

Article

Regional Mean Sea Level Variability Due to Tropical Cyclones: Insights from August Typhoons

MyeongHee Han ¹, SungHyun Nam ² and Hak-Soo Lim ^{1,*}¹ Marine Natural Disaster Research Department, Korea Institute of Ocean Science and Technology, Busan 49111, Republic of Korea; mhan@kiost.ac.kr² School of Earth and Environmental Sciences/Research Institute of Oceanography, Seoul National University, Seoul 08826, Republic of Korea; namsh@snu.ac.kr

* Correspondence: hslim@kiost.ac.kr

Abstract: This study investigates the interannual variations in regional mean sea levels (MSLs) of the northeast Asian marginal seas (NEAMS) during August, focusing on the role of typhoon activity from 1993 to 2019. The NEAMS are connected to the Pacific through the East China Sea (ECS) and narrow, shallow straits in the east, where inflow from the southern boundary (ECS), unless balanced by eastern outflow, leads to significant convergence or divergence, as well as subsequent changes in regional MSLs. Satellite altimetry and tide-gauge data reveal that typhoon-induced Ekman transport plays a key role in MSL variability, with increased inflow raising MSLs during active typhoon seasons. In contrast, weak typhoon activity reduces inflow, resulting in lower MSLs. This study's findings have significant implications for coastal management, as the projected changes in tropical cyclone frequency and intensity due to climate change could exacerbate sea level rise and flooding risks. Coastal communities in the NEAMS region will need to prioritize enhanced flood defenses, early warning systems, and adaptive land use strategies to mitigate these risks. This is the first study to link typhoon frequency directly to NEAMS MSL variability, highlighting the critical role of wind-driven processes in regional sea level changes.

Keywords: sea level; typhoon; interannual variation; sea surface wind; Ekman transport; satellite altimeter

**Citation:** Han, M.; Nam, S.; Lim, H.-S.Regional Mean Sea Level Variability Due to Tropical Cyclones: Insights from August Typhoons. *J. Mar. Sci. Eng.* **2024**, *12*, 1830. <https://doi.org/10.3390/jmse12101830>

Academic Editor: Anatoly Gusev

Received: 12 September 2024

Revised: 9 October 2024

Accepted: 9 October 2024

Published: 14 October 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The rapid rise in mean sea levels (MSLs) globally [1] and regionally [2] has necessitated the elucidation of changes in MSLs. To identify anthropogenic effects on climate and adaptation strategies for coastal communities, the causal relationship between observed sea level change (SLC) and underlying processes needs to be addressed. Also, reliable projections of regional [3] and global MSLs should be provided [4]. Meyssignac et al. [5] largely attribute the variability in observed regional sea levels over the past two decades to steric effects, which are related to changes in water temperature and salinity that cause the expansion or contraction of water columns. However, Pinardi et al. [6] emphasize that, in the semi-enclosed Mediterranean Sea, in addition to almost periodic seasonal steric effects, mass changes play a crucial role in regional MSL variability. They identified significant stochastic-like mass effects that result from imbalances between inflow and outflow transports, leading to either convergence or divergence of water masses. These imbalances generate variability in sea levels independent of steric changes. Similar processes are expected in the northeast Asian marginal seas (NEAMS), which include the northern East China Sea (ECS; 31.5° N north), Yellow Sea (YS), Bohai Sea (BS), and East Sea (ES; till west of Tsugaru and Soya Strait, till south of 52.0° N). In this region, regional MSLs may vary significantly, owing to mass convergence–divergence. The monitoring and analysis of sea level fluctuations in the NEAMS have become critical, as damages caused by storm surges pose a major risk of local flooding owing to climate change [7]. The SLCs driven by

typhoon activities have significant implications for regional sea level fluctuations, which are generally caused by tropical cyclones, e.g., hurricanes in the North Atlantic Ocean. However, SLC issues associated with storm surges caused by tropical cyclones have not been widely discussed in terms of regional MSLs, and only locally inverted barometric responses to low atmospheric pressure systems have been studied [8]. Moreover, typhoon intensity is expected to increase in the future, along with warming conditions [9], indicating the increasing significance of SLC driven by typhoons.

In the western North Pacific Ocean, the average interannual variations in MSLs during summer and winter across the NEAMS (Figure 1) are primarily induced by changes in horizontal mass convergence and divergence owing to surface wind-induced Ekman transport and the consequent imbalances between inflow and outflow transport [10,11]. Also, those in summer and winter are caused by regional sea surface wind patterns related to western Pacific summer atmospheric pressure and Asian winter monsoons, respectively [10,11]. The NEAMS MSLs are sensitive to regional wind forcing together with regional ocean circulation and semi-enclosed marginal sea features [10–15]. The semi-enclosed NEAMS has an inlet–outlet system consisting of inflow from the Pacific across the wide and shallow ECS shelf along the southern boundary (Area B) and outflow into the Pacific through narrow and shallow straits across the eastern boundary (Area C) (Figure 1). The imbalance between inflow and outflow due to changes in wind-induced Ekman transport may cause horizontal convergence or divergence, leading to changes in the NEAMS MSL. However, although typhoon activities occasionally but significantly affect regional wind patterns, particularly in the typhoon season in summer, the effects of typhoons on the NEAMS MSLs have yet to be explored.

Several studies have investigated the responses of the local upper ocean to typhoons, including sea surface cooling [16], coastal surges [17] and jets [18], oceanic internal waves [19], and phytoplankton blooms [20]. However, only a few studies have focused on SLCs related to strong winds associated with storms, and fewer studies on long-lasting storm-wind-induced SLCs. For example, Wu et al. [21] reported a sea level rise (SLR) of up to 24 cm resulting from typhoon wind-induced Ekman transport in the BS in June 2011. Ragone et al. [22] recorded a sea level reduction of a few centimeters in the western Mediterranean Sea due to divergence and enhanced Ekman transport associated with Medicanes, which are hurricanes in the Mediterranean Sea. Liu et al. [23] indicated that the peripheral winds of typhoon Mangkhut shifted the sea surface flow from the southeastern South China Sea to the north in Beibu Gulf (BBG) and increased the sea surface height in most areas of BBG. Therefore, the effects of typhoon activity on month-long regional MSLs in semi-enclosed and/or marginal seas remain unclear. Despite these findings, the extent to which typhoons contribute to regional MSL variability in semi-enclosed seas like the NEAMS remains largely unexplored.

This study aims to fill this gap by investigating the impacts of typhoon-induced Ekman transport on interannual MSL variations in the NEAMS during August, a peak period for typhoon activity. The NEAMS, which includes the ES, ECS, YS, and BS, features a unique inflow–outflow system where inflow occurs across the ECS shelf, and outflow occurs through the Tsugaru and Soya Straits. Although the NEAMS includes regions of varying depth, such as the deep ES (1700 m) and the shallow YS and ECS (44 m and 77 m, respectively), we treat it as a single sea level system to better understand its overall dynamics. This research addresses a critical gap in understanding the long-term impacts of tropical cyclone-induced wind stress on regional MSLs, particularly in semi-enclosed marginal seas. Building on existing literature enhances our knowledge of how extreme weather events contribute to sea level variability. The findings of this study will improve projections of MSL changes under future climate conditions, especially for regions vulnerable to the increasing frequency and intensity of tropical cyclones. Furthermore, by connecting these insights to global concerns regarding tropical cyclones' impact on SLR, this research contributes to broader discussions on climate change and coastal vulnerability. The results not only deepen our understanding of regional MSL variability in the NEAMS but also

offer valuable perspectives on how tropical cyclone activity could influence sea levels in other semi-enclosed seas around the world. Such knowledge is essential for refining sea level projections and strengthening coastal resilience in the face of climate change.

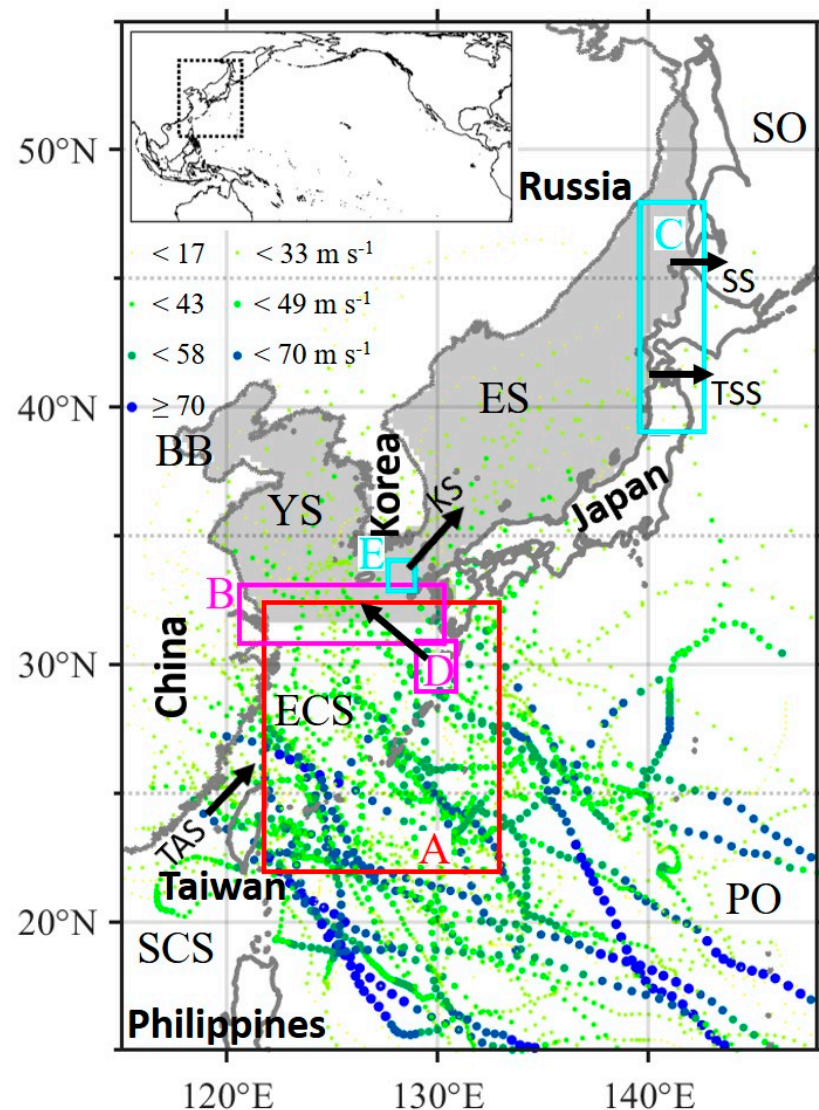


Figure 1. Domains of the NEAMS (gray shading), including Area A, where typhoon activity was assessed; Areas B and C, where inflow and outflow occur, respectively (black arrows indicate basic flow transport); and Areas D and E, which are related to time series of zonal and meridional winds. Typhoon tracks are superimposed with symbol sizes and color scales according to maximum sustained wind speeds of 17, 33, 43, 49, 58, and 70 m s^{-1} for the months of August from 1993 to 2019. ES, YS, BS, ECS, SCS, SO, and PO denote the East Sea (Sea of Japan), Yellow Sea, Bohai Sea, East China Sea, South China Sea, Sea of Okhotsk, and Pacific Ocean, respectively. KS, TAS, TSS, and SS represent the Korea/Tsushima Strait, Taiwan Strait, Tsugaru Strait, and Soya Straits, respectively.

2. Materials and Methods

Daily absolute dynamic topography (ADT: sum of mean dynamic topography and sea level anomaly) data were obtained from the Copernicus Marine Environment Monitoring Service (CMEMS), with data from all satellite altimeter missions gridded at a horizontal resolution of 0.25° [24,25]. We used Level 4 of the ADT data for the NEAMS (Figure 1), e.g., `dt_global_allsat_phy_l4_20190831_20200309.nc`, downloaded from the CMEMS portal [26,27] for 1993–2019. These data were accessed from the CMEMS portal on 30 November 2022. The ADT data were produced after applying geophysical range corrections, includ-

ing dynamic atmospheric correction (DAC), as well as corrections for the dry and wet troposphere, ionosphere, sea state bias, ocean tide, solid earth tide, and geocentric pole tide [28].

For the geophysical range corrections, DAC can effectively simulate sea level responses to atmospheric pressure force in the YS and ECS [29]. Along with recent improvements in barotropic models, this has allowed for the reconstruction of maximum storm surge levels over the past 60 years [30]. In addition, as we identified no visual effects of dynamic sea level responses to strong atmospheric pressure force associated with typhoons in daily ADT data, we examined the effects of typhoon-related winds on SLCs using ADT with DAC in the NEAMS.

Daily ADT data were climatologically averaged for August of each year, and long-term linear trends were removed at each grid point. The detrended August ADT anomalies were spatially averaged across the NEAMS to investigate interannual variations in summer MSLs [11]. Composite analyses were used to classify changes in the summer MSLs of the NEAMS into the following two periods: *Period H* for high MSL (>2 cm) and *Period L* for low MSL (<2 cm).

Typhoon track, storm grade, and maximum sustained wind speed data were obtained from the International Best Track Archive for Climate Stewardship on 15 January 2024. We used Version 4 with a temporal resolution of 3 h for the northwest Pacific Ocean over a 27-year period [31]. In addition, we counted typhoons that passed through the ECS shelf (Area A: 122.00–133.00° E and 22.00–32.50° N, Figure 1) every August within the same period. In our initial study, typhoons were included in this study only when 1 min maximum sustained wind speed exceeded 33 m s^{−1} [32]. However, in this study, we use data from all typhoons, regardless of wind speed.

We obtained 6 h zonal (positive eastward) and meridional (positive northward) wind stress data for the month of August and MSL atmospheric pressure data monthly from the European Centre for Medium-Range Weather Forecasts Re-Analysis fifth generation (ERA5) on 9 September 2021, and gridded these data at a horizontal resolution of 0.25° in the northwest Pacific Ocean (100.0–180.0° E and 0.0–63.0° N, Figure 1). In addition, hourly zonal and meridional wind velocity data at 10 m above MSL were used only for two Augusts (August 2001 and August 2002), Area D (129.00–131.00° E; 29.00–31.00° N; Figure 1) in 2001 and Area E (128.00–129.00° E; 33.00–34.00° N, Figure 1) in 2002, to examine the effect of typhoon wind on the MSLs in August 2001 and 2002, respectively. The monthly surface net heat flux, water temperature, and salinity data from the Ocean Reanalysis System 5 (ORAS5) were obtained on 15 November 2023 to calculate MSL by heat flux, heat transport, and salt transport.

Zonal and meridional Ekman transports per unit lateral width (VT_{E_Ekman} and VT_{N_Ekman} , m² s^{−1}) were calculated from the meridional and zonal surface wind stresses (τ_N and τ_E , respectively, N m^{−2}) using the following equations [10]:

$$VT_{E_Ekman} = \int_{D_{Ekman}}^0 u_{Ekman} dz = \int_{D_{Ekman}}^0 \frac{1}{f\rho} \frac{\partial \tau_N}{\partial z} dz = \frac{1}{f\rho} [\tau_N]_{D_{Ekman}}^0 = \frac{1}{f\rho} \{ \tau_N(z=0) - \tau_N(z=D_{Ekman}) \} = \frac{\tau_N(z=0)}{f\rho} \quad (1)$$

$$VT_{N_Ekman} = \int_{D_{Ekman}}^0 v_{Ekman} dz = - \int_{D_{Ekman}}^0 \frac{1}{f\rho} \frac{\partial \tau_E}{\partial z} dz = - \frac{1}{f\rho} [\tau_E]_{D_{Ekman}}^0 = - \frac{1}{f\rho} \{ \tau_E(z=0) - \tau_E(z=D_{Ekman}) \} = - \frac{\tau_E(z=0)}{f\rho} \quad (2)$$

where u_{Ekman} , v_{Ekman} , D_{Ekman} , f ($=2\Omega \sin \varphi$), Ω ($\approx 7.2921 \times 10^{-5}$), φ , ρ , and z denote the zonal (positive eastward) and meridional (positive northward) Ekman current velocities (m s^{−1}), Ekman depth (m), Coriolis parameter (rad s^{−1}), rotation rate of the Earth (rad s^{−1}), latitude, density of seawater (1025 kg m^{−3}), and vertical coordinate, respectively.

To examine the interannual variations in total inflow and outflow volume transport anomalies (m³ s^{−1}) through straits in Areas B and C, VT_{N_Ekman} and VT_{E_Ekman} values were zonally integrated across the strait in Area B (120.75–130.50° E; 30.75–33.00° N, Figure 1),

e.g., $\overline{VT}_{N_Ekman}L_{NS}$ ($\overline{}$ is the area averaged and L_{NS} is the width of Korea/Tsushima Strait), and meridionally across the straits in Area C (139.50–142.50° E; 39.00–48.00° N, Figure 1), e.g., $\overline{VT}_{E_Ekman}L_{EW}$ (L_{EW} is sum of the widths of Tsugaru and Soya Straits). Hereafter, we omit $\overline{}$ for convenience. Interannual anomalies of SLC owing to differences in Ekman inflow and outflow, and the consequent convergence or divergence within the NEAMS, were estimated as follows:

$$SLC = (VT_{N_Ekman}L_{NS} - VT_{E_Ekman}L_{EW})\frac{T}{A} = \frac{-\tau_E(z=0)L_{NS} - \tau_N(z=0)L_{EW}}{f\rho}\frac{T}{A} \quad (3)$$

where T represents the monthly time scale of 31 days in seconds, and A is the total area of the NEAMS ($1.6 \times 10^{12} \text{ m}^2$).

Daily ADT and six-hourly wind stress data were averaged monthly to yield monthly MSL, wind stress, and Ekman transport. Subsequently, the monthly MSL, wind stress, and Ekman transport, and SLC were composited to *Periods H and L* to investigate the impact of wind on the high and low NEAMS MSL in August.

Monthly MSL data from 1993 to 2019 were obtained from twenty tide-gauge stations, provided by the Permanent Service for Mean Sea Level [33,34] on 13 June 2024. These tide-gauge stations are distributed across three countries: Korea (nine stations: Incheon, Anheung, Mokpo, Jeju, Yeosu, Busan, Mukho, Sokcho, Ulleung), China (two stations: Lusi and Dalian), and Japan (nine stations: Hakata, Izuhara II, Hamada II, Saigo, Mikuni, Ogi, Awa Shima, Oshoro II, Wakkanai). To ensure consistency across datasets, the inverted barometer effect was removed from the tide-gauge sea level observations using atmospheric pressure data from ERA5. This correction was based on the standard assumption that 1 hPa change in atmospheric pressure corresponds to a 1 cm change in water level, following established methods [8,35]. After applying the inverted barometer correction, the tide-gauge data were adjusted to match the same MSL as the satellite altimetry data in August over the 27-year period from 1993 to 2019 (Figure 2). This adjustment ensures that the vertical reference datum of the tide-gauge data aligns with the satellite observations, allowing for accurate comparison between the two independent datasets.

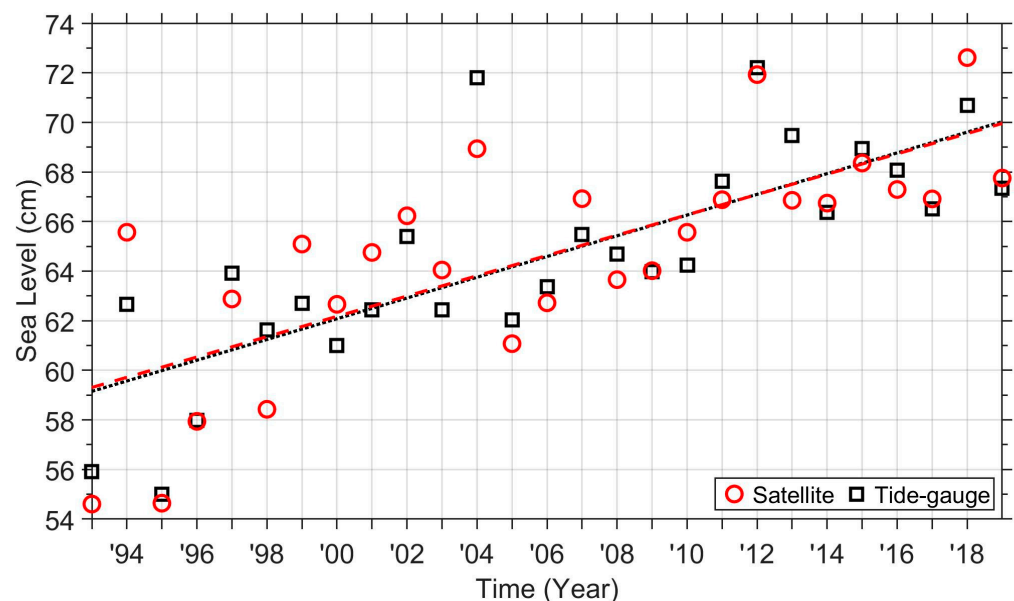


Figure 2. Time series of the summer (August) MSLs in the NEAMS region from 1993 to 2019, based on satellite altimetry (red open circles) and tide-gauge observations (black open squares), both adjusted to exclude the inverted barometer effect. The tide-gauge data have been referenced to a common vertical datum to match the MSL with satellite altimetry over the 27-year period. Dashed red and black dotted lines indicate the respective trends for satellite and tide-gauge measurements.

3. Results

3.1. MSL in August

To validate the satellite altimetry data and strengthen the overall conclusions, we compared the sea level patterns observed from satellite altimetry with tide-gauge measurements over a 27-year period. Both datasets exhibit similar up-and-down patterns, reflecting consistent sea level variability during this time. The rising rates of MSLs in August were derived from both satellite altimetry ($3.4 \text{ mm}\cdot\text{yr}^{-1}$) and tide-gauge observations ($3.5 \text{ mm}\cdot\text{yr}^{-1}$), after excluding the inverted barometer effect from 1993 to 2019. This comparison is depicted in Figure 2, where the dashed red line presents the trend from satellite altimetry, and the dotted black line shows the trend from tide-gauge observations. Despite potential discrepancies, such as the uneven distribution of tide-gauge stations, the trends observed from both datasets are remarkably similar, with a difference of $0.1 \text{ mm}\cdot\text{yr}^{-1}$ between the two. Notably, the variations in the two datasets, which are independent of each other, demonstrate a strong positive correlation, with a correlation coefficient of 0.93 for August data ($p\text{-value} < 0.01$). This high correlation indicates that both satellite and tide-gauge measurements consistently capture the same SLR pattern in the region during the summer months, reinforcing the reliability of the observed trends. This similarity further suggests that both methods are effectively capturing the regional MSL changes, supporting the robustness of the results. For clarity and ease of interpretation, the remainder of this paper will focus primarily on satellite data.

3.2. SLC by Ekman Transport

The role of wind-induced Ekman transport in driving SLC within the NEAMS region during August was analyzed using time series data. Specifically, anomalies in Ekman transport across the southern boundary (Area B) were compared with the MSL anomalies in the NEAMS to assess their correlation. Additionally, the differences between wind-induced Ekman transport anomalies across the southern (Area B) and eastern (Area C) boundaries were also considered to further refine the analysis of the inflow and outflow dynamics.

The results show a significant correlation between the anomalies in Ekman transport and the observed sea level variations. Specifically, the time series of SLC by wind-induced Ekman transport anomalies across the southern boundary of the NEAMS and those of SLC by wind-induced Ekman transport anomaly difference between the southern and eastern boundaries were significantly correlated with NEAMS MSL anomalies in August (Figure 3). The correlation coefficients between the SLC by Ekman transport anomaly in Area B and the MSL anomaly and between the SLC by Ekman transport anomaly differences in Areas B and C and the MSL anomaly were both 0.65 ($p\text{-value} < 0.01$). The SLC by Ekman transport anomaly in Area B was almost equal to the SLC by Ekman transport anomaly differences in Areas B and C (Figure 3). This near equivalence implies that the contribution of outflow through the eastern boundary (Area C) is minimal, meaning the outflow did not significantly offset the inflow from the southern boundary. As a result, the inflow driven by wind-induced Ekman transport across the southern boundary is largely responsible for the rise in sea levels observed within the NEAMS. These findings highlight the dominant role of wind-driven inflow from the south, particularly during the months of active typhoon occurrence, in driving regional SLCs. The fact that the outflow through the eastern boundary remains relatively negligible suggests that wind-induced processes primarily affect the inflow of water into the NEAMS, creating an imbalance that leads to elevated sea levels during these periods. The absence of compensatory outflow underscores the importance of wind-induced inflow transport as a key driver of sea level variability within this semi-enclosed marginal sea region.

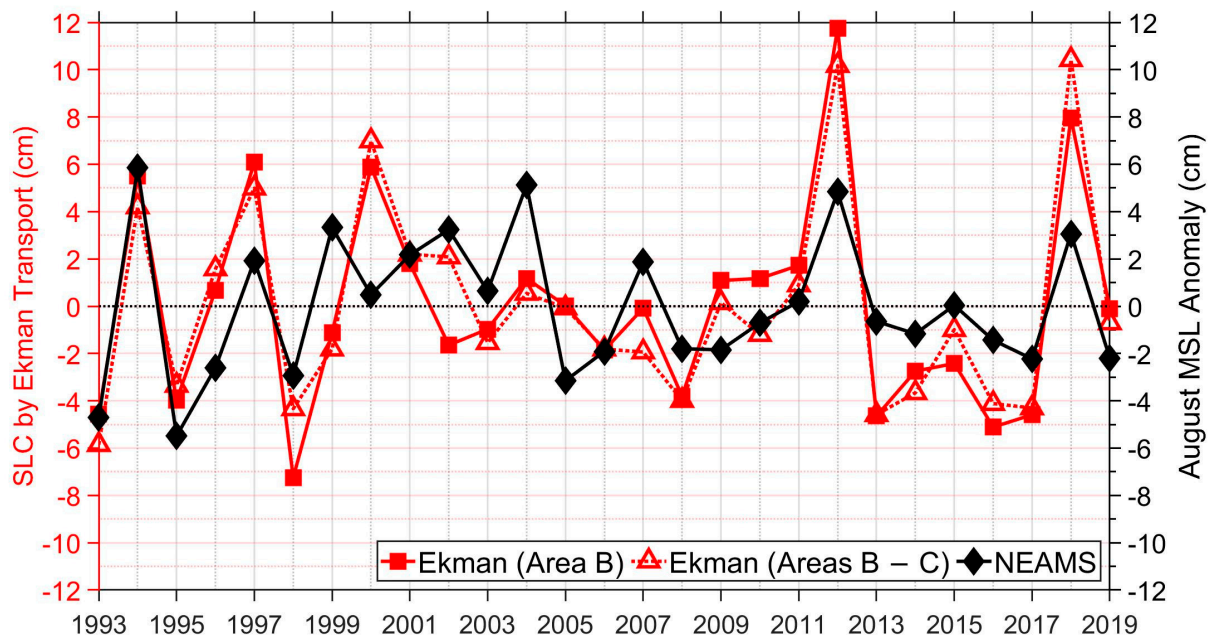


Figure 3. Time series of the detrended summer NEAMS MSL anomalies (black filled diamond) derived from satellite altimetry data, SLC by Ekman transport anomaly in Area B (red filled square), and SLC by Ekman transport anomaly differences between Areas B and C (red open triangle), derived from ERA5 data from 1993 to 2019. The correlation coefficients between the NEAMS MSL and SLC by Ekman transport anomaly in Area B and between the NEAMS MSL and SLC by Ekman transport anomaly differences between Areas B and C are both 0.65 (p -value < 0.01).

3.3. Interannual Variations in MSL and Wind-Induced Inflow

The interannual variations in MSL anomalies for August in the NEAMS, ES, and YS were analyzed over a 27-year period to understand the relationship between SLCs and typhoon activity. Interannual variations in the detrended August NEAMS-, ES-, and YS-MSL anomalies yielded standard deviations of 2.97, 2.92, and 3.63 cm, respectively, indicating noticeable fluctuations in sea levels across these regions. A significant finding from this analysis was the strong correlation between the number of typhoons passing through Area A and the MSL anomalies in the NEAMS, ES, and YS. The correlation coefficients were 0.59, 0.53, and 0.60 for the NEAMS, ES, and YS, respectively, all with p -values of less than 0.01, suggesting a robust statistical relationship between typhoons activity and MSL variations. This implies that the number of typhoons is a key factor in driving the observed interannual variability in sea levels across the region. To further investigate this relationship, two distinct periods were selected for composite analysis: *Period H*, characterized by higher-than-normal MSL anomalies, and *Period L*, marked by lower-than-normal MSL anomalies. *Period H* included years where the August MSL anomaly exceeded 2 cm (1994, 1997, 1999, 2001, 2002, 2004, 2012, and 2018), while *Period L* included years where the MSL anomaly fell below −2 cm (1993, 1995, 1998, 2005, and 2017). The composite analysis revealed that during *Period H*, the MSL anomalies for the NEAMS, ES, and YS were significantly higher (+3.69, +3.35, and +4.47 cm, respectively) compared with those during *Period L*, where the MSL anomalies were markedly lower (−3.70, −3.50, and −3.56 cm, respectively) (black, green, and blue solid lines in Figure 4a–c, respectively). Further analysis of the variability in MSL within these two periods indicated different levels of standard deviation, reflecting the extent of sea level fluctuation during these times. During *Period H*, the standard deviations from the August NEAMS-, ES-, and YS-MSLs were 1.42, 1.38, and 2.57 cm, respectively, indicating a relatively consistent rise in sea levels. In contrast, during *Period L*, the standard deviations were slightly lower for NEAMS (1.35 cm) but higher for the ES (1.89 cm) and YS (1.91 cm), suggesting that the magnitude of MSL changes was more variable during periods of lower sea level.

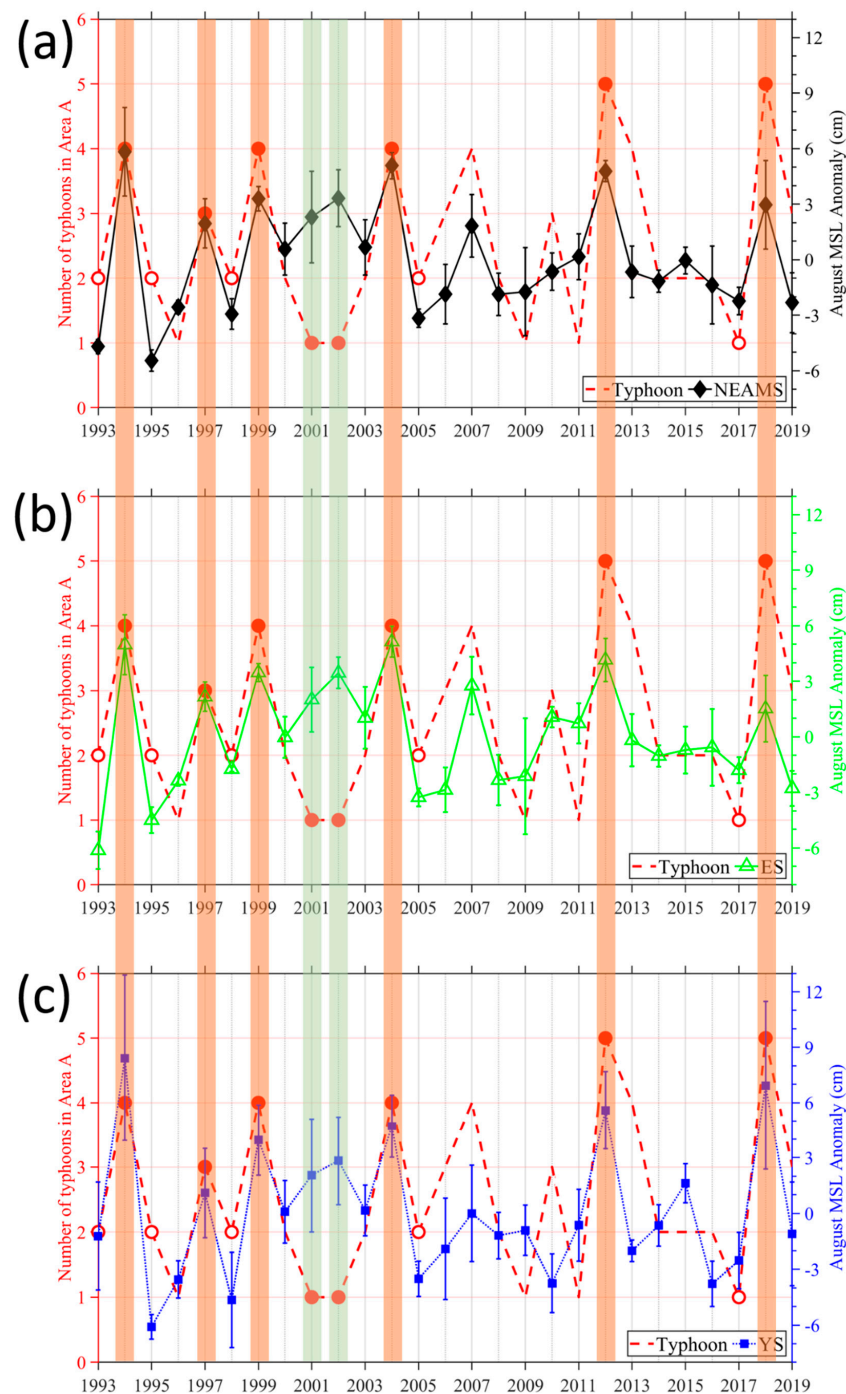


Figure 4. (a) Time series of detrended summer NEAMS MSL anomalies (black solid line) derived from satellite altimetry data and typhoon occurrence in the ECS (red dashed line) from 1993 to 2019. Summers with relatively high MSL changes (*Period H*; >2 cm, black solid diamonds) are denoted by orange and green shading, while summers with relatively low MSL changes (*Period L*; <-2 cm) are denoted by black-filled diamonds. During each summer throughout *Period H*, three or more typhoons passed through Area A (red solid circles), with the exception of the summers of 2001 and 2002 (green shading,) while two or fewer typhoons occurred during each summer of *Period L* (red open circles) (correlation coefficient = 0.54; p -value < 0.01). Error bar indicates the positive and negative standard deviations of daily detrended summer NEAMS MSL. Time series of detrended summer (b) ES (green triangle, correlation coefficient = 0.49; $p = 0.01$) and (c) YS (blue square, correlation coefficient = 0.55; p -value < 0.01) MSL anomalies derived from satellite altimetry data from 1993 to 2019. Error bar indicates the positive and negative standard deviations of daily detrended summer ES and YS MSLs.

The frequency of typhoons passing through Area A varied significantly between *Period H* and *Period L*, reflecting the impact of typhoon activity on SLCs in the region. The number of typhoons that passed through Area A was higher during *Period H* (3.25) and lower during *Period L* (1.60). Both of these values deviate from the long-term average of 2.41 typhoons per year over the 27-year study period, as shown by the red dashed lines in Figure 4a–c. This indicates that years with more frequent typhoon activity (*Period H*) tend to be associated with elevated sea levels, while years with fewer typhoons (*Period L*) correspond to lower sea levels. The variability in typhoon occurrences during these periods is also reflected in the standard deviations. The overall standard deviation of typhoon occurrences over the 27-year period was 1.25, indicating a moderate level of fluctuation in the number of typhoons passing through Area A. However, the standard deviation during *Period H* was notably higher at 1.58, suggesting greater variability in typhoon activity during years with elevated sea levels. In contrast, *Period L* had a lower standard deviation of 0.55, indicating more consistent but reduced typhoon activity during years with lower sea levels. Significantly higher (>2 cm) August NEAMS MSL anomalies in *Period H* were recorded following the occurrence of three or more typhoons in Area A (pale red shading in Figure 4a–c). This strong correlation between multiple typhoons and elevated MSLs suggests that typhoon frequency plays a crucial role in driving short-term sea level variability. However, there were notable exceptions to this pattern in August 2001 and 2002, where higher-than-normal MSLs were observed despite only one typhoon passing through Area A. These exceptions, indicated by the green shading in Figure 4a–c, suggest that other factors, such as wind-induced inflow or the intensity and path of the individual typhoons, may also have contributed to the wind-driven Ekman transport associated with these typhoons, even though their frequency was lower than in other high-activity years.

In Figure 5a, during *Period H*, the wind stress vectors show a prominent southeasterly component over the ECS and YS, particularly along the southeastern coast of the Korean Peninsula. These intensified wind patterns drive mass convergence in the ECS, enhancing Ekman transport, which pushes surface waters toward the coast. As a result, a larger volume of water accumulates in the shallow regions of the ECS, leading to a noticeable regional SLR. In contrast, during *Period L*, weaker wind forcing results in less pronounced Ekman transport and reduced water buildup. The strong southeasterly winds during *Period H* increase inflow from the Pacific Ocean across the ECS shelf, disrupting the equilibrium between inflow and outflow in the NEAMS. As a result, the imbalance becomes more pronounced, leading to the elevated MSLs observed in *Period H*, which are notably higher than those in *Period L*.

In addition, Figure 5a shows strong northwestward wind stress during *Period H*, which is closely associated with an increased number of typhoons passing through Area A. These cyclonic winds enhance northeastward Ekman transport, primarily occurring in the northwestern quadrant of the typhoons, driving water masses toward the NEAMS. This wind-induced transport contrasts sharply with the weaker northwestward winds observed during *Period L*. The dominant northwestward, northward, and northeastward Ekman transports during *Period H* increase inflow from the ECS to the ES or YS, and subsequently, from the western Pacific into the NEAMS, amplifying the inflow/outflow imbalance and contributing to higher regional sea levels (Figures 1 and 5a).

Although only one typhoon passed through Area A during both August 2001 and August 2002, the inflow transport into the NEAMS effectively increased in both cases due to wind-induced Ekman transport. This demonstrates the significant impact of typhoon-related wind patterns on the regional ocean circulation and mass transport dynamics in the NEAMS. During August 2001, as shown in Figure 6a, southwestward wind stress was prevalent in Area A. This wind pattern was driven by the passage of typhoon Pabuk, which traveled along the eastern boundary of Area A (Figures 6a and 7a). The southwestward wind stress associated with the typhoon induced strong northwestward Ekman transport, pushing surface waters toward the NEAMS. This wind-driven transport increased the inflow of water from the Pacific Ocean into the ECS, contributing to the mass convergence

in the region. As a result, the inflow transport into the NEAMS was enhanced, leading to a regional rise in sea levels. During August 2002, as depicted in Figure 6b, typhoon Rusa passed through the northeastern corner of Area A. This resulted in a markedly different wind pattern, with strong northwestward wind stress along the northeastern boundary of Area A (Figures 6b and 7b). The cyclonic winds generated by typhoon Rusa also induced significant northeastward Ekman transport, which further contributed to increased inflow into the NEAMS. Similar to August 2001, this wind-induced inflow from the Pacific Ocean increased the overall water volume in the NEAMS, amplifying the imbalance between inflow and outflow and contributing to regional sea level variability. Despite differences in the exact wind patterns and the paths of the typhoons, both August 2001 and 2002 exhibited a clear enhancement of inflow transport due to wind-driven Ekman dynamics. The prevailing wind stress in both cases played a crucial role in driving water from the ECS into the NEAMS, further emphasizing the sensitivity of the region's sea levels to typhoon activity. These results highlight the importance of wind-induced Ekman transport in controlling inflow transport into semi-enclosed marginal seas, particularly during extreme weather events like typhoons.

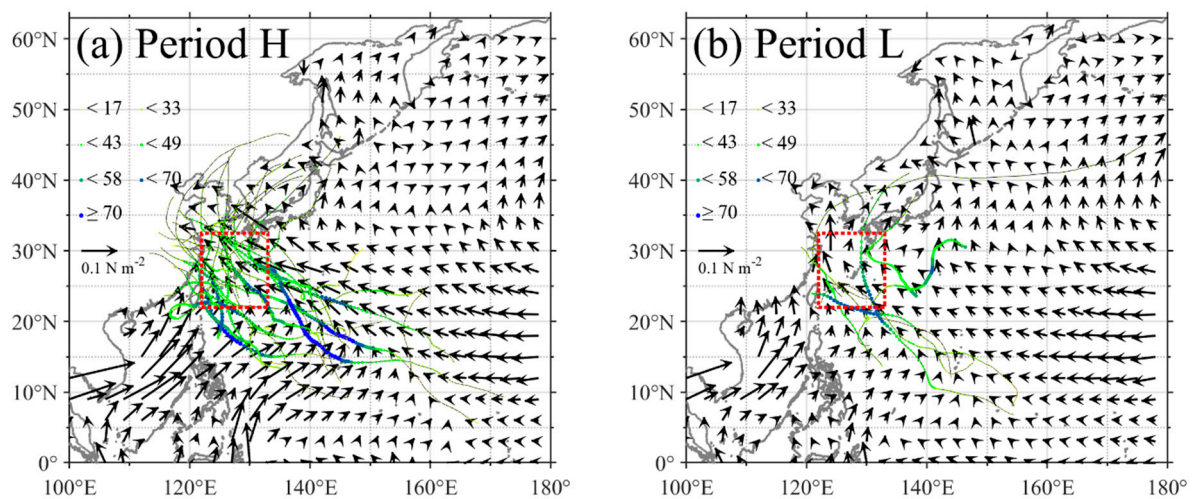


Figure 5. Surface wind stress vectors (black arrows) and typhoon tracks (dotted lines) for (a) composite *Period H* and (b) composite *Period L*. The legend for dotted lines can be found in the upper-left corner with criteria for maximum wind speed in m s^{-1} similar to Figure 1. Area A and coastlines are denoted by red dashed box and gray lines, respectively.

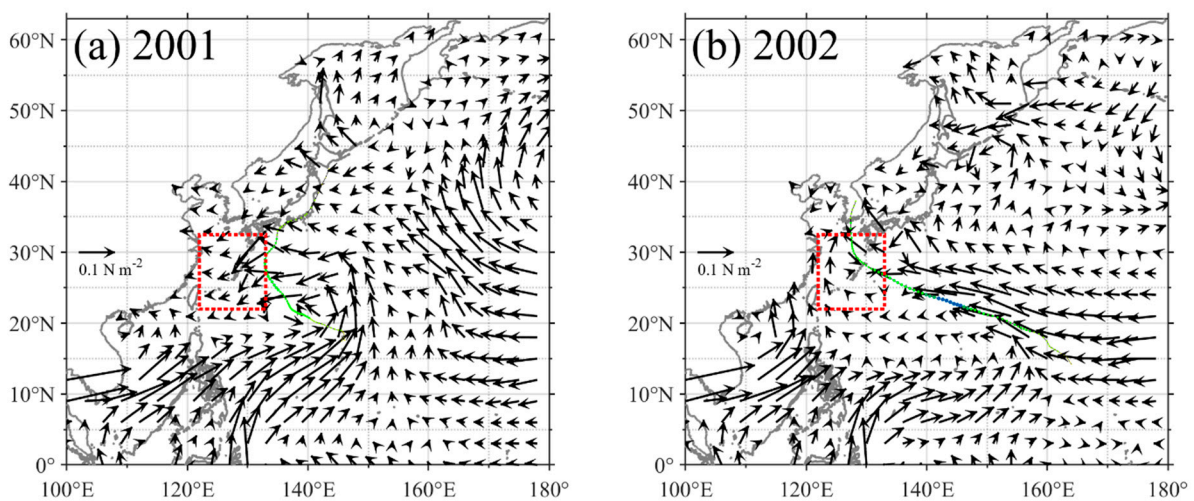


Figure 6. Surface wind stress vectors (black arrows) and typhoon tracks (dotted lines) in (a) 2001 and (b) 2002. Area A and coastlines are denoted by a red dashed box and gray lines, respectively.

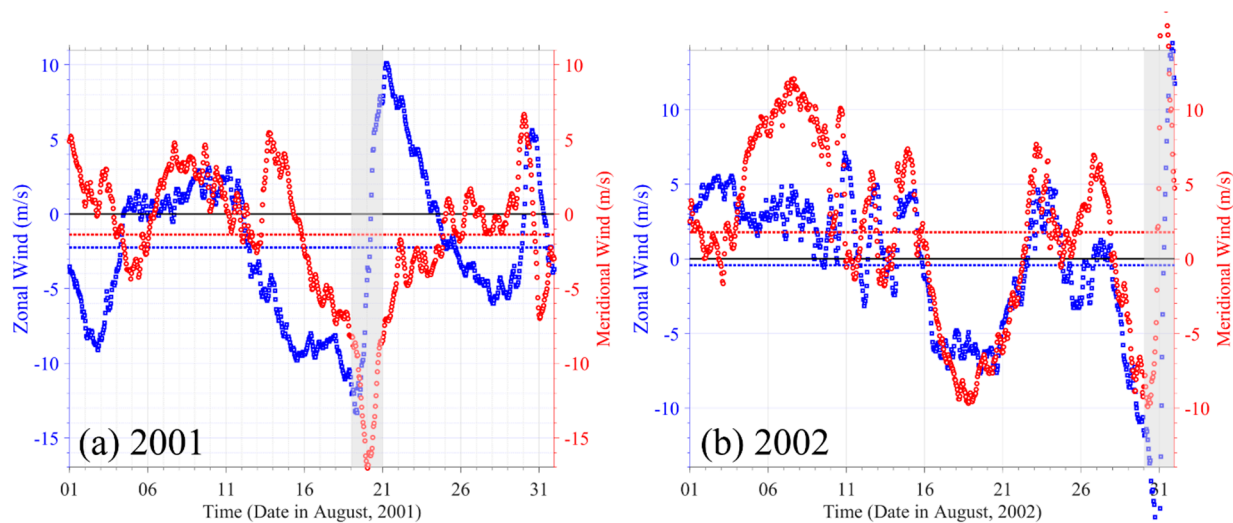


Figure 7. Time series of hourly zonal and meridional winds averaged over (a) Area D, summer 2001, and (b) Area E, summer 2002, are plotted using blue squares and red circles, respectively. Monthly mean zonal and meridional winds and zero wind speed lines are represented by the dotted blue and red horizontal lines and solid black lines, respectively. Gray shading represents typhoons Pabuk and Rusa during 19–20 August 2001 and 30–31 August 2002, respectively.

Looking forward, the long-term implications of these findings are substantial. Climate change is expected to increase the sea level and the frequency and intensity of tropical cyclones, particularly in the western Pacific region. Given the demonstrated impact of typhoon-driven wind stress on the NEAMS, it is likely that future tropical cyclone activity will further exacerbate MSL variability in the region. Stronger and more frequent typhoons could lead to more sustained periods of mass convergence and elevated sea levels in the NEAMS, increasing the risk of coastal flooding and other associated hazards. As tropical cyclones intensify, the corresponding wind-induced Ekman transport could result in even greater inflows of water into the NEAMS, amplifying the existing inflow/outflow imbalances. This will have significant implications for coastal management and policy planning in the region. Coastal areas along the ECS, YS, and ES, which are already vulnerable to SLR, may experience heightened risks due to the compounding effects of both global SLR and localized, wind-driven MSL variability. Proactive adaptation measures, such as improved coastal defenses and strategic land use planning, will be essential to mitigate the impacts of these future changes.

3.4. Wind-Induced Convergence and Divergence

The inflow and outflow dynamics driven by wind-induced Ekman transport play a critical role in determining SLCs within the NEAMS. Generally, increased inflow into the NEAMS due to wind-induced Ekman transport results in convergence within the NEAMS unless balanced by increased outflow across the eastern boundary (Area C). Within this context, the SLC induced by differences in Ekman inflow and outflow and consequent convergence or divergence within the NEAMS during *Period H* and *Period L* were quantified (Table 1). Despite significant changes in inflow across the southern boundary in Area B (positive anomaly of $+0.2350 \text{ m}^2\text{s}^{-1}$ during *Period H* compared with the negative anomaly of $-0.2428 \text{ m}^2\text{s}^{-1}$ during *Period L* in the detrended time series), differences between outflows across the eastern boundary in Area C for the two composite periods (-0.0103 and $-0.0297 \text{ m}^2\text{s}^{-1}$ during *Periods H* and *L*, respectively) were markedly small (Table 1). The imbalance between the substantial inflow across the southern boundary and the negligible outflow across the eastern boundary led to a net accumulation of water within the NEAMS, resulting in the observed SLR during *Period H*. On the other hand, during *Period L*, the negative inflow anomaly across the southern boundary, coupled with a

slight decrease in outflow across the eastern boundary, contributed to a net divergence of water from the NEAMS. This divergence led to lower sea levels during *Period L*. The small difference in outflow between the two periods emphasizes that wind-induced inflow across the southern boundary is the dominant factor influencing SLCs in the NEAMS, particularly during periods of significant typhoon activity.

Table 1. Wind-induced Ekman transport (VT_{Ekman}) and detrended VT_{Ekman} (DVT_{Ekman}) anomalies in Areas B and C, horizontal convergence due to differences between DVT_{Ekman} anomalies for Areas B and C, and SLC in the NEAMS induced by horizontal convergence during *Period H* and *Period L*. Det means detrended and $\pm$ values in VT_{Ekman} are standard deviations of wind stress in the *Periods H* and *L*. Positive (+) means flow or transport into the NEAMS, convergence, or higher-than-normal MSL in the NEAMS.

Quantity	Area	<i>Period H</i>	<i>Period L</i>
$VT_{N_{Ekman}}$ (m^2s^{-1})	B	$-\frac{\tau_E(z=0)}{f\rho} = \frac{0.0370 \pm 0.0226}{7.7 \times 10^{-5} \times 1025}$	$-\frac{\tau_E(z=0)}{f\rho} = \frac{-0.0016 \pm 0.0125}{7.7 \times 10^{-5} \times 1025}$
$VT_{E_{Ekman}}$ (m^2s^{-1})	C	$\frac{\tau_N(z=0)}{f\rho} = \frac{0.0185 \pm 0.0122}{10.0 \times 10^{-5} \times 1025}$	$\frac{\tau_N(z=0)}{f\rho} = \frac{0.0170 \pm 0.0089}{10.0 \times 10^{-5} \times 1025}$
$DVT_{N_{Ekman}}$ (m^2s^{-1}) anomaly	B	$-\frac{det\tau_E(z=0)}{f\rho} = \frac{0.0186}{7.7 \times 10^{-5} \times 1025} = +0.2350$	$-\frac{det\tau_E(z=0)}{f\rho} = \frac{-0.0192}{7.7 \times 10^{-5} \times 1025} = -0.2428$
$DVT_{E_{Ekman}}$ (m^2s^{-1}) anomaly	C	$\frac{det\tau_N(z=0)}{f\rho} = \frac{-0.0011}{10.0 \times 10^{-5} \times 1025} = -0.0103$	$\frac{det\tau_N(z=0)}{f\rho} = \frac{-0.0031}{10.0 \times 10^{-5} \times 1025} = -0.0297$
Horizontal convergence (+) or divergence (−) (m^3s^{-1})	NEAMS	$(DVT_{N_{Ekman}} L_{NS} - DVT_{E_{Ekman}} L_{EW})$ $= +0.2350 \times 10^5 - (-0.0103 \times 10^5) = 0.2453 \times 10^5$	$(DVT_{N_{Ekman}} L_{NS} - DVT_{E_{Ekman}} L_{EW})$ $= -0.2428 \times 10^5 - (-0.0297 \times 10^5) = -0.2131 \times 10^5$
SLC (m)	NEAMS	$(DVT_{N_{Ekman}} L_{NS} - DVT_{E_{Ekman}} L_{EW}) \frac{T}{A}$ $= +0.2453 \times 10^5 \times \frac{60 \times 60 \times 24 \times 31}{1.6 \times 10^{12}}$ $= +0.0411$	$(DVT_{N_{Ekman}} L_{NS} - DVT_{E_{Ekman}} L_{EW}) \frac{T}{A}$ $= -0.2131 \times 10^5 \times \frac{60 \times 60 \times 24 \times 31}{1.6 \times 10^{12}}$ $= -0.0357$

The estimated SLC was several centimeters higher during *Period H* than during *Period L*, e.g., 4.1 cm higher than normal during *Period H* compared with 3.6 cm lower than normal during *Period L* (Table 1). The difference in SLC of +7.7 cm induced by winds between the two composite periods (4.1 cm minus −3.6 cm; Table 1) is comparable to the SLC difference of +7.4 cm observed from satellite altimetry (3.7 cm minus −3.7 cm; black solid line in Figure 4a), indicating that wind-induced Ekman transport may be a dominant player in the observed interannual changes in August NEAMS MSL. The close alignment between these two independent measurements—one from the estimated wind-induced transport and the other from satellite altimetry—strongly suggests that wind-induced Ekman transport is a key driver of the interannual variability in August MSL in the NEAMS region.

A correlation map between NEAMS MSL anomalies and MSL atmospheric pressure changes during August for the 27-year period were highly negatively correlated in a significant portion of Area A (primarily the western part) because the August NEAMS MSLs increased with low atmospheric pressure accompanied by approaching typhoons (Figure 8a). As typhoons are generally attenuated as moving poleward and/or landing, strong wind-induced Ekman transport affects inflow transport in the south more than outflow transport in the northeast. Cyclonic circulation of the atmosphere around the typhoon center in Area A yielded northwestward, northward, or northeastward Ekman transport that increased inflow into the NEAMS (Figure 8b), resulting in higher-than-normal August NEAMS MSLs via horizontal convergence. This occurred through increased inflow, without compensatory increase in outflow during the year of active typhoon activities (*Period H*). This imbalance between inflow and outflow leads to an accumulation of water within the NEAMS, resulting in higher-than-normal sea levels in August. The strong wind-driven convergence associated with typhoon activity, combined with low atmospheric

pressure, further amplifies these SLRs. The absence of compensatory outflow emphasizes the dominance of wind-induced inflow in controlling SLCs during periods of active typhoon events, as observed during *Period H*.

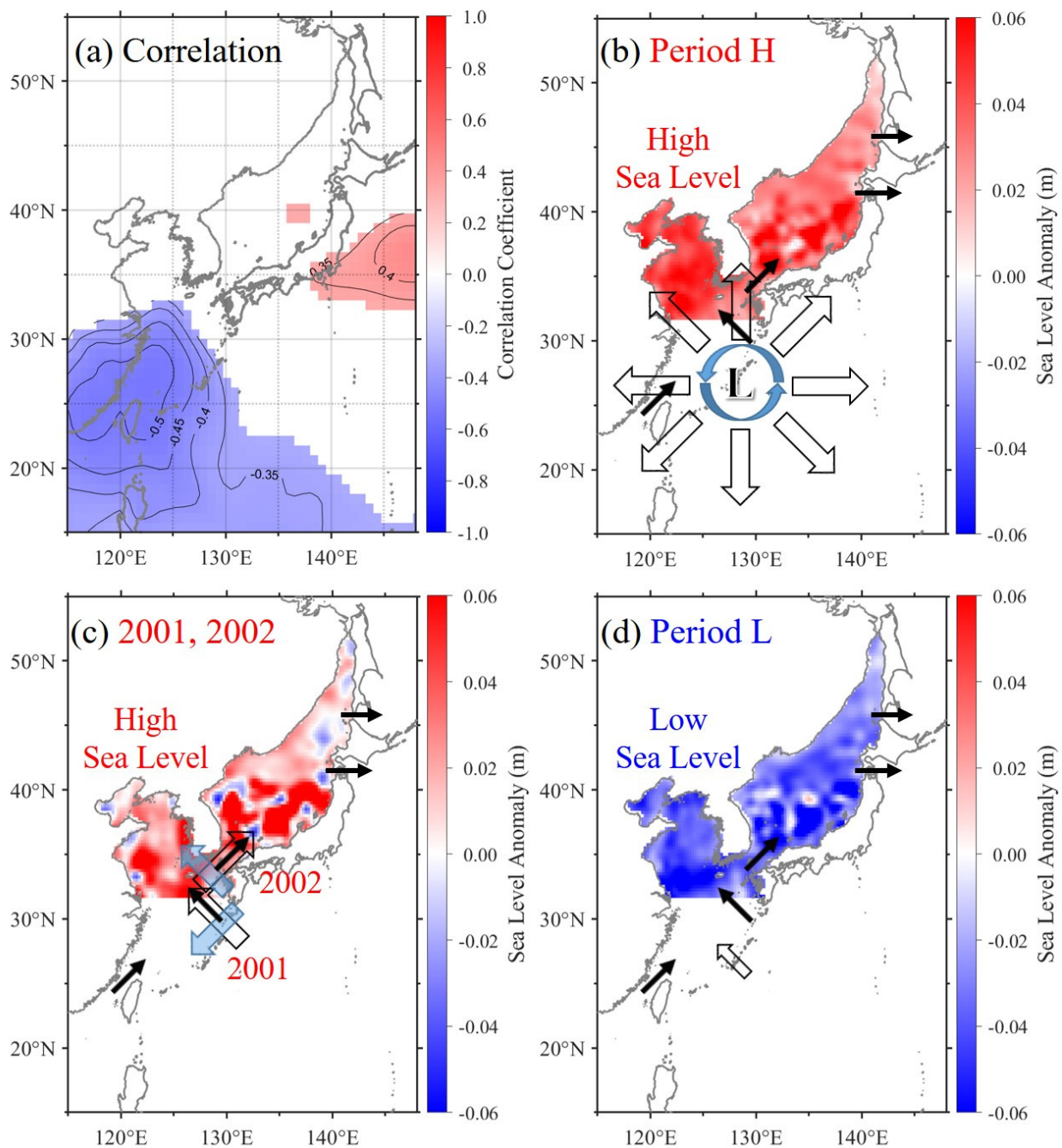


Figure 8. (a) Correlation map of MSL atmospheric pressure changes related to NEAMS MSL changes during August 1993–2019. In (a), contour intervals are 0.05, and correlations with confidence levels < 90% are discarded. Schematics demonstrate the ocean inflow and outflow (black filled arrows) of the NEAMS and NEAMS MSL anomalies (red and blue) in August driven by (b,c) convergence and (d) divergence during *Periods H* and *L*, respectively, related to inflow Ekman transport (black open arrows) induced by wind (blue shaded arrows). In (b), the large L represents the typhoon center. Composite sea level (ADT) anomalies for (b) *Period H*, (c) summers of 2001 and 2002, and (d) *Period L* in August obtained from satellite altimeters are indicated using colors.

The higher-than-normal NEAMS MSLs in August during *Period H*, including August of 2001 and 2002, were attributed to horizontal convergence driven by a wind-induced increase in inflow transport without a compensatory increase in outflow transport (Figure 8b,c). During these periods of heightened typhoon activity, strong winds associated with the cyclonic circulation of typhoons enhanced the inflow of water into the NEAMS, leading to an accumulation of water in the region. The lack of a compensatory increase in outflow resulted in a net rise in sea level, reflecting the significant role of wind-driven processes in causing these elevated MSLs. Inversely, the lower-than-normal NEAMS MSLs in August during *Period L* relate to horizontal divergence driven by wind-induced reductions in inflow transport without compensatory reductions in outflow transport (Figure 8d). During *Period L*, with fewer typhoons, the winds driving Ekman transport were weaker, resulting in a decrease in the volume of water entering the NEAMS. However, the outflow remained relatively stable, creating a divergence that led to lower sea levels. The reduced inflow without compensatory changes in outflow highlighted the key role of inflow dynamics in controlling sea level variability during periods of low typhoon activity.

4. Discussion

4.1. Typhoon Statistics in Periods H and L

In total, 27 typhoons were recorded in the ECS (Area A) during *Period H* from 1993 to 2019 (Figure 5a). Approximately half of them (13 typhoons) made landfall in China or Japan or moved back to the Pacific, whereas the rest (14 typhoons) passed through the NEAMS. However, typhoons that passed through the NEAMS or made landfall were significantly attenuated in the northern NEAMS as they moved northward, and they subsequently lost heat and momentum energy owing to vertically mixed cold sea surface water [36] and land surface friction [37]. Thus, the strength of the westward wind stress when the northern part of the typhoon is passing through Area B is stronger than that of the eastward wind stress when the southern part of the typhoon is passing through Area B if the typhoon moves northward. This means that strong westward wind stress in the north of the typhoon center is mainly prevalent in the northern ECS, where the typhoon intensity in the southern NEAMS is higher than that in the high latitude of the NEAMS (Figure 5a). Strong westward wind stress in the northern ECS or southern boundary of the NEAMS, along with a lack of significant wind stress near the eastern boundary of the NEAMS, increases Ekman inflow without a compensatory increase in outflow transport, driving convergence and resulting in higher NEAMS MSLs (Figure 8b,c). Therefore, this can raise the MSL in the NEAMS.

In total, nine typhoons were recorded in the ECS (Area A) during *Period L* from 1993 to 2019 (Figure 5b). In *Period L*, relatively few typhoons passed through the ECS, and only two typhoons entered the NEAMS. Therefore, westward wind stress in the north of the typhoon center was mostly prevalent in the southern ECS and the south of the NEAMS (outside the NEAMS) but not in the NEAMS (Figure 8d). This likely was unable to increase the lower-than-normal MSL in the NEAMS in *Period L*.

Although only one typhoon passed through Area A in both August 2001 and August 2002, the inflow transport into the NEAMS was effectively increased by wind-induced Ekman transport for a few days. During the remainder of August in both 2001 and 2002, other factors, such as low-pressure-induced Ekman transport in the ECS, may have contributed to an increase in the NEAMS MSL. The strengthening of East Korean Warm Current and Tsushima Warm Current in Figure 8c and high atmospheric pressure gradient between the Kuroshio Extension and around Taiwan (Figure 3 from [10]) could raise the MSL in both 2001 and 2002 in the NEAMS, especially related to the East Asian summer monsoon in 2001 (Figure 11a from [10]) and to the Oceanic Nino Index in 2002 (Figure 11b from [10]).

4.2. SLC Due to Varying Typhoon Intensity

In addition to typhoon-induced storm surges, which cause short-time scale SLC, convergence or divergence linked to imbalances in Ekman transport induced by strong

typhoon winds can cause significant SLC [38]. Therefore, typhoon activity can affect regional NEAMS MSL in areas influenced by typhoons, mainly limited to inflow. The correlation coefficients between detrended MSL anomalies and the number of typhoons passed through Area A according to maximum sustained wind speeds of 17, 33, 43, 49, 58, and 70 m s⁻¹ monthly from 1993 to 2019 were calculated as shown in Table 2. The correlation coefficients of typhoons that have maximum sustained wind speeds between 17 and 33 m s⁻¹, between 33 and 43 m s⁻¹, and between 43 and 49 m s⁻¹ are 0.49, 0.69, and 0.56 (p -value < 0.05), respectively, in August. The other notably weak and strong typhoons did not have high correlation coefficients, likely because there were few of them, and some did not pass close enough to the borders of Area A. To elaborate further, this may be attributed to the fact that weak typhoons did not significantly affect the sea levels, and only a few strong typhoons passed directly through Area A. Additionally, some strong typhoons did not approach its borders closely enough to have a substantial impact on the region's sea level dynamics. While stronger typhoons may intuitively seem to have a larger effect on MSL due to their higher wind speeds, the data suggest that even moderate typhoons can have significant impacts. This could be due to the broader spatial extent of wind-induced Ekman transport, which is not necessarily proportional to the intensity of the storm but rather to the duration and trajectory of the typhoon as it passes through Area A. Moderate typhoons, which may linger over the area for longer periods, can still drive substantial inflow through wind-driven processes, affecting the balance between inflow and outflow in the NEAMS. The correlation coefficients were significant in August, and those in other months except August were mostly insignificant. This may be because there were more typhoons that came north and passed through the ECS (Area A) in August compared with those that passed far from the ECS in July and September, including other months [39,40]. This typhoon-induced Ekman transport, and the low-pressure-induced Ekman transport that leads typhoons into the ECS, may be two of the main factors controlling the NEAMS MSL only in August. The correlation coefficients between the NEAMS sea level anomaly and the number of typhoons at each maximum sustained wind speed level were not always significant in August; therefore, strong typhoons do not always increase the NEAMS MSL compared with weak typhoons. This may be because few strong typhoons passed through Area A. Given these dynamics, we chose to focus on the number of typhoons rather than their intensity in this study. The frequency of typhoons, regardless of their strength, appears to be a more reliable indicator of MSL variability in the NEAMS, as even weak storms can disrupt the regional water balance through wind-driven transport. By concentrating on the number of typhoons, we aim to capture the cumulative effect of multiple storm events, which may collectively exert a stronger influence on sea levels than the occasional strong typhoon.

Table 2. Correlation coefficients between detrended sea level anomaly in the NEAMS and the number of typhoons passed through Area A according to maximum sustained wind speeds of 17, 33, 43, 49, 58, and 70 m s⁻¹ for July, August, and September from 1993 to 2019. The underlines represent that the correlation coefficients are significant at the 5% significance level.

Maximum Sustained Wind Speed (m s ⁻¹)	Jul.	Aug.	Sep.
Wind ≤ 17	0.33	−0.08	0.04
17 < Wind ≤ 33	0.36	<u>0.46</u>	−0.02
33 < Wind ≤ 43	0.19	<u>0.68</u>	−0.07
43 < Wind ≤ 49	−0.03	<u>0.56</u>	0.04
49 < Wind ≤ 58	0.14	0.36	0.19
58 < Wind ≤ 70	0.17	0.19	−0.06
Wind > 70	−0.17	−0.13	0.18
All Wind	0.27	<u>0.62</u>	0.05

4.3. SLC Due to Regional Wind

The correlation between NEAMS MSL and MSL atmospheric pressure in August (Figure 8a) explains the effect of low-pressure and low-pressure-induced wind on the NEAMS MSL in August beyond the inverted barometer effects eliminated by the DAC of the daily ADT data. The low-pressure-induced wind also causes Ekman transport into the NEAMS, and it can contribute a certain fraction of the MSL in the NEAMS. Thus, the distribution of MSL atmospheric pressures around the NEAMS, e.g., the high pressure in the Kuroshio extension region and the low pressure around Taiwan [10], could affect the NEAMS MSL in August. Typhoons pass through the NEAMS for a few days to several days, and there are many typhoons in the NEAMS in August.

We selected dates when there were typhoons in Area A, and we calculated typhoon wind-induced Ekman transports with mean wind stresses in Areas B and C, and days (time) during the above dates using Equations (1)–(3). The SLCs, due to typhoon wind-induced Ekman transports, which were calculated in the same way as Table 1, were 0.0217 m (52.8% of 0.0411 m due to regional wind-induced Ekman transports) in *Period H* and -0.0084 m (23.5% of -0.0357 m due to regional wind-induced Ekman transports) in *Period L*. Although there were not always typhoons in Area A (ECS) in August, 52.8% and 23.5% of the SLCs in *Periods H* and *L*, respectively, indicate that a typhoon was one of the main factors in controlling the sea level in the NEAMS. Therefore, we calculated the regional wind-induced Ekman transport in *Periods H* and *L* with the correlation (correlation coefficient = 0.54) between the number of typhoons and the SLC in the NEAMS. We concluded that the Ekman transport in the NEAMS was mainly controlled by typhoons in August, and we focused on the monthly mean regional wind-induced Ekman transport, including the typhoon wind-induced Ekman transport in this study.

4.4. SLC Due to Effects Other than Typhoon Wind

Regional MSL variations can be inferred using several factors beyond the horizontal mass convergence–divergence due to wind-induced Ekman transport, including, but not limited to, thermosteric and halosteric effects [41], melting ice [42], and river discharge [43]. NEAMS MSL anomalies in August caused by the imbalanced transport of heat (oceanic thermosteric effect), salt (oceanic halosteric effect), and mass (oceanic mass effect) across the ECS (Area B), Tsugaru Strait, and Soya Strait, as well as by net surface heat flux (atmospheric thermosteric effect), were quantified based on the using ORAS5 data from 1993 to 2019, and they were compared with the detrended NEAMS MSL anomaly (red, blue, magenta, green, and black lines in Figure 9).

Moreover, SLC caused by freshwater (atmospheric halosteric effect) flux between the ocean and atmosphere in the NEAMS was one order of magnitude smaller than that by the thermosteric sea level [11,44]. As mentioned above, the thermo- and halosteric effects on the NEAMS MSL in August were one order of magnitude less than those observed from satellite altimetry for the NEAMS MSL in August. Therefore, the steric (thermo- and halosteric) effect may not significantly affect the interannual variations in the NEAMS MSL in August.

Ocean stratification is related to the thermosteric effect, which can be affected by incoming and outgoing seawater characteristics and ocean-atmosphere heat exchange [45]. Ocean stratification [36] and mixed layer depth [46] are related to the vertical mixing and sea surface cooling produced by typhoons, and they are two of the controlling factors of typhoon intensity [47]. As shown in Table 2, the correlation coefficients between the detrended NEAMS MSL and the intensity (maximum sustained wind speed) of typhoons are not always significant in August, which means that stronger typhoons do not raise the NEAMS MSL all the time than weaker ones. Thus, we can ignore the effect of ocean stratification and mixed layer depth on the typhoon intensity, which may not be correlated with SLC in the NEAMS in August in this study.

River discharges along the NEAMS coasts were calculated using the data from the Global Flood Awareness System. Mean daily river discharge ($\text{m}^3 \text{s}^{-1}$) in a $0.1^\circ \times 0.1^\circ$

grid along the coasts in the NEAMS was combined and converted to total monthly river discharge (m^3) over the NEAMS ($1.6 \times 10^{12} \text{ m}^2$). Their effects on the NEAMS MSL anomaly were approximately -0.1 cm (*Period H*) and 0.5 cm (*Period L*). River discharges raised the NEAMS MSL in *Period L* more than in *Period H*, and their difference was less than 1 cm . Therefore, the effect of total river discharges on the SLC in the NEAMS could be disregarded.

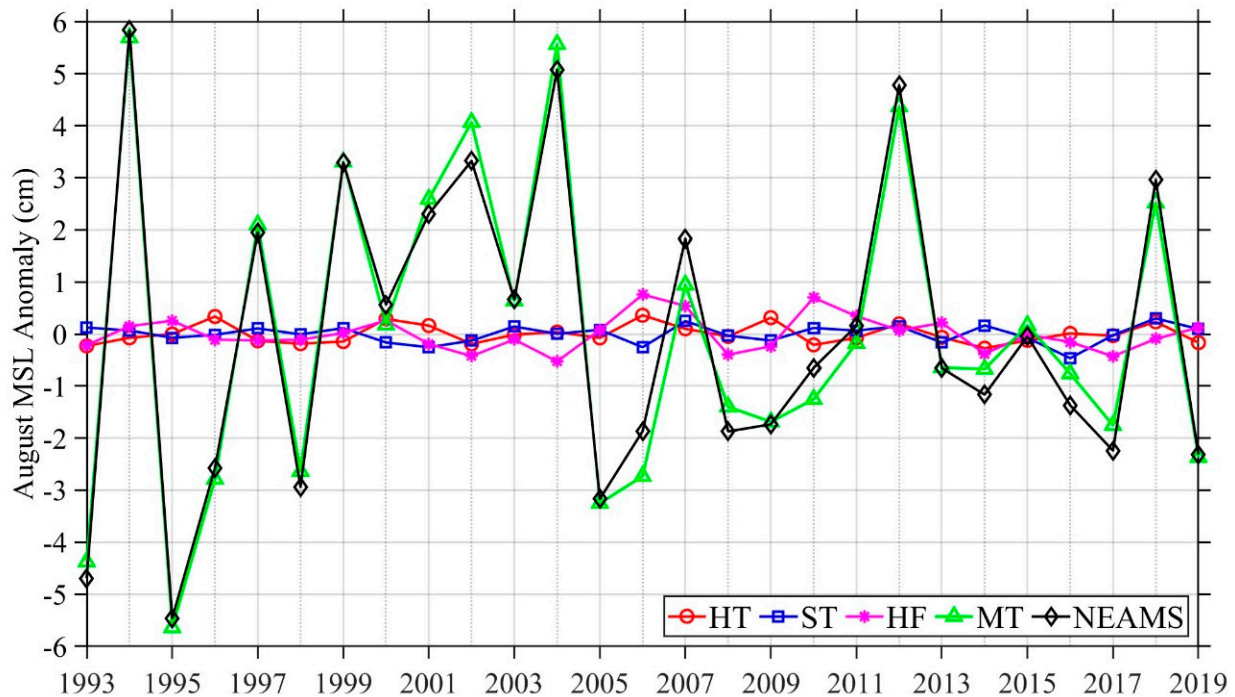


Figure 9. Time series of detrended summer NEAMS MSL anomalies derived from satellite altimetry data (black open diamonds, NEAMS) by heat transport (red open circles, HT) and salt transport (blue open squares, ST) differences in anomalies over the ESC (Area B) and the Tsugaru and Soya Straits, by net surface heat flux (magenta asterisk, HF) derived from the Ocean Reanalysis System 5 (ORAS5), and by subtracting MSL by HT, ST, and HF from altimetry MSL (green open triangle, mass transport (MT)) from 1993 to 2019.

When Kuroshio is strong and inertially flows eastward through the Tokara Strait, Tsushima Warm Current into the NEAMS is weak, and vice versa [48]. Using ORAS5 data from August 1993–2019 revealed that the volume transports of Kuroshio (using positive zonal velocity only at 129.98° E and $28.43\text{--}31.58^\circ \text{ N}$) and inflow from the Pacific Ocean to the NEAMS (using meridional velocity at 31.34° N from China to Japan) were negatively correlated with a correlation coefficient of -0.51 ($p\text{-value} = 0.01$). Thus, the strengthening and weakening of Kuroshio could affect the inflow from the Pacific Ocean into the NEAMS, which affects the SLC in the NEAMS and is also related to the wind stress and wind stress curl in the Pacific, such as Pacific Decadal Oscillation and El Niño/La Niña. This requires further investigation and is beyond our study. Thus, we did not investigate it further here.

Although the correlation coefficient between the differences in Ekman transport anomalies in Areas B and C and MSL anomaly is high and significant in Figure 3, there are some differences between them. These differences can be from oceanic heat, mass, and salt transports, and atmospheric heat and freshwater fluxes, as explained above. The deconstruction of these differences should be performed in the near future.

Monthly MSLs of the NEAMS are assumed to be spatially uniform, which is reasonable considering the fast propagating barotropic waves within the NEAMS [49]. The propagating speed of the barotropic waves is estimated to $O(100 \text{ m s}^{-1})$, e.g., $\sqrt{9.81 \text{ (m s}^{-2}) \times 1000 \text{ (m)}} = \sqrt{\text{acceleration of gravity} \times \text{depth}}$, yielding the Rossby radius of deformation is an order of

10^6 m, comparable to the size of NEAMS ($10^6 \text{ m} \approx \sqrt{1.6 \times 10^{12} (\text{m}^2)} = \sqrt{\text{total area of the NEAMS}}$). Thus, the barotropic waves take less than a few days (much shorter period than a month) to propagate across the whole NEAMS.

4.5. Implications for Coastal Management

The results of this study have significant implications for coastal management strategies, especially in light of the projected increase in the frequency and intensity of tropical cyclones due to climate change. The observed trends in sea level variability caused by typhoons suggest that coastal communities in the NEAMS region, including areas surrounding the ES, YS, and ECS, will face heightened risks from storm surges, flooding, and long-term SLR. These risks are exacerbated by the recurring inflow of water during typhoon seasons, driven by wind-induced transport, leading to prolonged periods of elevated sea levels.

To mitigate the potential impacts of such events, coastal management strategies should prioritize enhanced flood defenses and infrastructure resilience [50]. The results suggest that even moderate typhoons can induce significant SLRs in the NEAMS. Therefore, flood defenses in coastal cities and low-lying areas should be strengthened to withstand not only the immediate impact of strong storms but also the cumulative effects of frequent, moderate-intensity storms.

Coastal management strategies also prioritize early warning systems and monitoring [51]. Given the importance of wind-induced processes in driving sea level variability, real-time monitoring of wind stress patterns and typhoon trajectories will be essential for predicting potential SLCs during typhoon seasons. Coastal communities can benefit from enhanced early warning systems that integrate meteorological and oceanographic data to provide timely alerts for potential flooding risks.

Furthermore, adaptive land use planning should be a key focus of coastal management strategies [52]. The findings highlight the need for adaptive land use strategies that account for the growing risk of SLR and flooding in the NEAMS. Coastal development should be limited in the most vulnerable areas, particularly low-lying regions prone to storm surges and water inflows from nearby seas. Relocating critical infrastructure away from high-risk zones, creating buffer zones along coastlines, and promoting resilient building designs are all essential components of forward-looking coastal management.

Finally, climate change adaptation and policy planning must also be prioritized [53]. The long-term implications of increasing typhoon activity, combined with the broader effects of global SLR, call for robust climate adaptation policies. Governments and policymakers in the NEAMS region must integrate sea level projections and storm surge risks into urban planning and disaster preparedness frameworks. In particular, future infrastructure projects should be designed with higher sea levels in mind, incorporating flexible adaptation measures that can evolve as climate conditions worsen.

4.6. Comparison with Other Regions

To place the findings of this study within a global context, it is useful to compare the observed sea level variability in the NEAMS region with those in other regions impacted by tropical cyclones. In the Western Pacific, for example, especially in the South China Sea, studies have shown that the influence of tropical cyclones on sea level is similarly exacerbated by wind-induced transport and storm surges, leading to significant short-term SLCs, much like the findings in the NEAMS region [54].

In the Atlantic Basin, hurricanes contribute to sharp increases in coastal sea levels, particularly in areas such as the Gulf of Mexico [55] and the southeastern United States [56]. These regions have implemented adaptive strategies, including flood defense enhancements and early warning systems, similar to the recommendations for the NEAMS region. However, there are notable differences in cyclone frequency, storm strength, and regional topographies, which influence the specific impacts and management strategies required.

5. Conclusions

This study has provided valuable insights into the regional MSL variability due to tropical cyclones in the NEAMS region, particularly during the month of August. The results highlight the significant role that typhoons play in driving short-term SLCs through wind-induced transport and storm surges. The passing of more than the normal amount of (three or more) typhoons in the ECS accounted for higher-than-normal NEAMS MSLs in August (*Period H*), according to satellite altimetry observations. Wind-induced increases in northward inflow Ekman transport from the Pacific into the NEAMS are responsible for the regional SLR, without a compensatory increase in eastward outflow transport from the NEAMS into the Pacific Ocean and the Sea of Okhotsk. In contrast, a decrease in August NEAMS MSLs (*Period L*) is derived from the passing of fewer than the normal amount (two or fewer) typhoons in the ECS, primarily owing to a decrease in inflow Ekman transport without a corresponding decrease in outflow transport. As a result, there was a divergence of water from the NEAMS, causing sea levels to drop. This study identified that the imbalance between inflow and outflow mass transports—induced by the number of typhoon passages—created horizontal convergence and divergence, which in turn caused significant interannual variations in NEAMS MSL during August. Therefore, typhoon activity significantly affects interannual variation in regional MSL, as well as local (primarily coastal) and temporary SLCs, particularly in the midlatitudes and within semi-enclosed marginal seas. The relationship between typhoon frequency and sea level variability has significant implications for understanding how wind-driven processes affect regional ocean circulation and MSL fluctuations. To our knowledge, this is the first study to report a direct link between the number of typhoons passing through the ECS and regional MSL changes in the NEAMS. Specifically, the results indicate that August typhoon passages are a major driver of significant interannual MSL variability in this region, offering new insights into the dynamic interactions between atmospheric forces and oceanographic responses.

This study has significantly advanced the understanding of sea level variability induced by tropical cyclones in the NEAMS region. However, future research is required to address several key aspects. In particular, further studies should investigate the relative contributions of typhoon intensity on SLCs, which will aid in refining predictive models and improving mitigation strategies. Additionally, the interaction of other climatic factors, such as the El Niño/La Niña phenomena, with typhoon-induced sea level variability should be examined to achieve a more comprehensive understanding. Long-term studies are also essential to evaluate the impact of climate change on typhoon characteristics—both in terms of intensity and frequency—and their consequent influence on sea level variability, with implications for the NEAMS and beyond.

The practical implications of this research are clear, especially for coastal infrastructure and urban planning. The findings reveal that even moderate typhoons can lead to substantial sea level increases, highlighting the urgent need to reinforce flood defenses and enhance the resilience of coastal infrastructure in vulnerable, low-lying regions. These results should serve as a foundation for disaster preparedness policies, particularly in regions exposed to frequent typhoon activity. Coastal management strategies should focus on adaptive measures such as real-time early warning systems and the integration of sea level projections into infrastructure design to mitigate the risks posed by both short-term storm surges and long-term SLR.

Although this study centers on the NEAMS region, its findings have broader global relevance. Similar challenges are faced by coastal areas in the Western Pacific, the Gulf of Mexico, and the Southeastern United States, where tropical cyclones generate storm surges and wind-driven sea level fluctuation. The shared nature of these challenges underscores the importance of developing region-specific coastal management strategies, informed by insights from diverse geographic areas, while recognizing the global necessity for adaptive responses to tropical cyclone impacts.

Looking ahead, the intensifying effects of climate change on the frequency and strength of tropical cyclones will likely exacerbate the risks identified in this study. Rising sea levels,

coupled with stronger and more frequent storms, could result in increasing severe flooding events and prolonged periods of elevated sea levels. Mitigating these future risks requires incorporating climate change projections into coastal planning and policymaking. Proactive adaptation measures that account for climate uncertainties will be essential to protect coastal communities both in the NEAMS region and globally.

Author Contributions: M.H. and S.N. conceptualized the study. M.H. organized the methodology, selected software, performed all data analysis, visualized the figures, and wrote the original draft of the manuscript. S.N. contributed to writing—review and editing. H.-S.L. contributed to editing, supervision, and funding acquisition. All authors contributed to the manuscript in multiple ways. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Ministry of Trade, Industry, and Energy (MOTIE) of Korea under the “Regional Innovation Cluster Development Program (PN92300, P0025418)”, supervised by the Korea Institute for Advancement of Technology (KIAT). It was also supported by the Korea Institute of Ocean Science and Technology (PEA0231). Additionally, this study was supported by the project “Sustainable Research and Development of Dokdo (PG54141)” under the Ministry of Oceans and Fisheries, Korea.

Data Availability Statement: Data derived from public domain resources: The data presented in this study are available in [SSALTO/DUACS altimeter products] at [<http://www.marine.copernicus.eu>]. These data were derived from the following resources available in the public domain: [<http://www.ecmwf.int>] and [<https://www.ncei.noaa.gov/products/international-best-track-archive>].

Acknowledgments: Satellite altimetry data (SSALTO/DUACS altimeter products) produced and distributed by the CMEMS (<http://www.marine.copernicus.eu>, accessed on 30 November 2022), wind stress and MSL atmospheric pressure data from the ECMWF Reanalysis v5 (<http://www.ecmwf.int>, accessed on 9 September 2021), surface heat flux, ocean temperature, salinity, and velocity data from the ORAS5 (<https://www.ecmwf.int/en/research/climate-reanalysis/ocean-reanalysis>, accessed on 15 November 2023), and typhoon information from NOAA NCEI International Best Track Archive for Climate Stewardship (<https://www.ncei.noaa.gov/products/international-best-track-archive>, accessed on 15 January 2024) were used in this study.

Conflicts of Interest: The authors declare that there were no commercial or financial relationships to the study that could be construed as potential conflicts of interest.

Abbreviations

ADT: absolute dynamic topography, BS: Bohai Sea, CMEMS: Copernicus Marine Environment Monitoring Service, DAC: dynamic atmospheric correction, ECS: East China Sea, ES: East Sea, HF: heat flux, HT: heat transport, MSL: mean sea level, NEAMS: northeast Asian marginal seas, ORAS5: Ocean Reanalysis System 5, SLC: sea level change, SLR: sea level rise, ST: salt transport, YS: Yellow Sea.

References

1. Horwath, M.; Gutknecht, B.D.; Cazenave, A.; Palanisamy, H.K.; Marti, F.; Paul, F.; Le Bris, R.; Hogg, A.E.; Otosaka, I.; Shepherd, A. Global sea-level budget and ocean-mass budget, with a focus on advanced data products and uncertainty characterisation. *Earth Syst. Sci. Data* **2022**, *14*, 411–447. [[CrossRef](#)]
2. Lyu, K.; Zhang, X.; Church, J.A.; Slangen, A.B.; Hu, J. Time of emergence for regional sea-level change. *Nat. Clim. Chang.* **2014**, *4*, 1006–1010. [[CrossRef](#)]
3. Carson, M.; Köhl, A.; Stammer, D.; Meyssignac, B.; Church, J.; Schröter, J.; Wenzel, M.; Hamlington, B. Regional sea level variability and trends, 1960–2007: A comparison of sea level reconstructions and ocean syntheses. *J. Geophys. Res. Ocean.* **2017**, *122*, 9068–9091. [[CrossRef](#)]
4. Wang, J.; Church, J.A.; Zhang, X.; Chen, X. Reconciling global mean and regional sea level change in projections and observations. *Nat. Commun.* **2021**, *12*, 990. [[CrossRef](#)]
5. Meyssignac, B.; Piecuch, C.; Merchant, C.; Racault, M.-F.; Palanisamy, H.; MacIntosh, C.; Sathyendranath, S.; Brewin, R. Causes of the regional variability in observed sea level, sea surface temperature and ocean colour over the period 1993–2011. *Integr. Study Mean Sea Level Its Compon.* **2017**, *38*, 191–219. [[CrossRef](#)]

6. Pinardi, N.; Bonaduce, A.; Navarra, A.; Dobricic, S.; Oddo, P. The mean sea level equation and its application to the Mediterranean Sea. *J. Clim.* **2014**, *27*, 442–447. [\[CrossRef\]](#)
7. Wang, K.; Yang, Y.; Reniers, G.; Li, J.; Huang, Q. Predicting the spatial distribution of direct economic losses from typhoon storm surge disasters using case-based reasoning. *Int. J. Disaster Risk Reduct.* **2022**, *68*, 102704. [\[CrossRef\]](#)
8. Wunsch, C.; Stammer, D. Atmospheric loading and the oceanic “inverted barometer” effect. *Rev. Geophys.* **1997**, *35*, 79–107. [\[CrossRef\]](#)
9. Holden, W.N. Mining amid typhoons: Large-scale mining and typhoon vulnerability in the Philippines. *Extr. Ind. Soc.* **2015**, *2*, 445–461. [\[CrossRef\]](#)
10. Han, M.; Cho, Y.-K.; Kang, H.-W.; Nam, S.; Byun, D.-S.; Jeong, K.-Y.; Lee, E. Impacts of atmospheric pressure on the annual maximum of monthly sea-levels in the northeast Asian marginal seas. *J. Mar. Sci. Eng.* **2020**, *8*, 425. [\[CrossRef\]](#)
11. Han, M.; Nam, S.; Cho, Y.-K.; Kang, H.-W.; Jeong, K.-Y.; Lee, E. Interannual variability of winter sea levels induced by local wind stress in the northeast Asian marginal seas: 1993–2017. *J. Mar. Sci. Eng.* **2020**, *8*, 774. [\[CrossRef\]](#)
12. Li, Y.; Zuo, J.; Lu, Q.; Zhang, H.; Chen, M. Impacts of wind forcing on sea level variations in the East China Sea: Local and remote effects. *J. Mar. Syst.* **2016**, *154*, 172–180. [\[CrossRef\]](#)
13. Hsueh, Y.; Romea, R.D.; DeWitt, P. Wintertime winds and coastal sea-level fluctuations in the Northeast China Sea. *Part II Numer. Model. J. Phys. Oceanogr.* **1986**, *16*, 241–261. [\[CrossRef\]](#)
14. Liu, J.-W.; Zhang, S.-P.; Xie, S.-P. Two types of surface wind response to the East China Sea Kuroshio front. *J. Clim.* **2013**, *26*, 8616–8627. [\[CrossRef\]](#)
15. Trusenkov, O.; Nikitin, A.; Lobanov, V. Circulation features in the Japan/East Sea related to statistically obtained wind patterns in the warm season. *J. Mar. Syst.* **2009**, *78*, 214–225. [\[CrossRef\]](#)
16. Guan, S.; Zhao, W.; Sun, L.; Zhou, C.; Liu, Z.; Hong, X.; Zhang, Y.; Tian, J.; Hou, Y. Tropical cyclone-induced sea surface cooling over the Yellow Sea and Bohai Sea in the 2019 Pacific typhoon season. *J. Mar. Syst.* **2021**, *217*, 103509. [\[CrossRef\]](#)
17. Wang, K.; Hou, Y.; Li, S.; Du, M.; Chen, J.; Lu, J. A comparative study of storm surge and wave setup in the East China Sea between two severe weather events. *Estuar. Coast. Shelf Sci.* **2020**, *235*, 106583. [\[CrossRef\]](#)
18. Kao, Y.-C.; Jong-Dao Jou, B.; Chan, J.C.; Lee, W.-C. An observational study of a coastal barrier jet induced by a landfalling typhoon. *Mon. Weather Rev.* **2019**, *147*, 4589–4609. [\[CrossRef\]](#)
19. Zhang, H.; He, H.; Zhang, W.-Z.; Tian, D. Upper ocean response to tropical cyclones: A review. *Geosci. Lett.* **2021**, *8*, 1. [\[CrossRef\]](#)
20. Chai, F.; Wang, Y.; Xing, X.; Yan, Y.; Xue, H.; Wells, M.; Boss, E. A limited effect of sub-tropical typhoons on phytoplankton dynamics. *Biogeosciences* **2021**, *18*, 849–859. [\[CrossRef\]](#)
21. Wu, X.; Wang, H.; Bi, N.; Song, Z.; Zang, Z.; Kineke, G.C. Bio-physical changes in the coastal ocean triggered by typhoon: A case of Typhoon Meari in summer 2011. *Estuar. Coast. Shelf Sci.* **2016**, *183*, 413–421. [\[CrossRef\]](#)
22. Ragone, F.; Meli, A.; Napoli, A.; Pasquero, C. Ocean surface anomalies after strong winds in the Western Mediterranean Sea. *J. Mar. Sci. Eng.* **2019**, *7*, 182. [\[CrossRef\]](#)
23. Liu, S.; Li, J.; Sun, L.; Wang, G.; Tang, D.; Huang, P.; Yan, H.; Gao, S.; Liu, C.; Gao, Z.; et al. Basin-wide responses of the South China Sea environment to super typhoon Mangkhut (2018). *Sci. Total Environ.* **2020**, *731*, 139093. [\[CrossRef\]](#)
24. Rio, M.; Guinehut, S.; Larnicol, G. New CNES-CLS09 global mean dynamic topography computed from the combination of GRACE data, altimetry, and in situ measurements. *J. Geophys. Res. Ocean.* **2011**, *116*, C07018. [\[CrossRef\]](#)
25. AVISO; MDT. CNES-CLS18. Available online: <https://www.aviso.altimetry.fr/en/data/products/auxiliary-products/mdt.html> (accessed on 30 November 2022).
26. Taburet, G.; Pujol, M.-I. Sea Level TAC-DUACS Products. Available online: <https://catalogue.marine.copernicus.eu/documents/QUID/CMEMS-SL-QUID-008-032-062.pdf> (accessed on 1 June 2022).
27. CMEMS_portal. SEALEVEL_GLO_PHY_L4_REP_OBSERVATIONS_008_047. Available online: ftp://my.cmems-du.eu/Core/SEALEVEL_GLO_PHY_L4_REP_OBSERVATIONS_008_047/dataset-duacs-rep-global-merged-allsat-phy-l4 (accessed on 30 November 2022).
28. Watson, P.J.; Lim, H.-S. An update on the status of mean sea level rise around the Korean Peninsula. *Atmosphere* **2020**, *11*, 1153. [\[CrossRef\]](#)
29. Ding, Y.; Yu, H.; Bao, X.; Kuang, L.; Wang, C.; Wang, W. Numerical study of the barotropic responses to a rapidly moving typhoon in the East China Sea. *Ocean Dyn.* **2011**, *61*, 1237. [\[CrossRef\]](#)
30. Ji, T.; Li, G.; Liu, R. Historical reconstruction of storm surge activity in the southeastern coastal area of China for the past 60 years. *Earth Space Sci.* **2020**, *7*, e2019EA001056. [\[CrossRef\]](#)
31. Knapp, K.; Diamond, H.; Kossin, J.; Kruk, M.; Schreck, C. International Best Track Archive for Climate Stewardship (IBTrACS) Project, Version 4.[WP]. Available online: <https://www.ncei.noaa.gov/products/international-best-track-archive> (accessed on 1 June 2021).
32. Camelo, J.; Mayo, T. The lasting impacts of the Saffir-Simpson Hurricane Wind Scale on storm surge risk communication: The need for multidisciplinary research in addressing a multidisciplinary challenge. *Weather Clim. Extrem.* **2021**, *33*, 100335. [\[CrossRef\]](#)
33. PSMSL. Tide Gauge Data. Available online: <http://www.psmsl.org/data/obtaining/> (accessed on 13 June 2024).
34. Holgate, S.J.; Matthews, A.; Woodworth, P.L.; Rickards, L.J.; Tamsiea, M.E.; Bradshaw, E.; Foden, P.R.; Gordon, K.M.; Jevrejeva, S.; Pugh, J. New data systems and products at the permanent service for mean sea level. *J. Coast. Res.* **2013**, *29*, 493–504. [\[CrossRef\]](#)

35. Mathers, E.; Woodworth, P. Departures from the local inverse barometer model observed in altimeter and tide gauge data and in a global barotropic numerical model. *J. Geophys. Res. Ocean.* **2001**, *106*, 6957–6972. [\[CrossRef\]](#)
36. Park, J.H.; Yeo, D.E.; Lee, K.; Lee, H.; Lee, S.W.; Noh, S.; Kim, S.; Shin, J.; Choi, Y.; Nam, S. Rapid decay of slowly moving Typhoon Soulik (2018) due to interactions with the strongly stratified northern East China Sea. *Geophys. Res. Lett.* **2019**, *46*, 14595–14603. [\[CrossRef\]](#)
37. Wong, M.L.; Chan, J.C. Tropical cyclone motion in response to land surface friction. *J. Atmos. Sci.* **2006**, *63*, 1324–1337. [\[CrossRef\]](#)
38. Xiong, J.; Yu, F.; Fu, C.; Dong, J.; Liu, Q. Evaluation and improvement of the ERA5 wind field in typhoon storm surge simulations. *Appl. Ocean Res.* **2022**, *118*, 103000. [\[CrossRef\]](#)
39. Basconcillo, J.; Cha, E.-J.; Moon, I.-J. Characterizing the highest tropical cyclone frequency in the Western North Pacific since 1984. *Sci. Rep.* **2021**, *11*, 14350. [\[CrossRef\]](#) [\[PubMed\]](#)
40. Basconcillo, J.; Moon, I.-J. Recent increase in the occurrences of Christmas typhoons in the Western North Pacific. *Sci. Rep.* **2021**, *11*, 7416. [\[CrossRef\]](#) [\[PubMed\]](#)
41. Hu, A.; Bates, S.C. Internal climate variability and projected future regional steric and dynamic sea level rise. *Nat. Commun.* **2018**, *9*, 1068. [\[CrossRef\]](#)
42. Molden, D.J.; Shrestha, A.B.; Immerzeel, W.W.; Maharjan, A.; Rasul, G.; Wester, P.; Wagle, N.; Pradhananga, S.; Nepal, S. The Great Glacier and Snow-Dependent Rivers of Asia and Climate Change: Heading for Troubled Waters. In *Water Security Under Climate Change*; Springer: Singapore, 2022; pp. 223–250.
43. Durand, F.; Piecuch, C.G.; Becker, M.; Papa, F.; Raju, S.V.; Khan, J.U.; Ponte, R.M. Impact of continental freshwater runoff on coastal sea level. *Surv. Geophys.* **2019**, *40*, 1437–1466. [\[CrossRef\]](#)
44. Kang, S.K.; Cherniawsky, J.; Foreman, M.; Min, H.S.; Kim, C.H.; Kang, H.W. Patterns of recent sea level rise in the East/Japan Sea from satellite altimetry and in situ data. *J. Geophys. Res. Ocean.* **2005**, *110*, C07002. [\[CrossRef\]](#)
45. Kranenburg, W.M.; Tiessen, M.C.; Blaas, M.; Van Veen, N.P. Circulation, stratification and salt dispersion in a former estuary after reintroducing seawater inflow. *Estuar. Coast. Shelf Sci.* **2023**, *282*, 108221. [\[CrossRef\]](#)
46. Wu, L.; Wang, R.; Feng, X. Dominant role of the ocean mixed layer depth in the increased proportion of intense typhoons during 1980–2015. *Earth's Future* **2018**, *6*, 1518–1527. [\[CrossRef\]](#)
47. Wu, L.; Zhao, H.; Wang, C.; Cao, J.; Liang, J. Understanding of the effect of climate change on tropical cyclone intensity: A review. *Adv. Atmos. Sci.* **2022**, *39*, 205–221. [\[CrossRef\]](#)
48. Moon, J.-H.; Lee, J. Shifts in multi-decadal sea level trends in the East/Japan Sea over the past 60 years. *Ocean Sci. J.* **2016**, *51*, 87–96. [\[CrossRef\]](#)
49. Kim, S.B.; Fukumori, I. A near uniform basin-wide sea level fluctuation over the Japan/East Sea: A semiencloded sea with multiple straits. *J. Geophys. Res. Ocean.* **2008**, *113*, 338–358. [\[CrossRef\]](#)
50. Waryszak, P.; Gavaille, A.; Whitt, A.A.; Kelvin, J.; Macreadie, P.I. Combining gray and green infrastructure to improve coastal resilience: Lessons learnt from hybrid flood defenses. *Coast. Eng. J.* **2021**, *63*, 335–350. [\[CrossRef\]](#)
51. Jibiki, Y.; Kure, S.; Kuri, M.; Ono, Y. Analysis of early warning systems: The case of super-typhoon Haiyan. *Int. J. Disaster Risk Reduct.* **2016**, *15*, 24–28. [\[CrossRef\]](#)
52. Zhao, L.; Liu, F. Land-use planning adaptation in response to SLR based on a vulnerability analysis. *Ocean Coast. Manag.* **2020**, *196*, 105297. [\[CrossRef\]](#)
53. Hurlimann, A.; Barnett, J.; Fincher, R.; Osbaldiston, N.; Mortreux, C.; Graham, S. Urban planning and sustainable adaptation to sea-level rise. *Landsc. Urban Plan.* **2014**, *126*, 84–93. [\[CrossRef\]](#)
54. Li, Z.; Fung, J.C.; Wong, M.F.; Lin, S.; Cai, F.; Lai, W.; Lau, A.K. Future changes in intense tropical cyclone hazards in the Pearl River Delta region: An air-wave-ocean coupled model study. *Nat. Hazards* **2024**, *120*, 7139–7154. [\[CrossRef\]](#)
55. Bilskie, M.V.; Hagen, S.; Medeiros, S.; Cox, A.; Salisbury, M.; Coggin, D. Data and numerical analysis of astronomic tides, wind-waves, and hurricane storm surge along the northern Gulf of Mexico. *J. Geophys. Res. Ocean.* **2016**, *121*, 3625–3658. [\[CrossRef\]](#)
56. Dinan, T. Projected increases in hurricane damage in the United States: The role of climate change and coastal development. *Ecol. Econ.* **2017**, *138*, 186–198. [\[CrossRef\]](#)

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.