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News & Views

Unmanned vehicles probed inner-core air-sea conditions during Super Typhoon Koinu (2023)

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Tropical cyclones (TCs) are intense synoptic phenomena significantly impacting the upper ocean environment and influencing not only local air-sea interactions but also long-term ocean heat budgets, ocean circulations and sediment transports [1,2]. Because of strong winds, severe precipitations and unfavourable ocean conditions [1,3], it is difficult to obtain *in situ* observations during TCs, which limits the understanding of TC-ocean interactions. Traditional field observations during TCs are performed mainly via moored buoys/moorings [4], Argo floats [5], drifters [6] and air-deployed profiling floats [7]. These observation systems are deployed in the ocean in advance, and air-sea conditions are observed during TCs. Recently, autonomous vehicles (e.g., underwater gliders, wave gliders, and saildrones) have become reliable technologies for sampling the ocean during TCs [8,9]. Mobile vehicles can constitute an array [10], providing new methods and data for identifying TC-ocean interactions. Data collected via mobile platforms have increased the understanding of upper ocean processes and the representation of ocean operational coupled forecast models for the TC intensity and the air-sea environment [11]. Although oceanic unmanned vehicles have recently been developed and applied, *in situ* observations close to TC centres are still lacking. In October 2023, Super Typhoon Koinu passed over an unmanned observation array comprising underwater gliders and wave gliders in the Northwest Pacific and northern South China Sea (Fig. 1a-h), yielding a valuable dataset to directly study air-sea interactions close to the TC centre. Wave glider 3 (WG-3) occurred ∼10.57 km from the centre of Koinu at UTC 03:26 on 4 October, whereas underwater glider 1 (UG-1) occurred ∼93.64 km from the centre of Koinu at UTC 15:28 on 5 October. Thus, observations provided by WG-3 and UG-1 are shown and analysed here because of their close proximity of these gliders to the TC centre that observed inner-core air-sea conditions as well as the good quality of the provided data.

WG-3 is equipped with an automatic meteorological station ∼1.2 m above the sea surface and a temperature sensor at the surface (∼0 m), with data output nearly every 10 min. WG-3 recorded the minimum air pressure (∼940 hPa, Fig. 1k) at a low average wind speed (∼4 m/s), and the maximum wind speed was ∼11 m/s when the wave glider was closest to the TC centre. Two wind speed peaks were recorded immediately before and after the minimum air pressure and maximum wind speed (Fig. 1i), indicating that the eye of Koinu passed over WG-3. The post-eye average and maximum wind speed peaks (approximately 35.4 and 48.5 m/s, respectively) were greater than the pre-eye peaks (approximately 25.1 and 35.4 m/s, respectively), indicating that the eyewall was stronger in its rear part than in its front part. The air humidity increased from ∼75% in the background to ∼95% at the pre-TC centre (2 to 3 October) and ∼90% at the post-TC centre (4 to 5 October), as shown in Fig. 1k. The air humidity recovered to ∼75% on 6 October after TC passage. The wind speed increased relatively smoothly before 4 October and decreased relatively sharply after 4 October (Fig. 1i), possibly partly because WG-3 moved northwestwards and nearly perpendicular to the TC track before 4 October, rotated clockwise and then southeastwards approximately along the TC track after 4 October (Fig. 1a, d). Observed sea surface winds usually rotate clockwise on the right side of the TC track and anticlockwise on the left side [7]. The values recorded by WG-3 may also indicate the compression of wind isolines when Koinu travelled through the Luzon Strait and was influenced by Taiwan Island. The directions of the maximum winds greatly differed from those of the average winds and demonstrated spinning (Fig. 1i, m), which indicated, unless there were observation errors, small near-surface wind curls (e.g., helical roll circulations [12,13]). Previous observations also revealed the spinning of TC sea surface winds in the TC outer region [14].

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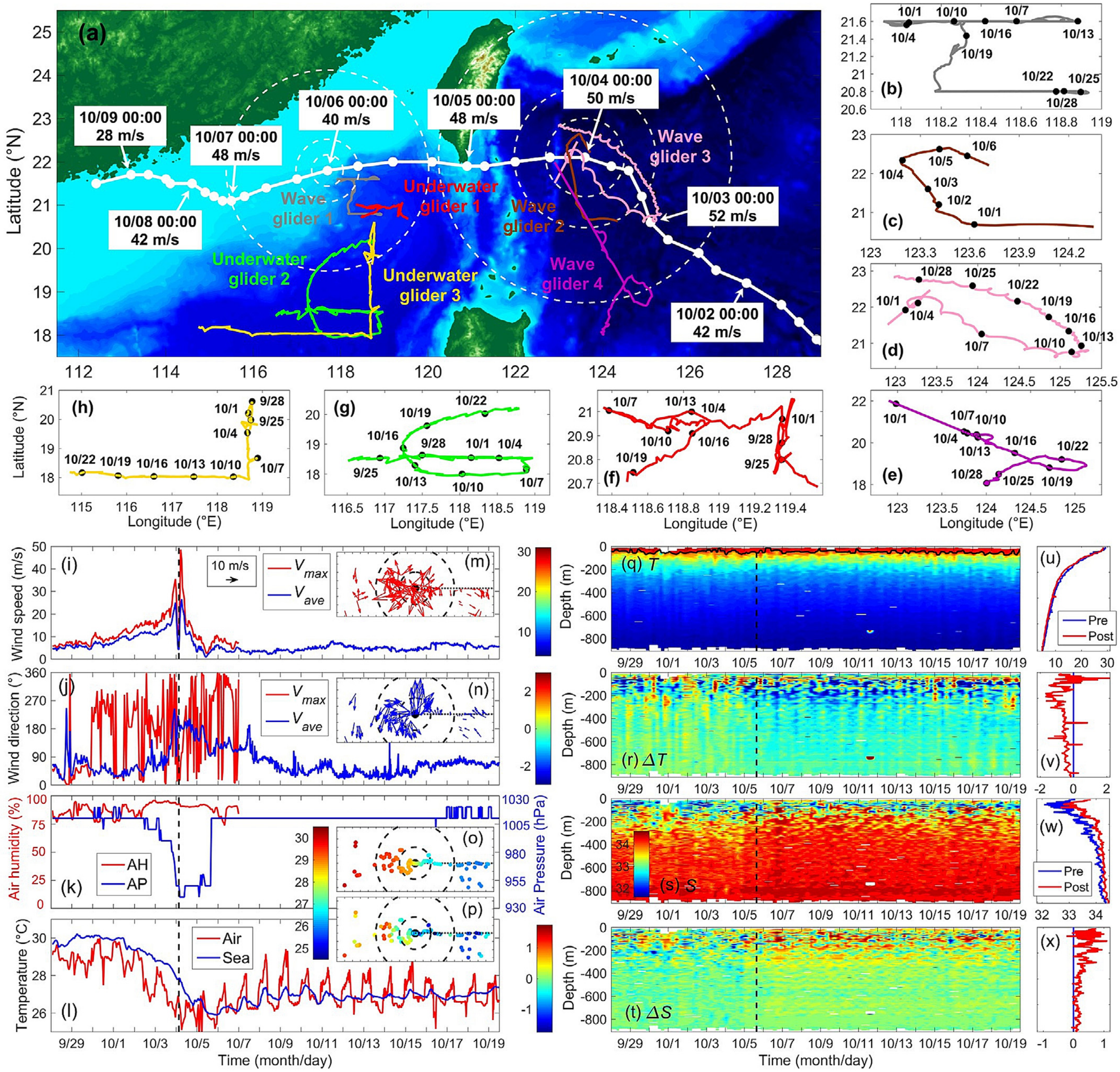

Fig. 1. Information on Typhoon Koinu (2023) and unmanned mobile observations (a-h), with observations provided by wave glider 3 (i-p) and underwater glider 1 (q-x). (a) Tracks of Typhoon Koinu (2023) and unmanned mobile observations. The white dashed circles denote the radii of gale-force winds of levels 7 (13.9–17.1 m/s), 10 (24.5–28.4 m/s) and 12 (32.7–36.9 m/s). (b-h) Tracks of the wave gliders and underwater gliders. (i) Maximum wind speed (red, m/s) and average wind speed (blue, m/s). (j) Same as (b) but for the wind direction (°). (k) Air humidity (red, %) and air pressure (blue, hPa). (l) Air temperature (red, °C) and sea surface temperature (blue, °C). (m-p) TC-relative maximum wind (m), average wind (n), air temperature (o) and sea surface temperature (p). (q-x) Ocean temperature (°C, q), salinity (psu, r) and anomalies (s, t), with their pre-TC (blue) and post-TC (red) averages (u-x). In (m-p), the black dots indicate the TC centre, the dashed black lines indicate 2 and 5 times the radius of wind greater than 10 (24.5–28.4 m/s), and the black dotted lines indicate the TC track. In (q-x), the average values over two days (2 to 3 October) refer to pre-TC average values, and the average values over three inertial periods after 7 October refer to post-TC average values. The vertical dashed black lines denote the time when underwater glider 1 was closest to Koinu (15:28 on 5 October), and the solid black line in (q) denotes the isotherm at 26 °C. The times in (a-x) are expressed in coordinated universal time (UTC).

The sea surface temperature (SST) observed by WG-3 (Fig. 1l, p) decreased from ∼30 °C beginning on 30 September and reached its minimum (∼26 °C) nearly two days after the glider occurred closest to the TC centre (6 October), indicating that Koinu subsequently induced cold sea surface wakes and that SST cooling continued shortly after TC passage, which is consistent with previous observations obtained via air-deployed profiling [7]. The surface air temperature was lower than the SST before 6 October, and the difference reached ∼2 °C at night from 2 to 3 October (Fig. 1k, l, o, p), indicating the transfer of sensible heat from the ocean to the air before and during Koinu. The post-TC SST increased gradually with the diurnal cycle of the surface air temperature but only reached ∼27.5 °C on 10 October but did not return to the value before the TC (∼30 °C), which may be partly due to seasonal background cooling, as the air-sea temperature in the whole region decreases in autumn, and the TC accelerated such cooling through the disruption of the pre-TC air-sea balance and formed another post-TC air-sea state.

UG-1 is equipped with a conductivity-temperature-depth (CTD) sensor that outputs data every 10 s and observes water from the surface (∼0 m) to a depth of ∼900 m. UG-1 occurred on the left side of the track of Typhoon Koinu and at nearly one to two times the radius of its level 10 wind (Fig. 1a and f). The diurnal tide influences the local temperature and salinity variations, but the impact of the TC was still significant at UG-1 (Fig. 1q-t). Koinu cooled the sea surface by ∼0.9 °C (Fig. 1q, r) and increased the sea surface salinity by ∼0.7 psu (Fig. 1k, t), indicating the entrainment of cold and saline water from the subsurface to the surface, and the occurrence of very low TC rainfall at UG-1. The TC-induced deepening of the mixed layer was limited, as the subsurface warm anomaly was thin (from 30 to 80 m), at ∼0.3 °C on average. As mentioned in previous works, vertical mixing is usually lower on the left side of the TC track than on the right side [4,7]. The tropical cyclone heat potential (TCHP), which is the vertical integration of the ocean temperatures above 26 °C decreased from ∼1497.7 to ∼1385 m°C with a reduction of ∼112.5 m°C at UG-1. There was nearly no net subsurface negative salinity because the initial subsurface salinity near a depth of 50 m was lower than that at the surface, and mixed layer deepening mainly increased the salinity. Below 85 m, Koinu induced net uplift of the temperature and salinity profiles at distances ranging from 10 to 50 m, resulting in a net cold anomaly of ∼1 °C and a net positive salinity anomaly of ∼0.5 psu near the 200-m depth (Fig. 1v, x). In general, net upwelling is caused by wind stress curls near the TC centre [1,4]. Averaged over three inertial periods after 7 October, the post-TC net cooling from 0 to 900 m was ∼470.0 m°C, which is ∼0.52 °C on average for the whole water column. In other words, the average vertical temperature anomaly was similar to that in the case controlled by vertical mixing and moderate upwelling mentioned in Ref. [4]. The observations of UG-1 also indicated that the TC-induced upwelling at least exceeded than the range of TC level-10 winds generated by Koinu and was deep enough to reach the ocean interior (>900 m). The local inertial frequency was ∼5.2 × 10^{-5} s, with inertial periods of ∼33.5 h and ∼1.4 days; notably, the near-inertial vertical oscillations in the temperature and salinity isolines at UG-1 were not as clear as those in previous observations of the TC track [7], indicating limited near-inertial pumping at UG-1. After Koinu, cold and saltwater anomalies still occurred within two weeks, with weak recovery (Fig. 1q-t), indicating that the TC-induced modulation of ocean stratification could be sustained for a long period.

Unmanned vehicles, which are more economical, more intelligent and swifter than traditional moored observation platforms, provide new methods for observing air-sea interfaces and upper ocean conditions. TC-oriented ocean observation systems that emphasize the application of unmanned vehicles have been a popular research topic in recent years [9,15]. This study provides a case with an array of unmanned vehicles, indicating that data from the core region influenced by tropical cyclones can be obtained, which has been observed less frequently before, and these data exhibit great potential for increasing our understanding of TC-ocean interactions. Further network observations with multiple mobile vehicles are needed, but this study provides insight into the processes of air-sea interactions during tropical cyclones.

Conflict of interest

The authors declare that they have no conflict of interest.

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Author contributions

Han Zhang performed the data analysis, wrote the entire manuscript, and created the figures and the table. Di Tian performed certain analysis of Typhoon Koinu (2023) and some primary data analyses and revised the manuscript. Yutong Sun and Ming Yang performed preprocessing and quality control of the underwater glider data. Shaoqiong Yang provided the underwater glider data and revised the entire manuscript. Ying Zhou performed preprocessing and quality control of the wave glider data. Xiujun Sun provided the wave glider data. Dake Chen provided suggestions for observation design and analysis.

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