Improving the understanding of the influencing factors on sea level on various time scales based on wavelet coherence and partial wavelet coherence

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15 **Abstract** The relationship between sea level change and a single climate indicator has
16 been widely discussed. Despite this, few studies focused on the relationship between
17 monthly mean sea level (MMSL) and several key impact factors, including CO₂
18 concentration, sea ice area, and sunspots, on various time scales. In addition, research
19 on the independent relationship between climate factors and sea level on various time
20 scales is lacking, especially when the dependence of climate factors on Niño 3.4 is
21 excluded. Based on this, we use wavelet coherence (WC) and partial wavelet coherence
22 (PWC) to establish a relationship between MMSL and its influencing factors. The WC
23 results show that the influence of climate indices on MMSL has strong regional
24 characteristics. Sunspots affect MMSL on a scale of more than 64 months. The
25 influence of the sea ice area on MMSL in the northern hemisphere is opposite to that in

the southern hemisphere. The PWC results show that after removing the influence of Niño 3.4, the significant coherent regions of the Pacific Decadal Oscillation (PDO), Dipole Mode Index (DMI), Atlantic Multidecadal Oscillation (AMO), and Southern Oscillation Index (SOI) decrease to varying degrees on different time scales in different regions, demonstrating the influence of Niño 3.4. Our work emphasizes the independent relationship between MMSL and its influencing factors on various time scales and the use of PWC and WC to describe this relationship. The study has important reference significance for selecting the best predictors of sea level change or climate systems.

Keywords: Wavelet coherence; Partial wavelet coherence; Monthly mean sea level; Influencing factors; Time scale; Interrelation

1. Introduction

Sea level is an important indicator of climate change and varies at broad spatial and temporal scales (Meng et al., 2019). It is necessary to analyze the relationship between sea level and climate indices on temporal and spatial scales to reveal the relationship between sea level and its influencing factors. Significant interannual and interdecadal changes occur in the sea level, exhibiting variation characteristics on multiple time scales. Therefore, using analysis methods with a robust periodic analysis ability is crucial for analyzing the relationship between sea level and its influencing factors.

Wavelet coherence (WC) has advantages for analyzing time-series data and determining the correlation of influencing factors on various time scales. This method was originally proposed by Torrence and Compo (1998) to analyze El Niño Southern Oscillation (ENSO) time series. Later, Grinsted et al. (2004) applied this method to geophysical time series. Since then, WC has been improved and used to analyze

periodic cycles caused by various physical mechanisms. These have included precipitation and groundwater (Yu and Lin, 2015), groundwater level and climate indices (Liesch and Wunsch, 2019), runoff and climate indices (Durocher et al., 2016), global mean temperature anomalies and sea level (Kirikkaleli and Sowah, 2021), Baltic Sea level and zonal wind (Medvedev and Kulikov, 2019), Pacific Decadal Oscillation (PDO) and sea level in the South China Sea (Xi et al., 2020), positive pressure sea level over the tropical Indian Ocean basin and the northern winter Madden-Julian oscillation (Rohith et al., 2019), Atlantic meridional overturning circulation and Mediterranean Sea level (Volkov et al., 2019), Arctic sea surface temperature variation and the Greenland blocking index (Carvalho and Wang, 2020), ocean signal and sea level change (Jevrejeva et al., 2006; Jevrejeva et al., 2010), ENSO and the Baltic Sea ice (Jevrejeva et al., 2003), Persian Gulf Sea level fluctuations and meteorological forcing (Afshar et al., 2020), sea level response of the Indian Ocean and ENSO (Tiwari et al., 2004), Bohai Bay and atmospheric forcing (Lü et al., 2019), East China Sea level and ENSO events (Liu et al., 2010), and sea level of the New England coast and the Atlantic meridional overturning circulation at 26°N (Piecuch et al., 2019).

Although WC is suitable for studying the relationship between sea level and its influencing factors, most studies have focused on single sea areas, including the east coast of North America (Little et al., 2021), European sea areas (Jevrejeva et al., 2006; Jevrejeva et al., 2010), Indian Ocean (Tiwari et al., 2004; Deepa and Gnanaseelan, 2021), East China Sea (Liu et al., 2010), South China Sea (Xi et al., 2020), Bohai Bay (Lü et al., 2019), Mediterranean Sea (Dogan et al., 2015; Volkov et al., 2019), New England coastal areas (Piecuch et al., 2019), Persian Gulf (Afshar et al., 2020), Baltic sea (Medvedev and Kulikov, 2019; Armin et al., 2021), the west coast of South America (Camayo and Campos, 2006), and global studies (Kirikkaleli and Sowah, 2021; Haddad

[et al., 2013](#)). Most of these studies revealed a close relationship between sea level and PDO, North Atlantic Oscillation (NAO), ENSO, Atlantic Multidecadal Oscillation (AMO), Southern Oscillation Index (SOI), and Atlantic Oscillation (AO).

However, most recent studies have focused on single sea areas or the effects of individual climate indices on monthly mean sea level (MMSL). In contrast, we use WC to study 10 regions, including the North Atlantic, South Atlantic, Black Sea, Mediterranean, and global oceans. In addition, we adopt WC to analyze the relationship between MMSL in 10 regions and 15 influencing factors, including sunspots, northern hemisphere sea ice area (NHSA), southern hemisphere sea ice area (SHSA), Niño 3.4, PDO, North Pacific pattern (NP), AO, pacific warm pool area average (PWAA), AMO, quasi-biennial oscillation (QBO), ocean temperature index (OTI), NAO, western hemisphere warm pool (WHWP), and Dipole Mode Index (DMI).

However, due to the interaction between climate indices (ENSO is highly correlated with PDO, AMO, SOI, and AMO), the relationship between climate indices and MMSL may not be independent. Therefore, using WC may be misleading to analyze the binary relationship between climate indices and sea level. Partial wavelet coherence (PWC) is similar to partial correlation analysis. It prevents errors caused by the interdependence between predictors and other variables ([Kenney and Keeping, 1954](#)) and reflects the relationship between control variables and response variables on various time scales. Several successful applications of PWC have been reported ([Hu and Si, 2021](#); [Tan et al., 2016](#); [Rathinasamy et al., 2017](#); [Aloui et al., 2018](#); [Wu et al., 2020](#); [Xin et al., 2018](#)). For example, [Hu et al. \(2021\)](#) used PWC to understand scale-specific and local binary relationships in geoscience applications. [Tan et al. \(2016\)](#) used PWC to analyze the relationship between extreme precipitation and climate anomalies. [Rathinasamy et al. \(2017\)](#) used PWC to analyze the relationship between oil price,

inflation, exchange rate, and economic growth. [Xin et al. \(2018\)](#) used PWC to explore the relationship between net ecosystem CO₂ exchange and meteorological conditions. However, we have not found any reports on using PWC for sea-level analysis. In addition, previous studies did not consider the interdependence between climate indices or influencing factors when analyzing the impact of these indices or factors on sea level. In this paper, we use PWC to clarify the independent relationship between MMSL and DMI, SOI, PDO, and AMO on various time scales (excluding the influence of Niño 3.4).

Due to the complex relationship between sea level and its influencing factors on various time scales, this study has two objectives: (1) to use WC to analyze the relationship between MMSL and its influencing factors (including CO₂, the area of sea ice in the northern and southern hemispheres, and other factors) on various time scales and rank the importance of the influencing factors; (2) to use PWC to study the independent relationship between MMSL and DMI, SOI, PDO, and AMO on various time scales after excluding the influence of Niño 3.4. The remainder of this paper is organized as follows. The principles of WC and PWC are introduced in [Section 2](#). The study area and data sources are described in [Section 3](#). The WC analysis results are presented in [Section 4.1](#), and the PWC analysis results are described in [Section 4.2](#). The conclusions are drawn in [Section 5](#).

2. Methods

This section describes the use of WC and PWC to study the relationship between sea level and the influencing factors on different time scales.

2.1 Wavelet coherence

Wavelet coherence (WC) has one main advantage in hydrological applications. It reveals the coherence of the cross wavelet transform in the time-frequency space. We define the WC of two time series as:

$$R_n^2(s) = \frac{|S(s^{-1}W_n^{XY}(s))|^2}{S(s^{-1}|W_n^X(s)|^2) * S(s^{-1}|W_n^Y(s)|^2)} \quad (1)$$

where S is a smoothing operator, and $w_n^X(s)$ is the continuous wavelet transform of the X series. Note that this definition closely resembles that of a traditional correlation coefficient, and it is useful to think of the WC as a correlation coefficient localized in the time-frequency space. We write the smoothing operator S as:

$$S(W) = S_{scale} S_{time}(W_n(s)) \quad (2)$$

where S_{scale} describes smoothing along the wavelet scale axis, and S_{time} denotes smoothing in time. A suitable smoothing operator for the Morlet wavelet was proposed by Torrence and Webster (1999):

$$S_{time}(W)|_s = (W_n(s) * c_1^{(-t^2/2s^2)})|_s, \quad S_{scale}(W)|_n = (W_n(s) * c_2 \Pi(0.6s))|_n \quad (3)$$

where c_1 and c_2 are normalization constants, and Π is the rectangle function. The factor 0.6 is the empirically determined scale decorrelation length for the Morlet wavelet (Torrence and Compo, 1998).

It should be noted that we evaluate the performances of single factors and combined factors using the average wavelet coherence (AWC, the average of the coherence value in the significant coherence region) and the percentage of the significant coherence area (PASC, $100 * \text{significant coherence area} / (\text{significant coherence area} + \text{insignificant coherence area})$). The larger the AWC and PASC, the more important that single factor or combination of factors is.

2.2 Partial wavelet coherence

PWC and partial correlation analysis are similar. However, PWC can be regarded as a partial correlation analysis on a given time scale. Assuming that y is affected by x_1

and x_2 , one can find the WC results between the two time series y and x_1 after eliminating the influence of time series x_2 . In short, we determine the influence degree of x_1 on y after excluding the effect of x_2 .

$$\rho^2(y, x_1, x_2) = \frac{|R_{y,x_1}(s, \tau) - R_{y,x_2}(s, \tau)R_{x_1,x_2}(s, \tau)|^2}{(1 - R_{y,x_2}^2(s, \tau))(1 - R_{x_1,x_2}^2(s, \tau))} \quad (4)$$

where $R_{y,x_1}(s, \tau)$, $R_{y,x_2}(s, \tau)$, and $R_{x_1,x_2}(s, \tau)$ are the square roots of $R_{y,x_2}^2(s, \tau)$, $R_{x_1,x_2}^2(s, \tau)$, and $R_{y,x_1}^2(s, \tau)$, respectively.

The widely used Monte Carlo method (Torrence and Compo, 1998; Grinsted et al., 2004) is used to calculate the PWC at the 95% confidence level. For more information on the PWC formula, please refer to Hu and Si (2021).

3. Study area and data sources

All data sources used in this study are listed in Table 1.

Table 1 Data sources

Data	Data sources
MMSL	https://www.aviso.altimetry.fr/en/data/products/ocean-indicators-products/mean-sea-level/data-access.html#c12195 (we used the average of the monthly data)
Sunspot	https://www.bis.sidc.be/silso/datafiles
DMI	https://psl.noaa.gov/gcos_wgsp/Timeseries/DMI/
NHSA、SHSA	https://nsidc.org/arcticseaicenews/sea-ice-tools/
CO ₂ concentration	https://gml.noaa.gov/webdata/ccgg/trends/co2/co2_mm_gl.txt (Ed and Pieter)
The remaining 11 climate indices	https://www.psl.noaa.gov/data/climateindices/list/

The MMSL changes in the 10 regions are shown in Fig. 1.

Fig. 1. MMSL change in ten sea areas (1993.01-2020.05)

It can be seen that the trend of the sea level change is very different in different regions. The rate of increase in the sea level is the largest in the South Atlantic (3.50 mm/year) and the smallest in the Black Sea (2.08 mm/year). The rate of increase in the global sea level is 3.42 mm/year. The sea-level change exhibits strong regional characteristics.

In addition, the MMSL in the southern hemisphere, the South Pacific, and the globally was abnormal around 1997-1998, which was due to the influence of the ENSO. Sea level anomalies globally and locally in a certain period are also primarily affected by ENSO events.

4. Results

4.1 Wavelet coherence analysis results

Previous studies primarily focused on the driving mechanism of the Pacific, Atlantic, Indian Ocean, Mediterranean, and global sea levels (Kirikkaleli and Sowah, 2021; Deepa and Gnanaseelan, 2021; Little et al., 2021). In contrast, we include the Black Sea, the southern hemisphere, and the northern hemisphere in addition to the above areas.

4.1.1 WC results of MMSL and sea ice area

Sea ice melting also contributes to sea level rise, but the interaction between sea ice area and MMSL on various time scales remains unclear. We use WC to analyze the time-scale dependence of the NHSA, SHSA, and MMSL; the results are shown in Fig. 2.

We found that the NHSA had significant coherence with MMSL in the North Atlantic, South Atlantic, North Pacific, Indian Ocean, and Northern Hemisphere at the 12-month scale. The NHSA was positively correlated with MMSL in the Pacific Ocean and the Northern Hemisphere and negatively correlated with MMSL in the Indian Ocean. However, at the 12-month scale, the SHSA showed a significant negative

correlation with MMSL in the North Pacific and northern hemisphere and a significant positive correlation with MMSL in the Indian Ocean. Interestingly, this is in contrast to the correlation between NHSA and MMSL in the North Pacific, northern hemisphere, and Indian Ocean. The decline rate of the sea ice area in the northern hemisphere is 0.0038 Mkm²/month, and that in the southern hemisphere is 0.0001 Mkm²/month. The decline rate of NHSA is greater than that of SHSA, indicating that the sea ice melts faster in the northern hemisphere and slower in the northern and southern hemispheres. The sea-level rise caused by sea ice melting is greater in the northern hemisphere than in the southern hemisphere, which may be one of the reasons for this abnormal phenomenon.

The significant correlation between NHSA, SHSA and MMSL for 16-32 months is not as strong as that for 12 months, indicating that NHSA and SHSA do not control the change in MMSL for 16-32 months.

In addition, we also found that NHSA has significant coherence with the South Atlantic, North Pacific, Indian Ocean, northern hemisphere, southern hemisphere, and global MMSL for 64 months, but this phenomenon does not occur with SHSA and MMSL. This result indicated that NHSA controlled the scale change of MMSL for 64 months, and NHSA and SHSA jointly controlled the changes in MMSL on the 12-month scale.

4.1.2 WC results of MMSL and climate factors

The WC between the climate factors and MMSL is shown in [Fig. 3](#) and [Fig. 4](#).

(a) WC between MMSL and OTI

(b) WC between MMSL and DMI

(c) WC between MMSL and AO

Fig. 3. WC between MMSL and OTI, DMI, and AO (the 5% significance level against red noise is shown as a thick contour. The relative phase relationship is shown as arrows (in-phase pointing right, anti-phase pointing left, and monthly mean sea level leading influencing factors by 90 pointing straight down))

In terms of the significant coherence region, the OTI has a more significant effect on MMSL in the Indian Ocean and South Pacific and a smaller effect in the Black Sea (the significant coherence region of the Black Sea is the smallest among the 10 regions). In addition, we identified a 72-120-month effect scale of OTI on MMSL in eight regions (all except the Black Sea and the North Pacific).

The DMI had a relatively large impact on MMSL in the South Pacific, Indian Ocean, and southern hemisphere, and the most significant impact on MMSL in the Indian Ocean. The significant coherent area is large on the scale of 16-32 months, and this phenomenon occurred from 1998 to 2003.

The AO had a relatively large impact on MMSL in the North Pacific, South Pacific, Indian Ocean, Mediterranean, and Black Sea, with the most significant impacts on the latter two regions. The scale was 32-64 months in the Mediterranean and the Black Sea, and the duration was more than 10 years. In addition, the effect of the AO on the MMSL in the Mediterranean occurred on a scale of 64-118 months and lasted about 10 years.

(a) WC between MMSL and sunspots

(b) WC between MMSL and NP

(c) WC between MMSL and WHWP

(d) WC between MMSL and PWAA

Fig. 4. WC between MMSL and sunspots, NP, WHWP, and PWAA

Sunspots had a significant impact on MMSL in the North Atlantic, South Atlantic,

North Pacific, Mediterranean, Black Sea, and the northern hemisphere. The relationship

between monthly MMSL and monthly sunspots indicated that the effect occurred at a

scale of more than 64 months in the North Atlantic, South Atlantic, North Pacific, Mediterranean, Black Sea, and northern hemisphere, and the correlation between sunspots and MMSL was significant and negative. In addition, the coherence between sunspots and MMSL was not very pronounced on a small time scale (12 months), indicating that sunspots primarily affect MMSL on a large time scale (more than 64 months).

The NP substantially influenced MMSL in the North Atlantic, South Atlantic, North Pacific, South Pacific, and the Indian Ocean. It showed a significant positive correlation with MMSL in the South Atlantic and Indian Ocean and a significant negative correlation with MMSL in the North Pacific and South Pacific on the 12-month scale. In contrast, the correlation was significant and negative in the South Pacific and the Black Sea on the time scale of 16-32 months.

The WHWP had a substantial influence on MMSL in the North Pacific, South Pacific, Indian Ocean, and the northern and southern hemispheres. On the 12-month scale, the WHWP showed a significant negative correlation with MMSL in the North Pacific and the northern hemisphere and a significant positive correlation with MMSL in the Indian Ocean. On the scale of 16-32 months, the WHWP had a significant positive correlation with MMSL in the South Pacific, Indian Ocean, Mediterranean, the southern hemisphere, and globally. The correlation was also positive in the Black Sea on a scale of more than 64 months.

On the 12-month scale, the PWAA showed a significant positive correlation with MMSL in the North Pacific (2003-2005), whereas the correlation with MMSL was weak in the other 9 regions. On the 32-64 months scale, the PWAA had no significant correlation with MMSL in the Black Sea but a significant positive correlation with MMSL in the other 9 regions. On the scale of more than 64 months, the PWAA showed

a significant positive correlation with MMSL in the North Atlantic and Mediterranean.

The WC between MMSL and Nino 3.4, SOI, PDO, and QBO are shown in [Fig. S1](#) in the [Supplementary Information](#). Niño 3.4 had the most significant and positive influence on MMSL in the south Pacific and southern hemisphere on the time scale of 16-48 months. We reached the same conclusion as [Haddad et al. \(2013\)](#) and [Hamlington et al. \(2016\)](#). The PDO and SOI also had the strongest significant correlations with MMSL in the South Pacific on the scale of 16-48 months. However, the effects of Niño 3.4 and SOI on MMSL in the South Pacific were stronger than those of the PDO. On the scale of 16-32 months, the QBO had a larger influence on MMSL in the North Pacific, Indian Ocean, Black Sea, and the northern hemisphere.

The WC between MMSL and NAO and AMO are shown in [Fig. S2](#) in the [Supplementary Information](#). The NAO had a strong impact on MMSL in the North Pacific, South Pacific, Mediterranean, Black Sea, and the northern hemisphere. The correlation was significant on scales of 32-64 months and more than 64 months. This result is consistent with that of [Stanev and Peneva \(2002\)](#), who found that the NAO was the dominant factor influencing sea level rise in the Black Sea. The AMO had a relatively large impact on MMSL in the North Pacific, South Pacific, Indian Ocean, Black Sea, and the northern hemisphere. The time scales of the AMO influence on MMSL in these regions were 12 months and 32-64 months, and the correlation was significant and positive in the Black Sea and North Pacific Ocean on a time scale of over 64 months.

4.1.3 Main driving factors of MMSL in the 10 regions

The relationship between the carbon dioxide concentration and MMSL on various time scales is described in the discussion section. The higher the percentage of the PASC, the greater the impact of a factor on MMSL is. The larger the AWC, the stronger the correlation between the influencing factor and MMSL is. We summarized the PASC

and AWC values corresponding to the influencing factors (Fig. 5) to determine the dominant driving forces affecting MMSL.

(a) AWC between MMSL and influencing factors

(b) PASC (%) between MMSL and influencing factors

Fig. 5. The PASC and AWC between MMSL and the influencing factors

The difference in the AWC values of the 13 climate factors was very small in most cases (~ 0.1), indicating similar correlations between the climate factors and MMSL. The exception was the OTI, which had relatively high AWC values, with the largest values globally, in the northern hemisphere, South Atlantic, and South Pacific (0.87, 0.88, 0.85, and 0.85, respectively). The AWC values between the MMSL and NHSA globally and in the South Atlantic were 0.84 and 0.84, and those between Niño 3.4 and MMSL in the North Atlantic and South Pacific were 0.78 and 0.81, respectively. The AWC values between sunspots and MMSL in the Indian Ocean, the southern hemisphere, and the South Pacific were 0.82, 0.82, and 0.82, and those between the

AMO and MMSL in the Black Sea, North Pacific, and South Pacific were 0.84, 0.83, and 0.81, respectively.

Since the difference in the AWC values between the influencing factors was not very large, we suggest using the PASC to evaluate changes in the MMSL. It should be noted that the PASC values are relatively small, indicating a relatively small influence on MMSL, although this does not mean that there is no impact on MMSL. We list the five main driving factors affecting MMSL according to the PASC values in [Table 2](#).

Table. 2 The five main driving factors of MMSL based on the PASC

Location	Main driving factors (the more important the elements, the higher the ranking)				
	First	Second	Third	Fourth	Fifth
North Atlantic	OTI	PWAA	Sunspot	SHSA	NHSA
South Atlantic	NHSA	OTI	SHSA	AMO	NP
North Pacific	NHSA	AMO	OTI	SHSA	WHWP
South Pacific	OTI	Niño 3.4	PWAA	SOI	NAO
Indian Ocean	OTI	NHSA	WHWP	AMO	DMI
Mediterranean	AO	NAO	OTI	Sunspot	PWAA
Black Sea	AO	AMO	NAO	Sunspot	WHWP
Northern Hemisphere	OTI	NHSA	PWAA	SHSA	Sunspot
Southern Hemisphere	OTI	NHSA	DMI	WHWP	PWAA
Global	OTI	NHSA	SHSA	DMI	WHWP

It can be seen that the OTI affects MMSL in all regions and was one of the most important driving forces, Niño 3.4 was one of the main driving forces of MMSL in the South Pacific, the AO was the most important driving force in the Black Sea and the Mediterranean, and NHSA was the most important driving force in the South Atlantic, North Pacific, Indian Ocean, the northern and southern hemispheres, and globally.

4.2 Partial wavelet coherence analysis results

ENSO causes sea level anomalies and is highly correlated with DMI, PDO, SOI, and AMO. The WC between Niño 3.4 and PDO, AMO, DMI, and SOI are shown in [Fig. 6](#).

Fig. 6. WC between Niño 3.4 and PDO, AMO, DMI, and SOI

Niño 3.4 showed significant coherence with PDO, AMO, DMI, and SOI, with the strongest coherence with SOI. Since Niño 3.4 is strongly correlated with PDO, AMO, DMI, and SOI, the relationships between these indices and MMSL are not independent on various time scales. In other words, the significant coherence between MMSL and PDO, AMO, DMI, and SOI is likely influenced by Niño 3.4. After eliminating the dependence of DMI, PDO, SOI, and AMO on ENSO, we used PWC to determine the independent relationship between MMSL and DMI, PDO, SOI, and AMO on various time scales. The results are shown in Figs. 7 to 10.

Fig. 7. PWC between monthly mean sea level and PDO after excluding the effect of Niño 3.4 (the subfigures below the bold black line are the WC results)

After excluding the effect of Niño 3.4, there is no significant correlation between PDO and MMSL in the South Pacific on the scale of 16-32 months, and the PASC between PDO and MMSL in the South Atlantic increased from 2015 to 2018. This result indicates a significant correlation between PDO and MMSL in the South Pacific on the scale of 16-32 months, which is caused by Niño 3.4.

After excluding the influence of Niño 3.4, the significant coherence regions increased significantly in the Black Sea and the Mediterranean on the scale of 32-64 months, indicating a significant correlation between PDO and MMSL on the scale of 32-64 months. The PWC between DMI and MMSL is shown in Fig. 8.

Fig. 8. PWC between monthly mean sea level and DMI after excluding the effect of Niño 3.4 (the subfigures below the bold black line are the WC results)

After excluding the effect of Niño 3.4 on DMI, there was no significant correlation between DMI and MMSL in the South Pacific, Indian ocean, and northern hemisphere on the scale of 16-32 months (1998-2002). In other words, on this time scale, the DMI had a significant correlation with MMSL in the South Pacific and the Indian Ocean, which is caused by Niño 3.4, not the DMI.

The PWC between the AMO and MMSL is shown in [Fig. 9](#).

Fig. 9. PWC between monthly mean sea level and AMO after excluding the effect of Niño 3.4 (the subfigures below the bold black line are the WC results)

After excluding the influence of Niño 3.4, the PASC between MMSL and AMO decreased in the North Atlantic, North Pacific, South Pacific, Indian Ocean, and the world decreased on the time scale of 16-32 months and increased in the Black Sea from 2008 to 2017. On the scale of 32-64 months, the PASC decreased in the North Pacific, South Pacific, Indian Ocean, Mediterranean, northern hemisphere and globally and increased in the South Atlantic and southern hemisphere. On the scale of more than 64 months, the PASC decreased in the North Pacific and the Black Sea and increased in the South Pacific.

In other words, a significant correlation exists between MMSL and the AMO in the North Pacific, South Pacific, Indian Ocean, Mediterranean, the northern hemisphere, and globally on the scale of 32-64 months because of the impact of Niño 3.4. On the scale of more than 64 months, the correlation is significant in the Black Sea and the northern hemisphere due to Niño 3.4.

Fig. 10. PWC between monthly mean sea level and SOI after excluding the effect of Niño 3.4 (the subfigure below the bold black line are the WC results)

Interestingly, on the scale of 16-32 months, the significant coherent regions in the South Pacific, northern hemisphere, southern hemisphere, and globally were significantly reduced after excluding the impact of Niño 3.4 on SOI. However, the significant coherent area in the Black Sea increased on the scale of more than 64 months (from 2003 to 2009).

These results demonstrate that the SOI had a small influence (not significant) on the MMSL in the South Pacific, the northern hemisphere, the southern hemisphere, and the world. Previous WC analyses showed a significant correlation between SOI and MMSL in these regions due to the effect of Niño 3.4 on SOI.

The PWC reflects the independent relationship between MMSL and PDO, DMI,

AMO, and SOI in the 10 regions on various time scales. However, this does not mean that the WC result is incorrect because it does not exclude the interaction between the indices.

5. Discussion

It is well known that global warming is caused by carbon emissions, but it also affects the sea level. However, since the time scale dependence of the CO₂ concentration and MMSL relationship is unclear, we used WC to analyze the influence of CO₂ concentrations on MMSL at various time scales.

Fig. 11. Globally averaged monthly mean carbon dioxide (CO₂) concentration at marine surface sites (elsewhere in the text, we refer to the globally averaged monthly mean carbon dioxide concentration)

The WC between CO₂ concentration and MMSL is shown in Fig. 12. The fluctuating trends of the CO₂ concentration and the MMSL are consistent.

Fig. 12. WC between CO₂ concentration and MMSL

The CO₂ concentration had a larger impact on MMSL in the North Atlantic, South Atlantic, North Pacific, Indian Ocean, and the northern hemisphere than elsewhere. On the 12-month scale, the CO₂ concentration showed a significant positive correlation with MMSL in the North Pacific and the northern hemisphere and a significant negative correlation in the Indian Ocean and the southern hemisphere. On the 12-month scale, the MMSL lagged 3 months behind the CO₂ concentration in the South Atlantic (2005-2013), indicating that a change in the CO₂ concentration occurred before a change in climatic conditions.

However, the global ocean surface CO₂ concentration had a negligible effect on MMSL in the Mediterranean and Black Sea (the PASC was relatively small). Although a significant correlation was observed between CO₂ concentration and MMSL, the correlation was weaker on the 6-month scale than on the 12-month scale. In addition, the CO₂ concentration showed a significant positive correlation with MMSL in the other 8 regions on the scale of more than 64 months. In general, the effects of CO₂ concentration on MMSL occurred on annual and interannual scales, but regional characteristics existed, and effects were negligible in the Black Sea and the Mediterranean Sea.

The PASC and AWC values between the MMSL and CO₂ concentration were higher than those between the MMSL and OTI, NHSA, and SHSA, indicating that CO₂ is the most important driving factor of MMSL change. The correlation between CO₂ concentration and MMSL was positive. Decision-makers in various countries should take measures to slow down CO₂ emissions to mitigate sea-level rise.

Furthermore, the WC and PWC results may be affected by the length of the MMSL sequence. In a future study, we will analyze MMSL changes and the influencing factors on a longer time scale and integrate data obtained from tide level stations. In addition, we only removed the influence of Nino 3.4 from the PWC results, but other variables may also affect PDO, AMO, DMI, SOI, and MMSL. We will consider these effects in a future study. This paper focused on improving our understanding of the independent relationship between climate indices and MMSL on various time scales after excluding the dependence of the five climate indices on ENSO.

Conclusions

We used WC and PWC to analyze the relationship between MMSL and its influencing factors on various time scales. The following conclusions were drawn:

(1) The correlation between the influencing factors and MMSL and the significance level depended on the region and time scale. The main driving forces included CO₂, OTI, NHSA, and SHSA. Sunspots affected MMSL on an interannual scale, and NHSA and SHSA showed significant and opposite correlations with MMSL. CO₂ concentration was positively correlated with MMSL on annual or interannual scales.

(2) After excluding the influence of Niño 3.4, the PWC could describe the independent relationship between MMSL and PDO, DMI, AMO, and SOI on various time scales. The combination of WC and PWC clarified the relationship between

MMSL and its influencing factors on various time scales. The same method can be used to analyze other geoscience processes, such as greenhouse gas emissions, atmospheric circulation, and ocean processes.

(3) This study is of great significance for determining the dominant response variables for climate system prediction (such as ENSO) or sea-level prediction. WC provides a new approach to obtain the most influential variables. The larger the area of the significant coherent region, the more important the variable is. In addition, we suggest using PWC to identify the independent relationship between predictor variables and response variables when a strong correlation exists between the response variables. If strongly correlated response variables are used, noise may be exacerbated, adversely affecting the prediction results.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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The data used to create the figures and tables are freely available upon request from the corresponding author. The codes for calculating wavelet coherence can be downloaded from <http://grinsted.github.io/wavelet-coherence/>, Grinsted et al. (2004). The codes for calculating PWC can be downloaded from <https://figshare.com/s/bc97956f43fe5734c784>, Hu and Si (2021). This research was financially supported by the National Natural Science Foundation of China (Grant No. U1911204, 51861125203), the National Key R & D Program of China (2017YFC0405900), and the Project for Creative Research from the Guangdong Water Resources Department (Grant No. 2018, 2020).

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