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Trend of Sea Level Change Along the Coast of Korean Peninsula

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Trend of sea level change has been analysed by using the tidal data gathered at the 12 tide stations along the coast of Korean peninsula. Analysis and prediction of the sea level change were performed by Principal Component Analysis (PCA). For the period of 20 years from 1976 to 1995, the trend generally shows a rising pattern such as 0.22 cm/yr, 0.29 cm/yr, and 0.59 cm/yr along the eastern, southern, and western coast of Korea, respectively. On the average the sea level around the Korean peninsula seems to be rising at a rate of 0.37 cm/yr. Adopting the average rate to the sea level prediction model proposed by EPA (Titus and Narrayanan, 1995), the sea level may be approximately 50~60 cm higher than the present sea level by the end of the next century.

Key words: sea level rise, global warming, tide record, principal component analysis

1. Introduction

Sea level change may cause a serious problem to the coastal environment by the regression or transgression of shoreline. Especially the rise in sea level may result in a disastrous effect such as coastal erosion, flooding, inundation of salt water, rising of groundwater level, and so on.

The fluctuations of sea level at a region consist of both long term and short term variations. The short term variations are generally local and caused by the surface waves, astronomical tides, occasional surges, seasonal cooling and heating of seawater, and changing atmospheric pressure (Murakami and Yamada, 1994; Pang and Oh, 1994; Sultan et al., 1995). The long term variations are usually due to the eustatic sea level change caused by global climatic change. The climatic change results in change of water volume in the ocean by thermal expansion or contraction of seawater. Freezing or melting of glaciers due to the climatic change also causes the change in volume of seawater. Recently global warming is attributed to the global rise in sea level by many investigators (Gornitz et al., 1982; Meier, 1984; Barnett, 1990; IPCC, 1990, 1996).

The crustal movement of uplift or subsidence at a region also adds a component to the long term sea level change, which appears as a regional relative sea level change. Emery and Aubery (1985, 1986) and Aubery and Emery (1986) suggest that the crustal motion is incorporated into the substantial part of the apparent sea level change in the world.

The periodicity of short term change is usually distinguishable easily. However, the periodicity of long term change is hardly discernible without a continuous record of several tens or hundreds of years. And the long term change only has a rising or falling trend for a considerable period of time. The trend results in a continuous shoreline transgression or regression, and it may cause an unexpected disaster after all (EPA, 1985; Titus, 1998)

For the present study, the trend of sea level change was analysed using the sea level data gathered at 12 tidal stations along the coast of Korean peninsula for the period of 20 years (1976~1995). The 12 stations consist of 4 stations (Sokcho, Mukho, Pohang, Ulsan) along the eastern coast, 4 stations (Pusan, Gadokdo, Chungmu, Yosu) along the southern coast, and 4 stations (Taehuksando, Mokpo, Inner Kunsan, Inchon) along the western coast (Fig. 1). Future predictions of sea level change along the coast of Korea were also done by applying the trend to the probability model of global sea level change proposed by Environmental Protection Agency of U.S.A. (Titus and Narrayanan, 1995).

2. Data Analysis

A total of 23 tidal gauge stations around Korea is in operation by the National Oceanographic Research Institute of Korea (Fig. 1). However, the durations of measurements are different each other and the areal distribution is not equally spaced either. Therefore, to avoid the bias by the regional distribution and the duration of measurement, four stations at each coast for the period of 20 years (1976-1995) were selected for the analysis.

To analyse the spatial and temporal variability of annual mean sea level, principal component analysis has been conducted. Principal component analysis is a useful tool to facilitate the understanding of complex physical phenomena by rather simple indices (principal components) with minimal loss of information contained in the data set (Preisendorfer, 1988; Barnett, 1990).

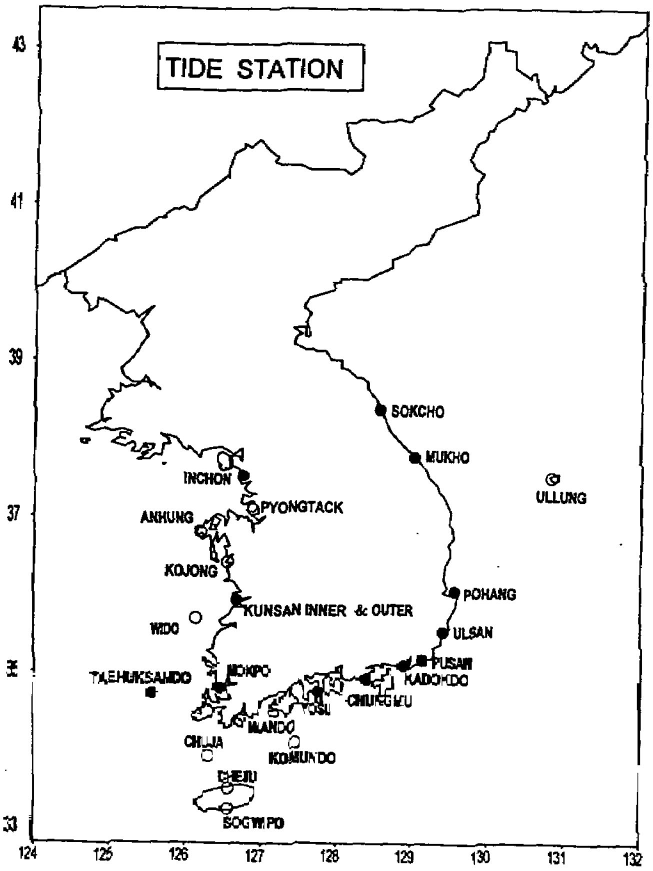

Fig. 1. Location of tidal stations (solid circles represent the stations used for data analysis).

At first each data set has been normalized to have unit variance with zero mean,

$$h_i'(t) = \frac{h_i(t) - \bar{h}_i}{\sigma} \tag{1}$$

where, $h_i(t)$: sea level at time t and location i

(i=1, 2, 3, ..., N),

$\bar{h}_i$: mean of $h_i(t)$

σ_i : standard deviation at the i-th station,

then, the normalized mean sea level can be represented as,

$$h_i'(t) = \sum_n A_n(t) e_{ni} \tag{2}$$

where, $A_n(t)$ is the n-th mode of principal components which can be calculated by

$$A_n(t) = \sum_i e_{ni} h_i'(t) \tag{3}$$

and the eigenvectors e_{ni} can be obtained from the correlation matrix of the mean sea level,

$$C_{ij} = [h_i'(t) h_j'(t)]_i \tag{4}$$

Now, the eigenvectors e_{ni} represent average patterns of spatial covariabilty among the N sets of sea level data, and the sign of e_{ni} at each station will be the same if the fluctuation at each station is behaving in the same trend (rise or fall). The principal components $A_n(t)$ modulate the intensity of the spatial patterns e_{ni} in time. Thus a secular trend in $h_i(t)$ coherent at all stations will be manifested by a secular trend in the first principal component $A_1(t)$. Deviations from this trend at a specific station are associated with the second and higher modes of principal components (Barnett, 1990).

The trend of mean sea level change in the region was estimated using the linear regression analysis of $A_1(t)$ by least square method.

3. Trend of sea Level Change

3.1. Trend during 1976~1995

Figure 2 shows the first and second principal components along the east coast. The first principal component shows a distinctive rising trend at a rate of about 0.22 cm/yr (r^2=0.57). However, the second principal component does not show any rising or falling trend. The first principal component could represent 71% of the total sea level change and the second principal component represented 23% of the total change. Thus the two components represent 94% of total sea level change in the east coast of Korea. Figure 3 shows that the trend at all stations along the east coast is rising. However, the sea level change at the Ulsan station is relatively less correlated to the general trend along the east coast. It also shows that the Sokcho and Mukho stations behave differently from the stations at Pohang and Ulsan to the second principal component.

Along the southern coast of Korea the trend is also rising generally at a rate of 0.29 cm/yr (r^2=0.58) (Fig. 4). The second principal component here also does not show any significant

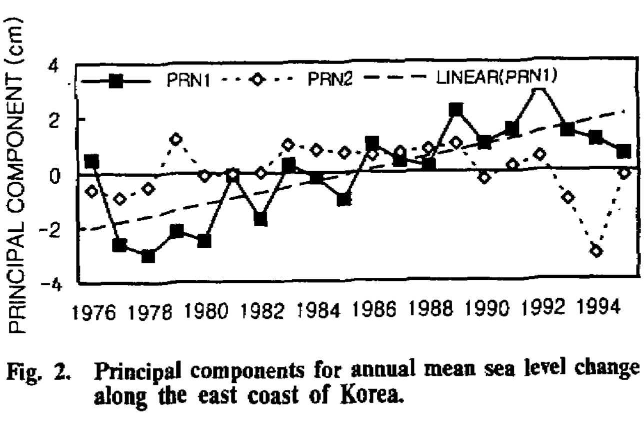

Fig. 2. Principal components for annual mean sea level change along the east coast of Korea.

falling or rising trend. The first and second principal components represent 78% and 18% of total sea level change, respectively. Figure 5 shows that all the 4 stations in this region contribute to the main trend of sea level change with approximately equal importance. However, the stations at Pusan and Yosu contribute differently from the stations at Kadokdo and Chungmu to the second principal component.

The trend along the west coast shows the most rapid rise in sea level at a rate of 0.59 cm/yr (r^2=0.69) (Fig. 6). Even though all the 4 stations contribute positively to the rise of sea level the contribution of the Inchon station is relatively small compared to the other stations (Fig. 7). The first principal component in this region represents 53% and the second principal component represents 30% of total sea level change, which means that the sea level change in this region may be more complex than the other coasts.

By making the data sets of the 12 stations into one data set the principal component analysis for the entire Korean peninsula has been conducted. The first principal component represents 63% of total sea level change, and it also shows a rising trend at a rate of 0.37 cm/yr (r^2=0.65) (Fig. 8). Figure 8 also shows that the second principal component, which could represent 15% of the sea level change, does not have a significant rising or falling trend. Figure 9 shows that all the stations contribute positively to the rise of sea level change even though the contribution to the second principal component is different among the stations.

The spatial correlation among the stations can be examined by the correlation coefficients of annual mean sea level (Table 1). It is seen that the sea level change at the stations along the Korean coast is generally correlated each other. However, the stations along the western coast and the Ulsan station are less correlated to the other stations.

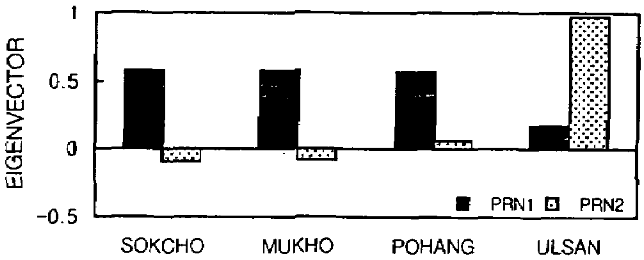

Fig. 3. Eigenvectors of stations along the east coast of Korea.

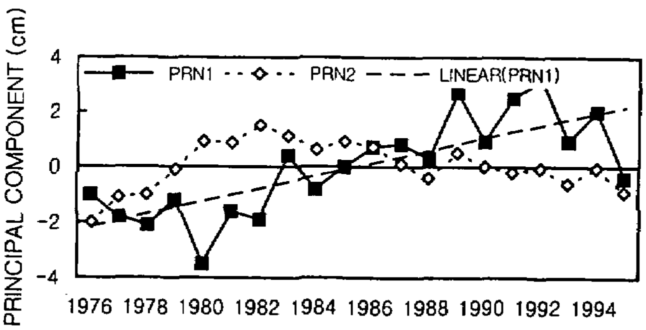

Fig. 4. Principal components for annual mean sea level change along the south coast of Korea.

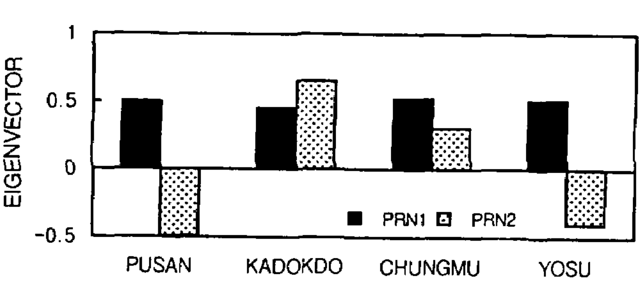

Fig. 5. Eigenvectors of stations along the south coast of Korea.

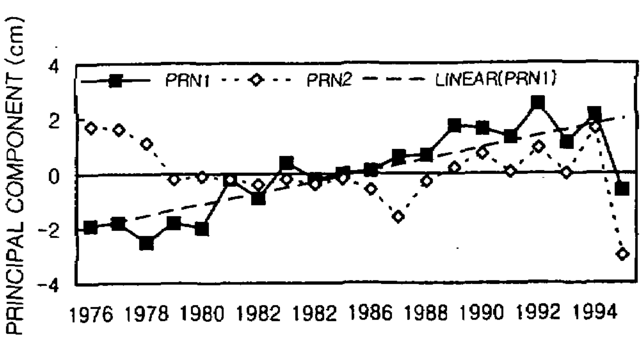

Fig. 6. Principal components for annual mean sea level change along the west coast of Korea.

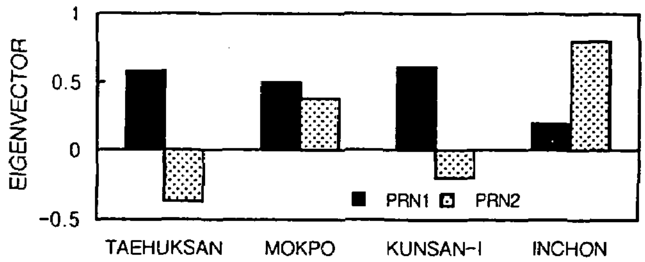

Fig. 7. Eigenvectors of stations along the west coast of Korea.

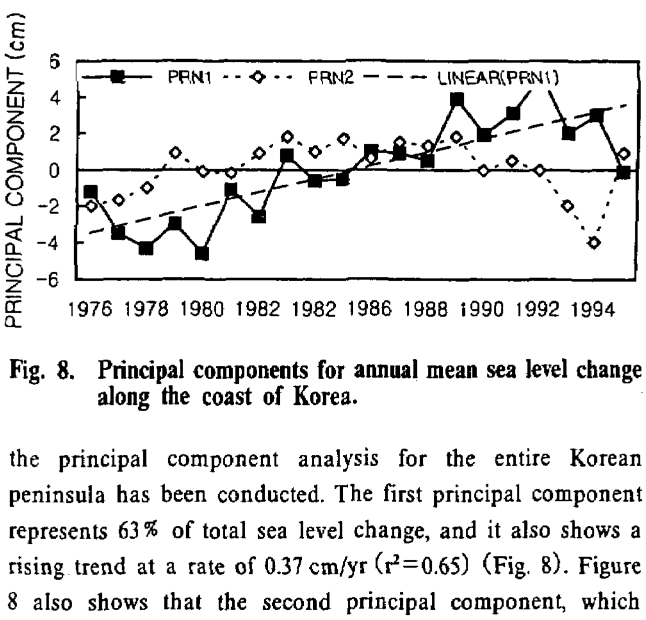

Fig. 8. Principal components for annual mean sea level change along the coast of Korea.

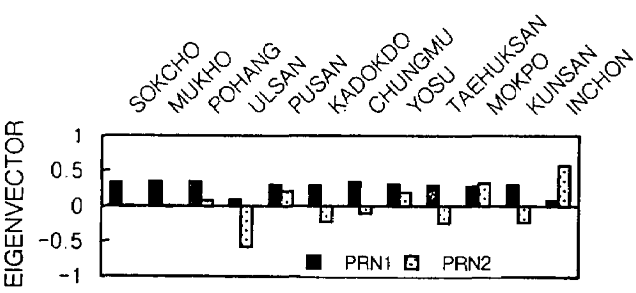

Fig. 9. Eigenvectors of stations along the coast of Korea.

Table 1. Correlation coefficients of the stations along the Korean coast

		XI	X2	X3	X4	X5	X6	X7	X8	X9	X10	XII	X12
Sokcho	X1	1.00	0.94	0.87	0.17	0.75	0.66	0.78	0.81	0.75	0.71	0.64	0.05
Mukho	X2	0.94	1.00	0.88	0.15	0.79	0.62	0.81	0.81	0.75	0.67	0.72	0.08
Pohang	X3	0.87	0.88	1.00	0.21	0.77	0.66	0.85	0.74	0.67	0.75	0.71	0.28
Ulsan	X4	0.17	0.15	0.21	1.00	0.10	0.41	0.32	0.08	0.19	-.08	0.39	-39
Pusan	X5	0.75	0.79	0.77	0.10	1.00	0.45	0.71	0.93	0.46	0.68	0.53	0.26
Kadokdo	X6	0.66	0.62	0.66	0.41	0.45	1.00	0.85	0.54	0.74	0.52	0.81	0.13
Chungmu	X7	0.78	0.81	0.85	0.32	0.71	0.85	1.00	0.72	0.84	0.69	0.87	0.17
Yosu	X8	0.81	0.81	0.74	0.08	0.93	0.54	0.72	1.00	0.52	0.71	0.60	0.26
Taehuk-sando	X9	0.75	0.75	0.67	0.19	0.46	0.74	0.84	0.52	1.00	0.44	0.79	-.11
Mokpo	X10	0.71	0.67	0.75	-.08	0.68	0.52	0.69	0.71	0.44	1.00	0.38	0.40
Inner Kunsan	X11	0.64	0.72	0.71	0.39	0.53	0.81	0.87	0.60	0.79	0.38	1.00	0.11
Inchon	X12	0.05	0.08	0.28	-39	0.26	0.13	0.17	0.26	-.11	0.40	0.11	1.00

3.2. Projection of Future Sea Level

Extrapolating the trend to the future, sea level at any time in the future can be predicted. However, the trend of relative sea level change is a representation of the superposition of local tectonic movement on the global eustatic sea level change. Even though the rate of tectonic movement can be assumed relatively constant within a few decades or centuries, the rate of global sea level change may not be constant due to the variable extent of global warming (Barnett, 1990; Titus and Narrayanan, 1995; IPCC, 1995, 1996).

For the global sea level change there are so many uncertainties and complexities, and many investigators estimate the future projection based on various models, assumptions, and scenarios (Church et al., 1991; Wigley and Raper, 1992; Wigley and Raper, 1993; Titus and Narrayanan, 1995; IPCC, 1990, 1992, 1996), which give various range at various time.

Due to the complexities and uncertainties in the projection of future sea level Titus and Narrayanan (1995) prepared a probability distribution of normalized projections of sea level rise supplied by experts of climatologists, oceanographers, and glaciologists. The normalized projections estimate the extent of excess rise over the current trend at a particular time compared with 1990 levels. The local sea level at a particular time can be calculated by

$$local\,(t) = normalized\,(t) + (t - 1990) \times \text{trend} \tag{5}$$

where, t is the time to be projected in year

Table 2 and Table 3 show the maximum (1% chance of occurrence) and median (most likely) estimated future sea level rises, respectively. The projection is continued until 2100 compared to the sea level in 1990 along the coast of Korea.

4. Results and Discussions

Various kinds of periodicities are contained within a tidal record, hence the analysis of sea level change using the tidal data should be done by a long continuous record of tidal measurements to eliminate such periodicities (Sturges, 1987; Barnett, 1990). Even though the record length of 20 years analysed in this study is not long enough to eliminate all the periodicities within the records, a reasonable trend can be obtained for several decades since the record length covers a whole metonic period (19 years) of tide. However, it should be noted that the rates of sea level change given in this study must be used with caution.

The rate of sea level rise along the coast of Korea is fastest at a rate of 0.57 cm/yr along the west coast. The rate along the east coast is slowest at a rate of 0.22 cm/yr, and the rate along the south coast is 0.29 cm/yr. These rates are much higher than the reported Quaternary sea level change based on C-14 age dating and pollen analysis of the sediment layers, which variably ranges from less than 0.1 mm/yr to approximately 1 mm/yr (KORDI, 1994). However, the works done with the sediment layers are the average rate for several thousands of years, and

Table 2. Projection of sea level (cm) over the sea level in 1990 along the coast of Korea (cumulative probability of 99%)

Year	Normalized (t) (cm)	East Coast	South Coast	West Coast	Korea
		trend 0.22 cm/yr	trend 0.29 cm/yr	trend 0.59 cm/yr	trend 0.37 cm/yr
2025	19	26.7	29.2	39.7	32.0
2050	35	48.2	52.4	69.2	57.2
2075	57	75.7	81.7	107.2	88.5
2100	92	116.2	123.9	156.9	132.7

Table 3. Projection of sea level (cm) over the sea level in 1990 along the coast of Korea (cumulative probability of 50%)

Year	Normalized (t) (cm)	East Coast	South Coast	West Coast	Korea
		trend 0.22 cm/yr	trend 0.29 cm/yr	trend 0.59 cm/yr	trend 0.37 cm/yr
2025	5	12.7	15.2	25.7	13.0
2050	10	23.2	27.4	44.2	32.2
2075	17	35.7	41.7	67.2	48.5
2100	25	49.2	56.9	89.9	65.7

thus the rates may reflect the global change with some effect of sediment compaction. The rates along the south and east coasts are similar to the reported rate of recent sea level rise along the most of U.S.A. coast, which is 2.5~3.0 mm/yr (Titus and Narrayanan, 1995).

The different rates along the east, south, and west coast may reflect different mechanism of relative sea level change at each region. The composition of water mass in the Yellow Sea is very complex and show a strong seasonal variation (Lee et al., 1999). The little correlation among stations along the west coast may also reflect the complexity of water masses in the region. Among the water masses the Yellow Sea Warm Current, which comes into the Yellow Sea from the south, may be most influential to the rise of mean sea level since the current is affected by the warm Kuroshio and Tsushima Current (Lee, 1992).

The most important component to the sea level change in the South Sea seems to be the Tsushima Current flowing over the South Sea. Murakami and Yamada (1994) implied that the variability of mean sea level at the seas around Japan may be the result of Kuroshio meandering. Tsushima Current is a branch of Kuroshio, and the mean sea level in the South Sea may be affected by Tsushima Current consequently. Pang and Oh (1994) also showed that the Tsushima Current was most affective to the long period fluctuation of mean sea level caused by ocean currents. The water temperature of Tsushima Current has been rising at a rate of 0.01~0.02℃/yr for the last 100 years (Lee, 1992). This warming of Tsushima Current may be the major factor to the sea level rise along the south coast.

The warm Tsushima Current flows into the East Sea. However the effect of the Tsushima Current becomes weaker as it enters the East Sea (Lee, 1992). Especially large part of the east coast is influenced by the cold North Korean Current. The little correlation of Ulsan to the other stations along the east coast suggests that the Tsushima Current is more affective to Ulsan compared to the other stations.

The future projection of mean sea level is still remained controversial and should be refined further (Barnett, 1990; IPCC, 1996). Even the precise assessment of past global sea level rise is difficult mainly due to difficulty in filtering of vertical land movement from the tidal record (IPCC, 1996). The projection of future sea level rise largely depends on models based on various emission scenarios of global warming (IPCC, 1990, 1992, 1996).

Parameters of projection model based on global warming scenarios include thermal expansion, glaciers and ice caps, Greenland ice sheet, and Antarctic ice sheet (Titus and Narrayanan, 1995; IPCC, 1966). All these parameters are hard to assess precisely and the future emission scenarios are also hard to predict exactly, and thus different models give different projections according to the assumptions and assessment of the model parameters (Church et al., 1991; Wigley and Raper, 1992; Wigley and Raper, 1993; Titus and Narrayanan, 1995; IPCC, 1990, 1992, 1996).

The projections of mean sea level until 2100 for this study were estimated by probability-based projections. The estimates of sea level rise by this model are somewhat lower than those by previous IPCC assessments because of lower temperature projections. The experts adopted lower temperature projections because they assumed lower concentrations of carbon dioxide and included the cooling effects of sulfates and stratospheric ozone depletion (Titus and Narrayanan, 1995). It should be noted that this model was not based on statistical experiments or tests. The probabilistic projections simply came out from the knowledge of the experts. Thus the projections given by this model should be used with caution.

Conclusion

The mean sea level along the coast of Korea seem to be rising at a rate of about 0.37 cm/yr on the average. However the rate is different at east, south, and west coast. It is fastest along the west coast with a rate of about 0.59 cm/yr, and slowest along the east coast at a rate of about 0.22 cm/yr. The rate along the south coast is approximately 0.29 cm/year.

Different rate at different part of the coast implies that the mechanism of relative sea level change is different at each coast. However, the thermal and dynamic behavior of the water masses at each coast seems to play major role to the rise of sea level in the region. Especially Yellow Sea Warm Current in the west coast, Tsushima Current in the south coast, and Tsushima and North Korean Currents in the east coast seem to be most affective.

Projection of future sea level rise based on a probability model suggests with a large uncertainty that the mean sea level along the coast of Korea may be approximately 50~60 cm higher than the present level near the end of the 21st century.

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