*J. of the Environmental Sciences*
*Vol. 11, No. 11, 1141~1147(2002. 11)*

# Sea-Level Trend at the Korean Coast

Kwangwoo Cho

*Environmental Impact Assessment Division, Korea Environment Institute, 613-2*
*Bulgwang-Dong, Eunpyong-Gu, Seoul 122-706, Korea*

(Manuscript received 19 April, 2002 ; accepted 11 October, 2002)

Based on the tide gauge data from the Permanent Service for Mean Sea Level (PSMSL) collected at 23 locations in the Korean coast, the long-term sea-level trend was computed using a simple linear regression fit over the recorded length of the monthly mean sea-level data. The computed sea-level trend was also corrected for the vertical land movement due to post glacial rebound(PGR) using the ICE-4G(VM2) model output[12]. It was found that the PGR-corrected sea-level trend near Korea was 2.310 ± 2.220 mm/yr, which is higher than the global average at 1.0~2.0mm/yr, as assessed by the Intergovernmental Panel on Climate Change(IPCC)[1]. The regional distribution of the long-term sea-level trend near Korea revealed that the South Sea had the largest sea-level rise followed by the West Sea and East Sea, respectively, supporting the results of the previous study by Seo *et al.*[7] However, due to the relatively short record period and large spatial variability, the sea-level trend from the tide gauge data for the Korean coast could be biased with a steric sea-level rise by the global warming during the 20th century.

Key words : sea level, sea-level rise, global warming, global warming impact

## 1. Introduction

Global warming is projected to accelerate during the 21st century due to human activities, thereby increasing steric sea-level rise and producing significantly adverse effects on the natural and human systems in coastal zones[1,2]. A rise in the sea level effects the inundation and displacement of lowlands and wetlands, intensifies coastal erosion and storm flooding, and increases the salinity of estuaries and salt-water intrusion into freshwater aquifers[3], leading to a wide range of socio-economic consequences, including crop production loss, a decline in land values, changes in human health, and deterioration of water and habitat quality, etc. It has been projected that regional variations of sea-level changes will be significant compared to the global mean value[4]. Accordingly, the regional assessment of long-term sea-level change in relation to global warming is important to cope with the impact of future sea-level rises that are expected to accelerate in the 21st century.

Previous studies on the long-term sea-level change near Korea using tide gauge data include Sohn[5], Choi *et al.*[6], and Seo *et al.*[7] Sohn[5] investigated the long-term sea-level change for Korea and the eastern Kyushu area of Japan using a least-square analysis of tide gauge data and found that the mean sea-level trend for all the stations(34 stations) was 1.98 mm/yr. Using data from 24 tide gauge stations in Korea, Seo *et al.*[7] also found that the sea level was generally increasing, especially around Jeju Island. Choi *et al.*[6] investigated the sea-level changes for Korea, Japan, China and Russia using tide gauge data from 24 stations based on a relatively long observation period. In their analysis, the sea-level trend at a particular station differed significantly according to the period used to calculate the sea- level trend, suggesting that careful interpretation of sea-level

---

Corresponding author ; Kwangwoo Cho, Environmental Impact Assessment Division, Korea Environment Institute, 613-2 Bulgwang-Dong, Eunpyong-Gu, Seoul 122-706, Korea
Phone : +82-2-380-7615
E-mail : kwcho@kei.re.kr

trends is required when a simple regression is used to determine long-term sea-level change. This finding was also highlighted by Douglas[8].

However, no previous studies have considered the vertical land movement at the tide stations. Since a tide gauge is installed on the land and measures sea-level changes relative to the land, tide gauge data is composed of both oceanic volume change and vertical land movement, which need to be separated. Accordingly, the current study removes the vertical land movement component from the tide gauge data based on post glacial rebound(PGR) model information, which is known as the only geological component to influence long-term sea-level changes on a global scale. Without this correction, no meaningful comparison can be made with other regional and global studies. As such, the goals of the current study are to investigate the long-term sea-level change near the Korean peninsula using the tide gauge data from the Permanent Service for Mean Sea Level(PSMSL) after the correction of the post glacial rebound for vertical land movement at the tide stations, determine the sea-level rise due to 20th century global warming, and help to cope with the socioeconomic impact of future sea-level changes in the coastal zone of the Korean peninsula. Section 2 briefly describes the PSMSL tide gauge data, data processing, and analysis method for long-term sea-level change. The predicted long-term sea-level change and PGR characteristics for the study area are presented in section 3 and some concluding remarks given in section 4.

## 2. Data and analysis

The current study used sea-level data from the Permanent Service for Mean Sea Level (PSMSL), which has collected sea-level data from a global network of tide gauges since 1933[8,9]. The PSMSL database contains monthly and annual mean sea-level data from over 1800 tide gauge stations around the world. Among them, 23 monthly mean data sets located around the Korean peninsula were selected. The station name, position, and observation period for the sea-level data are listed in Table 1 and corresponding geographical positions plotted in Figure 1. The PSMSL data exist in two formats: metric format and revised local reference (RLR) format. The metric format is raw data from the various authorities directly responsible for the tide gauge observation after quality check by the PSMSL. Details of the quality check applied to the PSMSL data are given by Woodworth *et al.*[10] and IOC[11]. The RLR format data are defined to be approximately 7000 mm below the mean sea level, which is arbitrarily determined to avoid negative numbers in the resulting RLR monthly and annual mean values, and construct a time series of sea-level measurements for each station relative to a common datum. The current study used the monthly mean RLR data for computing the secular trends, as recommended by the PSMSL. Among the tide data, the longest data record was a 40-year observation period of the sea level at the Korean coast(since 1960).

First, the sea-level trends were computed for the PSMSL tide gauge data(Table 1 and Fig. 1) using a simple linear regression model, such as

$$y = a + bx \tag{1}$$

where $a$ denotes the intercept and $b$ the slope of the regression line, i.e. the sea- level trend. The coefficients, $a$ and $b$, were computed by minimizing the Chi-square error statistic. The sea-level trends computed from the PSMSL tide gauge data were then corrected for post glacial rebound to remove the vertical land movement component. ICE-4G(VM2) model data was used to correct for vertical land movement. The ICE-4G model is a glacial rebound model that calculates the post glacial rebound(or glacial isostatic adjustment) on a global scale based on the following global response function

$$S(\theta,\lambda,t) = C(\theta,\lambda,t)\Big[\int_{-\infty}^{t} dt' \int\int_{\Omega} d\Omega' \big(L(\theta',\lambda',t')\, G_{\psi}^{L}(\gamma, t-t') + \Psi^{R}(\theta',\lambda',t')\, G_{\psi}^{T}(\gamma, t-t')\big) + \frac{\triangle\Phi(t)}{g}\Big] \tag{2}$$

where $S(\theta,\lambda,t)$ is the variation of the relative sea level at latitude $\theta$ and longitude $\lambda$ as a function of time $t$. The function $C(\theta,\lambda,t)$ in Eq. (2) is called the ocean function, which is equal to unity where there is ocean and zero elsewhere. The function $L(\theta,\lambda,t)$ is the surface mass load per unit area and composed of both ocean-water and land-ice components. $G_{\psi}^{L}$ and $G_{\psi}^{T}$ are the impulse response

Table 1. Name, position, and observational period for each PSMSL tide station on Korean coast

| Division | No. | Station | Position | Obs. Period(yrs) |
|---|---|---|---|---|
| East Sea | 1 | WONSAN | 39°10'N, 127°27'E | 1962~1992 (31) |
| | 2 | SOGCHO | 38°12'N, 128°36'E | 1974~1999 (26) |
| | 3 | MUGHO | 37°33'N, 129°07'E | 1965~1999 (34) |
| | 4 | ULNEUNG DO | 37°30'N, 130°55'E | 1979~1999 (21) |
| | 5 | POHANG | 36°01'N, 129°24'E | 1972~1999 (28) |
| | 6 | ULSAN | 35°31'N, 129°23'E | 1963~1999 (34) |
| South Sea | 7 | CHINHAE | 35°09'N, 128°39'E | 1960~1976 (16) |
| | 8 | GADEOG DO | 35°01'N, 128°49'E | 1977~1999 (22) |
| | 9 | PUSAN | 35°06'N, 129°02'E | 1961~1999 (38) |
| | 10 | TONGYONG | 34°49'N, 128°26'E | 1977~1999 (23) |
| | 11 | YOSU | 34°45'N, 127°46'E | 1970~1999 (30) |
| | 12 | KOMUNDO | 34°01'N, 127°19'E | 1982~1999 (18) |
| | 13 | WANDO | 34°19'N, 126°45'E | 1983~1999 (17) |
| | 14 | CHUJADO | 33°58'N, 126°18'E | 1984~1999 (16) |
| | 15 | JEJU | 33°31'N, 126°32'E | 1964~1999 (36) |
| | 16 | SOGWIPO | 33°14'N, 126°34'E | 1985~1999 (15) |
| West Sea | 17 | MOKPO | 34°47'N, 126°24'E | 1960~1999 (40) |
| | 18 | DAEHEUGSANDO | 34°41'N, 125°27'E | 1979~1999 (21) |
| | 19 | WIDO | 35°37'N, 126°18'E | 1985~1999 (12) |
| | 20 | KUNSAN | 35°58'N, 126°38'E | 1981~1992 (12) |
| | 21 | PORYONG | 36°24'N, 126°29'E | 1986~1999 (14) |
| | 22 | ANHUNG | 36°40'N, 126°08'E | 1989~1999 (11) |
| | 23 | INCHON | 37°27'N, 126°36'E | 1960~1998 (32) |

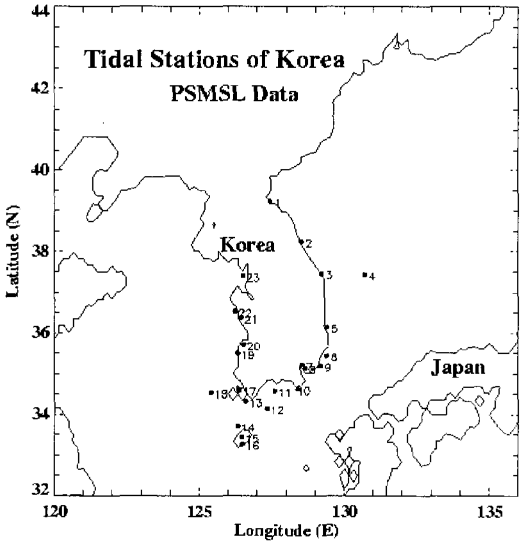

Fig. 1. Map showing PSMSL tide stations on Korean coast. The numbers in the map coincides with those in Tables 1 and 2.

functions(Green functions), which retain information on the radial viscoelastic structure required to determine the impact of this structure on the relative sea-level history. $\Psi^R$ is the force function required to compute the impact of the changing rotational state on the sea level. $\Phi$ and $g$ are the gravitational potential field and gravitational acceleration, respectively. As such, the solutions to equation (2) are constructed using an iterative method based on recognizing the influence of time variations on the ocean function and the feedback influence on the sea level from the changing rotational state of the planet due to variations in the surface mass load by the convolution of $\Psi^R$ with $G_\phi^T$. The detailed solution processes of equation (2) can be found in Peltier[12]. The PGR-corrected sea-level trends were then analysed for the whole region and each sea(East, South, and West Seas) based on the mean and standard deviation.

## 3. Results

To investigate the sea-level trend near Korea, 23 tidal stations with relatively long records were selected, as shown in Table 1 and Figure 1. The observation periods for the tide stations were within a range of 11 to 40 years with a mean of 24 years. The data was mainly from the southern part of the Korean peninsula, except for one station (Wonsan), and also from a land coast rather than an island(3 stations). Table 2 represents the sea-level trend without any correction, PGR value, and PGR-corrected sea-level trend for each station. As shown in Table 2, the overall mean for the PGR-corrected sea-level trends near Korea was 2.310 mm/yr, which is higher than the global average at 1.0 ~ 2.0 mm/yr, assessed by the Intergovernmental Panel on Climate Change(IPCC)[1]. The typical variability(represented by a standard deviation) of the sea-level trends between the 23 stations was 2.220 mm/yr, indicating that the variability of the mean sea-level trend over the study area

Table 2. PGR value, sea-level trend, and PGR- corrected sea-level trend for each PSMSL tide station on Korean coast

| Division | No. | Station | PGR(mm/yr) | SL. Trend(mm/yr) | Adj. SL. Trend(mm/yr) |
|---|---|---|---|---|---|
| East Sea | 1 | WONSAN | -0.420 | 1.315 | 0.895 |
| | 2 | SOGCHO | -0.370 | 2.250 | 1.880 |
| | 3 | MUGHO | -0.340 | -0.237 | -0.577 |
| | 4 | ULNEUNG DO | -0.310 | 0.118 | -0.192 |
| | 5 | POHANG | -0.310 | 1.435 | 1.125 |
| | 6 | ULSAN | -0.300 | 0.583 | 0.283 |
| | mean | | -0.342 | 0.911 | 0.569 |
| | std. dev. | | 0.046 | 0.926 | 0.906 |
| South Sea | 7 | CHINHAE | -0.260 | 4.633 | 4.373 |
| | 8 | GADEOG DO | -0.270 | 2.022 | 1.752 |
| | 9 | PUSAN | -0.280 | 1.862 | 1.582 |
| | 10 | TONGYONG | -0.250 | 2.608 | 2.358 |
| | 11 | YOSU | -0.230 | 2.231 | 2.001 |
| | 12 | KOMUNDO | -0.170 | 4.699 | 4.529 |
| | 13 | WANDO | -0.300 | 2.196 | 1.896 |
| | 14 | CHUJADO | -0.190 | 1.665 | 1.475 |
| | 15 | JEJU | -0.120 | 4.484 | 6.364 |
| | 16 | SOGWIPO | -0.120 | 7.036 | 6.916 |
| | mean | | -0.219 | 3.344 | 3.125 |
| | std. dev. | | 0.065 | 1.773 | 1.819 |
| West Sea | 17 | MOKPO | -0.270 | 2.338 | 2.068 |
| | 18 | DAEHEUGSANDO | -0.120 | 2.955 | 2.835 |
| | 19 | WIDO | -0.200 | -0.433 | -0.633 |
| | 20 | KUNSAN | -0.240 | 6.573 | 6.333 |
| | 21 | PORYONG | -0.250 | 6.407 | 6.157 |
| | 22 | ANHUNG | -0.260 | 2.764 | 2.504 |
| | 23 | INCHON | -0.330 | -0.467 | -0.797 |
| | mean | | -0.239 | 2.877 | 2.638 |
| | std. dev. | | 0.065 | 2.845 | 2.855 |
| overall mean | | | -0.257 | 2.567 | 2.310 |
| overall std. dev. | | | 0.078 | 2.177 | 2.220 |

was quite large.

The mean sea-level trend for the East Sea coast was calculated using data from 6 stations(Wonsan, Sogcho, Mugho, Ulneungdo, Pohang, and Ulsan) and exhibited a relatively small trend of 0.569 mm/yr with a standard deviation of 0.906 mm/yr and distribution ranging from - 0.577 mm/yr at Mugho to 1.880 mm/yr at Sogcho. For the South Sea, 10 stations(Pusan, Chinhae, Gadeogdo, Tongyong, Yosu, Komundo, Wando, Chujado, Jeju, and Sogwipo) were used to calculate the mean sea-level trend, which was 3.125 mm/yr with a standard deviation of 1.819 mm/yr and distribution ranging from 1.475 mm/yr at Chujado to 6.916 mm/yr at Sogwipo. The mean sea-level rise for the South Sea was relatively large compared to those for the East and West Seas, especially at the Jeju Island station, which supports the previous results of Seo *et al.*[7)] For the West Sea, 7 stations (Mokpo, Daeheugsando, Wido, Kunsan, Poryong, Anhung, and Incheon) were used to calculate the mean sea-level change, which exhibited a trend of 2.638 mm/yr with a standard deviation of 2.855 mm/yr and distribution ranging from -0.797 mm/yr at Incheon to 6.333 mm/yr at Kunsan. The mean sea-level rise was in the order of the South Sea, West Sea, and East Sea, respectively.

The vertical land movement due to post glacial rebound for the tide stations near Korea exhibited an overall mean value of -0.257 mm/yr and standard deviation of 0.078 mm/yr. The East Sea experienced the largest vertical emergence of land due to PGR with a mean value of -0.342 mm/yr and standard deviation of 0.046 mm/yr, while the South and West Seas showed a comparable emergence with mean values of -0.219 and -0.239 mm/yr and standard deviations of 0.065 and 0.065 mm/yr, respectively.

To test the convergence of the sea-level trends for the stations near Korea, the PGR-corrected sea-level trends calculated by a linear regression fit as in equation (1) for the 23 tide stations near Korea were plotted against the record length in years, as shown in Figure 2. As a result, the mean sea-level revealed a decreasing trend with a longer observation period. Large fluctuations in the sea-level trends appeared for tide records of 10 - 20 years, plus there was a considerable scatter among the tide records longer than 20 years. Accordingly, no stable convergence of the mean sea-level trend as related to the global warming of the 20th century was identified for the stations near Korea.

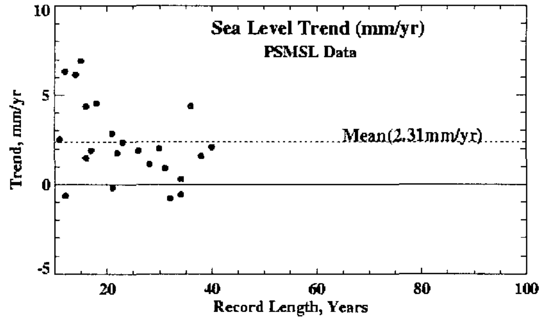

Fig. 2. PGR-corrected sea-level trends relative to record length.

## 4. Discussion and concluding remarks

The long-term sea-level trend at the Korean coast was calculated using the PSML data from 23 tide stations in Korea. The method of analysis was a simple linear regression fit over the monthly mean sea level for the record length of each tide station. The calculated sea-level trends were corrected to remove the vertical land movement component due to post glacial rebound(PCR) at each station using the ICE-4G(VM2) model[12)]. As a result, the PGR-corrected sea-level trend near Korea was found to be 2.30 mm/yr ±2.22 mm/yr, which is higher than the global average at 1.0~2.0mm/yr, as assessed by the IPCC(2001)[1)]. The regional distribution of the long-term sea-level trend near Korea supported the previous results of Seo *et al.*[7)], as the South Sea showed the largest sea-level rise followed by the West Sea and East Sea, respectively.

In spite of the PGR correction for vertical land movement at the tide stations, it is still questionable whether the sea-level trends based on the tide gauge data for the seas neighboring Korea were related to global warming because of the relatively short observation period and large spatial variability. Figure 3 shows the record lengths(all less than 40 years) for the 23 PSMSL tide stations used in the current study. Based on 175 tide gauge PGR-corrected data sets from around the world, Douglas[8)] found that the sea-level trends were quite variable when the record lengths of the tide gauge data were less than 50 years. The regional distribution of sea-level change can be quite complex because of the regional distribution of thermal expansion, heat transport into ocean interiors, ocean circulation changes due to density structure changes related to temperature and salinity changes, horizontal heat transport changes due to ocean circulation changes, wind-field changes related to climate changes, and various geological effects in coastal zones etc. Furthermore, the interannual and decadal variabilities of the ocean are also superposed with the long-term sea-level change due to global warming in the mean sea-level time series from tide gauge data. Accordingly, the long- term sea-level trend calculated in the present study based on tide gauge data with a relatively short record length may have been significantly biased with the weak signal of a steric sea-level change due to global warming in spite of the PGR correction.

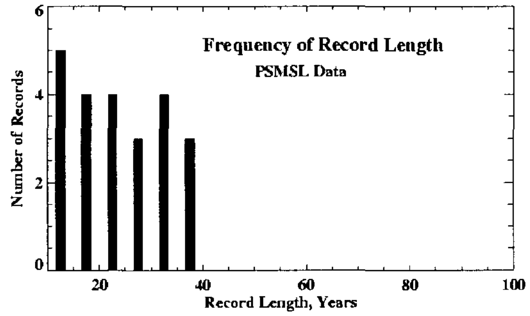

Fig. 3. Distribution of record lengths for PSMSL tide stations on Korean coast.

In addition to the temporal sampling problem related to the tide gauge data from Korea, there was also a spatial sampling problem in calculating the long-term sea-level trend near Korea. Most data was from in the southern part of the Korean peninsula. Also the data was mainly from coastal zones rather than islands. Coastal zones have a wide range of physical and geological processes, as reflected in a comparison of the tide gauge data from the Kunsan inner and outer ports, which revealed a large discrepancy in spite of the geographical proximity[13]. The large spacial variability was also revealed by the standard deviation of the sea-level trend, comparable to the mean value.

The IPCC[1] assessed the global average sea-level rise during the 20th century to be within a range of 10~20 cm, which was higher than that for the 19th century. An accelerated increase in the global mean sea level is projected for the 21st century due to enhanced global warming. Based on 35 IPCC emission scenarios, the sea-level rise in the 21st century is estimated to be within a range of 9~88 cm with a median value of 48cm, which is 2.2~4.4 times higher than that in the 20th century. As such, this will have a serious natural and socio-economic impact on coastal systems, such as Korea. However, state-of-the-art climate model predictions on the regional distribution of the sea-level change in the 21st century show little similarity between models[4]. Therefore, to cope with the impact of a possible sea-level rise in the coastal zone of Korea, it is essential to detect sea-level trends in relation to global warming. However, in the absence of long-term tide gauge records, a variety of approaches for detecting the relatively weak signal of a steric sea-level change is recommended, for example, studies using long-term hydrographic data, altimeter data, and regional models etc.

## Acknowledgement

This research was conducted based on funding from the Korea Environment Institute(KEI) : reference number KEI/2001/RE-13.

## References

[1] IPCC, 2001a, Climate Change 2001-The Scientific Basis. Cambridge Univ. Press, Cambridge, UK, p.881.

[2] IPCC, 2001b, Climate Change 2001-Impacts, Adaptation, and Vulnerability. Cambridge Univ. Press, Cambridge, UK, p.1032.

[3] Nicholls, R. J., F. M. J. Hoozemans and M. Marchand, 1999, Global Environmental Change, 9, S69-S87.

[4] Gregory, J. M., J. A. Church, G. J. Boer, K. W. Dixon, G. M. Flato, D. R. Jackett, J. A. Lowe, S. P. O'Farrell, E. Roeckner, G. L. Russell, R. J. Stouffer and M. Winton, 2001, Climate Dynamics, 18, 225~240.

[5] Son, C. B., 1999, Prediction of Potential Shoreline Retreat by Sea Level Rise, Proceedings of Coastal and Ocean Engineering in Korea, 11, 34~40.

[6] Choi, B. H., S. J. Roh, J. H. Lee and F.

Guohong, 1999, Acta Oceanologica Sinica, 18, 337~353.

[7] Seo, B. D., Y. Huh and K.C. Lim, 1999, Study Paper of National Oceanographic Research Institute, 3~8.

[8] Douglas, B. C., M. C. Kearney and S. P. Leatherman, 2001, Sea Level Rise, Academic Press, California, USA, pp.37~64.

[9] Spencer, N. E. and P. L. Woodworth, 1993, Data holdings of the Permanent Service for Mean Sea Level, Bidston, Birkenhead : Permanent Service for Mean Sea Level, p.81.

[10] Woodworth, P. L., N. E Spencer and G. A. Alcock, 1990, International Hydrographic Review, 67, 131~146.

[11] IOC, 1992, Joint IAPSO-IOC workshop on sea level measurements and quality control, Intergovernmental Oceanographic Commission, Workshop Report, No.81, p.167.

[12] Peltier, W. R. and X. Jiang, 1997, Surveys in Geophysics, 18, 239~277.

[13] Cho, K. and J. H. Kim, 2001, Sea Level Change on Korea Coast and its impact due to the Global Warming I, Korea Environment Institute, KEI-2001-RE-13, p.125.