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# The cold wake of typhoon Chaba (2010)

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ABSTRACT

The cold wake of typhoon Chaba (2010) is investigated using an array of temperature sensors connected from the surface to 540 m along the mooring line of an air-sea interaction buoy. Initially, surface forcing caused upper ocean water to entrain across the base of the thermocline, producing a mixed layer cooling and subthermocline warming between 42 and 100 m. However, this warm layer lasted just 12 h before it became overwhelmed by an upwelling of cold water. Observations indicate this upwelling occurred to at least 540 m while further analysis suggests that the actual depth of the ocean response to Chaba was closer to 700 m. This caused a massive reduction in heat content at the mooring site. The sea surface temperature decreased 2.5 °C. Due to the lateness of the season, the ocean didn't recover to its pre-typhoon state, however, after sixteen days it did match the temperature outside the wake. These observations reveal intricate processes in a cold wake that redistribute heat between the mixed layer, the subthermocline region, and greater depths. This has implications for tropical storm intensity—by altering enthalpy fluxes, and climate—through the lateral and vertical movement of water which modifies the local temperature profile and impacts the transportation of heat to high latitudes.

## 1. Introduction

Satellites provide information about the surface cooling in tropical cyclone (TC) wakes, their horizontal spatial distribution, and the time it takes for the sea surface temperature (SST) to recover (e.g., Mrvaljevic et al., 2013). However, they provide little information about below surface cooling and heat budgets, so in situ observations are essential to form a cohesive picture of the ocean under TCs. This is beneficial for TC forecasting because high wind speeds in TCs generate strong, near-inertial internal waves which efficiently mix the upper ocean (Price et al., 1981) bringing cool water to the surface. It was long-ago shown that TCs strengthen over warmer surface water and weaken over cooler (Fisher, 1958). This is because TCs get their energy from surface fluxes. A strong relationship between SST and TC intensity has been demonstrated many times (e.g., DeMaria and Kaplan, 1994) and a cold wake can reduce TC intensity by up to 70% (Schade and Emanuel, 1999).

Another significant advantage of recording the ocean response to TCs from the surface to depth is that it helps guide our understanding of the impact TCs have on climate. When water is entrained across the thermocline creating a cold wake, heat is simultaneously transported to below the thermocline base (e.g., Potter et al., 2017). Cold wakes last several days or weeks while surface fluxes return the surface water to its approximate pre-TC temperature. Meanwhile, the warmed subthermocline water remains, resulting in a net warming of the water column. Some studies (e.g., Emanuel, 2001; Sriver and Huber, 2007) have suggested this contributes substantially to the annual poleward heat flux by the oceans. However, the equation becomes more complex when considering the upwelling of cold water from deep below the mixed layer. This cold water can reduce or eliminate the heat mixed across the thermocline whereby mitigating the entrainment warming (e.g., Greatbatch, 1985) and altering the potential climate impact. Insight into the contributions of mixing and upwelling under TCs, which are essential for understanding the global impacts of TCs on climate, are best gained through observations.

Observations of TC cold wakes frequently report temperatures are impacted in the upper tens of meters (e.g., Black and Dickey, 2008), less frequently to depths in excess of 100 m (e.g., D'Asaro et al., 2007), and few to several hundred meters. Leipper (1967) and Jaimes and Shay (2009) reported at least 300 m, and Pudov et al. (1979) reported 350 m. Withee and Johnson (1976) observed current disturbance at 530 m, showing TC impacts can extend to even greater depths, and some models (e.g., Jullien et al., 2012) suggest an ocean thermal response to over 500 m is possible. Here, as never before, observational evidence is presented that shows the ocean temperature decreased following Typhoon Chaba to at least 540 m, a parametric analysis indicates that the actual depth was closer to 700 m. This led to a large net decrease in ocean heat content at the mooring site, the implications of which are discussed. The manuscript is laid out as follows: the data and experimental method are introduced in Section 2, results are presented in Section 3, discussion is reserved for Section 4, and concluding remarks are in Section 5.

## 2. Experiment and data

The Impact of Typhoons on the Ocean in the Pacific (ITOP) field campaign took place between August and November 2010. The aim was to studying the ocean response to TCs in the Philippine Sea using multiple instruments, platforms, ships, aircraft, models, and satellites. The campaign has been written about extensively (e.g., D'Asaro et al., 2014; Potter et al., 2015a; Collins et al., 2018) so it will not be rehash

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here.

Data examined herein were collected from an Extreme Air-Sea Interaction (EASI) buoy. EASI is a surface follower with 6 m hull and equipped to record above and below surface parameters including ocean temperatures using an array of recorders connected to the mooring line. See Drennan et al. (2014) for an EASI photo and additional information about its design, instruments, and mooring layout, as well as time series of wave height and atmospheric parameters including air temperature, humidity, atmospheric pressure, and shortwave radiation.

Potter et al. (2017) hereafter P17, provides an overview of ocean temperatures during ITOP which were recorded at two mooring locations over approximately 90 days and includes data collected in a tropical storm and three typhoons. Several temperature loggers reached capacity and stopped recording around day of year (DOY) 305 when EASI's original recovery was scheduled. These included loggers at the surface and upper 40 m. Temperatures at these depths were essential to P17's narrative and limited the study period presented in that manuscript. However, EASI's recovery was postponed because it coincided with typhoon Chaba, consequently, several temperature recorders continued operating for several weeks. These data, collected at the northernmost mooring, build upon the research presented in P17 by extending temperatures from DOY 305 to DOY 328 and from 150 m to 540 m (deep ocean temperature was previously neglected because of P17's focus on the upper ocean). The result, presented here, provide a detailed study of ocean temperature following typhoon Chaba.

Observational data is supplemented with optimally interpolated (OI) microwave plus infrared satellite SST. These have 9 km grid resolution and were obtained from remote sensing systems (RSS). Satellite SSTs represent the foundation temperature at noon local time.

EASI was deployed approximately 750 km east of Taiwan where the water depth is around 4000 m. Data were recorded from an array of temperature and depth sensors attached to EASI's mooring line. Temperature data were recorded once every 4 s to 8 min, depending on the sensor type and location, and averaged over 30 min. Collection and processing are discussed in P17 with the exception of the supplemental data examined here: 1) temperature and depth at approximately 540 m recorded until DOY 305 by an RBR TDR2050; 2) temperatures recorded at approximately 45, 65, 76, and 147 m are extended from DOY 305 to DOY 322 (65 and 76 m) and DOY 327 (45 and 147 m). Because these sensors do not record pressure, depths are estimates based on their respective mean values from P17 which were determined from adjacent pressure sensors in the array. Mean, standard deviation, and range (m) for each aforementioned logger are: [45.2, 0.4, 2.3]; [64.7, 0.5, 3.1]; [76.1, 0.8, 4.8]; [146.8, 1.4, 8.40], therefore some inherent but minimal uncertainty in depths exist ($O$ few meters) and increase with depth.

Chaba became a tropical storm on DOY 297 and a typhoon on DOY 298 (Angrove and Falvey, 2010). When it passed EASI, Chaba reached category 4 with Joint Typhoon Warning Center (JTWC) estimated radius of maximum winds (RMW) wind speed ($U_{RMW}$) between 49 and 59 m s$^{-1}$. Maximum 30-min mean wind speeds at 10 m ($U_{10}$) recorded on EASI were 26.5 m s$^{-1}$ (Potter, 2014). Chaba approached EASI from the southeast, on DOY 300—when its RMW were within 49 km of EASI—it turned northeast putting EASI directly behind the typhoon where it remained for several days as Chaba departed. Chaba's track in relation to EASI for DOY 297.5–302 can been viewed in Fig. 1 and a comprehensive analysis of Chaba's movement and physical characteristics can be found at Potter et al. (2015b).

## 3. Results

### 3.1. Immediate Ocean response

Fig. 2 shows wind speed and ocean temperatures from DOY 290–327.5. The top plot is $U_{10}$ and $U_{RMW}$, in situ temperature at 1 m (SST proxy), and SST from satellite. The bottom plot is ocean temperature to 540 m. Mean in situ SST was 0.3 higher than satellite IO with differences likely due to limited IO resolution and depth differences. In situ data show SST dropped by 1.6 °C during the week following the storm. IR show temperature decrease continued over the following three days leading to a total decrease of 2.5 °C. Although no longer being directly forced by Chaba, satellite images (Fig. 1) indicate this continued SST reduction was due to Chaba's lingering cold wake.

Temperature profiles from the surface to 100 m are shown in Fig. 3. The profiles are from DOY 298.5 (-36 h) to DOY 302 (+48 h) surrounding DOY 300 (0 h) when Chaba was closest to EASI. Profile −36 h characterizes the general ocean conditions before Chaba. Initially, temperatures below the mixed layer increased due to entrainment across the thermocline. The water was up to 0.3 °C warmer from 42 to 100 m for just over 12 h, peaking at −28 h. This was coincident with a 7 m mixed layer depth (MLD) increase—estimated as the depth where the temperature was 0.5 °C cooler than the SST (Levitus, 1982)—establishing the mixed layer depth at 77 m.

By −19 h upwelling had overwhelmed the warm water below the thermocline base and caused the MLD to shoal by 10–67 m. The upwelling, which started approximately 24 h before Chaba passed EASI, continued for several days, as indicated by profiles 0 h, +24 h, and +48 h. The shallowest MLD, of 58 m, also occurred at +48 h. Upper ocean cooling was greatest on the second day following the typhoon when $U_{RMW}$ was at its peak and EASI was in Chaba's wake. The temperature decrease was greatest in the area below the mixed layer (Fig. 4) where the vertical temperature gradient was greatest.

Coincident with SST decrease, temperatures fell throughout the water column at the mooring site. This is visible in Fig. 2 as a rapid upward migration of the isotherms. Table 1 lists the mean depths of the 26, 21, 16, and 11 °C isotherms over five days before and five days after Chaba passed EASI. For 21 and 26 °C, mean depths are also given surrounding the 13th and 23rd days. The 11 °C isotherm shoaled 27 m from its original depth of 501 m indicating that the ocean was impacted to at least half a kilometer.

### 3.2. Upwelling and penetration depth

EASI was within 3 RMW of Chaba for over 24 h during which mean $U_{RMW}$ was 47 m s$^{-1}$ and translation speed $V_p$ stayed below 3.6 m s$^{-1}$ (1.8 m s$^{-1}$ minimum $V_p$ occurred on DOY 300 as Chaba passed closest to EASI then changed direction). When a storm is intense and slow-moving, as was the case here, greater uplift of the underlying ocean tends to occur (e.g., Dare and McBride, 2011; Price, 1981) which contributes to a substantial ocean response. Chaba's path put EASI behind the typhoon around DOY 300.25 (+6 h), where it remained for over two days while Chaba moved away intensifying (60 m s$^{-1}$ max $U_{RMW}$ occurred on DOY 301.25). In the region behind the eye, surface currents are strongly divergent and upwelling can be substantial (e.g., Price et al., 1994).

Factors that determine the penetration depth and the energy that remains in the geostrophic currents are the Froude number, $F = V_P c^{-1}$ (the ratio of storm translation speed $V_P$ to the gravest mode internal-wave phase speed $c$) and the aspect ratio $LR^{-1}$ (the ratio of the storm scale $L$ to the baroclinic Rossby radius of deformation $R$). When $V_p$ is only slightly greater than $c$, $F$ is close to unity meaning a more energetic geostrophic response occurs (e.g., Geisler, 1970; Greatbatch, 1985) and $LR^{-1}$ is larger, causing deeper penetration and enhanced upwelling (Orlanski and Polinsky, 1983). For larger Froude numbers, more hurricane energy is supplied to the near-inertial wave field and less to the geostrophic currents. Values of $c$ usually range from 2 to 3 m s$^{-1}$ for the longest waves and decrease for larger modes (Ginis, 2002). Here a value of $c$ = 3 m s$^{-1}$ is adopted. This is within the range provided by Ginis (2002) and consistent with the value for the Philippine Sea numerically computed by Chelton et al. (1998). $V_p$ is set to 3.4 m s$^{-1}$ (the mean value for DOY 300-300.5) whereby $F$ = 1.1, indicating a strong geostrophic