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Uncovering Interdecadal Pacific Oscillation's Dominance in Shaping Low-Frequency Sea Level Variability in the South China Sea

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Abstract: The low-frequency sea level variability in the South China Sea (SCS) is examined using high-resolution regional ocean model simulations that span the last six decades. The analysis reveals interdecadal oscillations with a periodicity of 12–13 years as the dominant mode of sea level variability in the SCS. The fluctuations in the Luzon Strait transport (LST) are identified as primary drivers of interannual to interdecadal sea level variability, rather than atmospheric forcing within the SCS. Fourier spectrum analysis is employed to investigate the association between SCS sea level variability and the Interdecadal Pacific Oscillation (IPO), using principal components of SCS sea surface height anomalies, wind stress curl, wind stress components, net short wave flux, as well as the LST and various climate indices. The variations in the SCS sea level are driven by the IPO, which modifies the LST and ocean heat content, impacting the steric sea level.

Keywords: South China Sea; Interdecadal Pacific Oscillation; NEMO



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1. Introduction

Spatial and temporal non-uniformity is a prominent characteristic of sea level change/variability, as it manifests significant variations across diverse geographical locations and time periods [1]. Furthermore, regional sea level variability is subject to the influence of large-scale climate phenomena that span seasonal, interannual, decadal, and multidecadal timescales. In the present study, the term “low-frequency” is defined to encompass the sea level variability observed across interannual to multidecadal timescales. The superimposition of low-frequency sea level variability upon long-term trends can induce temporal fluctuations, resulting in a decrease or increase in regional sea level trends [2,3]. Therefore, a comprehensive understanding of the patterns and drivers of such variability is imperative for advancing our knowledge of sea level change and its implications for marine and coastal applications, particularly in the context of a warming climate where coastal areas and low-lying islands are vulnerable to the risks associated with sea level rise. The El Niño-Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), Southern Annular Mode (SAM), and Indian Ocean Dipole/Zonal Mode (IOD) have been identified as the dominant processes that modify sea level variability over the Pacific Ocean [2,4,5]. Similarly, the IOD has been recognised as the primary driver of sea level variability in the Indian Ocean [6].

The geographical location of the South China Sea (SCS) and its interconnections with the Pacific and Indian Ocean through diverse straits have profoundly shaped its seasonal [7], interannual [8,9], and interdecadal [10,11] variability, establishing a close and intricate relationship between the SCS and these neighbouring oceans. The ENSO, IOD, and PDO have gained widespread recognition as principal climate phenomena significantly influencing the climate of the SCS across multiple timescales [7,10,12–15]. The

low-frequency sea level variability over the SCS has been investigated in earlier studies, e.g., [12,16]. However, there is a limited body of research on the decadal variability of sea levels in the SCS, with most studies relying on coarse resolution global reanalysis datasets or satellite observations starting from 1993 [8,9,17,18]. The variability in the Luzon Strait transport is suggested to play a key role in the interannual sea level variability of the SCS [12]. While the ENSO has traditionally been acknowledged as the primary driving force, recent studies have indicated that the PDO and Interdecadal Pacific Oscillation (IPO) also exert a substantial influence on the low-frequency sea level variability within the SCS [15,17,18].

The PDO and IPO are two closely related modes of decadal to interdecadal climate variability in the Pacific Ocean [19]. The IPO represents the interdecadal variation within the ENSO [20], while the PDO pattern dominates in the North Pacific Ocean [21]. As the time series of the PDO and IPO exhibit a significant correlation, unravelling the dominant driver of decadal timescale sea level variability is a complex task that necessitates careful investigation. Ocean hindcast simulations provide valuable insights into understanding low-frequency climate variability, especially on decadal or multidecadal timescales, by offering longer time series data compared to available observational records. In this study, we utilise a high-resolution ocean model simulation spanning the last six decades to investigate the patterns and drivers of low-frequency sea level changes in the SCS. As an initial step, the model sea level simulations are validated against observed sea level variability from satellite and tide gauge records. We then employ the empirical orthogonal function (EOF) analysis on the model sea surface height (SSH) to identify the dominant patterns of variability. Furthermore, a comprehensive analysis is conducted to elucidate the drivers and physical mechanisms of these variabilities, including the examination of the Luzon Strait transport (LST), ocean surface forcing, and various climate indices.

The paper is organised as follows: Section 2 discusses the model used for the study and the various datasets employed in the analysis. Section 3 presents the validation of the model SSH simulations using observational data, as well as an analysis of low-frequency sea level variability in the SCS, along with a discussion of the various forcings responsible for this variability. Finally, the main results of the study are summarised in the Section 4.

2. Materials and Methods

The study utilises a regional version of the Océan Parallélisé ocean engine, implemented within the Nucleus for European Modelling of the Ocean (NEMO v4.0.6) framework [22], configured for the Maritime Continent (MC) domain spanning from 90° E to 142° E and from 18° S to 27° N (Figure 1). NEMO is a primitive-equation, hydrostatic, Boussinesq ocean model extensively used in global as well as regional climate modelling studies [23,24]. The model has a horizontal resolution of 4.5 km $\times$ 4.5 km and has 51 vertical levels in a terrain-following coordinate system. The model employs a horizontal grid in orthogonal curvilinear coordinates, using the Arakawa-C grid staggering scheme. The model bathymetry is derived from the General Bathymetric Chart of the Oceans (GEBCO 2020) dataset, with a horizontal resolution of 15 arc-seconds. A non-linear free surface following the variable volume layer formulation by [25] is used for model free surface computation. The computation of turbulent viscosities and diffusivities in this study is performed using the Generic Length Scale (GLS) turbulence model [26] with the K- ϵ turbulent closure scheme and the stability function introduced by [27]. The bottom drag coefficient is calculated using an implicit form of non-linear parameterization with a log layer formulation. For the lateral open-ocean boundaries, the flow relaxation scheme [28] is used to control the tracers and baroclinic velocities, while the Flather boundary condition [29] is applied to the sea surface height (SSH) and barotropic velocities.

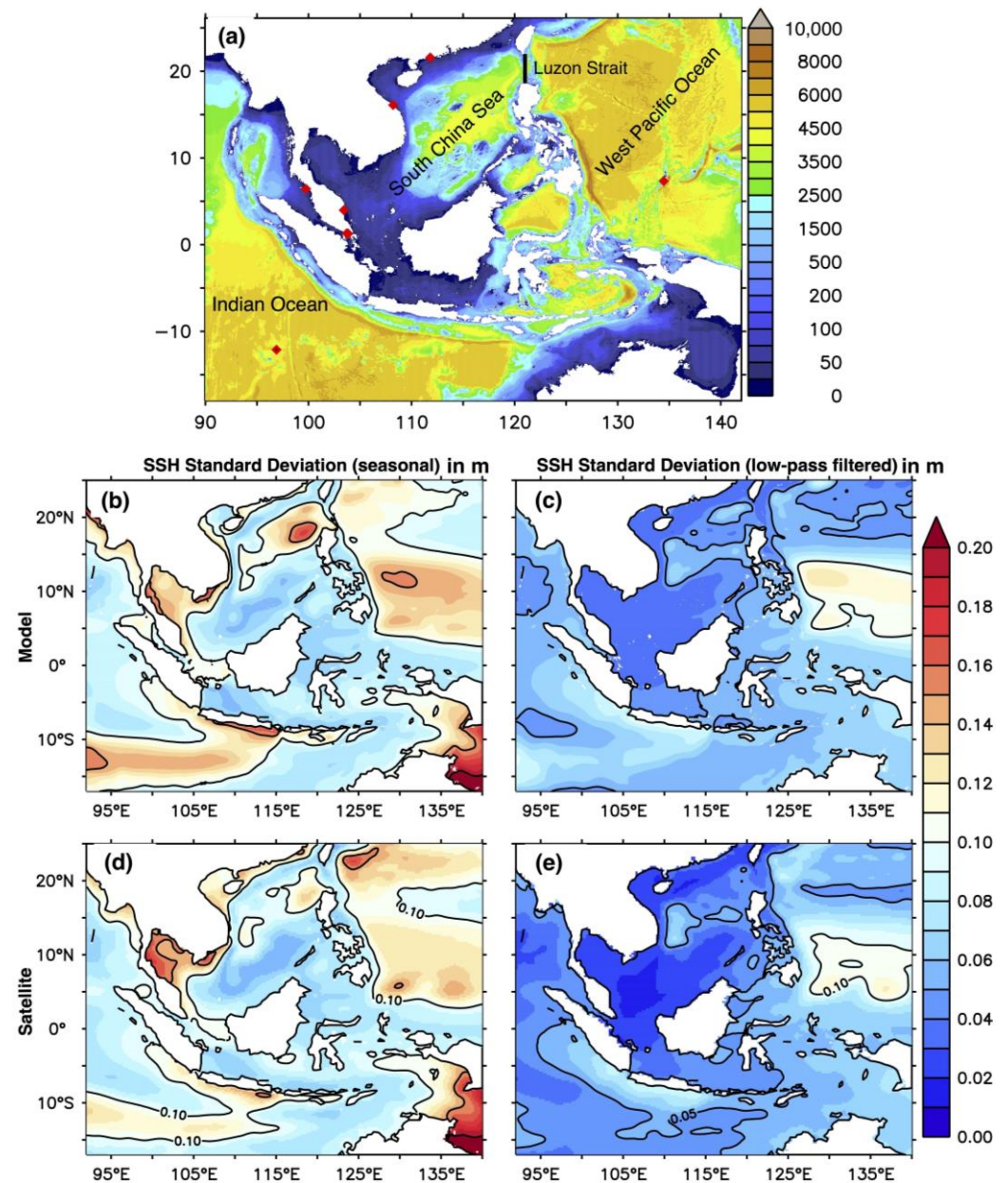


Figure 1. (a) Model domain and bathymetry in metres (GEBCO 2020). The locations of tide gauges used in the analysis are shown as red squares. SSH standard deviation (in metres) derived from the model (b,c) and satellite observations (d,e) for the period 1993–2022. The left panel displays the standard deviation including the seasonal cycle, while the right panel presents the estimation derived from 13-month low-pass filtered data.

The model surface forcing includes hourly varying downward shortwave and long-wave radiation at the ocean surface, total precipitation, mean sea level pressure, river runoff, 10 m wind velocities, air temperature, and specific humidity fields obtained from the ERA5 data. The estimation of air–sea heat fluxes is performed using the Common Ocean-ice Reference Experiment (CORE 3.5) bulk formulae [30]. For the model initialization, the monthly averaged temperature, salinity, zonal and meridional currents, and SSH derived from the Ocean Reanalysis System 5 (ORAS5) [31] for December 1958 was used. The monthly averaged temperature, salinity, baroclinic and barotropic velocities, and SSH from the ORAS5 are included in the lateral boundary forcing. Monthly chlorophyll climatology from SeaWiFS satellite observation is provided to compute light absorption

coefficients, which estimate the penetration of shortwave radiation into the ocean using the red-blue-green (RGB) scheme [32].

The model integration period spans from January 1959 to October 2022. Surface boundary forcing is provided by the European Centre for Medium Range Weather Forecasting (ECMWF) Reanalysis 5 (ERA5) [31], while lateral ocean boundary forcing is obtained from the ECMWF Ocean Reanalysis System 5 (ORAS5) [23]. The monthly averaged fields from model hindcast simulations from January 1961 to October 2022 are used for further analysis in the study.

For the validation of the model SSH simulations, the monthly averaged tide gauge records from randomly selected locations (shown in Figure 1) obtained from the Permanent Services for Mean Sea Level (PSMSL) [33] and the merged satellite SSH observation product from the Copernicus Marine Environment Monitoring Service (CMEMS) (<https://doi.org/10.48670/moi-00145>, accessed on 22 September 2024) are employed in the study. In order to focus on the analysis of sea level variability, the linear trend is removed from the model and observation data. To remove the seasonal cycle from the SSH data, a 13-month low-pass Lanczos filter is applied to both the model simulations and observations.

To represent the ENSO, PDO, IPO, and IOD events, monthly time series of the Niño 3.4 index [34], PDO index [35], IPO tripolar index [19], and Dipole Mode Index (DMI) [36] are employed in the analysis. The relative Niño 3.4 index, as proposed by [34], is defined as the difference between sea surface temperature (SST) anomalies averaged over the region 5° S–5° N, 120° W–170° W in the tropical Pacific Ocean and those averaged over all tropical oceans (20° S–20° N). The PDO is characterised by the leading EOF of SST anomalies in the North Pacific Ocean, typically north of 20° N, with the leading principal component (PC) of these anomalies defining the PDO index. The IPO tripolar index is calculated as the difference between SST anomalies averaged over the central equatorial Pacific Ocean and the combined average of SST anomalies in the northwest and southwest Pacific regions [19]. The DMI is defined as the anomalous SST gradient between the western equatorial Indian Ocean (50° E–70° E and 10° S–10° N) and the southeastern equatorial Indian Ocean (90° E–110° E and 10° S–0° N) [36]. The climate indices are freely available from <http://climexp.knmi.nl> (accessed on 22 September 2024).

3. Results and Discussions

3.1. Model Sea Surface Height

The SCS exhibits pronounced seasonal variations in the sea level due to the reversal of surface winds associated with the southwest (June–August) and northeast (December–February) monsoons. Figure 1b–e illustrates the standard deviation of SSH from model and satellite observations during the period from 1993 to 2022. The regions exhibiting the most significant amplitudes of seasonal sea level variability are primarily located along the shelves of the SCS, the northeastern SCS west of the Luzon Strait, the southeastern tropical Indian Ocean, the Arafura Sea, the Gulf of Carpentaria off the northern coast of Australia, and the northwestern tropical Pacific Ocean (Figure 1b,d). Within the SCS, the highest variability is observed over the Gulf of Thailand, with SSH variability reaching approximately 0.2 m. After the removal of the SSH seasonal cycle with a 13-month low-pass filter, the non-seasonal or inter-annual sea level variability is estimated (Figure 1c,e). The standard deviation is generally smaller over most of the SCS when the seasonal cycle is excluded, except for the central region and the area west of the Luzon Strait. The non-seasonal SSH variability is greater in the southeastern tropical Indian Ocean and northwestern equatorial Pacific regions, as observed in both the model simulations and satellite observations. In general, there is a good agreement between the model and satellite observations in terms of the spatial patterns of both the seasonal and interannual sea level variability. The standard deviation estimated from the model simulations generally exhibits higher magnitudes compared to the satellite observations, which can be attributed to the higher resolution of the model in comparison to the satellite data. The spatial pattern

of sea level variability remains mostly unchanged throughout the entire analysis period (1961–2022), albeit with a slightly weaker magnitude (Figure 2).

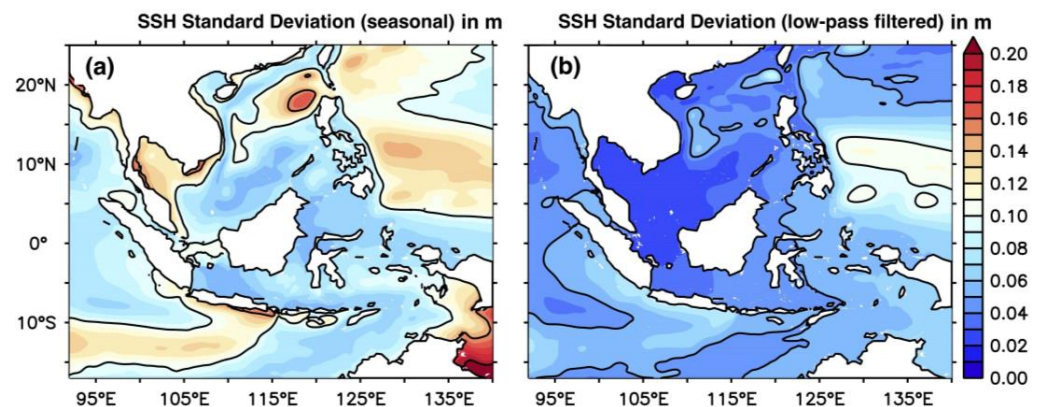


Figure 2. SSH standard deviation (in metres) computed from the model for the period 1961–2022. The left panel displays the standard deviation including the seasonal cycle (a), while the right panel presents the estimation derived from 13-month low-pass filtered data (b).

To further assess the models' ability to reproduce low-frequency sea level variability, a comparison is performed between the 13-month low-pass filtered model sea surface height anomaly (SSHA) and observations from tide gauges as well as satellite altimeters. The time series of SSHA from the model, tide gauge, and satellite observations at the locations of tide gauge stations are shown in Figure 3. The model SSHA from the nearest model grid point to the tide gauge station is used for comparison. Statistically significant correlations, above the 99.9% confidence level, are observed between the tide gauge and model (r_{TN}) sea level anomalies, as well as between the satellite and model (r_{SN}) sea level anomalies, at all stations selected in our analysis. As observed in the spatial patterns of SSH standard deviation (Figure 1), the amplitude of sea level variability is relatively weaker at the SCS stations compared to the Malakal-B and Cocos Island stations in the western Pacific and southeastern tropical Indian Oceans, respectively. The significant correlation observed between the model and observations highlights the capacity of the models to accurately capture low-frequency sea level variability in the Maritime Continent, with particular emphasis on the SCS region. The satisfactory performance of the model in simulating sea level variations has encouraged further analyses aiming to discover dominant modes of low-frequency sea level variability and their underlying drivers, as presented in the subsequent sections.

3.2. Low-Frequency Sea Level Variability in the SCS

The dominant patterns of SCS sea level variability during the period 1961–2022 were identified using EOF analysis on the detrended and 13-month low-pass filtered model SSHA data. The spatial patterns of the first (EOF1) and second (EOF2) dominant modes of low-frequency sea level variability in the SCS are illustrated in Figure 4a,b, respectively. These modes account for 49% and 11% of the total variability, respectively. The first mode exhibits a spatially uniform sea level variability across the entire SCS, with the lowest variability observed in the central region and the highest variability of approximately 0.04 m in the eastern regions of the SCS. Meanwhile, the second mode is characterised by sea level anomalies of opposite variability in the central SCS, extending from the east of Vietnam to Luzon Island in a slightly diagonal orientation, as well as in the remaining regions of the SCS. The peak variability of approximately 0.04 m observed in the EOF2, located off the east coast of Vietnam, almost corresponds to the spatial pattern of low-frequency sea level variability in the region (Figure 1c,e). The analysis suggests that the low-frequency sea level variability in the central SCS region is strongly influenced by EOF2, while EOF1 plays a dominant role in shaping the sea level variability in the eastern SCS

and shelves. It is also worth noting that the spatial patterns of EOF2 exhibit a distinct transition in the Malacca Strait region, particularly west of the Singapore Strait (Figure 4b). This result is consistent with the findings discussed by [37]. Their study unveiled that the IOD exerts dominance over the interannual sea level variability in the oceanic regions west of the Singapore Strait.

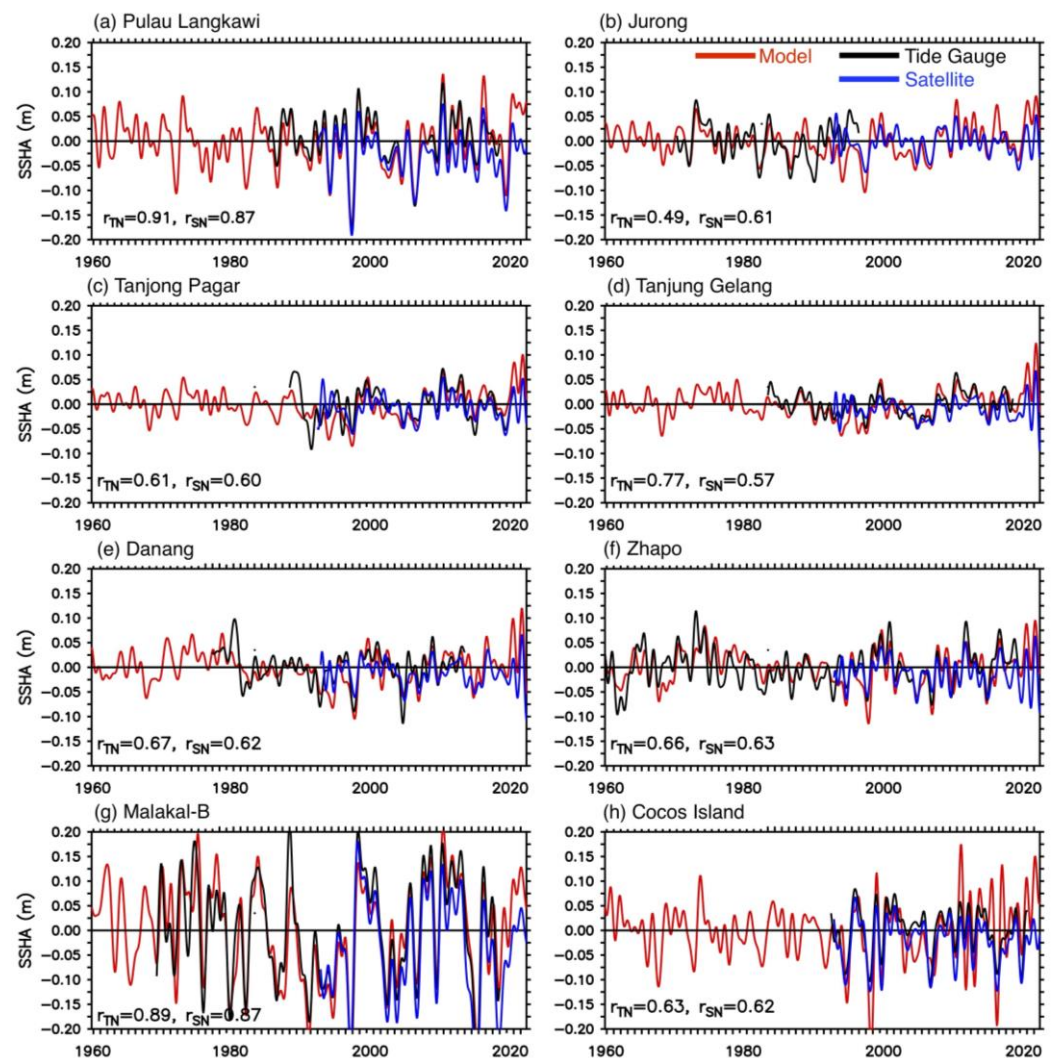


Figure 3. Time series of sea surface height anomaly (in metres) from the model (red line), tide gauge (black line), and satellite observations (blue line) at selected stations within the model domain. The panels also display the correlations between the tide gauge and model (r_{TN}) as well as between the satellite and model (r_{SN}).

To gain further insight into the drivers of SCS sea level variability, we extended our analysis to encompass the major climate phenomena, including the ENSO, IOD, PDO, and IPO, which are well established as exerting substantial influence on global and regional atmospheric and oceanic climate patterns. The linear regression of the principal component of first dominant mode (PC1) of SCS SSHA, Nino3.4 index, PDO index, and IPO index on the ORAS5 SSHA over the eastern Indian–Pacific Ocean region is also shown in Figure 4c–f. The spatial patterns of sea level regression coefficients for the SCS SSHA PC1, PDO (Figure 3e), and IPO (Figure 4f) exhibit distinct characteristics compared to the ENSO, with a relatively stronger variability observed in the mid-latitudes. However, a stronger agreement between the regression patterns of the ENSO and IPO is observed in the tropical region, providing further support to the idea that the IPO represents interdecadal oscillations within the ENSO system [20]. A careful examination of the maps reveals a closer agreement among

the regression patterns of PC1 (Figure 4c) and the IPO (Figure 4f) in the canonical extension within the equatorial Pacific Ocean, variability in the Kuroshio extension east of the Yellow Sea, and in the subtropical south Pacific Ocean and southeastern tropical Indian Ocean regions.

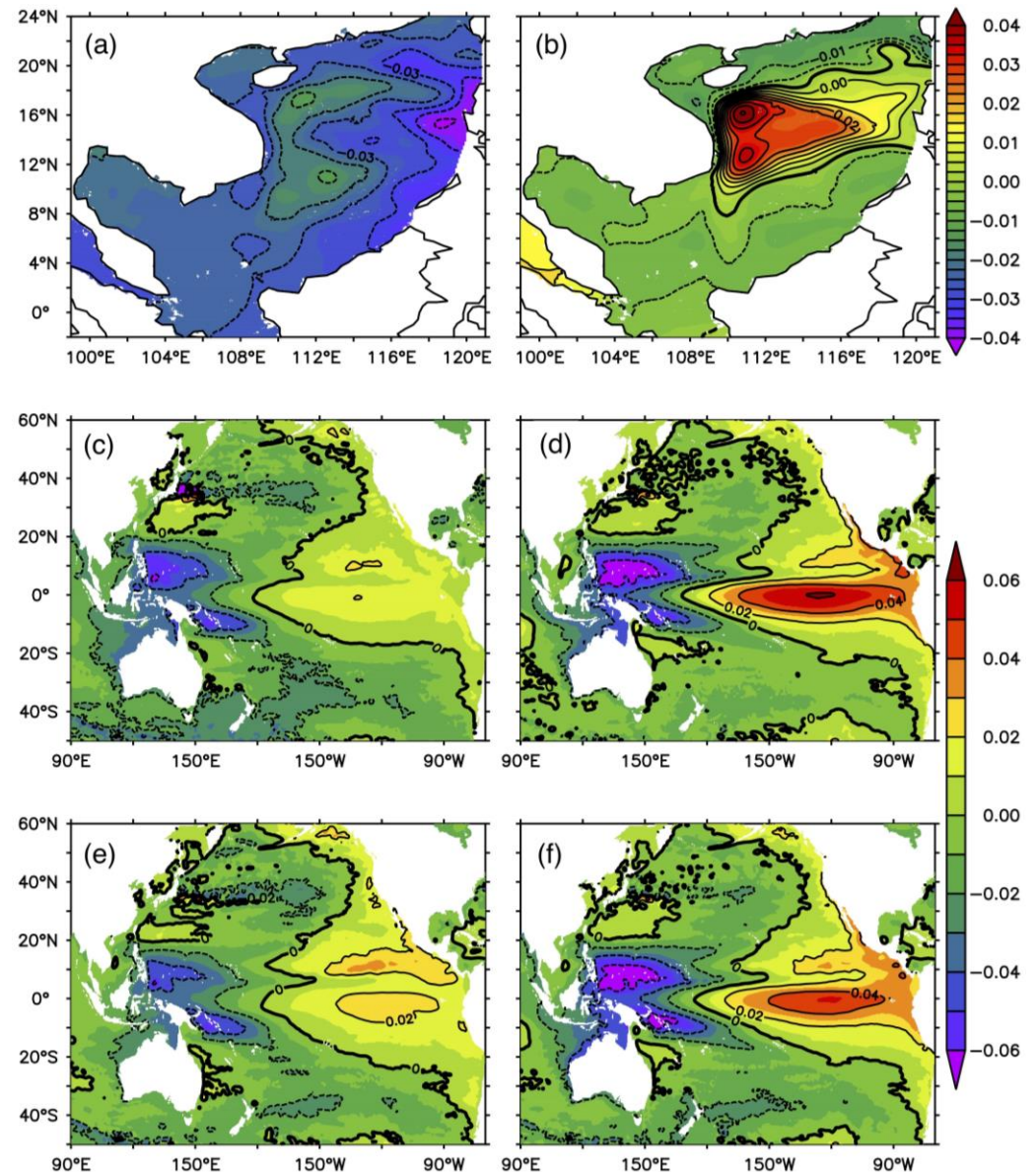


Figure 4. (a,b) Maps of regression coefficients of the model SSHA against the SCS SSHA PC1 and PC2, respectively. Maps of regression coefficients of the ORAS5 SSHA against the (c) SCS SSHA PC1, (d) Nino3.4 index, (e) PDO index, and (f) IPO Tripolar index over the eastern Indian–Pacific Ocean region. Normalised principal components and indices are used for the regression analysis. Units are in metres.

The dominant periods in the first (PC1) and second (PC2) leading modes were identified through the Fourier spectrum analysis of the principal components. Figure 5a displays the Fourier amplitude spectrum of PC1 and PC2, derived from the 13-month low-pass filtered sea level anomalies. The figure shows that the first dominant mode exhibits a periodicity of 12–13 years, while the EOF2 displays higher frequency oscillations with a periodicity of 1.5–5 years. In order to identify the dominant oscillations within the climate phenomena, a similar analysis was conducted using the low-pass filtered Nino3.4 index, DMI, IPO index, and PDO index (Figure 5b). Consistent with previous studies, the ampli-

tude spectrum of the Nino3.4 index reveals significant oscillations with a periodicity of 1.5–5 years [38]. Importantly, the Fourier spectrum of the IPO index reveals a dominant decadal oscillation with a periodicity of 12–13 years, which aligns with the low-frequency periodicity observed in the ENSO. The dominant periodicities observed in the PDO are approximately 6, 9–10, and 20 years, while the IOD exhibits a periodicity of around 2–6 years in our analysis. The analysis reveals that the dominant periodicity in PC1 corresponds to the IPO or the low-frequency mode of the ENSO, while PC2 shows a strong association with the higher frequency ENSO. However, the analysis does not demonstrate a clear influence of the DMI or PDO on the low-frequency sea level variability in the SCS.

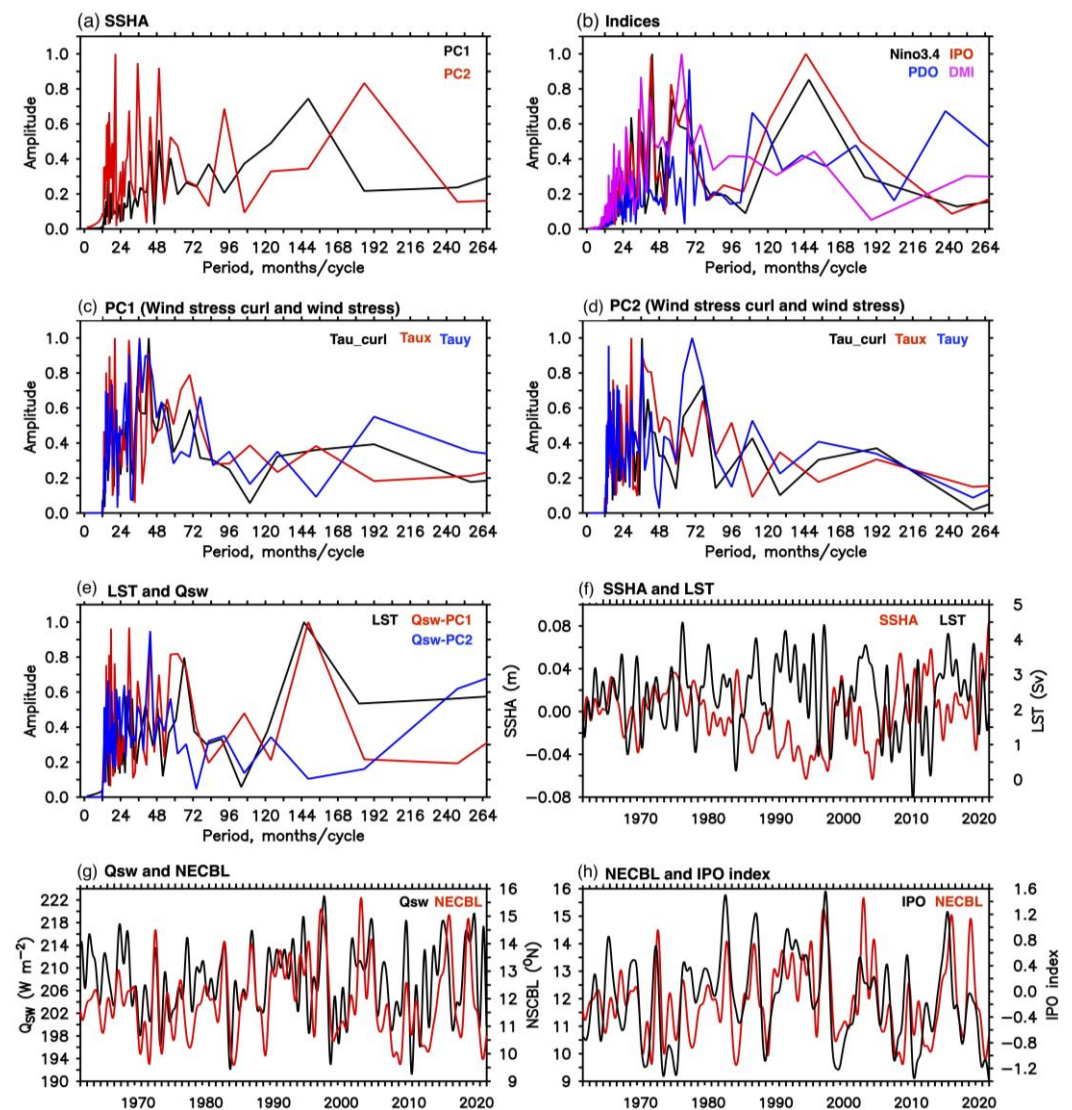


Figure 5. (a) Normalised Fourier amplitude spectrum of PC1 (black line) and PC2 (red line) of model SSHA in the SCS. (b) Normalised Fourier amplitude spectrum of Nino3.4 index (black line), IPO tripolar index (red line), PDO index (blue line), and DMI (purple line) for 1961 to 2022 period. (c) and (d) Normalised Fourier amplitude spectrum of PC1 and PC2, respectively, of wind stress curl (Tau_curl, black line), zonal wind stress (Taux, red line), and meridional wind stress curl (Tauy, blue line) over the SCS during 1961–2022. (e) Normalised Fourier amplitude spectrum of LST (black line), and the PC1 (red line) and PC2 (blue line) of Q_{SW} averaged over the SCS. (f) SSHA (red line) averaged over the SCS and LST (black line) estimated in the section shown in Figure 1. (g) Q_{SW} (black line) averaged over the SCS and Pacific North Equatorial Current Bifurcation Latitude (NECBL) (red line) estimated using the model SSHA using Equation (2) from [39]. (h) NECBL (red line) and IPO Tripolar index (black line).

In order to investigate the underlying physical mechanisms behind the low-frequency sea level variability, our analysis is expanded to include ocean surface boundary forcings, including wind stress curl, zonal/meridional wind stress components, and shortwave radiation flux, as well as the volume flow processes associated with the SCS Throughflow (SCSTF). The volume transport through the Luzon Strait, estimated at the section depicted in Figure 1, is utilised as a representation of the SCSTF. The Fourier amplitude spectra of PC1 and PC2 for the wind stress curl (τ_{curl}) and zonal (τ_{ux}) and meridional (τ_{uy}) wind stress are plotted in Figure 5c,d, respectively. Furthermore, Figure 5e displays the amplitude spectra of PC1 and PC2 for the surface net shortwave radiation (Q_{sw}) and LST. The periodicity of the first two dominant modes of the wind stress curl, as well as the zonal and meridional components, predominantly falls within the range of 1–6 years. Remarkably, the amplitude spectra of the LST and the PC1 of surface net shortwave flux exhibit low-frequency oscillation with a periodicity of 12–13 years, which is consistent with the analysis in the PC1 of SCS level anomalies and the IPO. The LST and the averaged Q_{sw} over the SCS exhibit a significant correlation of 0.40 (Figure 5e). Additionally, both the LST and Q_{sw} demonstrate a mostly inverse relationship with the SCS averaged SSHA (Figure 5f,g). These results suggest the presence of a common large-scale forcing that influences the low-frequency variability of the LST, as well as the sea level and shortwave flux in the SCS. The periodicity of the PC1 of the SCS sea level and shortwave flux, along with the LST, is approximately 12–13 years, which coincides with the periodicity observed in the IPO index. Therefore, it is plausible to consider the IPO as the primary driver of low-frequency sea level variability in the SCS, which is consistent with the findings of sea level regression coefficient maps.

3.3. Role of External Forcing in SCS Sea Level Variability

The LST is recognised as a pivotal process that facilitates the propagation of ENSO and IPO influences from the Pacific Ocean to the SCS [7,15]. The interannual variability of the LST demonstrates a robust association with the fluctuations in the Kuroshio current and Pacific north equatorial current [40,41]. The southward (northward) migration of the Pacific North Equatorial Current Bifurcation Latitude (NECBL) off the eastern coast of the Philippines leads to the weakening (strengthening) of the LST (Figure 5f,g). The LST and NECBL exhibit a significant correlation of 0.61. These findings are consistent with the earlier studies [7,15,42]. The southward migration of the NECBL occurs during the La Niña or negative phase of the IPO, whereas a northward shift takes place during the El Niño or positive IPO phase [42]. Our analysis also reveals a significant correlation (0.60) between the NECBL and the IPO index, indicating a strong relationship between these two (Figure 5h). The influence of the IPO on the NECBL is notably significant, particularly in recent decades, as evidenced by the impact of IPO-related wind stress curl anomalies over the tropical west Pacific Ocean on the NECBL [15]. Due to the cooler water entering the South China Sea from the western Pacific Ocean compared to the warmer outflow through the Mindoro, Balabac, Karimata, and Malacca Straits, the LST contributes to the cooling of the SCS's thermal balance [7]. Consequently, increased LST results in negative ocean heat content anomalies in the SCS, while decreased LST leads to positive anomalies, thereby influencing the variability of the steric sea level. The low-frequency variations in sea levels observed in the SCS could be a direct result of the variability in the ocean heat content driven by the IPO through the variations in the LST, leading to changes in steric sea levels.

4. Conclusions

The low-frequency sea level variability in the SCS is investigated using validated high-resolution regional ocean model simulations that span the last six decades. The first dominant mode of sea level variability is characterised by the same sign over the entire SCS, while the second mode demonstrates opposite variabilities in the central SCS and the surrounding shelf regions. The Fourier spectrum analysis of the IPO index, LST, and PC1 of net shortwave radiation flux over the SCS yields oscillations with a periodicity

of 12–13 years, which is identical to the dominant periodicity observed in the SCS sea level anomaly PC1. The LST plays a significant role in the climate variability of the SCS, particularly in low-frequency timescales, and its influence becomes more pronounced at decadal and longer timescales. Notwithstanding higher (lower) shortwave flux into the ocean, the stronger (weaker) LST contributes to a decrease (increase) in the sea level in the SCS through enhanced (diminished) heat loss. The wind stress curl anomalies induced by the IPO over the tropical Pacific Ocean modulate the intensity of the Kuroshio current through the southward or northward migration of the NECBL [15], which, in turn, results in the weakening or strengthening of the LST. Due to the strong correlation and close relationship between the PDO and IPO as recognised climate modes of variability, relying solely on the correlation analysis of their indices with SCS sea levels may not provide sufficient evidence to identify the primary driver of sea level changes.

In this study, we employed Fourier spectrum analysis to identify the periodicity of SCS SSHA PC1, as well as the PDO and IPO indices. Our analysis reveals the presence of oscillations with the same periodicity in the SCS low-frequency sea level variability and IPO. The resemblance between the regression coefficient maps of the SCS SSH PC1 and IPO against the sea level in the Indo-Pacific regions support for this argument. Furthermore, the IPO represents interdecadal variations in the ENSO, which itself exerts a significant influence on tropical climate variability. Thus, it is highly conceivable that the IPO plays a prominent and influential role in shaping the sea level variability in the SCS at decadal and interdecadal time scales. During El Niño events, anticyclonic surface wind anomalies in the SCS induce positive SSHAs in the central basin, contrasting with the opposite pattern observed during La Niña events [16]. The surface wind anomalies, combined with the ocean circulation changes attributed to the LST, offer additional evidence to support the assertion that the ENSO serves as the primary driver of the second dominant mode of low-frequency sea level variability in the SCS.

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Data Availability Statement: The NEMO v4.0.6 model code and documentation are freely available from the NEMO website (<https://www.nemo-ocean.eu>) (accessed on 22 September 2024). The data size of the model output in our simulations is of several terabytes and requires a large storage facility. However, all model outputs analysed in the paper can be made available upon contacting the authors. The ERA5 and ORAS5 data are obtained from the <https://cds.climate.copernicus.eu> (accessed on 22 September 2024). The satellite SSH data are available from <https://data.marine.copernicus.eu/products> (accessed on 22 September 2024). The climate indices are obtained from <http://climexp.knmi.nl> (accessed on 22 September 2024).

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Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Church, J.A.; Woodworth, P.L.; Aarup, T.; Wilson, S.W. *Understanding Sea-Level Rise and Variability*; Wiley-Blackwell Publishing: Hoboken, NJ, USA, 2010. [CrossRef]
2. Zhang, X.; Church, J.A. Sea level trends, interannual and decadal variability in the Pacific Ocean. *Geophys. Res. Lett.* **2012**, *39*, L21701. [CrossRef]

3. Royston, S.; Bingham, R.J.; Bamber, J.L. Attributing decadal climate variability in coastal sea-level trends. *Ocean Sci.* **2022**, *18*, 1093–1107. [\[CrossRef\]](#)
4. Frankcombe, L.M.; McGregor, S.; England, M.H. Robustness of the modes of Indo-Pacific sea level variability. *Clim. Dyn.* **2015**, *45*, 1281–1298. [\[CrossRef\]](#)
5. Hamlington, B.D.; Leben, R.R.; Strassburg, M.W.; Nerem, R.S.; Kim, K.-Y. Contribution of the Pacific Decadal Oscillation to global mean sea level trends. *Geophys. Res. Lett.* **2013**, *40*, 5171–5175. [\[CrossRef\]](#)
6. Nidheesh, A.; Lengaigne, M.; Vialard, J. Natural decadal sea-level variability in the Indian Ocean: Lessons from CMIP models. *Clim. Dyn.* **2019**, *53*, 5653–5673. [\[CrossRef\]](#)
7. Qu, T.; Kim, Y.Y.; Yaremchuk, M.; Tozuka, T.; Ishida, A.; Yamagata, T. Can Luzon Strait transport play a role in conveying the impact of ENSO to the South China Sea? *J. Clim.* **2004**, *17*, 3644–3657. [\[CrossRef\]](#)
8. Peng, D.; Palanisamy, H.; Cazenave, A.; Meyssignac, B. Interannual Sea Level Variations in the South China Sea Over 1950–2009. *Mar. Geod.* **2013**, *36*, 164–182. [\[CrossRef\]](#)
9. Soumya, M.; Vethamony, P.; Tkalic, P. Inter-annual sea level variability in the southern South China Sea. *Glob. Planet. Change* **2015**, *133*, 17–26. [\[CrossRef\]](#)
10. Thompson, B.; Tkalic, P.; Malanotte-Rizzoli, P. Regime shift of the South China Sea SST in the late 1990s. *Clim. Dyn.* **2017**, *48*, 1873–1882. [\[CrossRef\]](#)
11. Cheng, X.; Zhao, M.; Duan, W.; Jiang, L.; Chen, J.; Yang, C.; Zhou, Y. Regime shift of the sea level trend in the South China Sea modulated by the tropical Pacific decadal variability. *Geophys. Res. Lett.* **2023**, *50*, e2022GL102708. [\[CrossRef\]](#)
12. Rong, Z.; Liu, Y.; Zong, H.; Cheng, Y. Interannual sea level variability in the South China Sea and its response to ENSO. *Glob. Planet. Change* **2007**, *55*, 257–272. [\[CrossRef\]](#)
13. Deng, W.; Wei, G.; Xie, L.; Ke, T.; Wang, Z.; Zeng, T.; Liu, Y. Variations in the Pacific Decadal Oscillation since 1853 in a coral record from the northern South China Sea. *J. Geophys. Res. Ocean* **2013**, *118*, 2358–2366. [\[CrossRef\]](#)
14. Thompson, B.; Tkalic, P. Mixed layer thermodynamics of the Southern South China Sea. *Clim. Dyn.* **2014**, *43*, 2061–2075. [\[CrossRef\]](#)
15. Xiao, F.; Wang, D.; Yang, L. Can Tropical Pacific Winds Enhance the Footprint of the Interdecadal Pacific Oscillation on the Upper-Ocean Heat Content in the South China Sea? *J. Clim.* **2020**, *33*, 4419–4437. [\[CrossRef\]](#)
16. Cheng, X.; Xie, S.-P.; Du, Y.; Wang, J.; Chen, X.; Wang, J. Interannual-to-decadal variability and trends of sea level in the South China Sea. *Clim. Dyn.* **2016**, *46*, 3113–3126. [\[CrossRef\]](#)
17. Pei, Y.; Zhang, R.H.; Zhang, X.; Jiang, L.; Wei, Y. Variability of sea surface height in the South China Sea and its relationship to Pacific oscillations. *Acta Oceanol. Sin.* **2015**, *34*, 80–92. [\[CrossRef\]](#)
18. Li, J.; Tan, W.; Sun, W.; Yang, L.; Lin, L.; Fu, Q. Seasonal–interannual–decadal variations of sea level in the South China Sea and connections with the tropical–subtropical Pacific. *Int. J. Climatol.* **2023**, *43*, 5196–5207. [\[CrossRef\]](#)
19. Henley, B.J.; Gergis, J.; Karoly, D.J.; Power, S.; Kennedy, J.; Folland, C.K. A tripole index for the interdecadal Pacific oscillation. *Clim. Dyn.* **2015**, *45*, 3077–3090. [\[CrossRef\]](#)
20. Dong, B.; Dai, A.; Vuille, M.; Timm, O.E. Asymmetric Modulation of ENSO Teleconnections by the Interdecadal Pacific Oscillation. *J. Clim.* **2018**, *31*, 7337–7361. [\[CrossRef\]](#)
21. Newman, M.; Alexander, M.; Ault, T.; Cobb, K.; Deser, C.; Di Lorenzo, E.; Mantua, N.; Miller, A.; Minobe, S.; Nakamura, H.; et al. The Pacific Decadal Oscillation, Revisited. *J. Clim.* **2016**, *29*, 4399–4427. [\[CrossRef\]](#)
22. Madec, G. *The NEMO Team. NEMO Reference Manual 3.6_STABLE: NEMO Ocean Engine*; Note du Pôle de modélisation; Institut Pierre-Simon Laplace (IPSL): Guyancourt, France, 2016; ISSN 1288-1619.
23. Zuo, H.; Balmaseda, M.A.; Tietsche, S.; Mogensén, K.; Mayer, M. The ECMWF operational ensemble reanalysis-analysis system for ocean and sea ice: A description of the system and assessment. *Ocean Sci.* **2019**, *15*, 779–808. [\[CrossRef\]](#)
24. Chaigneau, A.A.; Refray, G.; Voldoire, A.; Melet, A. IBI-CCS: A regional high-resolution model to simulate sea level in western Europe. *Geosci. Model Dev.* **2022**, *15*, 2035–2062. [\[CrossRef\]](#)
25. Levier, B.; Tréguier, A.M.; Madec, G.; Garnier, V. Free surface and variable volume in the NEMO code. *Tech. Rep.* **2007**, MERSEA MERSEA IP report WP09-CNRS-STR-03-1A, 47.
26. Umlauf, L.; Burchard, H. A generic length-scale equation for geophysical turbulence models. *J. Mar. Res.* **2013**, *61*, 235–265. [\[CrossRef\]](#)
27. Canuto, V.; Howard, A.; Cheng, Y.; Dubovikov, M. Ocean turbulence, Part I: One-point closure model-momentum and heat vertical diffusivities. *J. Phys. Oceanogr.* **2001**, *31*, 1413–1426. [\[CrossRef\]](#)
28. Davies, H. A lateral boundary formulation for multi-level prediction models. *Q. J. R. Meteorol. Soc.* **1976**, *102*, 405–418.
29. Flather, R.A. A tidal model of the northwest European continental shelf. *Mem. Soc. Roy. Sci. Liege* **1976**, *10*, 141–164.
30. Edson, J.B.; Jampana, V.; Weller, R.A.; Bigorre, S.P.; Plueddemann, A.J.; Fairall, C.W.; Miller, S.D.; Mahrt, L.; Vickers, D.; Hersbach, H. On the exchange of momentum over the open ocean. *J. Phys. Oceanogr.* **2013**, *43*, 1589–1610. [\[CrossRef\]](#)
31. Hersbach, H.; Bell, B.; Berrisford, P.; Hirahara, S.; Horányi, A.; Muñoz-Sabater, J.; Nicolas, J.; Peubey, C.; Radu, R.; Schepers, D.; et al. The ERA5 global reanalysis. *Q. J. R. Meteorol. Soc.* **2020**, *146*, 1999–2049. [\[CrossRef\]](#)
32. Lengaigne, M.; Menkes, C.; Aumont, O.; Gorgues, T.; Bopp, L.; Madec, J. Bio-physical feedbacks on the tropical Pacific climate in a coupled general circulation model. *Clim. Dyn.* **2007**, *28*, 503–516. [\[CrossRef\]](#)

33. Holgate, S.J.; Matthews, A.; Woodworth, P.L.; Rickards, L.J.; Tamisiea, M.E. New data systems and products at the permanent service for mean sea level. *J. Coast. Res.* **2013**, *29*, 493–504. [\[CrossRef\]](#)
34. Van Oldenborgh, G.J.; Hendon, H.; Stockdale, T.; L'Heureux, M.; de Perez, E.G.; Singh, R.; van Aalst, M. Defining El Niño indices in a warming climate. *Environ. Res. Lett.* **2021**, *16*, 044003. [\[CrossRef\]](#)
35. Mantua, N.J.; Hare, S.R.; Zhang, Y.; Wallace, J.M.; Francis, R.C. A Pacific interdecadal climate oscillation with impacts on salmon production. *Bull. Am. Meteorol. Soc.* **1997**, *78*, 1069–1079. [\[CrossRef\]](#)
36. Saji, N.H.; Goswami, B.N.; Vinayachandran, P.N.; Yamagata, T. A dipole mode in the tropical Indian Ocean. *Nature* **1999**, *401*, 360–363. [\[CrossRef\]](#)
37. Luu, Q.H.; Tkalic, P.; Tay, T.W. Sea level trend and variability around Peninsular Malaysia. *Ocean Sci.* **2015**, *11*, 617–628. [\[CrossRef\]](#)
38. Zhao, S.; Jin, F.-F.; Stuecker, M.F. Understanding lead times of warm water volumes to ENSO sea surface temperature anomalies. *Geophys. Res. Lett.* **2021**, *48*, e2021GL094366. [\[CrossRef\]](#)
39. Qiu, B.; Chen, S. Interannual-to-Decadal variability in the bifurcation of the north equatorial current off the Philippines. *J. Phys. Oceanogr.* **2010**, *40*, 2525–2538. [\[CrossRef\]](#)
40. Yaremchuk, M.; Qu, T. Seasonal Variability of the Large-Scale Currents near the Coast of the Philippines. *J. Phys. Oceanogr.* **2004**, *34*, 844–855. [\[CrossRef\]](#)
41. Yang, J.; Lin, X.; Wu, D. Wind-driven exchanges between two basins: Some topographic and latitudinal effects. *J. Geophys. Res.* **2013**, *118*, 4585–4599. [\[CrossRef\]](#)
42. Weiss, T.L.; Linsley, B.K.; Gordon, A.L. Pacific North Equatorial current bifurcation latitude and Kuroshio Current shifts since the last glacial maximum inferred from a Sulu Sea thermocline reconstruction. *Quat. Sci. Rev.* **2021**, *264*, 106999. [\[CrossRef\]](#)

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