation analysis for the summer were significant at the Southern (Region B, $R^2 = 0.45$, $p < 0.05$) and Middle coasts (Region C, $R^2 = 0.72$, $p < 0.05$) of the East/Japan Sea, but not at southeastern region of southern sea (Region A).

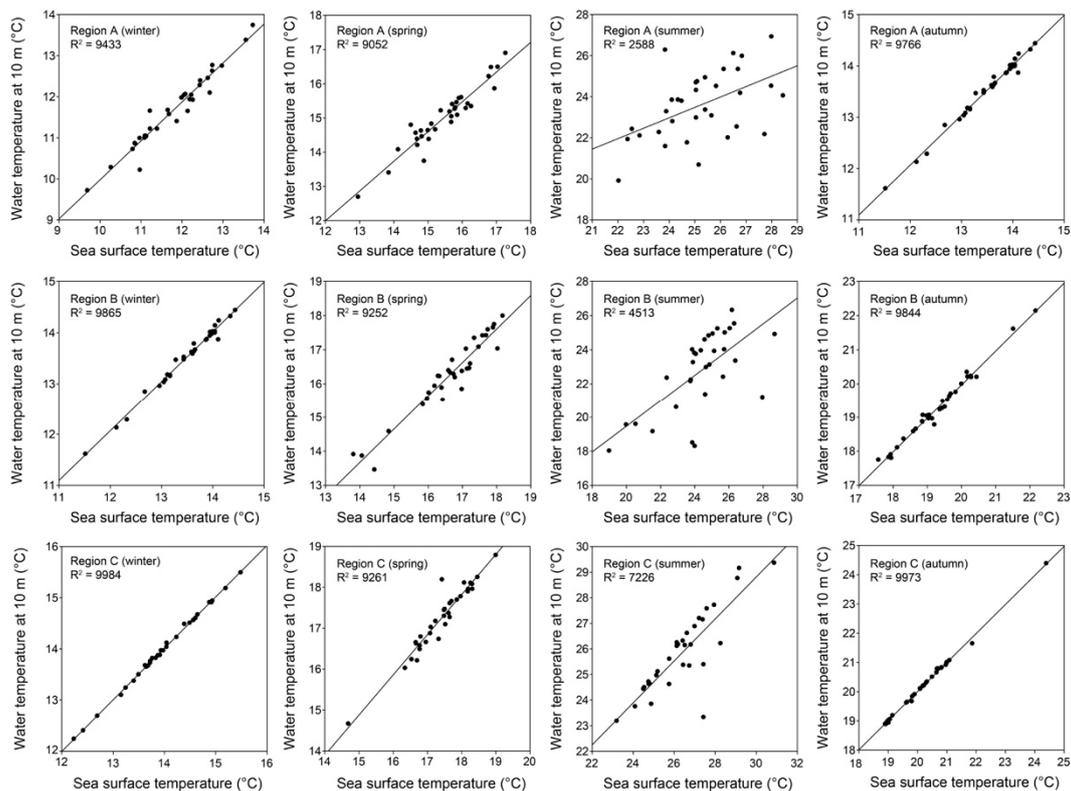


Figure 3. Correlations of water temperature between the surface and the 10 m isobath (°C); all relationships are statistically significant at $p < 0.05$, except Region A during summer.

Sea surface mean water temperatures tended to gradually increase in Korean seas with time, displaying poleward shifts of isothermal lines (Figure 4). Although the 12 °C isothermal line varied slightly in position from 1980s to 2010s during the winter, the lines were diagonal southwest to northeast between 34° N and 36° N regardless of decades. While the 22 °C isothermal lines during the summer showed distinct inter-decadal trends in its latitudinal position, gradually moving northward from 39° N in 1980s to beyond 40° N in 2010s at the East/Japan Sea (Figure 4).

Latitudinal shifts for the 22 °C isothermal line during summer were significantly different among the four decades (Kruskall–Wallis: $H = 65.214$, $df = 3$, $p < 0.05$; Figure 5). The Mann–Whitney U tests with the Bonferroni correction for multiple comparisons showed that there were no significant differences in mean position between the 1980 and 1990 decades, and between the 1990 and 2000 decades ($p > 0.05$). Mean position was different between comparisons of 2010s versus other decades ($p < 0.05$), showing that 2010 had an unusually high shift in the 22 °C isothermal line during the summer for the study area. No significant differences were observed for the 12 °C isothermal positions in the winter among decades (Kruskall–Wallis: $H = 0.272$, $df = 3$, $p > 0.05$).

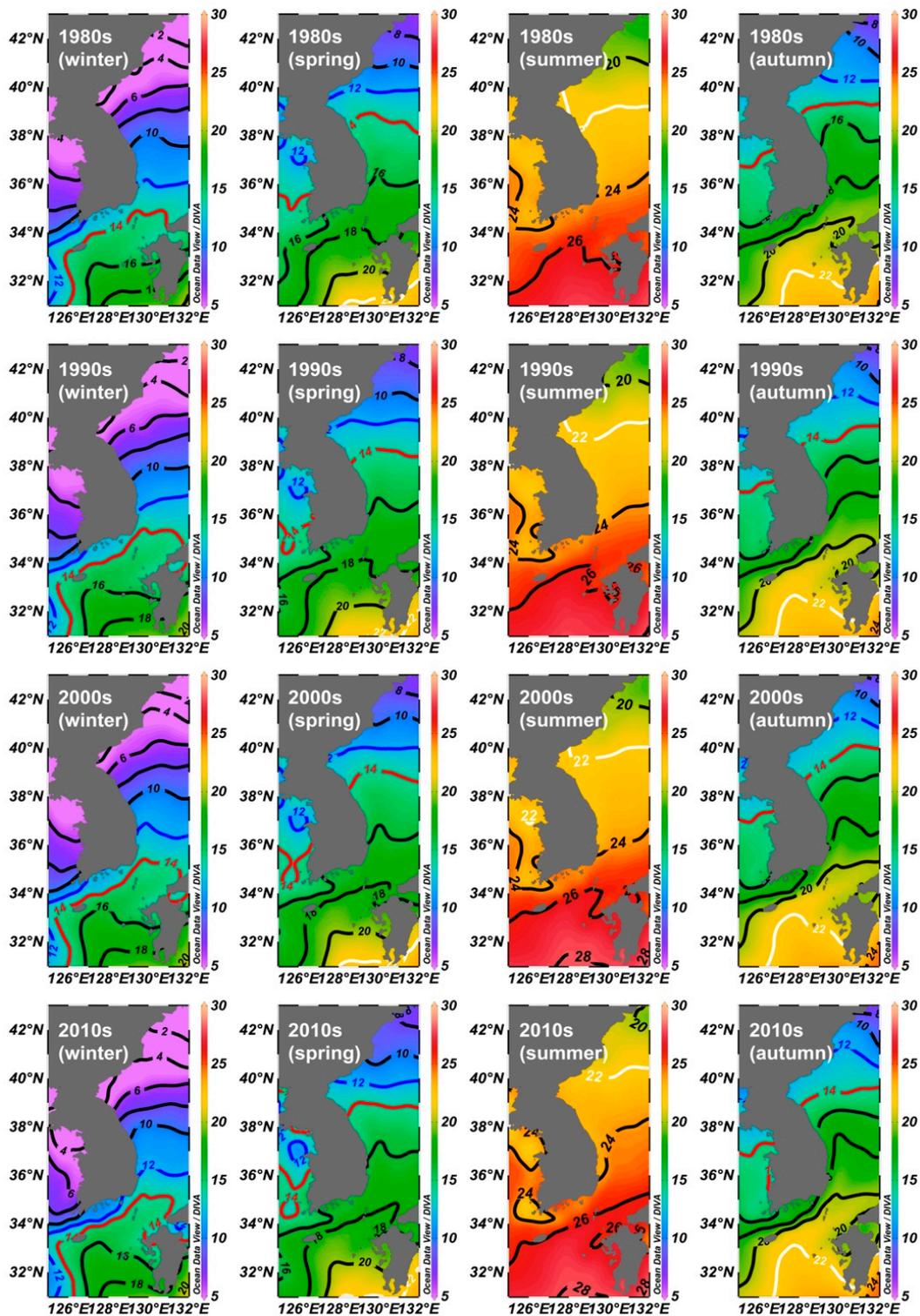


Figure 4. Horizontal distribution of sea surface water temperature around the Korea Peninsula from 1985 to 2018, averaged over decades; numbers and colors on the right of graph are sea surface water temperature (°C); axes are geographical coordinates.

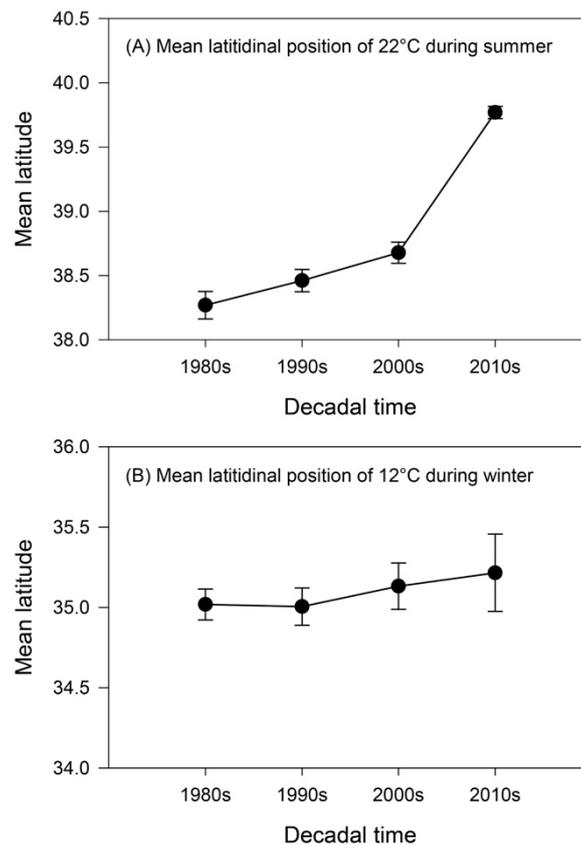


Figure 5. Decadal changes in mean latitudinal position of 22 °C isothermal lines during summer and 12 °C isothermal lines during winter from the 1980 to the 2010 decades; bars indicate standard deviations.

4. Discussion

Recent global climate change has resulted in dramatic shifts in geographic distributions of tropical species into temperate waters [7]. Poleward expansions of distribution ranges for marine organisms have been observed for many marine flora and fauna, including seaweeds [45,46], zooplanktons [47,48], intertidal invertebrates [49–51], corals [52,53] and fishes [19,54]. Within gastropods, northward expansions of *Gibbula umbilicalis* in the Atlantic Ocean have been observed to be as much as 85 km, coupled with extended spawning periods, in response to long-term increases in seawater temperature [55]. Although changes in species distributions (both, expansions and contractions) occur naturally [26], it recently became more apparent and significant due to the acceleration of climate change and anthropogenic effects [56–58].

Water temperature in the southern and eastern seas of the Korean Peninsula show distinct seasonal patterns, with strong inter-annual trends [3,59]. Such temperature patterns are primarily affected by warm water masses from the East China Sea [3]. Long-term variation in seawater temperature is the greatest at the surface, with decreasing effects with depth [60]. Despite this effect, water temperature at the preferred depth of *T. sazae* (10 m) closely follows the trends observed at the surface. It is also worth mentioning that the depth of the mixed layer within the study area varied with season, becoming deeper during the winter and more superficial during the summer. The mixed layer, however, never intruded on depth less than 10 m [61], making sea surface temperatures in the study area a viable surrogate for reflecting temperatures at the depth of *T. sazae* habitats.

Turbo sazae is a warm water species, mainly distributed in coastal habitats (mainly algal beds with hard substrate) along the Kuroshio-Tsushima current system [37,42]. The Tsushima Current branches off the Kuroshio Current as it enters the East/Japan Sea through the Korea Strait. The Tsushima Current has a substantial influence on the several marine ecosystems along its path [62]. The influence of

the Tsushima Current on coastal marine ecosystem of Korea has gradually increased, mostly due to increases in water temperature [63] particularly evident in the East/Japan Sea, as compared with the adjacent southern seas and Yellow Sea [64,65]. The recent poleward expansion of *T. sazae* occurrence, as well as those observed for the majority of Korean warm water fishes, may be linked to the evident northward extension of the Tsushima warm current into the East/Japan Sea [30]. Further evidence of the Tsushima Current northward expansion was provided by the analysis above for the isothermal lines. Both, the 12 °C isothermal line during the winter and the 22 °C during the summer have moved north since the 1990s, possibly facilitating the distributional shift of *T. sazae*. Such sustained long-term changes of the physical environment have had observable effects on changes in habitat locations, including spawning and fishing grounds of major fisheries resources [66,67]. Because of the greater extent of water temperature increases in Korean seas influenced by the Tsushima Current relative to other seas worldwide [29], distributional shifts and expansions of Korean marine organisms may accelerate in near future. Therefore, future detailed monitoring of organism occurrences and water temperatures are required for detection and mitigation of climate change impacts on marine ecosystems.

When warm water marine benthos are introduced in or invade a colder habitat, the species needs to acclimate to colder temperatures during their ontogeny. Such process, however, may require considerable time [68], keeping distribution shifts from occurring in shorter periods (within one or two years). The northern range limit of *T. sazae* was at 35° N in 2010, but expanded beyond the 37° N line in 2016, a 124 km northward expansion during only six years. Given the maximum recorded speed of the Tsushima Current (42.3 km/d), in theory transportation of *T. sazae* larvae from Jeju island to the northmost site in this study (500 km) would be 11.8 days. The successful settlement of *T. sazae* at northmost site, however, did not occur until approximately 10 years. Two factors may, therefore, be at play in the observed expansion of *T. sazae* habitat in the study area. One may conclude that adequate temperatures for adult survival may not have occurred until later years or that larval mortality in earlier years might have precluded early settlement [69]. Meso-scale distributional shifts of marine organisms are not limited to *T. sazae*, but also observed in various marine benthos worldwide. The Atlantic gastropod *Gibbula umbilicalis* extended its distribution 141 km northward over the past 20 years, with an estimated additional 243 km northward to be observed in the near future [70]. This study, therefore, may serve as an additional warning for the strength of impacts stemming from global climate change.

The stress to marine species from temperature changes is greater for larvae or juveniles than for adults (e.g. [71] in *Uca* sp.). *Turbo sazae* is warm-season spawning gastropod and their larvae hatch out under the temperature range between 20 and 25 °C [33,35] in which correspond with recent pattern of sea surface temperature in the southern and eastern waters of Korea. In addition, Kim [72] suggested that the growth rate of juvenile *T. sazae* was higher under heated seawater (24±0.5 °C) than in natural coastal water temperature (13 to 18 °C) of Jeju island, Korea. Therefore, the recent trend of seawater temperature, especially during summer is probably favorable for their northward spawning and early survivals of juveniles. Successful settling requires that recruitment to younger stages should exceed mortalities during those stages, allowing the populations to increase and become established [6]. Mieszkowska et al. [17] reported the range limits of *Osilinus lineatus* inhabiting the coastal sea in Britain extended up to 55 km northward between the 1980s and 2000s, suggesting increased recruitment success of their larvae to the new habitat. Although geographical extension of the species' distribution is dependent on recruitment successes [17], settlement of planktonic larvae is critical for sessile species and closely linked to favorable environmental conditions, especially temperature. If larval dispersal is not hindered by physical conditions, such as barring oceanic fronts or sub-optimal temporary temperature changes, habitat expansion will correspond to changes of sea and air temperatures, allowing populations to establish in new habitats [6].

Another possible factor facilitating the expansion of habitat, particularly for *T. sazae*, is the presence of stopover habitats. Since successful colonization of marine organisms at new habitats occur over a period of time (e.g. decadal time scale), several habitats may play critical roles as "stepping stones" providing favorable environmental conditions in a limited space. Such habitats may include

locations of thermal discharge from nuclear power plants or any anthropogenic activity leading to localized warm water habitats. Stepping stone marine habitats often harbor several sub-tropical marine organisms which are absent or scarce in colder, temperate habitats of the East/Japan Sea [73]. East/Japan Sea stepping-stone habitats may reach temperatures of over 4 °C higher than adjacent unaffected areas [73,74]. Planktonic larvae of *T. sazae* may occasionally get entrained around thermal discharging area during their northward transportation by the Tsushima Current, forming new communities, which in turn are a source for larvae moving poleward. The mechanism operation within the influence of thermal discharges, however, needs further investigation as to the dynamics of settlement and population development of *T. sazae*. As settling of *T. sazae* larvae is influenced by the coralline algae *Marginisporum crassissima* on the hard bottoms [75], it's role in population establishment needs further investigation, especially because of the scarce abundance of the algae in the East/Japan Sea [76–78].

Changes in organism distribution may be categorized as “range shift” [13] or “range extension or expansion” [17]. Because of the historical occurrence of *T. sazae* in Jeju Island [33] (2018, M.H.Son personal observation) and the recent distributional extension from Jeju Island to the northmost station of this study, the latter type of distribution change is a more adequate pattern for *T. sazae*.

This study assessed the effects of recent increases in water temperature in Korean seas have led to changes of geographical distribution of *T. sazae* during the 10 years following SCUBA surveys in conjunction with long-term records of water temperature. Results from this study revealed that the distributional range of *T. sazae* was mainly concentrated to the water adjacent Jeju Island and Busan (~35° N) at the end of 2000s and expanded to 37°06' N ten years later (see Figure 2). The observed distributional range expansion strongly parallels the northern shifts of both, the 12 °C and the 22 °C isothermal lines during the recent past. This study, therefore, showed the intimate relationship of the Tsushima Current in determining shifts in habitats of *T. sazae*. The influence of this current in determining expansions and shifts of habitats for other ecologically and economically important marine species should, therefore, not be diminished and strongly considered in further studies.

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