Upper ocean response to tropical cyclones: a review

Han Zhang$^{1,2,3}$*, Hailun He$^{1,2,*}$, Wen-Zhou Zhang$^3$ and Di Tian$^1$

Abstract
Tropical cyclones (TCs) are strong natural hazards that are important for local and global air–sea interactions. This manuscript briefly reviews the knowledge about the upper ocean responses to TCs, including the current, surface wave, temperature, salinity and biological responses. TCs usually cause upper ocean near-inertial currents, increase strong surface waves, cool the surface ocean, warm subsurface ocean, increase sea surface salinity and decrease subsurface salinity, causing plankton blooms. The upper ocean response to TCs is controlled by TC-induced mixing, advection and surface flux, which usually bias to the right (left) side of the TC track in the Northern (Southern) Hemisphere. The upper ocean response usually recovers in several days to several weeks. The characteristics of the upper ocean response mainly depend on the TC parameters (e.g. TC intensity, translation speed and size) and environmental parameters (e.g. ocean stratification and eddies). In recent decades, our knowledge of the upper ocean response to TCs has improved because of the development of observation methods and numerical models. More processes of the upper ocean response to TCs can be studied by researchers in the future.

Keywords: Tropical cyclone, Upper ocean, Dynamic response, Temperature and salinity variation, Marine biology

Introduction
Tropical cyclones (TCs) are strong natural hazards that are generated and developed in the ocean. TC wind as well as the TC-induced currents and waves usually damages offshore platforms and vessels, erode coastlines, threaten coastal areas and causes economic and personnel losses (Keim et al. 2007; Wang and Oey 2008; Han et al. 2012; Sun et al. 2013; Zhang et al. 2016b; Li et al. 2018). In recent decades, TC track forecasts have steadily improved because of the development of numerical models (Krishnamurti et al. 1999; McAdie and Lawrence 2000; Bender et al. 2007; Cangialosi and Franklin 2013; Ruf et al. 2016; Montgomery and Smith 2017), while the forecast skill of TC intensity has improved slightly (Cangialosi and Franklin 2013), partly because of inadequate observations and modelling of TC inner cores (Ruf et al. 2016) and TC–ocean interactions (Yano and Emanuel 1991; Montgomery and Smith 2014, 2017). Sea surface temperature is important for TC intensity. For example, a simple coupled model of an axisymmetric hurricane model and one-dimensional ocean model can significantly improve the intensity predictions if the negative feedback of the sea surface temperature to TCs is taken into account (Emanuel 1999). Sea surface temperature cooling greater than 2.5 °C is considered not conducive to TC strengthening (Emanuel 1999) and may even weaken TCs (Schade and Emanuel 1999; Lin et al. 2008). The sea surface cooling caused by a pre-existing TC alters the track and intensity of a subsequent TC (Baranowski et al. 2014; Wu and Li 2018). Note that salinity stratification can reduce sea surface cooling in favour of TC rapid intensification, and this effect increases significantly as the TC intensification rate increases (Balaguru et al. 2020).

TC is also important for the ocean environment, TCs import kinetic energy into surface waves, surface currents and gravitational potential energy, which contributes to ocean diapycnal diffusivity and ocean circulation.
TCs can also change the local ocean heat uptake (Emanuel 2001) and contribute to global ocean heat transport (D’Asaro et al. 2007; Srir and Huber 2007; Korty et al. 2008; Pasquero and Emanuel 2008; Hu and Meehl 2009; Fedorov et al. 2010). Some research even considers TCs is important to maintain the permanent El Niño in the early Pliocene epoch (Fedorov et al. 2010). In addition to meridional heat transport, TCs can influence west wind bursts (Lian et al. 2018, 2019), enhance eastward-propagating oceanic Kelvin waves in the tropical Pacific (Wang et al. 2019b) and modulate the occurrence and development of the El Niño–Southern Oscillation. TCs usually cause plankton blooms, which contribute to local long-term primary productivity (Mooers 1975; Foltz et al. 2015). Research shows that TCs increase 20–30% of the primary productivity in the South China Sea every year on average (Lin et al. 2003b; Tang et al. 2004a, b; Sun et al. 2010) also explains 22% of the interannual variability in seasonally averaged (June–November) chlorophyll concentration in the western subtropical North Atlantic (Foltz et al. 2015).

In brief, understanding the ocean response to a TC not only increases the TC forecast skill but also enriches our knowledge of local and global variation of ocean environment.

Ocean response to a tropical cyclone

Current response

The strong TC wind stress arouses upper ocean current response, which usually biases to the right (left) side of TC track in Northern (Southern) Hemisphere, because of better wind-current resonance (Price 1981, 1983; Price et al. 1994; Sun et al. 2015; Zhang et al. 2020b). The wind-current resonance is controlled by non-dimensional TC translation speed which is the ratio of local inertial period to the TC residence time (Zhang et al. 2020b). Generally, a TC causes internal wake in its lee when it moves faster than the first baroclinic wave speed, and the main response is almost centred under the TC and the wake is relatively inconspicuous when a TC moves slower than the speed of first baroclinic wave (Geisler 1970). The current response is a stable Ekman response with surface (bottom) cyclonic divergence (convergence) when TC is stationary (Lu and Huang 2010), and there was weak current response in the lee of the Ekman-like divergence when TC moves slowly (Zhang et al. 2020b). Because the translation speed of most TCs is greater than the local first baroclinic wave speed (e.g. Zhang et al. 2020b), we usually find a near-inertial current response after the TC passage (Pollard 1970; Maeda et al. 1996; Firing et al. 1997; Jarosz et al. 2007; Xu et al. 2019). The upper ocean near-inertial current response to a TC can be divided into mixed layer current and thermocline current (Price 1981; Price et al. 1994; Zhang et al. 2016a, 2019). TC wind directly drives the mixed layer current, then the divergence and convergence of mixed layer current caused hydrostatic pressure anomaly that drives the thermocline current (Price et al. 1994). The phases of the mixed layer current and thermocline current are nearly uniform within themselves, while there is an angle between mixed layer current and thermocline current (Sanford et al. 2007, 2011; Prakash and Pant 2016; Zhang et al. 2016a), which depends on the ratio of TC translation speed to baroclinic wave speed (Geisler 1970). There is a transition layer between the mixed layer current and thermocline current, with the current phase turning clockwise as the depth increases (Price et al. 1986; Sanford et al. 2011; Zhang et al. 2016a). Velocity shear in transition layer is considered as the primary mechanism for deepening of upper ocean mixed layer during a TC (Glenn et al. 2016; Seroka et al. 2017; Yang et al. 2019). The TC-induced near-inertial current corresponds to upwelling and downwelling, with the transition of the upwelling (downwelling) branch to the downwelling (upwelling) branch being slow and moderate (quick and intense) (Greatbatch 1983, 1984, 1985). If the inertial period signal is removed, there is net mixed layer divergence and upwelling in the right rear quadrant of the TC, as well as net downwelling around the net upwelling zone (Zhang et al. 2018a, b).

Relative to open ocean, the current response to a TC in the marginal sea is more complicated because of the secondary local circulation due to the shallow ocean bottom and coastal wall (Halliwell et al. 2011; Glenn et al. 2016; Seroka et al. 2016). TCs also have import positive vorticity into ocean, which intensifies ocean cyclonic eddies (Walker et al. 2005) and alters the three-dimensional structure of eddies (Sun et al. 2014; Lu et al. 2016) or even generates new cyclonic eddies (Chen and Tang 2012; Sun et al. 2014). On the other hand, the circulation of eddies also modulates the TC-induced convection and vertical advection in upper ocean (Jaimes and Shay 2015; Liu et al. 2017).

After TC passage, the current response decays through dispersion and propagation of near-inertial waves (Gill 1984; Park et al. 2009) with an e-folding time from days to weeks (Chen et al. 2013; Yang and Hou 2014). The decay of current is not monotonous because different orders of near-inertial baroclinic waves occasionally resonate again and re-intensify the mixed layer current (Gill 1984). Note that the current velocity to the right side of the TC track decays faster than that to the left side in the Northern Hemisphere (Zhang et al. 2016a; Wu et al. 2020a). The dispersion of waves also results in the tilting of isophase lines of near-inertial current (Gill 1984; Zhang et al. 2016a). In general, the near-inertial waves propagate in the ocean with a vertical scale of approximately...
100–300 m (Kundu 1976; Yang and Hou 2014; Alford et al. 2016) and contribute to turbulent mixing (Qi et al. 1995; Zhai et al. 2009; Jochum et al. 2013). The TC-induced current response can reach the ocean bottom, which may be a major driver of sediment dynamics of continental shelves worldwide (Larcombe and Carter 2004; Galewsky et al. 2006; Dail et al. 2007; Liu et al. 2012), impacting benthic and pelagic habitats by changing water column turbidity or modifying seabed physical characteristics (Hearn and Holloway 1990; Drost et al. 2017). The near-inertial current caused by TCs usually has a blueshift of 1–20% relative to the local inertial frequency, along with slow downward propagation of energy and upward propagation of phase (Pollard 1980; Smith 1989; Yang and Hou 2014). In addition to near-inertial waves, TCs cause inertial waves at a frequency that is two times and three times the local inertial frequency, resulting in energy cascade and dissipation (Niwa and Hibiya 1997; Meroni et al. 2017). Mesoscale ocean processes alter local relative vorticity, which changes the effective planetary vorticity; then, TC-induced near-inertial waves propagate downward more easily in an anticyclonic eddy (Zhai et al. 2005; Guan et al. 2014) and tend to be trapped in a region with more negative vorticity than its surroundings (Oey et al. 2008; Jaimes and Shay 2010) (Fig. 1).

**Surface wave response**

TC wind also arouses strong surface waves. Sea surface wave height is a function of radial distance from the TC centre by empirical relationships (Young 1988; Wang et al. 2005; Young and Vinoth 2013) and can reach more than 10 m (Zhang et al. 2016a; Drost et al. 2017; Zhang et al. 2018a, b). Surface wave propagation is complicated, and multiple-wave systems are frequently observed. Previous studies typically assumed that TCs impact a region more than 10 times the radius of the maximum wind (Young 2006; Beeden et al. 2015; Esquivel-Trava et al. 2015). TC-induced wave spectra rapidly evolve and vary spatially by radius away from the centre and quadrant of the TC (Moon et al. 2003; Young 2003; Fan et al. 2009; Collins et al. 2018). The TC-induced wave spectra are often bimodal, sometimes trimodal, directional wave spectra (Wright et al. 2001), the waves are asymmetrical, and the directional spectra possess unique characteristics in each quadrant (Hu and Chen 2011; Esquivel-Trava et al. 2015). In reference to the TC heading, single-wave systems propagating towards the left and left-front are usually observed in the front half of the TC coverage area, and multiple-wave systems are generally observed in the back and right quarters outside the radius of maximum wind, while the directional differences and locations of multisystem spectra are Gaussian distributions (Hwang and Walsh 2018).

There is misalignment of wind and surface waves during a TC (Fan et al. 2009; Wang et al. 2019a). Swells dominate the surface waves at the front of and outside the central typhoon region (Xu et al. 2017b), and the wave field is more asymmetric than the corresponding TC wind field, mainly due to the “extended fetch”, which exists to the right of a translating TC in the Northern Hemisphere (Young 2003). TC-induced surface currents can reduce the fetch and inhibit the growth of surface waves (Wu et al. 2020b). Nonlinear wave–wave interactions efficiently transfer wave energy from high frequencies to low frequencies and prevent double-peak structures occurring in the frequency-based spectrum (Xu et al. 2017b).
TC-induced surface waves modulate the air–sea surface conditions and fluxes. TC-induced surface waves increase sea surface roughness (Donelan 2004; Makin 2005; Soloviev et al. 2014; Li et al. 2016; Tian et al. 2020) and reduce wind speeds (Olabarrieta et al. 2012). The wind-wave coupling deepens inflow layer, enhances boundary inflow outside the radius of maximum wind and increases the TC intensity (Lee and Chen 2012). Surface wave breaking during TCs also causes a large number of sea spray droplets (Zhang et al. 2011, 2012) in whitecaps and whipping spumes from the tips of waves, which is believed to significantly influence momentum transfer and contributes to the drag coefficient levelling off (or decreasing) at high wind speeds during a TC (Powell et al. 2003; Donelan 2004; Soloviev et al. 2014; Zhang and Song, 2018). Sea spray also influences the air–sea heat flux (Andreas and Mahrt 2016; He et al. 2018; Sun et al. 2019). The latent and sensible heat transfer coefficients are constant at low wind speeds and increase sharply when wind speed at the height of 10 m is greater than 35 m/s (Komori et al. 2018). The air–sea gas transfer also increased significantly due to the surface wave breaking (Iwano et al. 2013; Krall and Jähne 2014; Liang et al. 2020).

TC-induced breaking and unbreaking surface waves also contribute to turbulence in the upper ocean and deepening of the mixed layer (He and Chen, 2011; Toffoli et al. 2012; Aijaz et al. 2017; Stoney et al. 2017; Zhang et al. 2018a, b). The wave-breaking-induced acceleration transfers momentum from surface waves to surface currents and also contributes to sediment transport (Prakash and Pant, 2020). Non-breaking surface wave-induced mixing in numerical model improves the simulations of sea surface temperature and TC track (Guan and Zhao 2014; Li et al. 2014; Aijaz et al. 2017; Stoney et al. 2017). The Craik-Leibovich vortex force, which is the interaction between Stokes drift of surface waves and Eulerian current vorticity, causes Langmuir turbulence (Craik and Leibovich 1976), enhances turbulence entrainment and deepens mixed layer during a TC (Sullivan et al. 2012; Rabe et al. 2015; Reichl et al. 2016a,b; Zhang et al. 2018b; Wang et al. 2018, 2019). The Langmuir cell is roughly aligned with wind and Langmuir turbulence intensity is reduced by wind-wave misalignments during a TC (Wang et al. 2019a, b). Recent researches indicate that parameterization of Langmuir turbulence can improve the simulation of upper ocean temperature and current response during a TC (e.g. Sullivan et al. 2012; Reichl et al. 2016a,b; Blair et al. 2017). The Coriolis–Stokes force also increases the cold upwelling in a slow moving TC and modulates the horizontal advection of upper ocean cold wake (Reichl et al. 2016a; Zhang et al. 2018b).

Langmuir circulation generates high-frequency internal waves, induces near-inertial currents at the mixed layer bottom (the transition layer) and transports more near-inertial energy into deeper layers (e.g. Polton et al. 2008).

Temperature and salinity response

TC deepens the upper ocean mixed layer, cools the sea surface and warms the subsurface (Price 1981, 1983, 1994; Jacob et al. 2000; Zedler et al. 2009; Sanford et al. 2011; Yang et al. 2015; Chen et al., 2020), which is called the “heat pump” effect (Sriver and Huber 2007; Zhang et al. 2016a). Sea surface also lose heat through air–sea heat flux, but it is not as important as the mixing effect for the sea surface cooling (Price 1981; Zhang et al. 2016a). Sea surface cooling usually biased to the right (left) side of the TC track in the Northern (Southern) Hemisphere, and the amplitude of sea surface cooling is usually 1–6 °C (Price 1981; Zedler et al. 2002; Lin et al. 2003a; Black et al. 2007; D’Asaro et al. 2007), sometimes even reaching ~11 °C, resulting in reverse of air–sea surface sensible and latent heat flux (Glenn et al. 2016). The upwelling branch of the near-inertial pumping weakens the subsurface warm anomaly or even turns it to cold anomaly, while downwelling branch intensifies the subsurface warm anomaly. Subsurface warm anomaly caused by mixing can reach as much as ~4 °C, and usually be modulated by the TC-induced near-inertial pumping (Zhang et al. 2016a, 2019). After removing inertial period signal, TC caused a net upwelling with a net cooling in the right rear quadrant of TC, and net downwelling with net warming around the net cooling zone (Zhang et al. 2018a, 2019), which is called “cold suction” effect. During the TC relaxation stage, the air–sea heat flux dominates the upper ocean thermal response, which mainly recovers the sea surface cold anomaly through solar radiation (Price et al. 1986). Research shows that sea surface temperature usually recovers back to its original value in several days to several weeks (Hazelworth 1968; Price et al. 1986, 2008; Emanuel 2001; Hart et al. 2007; Wang et al. 2016), with an e-folding time of approximately one week (Jansen et al. 2010; Dare and McBride 2011), occasionally cooling again during recovery (Price et al. 2008). Subsurface ocean has no contact with air, so it usually recovers slower than the sea surface (Emanuel 2001; Wang et al. 2016).

The characteristics of the upper ocean temperature response to a TC are affected by the TC intensity, size and translation speed (Anthes and Chang 1978; Emanuel et al. 2004; Zhu and Zhang 2006; Samson et al. 2009; Wang et al. 2016; Lin et al. 2017). For example, a stronger TC produces more cooling up to Category 2, but TCs in Categories 3–5 produce less or approximately equal cooling (Lloyd and Vecchi 2011). Argo float observations show that the subsurface warm anomaly is comparable to the near-surface cold anomaly during strong TCs.
(≥ Category 4), while subsurface warming is not detectable and near-surface cooling is still significant during weak TCs (≤ Category 3), indicating that air–sea heat exchange and upwelling seem to play a somewhat greater role during weak TCs (Park et al. 2011). The sea surface cooling is quasi-symmetric for slow-moving (< 6 m/s) TCs and becomes asymmetric for fast-moving TCs (Samson et al. 2009). The background ocean condition also contributes to the upper ocean temperature response during a TC. For example, there is cold upwelling (warm downwelling) in the core of an anticyclonic (cyclonic) eddy, which intensifies (weakens) sea surface cooling (Jaimes and Shay 2009; Liu et al. 2017; Wu and Li 2018; Ning et al. 2019).

Similar to temperature response, TCs usually increase sea surface salinity and decrease subsurface salinity both within 1 psu, which bias to the right (left) side of TC track in Northern (Southern) Hemisphere (Bond et al. 2011; Girishkumar et al. 2014; Domingues et al. 2015; Zhang et al. 2016a; Abernathey and Haller 2018); the positive sea surface salinity sometimes even reaches 1.5–3 psu (Chaudhuri et al. 2019). However, TC precipitation usually weakens positive sea surface salinity anomaly (Girishkumar et al. 2014; Liu et al. 2020) and causes negative sea surface salinity anomaly to the left (right) side of TC track in the Northern (Southern) Hemisphere (Grodsky et al. 2012; Liu et al. 2014). The freshness of the sea surface by precipitation increases the upper ocean stratification and weakens the TC-induced mixing (Jourdain et al. 2013; Vissa et al. 2013; Liu et al. 2015, 2020), which restricts the sea surface cooling and the negative TC–ocean feedback (Balaguru et al. 2016). There is a barrier layer if the upper ocean isosaline layer is shallower than the isothermal layer, which also prohibits the deepening of the upper ocean mixed layer caused by a TC (Balaguru et al. 2012; Liu et al. 2015; Yan et al. 2017). Research shows that the upper ocean salinity response can persists about 10–12 days (Girishkumar et al. 2014). The background ocean condition (e.g. eddies) also contributes to the upper ocean salinity response during a TC. For example, the upwelling (downwelling) due to anticyclonic (cyclonic) eddies increases (decreases) upper ocean salinity (Jaimes and Shay 2009; Liu et al. 2017) (Fig. 2).

**Biological response**

TCs induce phytoplankton blooms and primary production increase, which is mainly attributed to the increased nutrient supply in the euphotic zone induced by vertical mixing (or entrainment) and upwelling during a TC (Mooers 1975; Morimoto et al. 2009; Siswanto et al. 2009; Zheng et al. 2010; Chiang et al. 2011; Shibano et al. 2011; Hung et al. 2013; Huang and Oey 2015) and ocean restratification after the TC (Huang and Oey 2015; Lin and Oey 2016). The chlorophyll increases after a TC usually ranges from 5 to 91% (Babin et al. 2004; Zhao et al. 2017; Xu et al. 2017a), while a lingered slow-moving TC (Kai-Tak in year 2000) can even triggered 30-fold of surface chlorophyll-a concentration (Lin et al. 2003b). In Northern (Southern) Hemisphere, the chlorophyll increases usually biases to the right (left) side of the TC track (Lin et al. 2003b; Babin et al. 2004; Yin et al. 2007; Hanshaw et al. 2008; Shan et al. 2008; Zhao et al. 2008; Zheng et al. 2010; Shibano et al. 2011), although the rightward (leftward) bias is not obvious or may even occur towards the left (right) side of the TC track (Zheng et al. 2010; Shibano et al. 2011). The amplitude and scope of surface

---

**Fig. 2** Sketch of the vertical temperature profiles during a tropical cyclone that caused by before (dashed lines) and after (solid lines) a) only mixing, b) composition of mixing and upwelling and (c) composition of mixing and downwelling. The dotted lines in (b) and (c) indicate the temperature profiles caused by only mixing. Red and blue shadings refer to warm and cold anomaly, respectively. There can be no subsurface warm anomaly in (b) if upwelling is strong enough. Salinity anomalies are similar to temperature anomalies.
plankton blooms depend not only on the TC characteristics but also on the ocean background conditions (Lin et al. 2003b; Zhao et al. 2008; Chen and Tang 2012; Shang et al. 2015; Xu et al. 2017a). For example, weak and slow-moving TCs induce phytoplankton blooms with higher chlorophyll-a concentrations, while strong and fast-moving TCs induce blooms over a larger area (Zhao et al. 2008). A pre-existing cold core eddy plays an important role in the increase in chlorophyll-a concentration by TCs (Chen and Tang 2012; Shang et al. 2015; Xu et al. 2017a; Jin et al. 2020), and the concentration of pre-existing chlorophyll-a in cold core eddies is approximately 25–45% (8–25%) of that of the post-existing chlorophyll-a in cold core eddies for relatively high (low) TC transition speeds (Shang et al. 2015). The biological response in coastal regions is more complicated than that in the open ocean (Pan et al. 2017). TC-induced mixing, enhanced terrestrial runoff and resuspension are considered three major processes that contribute to the increased nutrient concentrations and subsequent primary production in the euphotic layer (Chen et al. 2003). The chlorophyll-a reaches its peak three days after nitrate peak after a TC (Pan et al. 2017), and TC-induced phytoplankton blooms usually last for two to three weeks (Babin et al. 2004; Chen and Tang 2012; Foltz et al. 2015; Wang 2020).

**Discussion and conclusions**

This work reviews the upper ocean response to tropical cyclones, including the current, surface wave, temperature, salinity and biological responses. TC usually causes upper ocean near-inertial currents, increases strong surface waves, cools (warms) the surface (subsurface) ocean and increases (decreases) surface (subsurface) salinity, also causing plankton blooms. The upper ocean response is controlled by mixing, advection and air–sea flux (i.e. heat flux and fresh water flux). The upper ocean response usually biases to the right (left) side of the TC track because the wind-current resonance is stronger (weaker) and the corresponding mixing is stronger (weaker) on the right (left) side in the Northern (Southern) Hemisphere. The characteristics of the upper ocean response mainly depend on the TC parameters (e.g. TC intensity, translation speed and size) and environmental parameters (e.g. ocean stratification and eddies) (Fig. 3).

In recent decades, the understanding of upper ocean response to a tropical cyclone has improved because of the development of observations and modelling. Traditional observation methods such as buoys and moorings (Black and Dickey 2008; Zhang et al. 2016a, 2019; Yang et al. 2019), air-deployed drifters and floats (Black et al. 2007; D’Asaro et al. 2007; Pun et al. 2011; Sanford et al. 2011), Argo floats (Park et al. 2011; Vissa et al. 2012; Wu and Chen 2012; Fu et al. 2014; Liu et al. 2014; Lin et al., 2017; Chen et al., 2020) and satellite remote sensing (Li et al. 2018; Yue et al. 2018; Ning et al. 2019; Zhang et al. 2019), as well as new observation technology and methods such as gliders (Domingues et al. 2015; Miles et al. 2015; Hsu and Ho 2018) and wave gliders (Mitarai and McWilliams 2016), are now applied to TC–ocean observations. Regarding numerical model simulations, early
works use the slab ocean model to reproduce the ocean current response (Geisler 1970; Pollard and Millard 1970; Gill 1984), followed by several numerical models such as the three-dimensional Price–Wellner–Pinkel model (3DPWP) (Price et al. 1994; Sanford et al. 2007; Guan et al. 2014; Zhang et al. 2016a), the regional oceanic modelling system (ROMS) (Yue et al. 2018) and the Massachusetts Institute of Technology Ocean General Circulation Model (MIT OGCM) (Zedler et al. 2009) to reproduce the three-dimensional current, temperature and salinity responses. Wave models such as the Simulating WAVes Nearshore (SWAN) (Liu et al. 2007; Huang et al. 2013) and WAVESWATCH-III (Moon et al. 2003; Xu et al. 2017b; Qiao et al. 2019) models are used to reproduce the sea surface wave response to a TC. Recently, atmosphere–ocean-wave models such as the Coupled Ocean–Atmosphere–Wave-Sediment Transport (COAWST) modelling system (Prakash and Pant 2016; Wu et al. 2018) have been gradually applied to simulate the ocean response to TCs. Note that the ocean ecological model seems to have not been widely used for the simulation of ocean biological response to a TC yet. What is more, new technology such as big data and machine learning provide a new way to study TC–ocean interaction (e.g. Wei et al. 2017, 2018; Jiang et al. 2018).

Although our understanding of the upper ocean response to a TC has increased in recent decades, some fields merit further study, such as: 1. the characteristics of the air–sea interface as well as the surface flux during TCs; 2. the effect of varied TCs on the upper ocean response, e.g. the upper ocean response during curved TC track, during intensifying (weakening) TCs or accelerating (decelerating) TCs; 3. the interaction between TCS and mesoscale or submesoscale eddies; 4. the upper ocean response to sequential TCs; 5. the effects of TCs on large ocean circulation, e.g. modulation of global ocean circulation by the kinetic energy and heat uptake caused by TCs; 6. the processes that control the recovery of the upper ocean response after TCs; and 7. the propagation of TC-induced anomalies into the ocean interior and deep ocean.

Some existing issues in observation, numerical model and technology restrict the study of upper ocean response to TCs. In situ observation of air–sea interface (i.e. air–sea flux, surface waves) and deep ocean is in shortage, which restricts our understanding of the air–sea interaction and how upper ocean anomalies propagate into ocean interior. The coupling of atmospheric and oceanic model as well as the parameterization of the processes in air–sea interface merits further study for better simulation of TC–ocean interaction. What is more, it is a common problem that surface currents simulated by model seems stronger and persists longer as well as less vertical
Anthes RA, Chang SW (1978) Response of the hurricane boundary layer to changes of sea surface temperature in a numerical model. J Atmos Sci 35:1240–1255

Babin SM, Carton JA, Dickey TD, Wiggert JD (2004) Satellite evidence of hurricane-induced phytoplankton blooms in an oceanic desert. J Geophys Res Oceans 109:C03043

Balaguru K, Chang P, Saravanan R, Leung LR, Xu Z, Li M, Hsieh JS (2012) Ocean basin storm factors effects on tropical cyclone intensification. Proc Natl Acad Sci U S A 109:14343–14347

Balaguru K, Foltz GR, Leung LR, Emanuel KA (2016) Global warming-induced upper-ocean freshening and the intensification of super typhoons. Nat Commun 7:13670

Balaguru K, Foltz GR, Leung LR, Xu KJ, W, Reul N, Chapron B, (2020) Pro-

Chen Y, Tang D (2012) Eddy-feature phytoplankton bloom induced by a tropical cyclone. J Geophys Res Oceans 117:C08009

Chen SS, Lee CY (2012) Symmetric and asymmetric structures of hurricane boundary layer in coupled atmosphere—ocean models and observations. J Atmos Sci 69:3576–3594

Chen H, Li S, He HL, Song JB, Ling Z, Cao AZ, Zou ZS, Qiao WL (2020) Observations of surface wave fields under an extreme tropical cyclone. J Phys Oceanogr 50:3571–3589

Chen et al. Geosci. Lett.             (2021) 8:1

Collins CO, Potter H, Lund B, Tamura H, Graber HC (2018) Directional wave spectra observed during intense tropical cyclones. J Geophys Res Oceans 124:7973–7993

Craig ADD, Leibovitch S (1976) A rational model for Langmuir circulations. J Fluid Mech 73:401–426

D’Asaro EA, Sanford TB, Niler PP, Terrill EJ (2007) Cold wake of hurricane eddies. Geophys Res Lett 34:L15609

Dail MB, Corbett DR, Walsh JP (2007) Assessing the importance of tropical cyclones on continental margin sedimentation in the Mississippi delta region. Cont Shelf Res 27:1857–1874

Dare RA, McBride JL (2011) Sea surface temperature response to tropical cyclones. Mon Weather Rev 139:3798–3808

Domingues R, Goni G, Bringas F, Lee SK, Kim HS, Halliwell G, Dong J, Morell J, Pomailes L (2015) Upper ocean response to hurricane gonzo (2014): salinity effects revealed by targeted and sustained underwater glider observations. Geophys Res Lett 42:7131–7138

Donelan MA (2004) On the limiting aerodynamic roughness of the ocean in very strong winds. Geophys Res Lett 31:L18306

Drost EF, Lowe RJ, Ivey GN, Jones NL, Periquet CG (2017) The effects of tropical cyclone characteristics on the surface wave fields in Australia’s North West region. Cont Shelf Res 139:35–53

Emanuel KA (1999) Thermodynamic control of hurricane intensity. Nature 401:665–669

Emanuel K (2001) Contribution of tropical cyclones to meridional heat transport by the oceans. J Geophys Res Atmos 106:14771–14781

Emanuel K, Desautels C, Holloway C, Korty R (2004) Environmental control of tropical cyclone intensity. J Geophys Res 61(7):843–858

Esquivel-Trava B, Ocampo-Torres FJ, Osuna P (2015) Spatial structure of directional wave spectra in hurricanes. Ocean Dyn 65:65–76

Fan Y, Ginis I, Hara T, Wright CW, Walsh EJ (2009) Numerical simulations and observations of surface wave fields under an extreme tropical cyclone. J Phys Oceanogr 39:2097–2116

Fedorov AV, Brierley CM, Emanuel K (2010) Tropical cyclones and permanent El Nino in the early plococene epoch. Nature 463:1066–1070

Firing E, Lien RC, Muller P (1997) Observations of strong inertial oscillations after the passage of tropical cyclone ofa. J Geophys Res Oceans 102:3317–3322

Foltz GR, Balaguru K, Leung LR (2015) A reassessment of the integrated impact of tropical cyclones on surface chlorophyll in the western subtropical North Atlantic. Geophys Res Lett 42:1158–1164

Fu H, Wang X, Chu PC, Zhang X, Han G, Li W (2014) Tropical cyclone footprint in the ocean mixed layer observed by argo in the Northwestern Pacific. J Geophys Res Oceans 119:8078–8092

Galevsky S, Stark CP, Sadson S, Wu CC, Sobel AH, Horng MJ (2006) Tropical cyclone triggering of sediment discharge in Taiwan. J Geophys Res Earth Surf 111:F03014

Geisler JE (1970) Linear theory of the response of a two layer ocean to a moving hurricane. Geophysical Fluid Dyn 1:249–272

Gill AE (1984) On the behavior of internal waves in the wakes of storms. J Phys Oceanogr 14:1129–1151

Girishkumar MS, Suprit K, Chiranjivi J, Bhaskar TVSU, Shesu RV, Rao EPR (2014) Observed oceanic response to tropical cyclone jal from a moored buoy in the South-Western Bay of Bengal. Ocean Dyn 64:325–335

Gillen SM, Miles TN, Seroka GN, Xu Y, Forney RK, Yu F, Roarty H, Schofield O, Kohut J (2016) Stratified coastal ocean interactions with tropical cyclones. Nat Commun 7:10887

Greatbatch RJ (1983) On the response of the ocean to a moving storm: the nonlinear dynamics. J Phys Oceanogr 13:357–367

Greatbatch RJ (1984) On the response of the ocean to a moving storm: parameters and scales. J Phys Oceanogr 14:59–78

Greatbatch RJ (1985) On the role played by upwelling of water in lowering sea surface temperatures during the passage of a storm. J Geophys Res 90:11751

Grodksy SA, Reul N, Lagerloef G, Reverdin G, Carton JA, Chapron B, Quilfen Y, Kudryavtsev VN, Kao HY (2012) Haline hurricane wake in the Amazon/Orinoco plume: AQUARIUS/SACD and SMOS observations. Geophys Res Lett 39(20) L20663

Guo S, Zhao W, Huuthance J, Tian J, Wang J (2014) Observed upper ocean response to typhoon meg from a moored buoy in the South-Western Bay of Bengal. Ocean Dyn 64:1175–1185

Hart RE, Maue RN, Watson MC (2007) Estimating local memory of tropical cyclone characteristics on continental margin sedimentation in the Mississippi delta region. Cont Shelf Res 27:1857–1874

Halliwell GR, Shay LK, Brevester JK, Teague WJ (2011) Evaluation and sensitivity analysis of an ocean model response to hurricane Ivan. Mon Weather Rev 139:921–945

Han G, Ma Z, Chen D, Deyoung B, Chen N (2012) Observing storm surges from a moored buoy. Acta Oceanol Sin 31:253–270

Huihji Y, Yoshida K, Watanabe S, Sato T, Chang SW, Ikeda K, Wang X (2011) Evaluation of reanalysis systems for tropical cyclones in the Northwest Pacific. Geophys Res Lett 38:L12802

Huihji Y, Yoshida K, Watanabe S, Sato T, Chang SW, Ikeda K, Wang X (2011) Evaluation of reanalysis systems for tropical cyclones in the Northwest Pacific. Geophys Res Lett 38:L12802

Huihji Y, Yoshida K, Watanabe S, Sato T, Chang SW, Ikeda K, Wang X (2011) Evaluation of reanalysis systems for tropical cyclones in the Northwest Pacific. Geophys Res Lett 38:L12802

Huihji Y, Yoshida K, Watanabe S, Sato T, Chang SW, Ikeda K, Wang X (2011) Evaluation of reanalysis systems for tropical cyclones in the Northwest Pacific. Geophys Res Lett 38:L12802
Hazelworth JB (1968) Water temperature variations resulting from hurricanes. J Geophys Res 73:5105–5123
He HL, Chen DK (2011) Effects of surface wave breaking on the oceanic boundary layer. Geophys Res Lett 38(7):L07604
He HL, Wu QY, Chen DK, Sun J, Liang CJ, Jin WF, Xu Y (2018) Effects of surface waves and sea spray on the air-sea fluxes during the passage of Typhoon Hagupit. Acta Oceanol Sin 37(5):1–7
Hearn CJ, Holloway PE (1990) A three-dimensional barotropic model of the response of the Australian North West Shelf to tropical cyclones. J Phys Oceanogr 20:60–80
Hsu PC, Ho CR (2018) Typhoon-induced ocean subsurface variations from glider data in the Kuroshio region adjacent to Taiwan. J Oceanogr 75:1–21
Hu K, Chen Q (2011) Directional spectra of hurricane-generated waves in the Gulf of Mexico. Geophys Res Lett 38:L19608
Hu A, Meehl GA (2009) Effect of the Atlantic hurricanes on the oceanic meridional overturning circulation and heat transport. Geophys Res Lett 36:L03702
Huang SM, Oey LY (2015) Right-side cooling and phytoplankton bloom in the wake of a tropical cyclone. J Geophys Res Oceans 120:5735–5748
Huang PS, Sanford TB, Imberger J (2009) Heat and turbulent kinetic energy budgets for surface layer cooling induced by the passage of Hurricane Frances (2004). J Geophys Res Oceans 114:C12023
Huang W, Weisberg RH, Zheng L, Zilema M (2013) Gulf of Mexico hurricane wave simulations using SWAN: bulk formula-based drag coefficient sensitivity for hurricane ike. J Geophys Res Oceans 118:3916–3938
Hung CC, Chung CC, Gong GC, Jan S, Tsai Y, Chen KS, Chou WC, Lee MA, Chang Y, Chen MH, Yang WR, Tseng CJ, Gawarkiewicz G (2013) Nutrient supply in the Southern East China sea after Typhoon Morakot. J Mar Res 71:133–149
Hung PA, Walsh EJ (2018) Propagation directions of ocean surface waves inside tropical cyclones. J Phys Oceanogr 48:1495–1511
Iwano K, Takagaki N, Kurose R, Komori S (2013) Mass transfer velocity across the breaking-air-water interface at extremely high wind speeds. Tellus B 65:1341
Jacob SD, Shiad L, Marciano AJ, Black PG (2000) The 3D oceanic mixed layer response to hurricane Gilbert. J Phys Oceanogr 30:1407–1429
Jaimes B, Shay LK (2009) Mixed layer cooling in mesoscale oceanic eddies during hurricanes Katrina and Rita. Mon Wea Rev 137(12):4188–4207
Jaimes B, Shay LK (2010) Near-inertial wave wake of hurricanes Katrina and Rita over mesoscale oceanic eddies. J Phys Oceanogr 40(6):1330–1337
Jaimes B, Shay LK (2015) Enhanced wind-driven downsploring flow in warm oceanic eddies during the intensification of tropical cyclone ISAAC (2012): observations and theory. J Phys Oceanogr 45(6):1667–1689
Jansen MF, Ferrant R, Mooring TA (2010) Seasonal versus permanent thermocline warming by tropical cyclones. Geophys Res Lett 37:L03602
Jarosz E, Hallock ZR, Teague WJ (2007) Near-inertial currents in the DeSoto Canyon region. Continent Shelf Res 27:2407–2426
Jiang G, Xu J, Wei J (2018) A deep learning algorithm of neural network for the parameterization of typhoon-ocean feedback in typhoon forecast models. Geophys Res Lett 45:3706–3716
Jin W, Liang C, Hu J, Meng Q, Lu H, Wang Y, Lin F, Chen X, Liu X (2020) Modulation effect of mesoscale eddies on sequential typhoon-induced oceanic responses in the South China Sea. Remote Sens 12:2059
Jochum M, Briegleb BP, Danabasoglu G, Large WS, Norton N, Jayne SR, Alfred MH, Bryan FO (2013) The impact of oceanic near-inertial waves on climate. J Clim 26:2833–2844
Jourdain NC, Lengaigne M, Vialard J, Madec G, Menkes CE, Vincent EM, Jullien S, Barrier B (2013) Observation-based estimates of surface cooling inhibition by heavy rainfall under tropical cyclones. J Phys Oceanogr 43:205–221
Keim BD, Muller RA, Stone GW (2007) Spatiotemporal patterns and return periods of tropical storm and hurricane strikes from Texas to Maine. J Clim 20:3498–3509
Kraul KE, Jahne B (2014) First laboratory study of air-sea gas exchange at hurricane wind speeds. Ocean Sci 10(2):257–265
Komori S, Takahashi K, Kurono L, Osinski R, Takagaki N, Iwano K, Suzuki N (2018) Laboratory measurements of heat transfer and drag coefficients at extremely high wind speeds. J Phys Oceanogr 48:959–974
Korty RL, Emanuel KA, Scott JR (2008) Tropical cyclone-induced upper-ocean mixing and climate: application to equable climates. J Clim 21:638–654
Krishnamurti TN, Kistinwal CM, LaRow TE, Bachiori DR, Zhang Z, Willford CE, Gadgil S, Surendran S (1999) Improved weather and seasonal climate forecasts from multimodel superensemble. Science 285:1548–1550
Kundu PK (1976) An analysis of inertial oscillations observed near oregon coast. J Phys Oceanogr 6:879–893
Lacroix P, Carter R (2004) Cyclone pumping, sediment partitioning and the development of the great barrier reef shelf system: a review. Quat Sci Rev 23:107–135
Li X, Han G, Yang J, Chen D, Zheng G, Chen N (2018) Using satellite altimetry to calibrate the simulation of typhoon seth storm surge off Southeast China. Remote Sens 10:657
Li Y, Peng S, Wang J, Yan J (2014) Impacts of nonbreaking wave-stirring-induced mixing on the upper ocean thermal structure and typhoon intensity in the South China Sea. J Geophys Res Oceans 119:5052–5070
Lin FN, Song JB, He HL, Li S, X, Guan SD (2016) Assessment of surface drag coefficient parameterizations based on observations and simulations using the Weather Research and Forecasting model. Atmos Oceanic Sci Lett 9(4):327–336
Lian T, Chen D, Tang Y, Liu X, Feng J, Zhou L (2018) Linkage between westerly wind bursts and tropical cyclones. Geophys Res Lett 45:11431–11438
Lian T, Ying J, Ren HL, Zhang C, Liu T, Tan XX (2019) Effects of tropical cyclones on ENSO. J Clim 32:6424–6443
Liang J-H, D'Asaro EA, McNeil C, Fan Y, Harcourt RR, Emerson SR, Yang B, Sullivan PP (2020) Suppression of CO2 outgassing by gas bubbles under a hurricane. Geophys Res Lett 47:20
Lin H, Liu WT, Wu C-C, Chang JCH, Sui C-H (2003a) Satellite observations of modulation of surface winds by typhoon-induced upper ocean cooling. Geophys Res Lett 30(31):131
Lin H, Liu WT, Wu C-C, Wong GFT, Hu C, Chen Z, Liang W-D, Yang Y, Liu K-K (2003b) New evidence for enhanced ocean primary production triggered by tropical cyclone. Geophys Res Lett 30:1718
Lin YC, Oey LY (2016) Rainfall-enhanced blooming in typhoon wakes. Sci Rep 6:31310
Lin H, Wu C-C, Pun IF, Ko DS (2008) Upper-ocean thermal structure and the Western North Pacific category 5 typhoons. Part I: ocean features and the category 5 typhoons' intensification. Mon Wea Rev 136:3288–3306
Lin S, Zhang W-Z, Shang S-P, Hong HS (2017) Ocean response to typhoons in the western North Pacific: composite results from Argo data. Deep-Sea Res, Part I 123:652–74
Liu J, Lou YW, Wu MX, Lee YJ, Cheng CH, Kuei CP, Hong RM (2015) Analysis of interactions among two tropical depressions and typhoons tembin and bolaven (2012) in Pacific ocean by using satellite cloud images. IEEE Trans Geosci Remote Sens 53:1394–1402
Liu SS, Sun L, Wu Q, Yang YJ (2017) The responses of cyclonic and anticyclonic eddies to typhoon forcing: the vertical temperature-salinity structure changes associated with the horizontal convergence/divergence. J Geophys Res Oceans 122:4974–4989
Liu LL, Wang W, Huang RX (2008) The mechanical energy input to the ocean induced by tropical cyclones. J Phys Oceanogr 38:1253–1266
Liu JT, Wang YH, Yang RJ, Hsu RT, Kao SJ, Lin HL, Kuo FH (2012) Cyclone-induced hyperpycnal turbidity currents in a submarine canyon. J Geophys Res Oceans 117:C04033
Liu X, Li PC, Liang BM, Liu J, Zhao C, Song G (2008) A new technique for typhoon aerosol detection. IEEE Trans Geosci Remote Sens 46:2012–2021
Liu Z, Wang G, Zhang X (2016) Response of a preexisting cyclonic ocean eddy to a typhoon. J Phys Oceanogr 46:2403–2410
parametrization of mixing from unbroken surface waves. J Adv Model Earth Syst 9:759–780
Sullivan PP, Romero L, McWilliams JC, Melville WK (2012) Transient evolution of Langmuir turbulence in ocean boundary layers driven by hurricane winds and waves. J Phys Oceanogr 42:1959–1980
Sun Y, Chen C, Beardsley RC, Xu Q, Qi J, Lin H (2013) Impact of current-wave interaction on storm surge simulation: a case study for hurricane bob. J Geophys Res Oceans 118:2685–2701
Sun J, He HL, Hu XM, Wang DQ, Gao C, Song JB (2019) Numerical simulations of typhoon Hagupit (2008) using WRF. Wea Forecasting 34(4):999–1015
Sun L, Li YY, Yang YL, Wu Q, Chen XT, Li QY, Li YB, Xian T (2014) Effects of super typhoons on cycloonic ocean eddies in the Western North Pacific: a satellite-data-based evaluation between 2000 and 2008. J Geophys Res Oceans 119:5585–5598
Sun J, Oey LY, Chang R, Xu F, Huang S-M (2015) Ocean response to typhoon Nuri (2008) in western Pacific and South China Sea. Ocean Dyn 65(S1):735–747
Sun L, Yang Y, Xian T, Lu Z, Fu Y (2010) Strong enhancement of chlorophyll a concentration by a weak typhoon. Mar Ecol Prog Ser 404:39–50
Tang DL, Kawamura H, Van Dien T, Lee MA (2004b) Offshore phytoplankton biomass increase and its oceanographic causes in the South China sea. Mar Ecol Prog Ser 268:31–41
Tian D, Zhang H, Zhang W, Zhou F, Sun X, Zhou Y, Ke D (2020) Wave glider observations of surface waves during three tropical cyclones in the South China Sea. Water 12:1331
Toffoli A, McConochie J, Ghantous M, Loffredo L, Babanin AV (2012) The effect of wave-induced turbulence on the ocean mixed layer during tropical cyclones: field observations on the Australian North-West shelf. J Geophys Res Oceans 117:C4
Vissa NK, Satyanarayana ANV, Kumar BP (2012) Response of upper ocean during passage of MALA cyclone utilizing ARGO data. Int J Appl Earth Obs Geoinf 14:149–159
Vissa NK, Satyanarayana ANV, Kumar BP (2013) Response of upper ocean and impact of barrier layer on side cyclone induced sea surface cooling. Ocean Sci J 48:279–288
Walker ND, Leiben RR, Balasubramanian S (2005) Hurricane-forced upwelling and chlorophyll enhancement in cold-core cyclones in the Gulf of Mexico. Geophys Res Lett 32:L18610
Wang Y (2020) Composite of typhoon induced sea surface temperature and chlorophyll-a responses in the South China Sea. J Geophys Res Oceans 125:20
Wang D, Kukulka T, Reichl BG, Hara T, Ginis I (2019a) Wind-wave misalignment effects on Langmuir turbulence in tropical cyclone conditions. J Phys Oceanogr 49:3109–3126
Wang D, Kukulka T, Reichl BG, Hara T, Ginis I, Sullivan PP (2018) Interaction of Langmuir turbulence and inertial currents in the ocean surface boundary layer under tropical cyclones. J Phys Oceanogr 48(1921):1940
Wang Q, Li J, Jin FF, Chan JCL, Wang C, Ding R, Sun C, Zheng F, Feng J, Xie F, Li Y, Lu F, Xu Y (2019b) Tropical cyclones act to intensify El Nino. Nat Commun 10:3793
Wang DW, Mitchell DA, Teague WJ, Jarosz E, Hulbert MS (2005) Extreme waves under hurricane Ivan. Science 309:896
Wang D, Kukulka T, Reichl BG, Hara T, Ginis I, Sullivan PP (2018) Interaction of Langmuir turbulence and inertial currents in the ocean surface boundary layer under tropical cyclones. J Phys Oceanogr 48(1921):1940
Wang DP, Oey LY (2008) Hindcast of waves and currents in hurricane katrina. Bull Am Meteorol Soc 89:487–496
Wang G, Wu L, Johnson NC, Ling Z (2016) Observed three-dimensional structure of ocean cooling induced by Pacific tropical cyclones. Geophys Res Lett 43:7632–7638
Wei J, Jiang G, Liu X (2017) Parameterization of typhoon-induced ocean cooling using temperature equation and machine learning algorithms: an example of typhoon Soulik (2013). Ocean Dyn 67:1179–1193
Wei J, Liu X, Jiang G (2018) Parameterizing sea surface temperature cooling induced by tropical cyclones using a multivariate linear regression model. Acta Oceanol Sin 37(1–10)
surface mixed layer to Supertyphoon Haitang (2005). J Phys Oceanogr 48:1651–1674
Zhang W, Cui Y, Santos A, Hanebuth TJJ (2016) Storm-driven bottom sediment transport on a high-energy narrow shelf (NWiberia) and development of mud depocenters. J Geophys Res Oceans 121:5751–5772
Zhang X, Han G, Wang D, Deng Z, Li W (2012) Summer surface layer thermal response to surface gravity waves in the yellow sea. Ocean Dyn 62:983–1000
Zhang X, Han G, Wang D, Li W, He Z (2011) Effect of surface wave breaking on the surface boundary layer of temperature in the yellow sea in summer. Ocean Model 38:267–279
Zhang H, Liu X, Wu R, Chen D, Zhang D, Shang X, Wang Y, Song X, Jin W, Yu L, Qi Y, Tian D, Zhang W (2020) Sea surface current response patterns to a tropical cyclones. J Mar Syst 12:56
Zhang H, Liu X, Wu R, Liu F, Yu L, Shang X, Qi Y, Wang Y, Song X, Xie X, Yang C, Tian D, Zhang W (2019) Ocean response to successive typhoons Sarika and Haiyan (2016) based on data acquired via multiple satellites and moored array. Remote Sens 11:2360
Zhang T, Song JB (2018) Effects of sea surface waves and ocean spray on air-sea momentum fluxes. Adv Atmos Sci 35:469–478
Zhang H, Wu R, Chen D, Liu X, He H, Tang Y, Ke D, Shen Z, Li J, Xie J, Tian D, Ming J, Liu F, Zhang D, Zhang W (2018) Net modulation of upper ocean thermal structure by typhoon kalmaegi (2014). J Geophys Res Oceans 123:7154–7171
Zhang D, Zhang H, Zheng J, Cheng X, Tian D, Chen D (2020a) Changes in tropical-cyclone translation speed over the Western North Pacific. Atmosphere 11:93
Zhao H, Pan J, Han G, Devlin AT, Zhang S, Hou Y (2017) Effect of a fast-moving tropical storm wash on phytoplankton in the northwestern South China sea. J Geophys Res Oceans 122:3404–3416
Zhao B, Qiao F, Wang G (2008) The effects of the non-breaking surface wave-induced vertical mixing on the forecast of tropical cyclone tracks. Chin Sci Bull 59:3075–3084
Zhao H, Tang D, Wang Y (2008) Comparison of phytoplankton blooms triggered by two typhoons with different intensities and translation speeds in the South China sea. Mar Ecol Prog Ser 365:65
Zheng ZW, Ho CR, Zheng Q, Kuo NJ, Lo YT (2010) Satellite observation and model simulation of upper ocean biophysical response to super typhoon nakri. Cont Shelf Res 30:1450–1457
Zhao H, Tang D, Wang Y (2008) The effects of the non-breaking surface wave-induced vertical mixing on the forecast of tropical cyclone tracks. Chin Sci Bull 59:3075–3084
Publisher’s Note
Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.