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## RESEARCH LETTER

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## Key Points:

- Extreme waves will change along a large portion of the coasts generally increasing in the S. Hemisphere and decreasing in the N. Hemisphere
- The projected changes of extreme waves can be explained with a projected intensification of climatic patterns such as AAO, ENSO, and NAO

## Supporting Information:

- Supporting Information S1

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## Global changes of extreme coastal wave energy fluxes triggered by intensified teleconnection patterns

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**Abstract** In this study we conducted a comprehensive modeling analysis to identify global trends in extreme wave energy flux (WEF) along coastlines in the 21st century under a high emission pathway (Representative Concentration Pathways 8.5). For the end of the century, results show a significant increase up to 30% in 100 year return level WEF for the majority of the coastal areas of the southern temperate zone, while in the Northern Hemisphere large coastal areas are characterized by a significant negative trend. We show that the most significant long-term trends of extreme WEF can be explained by intensification of teleconnection patterns such as the Antarctic Oscillation, El Niño–Southern Oscillation, and North Atlantic Oscillation. The projected changes will have broad implications for ocean engineering applications and disaster risk management. Especially low-lying coastal countries in the Southern Hemisphere will be particularly vulnerable due to the combined effects of projected relative sea level rise and more extreme wave activities.

## 1. Introduction

Waves are a prominent component of coastal hazard, contributing to extreme water levels manifested as wave setup and runup [Stockdon et al., 2006; Hemer et al., 2012; Vousdoukas et al., 2012a]. Extreme waves transfer large amounts of energy to the coast, applying huge stress to coastal installations and protection structures [Oumeraci, 1994; Van der Meer et al., 2016], accelerating sediment transport processes and coastal erosion [Masselink and Puleo, 2006; Vousdoukas et al., 2012b; Archetti et al., 2016; Masselink et al., 2016; Monioudi, 2016; Postacchini et al., 2017], and driving dune breaching [Matias et al., 2008; Roelvink et al., 2009] and inundation [Bertin et al., 2012; Vousdoukas et al., 2016b]. By modulating interactions between oceans and the atmosphere waves play an important role in the climate system [Hemer et al., 2012] and are likely to be affected by global warming. In several regions of the world, wave heights show already an upward trend in recent decades, especially the extremes [Wang et al., 2009; Young et al., 2011, 2012].

Regional impacts of climate change in coastal areas could be dominated by increased flooding and erosion from storm wave extremes, independent of relative sea level rise (RSLR) [Ruggiero, 2013; Barnard et al., 2015]. Yet the focus in literature when addressing future coastal impacts has been prevalently on the effects of RSLR [Hinkel et al., 2014]. The few global studies discussing large-scale projections of waves in view of climate change mainly focus on average wave conditions [Hemer et al., 2013a]. In global studies changes in extreme wave conditions have been marginally explored by focusing on high percentile values or on low return levels [Mori et al., 2010; Hemer et al., 2013a, 2013b; Semedo et al., 2013; Wang et al., 2014; Perez et al., 2015], omitting the rare extremes that may give rise to catastrophic impacts, although more detailed local studies exist [De Winter et al., 2012; Lionello et al., 2012; Casas-Prat and Sierra, 2013; Erikson et al., 2015; Shimura et al., 2016].

Studies based on satellite altimeter [Izaguirre et al., 2011] and reanalysis data [Dodet et al., 2010; Plomaritis et al., 2015; Kumar et al., 2016] revealed strong relationships between wind-wave climate and large-scale teleconnection patterns, such as the Antarctic Oscillation (AAO), the El Niño–Southern Oscillation (ENSO), and the North Atlantic Oscillation (NAO). Some of these indices are expected to intensify under increased anthropogenic forcing [Zheng et al., 2013; Cai et al., 2014], but it is not well understood how wind-wave variability and especially extreme waves will relate to these climate indices in a warmer world.

In this work we dynamically simulated the wave energy flux (WEF) with a global wave model driven by an ensemble of global coupled models (GCMs) from the Coupled Model Intercomparison Project Phase 5 (CMIP5) [Taylor et al., 2012] under the Representative Concentration Pathways scenario 8.5 [Meinshausen et al., 2011; van Vuuren et al., 2011]. We focused in particular on the 100 year return level of WEF, as a

proxy for coastal flooding and erosion, studying the long-term changes of its extremes estimated from a nonstationary extreme value analysis technique [Mentaschi *et al.*, 2016].

To explain the projected variations in extreme WEF, we investigated their correlation with long-term trends of climatic indices, such as the Antarctic Oscillation (AAO) index [Gong and Wang, 1999], often indicated also as Southern Annular Mode index in literature, the El Niño-Southern Oscillation (ENSO) index [Rasmusson and Wallace, 1983], and the North Atlantic Oscillation (NAO) index [Rodwell *et al.*, 1999]. These indices can be used to characterize the behavior of global and local geophysical systems, and are associated with the degree of instability of geophysical fluxes (like the jet streams or the thermohaline circulation) that induce extreme events and disasters, and are therefore useful to understand the consequences of climate changes.

## 2. Methods

The wave projections have been generated with the spectral wave model Wavewatch III (version 4.18 [Tolman, 2014]) forced by six CMIP5 models (for details see the supporting information and Perez *et al.* [2014]). In the wave model the source terms of growth/dissipation ST4 [Ardhuin *et al.*, 2010; Rascle and Ardhuin, 2013; Mentaschi *et al.*, 2015] was employed. The model setup consists of a global regular mesh with a resolution of 1.5°, spanning from latitude 80°S to 80°N, with nests on specific areas. The simulations were carried out on a 130 year time interval from 1970 to 2100 (for details see Vousdoukas *et al.* [2017]). The results of the simulations were saved for 4986 locations along the coast worldwide (Figure 1). For each location and each model, the wave energy flux (WEF, W/m) was computed as

$$\text{WEF} = E \cdot c_g = \frac{1}{64\pi} \rho g^2 T_{-10} H_s^2, \quad (1)$$

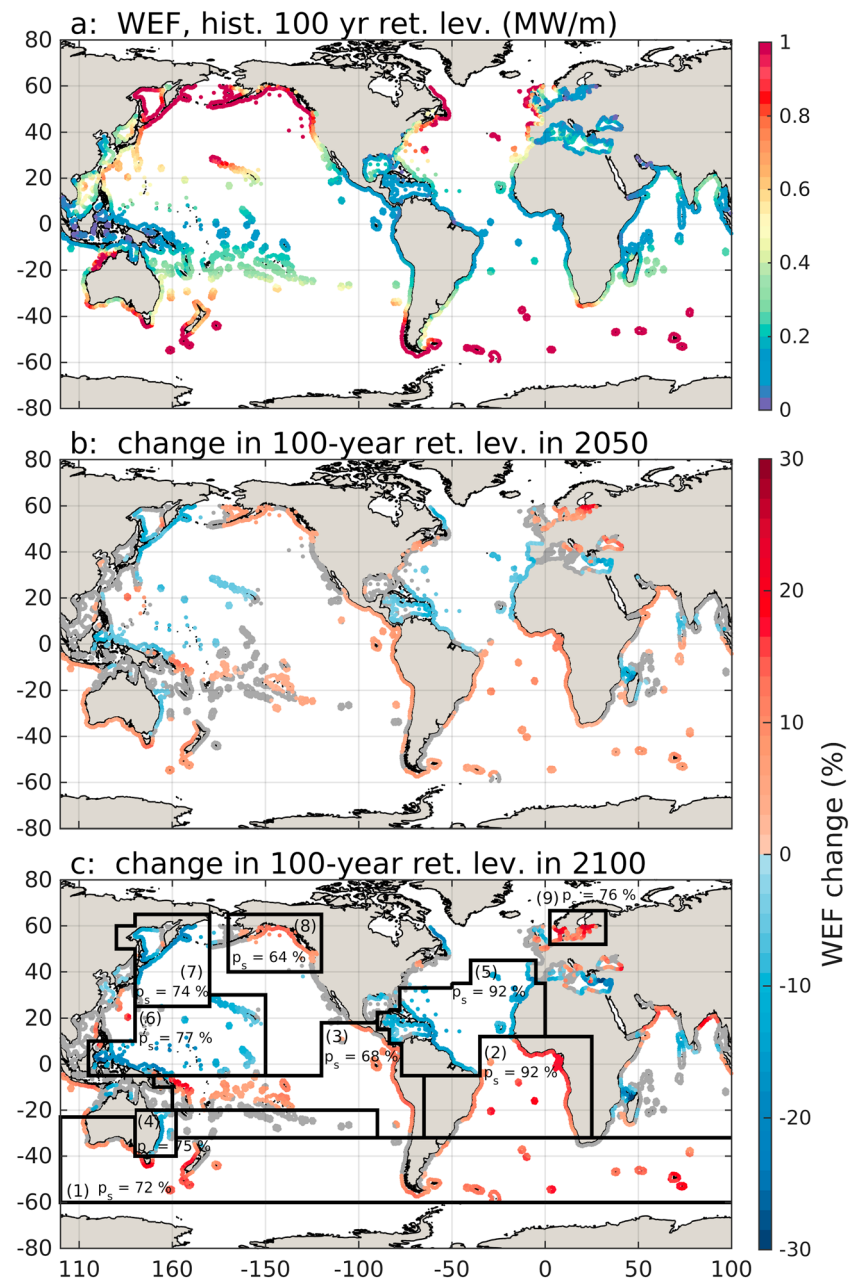
where  $E$  is the energy density ( $\text{J/m}^2$ ),  $T_{-10}$  is the average period (s), and  $H_s$  is the significant wave height (m). A nonstationary extreme value analysis (EVA) was performed on each WEF time series by using the approach described by Mentaschi *et al.* [2016] in order to detect long-term trends in the extremes. The nonstationary EVA algorithm was set in order to filter out the variability on time scales below 30 years, to exclude from the analysis noise and sharp variations. The output of the EVA analysis was a location-specific time-varying generalized Pareto distribution for each WEF series, from which time-varying return levels were derived for specific return periods (50, 100, 200, and 500 years, focusing on the 100 year return level). The relative change of the  $N$ -year return levels of WEF was evaluated separately for each CMIP5 model. Then the absolute change of each model was computed applying its relative change to the ensemble return level of the historical scenario (see the supporting information). For each location the significance of the ensemble change in the 100 year return level of WEF was evaluated by means of the coefficient of variation  $\text{CV}_{2100}$  computed for the year 2100:

$$\text{CV}_{2100} = \frac{\sigma_{2100\text{WEF}}}{\langle \text{WEF}_{2100} - \text{WEF}_{\text{baseline}} \rangle}, \quad (2)$$

where  $\langle \text{WEF}_{2100} - \text{WEF}_{\text{baseline}} \rangle$  is the ensemble average change between the end of the century and the baseline period and  $\sigma_{2100\text{WEF}}$  is the intramodel standard deviation of WEF for the year 2100. The ensemble change in extreme WEF was considered significant if  $|\text{CV}_{2100}| \leq 1$  [Alfieri *et al.*, 2015; Vousdoukas *et al.*, 2016a].

To investigate the correlation between extreme WEF and climatic indices a set of macroareas was selected in order to contain contiguous segments of coast with changes of extreme WEF of the same sign. The selected areas do not cover entirely the global coastline and have been arbitrarily identified so that each of them extends over a large area and contains a high percentage of points  $p_s$  with a significant and coherent trend, positive or negative. Therefore, important areas such as the northern Atlantic, the Yellow Sea, and the U.S. Pacific Coast were excluded from the correlation analysis because the majority of their locations do not present a significant ensemble change of extreme WEF. Other areas, such as the whole Indian Ocean, the Mediterranean Sea, and the British coast, were neither considered in the correlation analysis, because they contain subareas with opposite trends. This suggests that wave climate changes in these areas are characterized by a higher spatial variability, and that it would be difficult to connect them directly with the long-term intensification of large climatic patterns.

The climatic indices have been estimated as the first empirical orthogonal function of a principal component analysis of the anomalies of geophysical fields, such as the geopotential height (AAO and NAO) and the sea

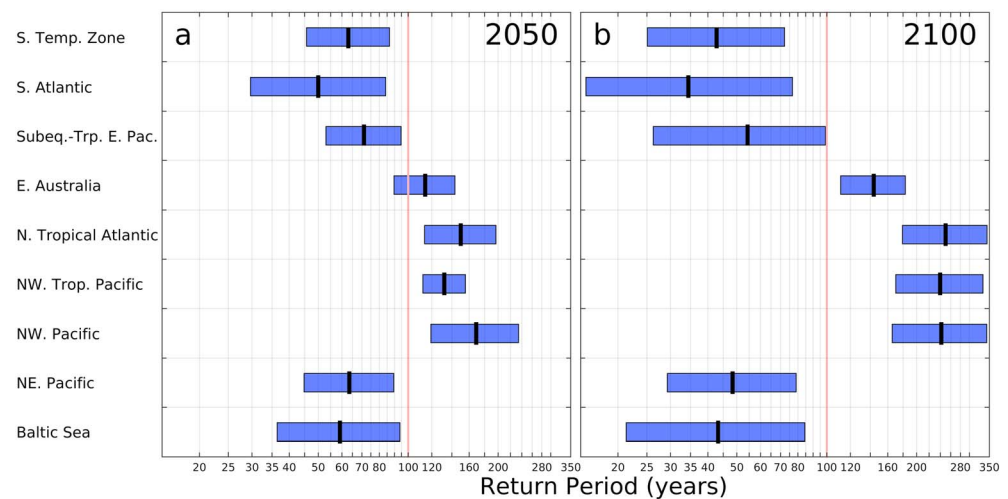


**Figure 1.** Ensemble projection of WEF along the global coastline: (a) baseline 100 year return level, ensemble relative change of the 100 year WEF for the year (b) 2050, and (c) 2100. The gray dots correspond to locations where no significant change was projected. In Figure 1c the areas of significant change are reported together with the percentage  $p_s$  of points where the increase is significant. The considered areas are the (1) southern temperate zone, (2) southern Atlantic, (3) subequatorial-tropical eastern Pacific, (4) eastern Australia, (5) northern tropical Atlantic, (6) north-western tropical Pacific, (7) north-western Pacific, (8) north-eastern Pacific, and (9) Baltic Sea.

surface temperature (ENSO). Since we are interested in long-term variations, the indices were low-pass filtered by means of a 30 years moving average.

For each model and area a correlation coefficient  $\rho$  was computed between the time-varying return level of WEF averaged over the area and the long-term change of a given climatic index. The ensemble correlation coefficient  $\bar{\rho}$  was computed as the average of the correlations estimated for each CMIP5 model.

For all the locations the extreme wave direction was estimated as the mean direction of the waves beyond the 98.5 moving percentile of WEF. The ensemble difference between the directions of extreme WEF in



**Figure 2.** Projected return period of the present-day 100 year event (shown as vertical black line) for (a) 2050 and (b) 2100. The rows correspond to different areas, the black lines represent the projected return period, and the blue patches the confidence interval (defined by the intermodel standard deviation).

the time windows 2070–2100 and 1980–2010 was taken as the change in direction of extreme WEF. The ensemble change in direction  $\Delta_e\theta$  was considered relevant for these locations where it exceeds the intermodel mean absolute deviation  $MAD(\theta)$  of direction.

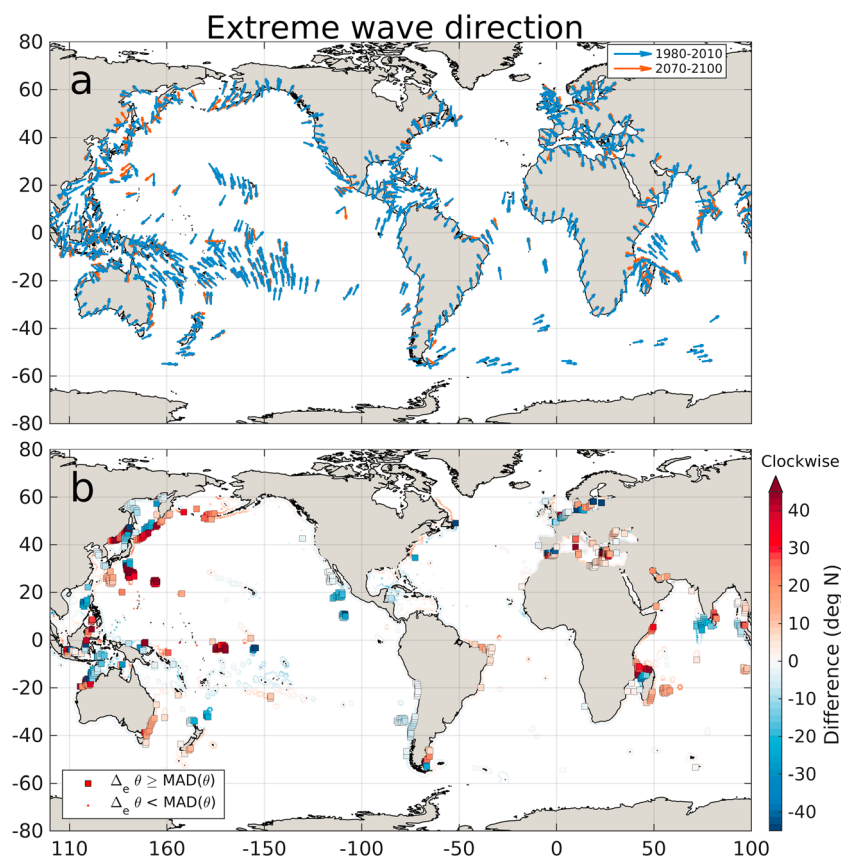
### 3. Results

The projected trend in the 100 year return level of WEF shows a remarkable variation between regions (Figure 1). A significant increase (decrease) in extreme WEF is projected by the end of this century along 29% (26%) of the global coastline. A significant increase of extreme WEF is projected along 43% of the Southern Hemisphere coastline, in particular for the whole southern temperate zone with the exception of Eastern Australia, the southern Atlantic, and the subequatorial-tropical eastern Pacific. In the Northern Hemisphere large coastal areas are characterized by a clear negative trend, including the northern tropical Atlantic, north-western tropical Pacific, and north-western Pacific. The north-eastern Pacific and Baltic Sea, on the other hand, show positive trends, with rises up to 30%, in extreme WEF.

The relative changes found for the 50, 200, and 500 year return levels (see Table S1 in the supporting information) appear to increase slightly with the return levels, and the increase for more exceptional events is consistently larger than the changes found for the mean WEF. The average change of the 100 year return level at the locations where we find increase (decrease) is of about 12.5% (–13%), while the average change of the mean WEF is 5.48% (–6.83%). This finding is in line with previous studies based on historical data [Young *et al.*, 2011]. Moreover, similar relative changes of different return levels involve higher absolute changes of power for more extreme events. In particular, the increase (decrease) of power of the 500 year extreme is on average 37% higher (61% lower) than the one of the 50 year extreme.

The increase in WEF projected along several areas (southern temperate zone, southern Atlantic, subequatorial-tropical eastern Pacific, north-eastern Pacific, and Baltic Sea) translates into an increase in frequency (Figure 2), with the present-day 100 year event being projected to occur at least every 50 years, towards the end of the century. A smaller increase in frequency was projected along the subequatorial-tropical eastern Pacific, where the present-day event of the century occurs every 54 years in 2100. Conversely, the projected decrease in WEF in other areas is expressed also in a more than 50% reduction of the frequency towards the end of the century. Eastern Australia is an exception as the present-day event of the century is projected to occur every 150 years.

The changes of extreme WEF projected for 2050 present spatial patterns similar to the ones projected for 2100, but the variation is smaller in both magnitude and frequency (Figures 1 and 2), with absolute changes in magnitude always below 20% and absolute changes in frequency below 50%.



**Figure 3.** Ensemble mean change of extreme WEF direction: (a) quiver plots showing the direction of propagation for the baseline and 2070–2100. (b) Scatterplot showing the direction change between the start and end of the century, expressed by the box color; the box type indicates that the change in direction exceeds the intermodel MAD of the change.

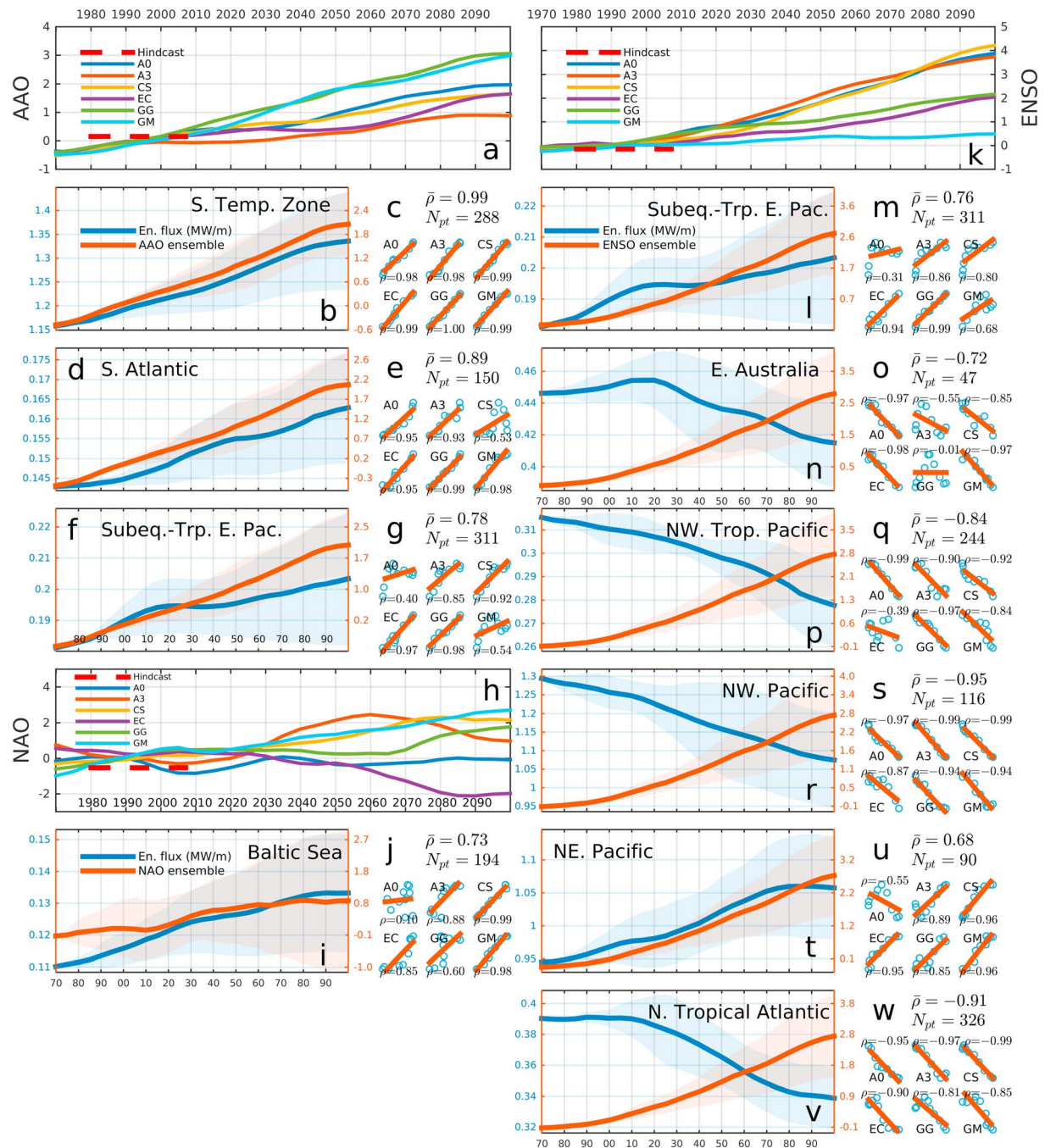
In many locations the direction of extreme WEF is projected to change significantly by the end of the century (Figure 3), with variations in some cases of tens of degrees, in some locations of the north-western Pacific, of the equatorial Pacific, of north-western Australia, and in the area north-west of Madagascar. In the majority of the locations of the Southern Hemisphere we projected a northward rotation of extreme WEF, except for Eastern Australia and a few other areas sheltered from the Southern Ocean swell. In the majority of the locations of the northern temperate zone we projected an eastward rotation of extreme WEF.

#### 4. Discussion

The projected changes are for many regions qualitatively similar to those for the 10 year return level obtained by Wang *et al.* [2014] using statistical modeling. The magnitude of the changes presented herein are generally more pronounced in both directions, and this is consistent with the employment in this study of the WEF, that is proportional to  $H_s^2 \cdot T$ , while Wang *et al.* [2014] studied the 10 year return level of  $H_s$ . The present projections show an overall stronger statistical significance, partially due to the nonstationary extreme value analysis, which allows for bigger samples and consequently less statistical fitting uncertainty, compared to a stationary approach applied on time slices [Mentaschi *et al.*, 2016]. Moreover, dynamical models allow for a more accurate representation of extreme conditions compared to statistical methodologies, due to the scarce availability of extreme data to train the statistical models [Breivik *et al.*, 2014; Laugel *et al.*, 2014; Martínez-Asensio *et al.*, 2014].

To explain the projected changes of extreme WEF, we studied their correlation with the long-term tendencies of the AAO, NAO, and ENSO indices. Some aspects of the complex dynamics related to these indices are not yet fully understood and represented by GCMs [Davini and Cagnazzo, 2013; Kim and Cai, 2014; Yeo and Kim, 2015]. Yet the CMIP5 models are able to catch their basic features both in terms of shape and percentage of





**Figure 4.** Projected long-term trend of (a) AAO, (h) NAO, and (k) ENSO indices. The dashed thick red line indicates the index estimated for ERA-Interim. (b, d, f, i, l, n, p, r, t, and v) Comparisons of one of the ensemble indices (b, e, and f: AAOI; i: NAO, and n–v: ENSO) with the ensemble 100 year WEF for different regions. (c, e, g, j, m, o, q, s, u, and w) Scatterplots and the correlation coefficients  $\rho$  between the AAO index (Figures 4c, 4e, and 4g) or the NAO index (Figure 4j) or the ENSO index (Figures 4q, 4s, 4u, and 4w) and the 100 year return level of WEF for each of the CMIP5 models and for the respective regions. The average correlation coefficient  $\bar{\rho}$  and the number of points  $N_{pt}$  of the area are also reported.

explained variance, i.e., the weight of the pattern to the total climatic variability [Lee and Black, 2013; Zheng et al., 2013; Cai et al., 2014]. Projections along the 21st century show a significant long-term increase of AAO (Figure 4a) characterized by an intensification of the AAO pattern. The low pressure over Antarctica is expected to deepen, and the meridional thermal gradient at high latitudes in the Southern Hemisphere is expected to strengthen, with a consequent poleward shift of the storm tracks [Arblaster et al., 2011; Zheng et al., 2013]. This is coherent with the increase of extreme WEF projected for the Southern Hemisphere

(Figures 4b–4g), with the exception of Eastern Australia and a few other areas sheltered from swell from the Southern Ocean. The positive correlation is particularly significant in the southern temperate zone, where the ensemble average correlation coefficient  $\bar{\rho}$  is very close to 1 ( $\bar{\rho} = 0.99$ ). This confirms that AAO has a strong influence on the climate of the Southern Hemisphere. Especially at high latitudes a positive phase of AAO is associated with an intensification of the meridional thermal gradient and of the inherent baroclinic instability [Mo, 2000; Gupta and England, 2006] that generates storms and extreme winds related to extreme waves. The increase of extreme WEF at lower latitudes in the Southern Hemisphere, in the southern Atlantic, and in the subequatorial-tropical eastern Pacific can also be connected with the long-term variation of AAO. This is partly due to an increase of the swell coming from the Southern Ocean that also explains the equatorward rotation of extreme WEF projected by the end of the XXI century in many areas of the Southern hemisphere (Figure 3). On the other hand, an intensified AAO can be associated with a warming sea surface at subtropical latitudes, involving more intense convection and more frequent storms [Grassi *et al.*, 2005].

In a way similar to AAO for the Southern Ocean, the NAO index is a proxy for the meridional thermal gradient in the northern Atlantic. A high NAO phase corresponds to a northward shift and an intensification of storm tracks over northern Europe [Rodwell *et al.*, 1999]. This explains the good correlation between the long-term variations of the NAO index and the change of extreme WEF in the Baltic Sea (Figures 4i and 4j), because a stronger NAO is associated with more powerful and unstable westerlies and with an enforced storm activity that leads to more intense extreme waves [Hurrell, 1995]. Conditions of more intense westerlies over the Baltic Sea can also explain the eastward rotation of the extreme WEF in this area (Figure 3). Although we find a strong correlation between the long-term changes of NAO and of extreme WEF, the weaker and more uncertain intensification of NAO (Figure 4h) does not fully explain the robust increase of extreme WEF in the Baltic Sea. The disagreement within the model ensemble about the trend of NAO can be connected to the absence of a significant change of extreme WEF in wide portions of the northern Atlantic coasts.

ENSO shows a significant tendency to increase (Figure 4k) expressed by an intensification of the ENSO pattern and a shift of climate toward El Niño conditions [Cai *et al.*, 2014]. This indicates a warming of the Peruvian upwelling zone and a strengthened thermal gradient to the western side of the Pacific Ocean, while the jet stream in the Northern Hemisphere is expected to shift southward [Philander, 1983]. The geophysical dynamics related to ENSO are complex and have vast consequences worldwide [Cai *et al.*, 2014]. The warm temperature anomalies of the Peruvian upwelling zone during El Niño enforce convective motions and cause a strengthened instability in the equatorial eastern Pacific, resulting in more intense and frequent storms and extreme winds and subsequently waves [Philander, 1983; Rasmusson and Wallace, 1983; Timmerman *et al.*, 1999; Jin *et al.*, 2014]. This explains the significant positive correlation between the projected long-term variation of ENSO and the increase of extreme WEF in the subequatorial-tropical eastern Pacific (Figures 4l and 4m). We note that CMIP5 models present some shortcomings in the simulation of tropical cyclones that dominate the extreme WEF in areas such as the subequatorial-tropical eastern Pacific, usually modeling features weaker, larger, and less frequent than observed, and underestimating the peaks mainly due to the low resolution [Camargo, 2013] and to the lack of ocean-atmosphere coupling in many CMIP5 models [Shimura *et al.*, 2016]. Moreover, the complex coupled dynamics of tropical cyclones and waves are not yet fully understood [Babanin *et al.*, 2012; Toffoli *et al.*, 2012; Chen *et al.*, 2013; Janssen *et al.*, 2013; Zappa *et al.*, 2016]. However, they are designed to model properly the large features of geophysical fields that impact on the intensity and frequency of the tropical cyclones [Camargo, 2013]. In addition, a strong connection between positive ENSO phases and more frequent and intense tropical cyclones in the tropical eastern Pacific is well documented [Jin *et al.*, 2014]. Therefore, the increase of the extreme WEF projected with the CMIP5 models for the subequatorial-tropical eastern Pacific and for other tropical regions can be considered a proxy of an increase of the extreme WEF associated with full-scale tropical cyclones.

El Niño conditions are also generally associated with a strengthening of the Aleutian low and of high pressures west of the Rocky Mountains [Philander, 1983; Barnard *et al.*, 2015]. This enforces the winds over north-western Canada and Alaska, explaining why the long-term increase of ENSO is correlated with the growth of extreme WEF along the north-eastern Pacific coasts (Figures 4t and 4u). This mechanism also explains the eastward rotation of extreme WEF in many locations in the northern Pacific (Figure 3) [Raible *et al.*, 2005]. For many other regions the intensification of ENSO will result in less extreme wave climate. Along the coasts of the western Pacific and in Eastern Australia (Figures 4n and 4o) the inverse correlation is consistent with colder and dryer conditions in Eastern Asia and Eastern Australia during El Niño episodes,



with reduced cyclonic activity and consequently less frequent storms and extreme winds and waves [Power et al., 1999; Wang et al., 2000; Verdon et al., 2004]. In the north-western Pacific, a progressive shift southward of the jet stream and of the storm-tracks under El Niño conditions results in a colder and more stable climate [Wang et al., 2000; Barnard et al., 2015], exemplified by strong negative correlation between the trends in extreme WEF and the ENSO index ( $\bar{\rho} = -0.95$ ). A rather strong negative correlation is also observed for the northern tropical Atlantic ( $\bar{\rho} = -0.91$ ; Figures 4v and 4w). There is evidence from historical data of a robust teleconnection of El Niño with the northern tropical Atlantic [Chang et al., 2006]. Although the mechanism is not yet fully understood, a possible explanation is that a warmer-than-the-average northern tropical Atlantic can induce a low-level atmospheric flow over eastern Pacific, triggering La Niña conditions [Ham et al., 2013]. Conversely, El Niño conditions are generally associated to cooler-than-the-average and more stable conditions in the northern tropical Atlantic, with less intense and frequent storms and extreme waves.

The projected changes of extreme WEF can lead to increased coastal impacts, especially along low-lying, densely populated, and often scarcely protected coastal areas along the Southern Hemisphere, where an increase of extreme WEF is projected. For example, extreme WEF is projected to increase by 25% along the Guinea Gulf (western Africa), and the present-day 100 year event is expected to more than double in frequency toward the end of the century, while the area is already experiencing coastal erosion and inundation issues [French et al., 1995; Odunuga et al., 2014]. Such an increase, combined with anticipated RSLR of 0.5–1.5 m [Church et al., 2013; Hinkel et al., 2014], and fast-growing population trends [Zinkina and Korotayev, 2014], can lead to higher wave-induced water levels, energy, and thus coastal impacts. Small Island Developing States located in the tropical southern Pacific are known for their limited and low-lying areas and their strong exposure to coastal hazard [Strolazzi et al., 2011; Duvat et al., 2013]. An increase of extreme WEF of about 10% by the end of the century, together with the effects of RSLR, could compromise a significant portion of their surface and even threaten the existence of some atolls.

On the other hand, the projected decrease in extreme WEF along other parts of the world could partially counterbalance RSLR and related impacts, highlighting the need to assess all hazard components in view of climate change in order to have the full picture of future risks.

## 5. Conclusions

The extreme WEF along the coast worldwide is projected to change significantly by the end of the century. In the Southern Hemisphere the change is positive in 43% of the examined locations, with an increase of the 100 year return level of ~15%. A significant decrease of extreme WEF is instead projected along most of the Northern Hemisphere, with the exception of the north-eastern Pacific (with an average increase of ~10%), and the Baltic Sea (~20% on average, with maxima up to 30%).

The changes in magnitude translate into considerable changes in the recurrence frequency of extreme events, which are projected to occur twice as frequently along many areas, especially in the Southern Hemisphere. The latter could imply an intensification of coastal erosion and wave-induced impacts.

In many areas the changes of extreme WEF can be explained as a consequence of a long-term intensification of climatic patterns such as AAO, ENSO, and, to a lesser extent, NAO. The link between the long-term variations of the climatic indices and the change of extreme WEF is, in general, strong for all the models of the ensemble, along all the considered areas, and is particularly significant in the southern temperate zone, where the average correlation between the AAO index and the change of extreme WEF is 0.99; the southern Atlantic, where the correlation with the AAO index is 0.89; the north-western Pacific, where the correlation with the ENSO index is  $-0.95$ ; and the northern tropical Atlantic, where the correlation with the ENSO index is  $-0.91$ .

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