Global Trends of Sea Surface Gravity Wave, Wind, and Coastal Wave Setup

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ABSTRACT

Assessing trends of sea surface wave, wind, and coastal wave setup is of considerable scientific and practical importance in view of recent and projected long-term sea level rise due to global warming. Here we analyze global significant wave height (SWH) and wind data from 1993 to 2015 and a wave model to (i) calculate wave age and explain the causal, or the lack thereof, relationship between wave and wind trends; and (ii) estimate trends of coastal wave setup and its contributions to secular trends of relative sea level at coastal locations around the world. We show in-phase, increasing SWH and wind trends in regions dominated by younger waves, and decreasing SWH trends where older waves dominate and are unrelated to the local wind trends. In the central North Pacific where wave age is transitional, in-phase decreasing wave and wind trends are found over the west-northwestern region, but wave and wind trends are insignificantly correlated in the south-southeastern region; here, a reversed, upward momentum flux from wave to wind is postulated. We show that coastal wave setup depends primarily on open-ocean SWH but only weakly on wind, varying approximately like $\text{SWH}/(\text{wind speed})^{1/5}$. The wave-setup trends are shown to be increasing along many coastlines where the local relative sea level trends are also increasing: the North and Irish Seas, Mediterranean Sea, East and South Asian seas, and eastern United States, exacerbating the potential for increased floods along these populated coastlines.

1. Introduction

A substantial portion ($\sim 90\%$) of wind energy input into the global ocean generates surface gravity waves (hereafter, waves) (Lueck and Reid 1984; Wunsch and Ferrari 2004). When locally dissipated, mostly as young wind seas, that is, waves under the influence of local wind, waves produce and modulate mixing in oceanic surface layer, modifying the surface fluxes (Andreas and Emanuel 2001; Mellor and Blumberg 2004). The exchange of momentum, mass, and heat across the air-sea interface influences global and regional weather and climate (Trenberth et al. 2007; Oey et al. 2013; Li et al. 2017), small-scale winds (Wallace et al. 1989; Chelton et al. 2004; Oey et al. 2015), storm tracks (Nakamura et al. 2004; Huang and Oey 2019a), cyclone intensification (Zhang and Oey 2019a), ecosystem and fisheries (Oey et al. 2014, 2018), and others. Open-ocean waves can traverse long distances as swells, that

is, surface waves that outrun their generating wind. In the open ocean, swells can transfer momentum upward into the marine boundary layer (Harris 1966; Grachev and Fairall 2001; Ardhuin et al. 2009). When dissipated across shallow seas near the ocean's continental perimeter (Komen et al. 1994; Wunsch and Ferrari 2004), waves contribute in altering the local morphology (Hyndman and Hyndman 2010); influencing the regional ecosystem (Rogers et al. 2016); creating hazardous conditions for ships, civilians, and infrastructures (Salamon et al. 2017); breaking up ice shelf and accelerating sea ice loss (Massom et al. 2018); and others. Knowledge of ocean surface waves is thus essential in many applications and in improving our understanding of the climate system and interaction between various components of the planetary ecosphere (Möller 2010).

In conjunction with global warming and sea level rise, there is interest in using observations to examine long-term (longer than, say, two or more decades) changes of wind and wave in the global ocean, and their influence near the coast. Gulev and Hasse (1999) used ship data

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and found an increase in the significant wave height [SWH; $= H_s = 4E^{1/2}$, where E is the total energy of the wave field (Longuet-Higgins 1952)] from 1964 to 1993 over most of the North Atlantic Ocean except the western and central subtropics. Kushnir et al. (1997) showed that the increased SWH may be related to the positive phase of the North Atlantic Oscillation (see also Cox and Swail 2001; Fan et al. 2012). Allan and Komar (2000) used buoy data along the U.S. West Coast and found that wave trends there are significantly affected by shifts in storm tracks caused by the changing phase of El Niño–Southern Oscillation. Young et al. (2011) analyzed trends of global ocean wind speed and wave height from 1991 to 2008 and 1985 to 2008, respectively, on a $2^\circ \times 2^\circ$ grid. They found generally increasing trends of wind speed (the “10-m wind”) but less significant trends in the SWH. In the Southern Ocean, there appears to be a causal relationship between increasing trends of wind speed and wave height. The relationship in the Northern Hemisphere is unclear; the authors pointed out the difficulty of distinguishing locally generated wind seas and remotely generated swells. Young and Ribal (2019) extended the wind and wave trend analyses using a longer dataset, from 1985 to 2018, on the same $2^\circ \times 2^\circ$ grid. They found significantly negative SWH trend in the North Pacific that is inconsistent with the unclear (slightly positive) wind speed trend. There are also significant differences between the two studies in the wind speed trends over the western equatorial Pacific. Here, significantly negative wind speed trend extends into the Maritime Continent and the eastern Indian Ocean in Young and Ribal (2019), consistent with Huang and Oey (2019b); however, the wind speed trend is slightly positive and insignificant in Young et al. (2011).

This study examines trends of global wind, wave and coastal wave setup from 1993 to 2015. The first goal is to use (near-)global $1^\circ \times 1^\circ$ wave and $1/4^\circ \times 1/4^\circ$ wind resolution, and a common time period for both variables to compute the corresponding trends and then, by also estimating the wave age, to more completely explain and discover new things about the spatially variable wind and wave trends in different parts of the global ocean. The resolutions we use are higher than the $2^\circ \times 2^\circ$ global data used in Young et al. (2011) and Young and Ribal (2019), and allow improved representations of wind and wave in marginal and coastal seas. The second goal of our study is to use the above data to assess how long-term trends of open-ocean wind and wave affect near-coast wave “setup” (Longuet-Higgins and Stewart 1964), and how the latter in turn may modify the secular trends of relative sea level at tide gauge stations around the globe. Accelerated global sea level rise is observed

in recent decades and is projected for the next century (Trenberth et al. 2007; Hay et al. 2015). Knowledge of how wave setup near the coast may be modulated by changes in open-ocean wind and wave climate is of societal interest. Along populated coastlines where increasing trends of (relative) sea level are strong, for example, the U.S. East Coast (Mulkern 2017; Piecuch et al. 2018), South Asia, and others (see below), a concurrent rising trend in wave setup can potentially pose more dire consequences to coastal residents and infrastructures, especially in the event of high tides and intense storms (Oey and Chou 2016).

The remainder of the paper is organized as follows. Section 2 describes the data and method used. We present the results in section 3, and summary and discussion in section 4.

2. Data and method

a. SWH

We use the near-global (80°S to 80°N) along-track satellite SWH data (from [ftp://ftp.ifremer.fr/ifremer/cersat/products/swath/altimeters/waves/](http://ftp.ifremer.fr/ifremer/cersat/products/swath/altimeters/waves/)) for the period 1 January 1993 to 31 December 2015 to estimate SWH trends. The data are monthly in order that sufficient number of satellite track data can be collected and averaged onto $1^\circ \times 1^\circ$ near-global grid. Grids with missing data were filled using a two-dimensional Gaussian filter; they represent about 1.2% of the total data. Neither smoothing nor interpolation was applied. Other details including validation against buoy data are given in Lin et al. (2019), and are not repeated here.¹

b. Surface (10 m) wind speed and wind power

The Cross-Calibrated Multi-Platform, version 2 (CCMPV2; <http://www.remss.com/measurements/ccmp>) (Atlas et al. 2009; Wentz et al. 2016), wind at $1/4^\circ \times 1/4^\circ$ spatial resolution and 6-h temporal resolution from 78.375°S to 78.375°N and from July 1987 to present are available, although we only use the data from 1 January 1993 to 31 December 2015 to coincide with the SWH data. The CCMPV2 wind underestimates strong winds and was therefore corrected by incorporating cyclone winds. Detailed descriptions are given in Zhang and Oey (2019a,b), and are therefore not repeated here;

¹ In Lin et al. (2019), we misstated that the SWH data were monthly *averaged* instead of simply monthly and that the Gaussian filter could smooth the data instead of being used to simply fill the missing grids.

the cyclone-corrected data are referred to as CCMPV2-C and are freely available (see link in acknowledgments).

The frequency-integrated rate of wind energy input into surface waves is proportional to wind power (minus dissipation) (Hwang and Sletten 2008; Mellor et al. 2008; Donelan et al. 2012; Hwang and Walsh 2016). In addition to wind speed, we also use wind power to examine the potential connection between wind and wave (Lin et al. 2019). The wind power is estimated as $\rho_a C_d V^3$, where $\rho_a = 1.23 \text{ kg m}^{-3}$ is the air density, V is the 10-m wind speed in m s^{-1} , and C_d is the wind speed-dependent drag coefficient based on a formula (see Oey et al. 2006, 2007) that imposes the high wind speed limit of Powell et al. (2003). Wind speed and power were calculated using the 6-hourly data and then daily averaged to calculate trends.

As a check, we compare the wind speed trend calculated using the present data with Young et al. (2011), for the same period from 1991 to 2008. In comparing our calculated trend with theirs, wind speed is the only variable with the common period that can be compared. The result is shown in Fig. A1 (top), which we compare with Young et al.'s Fig. 1 (top). There is general agreement between the two trends, which show mostly positive trends with pockets of negative trends. However, because the present data have higher spatial ($1/4^\circ \times 1/4^\circ$ vs $2^\circ \times 2^\circ$) and temporal (daily vs monthly) resolutions, Fig. A1 shows much more distinct areas of statistically significant trends, of both signs, as well as clearer trends in coastal regions that are better resolved. For example, across the central North Pacific 150°E – 150°W and 30° – 55°N , Fig. A1 shows significant negative wind speed trend compared with insignificant, weak negative trend in Young et al. As a further check, Fig. A1 also shows trends calculated using two other daily datasets: ECMWF (middle) and NCEP (bottom). The above negative trend over the central North Pacific also appears in both data. However, over the global ocean, both ECMWF and NCEP wind speed trends show more negative values than Young et al. and our data.

c. The inverse wave age

We estimate the inverse wave age, ω_n , derived in Zhang and Oey (2019a) using the Hwang and Walsh (2016) wind-wave triplets formulation for the peak phase speed C_p :

$$\omega_n = V/C_p, \quad C_p = 9.2918 H_s^{0.5848} / V^{0.1696} (\text{m s}^{-1}), \quad (1)$$

where the constant 9.2918 involves the Earth gravity g and has a dimension of $(\text{m s}^{-2})^{0.5848}$. The derivation of C_p made use of a wave-growth function, and the formula is strictly consistent only with younger waves, that is,

wind seas, for which ω_n is near one or larger. On the other hand, we found that when using the observed H_s from satellite altimetry, the spatial pattern of ω_n obtained from (1) compares well with the ω_n -pattern calculated directly using the peak phase speed $C_{p\text{Model}}$ from a 23-yr (1993–2015) WAVEWATCH III model output (Lin et al. 2019) in the Pacific (Fig. A2); the corresponding regression $r^2 = 0.74$ and slope = 1.13. The good agreement is perhaps fortuitous but allows an empirical delineation of potential regions of dominance of wind seas or/and swells.

d. Relative sea level (η_{RSL}) and absolute sea level (η_{ASL})

Relative sea level (RSL) is defined as the distance between Earth's crust and sea surface, that is, it is referenced to the local solid surface of Earth. In contrast to satellite altimeter, which measures absolute sea level (η_{ASL}) referenced to Earth's center of mass and is available for a relatively short time since the 1990s (Mitrovica et al. 2001; Nerem and Mitchum 2001; Clark et al. 2002; Douglas and Peltier 2002), RSL is recorded by coastal (or island) tide gauges, many dating back to the 1860–1930s. Secular trend of relative sea level, $d\eta_{\text{RSL}}/dt$, is therefore the algebraic sum of changes in vertical movement of the Earth crust, dh_{EC}/dt (positive upward), and absolute sea level $d\eta_{\text{ASL}}/dt$ (Farrell and Clark 1976; Milne et al. 2001):

$$d\eta_{\text{RSL}}/dt = -dh_{\text{EC}}/dt + d\eta_{\text{ASL}}/dt + \varepsilon, \quad (2)$$

where ε includes effects of geoid and rotational feedback (e.g., Milne and Mitrovica 1998; Mound and Mitrovica 1998; Mitrovica et al. 2001; Tamisiea et al. 2001; Peltier 2004). For $d\eta_{\text{ASL}}/dt$, in addition to a global long-term rise due to, for example, seawater expansion and addition of ocean water mass by land-ice and glacier melting because of ocean warming, it can be generalized to locally also include changes caused by ocean dynamics at interannual and interdecadal time scales (Merrifield and Maltrud 2011; Goddard et al. 2015; Swapna et al. 2017; Domingues et al. 2018; Volkov et al. 2019). We use absolute sea level data (from <https://www.aviso.altimetry.fr/en/data.html>) and relative sea level from tide gauge data provided by the National Oceanic and Atmospheric Administration (<https://tidesandcurrents.noaa.gov/sltrends/sltrends.html>) and the Permanent Service for Mean Sea Level (<https://www.psmsl.org/>) at coastal stations around the globe. The tide gauge data were monthly averaged to remove high-frequency fluctuations and, due to their long records, the trends approximate long-term changes in “still water level,” in which variation due to waves and ocean dynamics are filtered.

e. Wave setup (η_{ws})

Surface gravity waves produce “wave setup” when open-ocean waves run up a sloping beach and break (Longuet-Higgins and Stewart 1964). The loss of wave energy leads to an onshore decrease in the wave radiation stress S_{xx} , that is, $dS_{xx}/dx < 0$ (where x is directed normal to the shoreline, positive onshore), which, in order to balance the excess momentum flux, requires an onshore increase in sea level, that is, wave setup (η_{ws}): $d\eta_{ws}/dx = -(\rho gh)^{-1}dS_{xx}/dx$, h = water depth and ρ = seawater density. We relate the wave setup near shore to open-ocean significant wave height H_s from satellite and peak wavelength λ_{po} using the empirical formula of Stockdon et al. (2006):

$$\eta_{ws} = 0.385 \beta (\lambda_{po} H_{so})^{1/2}, \quad (3)$$

where β is the beach slope, which is taken to be a constant, = 0.05; the same formula was used by Ruggiero (2013), Serafin et al. (2017) and Melet et al. (2018). The λ_{po} is related to the peak phase speed C_{po} using the deep-water dispersion relation:

$$\lambda_{po} = 2\pi C_{po}^2/g. \quad (4)$$

This equation is used over deep water only using satellite data, for open-ocean waves/swells that propagate to the edge of the continental shelf where the water depth exceeds 200–500 m, say.

In (4), we may approximate $C_{po} \approx C_{p(1)}$ obtained from formula (1), which, however, is strictly valid only for wind seas. To correct for swells, we regress the inverse wave age ω_{nWW3} calculated directly from a 23-yr (1993–2015) WAVEWATCH III (WW3) model that included both wind seas and swells and that yielded results in good agreements with buoy and satellite observations (Lin et al. 2019), against the $\omega_{n(1)}(H_{sWW3}; V)$ obtained from (1) using the model H_{sWW3} . The result is

$$\omega_{nWW3} = 0.782\omega_{n(1)}(H_{sWW3}; V) + 0.084 \quad (r^2 = 0.67, p < 10^{-3}). \quad (5)$$

In most region, the inverse wave age $\omega_n \approx 0.385$ (Fig. A2 lower-left panel), and (5) then gives $\omega_{nWW3} < \omega_{n(1)}$, as it should to correct for swell effects. We assume that this model-derived statistical relation (5) between the true ω_n , that is, the left side, and the approximate ω_n from formula (1), that is, the right side, is valid also for observations. The closeness of modeled and observed ω_n , noted previously in Fig. A2, justifies the assumption. Thus,

$$C_{po} = V/(0.782V/C_{p(1)} + 0.084), \quad (6)$$

where the $C_{p(1)}$ is calculated from (1) using the observed H_s from satellite. Substituting (6) into (4) gives λ_{po} , and the η_{ws} is then calculated from (3). In general, the correction is only significant at stations near the eastern boundary of the ocean basin; otherwise, $C_{po} \approx C_{p(1)}$ using (1) provides a good approximation.

The use of (3) for wave setup is not without controversy—see, for example, Aucan et al. (2019) and Melet et al. (2019). Nonetheless, the formula provides a simple estimate. Substituting the above numbers, using (1) and (4) for λ_{po} , and noting that the wind speed dependency in (1) is weak, we obtain $\eta_{ws} \approx 0.17 H_s$, which agrees with the formula used by Vousdoukas et al. (2017, 2018): $\eta_{ws} = 0.2 H_s$. The use of (3) in the present study may therefore be regarded as providing a conservative, low estimate of the wave setup.

f. Trends, regressions, and significance

Linear trends and regressions are used in all the analyses (Bendat and Piersol 1986; Press et al. 1992). They are considered significant only if the corresponding p value ≤ 0.05 (i.e., 95% confidence level). Least squares regression can be sensitive to outliers. We therefore also rechecked the trends as the “Sen slopes” using the Theil–Sen estimator (Theil 1950a,b,c; Sen 1968), used also by Young et al. (2011) and Young and Ribal (2019). Applied to our data, the two methods give virtually identical results.

3. Results

a. Seasonal climatology

Seasonal variability of wave and wind were previously examined by Young (1999) for the period 1990–99. We reexamine seasonal variability here using our data, as a prelude to presenting long-term trends, to assess potential regions of dominance of wind seas or/and swells. Figure 1 shows seasonal maps of SWH (shading) and wind (vectors). The months of highest SWH are during the winter season in both hemispheres. The SWH and wind are larger at higher latitudes in the winter seasons, exceeding 5 m and 10 m s^{-1} , respectively, in both the Southern Ocean and subpolar North Pacific and Atlantic Oceans. Higher SWH in northern Pacific and Atlantic Oceans are related to boreal winter’s cyclonic low pressure systems that generate strong westerly winds (Fig. 1a). In austral winter (Fig. 1c), largest SWH and wind appear in the Indian Ocean sector of the Southern Ocean due to the strong westerly wind jet. Figure 1c also shows high SWH in the Arabian Sea,

FIG. 1. Climatological SWH (color shading) and wind velocity (vectors) in (a) DJF, (b) MAM, (c) JJA, and (d) SON from January 1993 to December 2015. The SWH data are based on satellite altimetry and the wind is from the CCMPV2-C data—see text.

caused by the strong Indian summer monsoon wind. These results generally agree with those presented by Young (1999; see his Figs. 1a,b).

Figures 2a and 2b show months of maximum SWH and wind power for the global ocean. Peak waves (Fig. 2a) generally occur in winter months in both hemispheres and are generally nearly in phase with, or slightly lag, the months of peak winds over roughly half

FIG. 2. (a) Calendar month of maximum SWH at each 1° × 1° grid cell indicated by color shading. (b) As in (a), but for wind power = $\rho_{\text{air}} C_D (\text{wind speed})^3$, $\rho_{\text{air}} = 1.23 \text{ kg m}^{-3}$, and wind speed in m s^{-1} . The drag coefficient C_D was based on Oey et al. (2006, 2007) formula, which imposes a high wind speed limit (Powell et al. 2003). (c) Area-averaged SWH (m) and wind power (W m^{-2}) for Northern and Southern Hemispheres. In (a), stippling indicates where peak SWH and wind power occur in the same month.

of the grid points (Fig. 2b). In Fig. 2a, stippling indicates grids where peak SWH and wind power occur in the same month. They cover 48% of the global ocean points and are regions where the waves are generally “not too old”; the inverse wave age $\omega_n = (\text{wind speed})/(\text{phase speed})$ is approximately 0.65 or greater (detailed below; Fig. 3). In winter, they cover most prominently north of about 30°N in the North Pacific and Atlantic, in the Southern Ocean, as well as over most shelves and marginal seas: the Nordic seas, the North/Irish Sea, the Mediterranean Sea, the Arabian Sea, Bay of Bengal, along parts of the North and South American east coasts, and the East Asian seas. Smaller-scale, coastal wind features, such as the Tehuantepec (~16°N, 95°W) and Papagayo (~12°N, 86°W) jets (Chelton et al. 2000),

FIG. 3. The winter-mean (December, January, and February in Northern Hemisphere and June, July, and August in Southern Hemisphere), inverse wave age (ω_n) estimated from (1) using the observed 10-m wind speed V and significant wave height H_s data from 1993 to 2015. Winter mean is shown because of the correspondingly strong wind and wave that dominate their trends.

and the low-level coastal jet off Peru ($\sim 12^\circ\text{S}$, 78°W) (Aguirre et al. 2017), which peak in the respective hemispheric winter, are also in phase with the corresponding wind seas. Because of the monthly resolution used, the correspondence with regions where $\omega_n \geq 0.65$ is only approximate. For examples: in subtropical North and South Atlantic between the $\pm 20^\circ$ and $\pm 40^\circ$ latitudes where the peak wave and wind months coincide (there are some dots in Fig. 2a) but ω_n is less than 0.65, and in the Southern Ocean south of $\sim 50^\circ\text{S}$ between 160°E and 120°W where there are no dots in Fig. 2a but $\omega_n > 0.65$.

The remaining 52% of the ocean grids are where peaks of SWH and wind power occur in different months and waves are generally older ($\omega_n \leq 0.65$). They are generally in the south Indian Ocean, the southeastern African coast including the Mozambique Channel, near the equator, and the eastern boundary of the ocean basin: U.S./Mexico west coast, Columbia/Peru/Chile coast, and along most of the West African coast. For examples, coastal winds off the coasts of California ($\sim 30^\circ\text{N}$, 120°W), Namibia ($\sim 30^\circ\text{S}$, 15°E), and Chile ($\sim 30^\circ\text{S}$, 15°E) peak in their respective hemispheric summer, and are out of phase with the peaks in SWH in winter due to the presence of strong swells (Semedo et al. 2011; Aguirre et al. 2017). A notable out-of-phase region that will be revisited later is seen in the subtropical North Pacific between 18° and 28°N ; here the inverse wave age ω_n drops below approximately 0.5 (Fig. 3) indicating the dominance of swells. Other exceptional regions where peaks of SWH and wind power are in different months also occur east of Taiwan, southwestern Mexico, Madagascar, and northwestern Australia where strong tropical cyclones dominate and give rise to the summer–fall peak in the wind power, while on average the SWH peak is in winter.

Figure 2c shows monthly hemispheric averages of SWH and wind power. The Southern Hemispheric SWH is larger than the Northern Hemispheric SWH for all months except December, January, and February. The wind power shows no such biased asymmetry, and the Northern and Southern Hemispheric wind powers are nearly antisymmetrical with season: the Northern Hemispheric wind power is greater than the Southern Hemispheric wind power for 5 months from November to March, and the Southern Hemispheric wind power is greater than the Northern Hemispheric wind power also for 5 months, but from April to September; both hemispheric wind powers have nearly equal amplitude in October. The absence of blocking continents in the Southern Ocean allow waves to develop into greater amplitudes despite similar magnitudes of averaged wind in both hemispheres.

b. Inverse wave age ω_n

The above-identified regions where wave is either nearly in phase with wind power or where wave and wind power bear no obvious connection correspond in general with regions dominated by either younger or older waves, respectively, that is, either wind seas or swells. To demonstrate this, Fig. 3 shows ω_n over the global ocean, calculated from (1) using 10-m wind speed V from the CCMPV2-C data and H_s from the gridded satellite data. Regions with larger ω_n (approximately > 0.65) are where the wave field is likely dominated by younger waves, mostly in the Southern Ocean and marginal seas, and on the western side of the ocean basins; they generally coincide with the aforementioned areas in Figs. 2a and 2b where wave is seasonally in phase with wind power. On the other hand, regions with smaller ω_n (< 0.65) are mostly on the eastern side of the ocean basins, near the equator and in most of the Indian Ocean where, as pointed out before, seasonal wave and wind power have no obvious phase relationship.

c. Wave and wind trends

Figure 4a shows the SWH trend. Increasing SWH trend is generally seen throughout the tropical oceans, from 20°S to 20°N , which include some of the world's most populated and vulnerable regions: coastal Southeast Asia, India, Bangladesh, and Myanmar, as well as the South American and African coasts including western Madagascar and the Gulf of Aden, and the coastal areas of the Gulf of Mexico, the Caribbean Sea, and the Antilles. Outside the tropics, increasing SWH trend is seen in many marginal seas in the Northern Hemisphere: the North Sea and the Baltic Sea, the Mediterranean Sea, the Persian Gulf, the East China–Yellow Seas, the Japan Sea, and the Sea of Okhotsk, as

FIG. 4. Trends of (a) significant wave height SWH and (b) wind speed; legends show the units. Dots indicate where p value ≤ 0.05 (95% confidence). (c) Red (green) indicates where both SWH and wind speed trends are positive (negative) labeled “+InPhase” (negative labeled “-InPhase”), and gold (blue) labeled “+OutOfPhase” (blue labeled “-OutOfPhase”) indicates where SWH trend is positive (negative) but wind speed trend is either negative (positive) or insignificant with p value > 0.05 .

well as along the North American east coast and southern Greenland. In the Southern Hemisphere, increasing SWH trend is seen around the southern African and American continents, and in the Pacific/Atlantic sectors of the Southern Ocean poleward of approximately the 60°S latitude. In contrast to these increasing SWH trends, which predominantly occur in the tropics and the coastal seas, decreasing SWH trends mostly occur in open oceans in the subtropical and subpolar regions, generally over three areas: the central to eastern North and South Pacific Oceans and the south Indian Ocean.

Figure 4b shows the wind speed trend; the wind power trend shows similar patterns (Fig. A3b). Regions where both wind and SWH trends have the same signs generally coincide, but it is not always so. To clearly distinguish the

different patterns, we use red- and green-colored grid points to indicate where the trends of SWH and wind are of the same signs: red if both trends are increasing, labeled “+InPhase,” and green if both trends are decreasing, labeled “-InPhase” (Figs. 4c and A3c). On the other hand, the grids are colored gold and blue where the SWH and wind trends are of opposite signs: gold if the SWH trend is increasing and the wind trend is either decreasing or insignificant, labeled “+OutOfPhase,” and blue if the SWH trend is decreasing while the wind trend is either increasing or insignificant, labeled “-OutOfPhase.”

Most of the aforementioned areas of increasing SWH trend in the tropics and higher-latitude marginal seas, as well as near the southern tip of South America, where the wave is predominantly of the younger, wind-sea type, are seen to be also areas of increasing wind trend (red grids: +InPhase). In gold-colored areas in parts of the Gulf of Mexico and the Caribbean Sea, north Australian coast, and southwestern South China Sea, the wind trend is increasing but is statistically insignificant.

Decreasing SWH trend is seen in the Indo-Pacific and subtropical South Pacific sectors of the Southern Ocean, where, however, the wind speed trend is predominantly increasing (blue-colored grids). The increasing wind trend is consistent with the increasing trend of the southern annular mode since ~ 1990 (Fig. A4a) (Marshall 2003; Swart et al. 2015; Dätwyler et al. 2018). The opposite trends of SWH and wind speed suggest then that waves in this region may not be wholly driven directly by the local wind. Figure 3 indicates that the waves there are of mixed type consisting of some slow-moving waves or young wind seas with $\omega_n \geq 0.65$, and faster-moving swells $\omega_n \leq 0.65$.

Decreasing SWH is found also in subtropical central to eastern North Pacific Ocean: 160°E–120°W, 18°–50°N. The waves here are also of the mixed type. In the middle “green zone” (Fig. 4c, green-colored grids, roughly north of $\sim 30^\circ\text{N}$), the decreasing SWH trend coincides with decreasing wind trend due to anomalous easterly over the North Pacific (west of $\sim 120^\circ\text{W}$) associated with the “cool” pattern of the Pacific decadal oscillation since the late 1990s (Fig. A4b) (e.g., Newman et al. 2016). However, at many locations surrounding the “green zone,” in particular those to its south and east, the decreasing wind trend is insignificant (Fig. 4c blue-colored grids; roughly 18°–40°N and east of the date line).

d. Trends of relative sea level and wave setup near the coast

Approximately 10% of the world’s population, around 600 million, lives within coastal zones less than 10 m above the local sea level (McGranahan et al. 2007). Long-term (secular) trend of local water level modulated by

FIG. 5. Secular trends of (a) RSL at tide gauge stations around the globe with data length 50 years and longer, and (b) 23-yr, 1993–2015 trends of wave setup “ η_{ws} ” and (c) $RSL + \eta_{ws}$. See Fig. A6 for plots of coastal seas of Europe, Mediterranean, eastern United States, and East Asia where strong increasing trends are seen.

regional trends of storm surge and surface wave intensity is therefore of immense practical and societal importance and relevant. Trend of storm surge depends on intensity and movement of cyclones and is the topic of many studies (see Oey and Chou 2016 for a summary). Here we focus on effects of waves.

Warming climate has caused global absolute sea level (η_{ASL}) to steadily rise in the past several decades, due to seawater expansion and addition of ocean water mass by land-ice and glacier melting (Fig. A5) (Domingues et al. 2008; Leuliette and Willis 2011). Locally, however, the relevant water level is the relative sea level (η_{RSL}) referenced to the local solid surface of Earth, and therefore depends on the vertical movement of the Earth crust, dh_{EC}/dt (positive upward) (see section 2, data and method). For dh_{EC}/dt , the most recent significant Earth crust movement began following the deglaciation after

FIG. A1. Comparison of wind speed trends from 1991 to 2008, the same period as in Young et al.'s (2011) wind speed trend (their Fig. 1 top), using: (top) CCMPV2-C (this study), (middle) ECMWF, and (bottom) NCEP.

the last glacial maximum some 21 000 years ago, and it continues today, albeit at an exponentially slower rate. During this glacial isostatic adjustment (Mitrovica and Peltier 1993), the solid Earth rebounds (i.e., uplifts, $dh_{EC}/dt > 0$) in the “near field” where ice sheets and glaciers once existed including much of northern Europe, Eurasia, and North America, it collapses (i.e., sinks, $dh_{EC}/dt < 0$) in the peripheral regions, and it has a more complicated, second-order response in the “far field” (Milne and Mitrovica 1998; Milne and Shennan 2013). Prominent uplift occurs in northern Europe (Simon et al. 2018, their Fig. 1) including the Gulf of Bothnia in northern Baltic Sea (Ekman 1996; Milne et al. 2001) and Norway (Romundset et al. 2010; Simpson et al. 2015). Uplift also occurs in northeastern Canada: the Hudson and James Bays (Mitrovica and Peltier 1995; Tsuji et al. 2009), and in southern Alaska and the northwestern United States and Canada (Hicks

FIG. A2. Comparison of estimated, observed inverse wave age (ω_n) from (1) (top left) with the ω_n directly calculated from the Lin et al. (2019) WAVEWATCH III model output (bottom left) for the Pacific Ocean, averaged from 1993 to 2015 for hemispheric winter months DJF (JJA) Northern (Southern) Hemisphere. (right) Regression of model vs observed ω_n . Color indicates data density per 0.02×0.02 ω_n -bin, scale normalized by a maximum density of 210. Red line is the regression line and the corresponding equation, the r^2 and p value are shown in the top-left legend. For reference, the 45° ("perfect") line is shown as the black line. The regression line (including r^2 and p value) is nearly entirely determined by the high-data-density points, density >0.1 (the red-colored area), rather than the low-density points (faint red and gray colored areas). Where the red-colored area meets the "perfect" black line, near $\omega_n \approx 0.6$ – 0.7 , the observed ω_n estimated from the wave-growth function agrees with the direct modeled ω_n , and $\omega_n = 0.6$ – 0.7 is taken as the approximate transition value above (below) which the observed sea state is considered to consist of mostly younger (older) waves.

and Shofnos 1965; Larsen et al. 2004; Yousefi et al. 2018; Clark et al. 2019). We use tide gauge data to calculate the secular trends of relative sea level, $d\eta_{\text{RSL}}/dt$ [see (2)], at coastal stations around the globe (Fig. 5a).

Despite the global absolute sea level rise $d\eta_{\text{ASL}}/dt > 0$ due to warming, Fig. 5a shows strong falling relative sea levels at the above-mentioned sites of significant post-glacial rebound where trends are dominated by land uplift: northern Europe, northeastern Canada, and northwestern

America. There is also falling RSL trend along the Pacific side of the South American continent, which is, however, related to uplift caused by active seismic activity (Marquardt et al. 2004; Bookhagen et al. 2006; Melnick et al. 2009; Isla and Angulo 2016; Rodríguez Tribaldos et al. 2017). At other stations, rising trends are seen, contributed by both rising absolute sea level due to global warming and, at some sites, by sinking land in the peripheral of deglaciation area, for example, in the

FIG. A3. Trends of (a) significant wave height SWH and (b) wind power; legends show the units. (a) Same as Fig. 4a, but that all grid points are color-filled and dots show significant points (95% confidence); only significant points are shown in (b). (c) Red (green) indicates where both SWH and wind power trends are positive labeled “+InPhase” (negative labeled “-InPhase”), and gold labeled “+OutOfPhase” (blue labeled “-OutOfPhase”) indicates where SWH trend is positive (negative) but wind power trend is either negative (positive) or insignificant with p value > 0.05 .

mid-Atlantic states of the eastern United States (Maryland, Virginia, and North Carolina) (Peltier and Tushingham 1991; Davis and Mitrovica 1996; Engelhart et al. 2009; Piecuch et al. 2018), as well as by local land subsidence due to, for example, groundwater usage (e.g., New Orleans, Bangkok; Milliman and Haq 1996; Nutalaya et al. 1996).

We estimate how local, secular RSL trends (Fig. 5a) may be modulated by trends of wave setup (η_{ws}) forced by the regional open-ocean wave climate in recent decades since 1993. The η_{ws} is calculated using (3) (see section 2, data and method), and its trends are shown in Fig. 5b at the tide gauge stations, many of which are located in sheltered bays and/or inlets where wave effects are weak. The η_{ws} is therefore interpreted as wave setup over the nearby coastline along which the

FIG. A4. (top) SAM index from Marshall (2003) (<https://legacy.bas.ac.uk/met/gjma/sam.html>), and (bottom) Pacific decadal oscillation (PDO) index (<https://www.ncdc.noaa.gov/teleconnections/pdo/>). Bars are monthly values. Thick line is 60-month running mean, showing increasing (decreasing) SAM (PDO) since ~mid-1980s. PDO trend lines are shown for different periods, slopes, r^2 , and p values indicated in legends; in particular, the 3 periods: 1985–2018 [aqua, Young and Ribal (2019)], 1993–2015 (green, this study), and 1991–2008 [pink, Young et al. (2011), wind speed trend] show increasingly more negative or “cooler” PDO phase. The whole-period trend, 1955–2018 (black), is included for reference, showing zero trend.

corresponding secular RSL trend may be estimated using the tide gauge measurement. Increasing η_{ws} trends (Fig. 5b) mimic closely the H_s trends, but weaker, since $\eta_{ws} \sim H_s/V^{1/5}$ and the wind speed (or wind power) trends are also generally increasing at the same coastal stations (Fig. A6). Nonetheless, the η_{ws} trends (Fig. 5b) are increasing at many of the stations where the RSL trends are also increasing, for example, the North and Irish Seas, the Mediterranean Sea, the East Asian seas, India, and eastern United States. The rising relative sea level trends are therefore amplified by increasing wave setup trends along these populated coasts, potentially making them more vulnerable to floods (Fig. 5c; see Fig. A7 for enlarged plots in the above-mentioned regions). In contrast, decreasing η_{ws} trends are seen at stations in the central Pacific and along the U.S. West Coast.

4. Summary and discussion

This study calculates trends of sea surface wave, wind and coastal wave setup in the global ocean, from 1993 to 2015, and provides explanations of their interconnection

FIG. A5. Absolute sea level trend from 1993 to 2015 based on satellite altimetry. Color indicates trend significant at the 95% confidence level; the scale is $\pm 0.1 \text{ m (10 yr)}^{-1}$ ($= \pm 10 \text{ mm yr}^{-1}$). Data are <https://www.aviso.altimetry.fr/en/data.html>; see supporting information in Sun et al. (2017) and Oey et al. (2018) for details of the data processing. The global average of $3.4 \pm 0.3 \text{ mm yr}^{-1}$ is consistent with the value of about $3.3 \pm 0.3 \text{ mm yr}^{-1}$ reported in the literature (Bindoff et al. 2007; Hay et al. 2015).

with the aid of a wave model and some semiempirical relationships. In general, increasing wave and wind trends occur in regions dominated by younger waves, while decreasing wave trends unrelated (or statistically insignificantly related) to wind are found where older waves dominate. Increasing wave setup trends are found along many populated coastlines, including regions where the local infrastructure and economy are potentially more vulnerable to extreme events.

A complex, mixed pattern of wind-wave relationship is found over the central to eastern North Pacific. Here, the coexistence where SWH and wind trends appear to be related (Fig. 4c, green) and where they do not (Fig. 4c, blue) is interesting. Measurements in the Baltic Sea (Smedman et al. 1999, their Fig. 7) and during the San Clemente Ocean Probing Experiment (offshore of San Diego, California) (Grachev and Fairall 2001, their Fig. 3) indicate that the surface vertical momentum flux undergoes a rapid decrease as the wave state changes from young wind seas to older swells, near an empirical ω_n -transition range of approximately $0.8 \gtrsim \omega_n \gtrsim 0.5$. Using direct numerical simulation based on the Navier–Stokes equations, Sullivan et al. (2000, their Table 1 and Fig. 10b) showed that the rapid decrease in the surface vertical momentum flux is caused by a change of sign near $\omega_n \approx 1$, in the model, of the form stress or pressure drag due to waves. The form drag changes from being positive for young wind seas, which acts in concert with turbulent (and viscous) stresses to decelerate the wind, to negative for older swells, which causes a reversed, upward transfer of momentum from wave to wind, and therefore acts to reduce the total surface drag, or even to accelerate the wind in the direction of the swells (Harris 1966). Thus, “swell waves perform work on the

FIG. A6. Trends (1993–2015) of (a) wind speed V (dots indicate significance at 95% confidence level), and of (b) SWH H_s and (c) wave setup η_{ws} at tide gauge stations. The H_s trends are strongly increasing at many stations where V s are also increasing (e.g., North and Irish Seas, Mediterranean Sea, East Asian seas, India, and eastern United States). However, since $\eta_{ws} \sim H_s/V^{1/5}$, the increasing η_{ws} trends are more moderate.

overlying atmosphere because they propagate faster than the wind, producing a forward thrust on the flow” (Semedo et al. 2009). During winter in the aforementioned central to eastern North Pacific region, swells propagate southeastward, produced by powerful storms that traverse west to east across the region (Fig. A8). The ω_n decreases eastward and southward from a wind-sea state with $\omega_n \gtrsim 0.65$ north and west of the region, to a swell state with ω_n dropping below 0.5 south and east (Fig. 3). We posit that this ω_n -transition (i.e., ω_n changing from approximately 0.65 to 0.5 and smaller) is where the form drag decreases rapidly or even reverses sign. Thus, while the total surface drag retards the wind north and west and wind energy is transferred to the wave, it decreases rapidly south and east because of

FIG. A7. Enlarged trend plots of $RSL + \eta_{ws}$ (from Fig. 5) for coastal seas of Europe, Mediterranean, eastern United States, and East Asia where strong increasing trends of local relative sea level and wave setup are seen.

reduced or reversed form drag as the wind flows over the swell-dominated region; there, the wind experiences a nearly frictionless surface or is even driven by the swell field. This would result in SWH and wind speed being more significantly correlated (e.g., both have decreasing trends, Fig. 4c, green) in the north and west, while they become *less* significantly correlated (Fig. 4c, blue) in the south and east. In other words, younger waves contribute to further decelerate the wind in the “green zone,” tending to make the decreasing wind trend significant, while wind is decoupled from (or driven by) the swell field at the blue points, and wind trend can be insignificant or

increasing even as wave trend is decreasing (Fig. 4c, blue). The central North Pacific appears to be a fertile region for this ω_n transition. A similar ω_n -transition region also occurs in the south Indian Ocean (15° – 50° S). More focused observational and modeling studies may be carried out to further explore the phenomenon.

The 23-yr analysis period used in our study is relatively short, which means that the calculated trends are multidecadal “snapshots” rather than being truly long term. As mentioned previously, the wind speed trend is consistent with the negative trend of the Pacific decadal oscillation and positive trend of the southern annular

FIG. A8. Lin et al. (2019) WAVEWATCH III model. (top) Wave period (s; color with contours) and wind vectors during the passage of a cyclone west to east across the North Pacific on 25 Jan 2019; squares indicate buoy locations where model validations were conducted by Lin et al. (bottom) Peak wave vector with length representing peak wave period averaged for boreal winter from December through February, and from 1993 to 2015.

mode since the 1990s. Should these climate modes reverse, the global patterns of wind, wave and wave setup trends may be expected to also reverse, that is, the “warm–cool” colors of Figs. 4 and 5b would reverse, as it is unlikely that the global pattern of the wave age would fundamentally change. Such interdecadal reversal of the trend pattern at the global scale is practically important; it will be interesting to further investigate the phenomenon using longer (a few hundred or more years) data, say, from models.

Finally, we examine our results in comparison to those obtained by Young et al. (2011), Ruggiero (2013), and Young and Ribal (2019). The relative shortness of the time periods used in these trend calculations (including ours) explain most of the differences. The influence on wind and wave of El Niño–Southern Oscillation and other interannual/interdecadal climate signals is significant, particularly in the Pacific Ocean (Lin et al. 2019). The PDO index rises rapidly from its lowest negative value (since the 1950s) in ~ 2010 to a slightly positive value in ~ 2018 (Fig. A4), so that trend calculations with

data that end in ~ 2010 (Young et al. 2011; Ruggiero 2013), 2015 (this study), and 2018 (Young and Ribal 2019) can yield wind and wave trends that are different especially in the Pacific Ocean. For example, at buoys along the U.S. Pacific Northwest coast, Ruggiero (2013) found a rising wave setup trend, caused by rising wind and hence SWH trends along the Pacific Northwest coast due to the strong negative PDO pattern for the period that ends in ~ 2010 ; the PDO slope is $-0.69 (10 \text{ yr})^{-1}$ from 1991 to 2008 (Fig. A4). By contrast, we obtained a decreasing SHW trend (Fig. A3a) and hence also a wave setup trend (Fig. 5c) at stations along the U.S. West Coast for the period that ends in 2015 when the PDO slope is weaker $= -0.49 (10 \text{ yr})^{-1}$ from 1993 to 2015. For the Young and Ribal (2019) period from 1985 to 2018, the PDO slope weakens further to $-0.27 (10 \text{ yr})^{-1}$, resulting in weakly positive wind speed trend in the central North Pacific (see their Fig. 1A), compared to the significant negative trend we obtained (Fig. 4b). In the tropical Indo-Pacific, the wind speed trend displays an El Niño–like pattern of significantly negative trend over the western equatorial Pacific including the Maritime Continent (see their Fig. 1A), compared to the positive trend we obtained (Fig. 4b). It is interesting that over the central to eastern North Pacific, including the U.S. northwest coast, Young and Ribal (2019) obtained a significantly negative SWH trend (their Fig. 2A), which agrees well with our negative SHW trend (Fig. 4a). These negative SWH trends are consistent with the negative wind trend that we obtain (Fig. 4b), which we explained above in terms of how wind seas and swells can affect the surface form drag but are inconsistent with the slightly positive wind speed trend that Young and Ribal (2019) obtained. Further investigation is required.

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APPENDIX

Supporting Figures

Figures A1–A8 and captions provide further details of the analyses and results presented in the text.

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