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Typhoon induced summer cold shock advected by Kuroshio off eastern Taiwan

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ABSTRACT

In this study, we used satellite observations, in-situ measurements, and numerical modelling to investigate an extreme temperature change triggered by a typhoon in the ocean near the Kuroshio region off eastern Taiwan. With the westward passage of Typhoon Morakot in 2009 through Taiwan, a distinct cool wake was generated at the southeastern corner of Taiwan (CWSET) and moved towards the downstream Kuroshio region; it involved a precipitous cooling of at least 4 °C within 10–20 km of the coast. Rapid and drastic temperature drops triggered by the CWSET and advected by the strong conveyor belt effect of the Kuroshio Current are highly probable sources of cold shocks in summer. We clarified the mechanism that generated the CWSET through a series of sensitivity experiments using the Regional Oceanic Modeling System. The cold shock was mainly triggered by local wind stress associated with the typhoon. In addition, the Kuroshio Current was demonstrated to have played a crucial role in both the generation of upwelling off the southeastern coast of Taiwan during the passage of the typhoon and the transporting of this impact downstream. This process was verified through a systematic analysis of all typhoons moving westward through Taiwan from 2005 to 2013. Cold-shock stress is thought to be linked with naturally occurring 'fish kills', and obtaining a more thorough understanding of the CWSET will be helpful for protecting aquaculture off the eastern coast of Taiwan from the impacts of cold shocks triggered by typhoons moving westward through Taiwan in summer.

1. Introduction

Zheng, et al. (2014) investigated Kuroshio Current modulation in response to the passage of Typhoon Morakot in 2009 and noted that a distinct cool wake was generated off the southeastern tip of Taiwan (CWSET). Later, the cool wake extended northeastward towards the Kuroshio downstream region (KDR) along the Kuroshio main pathway. The CWSET was characterised by a precipitous cooling of the sea surface temperature (SST) to at least 4 °C lower than the ambient environment. Previous investigators have proposed that the transport of water with anomalous temperature differences is responsible for unusual weather patterns (e.g. surface winds, clouds, regional atmospheric circulation, and rainfall) that eventually affect continents (Barrick, et al., 1977; Beal, et al., 2011; Reason, 2001). The impacts of rapid decreases in water temperature on fish and aquaculture have been well documented (et al., 2008; Hoag, 2003; Troy, et al., 2012). Because of the drastic temperature drop caused by the cool wake and its unique position over the Kuroshio Current, a rapid conveyor of mass, heat, and energy in the western North Pacific (Hsin, et al., 2008; Liang, et al., 2003; Nitani, 1972), the generation of this type of cool wake by the passage of a typhoon posed unexpected threats to the oceanic environment, ecological system, and regional weather conditions in the KDR.

Previous investigations have suggested that a rapid decrease of water temperature may result in a number of physiological, behavioural, and fitness-related consequences for fish, collectively referred to as 'cold-shock stress' (Donaldson et al., 2008; Hoag, 2003; Troy et al., 2012). This phenomenon occurs when fish have become acclimated to a specific water temperature and are subsequently exposed to a rapid temperature decrease (Donaldson et al., 2008). This can occur under various conditions, such as thermocline temperature variation, rapid changes in solar heat, abnormal water movements, rapid precipitation events, or rapid changes in

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seasonal temperatures (Basu et al., 2002; Donaldson et al., 2008; Hoag, 2003). Because the magnitude of the cold-shock response is dependent on both the rate of temperature decrease and the magnitude of change (Tanck, et al., 2000; Van den Burg et al., 2005), the rapid temperature drops triggered by a combination of the CWSET and advection caused by the conveyor belt effect of the Kuroshio Current are highly likely to be sources of summer cold shocks. Cold-shock stress is thought to be linked with naturally occurring 'fish kills' (Donaldson et al., 2008; Emery, 1970; Hoag, 2003; Hurst & Conover, 1998). Thus, a deeper understanding of the CWSET will be helpful for protecting aquaculture off the eastern coast of Taiwan from the impacts of cold shocks triggered by typhoons moving westward through Taiwan in summer.

To further understand the CWSET and the possible threats of cold shocks associated with it, this study investigated the following: (1) the progress and possible impacts of the CWSET, (2) the main physical mechanism involved in its generation, and (3) the predictability of the CWSET. The answers might provide early warnings of the possible effects of the CWSET on KDR. Therefore, a comprehensive investigation focusing on the formation and evolution of the distinct cool wake off the southeastern tip of Taiwan is crucial.

Investigations and analysis of coastal ocean variations using in-situ observations have been sparse, intermittent, difficult, or expensive to conduct, particularly in the wake of the great variations that accompany the passage of a typhoon (Glenn et al., 2016; Teague, et al., 2007). These limitations can be partially avoided by the use of numerical modelling. The main contribution of the present study is a series of numerical experiments intended to realistically simulate the coastal oceanic variations off eastern Taiwan in response to all typhoons moving westward directly through Taiwan. The results derived from these numerical experiments were validated with the limited in-situ measurements available. In the first part of this study, a well-documented and largely typical case, the passage of Morakot in 2009, was simulated in detail to elucidate possible summer cold shocks triggered by the passage of the typhoon along the east coast of Taiwan. In the second part of this study, the main mechanism triggering CWSETs was determined through a series of numerical runs. Finally, the ocean responses to typhoons with similar trajectories as that of Morakot that passed directly through Taiwan between 2005 and 2013 were simulated and systematically analysed to validate our identification of the mechanism. We determined that cold shocks triggered by the CWSET can be reasonably predicted on the basis of the close relationship between local offshore winds over the southeastern tip of Taiwan and subsequent CWSETs.

2. Data and methodology

2.1. Model description and experiments design

To systematically resolve important issues raised in Section 1, all westward moving typhoons striking Taiwan from 2005 to 2013 are simulated by Regional Oceanic Modelling System (ROMS) (Shchepetkin & McWilliams, 2003; 2005) with realistic topography derived from ETOPO2 (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Geophysical Data Centre, 2006) and forcing from 6-hourly gridded ECMWF/QSCAT blended winds (0.25° × 0.25°, for typhoon cases during 2005–2009) or 6-hourly Global Forecast System (GFS) winds (0.5° × 0.5°, for typhoon cases during 2010–2013). The available blended-wind data might be too coarse to force an ocean response under the storm centre (Halliwell, et al., 2011). However, the key processes discussed in this study mostly occurred far from the inner-core region of the typhoon case studies. Fig. 1 shows the seafloor topography off eastern Taiwan. The model domain covers a portion of the western North Pacific (16°N-27°N, 117°E-132°E) with a horizontal resolution of ∼12 km. Vertically, 36 s-coordinate levels are distributed unevenly for a good resolution of the upper ocean (referring to Zheng et al. (2010)). The initial and open boundary conditions are derived from the data assimilated Hybrid Coordinate Ocean Model (HYCOM) global solutions (Chassignet et al., 2007). Through the Navy Coupled Ocean Data Assimilation (NCODA) system, HYCOM assimilates all available satellite altimeter observations, satellite and in situ SST as well as in situ temperature and salinity profile data (Cumming, 2005). We use these data to determine initial conditions for model simulations. The heat flux in ROMS is calculated from atmospheric parameters obtained from GFS (http://nomads.ncdc.noaa.gov/) using a bulk formulation during the model run. The drag coefficient was computed following Large and Pond (1981). The wind data are interpolated on to the ROMS grid. The performance of ROMS using these initial conditions and surface fluxes is evaluated by comparisons of both currents and temperature profiles in Zheng et al. (2014).

2.2. Observations

In this work, 1.1 km Moderate Resolution Imaging Spectroradiometer (MODIS) Aqua SST images during the passage of Morakot (2009) are collected and composited to sketch the outline of cold shock along east coast of Taiwan triggered by Morakot in 2009 summer (seeing Fig. 2). After inspecting all available images corresponding to 17 individual typhoon cases, on account of the high percentage of cloudiness during the severe weather conditions accompanying with typhoon passages, case Morakot provides a very rare opportunity for sketching a relative clear outline of typhoon triggered CWSET flowing along KDR. MODIS SST data are downloaded from http://oceancolor.gsfc.nasa.gov/ and processed by SeaDAS version 6.4. Moreover, our modelled results were compared with several in-situ measured data sources. Limited in-situ measurements provided by GTSPP, Argos drifters, Argo floats, and Central Weather Bureau (CWB) Chenggong weather station corresponding to those typhoon passages are collected for validating the existence of model simulated CWSETs (referring to Table 1). Typhoon related background information is obtained from the best-track data from Joint Typhoon Warning Centre (JTWC) and CWB, Taiwan.

3. The distinct cool wake off southeastern Taiwan triggered by a westward impinging typhoon

Fig. 3 shows the simulated evolution progress of the CWSET response to the passage of Morakot in August 2009, revealing that a slightly cool patch was generated near the southeastern tip of Taiwan. Subsequently, a marked cool wake, with a more than 5 °C drop relative to the ambient environment, was generated off the southeastern coast of Taiwan at 00:00 UTC on 8 August 2009 (Fig. 3b and c). Notably, the cool wake then extended gradually northward along the Kuroshio main path off the east coast of Taiwan (Fig. 3d). Finally, it extended northeastward towards the KDR (Fig. 3e–f); when it arrived at 26°N on 12 August 2009, it decreased slightly to approximately 4 °C lower than the surrounding region (Fig. 3f). We determined that, according to the extension and movement of the cold patch shown in Fig. 3, the cool water associated with the CWSET was clearly carried by the Kuroshio Current. The existence of this cool wake was verified by in-situ temperature profiles derived from Argo floats that passed by the southeastern coast of Taiwan during Morakot (Table 1 and Fig. 11, Zheng et al., 2014). The lateral advection occurring in the storm wake-induced cooling in the area remote from the storm track has also been investigated in previous studies (Jaimes & Shay, 2010 Jaimes, et al., 2011; Walker et al., 2014).