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Sea level rise around Korea: Analysis of tide gauge station data with the ensemble empirical mode decomposition method

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Abstract

This study estimates the trend and acceleration of sea level rise (SLR) at the tide gauge stations around Korea as now the data from the stations are recorded for approximately 50 years, which allow us to estimate the acceleration of SLR. We use not only traditional polynomial regression analysis but also the ensemble empirical mode decomposition (EEMD) approach, whose strength is the elimination of long-term variations in sea level data, to process this relatively short-term data. The relative sea level data from the five tide gauge stations around Korea, including Mokpo, Jeju, Busan, Ulsan and Mukho are used in this study. With Jeju showing the highest trend of SLR, all stations exhibit rising trend of sea level regardless of the methods used in this study. Positive accelerations of SLR are found in four out of five stations with the highest acceleration at Mukho. We also compare the results based on the EEMD approach and those based on the regression analysis and find generally consistent results between two. While the trends show the slight differences at the five stations with no tendency toward over- or under-estimation, the accelerations are slightly lower with the EEMD approach than with the regression analysis at all four stations with positive accelerations.

Keywords: Sea level acceleration; Sea level rise; Empirical mode decomposition

1. Introduction

Rising sea level threatens the populations and also the natural environment in the coastal area so that it is necessary to seek for a better understanding of historical and future sea level changes (Cho et al., 2009, 2012) While much attention has been given to the issue of global sea level rise (SLR) and its acceleration over the last two centuries (Boon, 2012), their regional and local variations are also of great interests. Assessing the local and regional pattern of sea level variation plays a crucial role in not only long-term climate change adaptation but also short-term operational hazard management (e.g., Xue and Leetma, 2000).

To estimate SLR and sea level acceleration (SLA), a polynomial regression has been used conventionally. This approach is convenient in that it provides a single value of acceleration and its use is almost universal, making it easier to compare results from different studies (Breaker and Ruzmaikin, 2013). Recently, several studies of sea level acceleration across the coastal regions over the USA (e.g., Breaker and Ruzmaikin, 2011; Ezer and Corlett, 2012; Breaker and Ruzmaikin, 2013) have adopted an approach of the empirical mode decomposition (EMD) method (Huang et al., 1998; Wu and Huang, 2009). It considers oscillatory contributions in a data-adaptive manner and adaptive and thus highly efficient. It is also applicable to nonlinear and nonstationary processes, because it is based on the local characteristic timescale of the data. Since its development by Hunag (1998), it has been used to analyze and model various geophysical data such as sea level, precipitation, radiation and runoff (e.g., Duffy, 2004; Peel et al., 2009; Kuo et al., 2013; Di et al., 2014). For example, Kuo et al. (2013) used the ensemble empirical mode decomposition (EEMD), a successor of EMD, to derived regional intensity-duration-frequency

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(IDF) curve for Edmonton, Canada based on the scaling property of precipitation, and Di et al. (2014) used the EEMD in combination with artificial neural network models to develop a hydrological forecasting model of precipitation and runoff.

The EMD decomposes the data into a number of modes; the final mode, known as the residual, corresponds to a monotonic trend or a curve with only one extremum. It virtually eliminates contamination from interannual, decadal, and multi-decadal variability of sea level and thus the oscillatory behavior of sea level data is contained in the lower modes and not in the residual. Therefore the residual can be analyzed as a separate time series to derive the trend and acceleration of sea level (e.g., Breaker and Ruzmaikin, 2011; Ezer and Corlett, 2012; Breaker and Ruzmaikin, 2013). These studies used the EMD to eliminate the impact of long term variability of sea level height such as the inter-decadal variability of the Pacific Decadal Oscillation (PDO) and the inter-annual variability of the El Niño and the Southern Oscillation (ENSO), which could lead overestimate the sea level rise as a result of climate change. Furthermore, the timescales of such long-term oceanic processes are varying and thus the EMD approach can be better used than the conventional methods, which assume linearity and stationarity: for example, the timescale of the ENSO ranges from one to eight years and averages 3.6 years (Salisbury and Wimbush, 2002).

Using the EEMD, Breaker and Ruzmaikin (2011) decomposed the sea level record from San Francisco (California, USA) to examine the temporal behavior of different modes, such as the interdecadal variability related to the PDO. In particular, Breaker and Ruzmaikin (2013) focused on SLA, investigating the effect of record length on SLA, and derived SLA of +0.011 ± 0.003 mm/yr^2 and 0.013 mm/yr^2 using EEMD and conventional quadratic equations, respectively. Similarly, Ezer and Corlett (2012) employed the EMD approach to analyze sea level data for Chesapeake Bay (Virginia, USA), performing a bootstrapping test to ensure the robustness of the decomposition; they obtained SLA estimates of 0.05–0.10 mm/yr^2, which exceed the estimates obtained by all but one previous studies conducted for Chesapeake Bay.

In Korea, SLR and its impact are of particular interests because three seas surround the landmass encompassing the country. Few studies, however, have estimated rates of SLR along the coast of the Korean Peninsula. Cho (2002) estimated an average SLR of 2.310 ± 2.220 mm/yr based on tide gauge data, after correcting for vertical land movement due to postglacial rebound. Youn et al. (2004) estimated a comparable average SLR of 2.8 mm/yr around the Korean Peninsula. Using TOPEX/Poseidon sea level data as well as the tide gauge station data, Kang et al. (2005) investigated the patterns of sea level rises in East sea of Korea. Their estimated mean trend using the tide gauge data around the Korean Peninsula is 2.9 ± 0.7 mm/yr for 26 years (1977–2002) and 6.6 ± 3.3 mm/yr for 9 years (1993–2001). Such high trend in recent years possibly implies the sea level acceleration but the acceleration is not explicitly estimated in the study.

No studies published to date have presented estimates of SLA in the region. This can be attributed to the lack of observational data records covering sufficiently long time periods as Douglas (1991) noted that record lengths approaching 50 years are required to determine global SLA from tide gauge data. Currently, the longest available record in the region spans only 52 years (1960–2011, Incheon and Mokpo stations), and only three stations (Mokpo, Busan, and Ulsan) have recorded sea level variations for slightly shorter than 50 years (Fig. 1 and Table 1).

In this study, we investigated sea level variations, both trend and acceleration, around Korea using data from the tide gauge stations with record lengths approaching 50 years (specifically, longer than 47 years). We utilized the modified EEMD approach in addition to the conventional polynomial analysis to analyze these data. With these estimates, this study provides the first look of not only trends and accelerations of SLR at the selected locations in Korea to support the community's efforts for adapting and mitigating the recent SLR.

2. Data

2.1. Sea level data around Korea

We obtained monthly sea level data from a global network of tide gauges, the Permanent Service for Mean Sea Level (PSMSL, http://www.psmsl.org; Woodworth et al., 2003). Established in 1933, the PSMSL is based at the National Oceanography Centre in Liverpool, UK, where it is a component of the Natural Environment Research Council and has been responsible for the collection, publication, analysis, and interpretation of global sea level data.

The PSMSL network includes 24 tide gauge stations for the Korean Peninsula: 23 stations from South Korea and 1 from North Korea (Fig. 1a). We used the data from the five stations that had collected data for the longest time (Fig. 1b) Moreover, we ensured that the data coverage extended to recent times (i.e., 2011) and that the ratio of gaps to the total length of each data record was less than 5%. Therefore, the data from Mokpo, Jeju, Busan, Ulsan, and Mukho were analyzed in this study (Table 1). It should be noted that Incheon station (Fig. 1a) produced data over a period of more than 50 years. However, data gaps in the Incheon record exceeded 10% of the total data length; therefore, these data were excluded from this study.

Of the various types of data provided by the PSMSL, we used the monthly revised local reference (RLR) dataset. In case of Korean data, hourly sea level measurements at each station were quality-controlled and processed to generate the monthly data by the Korea Hydrographic and Oceanographic Administration (KHOA). Such data is then provided to the PSMSL, who processes to the monthly RLR data by reducing the monthly and annual means to a common datum. PSMSL performs this reduction using a tide gauge datum history provided by KHOA. The RLR datum at each station is defined to be approximately 7000 mm below mean sea level; this arbitrary choice was made many years ago to avoid negative numbers in the resulting RLR monthly and annual mean