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Influence of Steric Effect on the Rapid Sea Level Rise at Jeju Island, Korea

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ABSTRACT

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According to a report by the Korea Hydrographic and Oceanographic Agency (KHOA), the sea level rise in west coast (1.31 mm/yr), east coast (2.69 mm/yr) and south coast (2.05 mm/yr) of Korea are different. Especially, the seas around Jeju Island show one of the most rapid increase of sea level rise in recent years. This investigation on the data from Jeju and Seogwipo tidal station indicated that the sea level rises around Jeju and near Seogwipo were 5.63mm/yr and 3.75mm/yr, respectively. This shows that the northern and southern parts of the island have different temporal rates of sea level rise. The purpose of this research is to analyze the influence of the steric effect caused by density change in the water to the rate of sea level rise, by using sea temperature and salinity data measured by the National Institute of Fisheries Science (NIFS). It is found that the trend of seawater density variation near Jeju Island changed by the time of around 2006 and so does the sea level rise, indicating that there is a meaningful correlation between sea level rise and density variation. The rate of steric height rise by the density were calculated, resulting in a 15.8% and 23.2% of sea level rise in Jeju and Seogwipo, respectively.

ADDITIONAL INDEX WORDS: *Jeju Island, sea level rise, change of density, steric height.*

INTRODUCTION

The sea level rise (SLR) resulting from global warming has accelerated rapidly in recent years. A sea level increase in coastal areas bring about various coastal damage as well as the risk of flooding and inundation, causing immediate threat to large cities mostly located on the shoreline with high population densities. Recently, several studies have examined SLR in many countries and regions as well as at the global level (Nicholls and Cazenave, 2010).

According to the IPCC 5th Assessment Report (Stocker *et al*., 2014), the global mean SLR was calculated for each time period and was more than 2.0±0.3 mm/yr from 1971 to 2010. Report published by Korea Hydrographic and Oceanography Agency (KHOA, 2015) showed that the average SLR of the entire coastal areas in Korea was 2.48 mm/yr, which is rather higher than the global mean SLR. Also it is reported that each coastal region in Korea face a different rate of SLR, i.e., 1.31mm/yr in the west coast, 2.69mm/yr in the east coast and 2.89mm/yr in the South coast of Korea. Especially, the vicinity of Jeju Island showed one of the highest rate of SLR, which is 4.56mm/yr. Due to its geographic characteristics, the island Jeju is much more vulnerable to high rate of SLR. However, a serious study has not been made to understand what causes this high rate SLR.

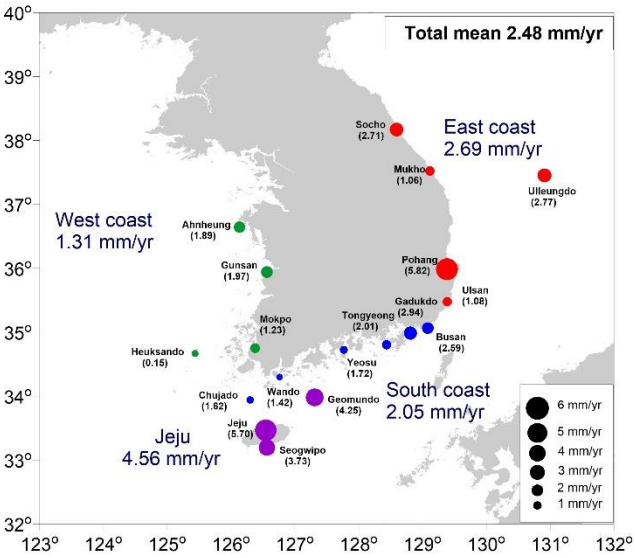


Figure 1. Sea level rise around Korea: The west coast (1.31 mm/yr), east coast (2.69 mm/yr) and south coast (2.05 mm/yr) of Korea. In particular, the sea level rate around Jeju Island (4.56 mm/yr) has increased rapidly. (KHOA, 2015).

In this study, we try to determine the reason for the rapid increase in sea level, using the field measurement data of tidal

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level, sea temperature and salinity. We aim to find out the relationship between high rate SLR and recent steric effect caused by density change. The tidal level data is measured and published by KHOA (http://www.khoa.go.kr/koofs) and sea temperature and salinity data are from National Institute of Fisheries Science (NIFS). The tide level data was used to estimate the increase rate of, and the salinity data was adapted to understand the impact of steric height by a density change on the SLR.

METHODS

Data

KHOA provides tide level data at hourly intervals, and among them the materials from Jeju Tidal Station (JTS) and Seogwipo Tidal Station (STS) were used to analyze the trend of SLR. The observation period of the data was from 1978 to 2015 (38 years) for JTS and from 1985 to 2015 (31 years) for STS. Temperature and salinity data was obtained from 1978 to 2015 and the data measured from 5 selected vertexes near the island were used in the study. The locations of each tidal station (red triangulation point) and TS observation point (blue dot points) are marked at Figure 2.

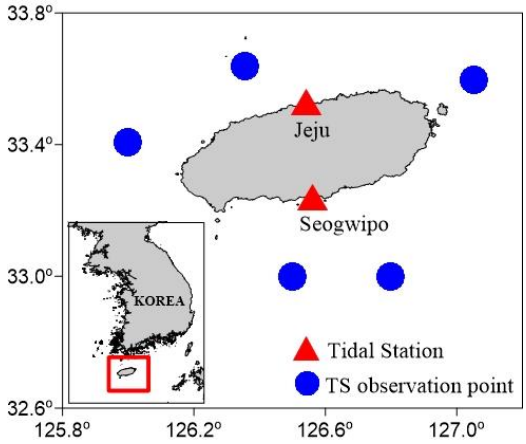


Figure 2. Research area around Jeju. The red triangulation points are the tidal station and the blue dot points are the temperature-salinity observation point.

Methodology

An analysis of the sea level trend was implemented through the analysis method KHOA (2015) and the Korean sea level change analysis program in KHOA after preprocessing the hourly data, including the abnormal data detection and missing data compensation.

In this study, the interpolation using a harmonic constant was applied to compensate for the missing data after any abnormality of the data from each station was checked. The harmonic analysis and sea level estimation TASK-2000 program (Tidal Analysis Software Kit 2000, 1999), which was developed by the British organization, Permanent Service for Mean Sea Level (PSMSL), was utilized.

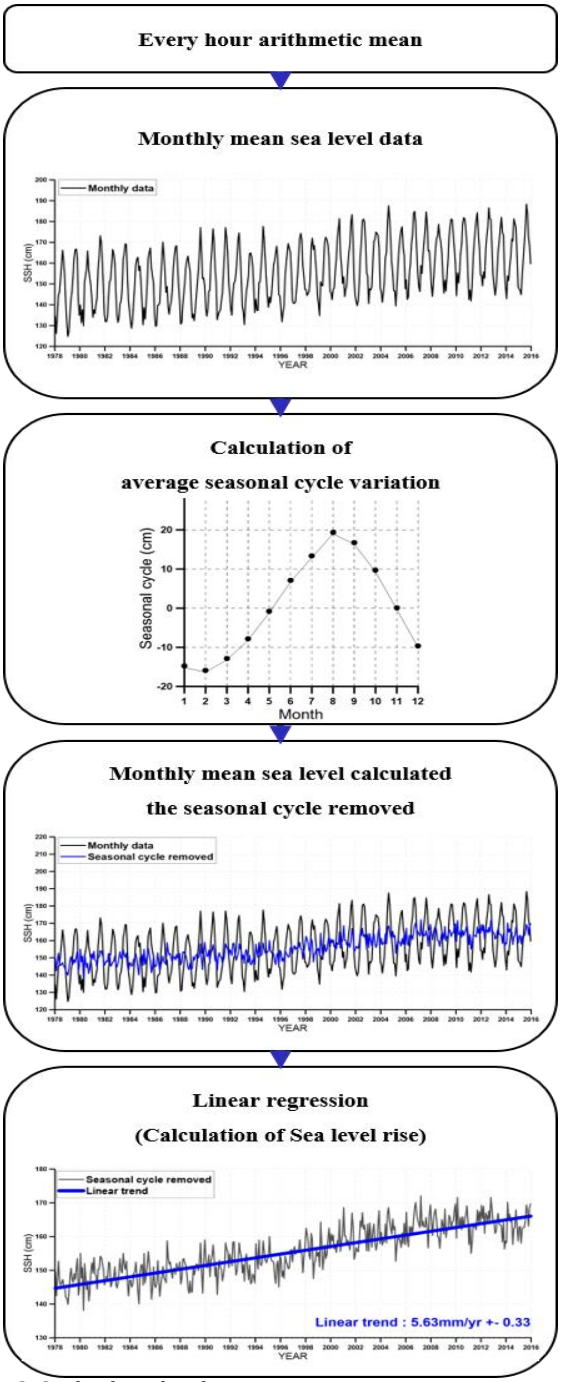


Figure 3. Sea level trend analysis process.

A total 62 harmonic constants were calculated in this study during missing data compensation through the hourly sea level data from each station for the concerned year (369 days). In order to estimate the average sea level as accurately as possible and determine the most significant factors that could impact on the

long-term SLR, a careful data quality checking is made. The abnormal data was compensated for by inserting the estimated sea level in the missing sectors that was calculated through the harmonic constants and the programs included in TASK-2000. During harmonic analysis process, if the missing period exceeded 30 days for the year of concern, the harmonic constant from the previous year was adapted to compensate for the missing data.

To analyze the accurate linear trend of the mean sea level, seasonal cycle should be removed using the monthly mean data. The seasonal cycle was calculated using the 5~19 year measured monthly mean data, which is by the cumulative average (so called normals) or can be calculated obtaining Sa (Solar annual) and Ssa (Solar semiannual) through harmonized analysis by the least squares method. In this study, the seasonal cycle can be calculated by the monthly average normals data. Figure 3 presents the flow chart of the sea level trend analysis process.

The observation data from NIFS was used to determine the influences of temperature and salinity on the sea level change. The NIFS measures the temperature and salinity around the Korean peninsula 6 times a year in February, April, June, August, October, and December. Among the measured materials, the data acquired from more than 5 measurements a year including summer and winter season was selected for analysis.

RESULTS

Analysis of Sea Level around Jeju Island

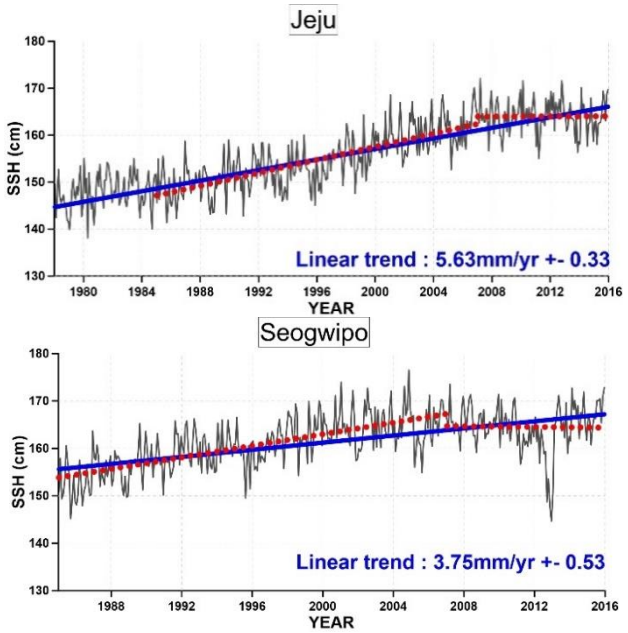


Figure 4. Time series of the sea level rise at JTS and STS. The blue line shows the linear trend from 1978 to 2015 in the first graph and from 1985 to 2015 in the second graph. The red dot line shows the linear trend for 1985~2006 and 2006~2015. Trend changes occurred near 2006.

Figure 4 presents trend analysis based on the sea level data from JTS and STS. The monthly average data was used for trend analysis. As a result, the SLR was 5.63 mm/yr and 3.75 mm/yr at JTS and STS, respectively. The sea level observed from JTS was 1.88 mm/yr higher than that from STS, meaning that the northern part of Jeju Island shows higher rate of SLR than the southern region. Also, although the sea level around Jeju Island was rising consistently, the areas near STS displayed a sudden drop in sea level in around 2012.

Another characteristic of SLR near Jeju Island is that there is change of rate SLR by the time of 2006. The rate was 6.93/6.11 mm/yr for JTS and STS, respectively, before 2006, turning to 0.1/-0.36 mm/yr after 2006 (Table 1). The rise tended to slow down since 2006, and interestingly, this shows a similar tendency to the global mean sea level trend suggested by the Ablain *et al.* (2009).

Table 1. *Sea level linear trend at JTS and STS (mm/yr).*

Station	Linear Trend	Linear Trend (1985~2006)	Linear Trend (2006~2015)
JTS	5.63	6.93	0.1
STS	3.75	6.11	-0.36

Analysis of the Reason for the SLR near Jeju Island through Density Changes

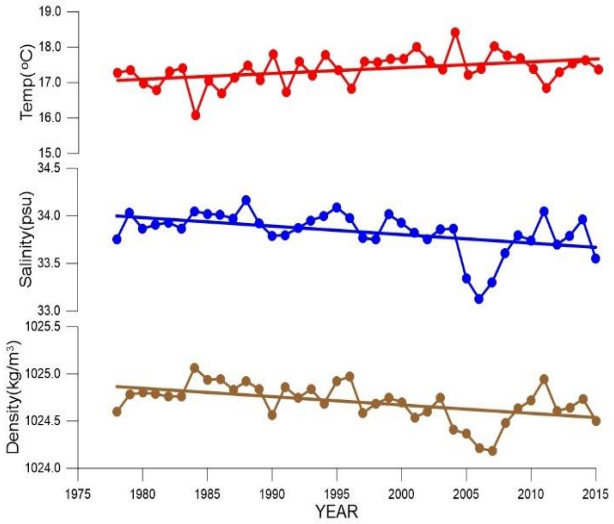


Figure 5. Temperature (red line), salinity (blue line), density (brown line) time series. Temperature is increased, salinity and density are decreased.

Spatially averaged density of sea water was calculated using temperature and salinity, as indicated in Figure 5. The equation of state presented by UNESCO in 1980 was used in the density calculation. Figure 5 shows that the temperature increased, and the salinity and density decreased. The density showed a sudden increase as a result of a temperature decrease at 1984 and a density decreases due to a salinity decrease from 2005 to 2007. The correlation coefficient of the density was -0.67 to temperature and 0.87 to salinity. The density of Jeju Island had a stronger impact due to salinity.

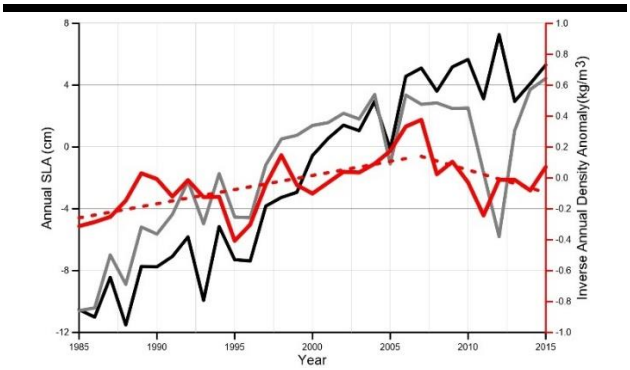


Figure 6. Annual see level anomaly, which is the black line (JTS) and gray line (STS). The inverse annual density anomaly is the red line. The figure shows the tendency of an increase before 2006 and a decrease after the year.

Figure 6 shows annual sea level anomaly (JTS:black line, STS:gray line) and inverse annual density anomaly (red line), which corresponding to the so-called dynamic height due to density change. The anomaly of data was calculated using the mean value during 1993 ~ 2012. It showed a change in terms of its trend from 2006 when the SLR started to decline. The density showed a tendency of a decrease before 2006 and an increase after the year, and this temporal trend change is also showed in Figure 3 for SLR. In other words, it is by the time of 2006 when the trend change for both SLR and density of sea-water is made. According to the result, the SLR slowed down around Jeju Island in 2006, which would be determined by the density.

The steric heights were estimated using the density, which is calculated from temperature and salinity measurement data. The steric height indicates the sea level that varies by the changes in density and has been considered to be more important recently due to global warming. The steric height is defined by Equation (1) (Landerer *et al.*, 2006; Siegismund *et al.*, 2007):

$$\text{Steric height} = -\int_{-H}^{0} \rho'/\rho_o \, dz \qquad (1)$$

where ρ' is the density, ρ_o is usually referenced to a temperature of 0 °C and a salinity of 35 psu. The rising of steric height near Jeju Island, calculated from Equation (1), was found to be 0.883 mm/yr, meaning that the contribution of steric effect on total SLR is 15.8 % at Jeju and 23.2 % at Seogwipo, respectively (Figure 4). This rising of steric height near Jeju Island is higher than that of global mean steric height, which is 0.6 mm/yr (during 1971 to 2010, for 0 to 700 m depth), presented in the IPCC 5th Assessment Report (Stocker *et al*., 2014).

DISCUSSION

This density change is believed to have originated from the complicated ocean environment around Jeju Island. Jeju Island is located at an area that is exposed to the direct influences from the Kuroshio current, the Taiwan current, Changjiang diluted water of the East China Sea, Yellow Sea bottom water, coastal waters around the Korean peninsula, and inflow of rivers to the South sea. These regional characteristics are a reflection of the complicated seasonal changes (Chen *et al.*, 1994; Chen, 2009; Ichikawa and Beardsley, 2002; Lie and Cho, 2016). Further studies will be required on the sea level changes considering these complex characteristics in the area.

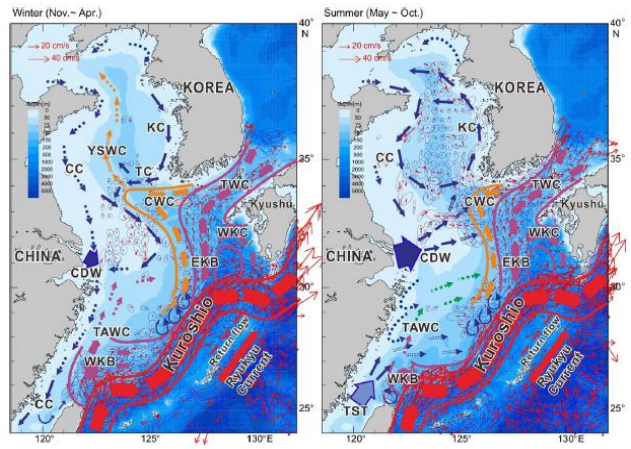


Figure 7. Research around the Jeju Island in summer (right) and winter (left) (Lie *et al.* 2016).

According to Lie *et al*. (2016), around Jeju Island is influenced clearly in summer and winter. Figure 7 shows phase change of major current around Jeju in summer and winter. In winter, the current based on Kuroshio and its branch are the major flow that affect the formation of water mass around Jeju. As is known, Kuroshio current has the characteristics of high salinity and high temperature and the Jeju warm current, which is the branch of Kuroshio, drive the density change around Jeju Island.

On the other hand, in summer, it is more influenced by Yellow sea bottom cold water as well as Changjiang diluted water. In recent years, it seems the Jeju water mass are more affected by the Changjiang diluted water discharge. Since the diluted water has relatively lower density, its steric effect is getting stronger in the summer. In 2006, rapid changes of salinity that is thought occurred from the change due to Changjiang diluted water affecting around Jeju Island. On top of this effect, the wind-drive current is another factor to be considered the sea structure around Jeju Island (Bai *et al*., 2014).

CONCLUSIONS

The rate of SLR around Jeju Island is one of the highest in Korea. It is shown that the pattern of SLR is also different in the areas of northern and southern part of the island. The SLR was found to be 5.63 mm/yr at JTS located in the northern part and 3.75 mm/yr at STS in the southern part of the island. To investigate the cause of this high rate of SLR, temperature and salinity data was examined to grasp the contribution of steric effect to the SLR. Through calculations and an analysis of the density of water mass, it is find that there is strong correlation between the SLR and sea-water density variation, *i.e.*, there is a continuous density decrease during the time of continuous increase of SLR around Juju island.

It is also found that, SLR trend changed and has slowed down since 2006 and the it seems it is also resulted from density alterations. Steric height change was due to density alterations

and the rise rate was indicated in this study. The contribution of steric effect to the SLR in Jeju Island is calculated, *i.e.*, 15.8% at Jeju and 23.2% at Seogwipo.

Therefore, the density change around Jeju Island is inevitably strongly affected by this seasonal oceanic current system. A further quantitative SLR analysis concerning the seasonal change of density structure is needed in the future.

ACKNOWLEDGEMENT

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