Climate Change Implications Found in Winter Extreme Sea Level Height Records around Korea

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Abstract: The impact of climatic variability in atmospheric conditions on coastal environments accompanies adjustments in both the frequency and intensity of coastal storm surge events. The top winter season daily maximum sea level height events at 20 tidal stations around South Korea were examined to assess such impact of winter extratropical cyclone variability. As the investigation focusses on the most extreme sea level events, the impact of climate change is found to be invisible. It is revealed that the measures of extreme sea level events—frequency and intensity—do not correlate with the local sea surface temperature anomalies. Meanwhile, the frequency of winter extreme events exhibits a clear association with the concurrent climatic indices. It was determined that the annual frequency of the all-time top 5% winter daily maximum sea level events significantly and positively correlates with the NINO3.4 and Pacific Decadal Oscillation (PDO) indices at the majority of the 20 tidal stations. Hence, this indicates an increase in extreme event frequency and intensity, despite localized temperature cooling. This contradicts the expectation of increases in local extreme sea level events due to thermal expansion and global climate change. During El Nino, it is suggested that northward shifts of winter storm tracks associated with El Nino occur, disturbing the sea level around Korea more often. The current dominance of interannual storm track shifts, due to climate variability, over the impact of slow rise on the winter extreme sea level events, implies that coastal extreme sea level events will change through changes in the mechanical drivers rather than thermal expansion. The major storm tracks are predicted to continue shifting northward. The winter extreme sea level events in the midlatitude coastal region might not go through a monotonic change. They are expected to occur more often and more intensively in the near future, but might not continue doing so when northward shifting storm tracks move away from the marginal seas around Korea, as is predicted by the end of the century.

Keywords: winter extreme sea level height; storm surge; extratropical cyclones

1. Introduction

Climate change poses a great threat to countries situated next to the ocean. Islands will be submerged and the available land mass will gradually be encroached, starting with the beach loss. Changes that initially come slowly may be permanent, but can be prepared against because such threats take time to come to fruition. Sea level disturbances driven by passing meteorological systems are more severe threats. Storm tides, are storm surges overlaid on the local tides approaching coastal areas, causing continuous flooding or water level drops for as long as a couple of days, directly affecting livelihoods and the socioeconomic value of coastal zones. The effect of these types of extreme fluctuations tends to be overlooked because the consecutive positive and negative surges cancel each other out when averaged over a long enough period of time. However, the rush of sea water off the coast, in a similar manner to how it floods over the levies in front of a shore village, is far more visible compared to the gradual mean sea level rises due to
thermal expansion and ice-melting (i.e., only a few centimeters in 10 years) [1]. Coastal communities are prepared against large tidal ranges, which are regular and predictable events, but the surges associated with the meteorological conditions can be unexpected as the conditions continuously change. This is especially true for the coasts of countries located in midlatitude regions where typhoons and extratropical cyclones frequently pass, such as the area of interest in this study.

Tropical cyclones and typhoons in the regional oceans around Korea, have been a popular subject as the second deadliest driving force of coastal dynamics, next to tides [2–4]. Among non-tidal surface height records, typhoons are highly likely drivers of the rarest sea level elevation events. However, there are distinct seasonal changes in this area and typhoons make landfall on the Korean Peninsula only in the four or five warmer months of the year. Having said this, the sea surface during the rest of the year is not quiet at all. In fact, the winter sea is much rougher than the summer sea, except for a few occasions lasting only a few days under the influence of typhoons. Extratropical cyclones are the most frequent and powerful driving force for coastal surge events when typhoons are absent.

Despite the fact that they dominate the extreme sea level events of the cold season, winter storm surges have received relatively less attention. This could be partly because of the secondary importance of extratropical cyclones compared to typhoons, and partly because of their atypicality. It is relatively straightforward to model a typhoon due to its formal and simple shape. Future synthetic typhoons, based on various assumptions about strength, size, and path modelled on a sound theoretical background [5,6], can be applied to numerical model experiments for future prediction of coastal environments with a great level of confidence [7]. In contrast, winter extratropical cyclones have no typical shapes or size. The spatial coverage of a single system can vary greatly even within a few hours, and the speed and direction of the winds associated with cyclone systems are highly sensitive not only to the depth of the center, but also to the surrounding air mass. It is too challenging to mathematically synthesize extratropical cyclones, i.e., see [8]. However, the ability to do this would be useful for further studies on the coastal impact of extratropical cyclones. This forms the motivation behind this study; to collect the most effective methodology and data sources, in order to establish a non-mathematical, but data-driven technique for the identification and future prediction of winter extratropical cyclones and winter extreme sea level events around Korea.

Previous studies [9,10] have provided future projections of extreme sea levels through rigorous data archiving from the global network of tidal stations and satellite altimeters, as well as numerically modelled sea levels. Additionally, the worst possible risk of extreme sea level events that could happen once every 100 years has been assessed. However, the assumptions behind these conclusions are straightforward in that the location, shape and scale of the extreme sea levels were predicted to remain as they are currently, or potentially change with time but only monotonically and positively. Thus, the assumed primary change comes from changing mean sea levels due to global warming. Some pioneering studies [11–15] have attributed climatic variability as the modulator for the parameters of extreme distribution, although the physical mechanism behind this has never been fully integrated, therefore, future predictions have remained basic in terms of the simple monotonic parameter changes used [16,17].

The main purpose of this study is to add regional, seasonal and dynamic aspects on top of the previous efforts. The hypothesis of this study is that winter extratropical cyclones are the main driver of winter extreme sea level fluctuations and that the impact of such cyclone systems might overwhelm continuous mean sea level rises. Thus, the extreme statistics of local sea level heights around Korea are expected to be non-stationary and the changes are predicted to be non-monotonic. This study focuses on providing insight into the extreme sea level events in midlatitude regions associated with winter extratropical cyclones. The measures of extremes are considered in two aspects, frequency and intensity. In order to overcome the lack of lengthy records, the impacts of climate variability embedded in the two extreme measures are assessed and compared with the
mean sea level rise range. Then, extratropical cyclones that are directly connected to each extreme sea level event around Korea are identified and characterized, seeking to find their connection with climate variability. Finally, a mechanism-based future projection of extreme sea level events near Korea, based on the Coupled Model Intercomparison Project phase 5 (CMIP5) scenario experiment data, is provided.

2. Materials and Methods

The sea level elevation data used in this study are 1 hourly records from 20 tidal stations in Korea, provided by the Korea Hydrographic and Oceanographic Agency [18]. The data were de-tided using 34 tidal constituents with the Python-based software pytide [19]. The commonly available period from 2000 to 2020 was used for the main analysis, but more long-term data were used for some analyses as needed. The original data were at 1 h intervals, but the daily maximum values were selected to be converted into 1 day intervals.

General extreme value (GEV) analysis [20] was used to fit data to a model distribution for block maxima. Usually, the GEV approach helps to improve estimates of rare extremes that have a greater returning period than the actual record length. The baseline heights of all-time top 5% and 1% events were obtained from the daily maxima in this study. The probability distribution of positive extremes, such as daily maximum of sea level height, are known to follow a Gumbell for zero shape ($\xi \sim 0$) or Fréchet distribution for positive shape ($\xi > 0$), as follows:

$$F(z, \mu, \xi, \sigma) = \begin{cases} \exp[-\exp(-x)]\exp(-x) & \text{for } \xi = 0 \\ \exp[-(1 - \xi x)^{\frac{1}{\xi}}(1 - \xi x)^{-\frac{1}{\xi} - 1}] & \text{for } x \leq \frac{1}{\xi}, \xi > 0 \end{cases}$$

where $z$ indicates block maxima, $\mu$ location, $\xi$ shape, and $\sigma$ indicates the scale of the distribution. This approach has been popular in the sea level research community [9–17]. In order to estimate the three parameters, Python3-based software package genextreme in scipy was used. The software utilizes the maximum likelihood method for parameter estimation [21].

Air pressure at sea level (SLP, hereafter), from the European Center for Medium-range Weather Forecast (ECMWF), atmospheric reanalysis at 3 h intervals [22] were used for the identification of the causes of local extreme sea level events. The regular seasonal cycle from each grid point was removed so that the synoptic meteorological patterns could be clearly identified. Additional storm track data were acquired through an advanced technique. These are the trajectories of the central positions of extratropical cyclones. In the storm tracking algorithm, the cyclones are detected from 3 hourly frames of anomalous SLP fields and the centers of the motion are traced in each frame directly without deducting from the eddy covariance. The software used here is version 1.4.2, developed by Hodges [23]. The storm tracks used in this study have been used in previous research studies, except that the production has been extended for as long as the raw SLP data are available. The detailed information can be found in the references [24,25]. In order to detect the change of the storm tracks due to future climate change, the storm tracks were also detected in the SLP data from CMIP5 climate model experiments. The raw SLP data from 2 different experiments, historical and RCP85 scenario runs [26], produced with the same model, CESM1 [27], were used for the detection of future change.

Empirical orthogonal function (EOF) analysis [28] was applied to efficiently detect the timing of the spatially coherent peaks of extreme sea level events around the Korean Peninsula that are caused by the same storms. Using 3 hourly mean sea levels at 20 tidal stations, standardized at each station, the EOFs and the principal components (PCs; time coefficients) identify the spatial patterns and temporal evolutions of leading surface elevation events. The principal components are utilized to detect the timing of the storm
passing. The detailed application is further described along with the interpretation in the results section.

Sea surface temperature data were from Optimum Interpolation Sea Surface Temperature v2 \[29\] on \(1^\circ\) by \(1^\circ\) grids. The climate indices, El Nino and Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), Western Pacific mode (WP) and Arctic Oscillation (AO) were downloaded from the National Center for Environmental Prediction \[30\] for assessing the remote connection to the measures of local extreme sea level events. Spearman’s correlation \[31\] was estimated to detect the association of extreme event frequency, and Pearson’s correlation \[32\] was estimated to assess the association of extreme event intensity.

3. Results

The measures of extreme sea level heights from 20 tidal station around Korea were assessed, an investigation into climatic impacts on extreme sea level measures was conducted and the current and the future characteristics of extreme changes in sea level caused by extratropical cyclones are suggested.

3.1. Extreme Sea Level Heights around the Korean Peninsula

The Korean Peninsula faces surrounding ocean in three directions. As most storms travel across the Yellow Sea from west to east, sea level fluctuations due to the same storm are usually larger along the west coast of Korea—which is directly exposed to the storm disturbance for a relatively longer period of time—than along the south and the east coasts. Additionally, the shallower bottom topography in the Yellow Sea helps sea water to pile up at the coastline more efficiently. Extreme statistics were assessed by fitting daily maximum sea level data at each station to the GEV model distribution. The three GEV parameters are presented at each station in Table 1. The results are based on the years after 1999, when quality-controlled data are commonly available for all 20 tidal stations. The rarest 1% sea level heights are higher than half a meter for the west coast. These values are about one third of the magnitude measured when compared to the 1% summer data for the west coast. Meanwhile, the rarest 1% sea level heights in the east and the south coasts range from 22~44 cm, with little difference in the summer data. The long-term data trends since 1999 were also assessed. Only one station, Pohang on the east coast, that shows a significant linear trend. Except for Pohang, the trend estimates are less than 5 cm per decade, which presents no visible sign of slow change over a long period of time in this area. This is the case even if reasons existed to expect a slow increase in extreme sea levels, such as rising surface temperatures or intensifying wind with climate change.

Figure 1 shows a detailed analysis of the daily maximum sea level heights since 1985 in Gunsan, one of the old harbors on the west coast of the Korean Peninsula. In the case of Gunsan, the location was 18.64 (cm), the scale determining the tail length of the distribution map was 12.58, and the parameter determining the shape bias was 0.13. These parameters produce a distribution at the 5% level of 49.64 (cm) and at the 1% level of 62.19 (cm). The inconsistency with the values in Table 1 reflects the inclusion of 15 additional years prior to 1999. Figure 1a shows the distribution of the daily maximum sea level at Gunsan. The extreme sea level phenomena in the station records were further explored from the aspect of climatic variation. Two temporal measures of the extreme sea level events were invented. First, temporal variations of the occurrence of extreme sea levels were produced. Using the extreme thresholds assessed with GEV analysis, the annual occurrences of the all-time rarest 5% and 1% cold season sea level events were counted. In Figure 1b, with the sample data from Gunsan harbor, a wide range of interannual variability for both the 5% and 1% events can be found, whereas no outstanding linear increase is detected. The cold season extreme sea level events in this harbor occurred more frequently in the first decade of the 21st century, but occurred less often before and after that. Second, the intensity of the extreme events was investigated in terms of the climatic aspects. The annual cold season 5% and 1% extreme sea level heights were selected and averaged (Figure 1c). Again, in the sample, data from Gunsan harbor do not show a linear increase in sea level heights.
Instead, relatively higher elevations were found both in the 5% and 1% averages during the first decade of the 21st century, but lower elevations were noted before and after that.

Table 1. General extreme value (GEV) parameters, the sea level extremes at 5% and 1%, and the embedded linear trends (cm/decade, with r-squared value) for daily maximum at 20 tidal stations around Korea, based on cold months (November–December–January–February–March–April) in 1999–2020.

| Basin | Station | Location, µ | Shape, ξ | Scale, δ | 5% (cm) | 1% (cm) | Linear Trend (cm/decade) |
|-------|---------|-------------|----------|----------|---------|---------|-------------------------|
| South coast | Gadekdo | 3.76 | 0.21 | 7.72 | 22.89 | 26.67 | 4.98 (0.11) |
| | Geomundo | 5.31 | 0.15 | 7.96 | 24.27 | 31.53 | 2.27 (0.02) |
| | Busan | 3.35 | 0.11 | 7.63 | 22.75 | 31.03 | 2.32 (0.03) |
| | Seogwipo | 3.92 | 0.13 | 8.68 | 25.31 | 33.97 | −0.01 (0.00) |
| | Yeosu | 7.10 | 0.11 | 8.80 | 29.36 | 38.78 | 0.58 (0.00) |
| | Wando | 9.37 | 0.15 | 10.25 | 33.84 | 44.22 | 1.86 (0.01) |
| | Jeju | 5.33 | 0.12 | 7.94 | 25.13 | 33.31 | 2.96 (0.04) |
| | Chujado | 8.63 | 0.20 | 10.21 | 31.49 | 39.34 | 3.78 (0.04) |
| East coast | Mukho | 0.38 | 0.16 | 6.93 | 16.66 | 22.73 | 2.63 (0.04) |
| | Sokcho | 0.17 | 0.17 | 7.03 | 16.65 | 22.77 | 3.41 (0.06) |
| | Ullengdo | −0.24 | 0.22 | 11.19 | 24.13 | 32.08 | 4.89 (0.05) |
| | Ulsan | 0.74 | 0.18 | 7.19 | 17.29 | 23.22 | 3.20 (0.05) |
| | Pohang | −0.17 | 0.22 | 9.34 | 20.33 | 27.11 | 10.41 (0.34) |
| | Gunsan | 14.63 | 0.15 | 11.96 | 43.43 | 54.65 | 5.46 (0.05) |
| | Heukseando | 10.35 | 0.04 | 14.90 | 51.80 | 72.33 | 4.78 (0.04) |
| | Mokpo | 15.61 | 0.08 | 10.91 | 43.32 | 57.30 | 1.06 (0.00) |
| | Boryeong | 17.95 | 0.14 | 13.12 | 49.72 | 62.20 | 2.12 (0.01) |
| | Wido | 12.41 | 0.11 | 13.02 | 45.40 | 59.41 | 1.07 (0.00) |
| | Pyeongtaek | 19.14 | 0.10 | 13.27 | 53.19 | 67.97 | −1.72 (0.00) |
| | Incheon | 19.65 | 0.14 | 13.57 | 52.75 | 65.93 | 0.79 (0.00) |

3.2. Identifying Physical Conditions behind the Extreme Sea Level Events Near Korea

In order to assess the influence of climate variability, the climate indices that are known to be geographically close to or remotely associated with the studied area were examined for coherence with the local measures of the extreme sea level events. Several climate indices, including ENSO, PDO, AO and WP, were closely examined. The rarer the extreme events, the harder it is to find general rules of temporal variation. Therefore, the results for the top 5% measures are mainly presented, as they correlate more highly and significantly with the climate indices than those for the top 1%.

The frequency of extreme sea level events is expected to closely connect with the frequency of extratropical cyclones passing nearby. Meanwhile, the average height of the extreme events can be explained both by the individual sea level height variation due to the intensity of each meteorological system and by the mean sea level variation due to local surface temperature anomalies associated with the specific climate indices. In order to confirm this expectation, we examined whether the measures of extreme sea level height correlate with the local temperature anomalies. This is an effective test of the hypothesis that the frequency of local extreme sea level events in the studied area is primarily driven by the number of passing storms, not by thermal expansion lifting the sea level more often above the extreme thresholds with warmer temperature anomalies. Figure 2a,b shows that local sea water temperature has little effect on the frequency throughout the studied area. However, the intensity of the extreme events shows some co-variability with the local surface temperature, with this being significant at some locations. It is not obvious, though, if the intensity variation is purely affected by the local temperature or due to the same mechanical cause that drives the variations in local temperature.
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Figure 2. Correlation coefficients between the labeled indices and the extreme measures at each station. Spearman's correlation for the annual frequency of all-time top 5% events on the left and Pearson's correlation for the average of the annual top 5% daily maximum heights on the right. Top panels, (a,b), indicate the correlation with anomalous winter mean local Sea Surface Temperature average. The middle panels, (c,d), depict the same, but with the Nino34 index. The bottom panels (e,f), depict the same, but with the Pacific Decadal Oscillation (PDO) index. Green triangles indicate significance at 95%.
Correlation coefficients with other indices were found to not be as significant as those with ENSO and PDO, except for AO, which was found to be positively and significantly correlated with the average intensity of annual extreme sea level heights along the east coast of Korea. No such significance was found on the west coast (not shown). It is notable that the AO index is the only climate indicator used here that shows an outstanding positive linear trend since 1999. Although it is beyond the scope of this study, the meteorological causality between intensity increases in individual extratropical cyclones and changes in large scale atmospheric circulation is worthy of investigation. WP does not correlate with the frequency or intensity of the extreme sea level events in Korea (not shown), probably because it is dominant in summer.

It is intriguing to see that the ENSO and PDO indices correlate significantly with extreme sea level events, meaning that extreme sea level height events occurred more frequently with the positive phases of ENSO and PDO, when the corresponding local SST values were preferentially negative. This obviously indicates that extreme sea level fluctuations are little affected by thermal expansion. Rather, it is implied that the mechanical forces carried by the passing winter extratropical cyclones could be the direct and primary cause of extreme water levels. A closer look at the direct relationship between winter extratropical cyclones and storm surge events around the Korean Peninsula is essential to better understand the connection between large-scale climate variability and the probability of regional extreme sea level events.

In order to select only the meteorological synoptic patterns that directly connect with the winter extreme sea level events in Korea, it is important to determine the timing at which extreme sea level events peak around the Korean Peninsula. Since it is highly likely that a single storm can cause spatially coherent extreme events in this region, we aimed to construct temporal evolutions of a few spatially coherent patterns of extreme events. For this purpose, empirical orthogonal function analysis is one of the most popular techniques, as it sorts out space–temporal modes according to the size of the variance. Thereby, an EOF analysis was performed on the 3 hourly sea level heights at the 20 tidal stations around Korea. Only the cold season records from November to April were considered. We were not interested in the size of the peaks at individual stations, so the data from each station were standardized before forming a covariance matrix. The first two EOF modes explain 54% and 19% of the total variance. The spatial patterns of the two leading modes are presented in Figure 3a,b. EOF1 depicts a nation-wide elevation (Figure 3a), as the mature state of EOF1 indicates positive elevation everywhere. Meanwhile, EOF2 presents some divisions in a slanted direction running from the southwest to the northeast (Figure 3b). The mature negative elevation is concentrated in the middle part of the peninsula, preferentially loaded on the west coast. Meanwhile, one station (Incheon) in the far off the north and the stations belonging to the south coast, showed a positive phase in the middle part. With the autocorrelation of the two PCs shown in Figure 3c, it is implied that EOF1 shows phase reversal, within 40 h. However, the reversal is very weak and did not recover the strength afterwards, so it is suggested that the EOF1-type surge event decays within less than 2 days. Meanwhile, EOF2 is not oscillatory, and its autocorrelation maintains a certain level for a long lag time, implying that longer time scale variability, such as persisting winter monsoon conditions, might be involved.

3.3. Classification of the Storm Surge Causing Synoptic Systems Near Korea

Data on the extratropical cyclones that cause winter extreme sea level events around the Korean Peninsula were collected and classified. The 3 hourly snapshots of SLP from the reanalysis data were used, after removing the seasonal cycle, to easily detect the outstanding synoptic low pressure systems.
EOF analysis was applied to obtain the timing of extreme events across the studied area, occurring within a reasonably short time. Additionally, it was assured that each elevation record was caused by the same synoptic metrological system. The timings of the extreme sea level events were detected using the principal components (PCs) of the two leading EOF modes. Since the passing of a synoptic system can last longer than several hours, counting the same event twice must be carefully prevented. The following procedure can minimize the possibility of double counting. The PCs of the two leading EOF modes are first sorted in descending order by the size of the coefficients. The time of the highest sea level peak is selected, then, any height records within 72 h before and after are removed, before collecting the timing of the next highest sea level. The selection is repeated until no unselected sea level height data points remain in the top 5% high sea level record, leaving 274 and 136 events.

Finally, two major types of extratropical cyclones that dominate about 73% of the 3 hourly sea level height fluctuations around the Korean Peninsula were identified. The sea
level pressure anomalies at the timing of the peak of the major extreme events, represented by EOF1 and EOF2, were collected to measure the composite averages and their spread.

When the frames of sea level anomalies were collected at each peak time, the frames prior to the peaks were also collected every 6 h backward to investigate the whole process, including the development and movement of the systems. In Figure 4, the sequential transitions of the typical synoptic pattern that causes two of the most dominant cold season sea level fluctuation patterns are presented. From the top left to the bottom right, for both the cases, the typical extratropical cyclone systems can be easily identified by naked eyes. The extratropical cyclones associated with EOF1-type surge activities develop in northwestern China, cross the Yellow Sea and keep traveling eastward across the Korean Peninsula. The other group, associated with EOF2-type surge activities, strengthens around Korea 30 h prior to the full development of EOF2 surge activities, moves southeastward and exits the East Sea to enter the Western North Pacific. Although the EOF patterns of coastal sea level heights are implied as being antisymmetric between the phase reversal, it is not guaranteed that the sea level pressure patterns accompanied by the extreme ends of positive and negative sea level height patterns will be antisymmetric. Nevertheless, the SLP patterns associated with the extremely negative PC2s are more or less antisymmetric to those shown in Figure 4b. When an extreme positive surge along the west coast occurs with an extreme negative one in the south, a synoptic anticyclone develops in the south and is eventually pushed away eastward by the low pressure system that develops in the north west of the Korean Peninsula (not shown).

These captured extratropical cyclone evolutions provide quite consistent explanations for the characteristics of each EOF mode of the coastal surge events. The first group involves a strong zonal pressure gradient, created between the oncoming low pressure and the high pressure already developing in the East Sea (Figure 4a). The spatial coverage between the two systems is large enough to cover the relatively narrow Korean Peninsula in the zonal direction. This is consistent with the EOF1-type surge events that occur everywhere in Korea almost synchronously. The second group starts with a pre-existing low pressure system above Korea (Figure 4b). This system travels eastward, while a meridional pressure gradient intensifies. The narrow zonal band of strong wind associated with the pressure

![Figure 4. Composite average of the sequential snapshots of average sea level pressure anomalies at every 6 h from 30 h prior to the time of top 5% peak coefficients for (a) EOF1 and (b) EOF2. See the text for details of choosing the “top 5% peaks” (CI = 0.5 hPa). The thick black contour indicates zero, and the dashed line indicates negative air pressure at sea level (SLP) anomalies. Shading indicates the uncertainty of the averages.](image-url)
gradient falls short of covering the whole Korean Peninsula lying on a meridional axis. This spatial distribution of meteorological conditions matches well with the EOF2-type surge events. EOF2-type surge events consist of 2–3 divisional bands aligned parallel to the isobaric contours, as shown above in Figure 4b.

3.4. Storm Track Variability and Future Change

The extratropical cyclones are suggested as the primary cause of the cold season extreme sea level events around Korea detailed in the previous section. ENSO and PDO are found to be significantly correlated with the frequency and intensity of these extreme events. The next question that needs to be answered, is how are the counts, intensity and paths of individual storms that cause extreme sea level events affected by large scale atmospheric circulation variability and changes, such as ENSO and climate change? As we find strong bonds between the frequency of extreme sea level events with ENSO, we first investigated if trajectories of the extratropical cyclones make such a difference between El Nino and La Nina in distinctively varying their influence on the coastal environment in the Korean Peninsula. Storm track data obtained by a cyclone tracking algorithm [23] were analyzed in order to identify such climatic implications. The frequency of a cyclone center passing $2^\circ$ by $2^\circ$ rectangles was measured everywhere in the presented domain (Figure 5). Although it is hard to assure the robustness of this method, because of the insufficient temporal coverage of the data, there are a couple of noteworthy implications. More extratropical cyclones tend to pass the Yellow Sea and the East Sea during El Nino winters than normal winters. In the meantime, fewer than normal numbers of storms pass the Korean territory and Japan during La Nina. These anomalies are a part of the large-scale storm track pattern variability, which are more or less symmetric between the phases of ENSO that occur when it is close to the center of the activity in the North Eastern Pacific [30]. However, in the Western North Pacific near Korea, the preferred storm tracks between El Nino and La Nina are asymmetric. This seems to be partly because the geographical location is in the skirt off of the center of the storm track activity, located in the Eastern North Pacific. Additionally, it is notable that the location of storm genesis can vary, which is not symmetric between El Nino and La Nina, but rather the locations shift here and there (not shown).

![Figure 5. Storm track density anomalies presented in count per unit rectangle per season. Composite average in (a) El Niño winters and (b) La Niña winters. The contours overlaid in green are the climatological means. Stippled where significant at 75% and hatched at 95% with Student’s t-test.](image)

It is worth mentioning that grid points with near zero counts do not mean that these locations are not affected by storm track variability. Rather, this map simply indicates more likely locations for the center of a cyclone to travel through. With its center following this
track, a single cyclone system—of which the size can be large enough to cover both the Yellow Sea and the East Sea, as shown in Figure 4—would travel as a single system. Both the preferred paths during El Nino and avoided paths during La Nina involve the Korean Peninsula and its neighborhood, implying a consistent message with the result presented in Figure 3, that the frequency of storms that cause extreme sea level changes is increased in El Nino years and decreased in La Nina years.

Meanwhile, the same method is applicable for investigating changing storm tracks in the future. Due to the lack of real data, the results from the CMIP5 experiment from a single model were analyzed in the same way as the reanalysis sea level pressure fields were examined. Figure 6 shows the future change (in approximately 70 years) in the winter storm tracks according to the worst CO2 emission scenario of RCP85. According to this experiment, a clear northward shift and expansion of the major storm tracks off to the northeastern region of China are expected in the next 70 years or so. Previous studies using multiple CMIP5 models have agreed on the northward shift of the major storm track in both the North Pacific [33] and the North Atlantic [34] in the future climate change scenario. Using a single model output, internal uncertainty was assessed and the results are presented in Figure 6. However, the uncertainty across different climate models, and uncertainty due to the coarse spatial resolution of climate models have not been fully assessed yet. At this point, uncertainty in the location and the spatial extent of the storm track shift remains large. The clearest finding here is that the long-term changes in the frequency and intensity of extreme sea level events are not expected to show a linear monotonic trend from a dynamical perspective. This is especially true for the locations near to where extratropical cyclones frequently pass. For example, extreme sea level events will be maximized when most cyclone centers pass both the Yellow Sea and the East Sea. In the more distant future, when storm tracks shift too far beyond the hot spots, extreme sea level events might decrease.

![Figure 6](image_url)

**Figure 6.** Same as Figure 5 except for future drift from the period [2034-2005] to [2099-2070] is shown, as simulated by Community Earth System Model 1 model, following the Representative Concentration Pathway 85 scenario, as a part of the Coupled Model Intercomparison Project phase 5 project.

4. Discussion

In this study, the regional characteristics of winter extreme sea level heights around the Korean Peninsula were examined. The frequency of all-time top 1% and 5% cold
season events and the average height of the annual 1% and 5% cold season events were investigated. The extreme measures vary interannually, but the long-term change for the last 20 years was not found to be significant anywhere in the studied area. To identify the mechanism behind the extreme variability, the correlation between the local temperature and various climate indices along with measures of local extreme sea levels was assessed.

The impact of mean sea level rise, due to local thermal expansion along with global warming, was found to not be important in the temporal change and variability of extreme sea level events in this region. This is supported by the low correlation with local SST for most of the tidal station records around Korea. Instead, it was found that the Nino3.4 index is positively and significantly correlated with the majority of station records of extreme sea levels around Korea. This reconfirms that thermal expansion is not as important for the occurrence of extreme sea level events as the storms that mechanically force the water level to rise and fall on a day-to-day time scale.

The 30 h evolution of winter surges, generating low pressure systems around Korea, is divided into two different types. The first type is associated with about 54% of sea level fluctuations that are almost synchronous across the Korean Peninsula. This type of low pressure system develops in the northeastern region of China, travels eastward across the Yellow Sea along an intensifying pressure gradient, and its center reaches central South Korea at the time of the peak. The second type is associated with about 20% of sea level fluctuations that seesaw around a slanted axis in the northeast-to-southwest direction. This pattern develops around Korea, travels southeastward, and exits to the northwest Pacific Ocean.

Both the typical systems churn up strong surface winds and produce an inverse barometer effect while passing through the Korean Peninsula, generating winter extreme sea levels. The cause of the extreme sea levels associated with El Nino events are partially explained via the preferred storm track paths that are dependent on the ENSO phase. The historical storm track expands the spatial coverage northwestward during the El Nino period, while it shrinks the spatial coverage during La Nina events in the vicinity of the Northwest Pacific. This qualitatively implies that a greater frequency of storms that typically cause extreme sea level events around Korea pass during El Nino years and fewer pass during La Nina years. This storm track variability is substantially more effective than thermal shrinking due to cold local SST anomalies that are associated with El Nino. Therefore, extreme events more frequently and more intensively occur in El Nino winters.

Meanwhile, we found that future predictions with the worst case CO₂ emission scenario (RCP85), results in future storm tracks being located further northward than the present locations. Based on the spatial extent of the storm track change in the climate model prediction, the storm tracks are expected to shift northward and accompany a non-monotonic change in the measures of extreme sea level around Korea. In the near future, greater exposure to storm tracks is expected in Korea. In the more distant future, however, the impact of winter storm tracks might decrease, as the storm tracks are expected to shift far northward from the vicinity, thus, not influencing the Korean Peninsula.

This study focuses on winter extreme sea levels, which have received relatively little attention due to their secondary importance in terms of typhoon-generated extreme sea levels. This study fills in a previously existing knowledge gap as regards the hidden risk of cold season surges. The independent measures of frequency and intensity of daily maxima, as well as the attempt to provide a wider view of the spatially and temporally coherent phenomena, enable this study to successfully capture the role of extratropical cyclones in generating winter extreme sea level events. However, we did not investigate if a relationship exists between the depth of the traveling low pressure system and the intensity of the extreme events. Depth data recorded from each storm are already available for use, since they have been archived along with the positions of the storm track for further investigation. However, this issue remains unsolved and is recommended as a topic for future study. This comprises a highly non-linear problem that requires the involvement of numerical model experiments.
As for future numerical studies of coastal surges, the statistical and physical findings of this study can serve as a guideline in synthesizing surface boundary forcing of future predictions. Such studies could employ ensemble model simulations, forced by the future surge-generating extratropical cyclone probability, which is justifiable based on the clever combination of current and future statistics related to extratropical cyclones. For instance, due to the fact that many studies have attempted typhoon simulations [3,4,7], it would be reasonable to use the current spatial shapes of the storms and the future paths and depth of the cyclone centers predicted with coarse grided climate models. In this way, it would be possible to suggest an alternative and improved method for assessing extreme sea levels with long return periods.

Finally, a cautionary remark should be made for this study. Namely, the narrow zonal bands near the extratropical storm tracks that happen to include a nonnegligible size of densely populated coastal areas, might not unilaterally face a monotonic rise in winter extreme sea levels as the result of climate change. As the climate model predicts that extratropical storm tracks under a warming climate migrate poleward, some areas might experience decreasing extreme events as the storm track moves away from the location, while some others might abruptly start seeing unprecedented extreme sea levels, as the vicinity will likely enter into a regularly stormy zone. On top of the expected global mean sea level rise 0.3–0.8 m [1,35], which would undoubtedly elevate the average height of the extreme sea level events in this area at the end of this century, the migrating storm tracks due to climate change would reshape the characteristics of winter sea level extremes in the locations within reach of the current and future storm tracks. In such a region as the Korean Peninsula, the added insight obtained by this study is certainly advantageous in implementing coastal risk management strategies.

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