THE OFFICIAL MAGAZINE OF THE OCEANOGRAPHY SOCIETY

Oceanography

CITATION

D'Asaro, E., P. Black, L. Centurioni, P. Harr, S. Jayne, I.-I. Lin, C. Lee, J. Morzel, R. Mrvaljevic, P.P. Niiler, L. Rainville, T. Sanford, and T.Y. Tang. 2011. Typhoon-ocean interaction in the western North Pacific: Part 1. *Oceanography* 24(4):24–31, http://dx.doi.org/10.5670/oceanog.2011.91.

DOI

http://dx.doi.org/10.5670/oceanog.2011.91

SPECIAL ISSUE ON THE OCEANOGRAPHY OF TAIWAN

Typhoon-Ocean Interaction in the Western North Pacific

Part 1

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An oceanographic float is air-deployed out the back of a C130 aircraft by the 53rd Air Force Reserve squadron, "Hurricane Hunters," during the 2010 Impact of Typhoons on the Ocean in the Pacific (ITOP) program in the western Pacific. Deployments of such instruments in front of typhoons provide a detailed view of the interactions between these storms and the ocean.

ABSTRACT. The application of new technologies has allowed oceanographers and meteorologists to study the ocean beneath typhoons in detail. Recent studies in the western Pacific Ocean reveal new insights into the influence of the ocean on typhoon intensity.

INTRODUCTION

The western North Pacific Ocean has the highest concentration of tropical cyclones in the world. These strong and dangerous storms—called hurricanes in the Atlantic Ocean and eastern Pacific Ocean, cyclones in the Indian Ocean, and typhoons in the western North Pacific Ocean—draw their energy from the warm, humid air found over warm ocean waters. A 150-year compilation of tropical cyclone tracks (Figure 1) shows hurricanes concentrated over the warm waters of the subtropical western Atlantic and Caribbean, and typhoons concentrated over the warm waters of the western Pacific.

On average, there are 16 typhoons per year, about twice the number of Atlantic hurricanes (Webster et al., 2005). Typhoons can occur in any season, unlike hurricanes, which occur almost entirely from June to November. However, both typhoons and hurricanes occur most commonly in the late summer and fall. The region of globally highest concentration of storms is the Philippine Sea, east of Luzon and Taiwan. Destructive landfalling storms are common in the Philippines, Taiwan, Japan, Korea, and mainland China, as well as other nearby countries.

The typhoons' strong winds can have a large effect on the underlying ocean under certain conditions. The warm ocean water that energizes typhoons occupies only a relatively thin layer on top of a colder deep ocean. The strong winds and large waves generated by a typhoon mix these two layers, often creating a trail of colder water—a typhoon "cold wake"—behind the storm. More importantly, this wake forms underneath the typhoon, decreasing the sea surface temperature, thereby reducing the energy supply to the storm and limiting its intensity (Emanuel, 1999; Lin et al., 2008, 2009).

Here, we present a brief description of these typhoon-ocean interactions and the methods used to study them, using examples and data from recent scientific programs sponsored by the US Office of Naval Research, the US National Science Foundation, and the Taiwan National Science Council. This article is intended to be an introduction to this subject, not a comprehensive review. Pun et al. (2011, in this issue) follow with a more detailed presentation of data from the Impact of Typhoons on the Ocean in the Pacific (ITOP) program.

THE TYPHOON WAKE

Satellite infrared images of the sea surface often identify typhoon cold wakes. An image of Typhoon Fanapi in 2010 (Figure 2) shows a narrow trail of cold water, 2–3°C colder than the surrounding ocean, that is located slightly to the north of the storm track. By the time of this image, the storm had moved west and was impacting Taiwan. The typhoon is the large masked region on the west side of the image; the storm clouds prevent this type of satellite (infrared radiometer) from sensing the ocean surface. Satellite microwave radiometers can see though many clouds, at reduced spatial resolution, but not through the heavy precipitation within

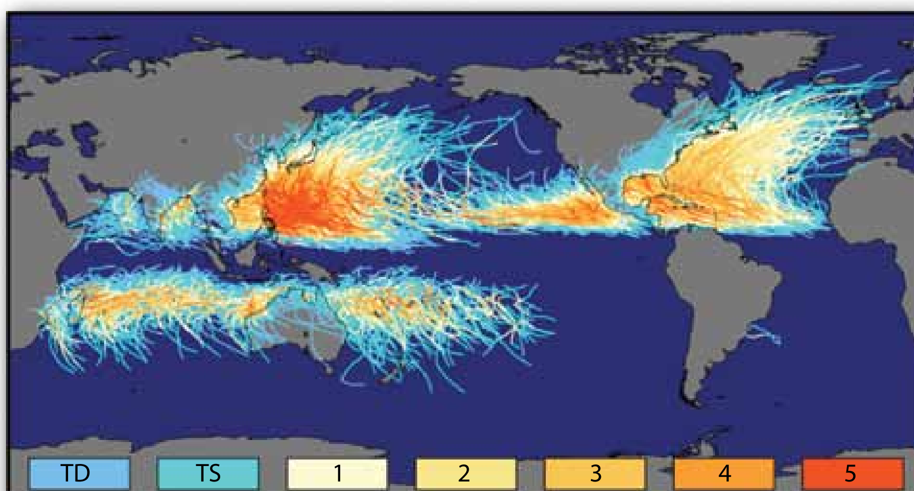

Figure 1. Worldwide tropical cyclone tracks through 2006 from the National Hurricane Center and the Joint Typhoon Warning Center, spanning nearly 150 years. Each track is colored by storm intensity using the Saffir-Simpson storm categories (Tropical Depression, Tropical Storm, and Tropical Cyclone categories 1 [wind 33–42 m s^{-1}] to 5 [wind > 70 m s^{-1}]). The tracks show that the regions of most frequent and intense storms are in the western North Pacific. *Image courtesy of NASA Earth Observatory*

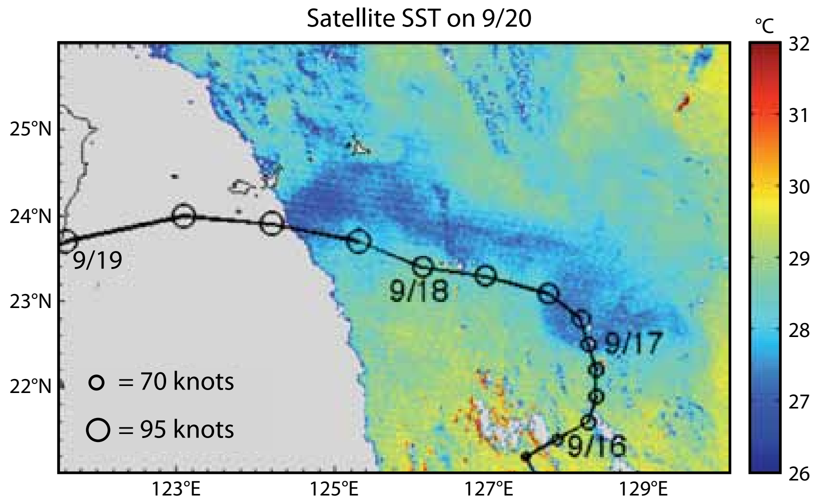

Figure 2. The track (black line) and cold wake (blue stripe) of Typhoon Fanapi on September 20, 2010. The diameters of the circles along the track are proportional to peak storm winds. The storm traveled along a complex S-shaped path as it strengthened, before heading westward and striking Taiwan. Here, the storm is centered off the western edge of the image; its cloud mass hides the sea surface from the satellite.

the central core of a typhoon. Thus, satellite instruments cannot observe the actual formation of the cold wake nor detect the ocean temperature beneath the core of the storm. These measurements require aircraft instruments or instruments at the sea surface.

Oceanographic ships cannot make measurements safely within typhoons. Even if a ship were to unfortunately find itself within a typhoon, the severe conditions would prevent measurements by most of the usual methods. One approach in tropical cyclone oceanography is to deploy instrumented moorings in the regions of most frequent typhoon activity for several years and wait for a storm to pass over (Pun et al., 2011, in this issue). Another approach uses aircraft to both deploy oceanographic instrumentation and measure the properties of the storm itself. Aircraft are the mainstay of meteorological measurements of tropical cyclones. In the Atlantic, "Hurricane Hunter" aircraft from the US Air Force Reserve Command 53rd Weather Reconnaissance Squadron and the National Oceanic and Atmospheric Administration Aircraft Operations Center routinely penetrate hurricanes, providing nearly continuous measurements of the strengths and positions of storms that threaten land as well as supporting research to improve hurricane forecasting. Adding aircraft-based oceanographic instrumentation to these operations capitalizes on decades of experience in tropical cyclone operations acquired by the "Hurricane Hunters."

Oceanographic profilers deployed from aircraft and telemetering data back to the aircraft have been used for several decades in tropical cyclone research (Black, 1983; Shay and Elsbery, 1987; Sanford et al., 1987). More recently, autonomous floats and drifters, capable of measuring the ocean throughout the entire passage of a tropical cyclone, have been developed. Typically, drifters and floats are deployed about one day in front of the storm. Each instrument is packed within a wood and/or cardboard box that is deployed off the back ramp of a WC-130J aircraft (see opening-spread photo). A parachute is used to deliver the box to the ocean surface.

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Once in the water, the box comes apart, usually through the use of dissolving salt blocks, and the instrument is released. Instruments are typically deployed along a line several hundred kilometers long, both to span the width of the storm and to allow for uncertainty in its forecast track. As the storm passes over the line, the instruments measure the proper-ties of the atmosphere and ocean and relay them, in nearly real time, using a satellite data link.

In September 2008, 12 drifters were deployed ahead of Super Typhoon Jangmi (Figure 3). The drifters measured surface wind and atmospheric pres-sure from a small buoy floating on the surface and ocean temperature along a line extending 150 m beneath the buoy (Black et al., 2007; Centurioni, 2010). The sea surface temperature (Figure 3b) decreased by about 1.5°C as Jangmi passed. The deeper temperature sensors (Figure 3c) showed that this cooling extended across the entire surface mixed layer, to about 90 m depth. After the storm had passed, the layer slowly warmed, particularly near the surface.

“AS THE STORM PASSES OVER THE LINE, THE INSTRUMENTS MEASURE THE PROPERTIES OF THE ATMOSPHERE AND OCEAN AND RELAY THEM, IN NEARLY REAL TIME, USING A SATELLITE DATA LINK.”

In 2004, a profiling EM-APEX float (D’Asaro et al., 2007; Sanford et al., 2011) was air-deployed ahead of Hurricane Frances (Figure 4). The EM-APEX repeatedly profiled vertically from the surface to about 200 m depth making a full round trip about once an hour and measuring temperature, salinity, and horizontal velocity. As the storm center passed just equatorward of this float, the upper 60 m of the ocean cooled by up to 2.2°C, while water from about 60–140 m warmed.

EM-APEX observations in Hurricane Frances revealed a phenomenon called

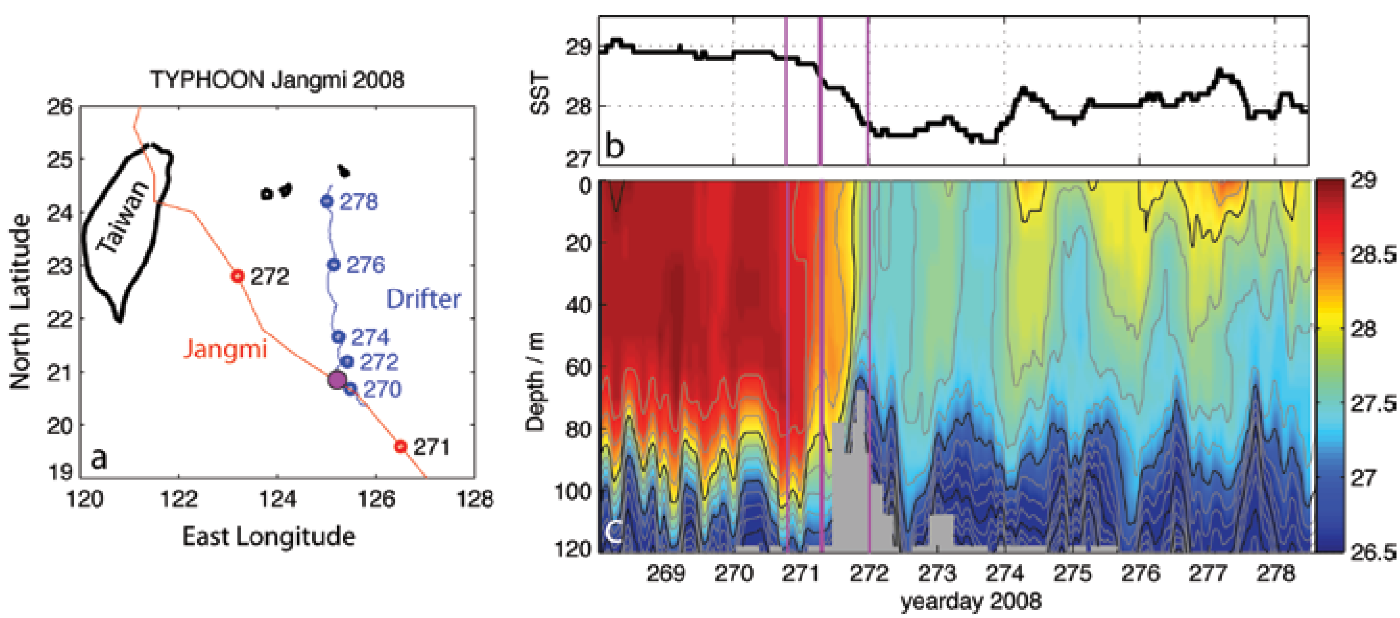

Figure 3. Upper-ocean response to the passage of Super Typhoon Jangmi as measured by a surface drifter. (a) Track of Jangmi (red) and drifter (blue). Labels are yeardays of 2008. (b) Sea surface temperature (SST). The heavy magenta line marks the time of Jangmi’s closest approach to the drifter; thin lines mark the approximate duration of gale force winds. SST decreases in response to the storm. (c) Temperature of the upper 120 m of the ocean as measured by the drifter’s temperature chain. The upper 90 m of the ocean cool as the storm passes and then slowly warms over the next week.

"inertial resonance" (Price, 1981), responsible for much of the structure of typhoon wakes. As the nearly circular storm travels westward just south of the float, the winds swing in a clockwise direction, from southwestward as the storm approaches, to westward at maximum intensity at the closest approach of the storm, to northwestward as the storm recedes to the west. The wind initially accelerates southwestward currents. Earth's rotation causes these currents to also swing in a clockwise direction and be continuously accelerated by the rotating wind. Such "inertial currents" can rapidly reach large amplitudes, nearly 1.5 m s^{-1} in Hurricane Frances (Figure 4). This "inertial resonance" causes a particularly strong ocean response on the right-hand side of the storm track (i.e., the poleward semicircle for a westward-going storm) and explains the poleward offset of the cold wake from the storm track (Figure 2). EM-APEX data from the Hurricane Frances observations also show that the strong, storm-forced currents were confined to the warm upper-ocean layer, with the deeper, colder underlying layer nearly unaffected (Figure 4). The shear between these layers caused intense mixing, which was evident as the rapid thickening and cooling of the upper layer between yeardays 245.5 and 245.8, (i.e., September 1, 2004; Figure 4). This event, occurring during the passage of the storm center, showed the initial formation of the cold wake by vertical mixing. During the next two days (yeardays 246 and 247, i.e., September 2–3), upwelling of cooler, deeper water could be observed, as well as further deepening and warming of the thermocline.

> "THE RESPONSE OF THE OCEAN TO TYPHOONS DEPENDS NOT ONLY ON THE SPEED AND SIZE OF THE STORM, BUT ALSO ON THE PROPERTIES OF THE UNDERLYING OCEAN."

Although ships are not suited for oceanographic measurements inside a typhoon, they can be used to study the evolution of the ocean after the typhoon has passed, if the ship schedule can be flexible enough to adapt to the unpredictable occurrence of a storm. An R/V *Revelle* cross section of the wake of Typhoon Fanapi four days after the storm's passage (Figure 5a) shows that the cold wake was immediately subject to warm and generally sunny subtropical conditions that caused the well-mixed surface layer to become capped by warm water in the days following the storm. The subsurface measurements also reveal that this warming was confined to a thin surface layer and that the deeper part of the cold wake had a significantly longer lifetime. A section 21 days after the storm (Figure 5b) shows there was still a thickened layer of 25–26°C water, which was a remnant of the typhoon wake. Although the surface manifestation of the cold wake had nearly disappeared and the wake was nearly invisible to satellite sensors, the observations from the ship and other platforms identified a much longer-lived subsurface thermal legacy of the typhoon.

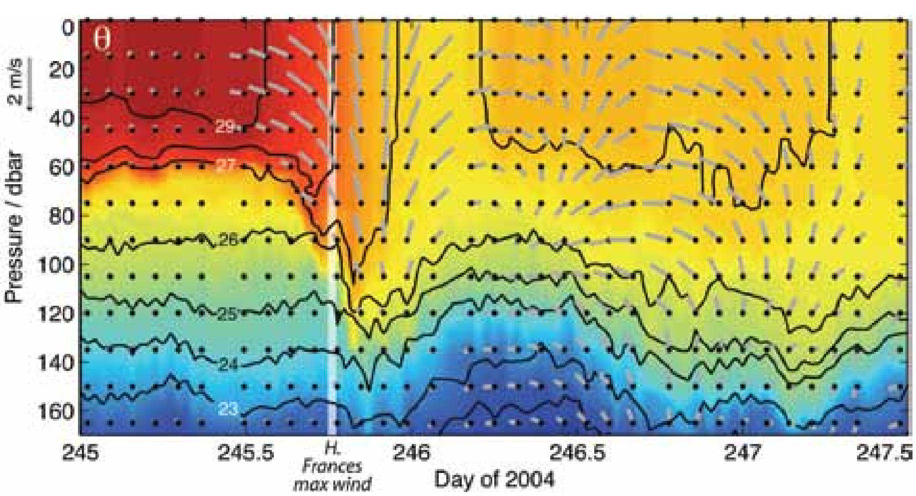

Figure 4. Ocean response to Hurricane Frances measured by a profiling EM-APEX float described by Sanford et al. (2011). Contours and colors show the temperature; gray bars show the velocity. Northward currents point up; eastward currents point right. The vertical white bar shows the time of maximum winds at the float. As in Figure 3, the surface layer cools during storm passage, but the layer from 60 m to 120 m warms.

TYPHOON-OCEAN INTERACTIONS

The response of the ocean to typhoons depends not only on the speed and size of the storm, but also on the properties of the underlying ocean. The warm ocean surface layer varies in thickness. Because the cold wake is caused primarily by mixing of this warm layer with the colder, underlying layer, the degree of cooling depends on the thickness of the warm layer and thus on the depth of the thermocline, the transition layer between the warm and cold layers. Deep thermoclines have a thick layer of warm water above them, while shallow thermoclines have a thin layer. Because warm water expands, the sea surface is slightly higher over deep thermoclines than over shallow ones. Thus, measurements of sea surface height from satellite altimeters, combined with sea surface temperatures measured from satellite infrared and microwave observations, and the large historical database of ocean temperature profiles, can be used to estimate the temperature profile (Shay et al., 2000) and thus predict the degree of ocean cooling from a typhoon (Pun et al., 2007).

The simplest such estimate, $\Delta T_{\overline{100}}$, is made by assuming that a typhoon will mix the top 100 m of the ocean (Price, 2009). The degree of cooling $\Delta T_{\overline{100}}$ is then the difference between the pre-storm sea surface temperature and $T_{\overline{100}}$, the average temperature of the upper 100 m of the ocean. Figure 6 shows such an estimate (Pun et al., 2011, in this issue) made just ahead of Typhoon Fanapi, overlaid with the storm track. At the location of the float and drifter deployments, it predicts a cooling of about 1.5°C, which is comparable to, but less than, the observed maximum cooling of 2.6°C. Satellite estimates are thus useful, particularly in determining regional patterns, but are not a replacement for in situ measurements.

There are large variations in $\Delta T_{\overline{100}}$ across the western Pacific. For example, south of about 15°N, the warm surface layer is very deep and the predicted cooling is less than 1°C. A temperature profile taken in this region (Figure 6b) shows a surface warm layer, defined by the 26°C isotherm, extending to well below 100 m. To the north, near 25°N, 140°E, the warm layer is much thinner (Figure 6c) and the predicted cooling much higher, up to 5°C. These differences primarily reflect the large-scale shallowing of the western Pacific thermocline toward the north. However, as can be clearly seen in Figure 6a, numerous ocean eddies modulate the depth of the thermocline, particularly within the eddy-rich "Southern Eddy Zone" (SEZ) between approximately 20°N and 26°N (Lin et al., 2008). Due to these oceanic variations, the same storm traversing different regions, or traversing the same region at a different time and thus with a different eddy, would be expected to produce a different wake. Thus, the response of the ocean to typhoons tends to be spotty as it is sensitive not only to sea surface temperature, which is nearly the same in Figure 6b and 6c, but also to variable ocean structure associated with eddies.

Because typhoons draw their energy from the warm water, the cold wakes that they produce have the potential to

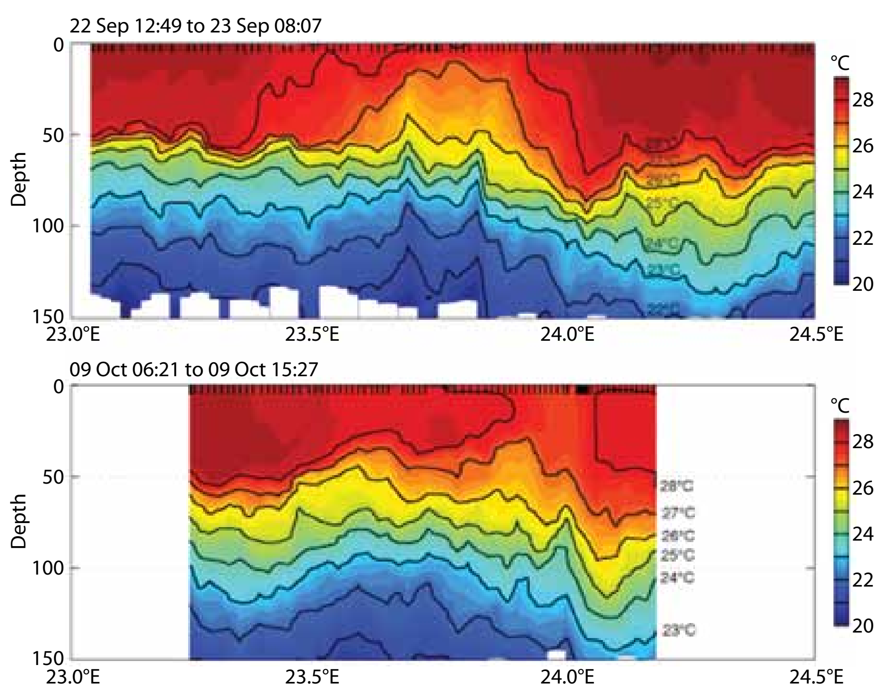

Figure 5. (a) Section across the wake of Typhoon Fanapi four days after the storm's passage. The cold wake at about 23.8°N is capped with warmer water but is still evident as a thick layer of water between 25°C and 27°C. (b) Same section 21 days after storm passage. A slightly thicker layer within the wake temperature range is still evident across the entire section, but particularly near 23.9°N. The persistence of this subsurface wake is typical of a large number of ocean measurements made in this region after Typhoon Fanapi's passage.

limit their intensity and reduce their rate of intensification. Storm intensity is most sensitive to the ocean temperature beneath the inner core of the storm (Emanuel, 2003), that is, within about twice the radius of maximum storm winds. Observations (Figures 3 and 4) show that the cold wake forms under the storm core, and can thus affect storm intensity. An analysis of the strongest typhoons (Lin et al., 2008) finds that these storms only develop if the warm surface layer is sufficiently deep. This is particularly true for slow-moving storms, which produce the coldest wakes nearest to the storm center (Lin et al., 2009). Equatorward of the SEZ, the warm layer is usually sufficiently deep to allow these storms to develop rapidly. However, within and poleward of the SEZ, they can develop only when a strong anticyclonic eddy depresses the thermocline beneath the typhoon track. Thus, the intensity of tropical cyclones can depend on the presence, or absence, of relatively small oceanic features.

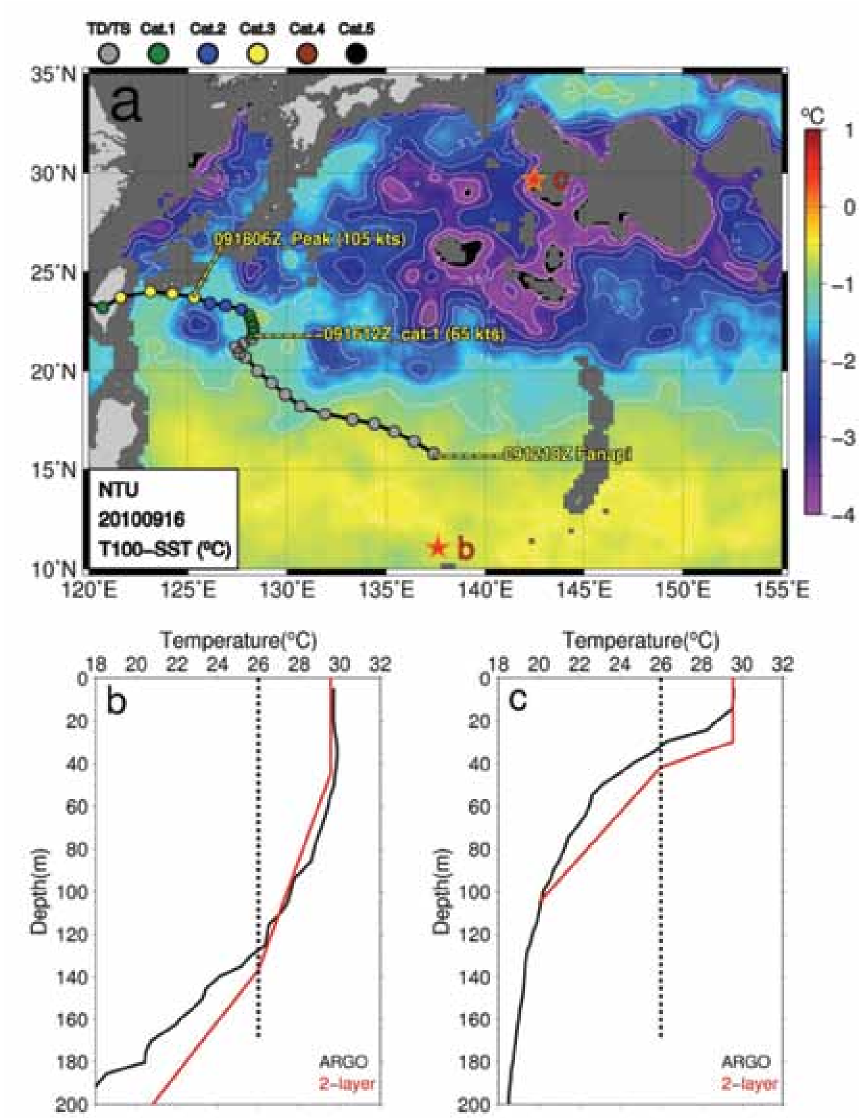

Figure 6. (a) Estimated cooling $\overline{T}_{100}$ sea surface temperature (SST) just before the passage of Typhoon Fanapi, based on satellite estimates. The storm track is also shown. Stars show locations of two Argo float profiles. (b) Temperature profiles in the southern region show a thick surface warm layer. (c) Temperature profiles in the northern region show a much thinner surface warm layer. Black profiles in (b) and (c) are from Argo floats; red profiles are from satellite estimates. The dashed vertical line at 26°C provides an approximate boundary between warm and cold water. The satellite estimates are imperfect compared to the observations, but still capture the overall change in stratification across this region. The Argo float data were collected and made freely available by the International Argo Program and the national programs that contribute to it. The Argo Program is part of the Global Ocean Observing System.

FUTURE PROGRESS

The factors controlling the intensity of tropical cyclones are not entirely understood; certainly, most are atmospheric, but the ocean also exerts influence. However, over the last decade, oceanographers and atmospheric scientists have been learning how the interactions between tropical cyclones and the ocean can affect both components of this system: the formation of cold wakes in the ocean and the enhancement (or inhibition) of rapid storm development in the atmosphere, as well as the modulation of both these effects by pre-existing ocean stratification and eddies. Measurement systems—moored, air-deployed, and satellite-based—have allowed us to measure these effects in some detail during limited research programs. Operational and research models of tropical cyclones (Bender et al., 2007) now routinely include both the atmosphere and the ocean and their coupling. Though measurements of the atmosphere are made routinely as part of operational tropical cyclone forecast systems and the influence of these measurements are analyzed continually to assess the accuracy of the forecast system, no similar program for in situ measurement of the ocean exists. If, as we now believe, the ocean has an important influence on tropical cyclone intensity, especially rapid intensification, oceanic measurements should be part of the operational observing system used for tropical cyclone forecasts and warnings.

ACKNOWLEDGEMENTS

This work is supported by grants from the Office of Naval Research, N00014-10-WX-20203 (Black), N00014-08-1-0656 (Centurioni), N00014-08-1-0577 (D'Asaro), N00014-09-1-0816 (D'Asaro), N00014-10-WX-21335 (Harr), N00014-08-1-0614 (Jayne), N00014-09-1-0133 (Lee), N00014-08-1-0560 (Lien), N00014-10-1-0313 (student support), N00014-08-1-0658 (Rainville), N00014-08-1-0560 (Sanford); the National Oceanic and Atmospheric Administration NA17RJ1231 (Centurioni); and the National Science Foundation OCE0549887 (D'Asaro). We also thank the Office of Naval Research for providing travel support for a student of I.-I. Lin.

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