Impact of Tropical Cyclones on Geostrophic Velocity of the Western Boundary Current

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Abstract  Tropical cyclones (TC), which are among the most destructive natural phenomena on Earth, have significant impacts on the western boundary current (WBC). We quantify the direct impact of TCs on the surface geostrophic velocity of the Kuroshio, the WBC in the western North Pacific, by analyzing satellite-derived geostrophic current data and using results from theoretical and numerical models. The study reveals that TCs decrease the surface geostrophic velocity by 14 cm s\(^{-1}\) which is 16% of the mean velocity of the Kuroshio (85 cm s\(^{-1}\)), with the reduced velocity maintained for a month. The decrease in velocity of the Kuroshio is mainly (87%) due to the effect of TC-driven upwelling (“Cooling effect”), the effect of ocean heat uptake after the TC (“Warming effect”) being minor (13%); these are basically enabled by the strong thermal gradient around the Kuroshio.

Plain Language Summary  The tropical cyclone (TC), also known as hurricane or typhoon, has a strong impact on the ocean as well as the land. In this study, we investigate how TCs affect ocean currents, with special focus on the Kuroshio, the western boundary current (WBC) in the North Pacific region. By analyzing satellite-derived data, and building theoretical and numerical models, we deduce that when a TC hits the Kuroshio, its surface velocity decreases by 16%. This work makes a significant contribution by providing a quantitative understanding of the influence of TCs on the WBC. Further, given that the WBC is the strongest ocean current system on Earth and plays a key role in maintaining global heat balance, this study emphasizes the potential importance of the TC-induced change on the current for the global distribution of heat energy.

1. Introduction

The tropical cyclone (TC) accompanied by tremendous winds is the most destructive atmospheric phenomenon on Earth. Recent studies have reported that the strength of TCs will increase under conditions of global warming (Mei et al., 2015; Walsh et al., 2016; Webster et al., 2005). Under these circumstances, it is all the more important to expand and advance knowledge about the TC not only for its improved prediction and prevention of damage from them, but also for a better understanding of its influence on the climate with respect to its interactions with the ocean.

The western boundary current (WBC) is one of the strongest ocean current systems on Earth. This poleward current of geostrophic nature, with a strong thermal gradient (i.e., thick warm layer of water on the ocean side and strongly stratified water on the shelf side), also carries heat into the middle latitudes and contributes toward global heat balance (Hu et al., 2015). The existence of warm water in the basins not only becomes a source of the WBC, but also leads to the generation of a large number of cyclones in the tropics, many of which pass through the WBC in the northwestern part of the Pacific and Atlantic oceans. What happens when these two strong natural processes interact?

Many studies on the thermal response of the ocean to TCs have been carried out. The wind stress associated with a TC transfers its momentum onto the upper layer of the ocean; this creates vertical current shear, resulting in vigorous vertical mixing accompanied by sea surface cooling, especially on the right side of the TC passage (D’Asaro et al., 2007; Park et al., 2019; Price, 1981). Also, within the radius of maximum wind of the TC, the strong cyclonic wind stress induces horizontal divergence in the ocean surface Ekman layer, and consequent temperature decrease (or density increase) in the water column is caused by upwelling (i.e., baroclinic ridge; Ginis, 2002; Liu et al., 2019; Vincent et al., 2013; Wei et al., 2014). The vertical mixing induces not only cooling of the sea surface but also the injection of heat into the subsurface layer (Dzvonkowski
et al., 2020; Emanuel, 2001; Park et al., 2011). After days or even a month, the thermal restoration of the upper layer through surface heating—while the injected heat remains in the subsurface layer—will increase the ocean heat content of the entire water column, the phenomenon being called ocean heat uptake. Similar oceanic responses are also observed around the WBC region (Liu & Wei, 2015).

There are a few studies on the impact of TCs on the WBC. A TC induces an ageostrophic current which persists for a relatively short period involving a few days. It possesses a larger energy, mainly from the baroclinic pressure work, than the geostrophic current (Kourafalou et al., 2016; Wei et al., 2014); this ageostrophic current also affects the path of the WBC (Kuo et al., 2018; Tada et al., 2018). For a change involving a longer time scale (~weeks to a month), qualitative studies about the TC-driven pressure field change and the corresponding geostrophic current variation have been conducted. It has been reported that intense vertical mixing and large waves can decrease the horizontal gradient of WBC (Ezer, 2018) and the coastal upwelling due to the equatorward wind in the western periphery of TCs and the open-ocean upwelling near the center of TCs reduce the pressure gradient around the WBC, resulting in decrease of transport both in the Gulf Stream and the Kuroshio (Ezer et al., 2017; Morimoto et al., 2009; Todd et al., 2018). On a decadal time scale, the strengthening/weakening of cyclonic/anti-cyclonic eddies by TCs can enhance the WBC (Zhang et al., 2020). In addition on the climatic-scale, the meridional heat transport is also predicted to increase in response to enhanced TC-induced ocean heat uptake under the global warming (Sriver & Huber, 2007).

Geostrophic velocity takes a major portion of a total current of WBC. It also has a nature to be maintained for longer time scale yielding implications on the long term variabilities of WBC (e.g., seasonal, interannual, or decadal variations). In spite of the importance, not many studies focused on the quantification of geostrophic response of WBC to TC. Also, a mean feature of the geostrophic response in the vicinity of the location where the TCs encounter the WBC was poorly examined both in dynamical and statistical ways.

The purpose of this study is to quantify the direct impact of TCs (within/around the radius of maximum wind speed of TC) on the geostrophic velocity of WBC, for a time scale of weeks to a month. We can hypothesize that a TC induces a change in pressure gradient because of the thermal nonhomogeneity, which results in a change in the WBC. To test this hypothesis, the Kuroshio region where TCs in the western North Pacific frequently penetrate is selected as the study area (Figure 1a).

### 2. Data and Methods

The along-stream component of the surface geostrophic velocity of the Kuroshio (VG), known to be proportional to its volume transport (Imawaki et al., 2001), is estimated from the satellite-based daily absolute dynamic topography (ADT) data for 1993–2018, to quantify the change in VG around the period of penetrations of the TCs. The data provided by the Copernicus Marine Environment Monitoring Service (Taburet et al., 2019) have a horizontal resolution of 0.25° × 0.25°. To avoid the effect of meandering of current, the region where the path of Kuroshio does not change much in time (bounded by 124.5–130°E; based on Wang & Oey, 2014), with the mean VG exceeding 0.3 m s⁻¹, is selected as the Kuroshio area to be studied (area bounded by red line in Figure 1). The axis of the Kuroshio (KAX) is defined as the location where the mean geostrophic current is maximum (black line in Figure 1a) in the Kuroshio area. It should be noted that the ADT data provide smoothed features for both the spatial (>50 km) and temporal (>10 days) domains due to limited samples of the orbiting satellite observations as well as limitations in the interpolation process for the grid data.

For the selection of the penetration period of TCs, the best track data from the Regional Specialized Meteorological Center are used (Kunitsugu, 2012). Only TCs passing through the KAX during the period 1993–2018 with strength exceeding category 1 (based on the Saffir-Simpson scale) are preliminary selected for analysis. To estimate the composite mean VG of the TC events, time and along-stream variation of VG over the Kuroshio area were extracted at times and locations the KAX and TC tracks meet (Day 0, along-stream distance = 0). The anomalies in VG, defined as the deviations of VG from VG on Day −20 are estimated, to show the changes occurring in VG during the penetration period of TCs. After the preliminary selection of TCs, we divide the TCs into two groups based on the comparison of the velocities of the Kuroshio averaged from Day −20 to Day 0 and from Day 0 to Day +20 within the along-stream distance of ±200 km; one is for increasing cases (15 TCs) and the other is for decreasing cases (24 TCs). In the composite means of VG of
each group, we found that the composite mean of the decreasing cases showed statistical significance in the mean feature while that of the increasing cases did not (not shown). For the robustness of the analysis, we selected the decreasing cases for the analysis (Table S1).

2.1. Simple One Dimensional Theoretical Model

A simple one-dimensional (1-D) theoretical model for the oceanic response to the TC is suggested, to understand the dynamics of VG change. The assumption of one dimensional process is reasonable because the vertical advection dominates the horizontal advection in the thermal response during the TC period even in the WBC region (Wei et al., 2014). The main idea behind the theoretical model is that the change of density caused by the TC-driven upwelling and thermal restoration after vertical mixing (i.e., ocean heat uptake) can alter the horizontal pressure gradient in the nonhomogeneous density field around the Kuroshio. The increase in depth-integrated density (i.e., decrease in temperature) driven by the TC-driven upwelling, called “Cooling effect” (blue hatched lines in Figure 2), can be estimated as follows:

\[
\text{“Cooling effect”} = \int_0^H \Delta \rho_{CE} \, dz = \int_0^H \rho_w - \rho_i \, dz = \frac{\int \text{curl} \tau \, dt}{\rho_0 f} (1)
\]

where \(z\) and \(\tau\) are the vertical coordinate and time, respectively; \(\rho_i\) is the initial potential density; \(\rho_w\) is the potential density after upwelling; \(\rho_0\)}
(=1.025 kg m$^{-3}$) is the reference density; $\tau$ is the wind stress calculated from the wind speed as per Large and Pond (1981). $\mathbf{r}$ is the wind stress calculated from the wind speed as per Large and Pond (1981). $\text{curl}\mathbf{r}$ (3.6 × 10$^{-3}$ N m$^{-3}$) is the vertical component of curl of wind stress estimated for a maximum wind speed of 42.5 m s$^{-1}$ and an estimated radius of maximum wind ($R_{\text{max}}$; Park et al., 2019) of 125 km, which are defined based on the mean values of the selected TCs. The $\text{curl}\mathbf{r}$ is integrated over a time which is estimated as $R_{\text{max}}$ multiplied by two and divided by the mean translation speed of TCs ($U_{h} = 7$ m s$^{-1}$), representing the duration for which positive wind stress curl (inside the radius of the maximum wind speed of the TC) is exerted at a certain location; $H$ is the water depth and $f$ is the Coriolis parameter at latitude 28°N. The depth-integrated density decreases with a corresponding increase in temperature, due to the ocean heat uptake after vertical mixing by the TC; this phenomenon called the “Warming effect” (red hatched lines in Figure 2) can be estimated as follows:

\[
\text{“Warming effect”} = \int_{-H}^{0} \Delta \rho_{\text{WE}} \, dz = \int_{-z_c}^{0} \rho_{\text{w}} - \overline{\rho}_{\text{w}} \, dz,
\]

where $z_{c}$ is the compensation depth where $\rho_{\text{w}}$ equals the potential density ($\overline{\rho}_{\text{w}}$) after vertical mixing by the TC, $L$ (=80 m; based on Lin et al., 2013) is the mixing length scale for the TC (Figure 2). Both the surface geostrophic currents induced by the “Warming effect” and the “Cooling effect” are estimated using the geostrophic relation $\mathbf{v}_{g} = -g/\rho_{0} (\hat{k} \times \nabla \left( \int \rho \, dz \right))$ (in a vector form) assuming an unchanged level of no motion, where $\nabla$ is the operator for gradient and $\hat{k}$ is the unit vector in the vertical direction. The detailed derivation of the theoretical model is provided in the Supporting Information S1. For quantification of the direct impact of TC on the pressure field around the Kuroshio, the “Warming effect” and “Cooling effect” are estimated at each grid point of climatological mean of temperature and salinity profile data for the TC season (July, August, and September) obtained from World Ocean Atlas 2018 (WOA18; Locarnini et al., 2018), with a horizontal resolution of 0.25° × 0.25°. The estimation is conducted assuming both effects are occurred under the influence of TC at each grid point.

### 2.2. Numerical Model

The time-dependent oceanic response to TCs is examined using the Regional Ocean Modeling System (ROMS) v3.9 (Haidvogel et al., 2000), to generalize the observational results. ROMS solves ocean governing equations using the hydrostatic and Boussinesq approximations. For the sake of simplicity, the model does not consider advection of the momentum, but that of tracers is estimated by the third order upstream difference scheme which is essential to simulate the change in pressure field. A harmonic horizontal diffusion for the momentum is applied with a viscosity of 100 m$^2$ s$^{-1}$. The model adopts Mellor-Yamada turbulence closure (Mellor & Yamada, 1982). The model domain is 1,000 km × 1,000 km with a horizontal resolution of 5 × 5 km. For simplicity, the bottom topography consisting of the shelf (depth 50 m, northward of 640 km), shelf slope (sinusoidal curve, Equation S7), and the deep plain (depth 1000 m, southward of 480 km) are considered to change in the y-direction without any changes in the x-direction, with 30 vertical levels of the s-coordinate system. The initial condition for the y-directional temperature section is obtained from the WOA18 across the Kuroshio (~127°E), that is, in the cross-stream direction, and the temperature data are linearly interpolated along the depth (z) and cross-stream (y) direction in the location where the simplified topography shows greater depth than the actual topography (Figure S1). There is also no temperature gradient in the along-stream (x) direction. We neglect the effect of salinity changes in the numerical model, and let the salinity be constant (=35).

We performed a spin-up to obtain an optimal geostrophic current field induced by an initial ocean density field maintained constant during the spin-up. After the spin-up, we conducted an experimental run integrated over 100 days. In this run, the northern and southern boundaries were considered as walls. With the open boundary conditions adapted from the spin-up field, nudging conditions (with a nudging time scale of 2 days) are applied at the eastern and western boundaries. For the consistency with the observational data, the numerical model data are smoothed both in space and time, with a box size of 50 km × 10 days. The TCs exert a symmetric wind field on the sea surface, according to Chavas et al. (2015). The TC appears from the southern boundary on Day –5, and moves north with $U_{h}$ of 7 m s$^{-1}$. The center of the TC encounters the KAX on Day 0, and disappears on Day 5. The density and surface geostrophic velocity data are compared to the observational and theoretical results.
3. Results and Discussions

3.1. Observations

Long-term mean VG is up to 85 cm s\(^{-1}\) near the 127°E longitude, with the width of the Kuroshio area being ∼125 km. The KAX is aligned from southwest to northeast with an angle of 45° in a clockwise direction from the north, on average. 24 cases of TCs penetrating the KAX were selected (Table S1) that reached the Kuroshio from July to October, with most arriving in August (Figure 1b). This indicates that at least one TC penetrates the Kuroshio in a year. The mean incident angle of the TCs to KAX is ∼−50° from the north in a direction almost normal to the KAX. A composite mean of VG anomalies for 24 TC cases (see Table S1) in the along-stream and time domains shows that the velocity of the Kuroshio decreases after penetrations by the TC. The magnitude of the decrease in mean VG exceeds the standard deviation of VG, which implies its statistical significance (pink hatched line in Figure 3a). Also, the magnitude of VG decrease is sufficiently larger than that of mean seasonal variation of VG, which is ∼3 cm s\(^{-1}\) month\(^{-1}\) in the TC season. After 6 days of penetration, the VG anomaly abruptly decreases down to 14 cm s\(^{-1}\), with a corresponding sea level gradient change of ∼10 cm over about 100 km. Similar to the sea surface cooling reported in previous studies, the rightward bias with respect to the TC track is also indicated in the decrease of VG anomaly. The decrease in velocity of over 10 cm s\(^{-1}\) is confined to the area around the TC passage with a width of around 200 km. This indicates that the decline does not originate from the upstream region and does not effectively propagate in the down-stream direction. Also, the location of the KAX does not significantly fluctuate after the TC (not shown). The velocity decrease of over 10 cm s\(^{-1}\) is maintained for ∼30 days, and then starts to recover its original state.

3.2. Dynamics

A simple 1-D model is applied to reveal the dynamics of the VG decrease after a TC. Because of the strong pressure/density gradient around the Kuroshio, nonhomogeneous response of the pressure field to the TC wind is expected. The depth-integrated density changes caused by the TC-driven upwelling (i.e., the “Cooling effect”) show the strong spatial contrast across the Kuroshio (Figure 4a). On the shelf side, the “Cooling effect” is smaller (∼60 kg m\(^{-2}\)) than that on the ocean side (between the shelf break of the East China Sea and Ryukyu Islands; ∼110 kg m\(^{-2}\)), that is, a density difference of ∼50 kg m\(^{-2}\) over about 50 km. The surface geostrophic current induced by the “Cooling effect” is 13 cm s\(^{-1}\) in a direction opposite to that of the
Kuroshio current, indicating a decrease in VG. As denoted in Equation 1, the magnitude of the “Cooling effect” is proportional to the density difference between the surface and the bottom of a water column. In summer, the density at the surface does not vary much spatially because of the surface heating while the density at the bottom exhibits spatial contrast. On the shelf side, the density at the bottom is relatively low because of the shallow water depth. On the ocean side, the bottom density tends to increase with increasing bottom depth. The spatial distribution of density at the bottom, rather than that at the surface, is critical for the “Cooling effect” distribution.

The changes in depth-integrated density due to the ocean heat uptake (i.e., the “Warming effect”) also show spatial contrast around the Kuroshio (Figure 4b). On the shelf side, the “Warming effect” is ∼−25 kg m$^{-2}$ while on the ocean side it is ∼−20 kg m$^{-2}$. The surface geostrophic current induced by the change indicates that a decrease in VG by 2 cm s$^{-1}$ is caused by the “Warming effect.” The vertical mixing itself does not affect the depth-averaged density change although it is one of the representative oceanic responses to the TC. Only thermal restoration through surface heating after the vertical mixing can alter the depth-integrated density field. As seen from Equation 2 and Figure 3, the magnitude of the “Warming effect” is largely dependent on the vertical density gradient in L. For the same mixing length scale of the TC, a greater amount of heat is injected into the subsurface layer in a more stratified ocean. Thus, on the shelf side, where the vertical stratification within L is greater than that on the ocean side, there is relatively greater decrease in density due to the ocean heat uptake. From the theoretical model results, it is revealed that the “Cooling effect” and “Warming effect” explains 87% (13 cm s$^{-1}$ out of 15 cm s$^{-1}$) and 13% (2 cm s$^{-1}$ out of 15 cm s$^{-1}$) of the decrease of the geostrophic current after TC. In addition, Because thermal restoration takes time (days to a month), the decrease in velocity by the “Warming effect” is progressively preceded by abrupt decrease induced by the “Cooling effect.”

3.3. Numerical Model Results

The numerical model reproduced the variations in the surface geostrophic current after the TC. The variation in VG anomaly from the numerical model in the along-stream (at y = 475 km, where the VG is maximum) and time domains shows features similar to the composite mean of VG anomaly from the satellite data (Figure 3), which supports the reliability of the observational results. There is an abrupt decrease of VG anomaly during the TC penetration. Until 6 days after the penetration, the VG anomaly continues to decrease, reaching 11 cm s$^{-1}$, with a rightward bias also indicated. The current with its velocity declined to less than 10 cm s$^{-1}$ is confined to the area around the TC passage with a width of about 100 km, which is slightly narrower than that indicated in the satellite data. It is clearly seen that the isopycnals, especially on the ocean side, are uplifted by the TC-driven upwelling (Figure S2). The horizontal gradient of the depth-integrated density field shows similar changes (∼40 kg m$^{-2}$ over ∼50 km) compared to the “Cooling effect.”
from the simple model results. The current with velocity reduced to below $-10$ cm s$^{-1}$ is maintained for $\sim 20$ days which is shorter than that for the satellite data (Figure 3b). It is likely that the “Warming effect,” which is not considered in the numerical model, is responsible for the discrepancy between the observed and numerical model results, in the durations for which the reduced velocity of Kuroshio prevails.

3.4. Others

The effect of the TC on VG is maintained for approximately one month, even when the duration of the strong positive wind stress curl exerted on the Kuroshio is relatively short ($\sim 12$ h). This indicates that the wind stress exerted by the TC is strong enough to break the equilibrium state of the oceanic pressure field and the corresponding geostrophic current. The restoration time scales of these pressure and geostrophic current fields are comparable to those suggested in a previous study (Park et al., 2011). The transient oceanic response (e.g., the effects of topographic Rossby wave, baroclinic instability, etc.) and nonlinear response to TCs remain to be studied.

We examine the response of WBC to TC in the mean sense. So the mean vertical mixing length scale induced by TCs should be chosen for the “Cooling effect” estimation. Lin et al. (2013) statistically found that the ocean temperature averaged from 80 m to the surface (T80) prior to the TC period can be a good proxy for the prediction of TC intensity. This indicates that the sea surface temperature, cooled mainly by the vertical mixing, is comparable to the T80 on average, which means the vertical mixing depth is 80 m in the mean sense. That is the reason why we choose the vertical mixing length scale of 80 m. This mixing length scale of 80 m is also comparable to that shown in the numerical model results ($\sim 75$ m at the ocean side: $y = 400$ km).

Park et al. (2011) showed that the ocean heat uptake is not evidently detected under the weak TC (<Category 3) condition based on the in-situ hydrographic data in the open ocean. However, the “Warming effect” by the TC-driven ocean heat uptake in this study was identified even though the mean strength of the selected TC is in category 2. This result is supported by Dzwonkowski et al. (2020), who detected ocean heat uptake on the shelf under category “Tropical Storm” which is much weaker than TC in category 3. We, therefore, think that there is a possibility that the “Warming effect” can occur even if the TC is in category 2 especially on the shelf side.

Our study seems to show results opposite to that of Zhang et al. (2020) which revealed an increase in the velocity of Kuroshio due to the influence of TCs. However, the results of this study cannot be inferred as contradictory to those of Zhang et al. (2020); the two studies have different target phenomena and time scales. In this study we focus on the direct impact of individual TCs on the Kuroshio velocity—an impact which was maintained for~30 days. The study of Zhang et al. (2020), on the other hand, focused on the indirect impact of TCs on the surface geostrophic current of the Kuroshio via eddies, on a much longer (decadal) time scale.

4. Conclusions and Implications

This study revealed that TC-driven upwelling and ocean heat uptake can decrease the surface geostrophic velocity of Kuroshio by $\sim 14$ cm s$^{-1}$ (16% of the mean velocity). Because of the nonhomogeneous thermal distribution conditions at the subsurface, spatially varied oceanic responses are induced by the TCs. The effect of TC-driven upwelling (i.e., the “Cooling effect”) exerts more influence on the ocean side where denser water occupies the deeper parts, compared to the shelf region. Also, the effect of TC-driven ocean heat uptake (i.e., the “Warming effect”) causes greater density decrease on the shelf side where there is more vertical stratification in L compared to the ocean side. The combined effect of the “Cooling effect” (87%) and the “Warming effect” (13%) reduces the pressure gradient and finally results in the decrease in velocity of the Kuroshio.

The dynamics suggested in this study is applicable to the response of WBCs to TC in other basins (e.g., the Gulf Stream, the East Australian Current) where strong pressure gradient exists. This study also has implications on the understanding TC-driven oceanic changes on the mesoscale current fields which are associated with the nonhomogeneous thermal structure. From the quantitative response of Kuroshio to TC,
we expect these effects to provide quantitative information to the impact of TC on meridional heat transport by the WBC and consequent climate variations as well as ocean circulation.

### Data Availability Statement

The satellite altimeter data (“SEALEVEL_GLO_PHY_L4_REP_OBSERVATIONS_008_047”) are available from the Copernicus Marine Environment Monitoring Service (http://marine.copernicus.eu). Best track data for the tropical cyclones were obtained from the Regional Specialized Meteorological Center of the Japan Meteorological Agency (http://www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-eg/Best-tracks_e_format bst.html). The World Ocean Atlas 2018 data were provided by the National Centers for Environmental Information (http://www.nodc.noaa.gov/cgi-bin/OC5/woa18/woa18.pl).

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