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Increased Intensity and Frequency of Global Coastal Compound Wind and Precipitation Extremes: Implications for Sea Level Anomalies

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Abstract

Coastal flooding and damage can result from compound extremes of wind and precipitation that elevate sea level anomalies. However, the global patterns and impacts of such conditions are poorly understood. Here we analyze observational and model data to reveal a positive correlation between wind and precipitation extremes across most of the global coastline, especially at higher latitudes. We also show that these variables exhibit stronger dependence on higher quantiles, indicating more frequent and severe compound conditions. Moreover, we demonstrate that sea level anomalies are enhanced during compound conditions compared to normal conditions, implying increased coastal flooding risk. We project that both the intensity and frequency of compound conditions will rise in 2020-2100 compared to 1940-2014 under two emission scenarios, with larger changes at high latitudes. Our findings highlight the need for assessing and managing the risks and impacts of compound extremes on coastal communities and infrastructure.

Keywords: Climate change; Extreme precipitation and wind; CMIP6; Sea level anomalies

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1 Introduction

Climate change and extreme weather conditions pose severe challenges for coastal regions that are exposed to multiple hazards such as strong winds, storms, and flooding (Hoegh-Guldberg et al., 2019; Mora et al., 2018). A particularly impactful class of hazards are compound wind and precipitation extremes (CWPEs), which arise from the joint occurrence of high wind speeds and heavy precipitation in some locations at the same time (Bevacqua et al., 2021; Martius et al., 2016; Messmer and Simmonds, 2021; Zscheischler et al., 2020). CWPEs can have devastating consequences for coastal infrastructure, ecosystems, and human lives by exacerbating storm surges and waves, resulting in elevated sea level anomalies (SLA) and coastal inundation (Davison et al., 2023; Deb et al., 2023; Vousdoukas et al., 2022; Wahl et al., 2015).

CWPEs are often associated with large-scale atmospheric disturbances such as extratropical cyclones (ETCs) and tropical cyclones (TCs) (Bermúdez et al., 2021; Gori et al., 2022). ETCs are low-pressure systems that develop in the mid-latitudes and generate strong winds and heavy rainfall along their fronts (Chen et al., 2010; Shaw et al., 2016). TCs are intense low-pressure systems that originate over warm tropical oceans and produce destructive winds, torrential rainfall, and storm surges that affect the coastal areas they encounter. Both ETCs and TCs can induce CWPEs, which in turn can elevate SLA and cause coastal flooding, damage, and disruption (Knutson et al., 2010; Lionello et al., 2019; Maduwantha et al., 2024; Martín et al., 2023; Woodworth et al., 2019). The occurrence of CWPEs is projected to increase under future climate change (Yaddanapudi et al., 2022), potentially worsening the impacts of SLA on coastal regions. To evaluate and manage the risks posed by these conditions in a warming world, we need to understand and the consequences of CWPEs on SLA as well as their future projections.

CWPEs have a high potential impact on SLA in coastal regions, yet their occurrence, characteristics, and changes under different climate scenarios remain poorly understood. Previous studies have largely examined single-variable extremes, such as precipitation (Bevacqua et al., 2020; Jiang et al., 2020) or wind speed (Wu et al., 2020; Zha et al., 2020), or have been restricted to specific regions or seasons (Maduwantha et al., 2024; Moustakis et al., 2021; Yaddanapudi et al., 2022). Few studies have investigated CWPEs in global coastal areas. Furthermore, the impact of global coastal CWPEs conditions on SLA, especially under future climate change, has not been well evaluated, despite its importance. Hence, a comprehensive and systematic

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assessment of CWPEs and their impact on SLA in global coastal regions is warranted.

In this study, we aim to fill this knowledge gap by addressing the following research questions: (1) How do CWPEs vary across global coastal regions in terms of frequency and spatial extent? (2) How do CWPEs conditions change under different climate scenarios compared to the historical period? (3) What is the impact of CWPEs on SLA in global coastal regions under historical and different climatic scenarios? To answer these questions, we use a combination of observational data from various sources and model data from the Coupled Model Intercomparison Project Phase 6 (CMIP6). We first defined the CWPEs and then we used the copula model to calculate the joint probabilities of these conditions and compare them with their independent probabilities. We also calculate the mean value of SLA at the time of the composite condition. Finally, we have used the CMIP6 model to make projections for different future scenarios.

2 Materials and methodology

2.1 Data

We used gridded monthly observations and modelled data from various sources to investigate the coupling between compound extreme wind speed and precipitation conditions and their relationship to SLA. We obtained the meteorological data (10-m wind speed and total precipitation) from the ERA5 reanalysis dataset, which covers the global atmosphere and surface at an hourly temporal resolution and a 0.25° × 0.25° spatial resolution. We utilized the monthly mean data extracted from this dataset due to its ability to capture detailed meteorological variations with high precision. The ERA5 dataset is preferred for its extensive validation and proven reliability in numerous climate studies, making it a trustworthy source for our analysis (Hersbach et al., 2020). We acquired the SLA data from satellite observations provided by the Copernicus Climate Change Service (C3S), which covers the global ocean at a daily temporal resolution and a 0.25° × 0.25° spatial resolution. We computed the monthly mean SLA for each grid point from this data. Both datasets span the period 1993–2020. By selecting these two datasets, we ensured a comprehensive and reliable analysis based on their high resolution, global coverage, and consistency. The use of these specific datasets allows for a detailed examination of the relationships between meteorological conditions and sea level changes, furthering our understanding of global climate

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patterns and their potential impacts.

We used 11 models from CMIP6 that provide monthly output of 10-m wind speed (‘sfcWind’), total precipitation (‘pr’), and SLA (‘zos’) for the historical (1940–2014) and future (2020–2100) periods under two scenarios: SSP245 (medium-low emissions) and SSP585 (high emissions). See Supplementary Table S1 for model details. We bilinearly interpolated all model data to a common 1° × 1° grid. We removed the seasonal effects from the SLA data by subtracting the monthly mean values for each grid cell over the entire study period (both observed and CMIP6 data), effectively isolating the seasonal cycle to focus on the interannual and long-term trends.

We obtained coastline data at a scale of 1:110m from Natural Earth (https://www.naturalearthdata.com/). This dataset provides a comprehensive and detailed representation of global coastlines, suitable for our study. Additionally, we excluded small islands to focus on major coastlines, as small islands may not be well-represented in our meteorological and sea level datasets due to their limited data availability. We used this data to select meteorological grid points along the coastline. We chose the grid point closest to the shoreline for each meteorological data grid cell (1° x 1° grid) that intersected the shoreline. This approach ensures that we reflect the meteorological conditions along the coastline as accurately as possible within the constraints of the gridded dataset. Our analysis is limited to the range from 60°N to 60°S latitude primarily due to the quality and integrity of satellite observations used in this study. At higher latitudes, data integrity and quality tend to be lower due to factors such as increased cloud cover, atmospheric and instrument noise, and reduced solar illumination (Gabarró et al., 2023). This can significantly impact the accuracy of sea level anomaly (SLA) measurements, which are crucial for our analysis. Moreover, the focus of this study is on global coastal regions, where most major coastal cities and populations are concentrated within the 60°N to 60°S latitude band. Limiting our analysis to this range allows us to focus on areas that are most vulnerable to the impacts of compound extreme wind and precipitation conditions. As the CMIP6 data are available in several models and with different resolutions between the models, to harmonize the calculations and analyses, we use information from the nearest grid point to the coastline to represent the meteorological and sea level conditions along the coastline. We chose the grid cell for each meteorological data intersecting the coastline as the grid point closest to the coastline. This approach ensures that we reflect the meteorological conditions along the coastline as accurately as possible within the constraints of the gridded dataset.

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2.2 Statistical analysis

2.2.1 Combined precipitation and wind probability

Our research focuses on identifying long-term trends and spatial patterns in the co-occurrence of these extreme conditions in coastal areas around the globe. By using monthly rather than daily data, we are able to analyze broad trends across multiple years, providing valuable insights into the potential impacts of climate change on coastal flood risk. To identify extreme conditions, we used the 90th percentile of the historical distribution as a threshold for both precipitation and wind in each grid cell (Meucci et al., 2020). That is, CWPEs conditions are considered to have occurred when both precipitation and wind speeds exceed the thresholds in a month at a grid point. To model the dependence structure of precipitation and wind, we employed bivariate copulas, which are flexible tools to capture the relationship between dependent variables . Copulas can overcome the limitation of using a small sample size to estimate the co-occurrence of extreme precipitation and wind, especially in regions where precipitation and wind are weakly or negatively correlated (Zscheischler and Seneviratne, 2017). The joint probability distribution of precipitation and wind can be expressed as

$$F_{X,Y}(x,y) = P(X \leq x, Y \leq y) \tag{1}$$

The marginal cumulative distribution of rainfall and wind is $F_X(x)$ and $F_Y(y)$. $F_X(x) = P(X \leq x)$, $F_Y(y) = P(Y \leq y)$. Their joint distribution is then found by the copulas model. Assuming that the cumulative distribution function of this joint distribution is $C(u,v)$, the joint probability distribution of X and Y can be written as

$$F_{X,Y}(x,y) = C(F_X(x), F_Y(\mathrm{y})) \tag{2}$$

where $u = F_X(x)$, $v = F_Y(y)$, are the probability values of precipitation and wind between 0 and 1.

Having obtained the joint distribution, the probability that they are both greater than or equal to the 90th percentile can be calculated by the following formula.

$$\begin{aligned} &P(u > 0.9 \cap v > 0.9) \\ &= 1 + C\big(F_X(0.9), F_Y(0.9)\big) - C\big(F_X(0.9), F_Y(1)\big) \\ &- C\big(F_X(1), F_Y(0.9)\big) \end{aligned} \tag{3}$$

So, the probability of this compound extreme condition is given by

$$\begin{aligned} P(u > 0.9 \cap v > 0.9) &= 1 + C(0.9,0.9) - C(0.9,1) - C(1,0.9) \\ &= 1 + C(0.9,0.9) - u - v \end{aligned} \tag{4}$$

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where $F_X(0.9)$ and $F_Y(0.9)$ are the 90% quantile of precipitation and wind, respectively.

To estimate the co-occurrence probabilities of extreme conditions, we used copulas to model the dependence of precipitation and wind. We fitted the data with five prevalent bivariate copulas: Gaussian, Student-t, Clayton, Frank, and Gumbel. Each copula is adept at capturing distinct forms of variable interdependence. To elaborate: The Gaussian copula presupposes a multivariate normal distribution of variables, making it apt for modeling symmetric dependencies, albeit with a potential underestimation of tail dependence. The student-t copula, while similar to the Gaussian, features heavier tails, thereby accommodating stronger tail dependence. The Clayton copula excels at capturing lower tail dependence, proving beneficial in scenarios where variables simultaneously tend towards extreme values in the same direction. Contrastingly, the Frank copula exhibits no tail dependence but effectively models positive dependence across the entire distribution range. Lastly, the Gumbel copula specializes in upper tail dependence, suitable for when extremes in one variable align with those of another. To ascertain the optimal copula fit for each grid cell, we compared the log-likelihood magnitudes. This metric serves as a gauge for how accurately a statistical model aligns with observed data, where higher values reflect a more precise fit. Selecting the most fitting copula is pivotal, as it dictates the joint probability distribution of precipitation and wind within each grid cell, forming the bedrock of our analytical approach. By evaluating multiple copula varieties, we strive to ensure the precision of our modeling reflecting the observed dependence patterns between precipitation and wind extremes. We used empirical distributions of precipitation and wind speed as the marginal distributions for our copula models. This choice allows us to capture the full range of variability, including the extreme tails, in our analysis of compound extreme conditions.

We used the probability multiplication factor (PMF) to quantify the joint probability of a compound condition, which is the ratio of the joint probability of two variables (accounting for their correlation) to the probability under the assumption of independence (Ridder et al., 2020; Yaddanapudi et al., 2022). High values of PMF (greater than 1) suggest a stronger dependence between extreme precipitation and wind conditions, indicating that they tend to co-occur more frequently than expected under independence. Conversely, low values of PMF (less than 1) imply a weaker dependence between these variables, suggesting less frequent co-occurrence. We obtained the joint probabilities under independence from the independent copula as follows: $P = 1 +$

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$C(0.9,0.9) - u - v = 1 + 0.81 - 0.9 - 0.9 = 0.01$. The PMF can be expressed as

$$PMF = \frac{P(u > 0.9 \cap v > 0.9)}{0.01} \quad (5)$$

In calculating PMF for future scenarios, we have used the same approach as for the historical period, maintaining the historical independence probability (0.01) in the denominator. This allows us to isolate the changes specifically due to the joint occurrence of extreme precipitation and wind conditions across historical and future periods. We acknowledge that changes in the marginal distributions of precipitation and wind may further impact the future compound effect. However, our primary focus in this study is on assessing the relative change in the joint probability of extreme conditions, taking into account the historical dependence structure as a reference.

2.2.2 Compound extreme conditions and their impacts

To quantify the coupling between precipitation and wind along the coastlines, we examined their joint probability distribution and computed the Pearson's correlation coefficient for each grid point over the global coastal area. We assigned coastal precipitation and wind values to 10 × 10 percentile bins and calculated the mean probability of each bin for each grid point. We also computed the mean SLA for each bin by averaging the SLA values that corresponded to the precipitation and wind values in that bin. This allowed us to assess the sea level response to different combinations of precipitation and wind, especially to extreme conditions.

We analyzed the CMIP6 simulations of historical (1940–2014) and future (2020–2100) scenarios under different emission pathways (SSP245 and SSP585) and estimated the mean SLA associated with compound precipitation and wind extremes. To isolate the changes in the joint occurrence of extreme events due to modifications in the copula structure, we adopted a revised approach. Instead of utilizing future thresholds, we focused solely on the changes in the joint distribution by using only the 90th percentile thresholds derived from the historical data, both for the historical period and the future projections. This allows us to evaluate the frequency changes of compound extreme events without confounding them with alterations in the marginal distributions of precipitation and wind. Our analysis using historical thresholds serves as a benchmark to assess changes in the frequency of extreme events similar to those currently considered extreme. This approach clarifies how the occurrence of these events is projected to evolve in the future. By maintaining a consistent threshold across

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historical and future scenarios, we are able to more accurately attribute changes in the probability multiplication factor (PMF) to modifications in the copula structure, reinforcing our conclusions regarding the changes in compound extreme events under future climate scenarios. In addition, we compared the 90th percentile of historical and future precipitation and wind speeds to assess changes in the intensity of events that calculate extremes.

3 Results

3.1 Observed precipitation-wind coupling and compound extremes

We used observational data to analyze the relationship between precipitation, wind, and SLA on a global scale. We defined extreme conditions as those exceeding the 90th percentile of the historical distribution for Precipitation and wind. We calculated the Pearson's correlation coefficient between precipitation and wind for each grid cell. Fig. S1a shows the global map of the correlation coefficients for the historical period (1993–2020). The results indicate a positive correlation between precipitation and wind on a global scale, with a mean value of 0.12 and a standard deviation of 0.38 (Fig. 1a and c). The strength of the correlation varies from region to region, ranging from 0.89 in the North Atlantic to -0.85 in northern South America. The correlation is generally stronger at higher latitudes than at lower latitudes.

We computed the joint probability of extreme precipitation and wind conditions for each grid cell using the copula approach, and in turn calculated the PMF. Fig. 1d shows the PMF of extreme precipitation and wind conditions for the historical period. The results reveal that extreme high values of precipitation and wind tend to co-occur more frequently than expected by chance (Fig 1a and d). The PMF has a mean value of 1.91 and a standard deviation of 1.48. These results indicate a stronger dependence between higher precipitation and wind values and emphasize that extreme conditions are not independent and are largely co-occurring.

We calculated the Pearson's correlation coefficient between precipitation and SLA (Fig. S1b), and between wind and SLA (Fig. S1c), for each grid cell over the coastal areas. The results show that precipitation and SLA are positively correlated in most regions, with a mean value of 0.21 and a standard deviation of 0.23, indicating that higher precipitation is associated with higher SLA. The correlation between wind and SLA is more complex, showing a non-linear and non-monotonic response. The mean

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value is -0.04 and the standard deviation is 0.3.

We also calculated the mean value of the SLA at the time of the CWPEs for each grid cell. Fig. 1e shows the mean SLA during CWPEs over the historical period. The results show that under CWPEs, SLA are increased relative to normal conditions (Fig. 1b). The mean increase is 1.15 cm, and the standard deviation is 10.50 cm. The large standard deviation reflects the large spatial heterogeneity. Therefore, it is important to further identify spatial patterns and hotspot areas for compound extreme events in current and future climate.

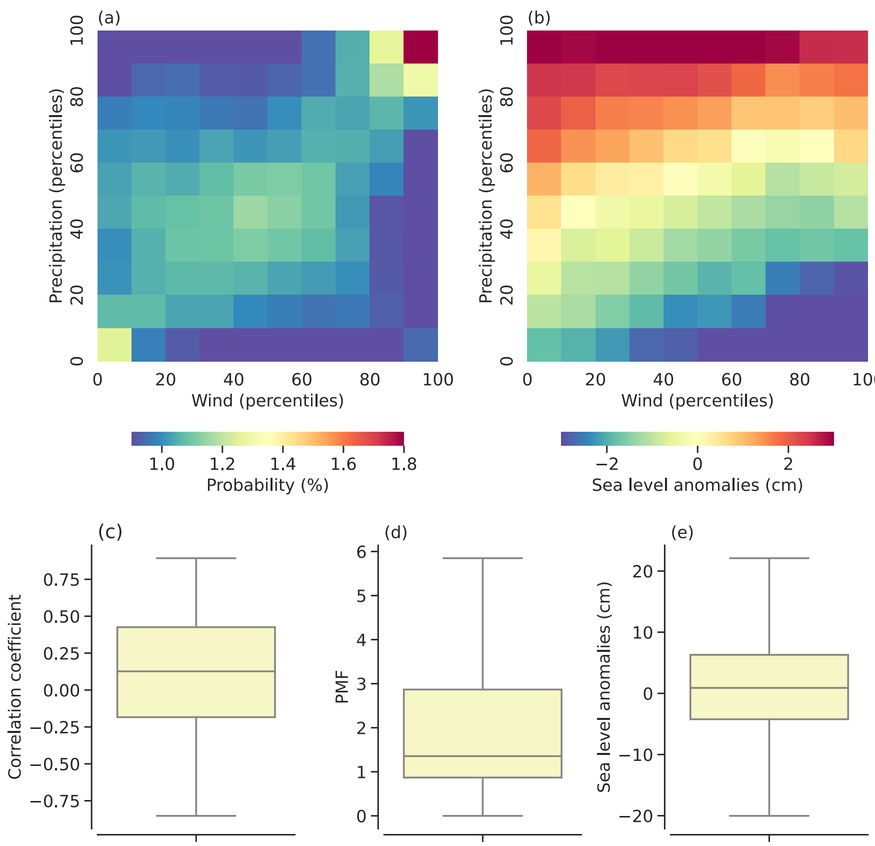

Fig. 1 Coupling of precipitation and wind and their effect on coastal sea level anomalies on the observed data (1993-2020).

(a) Average probability of each percentile bin for precipitation and wind. (b) Mean values of SLA per percentile bin for precipitation and wind. (c) Pearson's correlation coefficients for precipitation and wind. Values of PMF (d) and SLA (e) at compound precipitation and wind extremes.

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3.2 Increased intensity and frequency of compound extreme conditions in the future

We examined the relationship between CWPEs under historical and different future scenarios using 11 models from the CMIP6. The models simulated the historical period (1940-2014) and the projected future period (2020-2100). All models showed a positive correlation between precipitation and wind, as well as the bimodal distribution observed in Fig. 1a (Fig. S2, S3 and S4), for the historical simulations. These model results were consistent with observations from the ERA5 reanalysis data (Fig. 1a versus Fig. S2, and Fig. S3 versus Fig. S4), suggesting that CMIP6 captures the extremes of composite precipitation and wind realistically.

We applied copulas to model the bivariate distribution of precipitation and wind in the CMIP6 simulations and to estimate PMF. Fig. 2a displays the spatial distribution of PMF averaged across all models for the historical period. PMF is higher at higher latitudes, especially in the coastal regions of northern Europe and Alaska. These areas are prone to intense storms that may result from interactions between warm and cold air masses that can enhance precipitation and wind speeds (Waliser and Guan, 2017; Walsh et al., 2020). Moreover, the topography of these coastal areas, with their irregular coastlines and steep mountains, can also affect the formation of extreme weather conditions by altering the behavior of air masses and creating favorable conditions for storm development. These regions also coincide with areas with high correlation coefficients between precipitation and wind (Fig. S1a). PMF values are generally lower in tropical and subtropical regions, where the positive correlation between precipitation and wind is weaker.

PMF is projected to increase overall in future under both emission scenarios compared to the historical period (Fig. 2b and c). The highest increases occur at high latitudes, such as in coastal areas of northern Europe, Alaska, and Canada, where both precipitation and wind intensity and frequency are expected to increase. Global mean PMF values rose from 1.88 in the historical period to 1.98 in SSP 245 and 2.04 in SSP 585, implying a higher probability of future compound extreme conditions. In addition, while the future thresholds for extreme wind speeds used to define compound extreme conditions are almost constant (Fig. S5c and d), the thresholds for extreme precipitation are higher (Fig. S5a and b), indicating that composite extreme conditions become more

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extreme and more intense in the future.

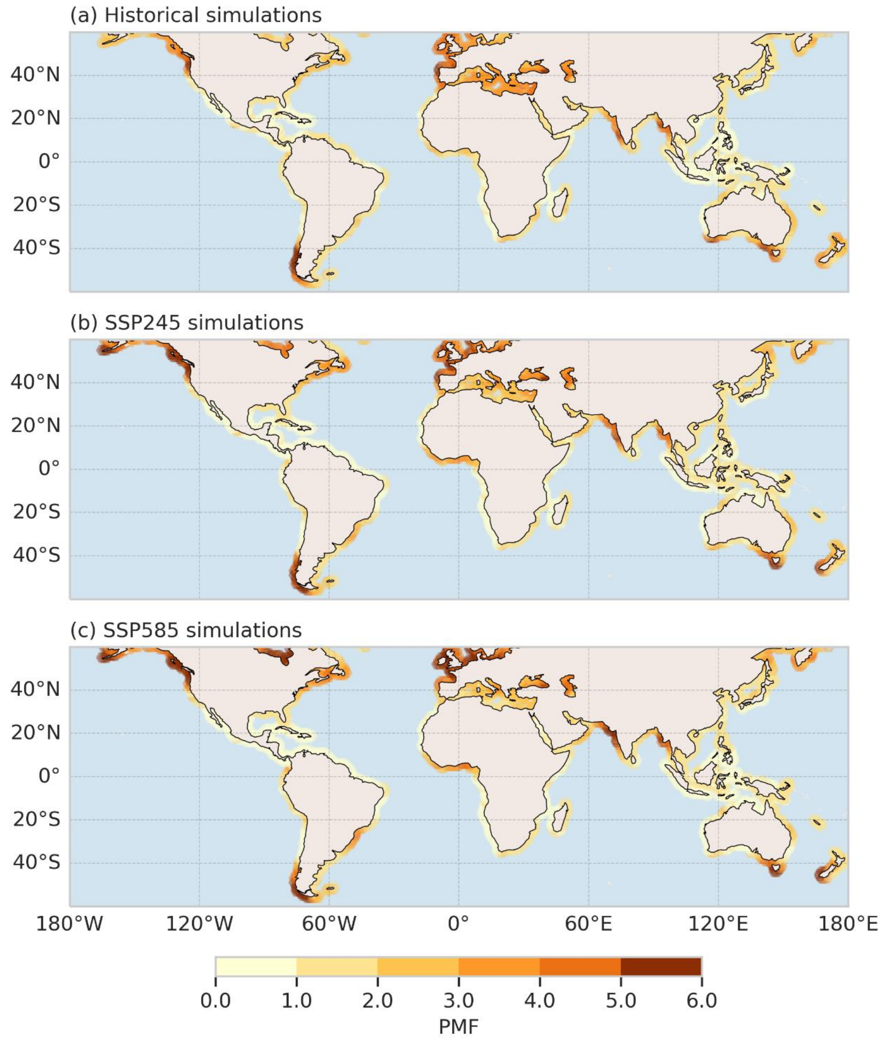

Fig. 2 PMF in CMIP6 models.

Model-averaged PMFs for extreme (above-90th percentile) precipitation and wind for both historical simulations (1940-2014) and future simulations (2020-2100): (a) for historical simulations, (b) for SSP245 future scenario, and (c) for SSP585 future scenario. The thresholds used to define future extreme conditions are based on historical.

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3.3 SLA due to compound extreme conditions

We estimated the mean SLA for each grid cell in the coastal zone when extreme precipitation and wind conditions coincided to evaluate the impact of compound extreme conditions on SLA. Fig. 3a presents a global map of the average SLA over the historical period. The results indicate that SLA during compound extreme conditions is positive in almost all regions, with a global mean of 2.7 cm. SLA is highest at high northern hemisphere latitudes, exceeding 15 cm in some regions, and decreasing slightly in most other regions between 60°S and 50°N (Fig. 3a and Fig. 4a). In both future scenarios, SLA increases more at higher emissions (Fig. 3b and c). Based on historical thresholds, in the future, compound extreme conditions lead to higher SLA with a global mean of 4.5 cm for SSP245 and 5.0 cm for SSP585. These results suggest that the impact of compound extreme conditions on SLA will increase in the future.

We also estimated the mean value of the SLA at the time of extreme precipitation conditions and extreme wind conditions separately for each grid cell over coastal areas using univariate thresholds. Fig. 5 presents the global maps of the mean SLA for precipitation and wind extremes. In historical simulations, extreme precipitation has a high impact on SLA in coastal areas such as northern Europe and northern Australia, and extreme winds have a high impact on SLA in coastal areas such as northern Europe and southern China (Fig. 5a and d). In future simulations, the impact of extreme precipitation on SLA increases in almost all regions (Fig. 5a, b and c), while the impact of extreme winds on SLA increases significantly at high northern hemisphere latitudes and remains almost unchanged elsewhere (Fig. 5d, e and f). The results indicate that in both historical and future simulations, the impact of precipitation on SLA is stronger than that of wind in most regions, with global mean values of 2.7 cm and 0.08 cm in the historical period respectively (Fig. 6). Only at high northern hemisphere latitudes is the impact of wind strong (Fig. 6). This also coincides with a stronger positive correlation between precipitation and SLA than between wind and SLA. The importance of analyzing compound extreme conditions is also highlighted by the fact that the area of high impact of compound conditions on SLA differs from that of individual variables (Fig. 5 versus Fig. 3).

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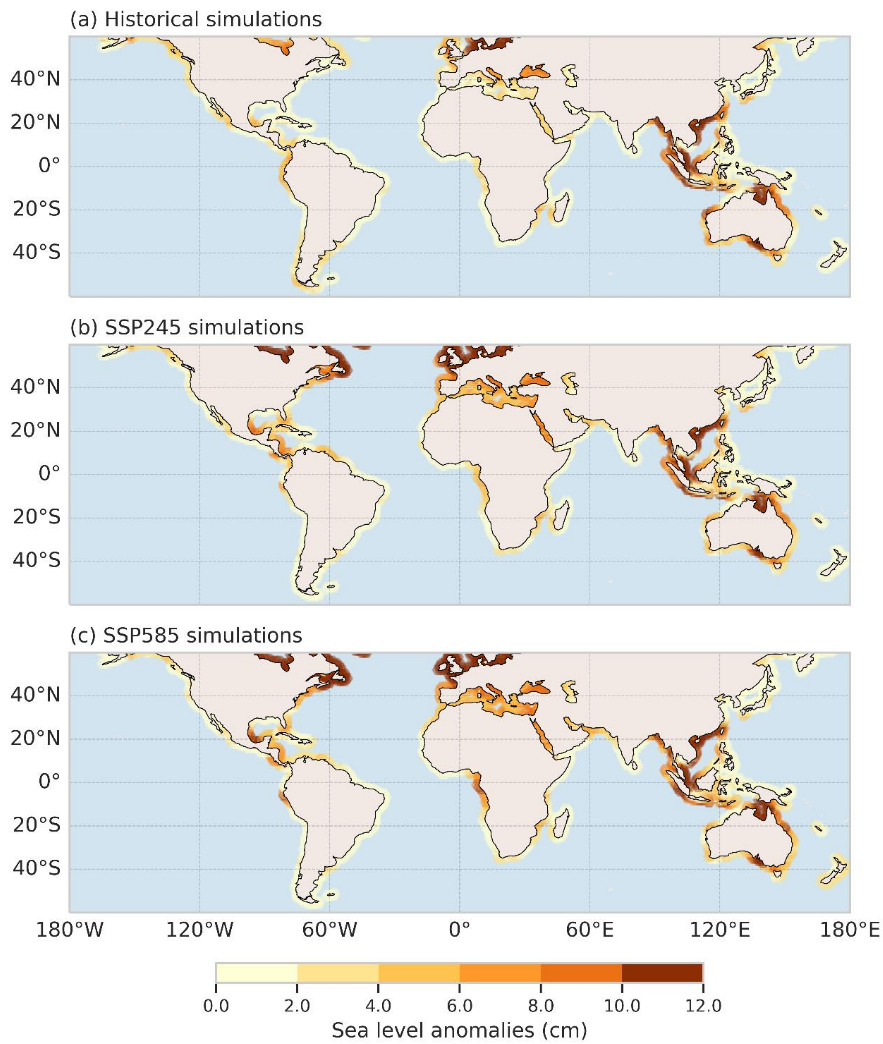

Fig. 3 SLA due to compound extreme conditions in CMIP6 models.

Model-averaged SLA for extreme (above-90th percentile) precipitation and wind for both historical simulations (1940-2014) and future simulations (2020-2100): (a) for historical simulations, (b) for SSP245 future scenario, and (c) for SSP585 future scenario. The thresholds used to define future extreme conditions are based on historical.

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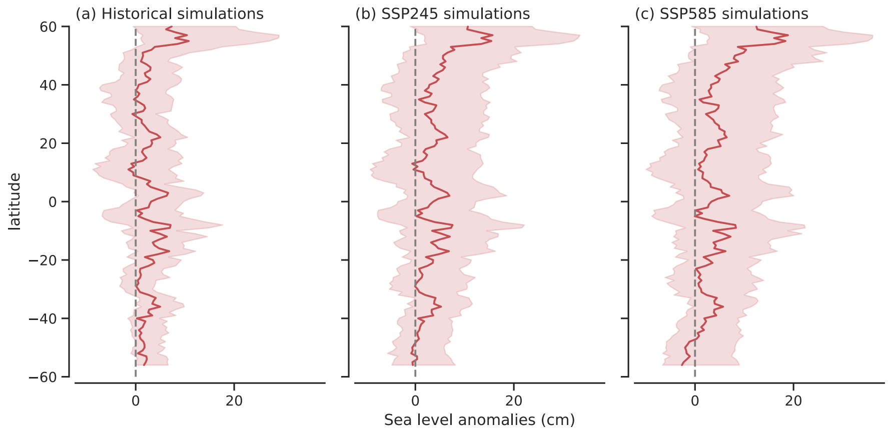

Fig. 4 Distribution of SLA along latitude due to compound extreme conditions in the CMIP6 model.

Distribution of SLA along latitude due to extreme (above-90th percentile) precipitation and wind for both historical simulations (1940-2014) and future simulations (2020-2100): (a) for historical simulations, (b) for SSP245 future scenario, and (c) for SSP585 future scenario. The solid lines are the multi-model mean of the SLA and the shading indicates the 11 GCM 5th and 95th percentiles in CMIP6. The thresholds used to define future extreme conditions are based on historical.

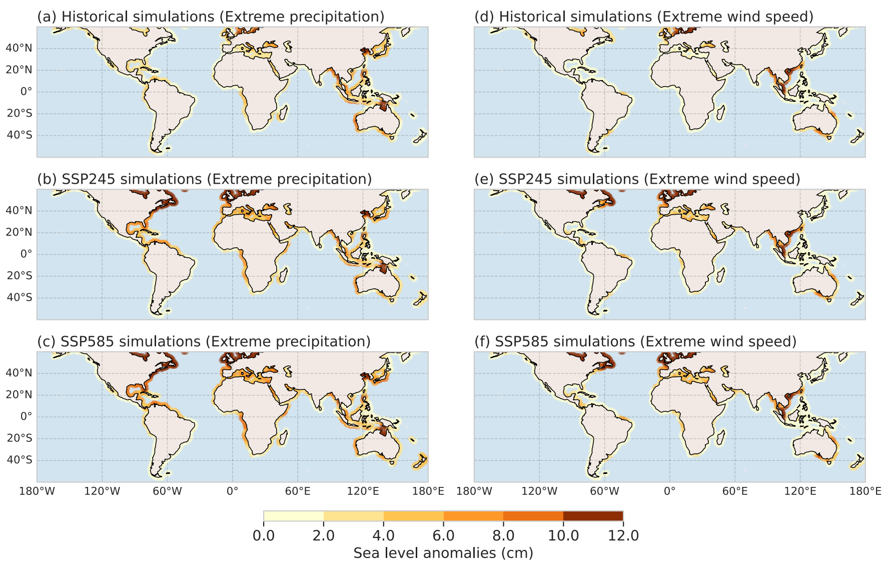

Fig. 5 Impact of extreme precipitation and wind on SLA in the CMIP6 model.

SLA due to extreme (above-90th percentile) precipitation or wind in historical

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simulations (1940–2014) (a and d), in future SSP245 simulations (2020–2100) (b and e), and in future SSP585 simulations (c and f). The thresholds used to define future extreme conditions are based on historical.

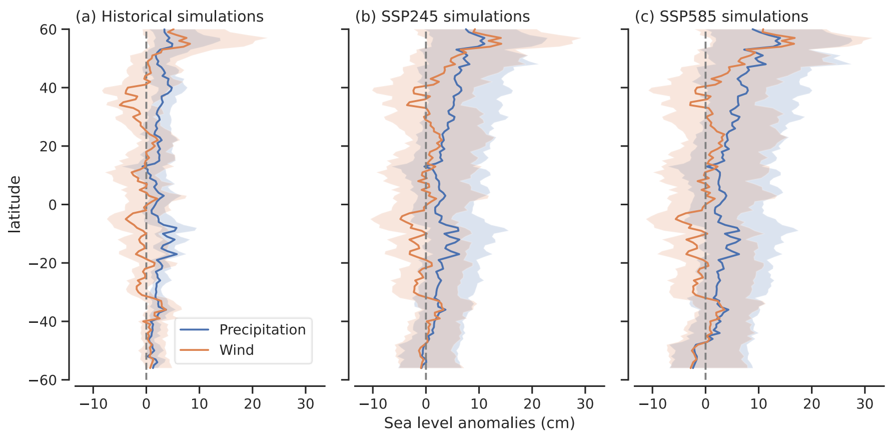

Fig. 6 Distribution of SLA along latitude due to extreme precipitation or wind conditions in the CMIP6 model.

Distribution of SLA along latitude due to extreme (above-90th percentile) precipitation or wind for both historical simulations (1940-2014) and future simulations (2020-2100): (a) for historical simulations, (b) for SSP245 future scenario, and (c) for SSP585 future scenario. The solid lines are the multi-model mean of the SLA and the shading indicates the 11 GCM 5th and 95th percentiles in CMIP6. The thresholds used to define future extreme conditions are based on historical.

4 Discussion and conclusions

In this study, we examined how compound extreme conditions of precipitation and wind affect SLA along global coastlines. We combined observational data and model simulations to assess the historical and future changes of these conditions under different emission scenarios. We found that:

(1) Precipitation and wind are globally and positively correlated, with a stronger coupling at higher latitudes.

(2) Extreme high values of precipitation and wind co-occur more often than expected by chance, indicating a higher dependence between these variables at the upper tail of their distributions.

(3) Compound extreme conditions of precipitation and wind are linked to higher

SLA than normal conditions, implying an influence of these conditions on coastal flooding risk.

(4) The intensity and frequency of compound extreme conditions are projected to increase in the future under both emission scenarios, with a larger increase at high latitudes, resulting in higher SLA during these conditions.

These findings address our research questions and confirm our hypotheses that compound extreme conditions of precipitation and wind have a significant impact on SLA and that this impact will amplify in the future due to climate change.

We explored the relationship between precipitation, wind, and SLA on a global scale, which has been largely overlooked in previous studies. Most of the existing studies have focused on regional or local scales, or on single variables such as precipitation or wind (Bui et al., 2023; Chen et al., 2017; Zittis et al., 2022). We are among the first to assess the global distribution and co-occurrence of extreme precipitation and wind conditions and their influence on SLA using a copula approach.

We found that precipitation and wind are globally and positively correlated, with a stronger coupling at higher latitudes. This coupling can be attributed to several physical mechanisms, such as the development of low-pressure systems that produce strong winds and heavy rainfall, the intensification of moisture transport by winds that increases precipitation intensity, or the feedback between surface fluxes of heat and moisture that affect both precipitation and wind (Back and Bretherton, 2005; Martius et al., 2016). The coupling strength varies across regions, depending on factors such as topography, land-sea contrast, orography, or ocean currents (Chen and Zhang, 2009; Zscheischler et al., 2021). We also found that the probability of extreme high values of precipitation and wind occurring together was higher than the probability of both occurring independently, indicating a higher dependence between these variables at the upper tail of their distributions. This dependence is measured by the PMF, which is the ratio of the joint probability of compound extreme conditions to the probability under independence. We found that PMF is higher at higher latitudes, especially in coastal regions that are exposed to intense storms. These regions also correspond to areas with high correlation coefficients between precipitation and wind. These results imply that compound extreme conditions are not independent and are largely co-occurring.

We also showed that compound extreme conditions of precipitation and wind are linked to higher SLA than normal conditions, implying an influence of these conditions on coastal flooding risk. SLA are affected by several factors, such as atmospheric pressure, wind stress, wind direction, ocean currents, waves, tides, or storm surges

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(Woodworth et al., 2019; Zubier and Eyouni, 2020). Precipitation and wind can influence SLA directly or indirectly through these factors. For instance, precipitation can increase river runoff and coastal freshwater discharge, which can elevate sea level locally (Dykstra and Dzwonkowski, 2021; Muis et al., 2016). Wind can generate storm surges by pushing water towards the shore or by altering ocean currents and waves. We found that in most regions, precipitation has a stronger influence on SLA than wind, except at high northern hemisphere latitudes where wind has a strong influence. This also corresponds to a stronger positive correlation between precipitation and SLA than between wind and SLA.

We found that the influence of compound extreme conditions on SLA will amplify in the future due to climate change. We showed that the intensity and frequency of compound extreme conditions are projected to increase in the future under both emission scenarios, especially at high latitudes where both precipitation and wind intensity and frequency are expected to increase (Gastineau and Soden, 2009; Kao and Ganguly, 2011). This results in higher SLA during these conditions compared to historical ones when using historical thresholds. However, when using future thresholds based on future distributions of precipitation and wind, we showed that SLA during future compound extreme conditions is similar to historical ones. This indicates an increase in the threshold for compound extreme conditions in the future relative to historical ones.

It is important to acknowledge several limitations of our study that future research could address. Firstly, one of the major shortcomings is the use of monthly mean data instead of daily data. Monthly means may obscure the temporal dynamics and intensities of compound extreme events, as they average out daily fluctuations. The analysis of daily data would provide a more detailed understanding of the temporal evolution and intensity of these conditions, as well as their specific impacts on sea level anomalies. However, daily data are more volatile and contain more short-term noise, and therefore may be more disturbing when used directly for long-term trend analysis. Our study of long-term changes in the status of CWPEs tends to, and monthly data provide more reliable and representative long-term trend information. Secondly, while we examined the intensity and frequency of precipitation and wind extremes, we did not specifically consider wind direction in our analysis. Wind direction is a crucial factor that influences coastal flooding, as it determines the direction and intensity of storm surges and waves. The inclusion of wind direction in future studies would provide a more comprehensive picture of the combined effects of precipitation, wind speed, and wind direction on sea level anomalies and coastal flooding risks. Addressing these limitations through future research would help refine our understanding of compound extreme conditions and their impacts on coastal regions.

Our findings have important implications for assessing the risks and impacts of compound extreme conditions on coastal areas. Coastal areas are susceptible to flooding due to sea level rise, storm surges, waves, tides, or river runoff (Becker et al., 2023; Bevacqua et al., 2019). Compound extreme conditions can aggravate these risks by increasing SLA during these conditions. Our results imply that coastal areas may experience more frequent and intense compound extreme conditions in the future due to climate change, which may increase their exposure and vulnerability to coastal flooding. Therefore, it is crucial to consider compound extreme conditions in evaluating coastal hazards, adaptation strategies, resilience planning. In summary, these findings have important implications for understanding the impacts of compound extreme conditions on a global scale and for assessing and managing the risks of coastal flooding due to compound extreme conditions.

Data Availability

The CMIP6 climate data layer for the 11 GCMs were obtained from the WCRP Coupled Model Intercomparison Project (Phase 6) (https://esgf-node.llnl.gov/search/cmip6/). ECMFW ERA5 data were obtained from Copernicus Climate Data Store (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels-monthly-means?tab=overview). Sea level gridded data from satellite observations were obtained from the Copernicus Climate Change Service (https://cds.climate.copernicus.eu/cdsapp#!/dataset/satellite-sea-level-global?tab=overview). Coastline data were obtained from Natural Earth (https://www.naturalearthdata.com/downloads/110m-physical-vectors/110m-coastline/).

Authors' contributions

Xinlong Zhang: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft. Jiayi Fang: Conceptualization, Methodology, Writing – review & editing. Yue Qin: Conceptualization, Methodology, Writing – review & editing. Weiping Wang: Conceptualization, Formal analysis, Investigation, Methodology, Writing – review & editing. Ping Shen: Conceptualization, Formal analysis, Investigation, Methodology, Writing – review & editing, Funding acquisition.

Competing interests

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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