MIXED-LAYER CURRENT AND CYCLONIC EDDY INDUCED BY GLOBAL TROPICAL CYCLONES

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ABSTRACT

A high-speed long-sustained ocean cyclonic eddy (named Nida Eddy) was observed under tropical cyclones (TC) Nida (23 November to 4 December 2009) in the western North Pacific with the translation speed less than 1.0 m/s for 48 hours at intensity reaching category-5. During TC-Nida ‘s passage, this eddy had a daily averaged maximum speed reaching 1.3 m/s identified from the Archiving Validation and Interpretation of Satellite data in Oceanography (AVISO) data, and an extremely high instantaneous ocean current speed (2.0 m/s) at 12:00UTC 29 November and 06:00UTC 3 December 2009 determined from the Surface Velocity Program (SVP) drifter data. After TC-Nida‘s passage, this eddy sustained for six months with slow westward propagation (from the AVISO data). Comparing to the averaged characteristics of oceanic eddies in the western North Pacific, it had near-double strength (0.79 m/s vs. 0.45 m/s), 50% longer lifespan (6 months vs. 4 months), and 50% increased to doubled radii (126-176 km vs. 85 km).

Introduction

During tropical cyclone (TC)’s passage, two distinct types of oceanic motion are generated depending on the ratio of the translation speed (U_h) of the TC and the phase speed of the oceanic first baroclinic mode (C_1) [Geisler, 1970; Nilsson, 1995]: eddies with upwelling if $U_h/C_1<1$ (slow-moving TC), inertial-gravity waves if $U_h/C_1>1$ (fast-moving TC). Numerous observational and modeling studies were conducted to characterize the horizontal structure in the wake of some fast-moving storms [Price, 1983; Chu et al. 2000; Chang et al. 2016; among others]. The TCs' mean translation speed is about 4.7 (4.0 m/s) in the Northern (Southern) Hemisphere. In the western North Pacific, the mean U_h of the 15 super typhoons (categories 4 and 5)[19] varied from a minimum value of 1.27 m/s (TC-Kirogi 2005) to a maximum value of 8.23 m/s (TC-Yagi 2006) with the averaged value of 5.64 m/s. The phase speed of oceanic first baroclinic mode (C_1) varies between 2.1 m/s and 2.9 m/s in the global TCs-rich zones during typhoon (or hurricane) season [Chang et al. 2016], which is much lower than TCs’ mean U_h [Sun et al. 2014]. The Saffir-Simpson scale is a 1 to 5 rating based on TC’s maximum sustained wind speed (VMAX) of 113-136 knots as category-4 and $\geq$ 137 knots as category-5 [http://www.nhc.noaa.gov/aboutsshws.php]. Near 3% (12%) of categories 4 and 5 TCs have translation speed U_h<2.1 m/s (<2.9 m/s) from the global TC data, and 18% with U_h<2.9 m/s in the western North Pacific [Chang et al. 2013]. Strong oceanic eddies are rarely observed during the passage of slow-moving (especially U_h < 1.0 m/s) category-5 TC. In this report, we first present evolution and track of slow-moving category-5 TC-Nida 2009 in the western North Pacific using the Joint Typhoon Warning Center (JTWC) data, and then identify an underneath high-speed long-sustained ocean cyclonic eddy using satellite altimetry data and Surface Velocity Program (SVP) drifter data.

Results

Slow-moving Category-5 TC-Nida

The JTWC maintains an archive of tropical cyclone track data, commonly referred to as "best-tracks". Each best-track file containing TC’s center locations and intensities (i.e., the maximum 1-minute mean sustained 10-meter wind speed) at six-hour interval can be downloaded from the website: http://www.usno.navy.mil/NOOC/nmfcph/RSS/jtwc/best_tracks/TC_bt_report.html. Slow-moving category-5 TC-Nida 2009 was found in the western North Pacific (Fig. 1a). It was generated and classified as a tropical depression about 900 km southeast of Guam on November 21, 2009, and moved continuously towards northwest. On November 23, the JTWC upgraded Nida to a tropical storm. Then, it was rapidly strengthened from category-1 to category-3 (VMAX: 96-112 knots) and then to an extremely strong category-5 typhoon as passing Guam on 25 November with the VMAX reaching 160 knots. TC-Nida was weakened to a category-4 typhoon on 06:00 UTC November 27, but strengthened once again to a category-5 typhoon 12 hours later (Fig. 1b). As TC-Nida's intensity at the level of super typhoon (category-4 above) from 27 to 29 November, its mean translation speed (U_h) was reduced from 4.3 m/s at 00:00 UTC 27 November to 0.5 m/s at 00:00 UTC 28 November and kept it until 18:00 UTC 29 November (Fig. 1c), i.e., it was a slow-moving super typhoon with the translation speed less than 1.0 m/s for around 48 hours. TC-Nida was gradually weakened into a category-3 typhoon by November 30. On December 1, TC-Nida was weakened to a category-1 typhoon, and began to slowly move towards west. Later on TC-Nida was further weakened into a tropical depression on 3 December 2009.

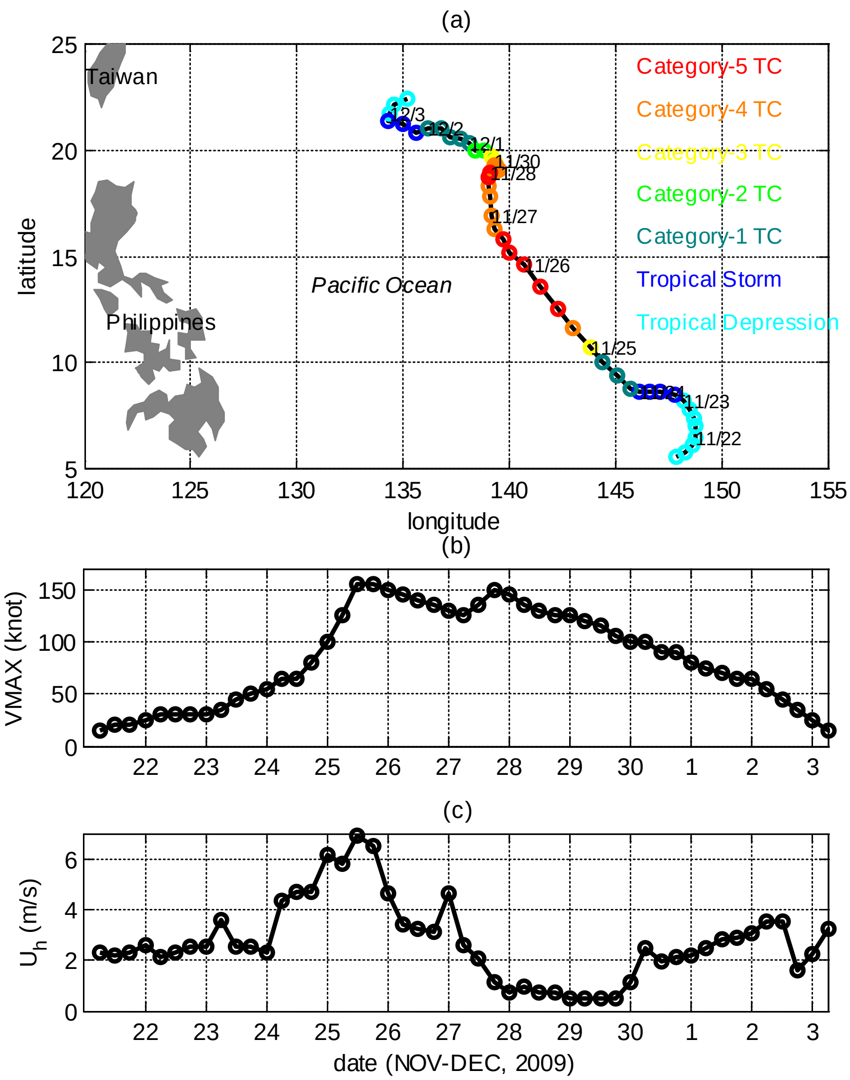

Figure 1. Movements and strength of TC-Nida. (a) TC-Nida 2009 in the western North Pacific was generated and classified as a tropical depression about 900 km southeast of Guam on 21 November 2009. It moved northwestward and was intensified into a category-1 typhoon during the evening of 23November 2009. On November 25, TC-Nida was strengthened from category-1 to category-3, and then was rapidly intensified into an extremely strong category-5 typhoon passing Guam. On November 27, TC-Nida was downgraded to a category-4 typhoon, but it strengthened

once again to a category-5 typhoon on November 28. TC-Nida was gradually weakened into a category-3 typhoon by November 30. On December 1, TC-Nida was weakened to a category-1 typhoon, and began to slowly move towards the west, and became a tropical depression on 3 December 2009. (b) Time series (6 hourly) of TC-Nida's maximum sustained wind speed (VMAX), it was monotonic strengthening from less than 20 knots on 21 November 2009 to 160 knots on 18:00 UTC 25 November 2009, fluctuating but above category-4 level on 25-29 November 2009, and monotonic weakening from 00:00 29 November 2009 to less than 20 knots as a tropical depression on 3 December 2009. (c) TC-Nida was in slow-moving from 21 to 23 November, speeding up from 00:00 UTC to a maximum value of 6.9 m/s at 12:00 UTC 25 November, slowing down to 0.5 m/s at 00:00 UTC 28 November and kept the low-speed until 18:00 UTC 29 November, and speeding up again to 3.8 m/s at 12:00 UTC 2 December 2009.

High-speed Ocean Cyclonic Nida Eddy

The Archiving Validation and Interpretation of Satellite data in Oceanography (AVISO) provides global daily absolute (ocean) dynamic topography (ADT) and absolute surface geostrophic velocity on a 1/4° × 1/4° grid over a 20-year period (1993－2012) (http://www.aviso.altimetry.fr/fileadmin/documents/data/tools/hdbk_duacs.pdf). The common criteria[20-23] were used to identify the mesoscale eddy: (1) the near-elliptic closed ADT contours, (2) the eddy center defined as the center of the innermost contour, (3) the eddy diameter defined as the diameter of the outermost contour, (4) the eddy can be tracked forward over 3 weeks, and (5) the ADT difference between its center and its outermost contour is greater than 0.06 m due to the measurement error about 0.02－0.03 m [Wang et al. 2003]. An ocean cyclonic eddy (we named it as the Nida Eddy) was discovered from the daily absolute surface geostrophic velocity fields for the region-A [135º-145ºE, 15º-25ºN] during TC-Nida's passage from 23 November to 4 December 2009 (Fig. 2).

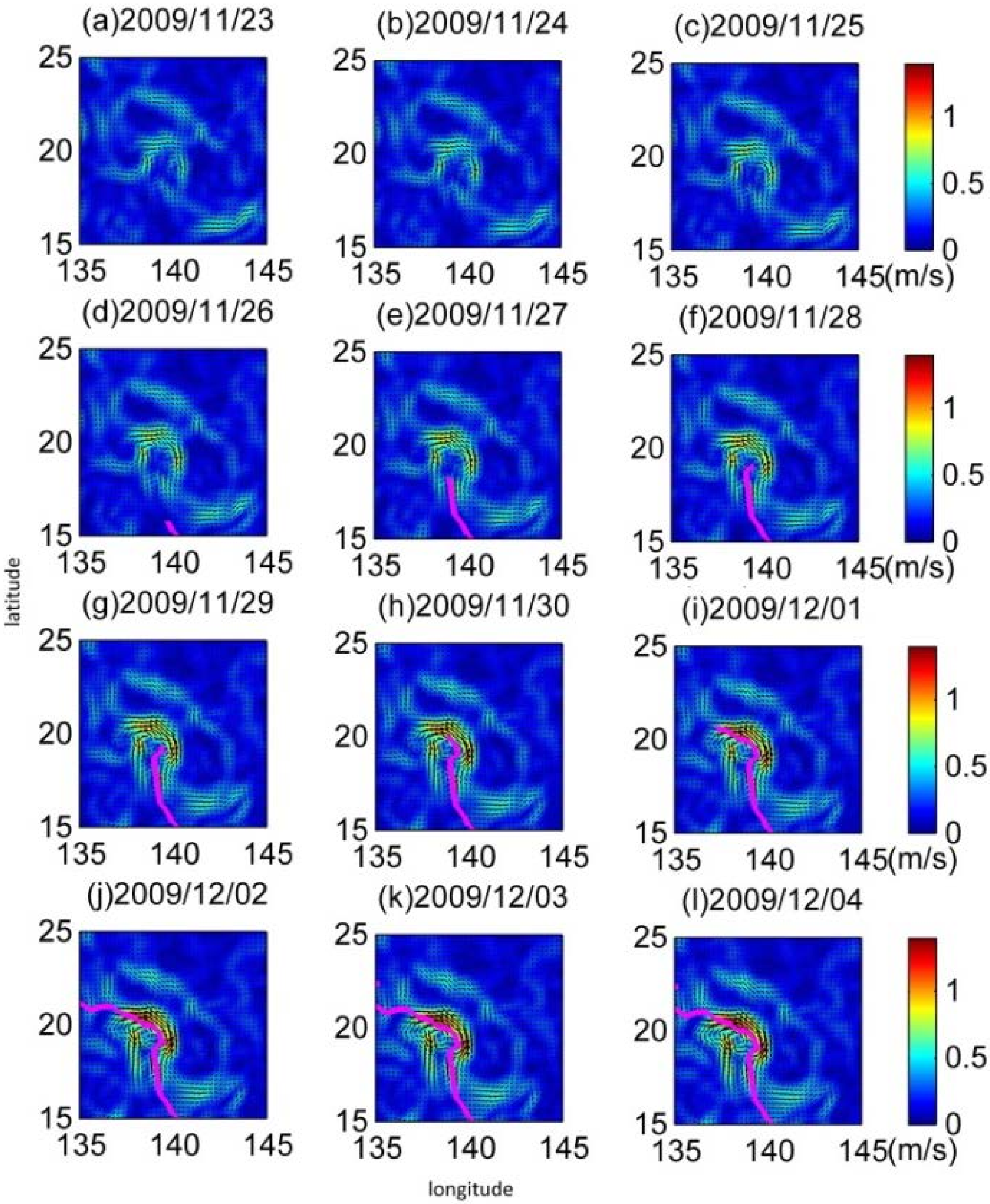

Figure 2. Intensification of the ocean cyclonic Nida Eddy under TC-Nida 2009. Daily mean surface absolute geostrophic currents from 23 November to 4 December 2009 with the direction represented by arrow and the speed represented by color in the region [135º-145ºE, 15º-25ºN] that TC-Nida translated. A weak ocean cyclonic eddy (i.e., the Nida Eddy) occurred at [138º-141ºE, 18º-21ºN] from 23-25 November 2009 with the maximum daily mean current speed less than 0.6 m/s and the radius around 125 km. The super typhoon Nida moved northward from the south at (140ºE, 15ºN) on 26 November, the ocean cyclonic Nida Eddy was still weak. During the slow-moving stage from 27 to 29 November, the super typhoon Nida approached the center of the ocean cyclonic Nida Eddy, and strengthened it with evident right-side bias, i.e., high daily mean maximum speed of 1.3 m/s on the right-side of the typhoon track. This oceanic eddy sustained its strength as TC-Nida monotonically weakened into and moved towards the west a category-3 typhoon by November 30.

Before TC-Nida entered the region-A, a weak ocean cyclonic eddy (i.e., the Nida Eddy) occurred at [138º-141ºE, 18º-21ºN] from 23-25 November 2009 with the maximum daily mean current speed less than 0.6 m/s and the radius around 125 km. During the fast-moving (6.7 m/s to 3.0 m/s) stage (08:00 UTC 25 November – 00:00 UTC 27 November), the super typhoon Nida moved northward from the south at (140ºE, 15ºN), the ocean cyclonic Nida Eddy was still weak with a maximum daily mean current speed of 0.7 m/s. During the slow-moving stage from 08:00 27 November to 00:00 29 November, the super typhoon Nida approached the center of the ocean cyclonic Nida Eddy, and strengthened it with evident right-side bias, i.e., high daily mean maximum speed of 1.3 m/s on the right-side of the typhoon track. This oceanic eddy sustained its strength as TC-Nida monotonically weakened into a category-3 typhoon and moved towards the west by November 30. On December 1, TC-Nida was weakened to a category-1 typhoon, and began to slowly move towards the west and out of the region-A (Fig. 2).

The 6-hourly positions of the SVP drifters drogued at a nominal depth of 15 m, downloaded from the NOAA Atlantic Oceanographic and Meteorological Laboratory website http://www.aoml.noaa.gov/phod/dac/dacdata.php, provide the near-surface oceanic current velocity (geostrophic plus ageostrophic currents). The estimated accuracy of the velocity measurements for SVP drifters under a wind speed of 10 m/s is about 10^{-2} m/s. Two SVP drifters (ID: 71417, and 81961) were drifting under TC-Nida in the western North Pacific Ocean from 10 November to 20 December 2009 (Fig. 3). The maximum velocity of 2.0 m s^{-1} were measured by two drifters at 12:00 UTC on 29 November (81961), and at 6:00 UTC on 3 December (71417) (Fig. 4). After TC-Nida weakened on 3 December and later disappeared, the drifter-measured velocities still kept high values with a maximum of 1.50 m/s on 14 December by the Drifter#71417 and 1.82 m/s on 15 December by the Drifter#81961, and reduced to 0.38 m/s on 20 December by the Drifter#71417 and 0.07 m/s on 20 December by the Drifter#81961.

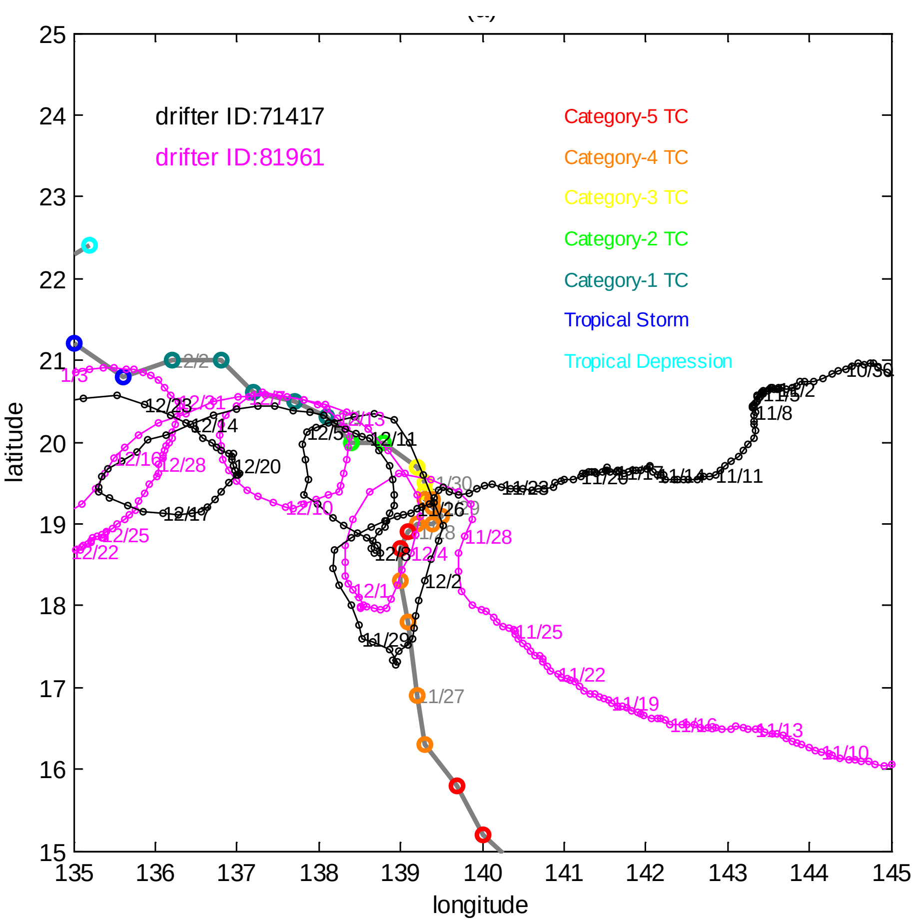

Figure 3. Tracks of TC-Nida and the two SVP drifters (ID: 71417, and 81961) in the western North Pacific Ocean from 10 November to 20 December 2009. During the slow-moving super typhoon period of TC-Nida (27-29 November-3 December 2009), the two SVP drifters were located in the vicinity of TC-Nida.

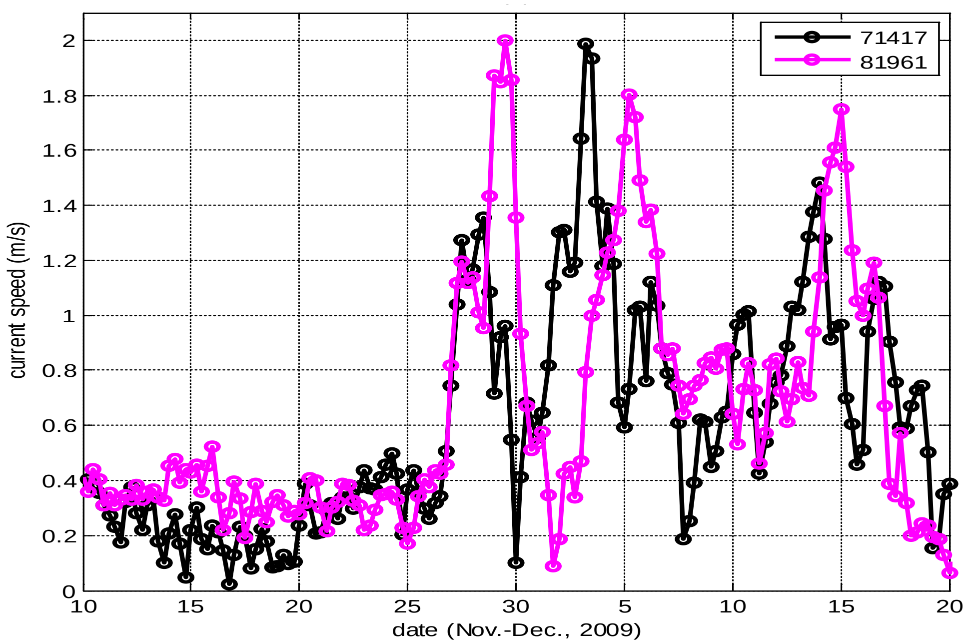

Figure 4. Intensity of the ocean cyclonic Nida Eddy measured by the two SVP drifters. Ocean current speed calculated from the 6-hourly positions of the two SVP drifters showing the maximum velocities of 2.0 m s^{-1} at 12:00 UTC on 29 November (81961), and at 6:00 UTC on 3 December (71417), the drifter-measured velocities still kept high values with a maximum of 1.50 m s^{-1} on 14 December by the Drifter#71417 and 1.82 m/s on 15 December by the Drifter#81961, and reduced to 0.38 m/s on 20 December by the Drifter#71417 and 0.07 m/s on 20 December by the Drifter#81961. The strong ocean cyclonic Nida Eddy sustained at least two weeks after TC-Nida moved out of the area.

Long Lifespan of the Nida Eddy

The radii of TC-induced ocean cyclonic eddies are about 2-4 times the mean radius of TCs' maximum tangential velocity (R_{max}), which is about 47 km [Hsu, 1998]. Ocean cyclonic eddies in the North Pacific have a mean lifespan of about 18 weeks (~4 months), a mean radius about 85 km [Liu et al. 2012; Cheng et al. 2014], and a mean eddy speed about 0.45 m/s [Wyrtki et al., 1976]. However, the ocean cyclonic Nida Eddy identified from the AVISO satellite data had a lifespan approximate 6 months, mean radii about 126-176 km (Fig. 5), a temporally (within the lifespan) and spatially mean absolute geostrophic current velocity of 0.79 m/s, and a maximum daily mean absolute geostrophic current velocity of 1.30 m/s. This oceanic eddy translated westward from [138^{o}-141^{o}E, 18^{o}-21^{o}N] on 30 November 2009 to [123^{o}-126^{o}E, 21^{o}-23^{o}N] on 29 April 2010 with a mean translation speed of 0.0484 m/s (or 4.18 km/day). Comparing to the averaged characteristics of oceanic eddies in the western North Pacific, the ocean cyclonic Nida Eddy under the influence of the super typhoon Nida had near-double strength (0.79 m/s vs. 0.45 m/s), 50% longer lifespan (6 months vs. 4 months), and 50% increased to doubled radii (126-176 km vs. 85 km).

Summary

The observational data show the generation of strong ocean cyclonic Nida Eddy in the western North Pacific during the passage of slow-moving category-5 TC-Nida (23 November to 4 December 2009) with a daily averaged maximum speed of 1.3 m/s. The Nida Eddy had a lifespan approximate 6 months, mean radii about 126-176 km, a temporally (within the lifespan) and spatially mean absolute geostrophic current velocity of 0.79 m/s, an extremely high instantaneous ocean current speed of 2.0 m/s at 12:00UTC 29 November and 06:00UTC 3 December 2009. It was near-double strength (0.79 m/s vs. 0.45 m/s), 50% longer lifespan (6 months vs. 4 months), and 50% increased to doubled radii (126-176 km vs. 85 km) comparing to the averaged characteristics of ocean eddies in the western North Pacific, and translated westward from [138^{o}-141^{o}E, 18^{o}-21^{o}N] on 30 November 2009 to [123^{o}-126^{o}E, 21^{o}-23^{o}N] on 29 April 2010 with a mean translation speed of 0.0484 m/s (or 4.18 km/day). These findings provide observational evidence of generation of extremely strong ocean cyclonic eddy or enhancement of weak existing ocean cyclonic eddy under slow-moving category-5 TCs, which will support further improvements of their representation in ocean dynamics and numerical air-ocean prediction.

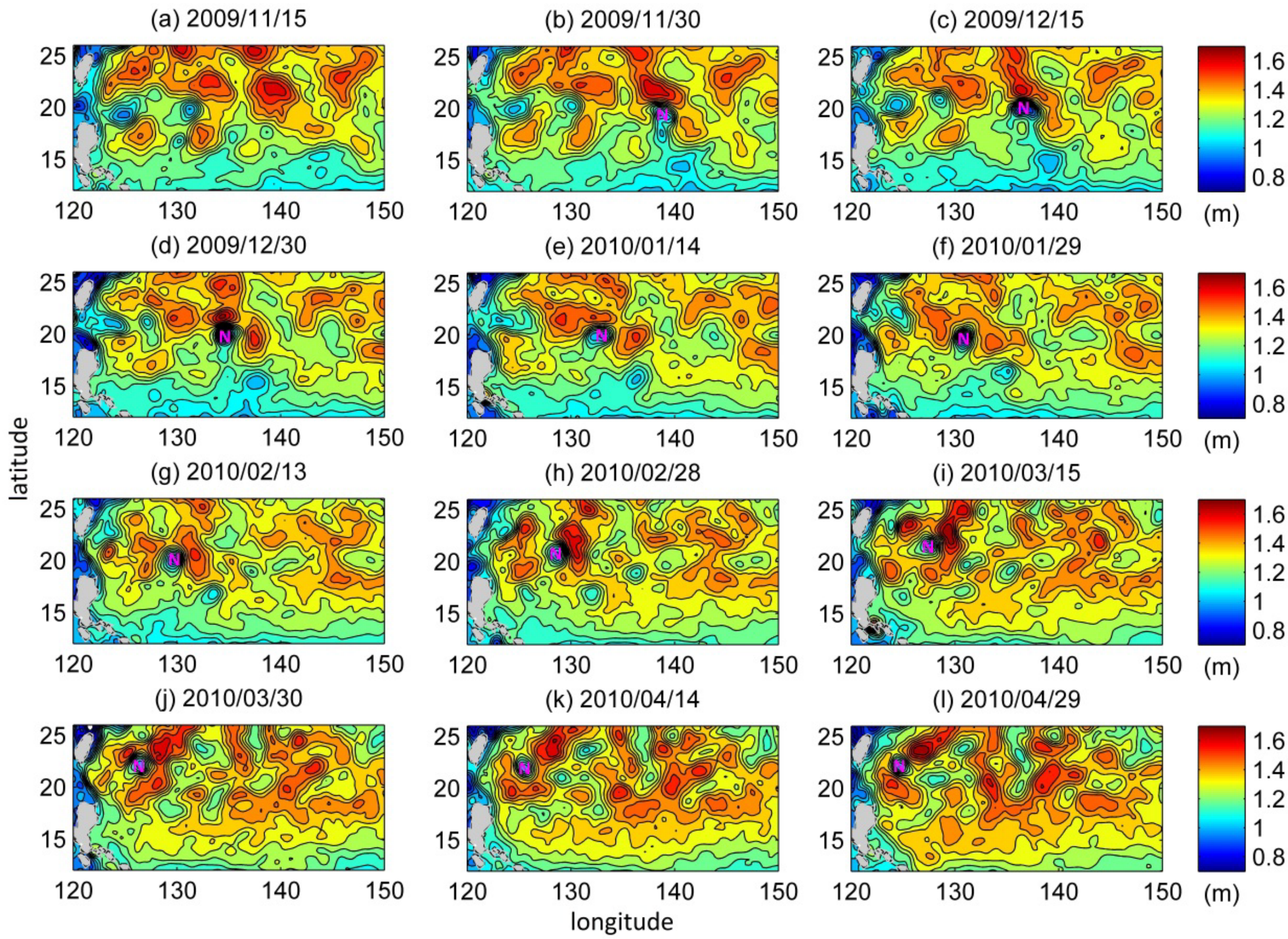

Figure 5. Intensity and location of the ocean cyclonic Nida Eddy from 15 November 2009 to 29 April 2010. Daily dynamic ocean topography fields with 15 day increment (15 November 2009 to 29 April 2010) in the western North Pacific [120°-150°E, 10°-25°N] from the AVISO satellite data show the size (mean radius around 126-176 km), strength, and westward translation of the cyclonic Nida after 6 months of TC-Nida passing by. The ocean cyclonic Nida Eddy was too weak to be identified on 15 November 2009, had the high strength from 30 November to 30 December 2009, and gradually weakened but was still evident on 29 April 2010. It translated westward from [138°-141°E, 18°-21°N] on 30 November 2009 to [123°-126°E, 21°-23°N] on 29 April 2010 with a mean translation speed of 0.0484 m/s (or 4.18 km/day).

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