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Spatial variability in oceanographic conditions of sea waters off Korea in relation to the regional climate changes during the past 40 years

Sukgeun Jung, Young Shil Kang, Young-Sang Suh, Joon-Yong Yang, Jinyeong Kim, and Yeong Gong

National Fisheries Research & Development Institute, 408-1 Sirang-ri, Gijang-eup, Gijang-gun, Busan, 619-902, South Korea, E-mail: sukgeun.jung@gmail.com, Telephone: 82-52-720-2293, Fax: 82-52-720-2277

ABSTRACT

We describe temperature changes in both of the land and ocean at a local scale to suggest that human factors could drive warming influences on coastal waters, impacting marine ecosystems and changing dominant species in fishery catches. Spatially-explicit analyses, based on available meteorological and oceanographic data from 1968 to 2005, suggested that industrialization processes in South Korea and related global, anthropogenic factors have apparently increased land surface temperatures by 1.267^{o}C during the past 37 years, at least for the urban areas, and consequently coastal sea surface temperatures have increased by 0.975^{o}C. However, the increasing trend of the sea water temperatures diminished with waters depths (0-100 m). The estimated linear trend of air temperature in South Korea is 2.6 times higher than the linear warming trend of 0.013^{o}C per yr^{-1} for the past 50 years reported by the IPCC(IPCC, 2007). Together with anthropogenic and natural climate-driven regime shifts at global scale, rapid industrialization in South Korea could have been driving warming influences on coastal sea waters, changing oceanographic conditions and marine ecosystems. We suggest that future ecosystem and fishery management plans should accommodate and prepare for such long-term climate changes.

INTRODUCTION

Recently, the Intergovernmental Panel on Climate Change (IPCC) reported that evidence for the warming of the climate system is unequivocal(IPCC, 2007). The report noted that the ocean has been absorbing more than 80% of the heat added to the climate system, suggesting impact of global warming on marine ecosystems around the world. However, detailed land-ocean interactions with respect to climate change at regional scale still remain unclear (Schiermeier, 2007). South Korea had the fastest growing economy in the world's history during mid and late 20th century, making it interesting to compare the human-driven regional climate change with the global trends recently reported by the IPCC.

The land mass of Korea covers 220,843 km^2, and extends ca. 1,000 km north-south (Fig. 1), and the population density is high (480 km^{-2} in 2005). The Korean peninsula falls entirely within the temperate zone and the climate is continental. The peninsula is surrounded by the three geomorphologically and ecologically distinctive seas, i.e., the East, West and South Sea. The East Sea of Korea is a deep basin (the maximum depth = 4,049 m) whereas the Yellow Sea, or the West Sea of Korea, is a shallow (the mean depth = 44 m), semi-enclosed shelf sea. The South Sea is intermediate in geomorphology and ecology between the East and Yellow Sea. The Tsushima Warm Current, a branch of the Kuroshio Current, enters the South Sea, flowing northeastward through the Korea Strait to the East Sea.

Despite lack of long-term monitoring programs, we utilized available time-series data to evaluate influences of climatic changes on oceanographic conditions and marine ecosystems in Korean coaster waters.

METHODS

The Korea Meteorological Administration (KMA) provided us with daily time-series of air temperature and daily precipitation that have been measured from up to 41 stations covering the South Korea since 1904, but we included only data after 1968 when the nationwide number of stations reached 22. The meteorological variables were averaged or summed monthly for each station to compare with oceanographic variables. At these 22 stations, monthly means of temperature and precipitation were available without any single missing value from 1968 to 2006, ruling out possibility of potential biases due to difference in the number of station.

Oceanographic factors (temperature, salinity, dissolved oxygen) have been measured bimonthly for the water columns at 175 fixed stations along 22 oceanographic lines in Korean coastal waters since 1961 by the National Fisheries Research & Development Institute (NFRDI), but we included only the 1968-2005 data to match with the period of the meteorological data. For consistency, we selected the data for the standard water depths of 0, 10, 20, 30, 50, 75 and 100 m. To exclude the effect of water temperature on gas solubility, DO saturation levels were also calculated based on the potential full saturation level.

In South Korea, fishery catch statistics have been compiled by the Korean central government since 1948. As a way to evaluate influence of oceanographic changes on marine ecosystems, species-composition changes in commercial fishery catches from

Korean coaster waters from 1968 to 2006 were summarized by multiple correspondence analysis (Hill, 1974; Jung and Houde, 2003; SAS, 1989) to be related with the regime-shift hypothesis (Steele, 1998).

Proc variogram and krige2d of the SAS version 9 (SAS, 1989), assuming anisotropic (both latitudinal and longitudinal) linear variogram functions without 'nugget' effect (Cressie, 1993), were used to estimate the meteorological and oceanographic variables by interpolation of values for unsampled 10 x 10 nautical-mile grids to generate distribution maps. The linear trend of long-term change from 1968 to 2005 was estimated by a seasonal analysis using proc GLM of the SAS for each grid. The seasonal analysis estimated the slope of a regression line and its significance for each grid after removing seasonality. We investigated causality in land-ocean climate interactions in Korea by cross-correlation analyses and ARIMA(1,12) using SAS version 9 proc CORR and ARIMA.

RESULTS AND DISCUSSION

CLIMATE AND OCEANOGRAPHIC CHANGES IN KOREA

Seasonal analysis for each city showed that air temperature has increased during the past 37 years without exception in South Korea (Table 1). The magnitude of the temperature increase generally corresponded to regional human population increase and degree of industrialization (Fig. 2-a). The spatial pattern of air-temperature increases shows that human factors have been a major force in the long-term air temperature increase. It was most pronounced in the capital area around Seoul (e.g., Suwon, Cheongju and Incheon) and the Yongnam area where industrialization has been most active in Korea during the past 40 years (e.g., Pohang and Daegu) (Table 1 and Fig. 2-a). Seasonally, the increasing trend was highest for February and March, and lowest for July and August. The nationwide mean temperature has increased by 1.267^{o}C (0.034 +/- 0.007^{o}C yr^{-1}, $p < 0.0001$) (Table 2), which is 2.6 times higher than the linear warming trend at the global scale of 0.013^{o}C per yr^{-1} reported for the past 50 years by the IPCC.

However, the increasing trend of air-temperatures for South Korea could be overestimated, because most of the 22 meteorological observation stations are located within the downtown areas where industrialization and population increase has been most active during the past 40 years. In other rural and undeveloped areas, the increasing trend of air temperature could be less than the rate reported here.

Although the nationwide monthly mean precipitation has not increased significantly in overall from 1968 to 2005 (20 mm mo^{-1}, $p = 0.15$), the area linking Gangneung and Pohang in the east of Korea showed significant increase in precipitation by > 25 mm mo^{-1} (Figs. 2-b). Seasonally, the precipitation has significantly increased for June-August, but has not changed or even slightly decreased for the other seasons, suggesting increasing trend of severe storms in summer during the past 40 years.

The IPCC also reported that the average temperature of the global ocean has increased to depths of at least 3,000 m. In Korean coastal sea waters, depth-specific water temperatures, averaged for the entire sea areas included in our analysis, has significantly increased in the entire water column from 0 to 100-m depth for the 1968 to 2005 period, but the magnitude of increase dwindled with water depth and became statistically not significant at 100-m depth (Table 2, Fig. 3). Seasonally, the increasing trend was most pronounced in June for the surface layer, possibly by strengthened, shallow mixed layer depth. Previous month's air temperatures (m-1) explained 93% of the variance in monthly means of coastal sea surface temperatures (m) off the peninsula (Fig. 5), but contemporaneous air temperatures (m) explained only 66% of the variance. Regarding the causality of land-ocean climate interactions, cross-correlation analyses also indicated that water temperatures change generally followed air temperature change with time lags of 0 to 12 months (Fig. 5), although they could precede air temperature changes by up to 3 months, possibly because of potential heat held by the sea. Seasonal ARIMA (1, 12) also suggested that air-temperature change precede sea water-temperature change, mostly with a time lag of 1 month. The degree of response to the annual mean air temperature dwindled with water depths. Cross-correlations of water temperatures (m) with respect to the mean air temperatures of the following month ($m+1$) also became less significant with water depths, suggesting that shallow sea waters interact more instantly with the air temperature of the peninsula than deep waters.

Spatially, the warming trend was most prominent in the East and South Sea (Fig. 3), suggesting additional warming influence from the tropical Pacific via the Kuroshio current (McPhaden and Zhang, 2002). At 0 and 10 m depths, water temperatures have increased for the entire ocean area off Korea. However, in some areas of Korean part of the Yellow Sea, water temperatures have decreased at 20-50 m depths. In the East Sea, water temperatures have decreased at some areas at < 30 m depths, and the area of decreasing trend expanded with water depths up to 100 m (Fig. 3), suggesting that the warming sea surface layer could strengthen the pycnocline, reducing heat transport by vertical mixing to deep water**.** The August pycnocline became generally shallower during the past 37 years, but the spatially-explicit linear trends were statistically significant only in the northern East China Sea (ECS). For the 1968 to 2005 period, depth-specific salinity, averaged for the entire sea areas, has decreased, but the degree of decrease diminished with water depths and became statistically not significant at > 20 m water depths (Table 2). Spatially, the decreasing trend of salinity was most visible in the northern ECS, probably related to the annual variations in Changjiang diluted water (Fig. 6). Monthly mean salinities at the surface layer did not show significant relationships with precipitation in the Korean peninsula. On the other hand, dissolved oxygen (DO) level, averaged for the entire sea areas, has decreased significantly from 1968 to 2005 at all of the standard depths from 0-100 m (Table 2), suggesting reduced gas solubility by increased water temperature.

Compared with the status of the regional climate in 2005, we anticipate that air-temperature in South Korea could increase by 0.82^{o}C in 2030 and by 3.12^{o}C in 2100, if the current trend continues. Under the same assumption, we project that sea surface temperatures around the Korean peninsula could increase by 0.63^{o} and 2.48^{o}C in 2030 and 2100, respectively.

RESPONSE OF MARINE ECOSYSTEMS TO CLIMATE CHANGE IN KOREA

Past studies suggested climate-related regime shifts as a mechanism to explain ecosystem changes (Scheffer and Carpenter, 2003; Steele, 1998). There are evidences of regime shift in marine ecosystems adjacent to the Korean peninsula. Meso- and macro-zooplankton biomass was reported to have been increased in seas around the peninsula since 1990 (Kang et al., 2002). In the Yellow Sea, abundance of a calanoid copepod, *Calanus sinicus*, significantly increased in 1990s, possibly affected by water temperature increase (Kang et al., 2007). In the South Sea, zooplankton biomass in April 1997 was over 2 times higher than the long-term means from1965 to 2000, which was related to warm water temperatures (Kang and Rebstock, 2004). In the East and South Seas copepods were dominated in all seasons from 1965-2000, although their dominance decreased slightly and macrozooplankton, such as chaetognaths, euphausiids and amphipods, gradually increased after the early 1990s (Rebstock and Kang, 2003).

Our multiple correspondence analysis (MCA) of Korean fishery statistics from 1968 to 2006 suggested that species composition in commercial catches dramatically changed in 1976-1977, 1982-1983 and 1990-1991 (Fig. 7). We divided the entire 1968-2006 period into 1) Pollack-dominant (1968-1982), 2) Sardine-dominant (1983-1990), and 3) Squid-dominant period (1991-2006). Past studies suggested that regime shift occurred in the

Pacific during the mid-1970s (Chavez et al., 2003) and the late-1980s (Zhang et al., 2000), and our MCA also indicated that the two shifts in 1976-1977 and 1990-1991 could correspond to them if accepting time lags of 1-3 years (Fig. 7). Because survival and growth of fish is most sensitive to oceanographic changes during their larval stages (Houde, 1987), and because it takes about 1 year for most fish larva to recruit in Korean coastal waters, the time lag of 1-3 years seems reasonable. However, the suggested regime shift of the Pacific in 1997-1998 (Chavez et al., 2003) was not evident in our MCA (Fig. 7). Instead, our MCA indicated that a regime shift could have occurred in 1982-1983, but we speculate that socioeconomic changes in Korean trawl fisheries also could partially explain the shift.

Squids, mostly *Todarodes pacificus*, chub mackerel (*Scomber japonicus*) and Pacific anchovy (*Engraulis japonicus*) have been dominant in fishery catches in both Korea and Japan since 1990 (Gong et al., 2006; Gong et al., 2007). Particularly, *T. pacificus* probably benefits by the human-driven warming sea water and increased zooplankton biomass off the Korean peninsula, because zooplankton biomass and abundance of major zooplankton groups were significantly correlated with commercial catch of *T. pacificus* in the East Sea for the 1978-1998 period (Kang et al., 2002). The historical trend of annual catch level of *T. pacificus* since 1920's show that it rebounded in the 1990's far more in the Tsushima-current areas off the Korean peninsula than in the seas off Japan's eastern coast where the Kuroshio current dominates (Gong et al., 2006; Gong et al., 2007), suggesting a northward shift in spatial distribution of recruited squids, probably driven by warming sea waters.

We agree that cyclic climate-related regime shift at decadal scale can explain sudden changes in marine ecosystems (Chavez et al., 2003), but we emphasize that the anthropogenic warming of coastal sea water off the Korean peninsula, overlapped with natural climate fluctuation (Zhang et al., 2000; Zhang et al., 2004), can be another major factor that influences on marine ecosystems and species compositions in the regional fishery catches. Particularly, we related the latest sudden shift in zooplankton community and catch of common squid in the early 1990's to the warming Korean sea waters, and our MCA demonstrated that the squid-dominant period has persisted at least until the present time, 2007. The price collapse of squid is currently a major fishery issue for the Korean government in summer 2007. We suggest that regional policy makers and scientists may consider potential long-term climate changes driven by natural and human forces when developing ecosystem and fishery management plans (King and McFarlane, 2006).

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Correspondence and requests for materials should be addressed to: 408-1 Sirang-ri, Gijang-eup, Gijang-gun, Busan, 619-902, South Korea. E-mail: sukgeun.jung@gmail.com, Telephone: 82-52-720-2293, Fax: 82-52-720-2277.

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Tables

Table 1. List of meteorological observation stations and the linear rates of temperature increase from 1968 to 2005.

	Longitude	Latitude	Annual rate			Linear increase (1968-2005)
	Decimal Degree		(^{o}C yr^{-1})	StdErr	P	(^{o}C)
Suwon	126.98	37.27	0.056	0.006	<.0001	2.055
Cheongju	127.45	36.63	0.052	0.006	<.0001	1.939
Pohang	129.38	36.03	0.050	0.005	<.0001	1.868
Incheon	126.63	37.47	0.049	0.005	<.0001	1.817
Daegu	128.62	35.88	0.048	0.005	<.0001	1.762
Seogwipo	126.57	33.25	0.046	0.004	<.0001	1.715
Seoul	126.97	37.57	0.044	0.006	<.0001	1.621
Ulsan	129.32	35.55	0.043	0.005	<.0001	1.592
Gangneung	128.90	37.75	0.036	0.006	<.0001	1.333
Jeju	126.53	33.52	0.036	0.004	<.0001	1.319
Busan	129.03	35.10	0.033	0.005	<.0001	1.211
Gwangju	126.90	35.17	0.032	0.005	<.0001	1.196
Yeosu	127.75	34.73	0.032	0.005	<.0001	1.174
Jeonju	127.15	35.82	0.031	0.005	<.0001	1.152
Chuncheon	127.73	37.90	0.029	0.006	<.0001	1.068
Ulleungdo	130.90	37.48	0.027	0.005	<.0001	0.984
Tongyeong	128.43	34.85	0.025	0.005	<.0001	0.934

Gunsan	126.75	36.00	0.024	0.005	<.0001	0.901
Mokpo	126.38	34.82	0.021	0.005	<.0001	0.782
Sokcho	128.57	38.25	0.017	0.006	0.0019	0.641
Seosan	126.50	36.77	0.017	0.005	0.0007	0.636
Chupungnyeong	128.00	36.22	0.016	0.005	0.0024	0.585

Table 2. The linear rates of land climate and depth-specific hydrological factors in the sea waters adjacent to the Korean peninsula from 1968 to 2005.

Factors	Depth (m)	annual rate (yr^{-1})	stderr	p-value	Linear increase (1968-2005)
Climate factors					
Air Temperature (^{o}C)		0.034	0.007	<.0001	1.267
Precipitation (mm mo^{-1})		0.537	0.375	0.1531	19.869
Hydrological factors					
Water temperature (^{o}C)	0	0.026	0.005	<.0001	0.975
	10	0.025	0.004	<.0001	0.918
	20	0.014	0.005	0.0054	0.500
	30	0.013	0.005	0.0188	0.470
	50	0.012	0.006	0.0274	0.454
	75	0.011	0.006	0.0479	0.411
	100	0.001	0.007	0.9117	0.028
Salinity	0	-0.006	0.002	0.0014	-0.229
	10	-0.005	*0.002	0.0133	-0.176
	20	-0.003	0.002	0.1009	-0.094
	30	-0.002	0.001	0.1332	-0.071
	50	-0.002	0.001	0.0915	-0.060
	75	-0.001	0.001	0.4492	-0.021
	100	0.000	0.001	0.9295	0.002

Dissolved Oxygen (ml l^{-1})	0	-0.006	0.002	0.0001	-0.238
	10	-0.008	0.002	<.0001	-0.299
	20	-0.011	0.002	<.0001	-0.418
	30	-0.013	0.002	<.0001	-0.490
	50	-0.012	0.002	<.0001	-0.460
	75	-0.013	0.002	<.0001	-0.490
	100	-0.015	0.002	<.0001	-0.549
Dissolved Oxygen					
Saturation	0	0.000	0.000	0.0498	-0.015
	10	-0.001	0.000	0.0046	-0.022
	20	-0.001	0.000	<.0001	-0.040
	30	-0.001	0.000	<.0001	-0.045
	50	-0.001	0.000	<.0001	-0.039
	75	-0.001	0.000	<.0001	-0.035
	100	-0.001	0.000	<.0001	-0.047

FIGURE LEGENDS

Fig. 1. Geomorphology of Korea (elevation and water depth at meter).

Fig. 2. Spatially-specific, long-term linear changes in (a) air surface temperature (^{o}C) and (b) precipitation (mm mo^{-1}) in the Korean peninsula from 1968 to 2006. All of the increases of air surface temperature in (a) were significant at $\alpha = 0.01$. The hatched area in (b) denotes that the precipitation increase was significant at $\alpha = 0.05$.

Fig. 3. Spatially-specific, long-term linear changes in water temperatures (^{o}C) at each standard water depth in sea waters off South Korea from 1968 to 2005. The color red denotes an increase whereas the blue denotes a decrease. The hatched areas denote that the increasing or decreasing trend was significant at $\alpha = 0.05$.

Fig. 4. Annually-averaged air surface temperatures and the sea surface temperatures in Korea.

Fig. 5. Month-specific regression analyses of mean sea surface temperatures with respect to mean air surface temperatures of the previous month from 1968 to 2005. Each point represents a year (n= 38, from 1968 to 2005). The equation denotes the overall regression line for all of the 6 months (n = 38 x 6).

Fig. 6. Spatially-specific, long-term linear changes in salinities at each standard water depth in sea waters off South Korea from 1968 to 2005. The color red denotes an increase whereas the blue denotes a decrease. The hatched areas denote that the increasing or decreasing trend was significant at $\alpha = 0.05$.

Fig. 7. Correspondence analysis of species composition in fishery catch from Korean coastal waters from 1968 to 2006. Column variable was year and row variable was fish

species. Points of fish species are not shown, but the characteristic species representing the three distinct periods are illustrated. Fishery catch statistics have been compiled by the Ministry of Maritime Affairs & Fisheries of Korea (http://www.momaf.go.kr).

FIGURES

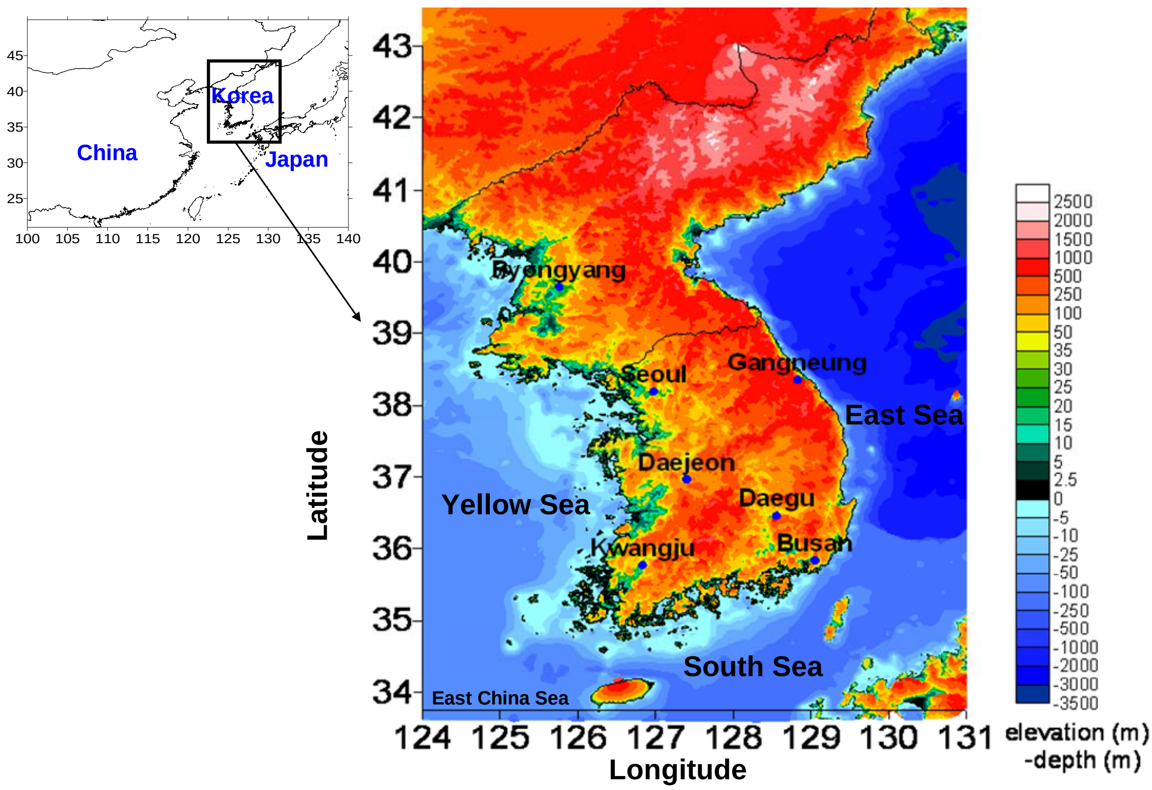

Fig. 1

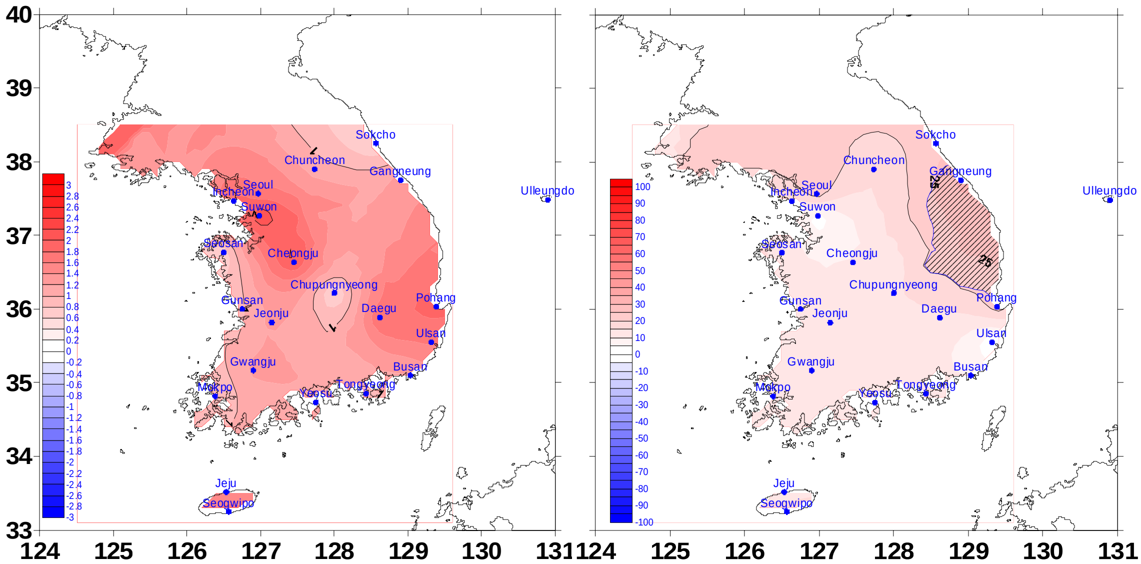

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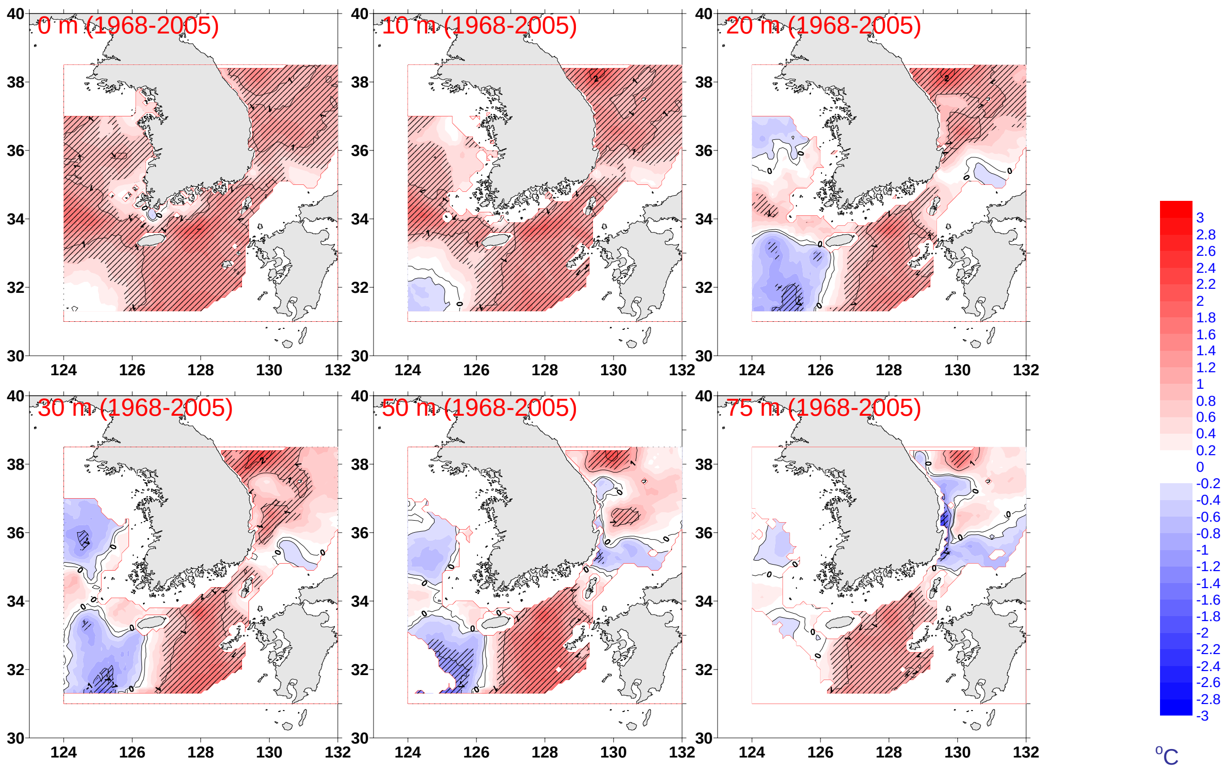
Fig. 2


0 m (1968-2005)
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75 m (1968-2005)
°C

Fig. 3

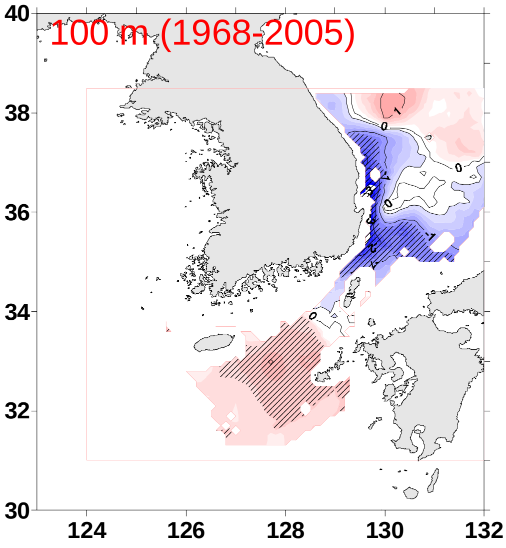
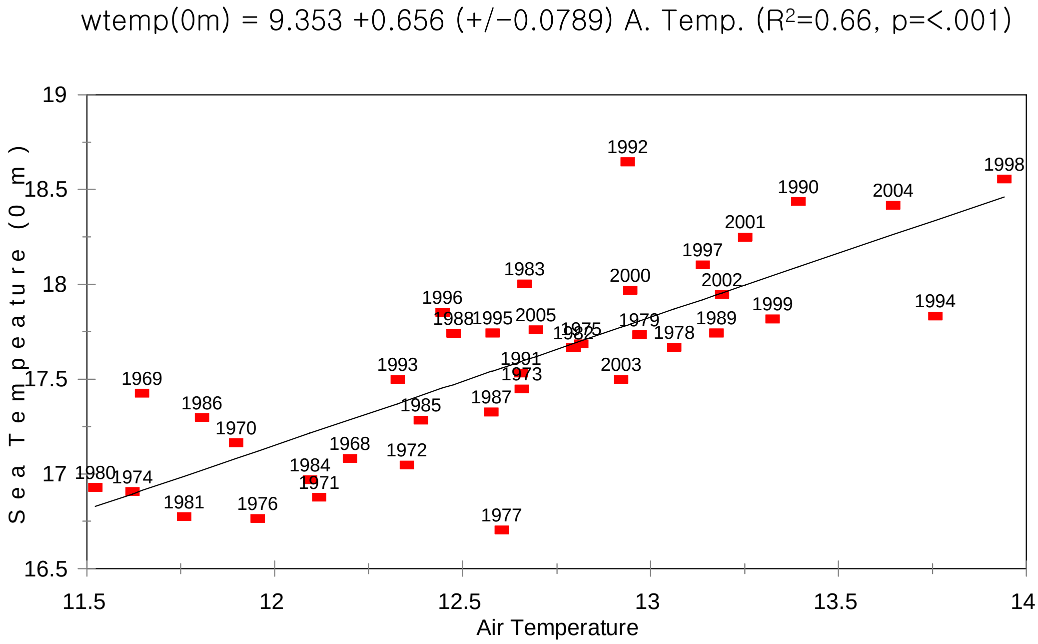


Fig. 3 (continued)



wtemp(0m) = 9.353 +0.656 (+/−0.0789) A. Temp. (R2=0.66, p=<.001)
Sea Temperature (0 m)
Air Temperature
1992
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1990
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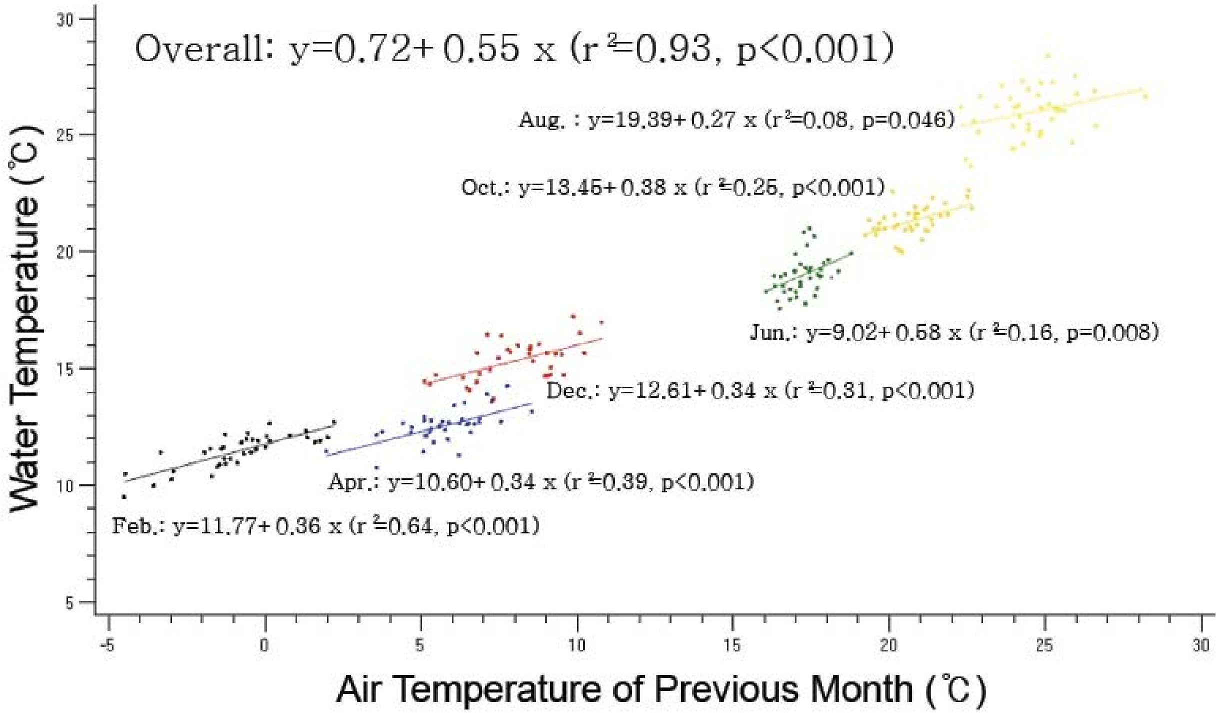
Fig. 4.


Overall: y=0.72+ 0.55 x (r 2=0.93, p<0.001)
Aug. : y=19.39+ 0.27 x (r 2=0.08, p=0.046)
Oct.: y=13.45+ 0.38 x (r 2=0.25, p<0.001)
Jun.: y=9.02+ 0.58 x (r 2=0.16, p=0.008)
Dec.: y=12.61+ 0.34 x (r 2=0.31, p<0.001)
Apr.: y=10.60+ 0.34 x (r 2=0.39, p<0.001)
Feb.: y=11.77+ 0.36 x (r 2=0.64, p<0.001)
Water Temperature (℃)
Air Temperature of Previous Month (℃)
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-5
0
5
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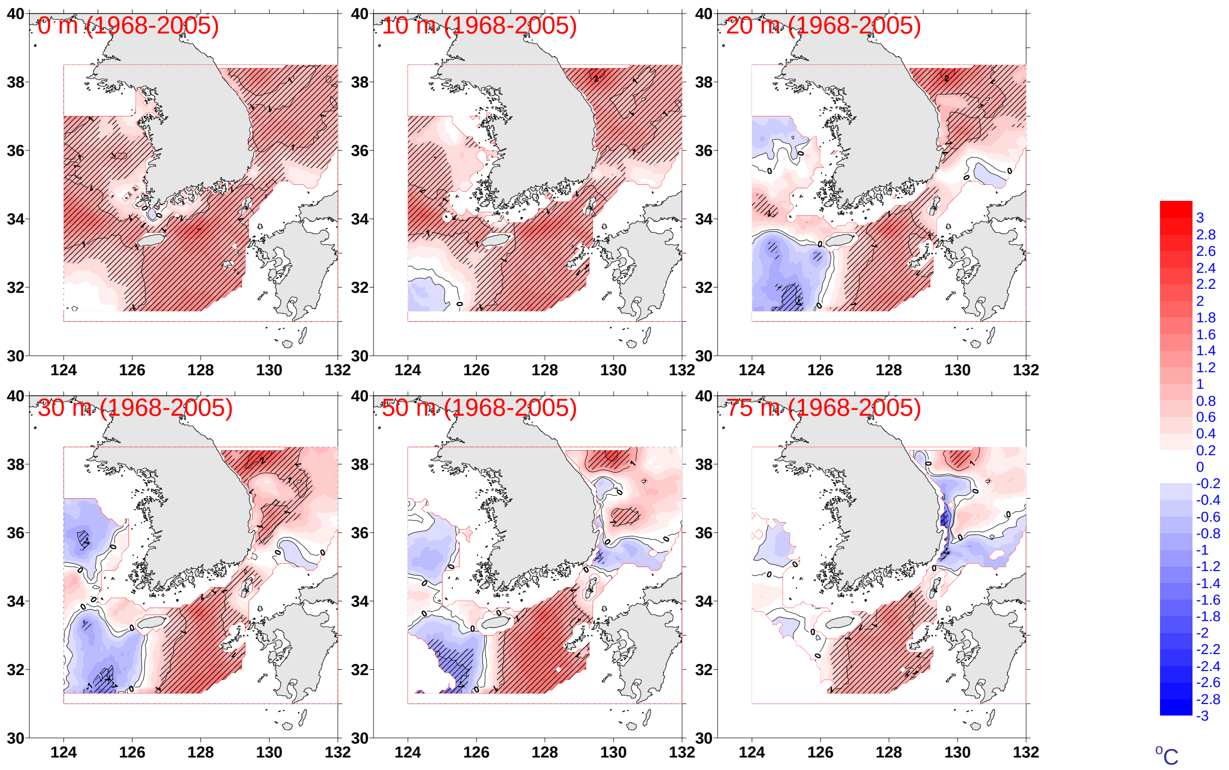
20
25
30

Fig. 5


0 m (1968-2005)
10 m (1968-2005)
20 m (1968-2005)
30 m (1968-2005)
50 m (1968-2005)
75 m (1968-2005)
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34
32
30
124
126
128
130
132
3
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-2
-2.2
-2.4
-2.6
-2.8
-3
^{o}C

Fig. 6

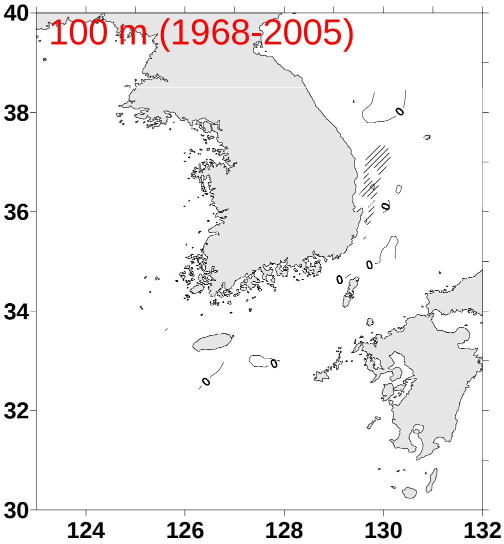
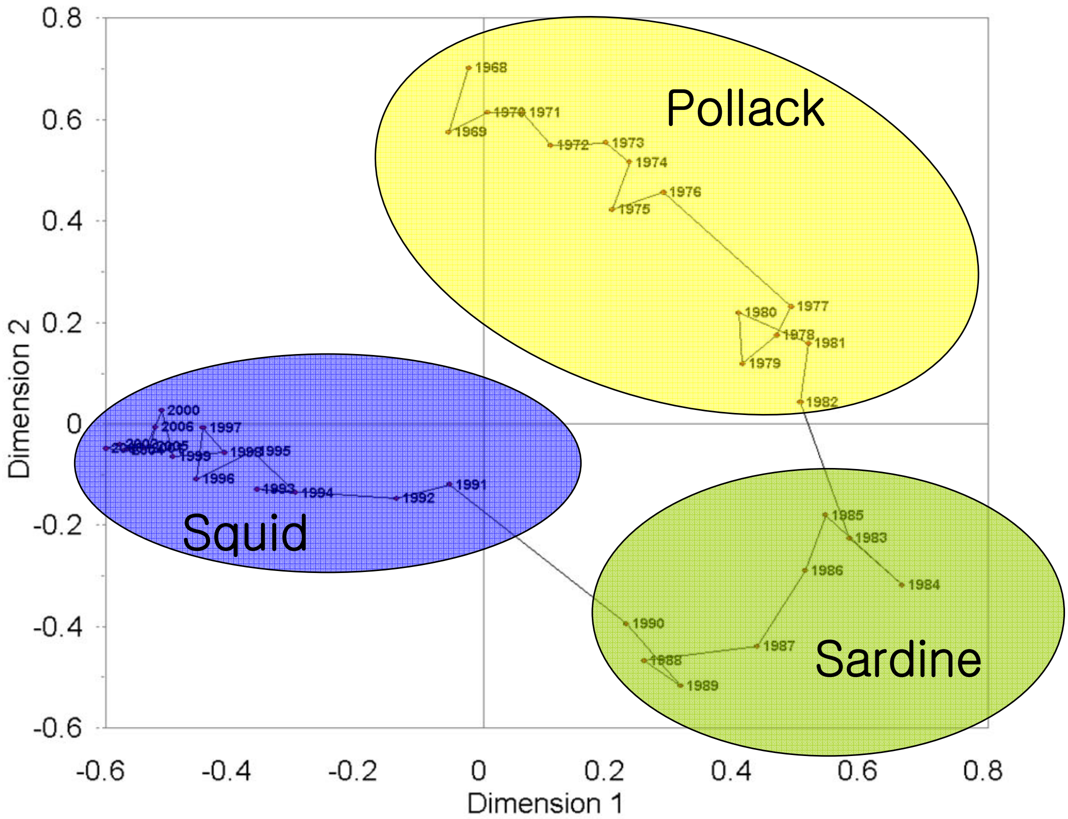


Fig. 6 (continued)



Pollack
Squid
Sardine
Dimension 1
Dimension 2
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1968
1969
1970
1971
1972
1973
1974
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
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1986
1987
1988
1989
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2000
2005
2006

Fig. 7