The Redistribution of Air–Sea Momentum and Turbulent Kinetic Energy Fluxes by Ocean Surface Gravity Waves

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ABSTRACT: The momentum flux to the ocean interior is commonly assumed to be identical to the momentum flux lost from the atmosphere in traditional atmosphere, ocean, and coupled models. However, ocean surface gravity waves (hereafter waves) can alter the magnitude and direction of the ocean-side stress \( \tau_\text{oc} \) from the air-side stress \( \tau_\text{a} \). This is rarely considered in coupled climate and forecast models. Based on a 30-yr wave hindcast, the redistribution of the global wind stress and turbulent kinetic energy (TKE) flux by waves was investigated. Waves play a more important role in the windy oceans in middle and high latitudes than that in the oceans in the tropics (i.e., the central portion of the Pacific and Atlantic Oceans). On average, the relative difference between \( \tau_\text{a} \) and \( \tau_\text{oc} \) can be up to 6% in middle and high latitudes. The frequency of occurrence of \( \gamma_r > 9\% \) can be up to 10% in the windy extratropics. The directional difference between \( \tau_\text{a} \) and \( \tau_\text{oc} \) exceeds 3.5° in the middle and high latitudes 10% of the time. The difference between \( \tau_\text{a} \) and \( \tau_\text{oc} \) becomes more significant closer to the coasts of the continents due to strong wind gradients. The friction velocity-based approach overestimates (underestimates) the breaking-induced TKE flux in the tropics (middle and high latitudes). The findings presented in the current study show that coupled climate and Earth system models would clearly benefit from the inclusion of a wave model.

SIGNIFICANCE STATEMENT: The purpose of this study is to investigate the redistribution of the global wind stress and turbulent kinetic energy flux due to surface waves based on a 30-yr wave hindcast. The mean relative difference of the magnitude between the air-side and ocean-side stress is up to 6% with a 90th percentile of more than 9% in the windy extratropics. Due to strong wind gradients, the redistributive role of waves in the stress becomes more significant closer to coasts. The results indicate that we should consider the redistributive role of waves in the momentum and energy fluxes in climate and Earth system models since they are the key elements in the predictability of weather forecasting models and climate models.

KEYWORDS: Wind stress; Coupled models; Air-sea interaction; Wind waves; Sea state

1. Introduction

Air-sea interaction is critical for weather and climate through the exchange of momentum, energy, and mass transfer between the atmosphere and the ocean. The wind stress (momentum flux) is commonly estimated by bulk formulae based on the Monin–Obukhov similarity theory (MOST) developed from land-based measurements (Monin and Obukhov 1954; Högström 1988). However, the wind stress over the ocean differs significantly from that over land since the atmosphere and the ocean are a coupled and rapidly interacting dynamical system. Ocean surface gravity waves (hereafter waves) significantly alter the wind stress on the air side (Donelan et al. 1997; Wu et al. 2019a; Chen et al. 2020), as an air–sea interaction process, including under swell (Högström et al. 2015) and extreme wind speed (Donelan et al. 2004). Despite that, the influence of the oceanic wave field on the wind stress is not properly considered in current coupled atmosphere–ocean models in use for climate studies and weather forecasting (Wu et al. 2016). In this study, we focus on the redistributive role of waves on the global wind stress and turbulent kinetic energy (TKE) flux across the air–sea interface.

Winds generate waves when blowing over the ocean surface. Under fully developed waves, the momentum flux from the wind to the wave field is the same as the momentum flux released to the ocean interior (Pierson and Moskowitz 1964) from breaking waves. However, waves rarely reach full development, and waves in different stages of growth and decay are thus the norm over the open ocean. Under growing waves, the momentum flux to waves from the atmosphere is higher than that released to the ocean interior by wave breaking. Conversely, waves release more momentum flux and TKE to the ocean interior under decaying waves as the wind dies...
down, or as waves propagate into calm waters (Breivik et al. 2015). The sea state is thus almost always a mix of local wind-forced waves, i.e., wind sea, and waves arriving from afar, i.e., swell (Semedo et al. 2015). The wind stress at the air–sea interface is modulated by all waves present, regardless of their growth stage. For simplicity, the momentum flux from the atmosphere, i.e., the air-side stress (τ_a), is commonly assumed to be identical (both in magnitude and direction) to the momentum flux to the ocean interior, i.e., the ocean-side stress (τ_oc). However, this assumption is not always valid due to the buffering role of waves in the transfer of energy and momentum. In other words, ocean waves redistribute the momentum and energy fluxes both in time and space. It is estimated that 5% of the momentum flux lost from the atmosphere is advected by waves propagating out of the area of active wave generation (Melville 1996).

Previous studies have found that the normalized stress (β = |τ_oc|/|τ_a|) is in the range [0.8, 1.2], and can even exceed 1.8 under extreme conditions (Alari et al. 2016; Wu et al. 2019b). The normalized stress varies roughly in proportion with the inverse wave age (Wu et al. 2019b). To the best of our knowledge, Huang and Qiao (2021) were the first to simultaneously measure the air and ocean-side stresses. They found that the ocean-side stress can be an order of magnitude greater than the air-side stress. The impact of waves on the magnitude of the ocean-side and air-side stresses has been implemented in recent coupled models with a wave model component (Breivik et al. 2015; Staneva et al. 2017; Law Chune and Aouf 2018). It is found that the magnitude difference between τ_oc and τ_a can alter the regional and global ocean circulation (Alari et al. 2016; Law Chune and Aouf 2018; Breivik et al. 2015). Due to the impact of the sea state on the magnitude of the stress, the coastal upwelling can also be significantly altered since it is determined by the ocean-side stress, not the air-side stress (Wu et al. 2019b; Alari et al. 2016). In contrast to the stress magnitude, the directional difference between τ_oc and τ_a has rarely been considered in models. In extreme cases, the stress into the ocean and the wind direction can diverge widely. Qiao et al. (2021) report deviations up to 50° and Chen et al. (2018) even report stress opposing the wind direction. Due to strong gradients in the wind field and wave–bottom interaction, the difference between τ_oc and τ_a, in terms of magnitude and direction, is generally stronger in coastal areas.

Measurements have shown that wave breaking enhances the TKE dissipation rate in the near-surface layer (Tettay et al. 1996), though the exact dissipation profile is still a matter of debate (Esters et al. 2018). The enhancement of breaking-induced TKE dissipation is usually taken into account in ocean models by adding a TKE flux (Φ_oc) from the energy dissipated by breaking waves. It is commonly taken to be a function of the surface friction velocity when a wave model is not available (Craig and Banner 1994). This kind of parameterization captures well the breaking-induced TKE flux under fully developed waves, but is not adequate under growing and decaying sea states (Feddersen et al. 2007; Breivik et al. 2015). Previous studies have shown that the breaking-induced TKE flux can significantly affect the sea surface temperature (SST) and surface currents (Alari et al. 2016; Staneva et al. 2017). Thus, accurate estimation of the breaking-induced TKE flux can potentially be important for coupled climate simulations through the thermodynamic feedback between the ocean surface and the atmosphere (Sheldon and Czaja 2014; Fan et al. 2014).

The global distribution of wave height, wave power (flux of energy per unit crest length), wave period, Stokes drift, wave-induced stress, and wave age and their response to climate change have been widely investigated (Hanley et al. 2010; Semedo et al. 2011; Young et al. 2011; Fan et al. 2014; Sterl and Caires 2005; Hemer et al. 2010; Breivik et al. 2019; Morim et al. 2019; Chen et al. 2020; Bao et al. 2020). These are all important parameters for ocean engineering applications and climate simulations. However, the buffering role of waves on the wind stress (altering the ocean-side stress from the air-side stress in both magnitude and direction) on the global scale, as well as the breaking-induced TKE flux, have rarely been investigated. It is important for the climate community in general, and the climate model community in particular, to understand the role of waves in air–sea interactions and for the further development of climate models. In this study, the redistributive role of waves in the global stress and breaking-induced TKE flux is investigated with a 30-yr global wave hindcast. The remainder of the paper is organized as follows: section 2 describes the theory and the data used in the study, section 3 describes the results, and the results are discussed and summarized in sections 4 and 5, respectively.

2. Theory and data

a. Theory

The momentum conservation at the air–sea interface can be expressed as (ECMWF 2020)

\[
\tau_a = \tau_{oc} + \tau_w + \tau_{ds},
\]

where \(\tau_w\) is the momentum flux from the atmosphere to waves, and \(\tau_{ds}\) is the momentum flux released from waves to the ocean interior through wave breaking. When the 2D wave spectrum is available, \(\tau_{ds}\) is calculated by

\[
\tau_{ds} = \rho_w g \int_0^{2\pi} \int_0^\infty -\frac{k}{\omega} S_{ds} d\omega d\theta.
\]

The ocean-side stress is calculated as (Janssen 2012)

\[
\tau_{oc} = \tau_s - \rho_w g \int_0^{2\pi} \int_0^\infty -\frac{k}{\omega} (S_{in} + S_{ds}) d\omega d\theta,
\]

where \(\theta\) is the wave direction, \(\omega\) is the angular frequency, \(k\) is the wavenumber, \(g\) is the acceleration due to gravity, \(\rho_w\) is the water density, \(S_{ds}\) is the dissipation due to wave breaking, and \(S_{in}\) represents the wind input source term. The air-side stress at the air–sea interface is calculated as (Tsagarlici et al. 2010)

\[
\tau_a = \tau_{oc} + \tau_w.
\]
where $\tau_{w}$ is the viscous stress and the wave-induced stress is calculated by

$$\tau_{w} = \rho_{w} g \frac{c_{w}}{2} \int_{0}^{k} \frac{k}{\omega} S_{in} d\omega d\theta. \tag{5}$$

The breaking-induced TKE flux is estimated from the 2D wave spectrum as

$$\Phi_{oc} = -\rho_{w} g \frac{c_{w}}{2} \int_{0}^{k} S_{dt} d\omega d\theta, \tag{6}$$

which can differ significantly from that estimated based on $\Phi_{oc}' = -\alpha_{CB} \rho_{w} u_{w}^{*}$ ($\alpha_{CB} \approx 100$ and $u_{w}^{*}$ is the friction velocity in the ocean side), which is widely used in ocean models (Craig and Banner 1994).

In this study, the following parameters are used to quantify the redistributive role of waves on the stress and TKE:

- the normalized breaking-induced TKE
- the absolute relative difference between $\tau_{oc}$ and $\tau_{w}$: $\gamma_{\tau} = [(||\tau_{oc}||/||\tau_{w}||) - 1] \times 100\%$;
- the fraction of the wave-induced stress: $\beta_{w} = ||\tau_{w}||/||\tau_{w}||$;
- the misalignment angle between $\tau_{oc}$ and $\tau_{w}$: $\Theta_{oc}$;
- the normalized breaking-induced TKE flux $\beta_{TKE} = \Phi_{oc}/\Phi_{oc}'$; and
- the absolute relative difference between $\Phi_{oc}$ and $\Phi_{oc}'$: $\gamma_{\Phi} = [(||\Phi_{oc}||/||\Phi_{oc}'||) - 1] \times 100\%$.

**b. Data**

The Integrated Ocean Waves for Geophysical and other Applications (IOWAGA) wave hindcast from IFREMER (Institut Français de Recherche pour l’Exploitation de la Mer) for the period 1990–2019 (Rascle and Ardhuin 2013) was used in this study. The hindcast was generated using WAVEWATCH III (Tolman 2009) with forcing data from the Climate Forecast System Reanalysis (Saha et al. 2010). The simulation domain is from 78°S to 80°N and from 180° to 179.5°E in longitude. The horizontal resolution is 0.5°. The wave spectrum is discretized in 24 directions and 31 frequencies logarithmically spaced from 0.037 to 0.7 Hz. The magnitude of the air-side stress is estimated as $\tau_{a} = \rho_{a} u_{a}^{2}$. Here, the air-side friction velocity $u_{a}$ is determined from the neutral wind profile

$$U_{10} = \frac{u_{*}}{c_{L}} \ln \left( \frac{10}{z_{0}} \right) \tag{7}$$

where $c_{L}$ is the von Kármán constant, and $z_{0}$ is the surface roughness length,

$$z_{0} = \frac{u_{*}^{2}}{g} \cdot \tag{8}$$

The Charnock coefficient is calculated as

$$\alpha = \frac{\alpha_{0}}{\sqrt{1 - \tau_{w}/\tau_{0}}}, \tag{9}$$

where $\alpha_{0}$ is a tunable parameter. The direction of the air-side stress is assumed to be the same as the mean wind. The other parameterizations used in the simulations, as well as the verification of the simulations, are described by Ardhuin et al. (2010). The IOWAGA hindcast has 3-hourly temporal resolution, and we used it here to calculate the impact of the oceanic wave field on the momentum flux (stress) at the air-sea interface as well as the breaking-induced TKE flux. To avoid the influence of sea ice on the results, only data from ice-free grid points are used in the following analysis.

**3. Results**

**a. Cyclone case**

Yutu was the most powerful tropical cyclone worldwide in 2018 with a minimum central pressure of about 900 hPa and a maximum 10-min sustained wind speed of about 60 m s⁻¹. Here, Yutu is used as an extreme case to explore the buffering role of waves on wind stress and breaking-induced TKE flux. Figure 1 shows the distribution of some air-sea parameters during the passage of the cyclone at 1200 UTC 26 October 2018. The wind speed $U_{10}$ is modeled at more than 40 m s⁻¹ in the center of the cyclone with a clear eye structure, despite the atmospheric model resolution being only 0.5° (Fig. 1a). In high wind speed areas, wind sea waves dominate the total wave energy. Near the center of the cyclone, the energy fraction of the wind sea, $F_{w}$, exceeds 90% (Fig. 1b). Here, the $F_{w}$ is the ratio between the energy in the part of the spectrum where the wind speed is larger than the local wave phase velocity and the total spectral energy. The value of $F_{w}$ decreases with the distance from the center of the cyclone and swell waves start to dominate ($F_{w} < 50$%) means the energy of swell is larger than the energy of the wind sea waves. Meanwhile, the distribution of $F_{w} > 50$% is similar to the distribution of $c_{p}/U_{10} > 1.2$. In the East China Sea and the South China Sea, the $F_{w}$ is higher than 70%, suggesting the presence of a local wind sea wave system. The misalignment angle between the mean wind and peak wave direction, $\Theta_{ww}$, is less than 40° in the areas with $F_{w} > 50$% (see Figs. 1b,c). For the swell-dominated areas, $\Theta_{ww}$ can be up to 170° (wind opposing waves), in particular in the tail areas of the cyclone with relatively weak winds (Fig. 1c). Figure 1d shows the mean wave directional spread (SPR), which represents the angular spread of wave energy around the mean wave direction (Kuik et al. 1988). The SPR is up to 70° in the areas with larger $\Theta_{ww}$.

More than 80% of the total wind stress (air-side stress) is absorbed by waves in wind-sea dominated areas (Figs. 1b,e). The remaining forces the ocean directly, generating currents locally. The momentum absorbed by waves is determined by the ratio between the wind speed and the dominant wave phase speed as well as the degree of alignment between the wind and wave direction. Under cyclone conditions, the wave field is made up of a broad spectrum of wave components which make the distribution of $\beta_{w}$ complex. Nevertheless, one can see that the fraction of the momentum input to waves is small (less than 40%) in the areas with $F_{w} < 20$%. In strong winds, intense wave breaking releases momentum to the ocean interior. However, $\beta_{w}$ is less than 1 in those high wind
speed areas, which means that a fraction of the momentum flux from the atmosphere is carried by waves propagating out of the region of active wave generation (about 5% is transferred from the high wind speed areas, the blue areas in Fig. 1f). Red colored areas in Fig. 1f indicate that an extra momentum carried by waves is released here. Thus, the momentum flux to the ocean interior is larger than the momentum flux lost from the atmosphere. In addition, the misalignment angle between the air-side stress and ocean-side stresses $\Theta_s (°)$ is larger than $4°$ in some areas around the cyclone center, mainly due to the direction difference between wind and waves and the large wave directional spread (Fig. 1g). In general, $\Theta_s$ is less than $1°$ when $\Theta_{ww}$ and SPR are small. With high intensive wave breaking in the high wind speed areas, the breaking-induced TKE flux is much larger than $\Phi_{TKE}$ since the latter is valid for equilibrium conditions (fully developed sea state).
The $\beta_{TKE}$ is larger than 150% in the areas with $F_w > 80\%$. One should note that $\Phi_{oc}$ is very close to zero in swell-dominated areas. To avoid a very large value of $\beta_{TKE}$, we treat it as $1$ when $\Phi_{oc}$ is less than 0.001 W m$^{-2}$ (Fig. 1h).

b. Annual climatology

1) STATUS PARAMETERS

Figure 2 shows the global mean/median of air–sea bulk parameters based on the monthly mean/median data in the period 1990–2019. Those parameters are directly related to the role of waves in the redistribution of momentum and TKE fluxes at the air–sea interface. The high-wind areas ($U_{10} > 9$ m s$^{-1}$) are in the northern Pacific Ocean, the northern Atlantic Ocean, and in the Southern Hemisphere westerlies (Fig. 2a). In particular, $U_{10}$ is up to 12 m s$^{-1}$ in the southern Indian Ocean. In the open ocean, the high-wind areas have a high value of $\beta_w$ (Fig. 2b) and a low frequency of occurrence of swell ($U_{10}/c_p < 0.83$, $c_p$ is the peak phase speed of waves, see Fig. 2c). The areas with a low frequency of occurrence of swell are mainly the storm areas (see Fig. 1 of Alves 2006). However, the coastal areas and semiclosed ocean basins (e.g., the South China Sea and the Baltic Sea) also have a high mean $\beta_w$ (more than 65%) and low frequency of occurrence (<60%) of swell-dominated sea states, although the mean wind speed is relatively low. This is mainly because 1) the short fetch in those areas limits the development of swell waves, and 2) many swell wave systems cannot propagate into the semiclosed ocean basins. The frequency of occurrence of swell-dominated sea states ($F_w < 50\%$) shown in Fig. 2d has a similar pattern as the frequency of occurrence estimated from the inverse wave age (Fig. 2c) and agrees well with the results of Hanley et al. (2010) using ERA40 (Uppala et al. 2005) and Chen et al. (2020) using the dataset from the China–France Oceanography Satellite (CFOSAT). The mean wave directional spread (SPR) is high (>55°) in the eastern Pacific Ocean and 0°–20°N in the North Atlantic Ocean (Fig. 2e). These regions are exposed to wind systems that leads to a convergence (Fig. 2a) of swell systems and hence large SPR. In general, the distribution of the misalignment angle between the wind and peak wave direction is similar to that of SPR, with $\Theta_{ww}$ up to 120°. However, the equatorial zone has a significantly lower $\Theta_{ww}$ than its surrounding ocean areas.

2) STRESS MAGNITUDE

The spatial distribution of $|\tau_a|$ is similar to that of $U_{10}$ (Figs. 3a and 2a) since the wind is the dominating factor of the wind stress. Waves absorb momentum flux from the atmosphere.
and release a momentum flux to the ocean interior, which varies with location and time. On average, more than 84% of the momentum flux lost from the atmosphere is transferred to waves in the midlatitudes (Fig. 3b). In contrast, less than 65% of the air-side stress is directly transferred to waves in the intertropical convergence zone (ITCZ). The difference between $|\tau_a|$ and $|\tau_{oc}|$ is marginal (less than 2%) (Fig. 3c). One needs to note that the marginal difference between $|\tau_a|$ and $|\tau_{oc}|$ does not mean that the influence of waves is marginal since positive and negative differences tend to average out. The temporal and spatial differences between $|\tau_{oc}|$ and $|\tau_a|$ can alter many processes, e.g., horizontal advection. Thus, we use $\beta_r$ and $\gamma_r$ for the following analysis which can represent well the redistributive role of waves in the stress. A large $\gamma_r$ means that waves have a more significant redistributive role on the stress and vice versa. In addition, $\beta_r$ can tell us whether waves absorb momentum flux from the atmosphere ($\beta_r < 100\%$) or release it to the ocean interior ($\beta_r > 100\%$).

Figure 4a shows the distribution of $\gamma_r$ (the mean value is calculated based on the monthly mean). In general, high wind speed areas have a large value of $\gamma_r$, which means that waves have a more significant role in the stress redistribution under high wind speed conditions. On average, more than 4% of the momentum flux lost from the atmosphere is not released directly into the ocean interior in the northern Pacific Ocean, the northern Atlantic Ocean, and the Southern Hemisphere westerlies. To further investigate extreme wave conditions in the stress redistribution, the mean of the 90th percentile of $\gamma_r$ ($\gamma_{90\%}$) is shown in Fig. 4b. The 10th and 90th percentile of $\beta_r$ are shown in Figs. 4c and 4d, respectively, revealing if the high value of $\gamma_{90\%}$ is caused by the net momentum flux release of waves in the location. The blue coloring in Fig. 4c indicates that the wave field has net momentum flux absorption in those areas. In contrast, the red color in Fig. 4d represents areas where there is a net loss of momentum flux from the wave field to the ocean. The wave field redistributes more than 7% of the momentum flux in 10% of the time in the northern Pacific Ocean, the northern Atlantic Ocean, and in the Southern Hemisphere westerlies. South of South Africa, up to 5.5% of the momentum flux is redistributed by waves (Fig. 4a) and $\gamma_{90\%}$ is up to 10%. Besides, the $\gamma_r$ and $\gamma_{90\%}$ are significantly larger in some coastal areas (i.e., the main coastal upwelling systems along eastern boundary currents including the California Current, the Benguela Current, and the Peru–Chile Current) than that in neighboring areas. The large wind gradient contributes to the large $\gamma_r$ in coastal areas. In particular, coastal areas with prevailing onshore wind exhibit larger $\beta_r$ since decaying waves dominate. It is worth noting that $\beta_{10\%}$ does not change significantly close to the coast. The larger value of $\gamma_r$ in the coastal areas is mainly contributed by the cases with $\beta_r > 100\%$, which means that the wave field causes a significant release of momentum flux in those coastal areas.
The frequency of occurrence of $\beta > 110\%$ is much higher in those coastal areas (not shown). The redistributive role of waves in the tropics is not significant ($\gamma_\beta$ is less than 3% and $\gamma_{90\%}$ is less than 5%). Compared with the ITCZ, the wind-convergence areas close to the equator have a much smaller $\gamma_\beta$ (<1.5%) and $\gamma_{90\%}$ (<3%).

The zonal mean of $\gamma_\beta$ has two peaks in the Southern Hemisphere (not shown). The two peaks are located at roughly $39^\circ$ and $62^\circ$S, and a trough is located in the zonal wind peak latitude ($55^\circ$S). The wind gradient in the latitudes of the two peaks are large and the wind speed is relatively lower compared with that in the trough. Thus, the waves under the high wind gradient areas have a high probability of nonequilibrium conditions, which contributes to the large $\gamma_\beta$. In comparison, the two peaks of $\gamma_\beta$ in the Northern Hemisphere are not significant due to the influence of complex land distribution which significantly affects the meridional wind gradients.

3) STRESS DIRECTION

The momentum flux released from waves to the ocean interior is the integral of the momentum flux released from all wave components with different directions and frequencies where wave breaking occurs [Eq. (2)]. Consequently, the ocean-side stress direction may differ from the mean wind direction (or the air-side stress direction) since different wave systems may and most probably will coexist in one location (see Figs. 2e,f). The mean and the 90th percentile of the misalignment angle between the air-side and ocean-side stresses, $\Theta_\beta$ and $\Theta_{90\%}$, are shown in Figs. 4e and 4f, respectively. The areas with a large $\gamma_\beta$ also have a high value of $\Theta_\beta$ and $\Theta_{90\%}$. The mean $\Theta_\beta$ is larger in the Southern Hemisphere westerlies.
(more than 0.8°) than in the Northern Hemisphere westerlies (less than 0.7°). The $\Theta_{90}$ is more than 3° in the Southern Hemisphere westerlies, the northern Pacific Ocean, and the northern Atlantic Ocean. The $\Theta_{90}$ is up to 4° in the south of South Africa and Australia and in the Southern Ocean close to Antarctica (Fig. 4f). Similar to $\gamma_e$, the zonal mean of $\Theta_e$ and $\Theta_{90}$ in the Southern Hemisphere have two significant peaks (39° and 62°S) with a trough around 55°S (roughly the highest mean wind latitude). The highest wind areas are dominated by locally generated waves which propagate to nearby areas with a different wind direction and contribute to the large $\Theta_e$.

4) TKE flux

The TKE flux $\overline{TKE}$ is high in the high wind speed areas, with a value of up to 0.8 W m$^{-2}$ in the southern Indian Ocean (Fig. 3d). By contrast, $\overline{TKE}$ drops below 0.1 W m$^{-2}$ between 30°S and 30°N. The traditional approach overestimates the TKE flux into the ocean between 30°S and 30°N (by up to 0.03 W m$^{-2}$, which is more than 30%). However, it underestimates the TKE flux by up to 0.06 W m$^{-2}$ (about 5%) in the Southern Hemisphere westerlies, the northern Pacific Ocean, and the northern Atlantic Ocean (Figs. 3e,f). The TKE flux $\Phi_{oc}$ is induced by wave breaking, which is naturally much stronger in windy regions (i.e., the Southern Hemisphere westerlies, the northern Atlantic Ocean, and northern Pacific Ocean). The wave breaking manifests itself as white caps on the ocean surface. The TKE flux from wave models has also been shown to be closely correlated with the wave cap coverage (Kraan et al. 1996; Scanlon et al. 2016) as well as with the number of bubbles in the ocean surface boundary layer (Wang et al. 2016; Strand et al. 2020). By contrast, the tropics are dominated by swell waves (Figs. 2c,d) which have a small probability of breaking and consequently a small breaking-induced TKE flux.

Similar to the stress, the difference between $\overline{TKE}$ and $\overline{TKE}^{oc}$ only illustrates the average TKE flux difference at the air–sea interface. For ocean simulations, the spatial and temporal difference of $\gamma_{TKE}$ is another important parameter for estimating the role of waves in the redistribution of the TKE flux. Figures 4g and 4h show the median and 90th percentile of $\gamma_{TKE}$, respectively. The significant high value of the median of $\gamma_{TKE}$ (>18%) happens in the western tropical ocean and the tropical Atlantic Ocean. The 90th percentile of $\gamma_{TKE}$: $\gamma_{TKE}^{90}$, has a significantly different distribution than that of the median of $\gamma_{TKE}$. The $\gamma_{TKE}^{90}$ is much smaller in the tropical areas (less than 45%) than that in the midlatitudes (up to 55%). Cases with extreme differences thus happen more often in the midlatitudes than in the tropics.

c. Seasonal variation

Figure 5 shows the normalized frequency of occurrence of several parameters at different bins in three representative areas, i.e., the center of the northern Pacific Ocean (180°–160°W, 35°–55°N), a subsection of the tropical Pacific Ocean (150°–120°W, 30°–10°S), and an area in the Southern Hemisphere westerlies (165°–36°E, 45°–30°S). In the tropics, the wind speed is in the range 0–12 m s$^{-1}$ with a median value around 7 m s$^{-1}$ and the significant wave height is in the range 0.5–4 m with a median value around 2 m. In contrast, the wind speed is in the range 0–23 m s$^{-1}$ with the median value around


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10 m s\(^{-1}\) in midlatitudes. Compared with that in the northern Pacific Ocean, the median wind in the Southern Hemisphere westerlies is higher and has less extreme wind speed. The wave height at the peak of the normalized frequency distribution south of South Africa is much higher (about 1 m higher) than that in the northern Pacific Ocean (Fig. 7b), which is partly due to the swell contribution from the Southern Ocean (one can see that the frequency of occurrence of swell in the south of South Africa is much higher). Even though swell waves dominate the tropics, the portion for \(F_{w} > 50\%\) is still significant. This indicates that the wave age cannot fully represent the source of the dominated wave energy (Fig. 7d). The dominant swell leads to a larger SPR and \(\Theta_{ww}\) in the oceans in the tropics (Figs. 7d,e).

The distribution of \(\beta_{r}\) is wider (with more extreme cases) south of South Africa compared with that in the tropical Pacific Ocean and the northern Pacific Ocean (Fig. 7g). The frequency with \(\beta_{r}\) about 1 in the tropical areas is about 2 times larger than that in the midlatitudes. Even though the \(\Theta_{ww}\) and SPR are larger in the tropics, the probability of the large \(\Theta_{ww}\) is higher in the oceans in the midlatitudes (Fig. 7h). The TKE flux \((\Phi_{oc})\) varies in approximately cubic proportion to \(U_{10}\) (not shown). Compared with the midlatitudes, the frequency of occurrence of \(\beta_{TKE} < 0.7\) is larger in the tropics which indicates that \(\Phi_{oc}\) overestimates the breaking-induced TKE flux. The distribution of \(\beta_{TKE}\) in the chosen midlatitude areas also shows that the frequency of occurrence that \(\Phi_{oc} < \Phi_{oc}^{'}\) is larger than that for \(\Phi_{oc} > \Phi_{oc}^{'}\) (Fig. 7i). Here, one needs to note that in areas with \(\Phi_{oc} < 0.001\) W m\(^{-2}\), \(\beta_{TKE}\) is set to 1 to avoid excessively large values.

4. Discussion

The buffering role of waves in the air–sea momentum and TKE fluxes is starting to be (partially) implemented into
regional and global models to improve their performance (Staneva et al. 2017; Law Chune and Aouf 2018; Wu et al. 2019a). The ocean-side stress was usually calculated by the product between the air-side stress (calculated from a bulk parameterization in stand-alone ocean models) and the normalized stress from a wave model (Alari et al. 2016; Staneva et al. 2017; Law Chune and Aouf 2018; Wu et al. 2019b). In those offline coupled models, the breaking-induced TKE flux was implemented through the parameter $\alpha_{CB}$, updated from external files. The redistributive role of waves on the stress and TKE flux has been implemented in atmosphere–wave–ocean coupled models to capture the two-way air–sea interaction (Breivik et al. 2015). Note that the ocean-side stress (wave breaking-induced TKE flux) may be altered if the normalized stress ($\alpha_{CB}$) is used to estimate the ocean-side stress (breaking-induced TKE flux) when a different bulk parameterization is used to estimate the air-side stress in ocean models. To conserve the stress and TKE flux at the air–sea interface, the quantities should be computed according to Eqs. (1) and (6), respectively, as was done by Wu et al. (2019a).

In combination with wave-induced ocean mixing (Qiao et al. 2004; Fan and Griffies 2014; Breivik et al. 2015; Li et al. 2016, 2017), the wave impact on the ocean-side stress magnitude and direction could have a positive influence on climate simulations. In addition, waves can significantly affect momentum flux in the coastal areas affected by coastal upwelling (Wu et al. 2019b), water level (Staneva et al. 2017; Wu et al. 2019b), and other ocean processes related to wind stress. Thus, the redistributive role of the sea state on coastal upwelling and climate simulations needs to be investigated further.

Besides the redistributive role of waves in momentum and TKE fluxes, swell waves have a significant influence on the air-side stress and wind profile (Hanley and Belcher 2008; Semedo et al. 2009; Wu et al. 2017). For example, the swell can induce upward momentum flux which transfers the momentum flux from waves to the atmosphere. The misalignment between wind and waves can alter the air-side stress direction (Zou et al. 2019; Wu and Qiao 2022). However, the air-side stress is assumed to align with the wind direction in the source package used in the model setup of the IOWAGA hindcast. Besides, the veering of the wind direction in the atmospheric boundary layer can also result in the misalignment between the mean wind and wind stress (Mahrt et al. 2001).

In general, existing wave models capture the evolution of wave bulk parameters, e.g., wave height (Kalourazi et al. 2021), reasonably well under extreme ocean conditions. However, the redistributive role of waves in the momentum and TKE fluxes has been less studied. It is worth noting that the development of tropical cyclones is sensitive to the wind stress (Reichl et al. 2014) and sea surface temperature (Jiang et al. 2008). The redistributive role of waves in the momentum and TKE fluxes can affect the ocean feedback to tropical cyclones, e.g., by altering the sea surface temperature. Importantly, the intensity of cyclones can be changed by the altered sea surface temperature

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**FIG. 6.** The 90th percentile of (a),(b) $\beta_90$ (%); (c),(d) $\Theta_90$ (°); and (e),(f) $\gamma_{TKE}$ (%). The mean of (left) JJA and (right) DJF.
Thus, the redistributive role of waves in the air–sea momentum and TKE fluxes should be considered in the forecast models of tropical cyclones.

5. Conclusions

In existing coupled climate models, the momentum flux from the atmosphere is assumed to be identical to the stress to the ocean interior. However, this assumption is invalid under growing and decaying waves as well as in fetch-limited conditions. In this study, the impact of the sea state on the wind stress (both magnitude and direction) and the breaking-induced TKE flux have been investigated using the 30-yr IO-WAGA wave hindcast.

Waves play a more significant role in the redistribution of the momentum flux at the air–sea interface in windy regions. On average, the ocean-side stress differs by up to 6% from the air-side stress in middle and high latitudes. The 90th percentile value of $\gamma_s$ (the relative difference between the air-side stress and ocean-side stress) is more than 9% in those areas. The mean of $\gamma_s$ is less than 2.5% in the tropical oceans. The directional difference between $\tau_a$ and $\tau_{oc}$ is more than

FIG. 7. The normalized frequency distribution of (a) $U_{10}$, (b) $H_s$, (c) $U_{10}/c_p$, (d) $F_w$, (e) SPR, (f) $\Theta_{ww}$, (g) $\beta_r$, (h) $\Theta_r$, and (i) $\beta_{TKE}$ for three representative areas: the center of the northern Pacific Ocean (180°–160°W, 35°–55°N), a subsection of the tropical Pacific Ocean (150°–120°W, 30°–10°S), and an area in the Southern Hemisphere westerlies (16.5°–36°E, 45°–30°S).
0.8° with the 90th percentile larger than 3.5° in the middle and high latitudes. The impact of the sea state on the directional difference between \( \tau_n \) and \( \tau_e \) is not significant in the tropics.

The breaking-induced TKE flux is high under strong winds. Compared with the TKE flux estimated from the two-dimensional wave spectrum, the traditional approach (as a function of the friction velocity) overestimates (underestimates) the breaking wave-induced TKE flux in the tropics (the middle and high latitudes).

The redistributive role of waves on the air–sea momentum flux has a significant seasonal pattern. The largest influence is found in the winter months with high winds and a correspondingly smaller influence is found in the summer months in both hemispheres. However, the influence of the sea state is significant in all seasons in areas with complex wind and wave conditions, such as south of South Africa.

We conclude that the buffering role of waves on the momentum and TKE fluxes across the air–sea interface should be considered in climate and Earth system models, in particular for the middle and high latitudes with prevailing high winds.

Acknowledgments. L. Wu is supported by VR (2020-03190), Formas (2017-00516), and Laboratory for Regional Oceanography and Numerical Modeling, Qingdao National Laboratory for Marine Science and Technology (2019B04). Ø. Breivik is grateful for support from the CMEMS Service Evolution 2 project WaveFlow. F. Qiao is supported by National Natural Science Foundation of China (41821004). The computations and data handling were enabled by the resources provided by the Swedish National Infrastructure for Computing (SNIC), partially funded by the Swedish Research Council through Grant Agreement 2018-05973. IFREMER is acknowledged for giving access to the IOWAGA hindcast data: ftp://ftp.ifremer.fr/ifremer/www3/HINDCAST/.

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