

The Effects of Ocean Eddies on Tropical Cyclones

By

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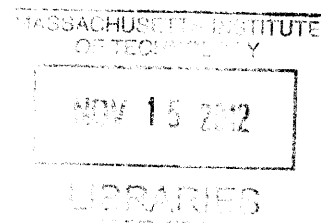
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Abstract

The purpose of this study is to understand the interactions of tropical cyclones with ocean eddies. In particular we examine the influence of a cold-core eddy on the cold wake formed during the passage of Typhoon Fanapi (2010). The three-dimensional version of the numerical Price–Weller–Pinkel (PWP) vertical mixing model has previously been used to simulate and study the cold wakes of Atlantic hurricanes. The model has not been used in comparison with observations of typhoons in the Western Pacific Ocean. In 2010 several typhoons were studied during the Impact of Typhoons on the Ocean in the Pacific (ITOP) field campaign and Fanapi was particularly well observed. We use these observations and the 3DPWP to understand the ocean cold wake generated by Fanapi. The cold wake of Fanapi was advected by a cyclonic eddy that was south of the typhoon track. The 3DPWP model outputs with and without an eddy are compared with observations made during the field campaign. These observations are compared to model outputs with eddies in a series of positions right and left of the storm track in order to study effects of mesoscale eddies on ocean vertical mixing in the cold wake of typhoons.

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Introduction

The purpose of this study is to understand the interactions of tropical cyclones with ocean eddies. In particular we examine Typhoon Fanapi (2010) and a cold-core eddy that was to the south of the typhoon trajectory. The one-dimensional and three-dimensional versions of the numerical Price–Weller–Pinkel (PWP) vertical mixing model have previously been used to simulate Atlantic tropical cyclones in the Northern Hemisphere. These versions of the PWP model have been used to study the mixing of ocean in the cold wakes of a number of Atlantic hurricanes. This model has not previously been used in comparison with observations of tropical cyclones in the Western Pacific Ocean. We use the 3DPWP to simulate Typhoon Fanapi and the ocean eddy's interaction with tropical cyclones such as Fanapi. In 2010 several typhoons were studied by the Impact of Typhoons on the Ocean in the Pacific (ITOP) field campaign. Fanapi, in particular, was particularly well observed by reconnaissance aircraft, air-deployed floats, autonomous gliders, research vessels, and moorings that had been emplaced in the storm's path. We use these observations collected during this field study to simulate Fanapi using the 3DPWP. Fanapi, which crossed Taiwan in September 2010, tracked to the south a anticyclonic eddy roughly equivalent in diameter to the typhoon and to the right of a second cyclonic eddy of an equivalent diameter. The cold wake of Fanapi was advected by this second cyclonic eddy. The 3DPWP model outputs with and without an ocean eddy are compared with observations made during the ITOP field campaign. These observations are also compared to model outputs with ocean eddies in a series of

positions to the right and left of the storm track in order to study the effect of ocean eddies in mixing of the cold wake in the case of typhoon Fanapi.

Description of ITOP

In 2008 a field study of the western Pacific—concentrated in the region of the world’s highest occurrence of tropical storms—was initiated to study the impact of typhoons on the ocean. The aptly named Impact of Typhoons on the Ocean in the Pacific (ITOP) was an international collaboration between the U.S. Office of Naval Research and Taiwan National Science Council that has several goals: studying the cold wake of typhoons, the affect of ocean eddies on typhoons and the ocean’s response to typhoons, typhoon genesis, typhoon forecasting, the surface wave field under typhoons, and the air-sea fluxes for winds greater than 30 m/s. The data used to compare with model outputs was collected during September 2010 of this field study and was part of observations collected for three typhoons: Fanapi, Malakas, and Megi. Observations of these three typhoons were made using long term mooring arrays, two C-130 aircrafts operated by the Air Force Reserve 53rd Weather Reconnaissance Squadron “Hurricane Hunters”, a DOTSTAR Astra jet, Synthetic Aperture Radar, and the US research vessel Revelle that was deployed in the wake of the typhoons to make hydrographic casts and deploy gliders.

A total of five long-term typhoon moorings were deployed in the western Pacific in March of 2009 and operated through the end of 2010 along with an additional subsurface and surface mooring deployed in August of 2010. Every 2-6 hours observations were

transmitted of air pressure, sea surface, sub-surface, and air temperature, humidity, wind speed and direction, and buoy position. Observations were also collected by four ATLAS surface-buoy moorings and three subsurface ADCP-CTD-chain moorings were deployed between 123°E and 128°E and 18°N and 22°N with an approximate depth of 5600 meters and transmitted by Iridium satellites. The ATLAS moorings were equipped with a suite of meteorological sensors, more than 10 temperature sensors above 500 meters, and several had conductivity sensors. The ADCP-CTD-chain moorings were equipped with an upward-looking 75-kHz Long Ranger and a chain of 7-8 SBE37 CTD sensors.

Two mooring were deployed that were made up of an Air-Sea Interaction Spar (ASIS) buoy tethered to a moored Extreme Air-Sea Interaction (EASI) buoy. These were deployed at 127°E and 21°N and 19° 30'N with the purpose of continuously measuring the response of the ocean and atmosphere to typhoon forcing. The moorings continuously measured directional ocean wave spectra, mean wind speed, wave heights, and air-sea fluxes of momentum and heat.

When a storm entered the operations area, a ASTRA-SPX aircraft, operated by the Taiwanese DOTSTAR program, was deployed with an Airborne Vertical Atmosphere Profiling System (AVAPS) and a flight level data system. If the decision to deploy oceanographic sensors was made after the reconnaissance flight, one or more lines of Lagrangian floats, EM-APEX floats [Sanford et al., 2005], and typhoon drifters were

deployed approximately one day ahead of the storm from one of two C-130J aircrafts operated out of Guam.

Three styles of Lagrangian floats were deployed by the C-130: 4 floats that measured broadband sound, oxygen, and gas tension, 4 floats that measured temperature and salinity at the top of the float, ocean velocity relative to the float, pressure, and broadband sound, and 2 floats that measured downwelling PAR and downwelling E490.

The C-130 deployed fourteen EM-APEX floats ahead of the storms. The EM-APEX floats profiled at a speed of approximately 1 m/s and measured temperature, salinity, and velocity from the surface down to 200 m with a resolution of approximately 1 meter. During this time the C-130 also performed a mini-reconnaissance flight and one day later performed a second flight to measure storm structure as the typhoon passed over the float arrays and completed a drop of dropsondes.

In total 65 drifters were deployed both in the wake and ahead of the storm by the C-130. Altogether 40 ADOS/SVP-B [Black et al., 2007] drifters were deployed in front of the typhoon. These drifters measured wind speed and direction, air pressure, surface temperature, and subsurface temperature every 15 to 150 meters. The C-130 also deployed 25 drifters in the wake of the typhoons: 20 SVP-T(z) and 5 Super-drifters. The SVP-T(z)'s were deployed in individual boxes and measure sea surface temperature and subsurface temperature at 11 and 19 meters. The Super-drifters measured sea surface temperature, wind speed and direction, air pressure, downwelling radiation, and 3D

velocity in variable resolution. Both the ADOS/SVP-B and SVP-T(z) drifters were expendable, but the super-drifters were recovered by the R/V Revelle.

During the deployment of the drifters in the wake of the typhoon the C-130 coordinated with the US research vessel, the R/V Roger Revelle, to survey the cold wake. The Revelle was used to deploy and recover the long-term and ASIS/EASI moorings, deploy regular and microstructure Seagliders [Eriksen et al., 2001] into the cold wakes, and recover some of the air-deployed floats and drifters. The flexibility of the ship schedule combined with the placement of moorings and deployed drifters made more complete observations obtainable as described in D'Asaro et al. [2011] and Pun et al. [2011]. The cruise track for the Revelle can be seen in Figure 1. Vertical profiles of temperature and salinity were made by the Revelle using an UnderwayCTD that was deployed along the track of the cruise [Rudnick et al. 2007]. The Oceanscience UnderwayCTD was deployed continuously between September 17 and October 11.

Moorings arrays located at 22°N, 124°E and 21°N, 123°E were able to continuously take observations in the water column during the lifetime and cold wake of typhoon Fanapi. Between September 15 and 21 there were 95 floats or drifters were deployed by the C-130 during four reconnaissance and survey flights. There were 72 AXBTs (Airborne eXpendable BathyThermograph) deployed in total, 7 EM-APEX floats and 8 ADOS drifters were deployed on September 17, and 6 ADOS drifters and 3 SUPER drifters were deployed on 19, 20, and 21 September after the passage of Fanapi to survey the cold wake. The cold wake of Fanapi was surveyed by the Revelle from its arrival in the

region on September 21 until October 11 [Mrvaljevic et al. 2012]. The Revelle also launched 9 Seagliders during this period.

Description of Typhoon Fanapi

Typhoon Fanapi was a typhoon that formed on September 14, 2010 to the southwest of Taiwan and was centered at an approximate latitude of 19.6°N and a longitude of 129.1°E and became a category 3 on September 18. The typhoon made landfall on Taiwan on September 19 and weakened to a severe tropical storm several hours later. The total death toll in Taiwan was officially listed as two while 75 people were injured and the official damage estimates were put at US\$210.9 million [Chen 2010]. Most of the damages and injuries caused by Fanapi were due to heavy rain and flooding. Fanapi had a lifetime of about 5 days and dissipated over China on September 20, 2010 at a latitude of 24.3° and a longitude of 113.1° E near Guangdong. In China heavy rains and flooding from Fanapi caused 70 deaths and US\$315 million in damages. The track of Fanapi is shown in Figure 1 and was the first typhoon to make landfall on Taiwan since August of 2009.

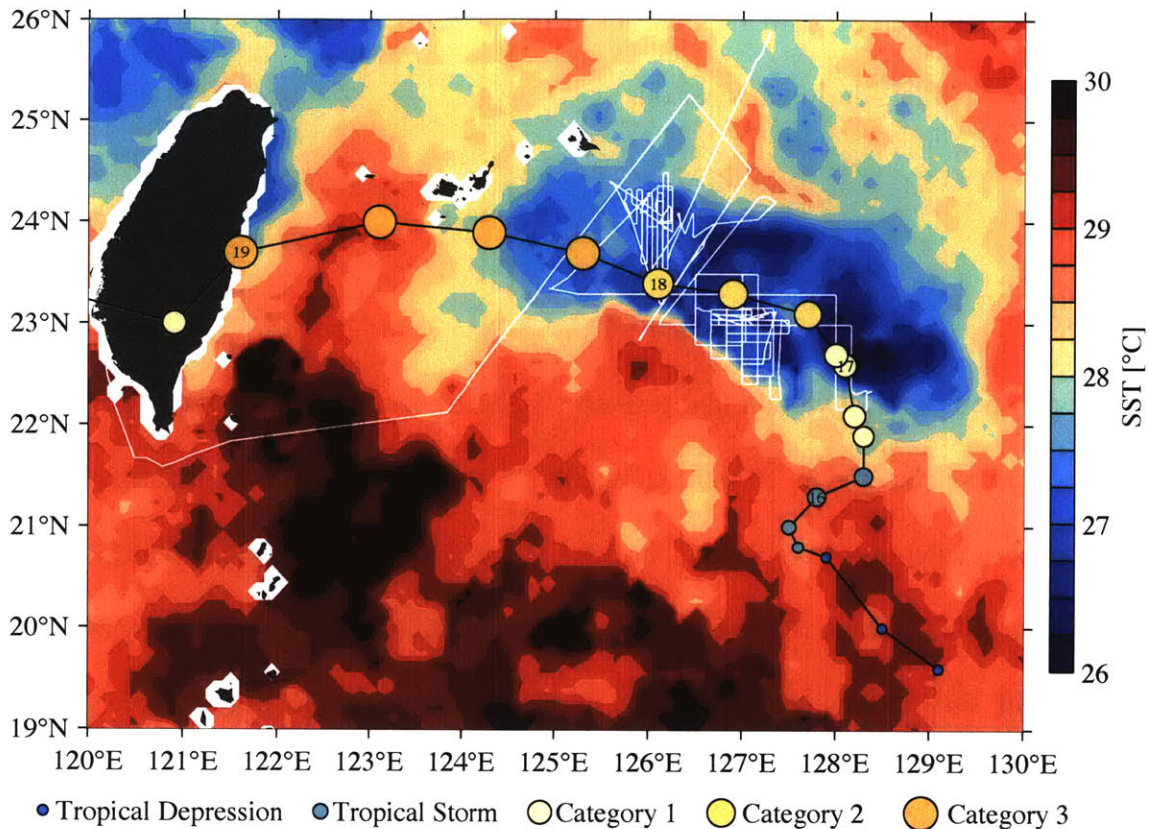


Figure 1 – Track of Typhoon Fanapi based on the best track estimate from the Joint Typhoon Warning Center along with the sea surface temperature on September 19, 2010. The thin white line represents the cruise track of the R/V Revelle.

Fanapi tracked northwest before abruptly turning north and pausing for a day. It then traveled westward across Taiwan and the Taiwan Strait. The maximum sustained winds were 175 km/h or 49 m/s with a radius of 85 km. The radius of gale winds was approximately 170 km. The storm moved a total distance of 2073 km with an average translation speed of 4.2 m/s. It left a cold wake of 2°C slightly to the north of the storm track described in Mrvaljevic et al. [2012]. The ocean was mixed to a depth of 80 to 100 m with a isotherm displacement amplitude of 20 to 30 meters of the 26°C isotherm.

During the jog in the storm track on September 16th and 17th it was near a warm-core ocean eddy that was to the northeast of the storm track and of the same size scale as the storm radius of Fanapi. On the third day of the storm, September 18th, Fanapi passed to the north of a second eddy. This eddy was a cyclonic, cold-core eddy that also had a radius of 170 km, approximately equal to the storm radius of Fanapi. This cold-core eddy is the eddy that we are studying in this paper and can be seen to the south of the storm track in Figure 2 below.

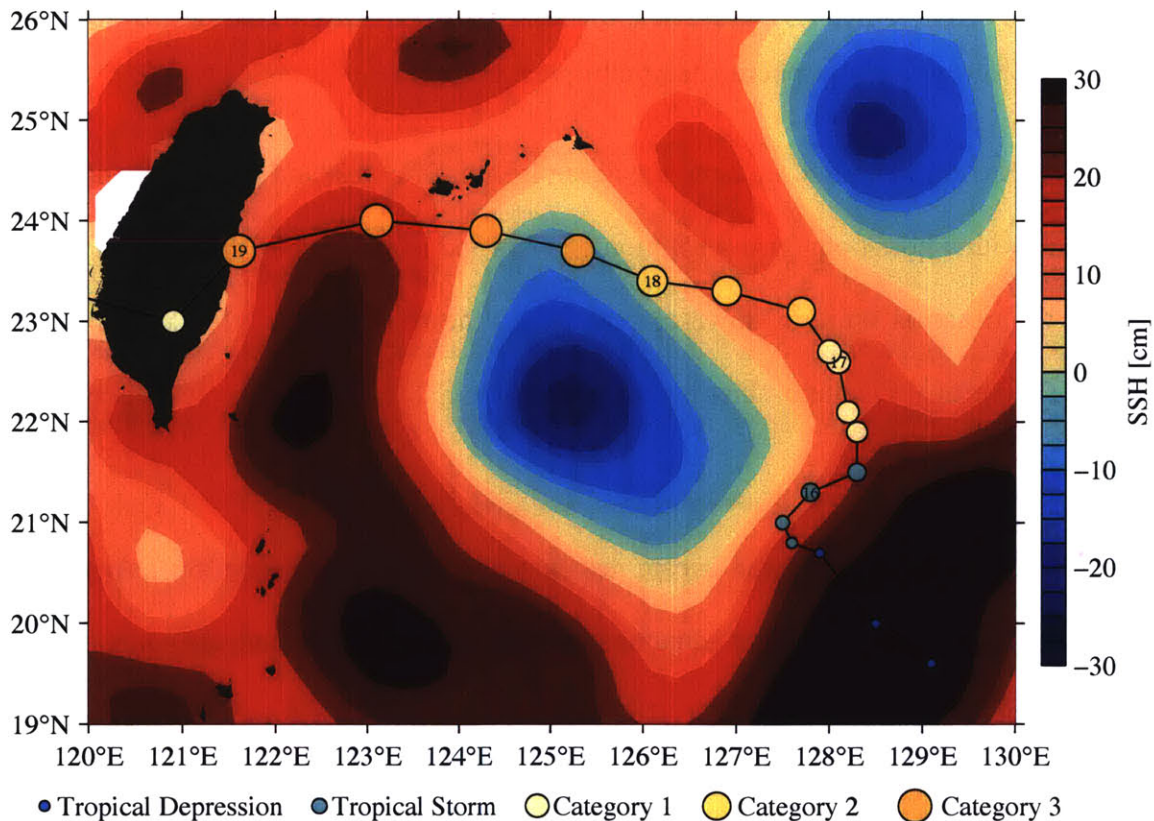


Figure 2 – Sea surface height anomaly during the lifetime of Typhoon Fanapi. A large cold-core eddy can be seen to the southwest of the storm track on September 18th, 2011, with a smaller one to the northeast.

Description of Model

The numerical ocean model is the three-dimensional and time-dependent Price-Weller-Pinkel model (3DPWP) as described in Price et al. [1994], [see also Price et al. [1986], Sanford et al. [2007], Sanford et al. [2011]]. The model uses the three-dimensional primitive equations given in equations 1-3 and hydrostatic model to simulate the upper ocean response to a hurricane. The only subgrid-scale process in this model is upper ocean shear-driven vertical mixing and is given by the one-dimensional hybrid mixed-layer formulation in Price et al. [1994]. In these papers the model was always employed to simulate Northern Hemisphere Atlantic tropical cyclones

In the model configuration used here, the ocean is initially at rest and homogeneous in the horizontal with a horizontal grid resolution of 5 km and is 601 by 501 grid points. In the vertical the ocean is uniform down to 300 m and the resolution is 10 m down to this depth. The vertical resolution then increases to 50 m and then increases to 100 m down to 1000 m.

The model computes an upper ocean response to moving hurricane by solving the momentum, heat, and salt budget equations on this fixed grid. The budgets equations are the given and described in Price et al. [1994] as:

$$\frac{\partial T}{\partial t} + \mathbf{V} \cdot \nabla T + W \frac{\partial T}{\partial z} = \frac{1}{\rho_0 C_p} \frac{\partial H}{\partial z} \quad (1)$$

$$\frac{\partial S}{\partial t} + \mathbf{V} \cdot \nabla S + W \frac{\partial S}{\partial z} = \frac{\partial E}{\partial z} \quad (2)$$

$$\frac{\partial \mathbf{V}}{\partial t} + f \mathbf{k} \times \mathbf{V} + \mathbf{V} \cdot \nabla \mathbf{V} + W \frac{\partial \mathbf{V}}{\partial z} = \frac{1}{\rho_0} \frac{\partial \boldsymbol{\tau}}{\partial z} - \frac{1}{\rho_0} \nabla P \quad (3)$$

where T and S are the temperature and salinity respectively, P is the hydrostatic pressure, H, E and $\boldsymbol{\tau}$ are the heat, salt, and momentum fluxes and \mathbf{V} the horizontal current and W is the vertical component of the velocity. The Coriolis parameter, f, is taken to be uniform over the model domain, which is valid for a few days following the typhoon passing while moving along a fairly constant latitude.

The model uses temperature and salinity profiles in vertical taken from data gathered during the survey of Fanapi's cold wake by Revelle. The profiles are taken from the survey before the vessel entered the cold wake. The vertical temperature and salinity profiles were taken at 0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, 120, 130, 140, 150, 175, 200, 300, 500, 1000, 2000, and 5000 m. These profiles are illustrated in Figure 3. In order to compute density from T and S the SeaWater matlab routines (version 3.3 library of EOS-80 seawater properties) was used. The only subgrid-scale process is shear-driven vertical mixing parameterized by the one-dimensional PWP model [Price et al., 1994].

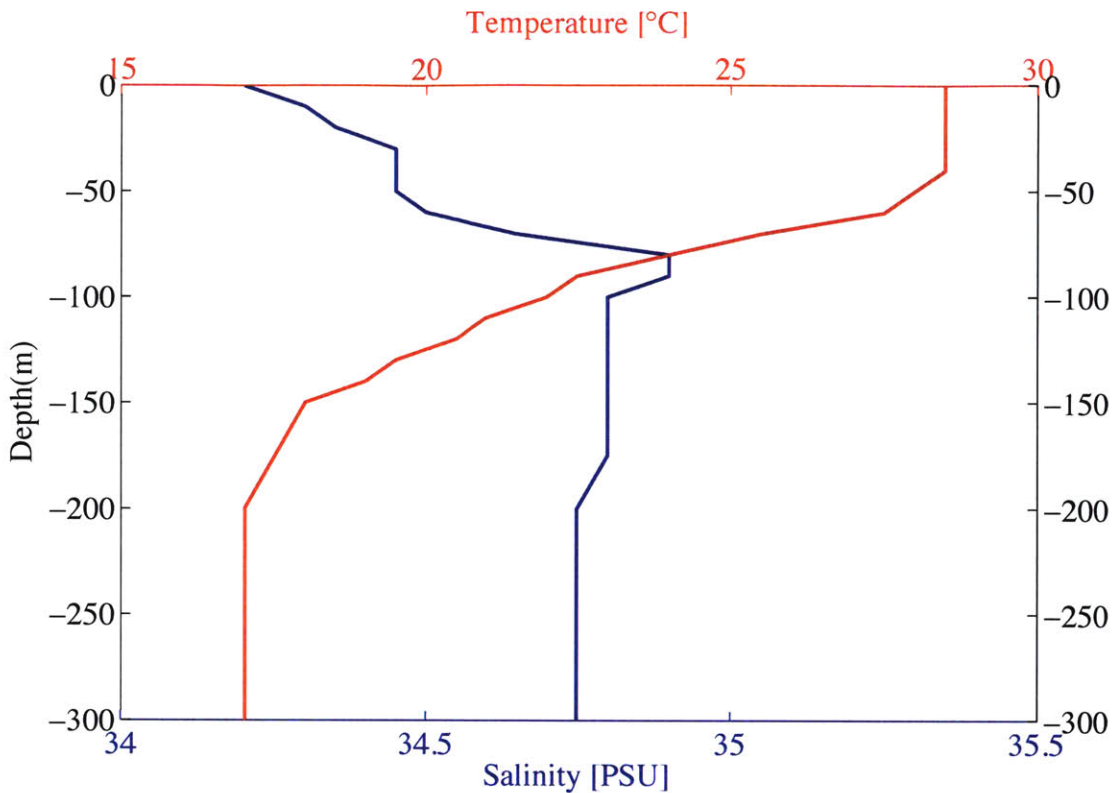


Figure 3 – Plot of vertical temperature (red) and vertical salinity profile (blue) taken from R/V Revelle CTD measurements used to initialize the 3DPWP model.

A total of eight inputs are required to run the model. These parameters describe the physical characteristics of the storm and the ocean eddy. They are: the amplitude of isotherm displacement (m), depth where isotherm displacement is at a maximum (m), half width of front or eddy (km), displacement of eddy to left or right of the track (km), the radius of the storm's maximum winds (km), maximum sustained wind speed (m/s), translation speed (m/s), and number of time steps. The model is initially setup with a time step of 400 s and 1000 time steps. The model is integrated with this time step using the three time level, leapfrog-trapezoidal method and the typhoon travels 1680 km in all

simulations. In all trials the values of maximum sustained winds, translation speed, and number of time steps are the same. The values of these parameters are given in Table 1.

Parameter	Value
Radius Maximum Winds	70 km
Maximum Sustained Winds	49.2 m/s
Translation Speed	4.2 m/s
Number of Time Steps	1000

Table 1 – Model parameters that remain fixed throughout simulations

The Powell drag coefficient for high wind speed-saturated drag was used, which uses an increasing drag coefficient for wind speeds up to 32 m/s and then decreases for winds above that speed until leaving off at 1.5×10^{-3} as described in Powell et al. [2003].

In order to describe the radius structure of the surface wind speed of the storm the model uses an adopted standardized wind profile from the NOAA technical report NWS 23 Meteorological Criteria for Standard Project Hurricane and Probable Maximum Hurricane Windfields, Gulf and East Coasts of the United States [Schwerdt et al., 1979]. Graphs 13.6 and 13.11 in this report illustrate functions for the percentage of maximum wind speed versus number of maximum wind speed radii for wind speed inside the radius of maximum winds speed and outside of this radius. The combined graph is given below in Figure 4.

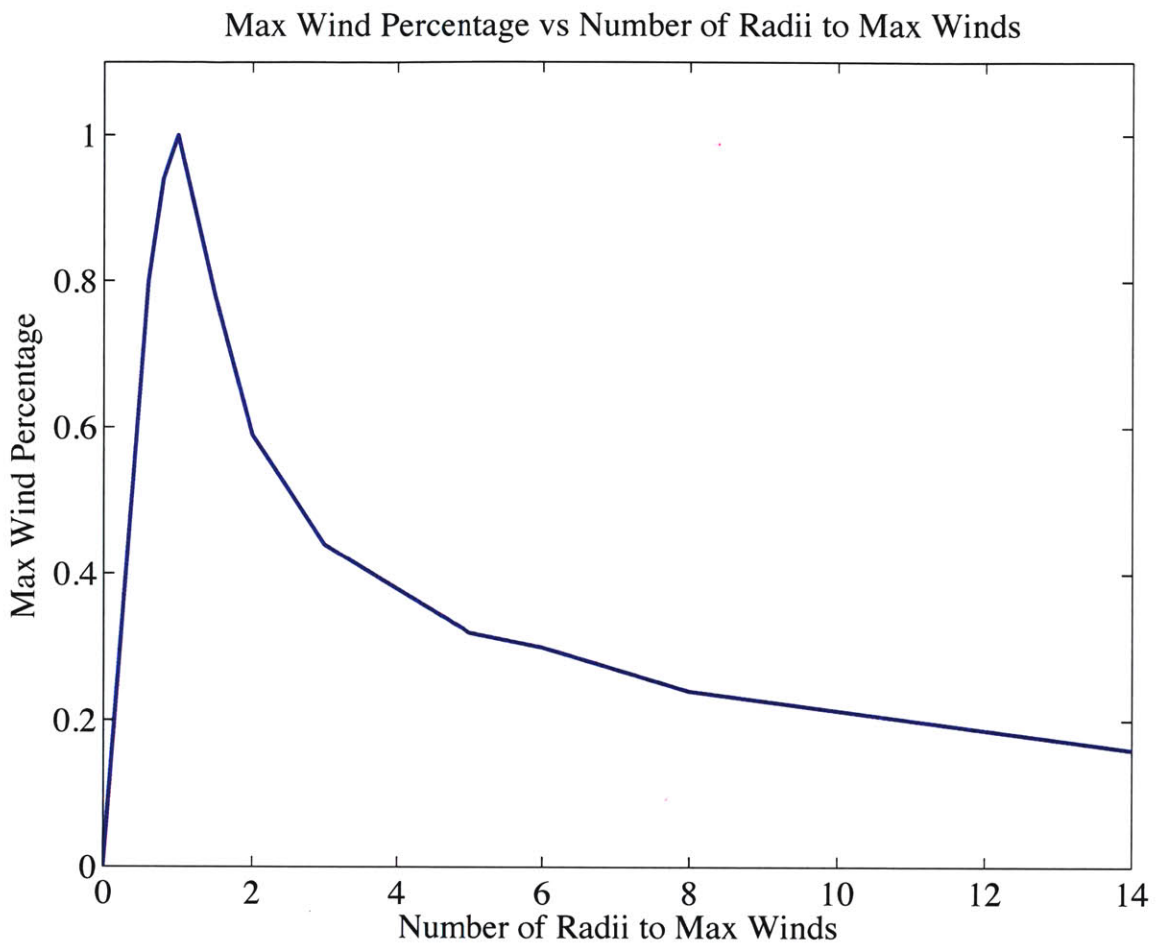


Figure 4 – Graph of NOAA NWS 23 for standard hurricane maximum storm winds projection to specify the wind structure in the model.

Results

Model outputs from the 3DPWP were compared to graphs of SST and vertical temperature and salinity profiles made from data that was gathered during cross-sections of Typhoon Fanapi's track by the Revelle. In order to study the effects of a cold-core ocean eddy in upper ocean mixing in this model, we ran a series of trials with and without an ocean eddy at various positions to the left or right of the storm track. For these seven trials the following were kept constant: maximum sustained winds, radius to maximum winds, translation speed, number of time steps, and depth where isotherm displacement is at a maximum. From observations taken the Revelle we assumed the amplitude of isotherm displacement was 30 m and the depth where the isotherm displacement was at a maximum was 130 m.

One trial had zero values for the amplitude of isotherm displacement, half the width of front or eddy, and displacement of eddy to left or right of track. This trial was the no eddy case that was used as a base to observe the differences between ocean mixing with no eddy and with ocean eddies at various positions to the right or left along the typhoon's track. In the six trials which had an eddy present, half of the eddy width was taken to be approximately equal to the radius of the typhoon, which can be seen from the graph of SSH in Figure 2 and is approximately 170 km. From the same figure we assumed that the ocean eddy in the Fanapi case was a cold core eddy; hence, the eddies added to the 3DPWP model in all of these trials were cold-core eddies and that the actual eddy position was one storm radii left of the storm track. In our simulations the eddy was

initially centered on the tropical cyclone and then moved by half a storm radius up to 2 radii right and left of the storm.

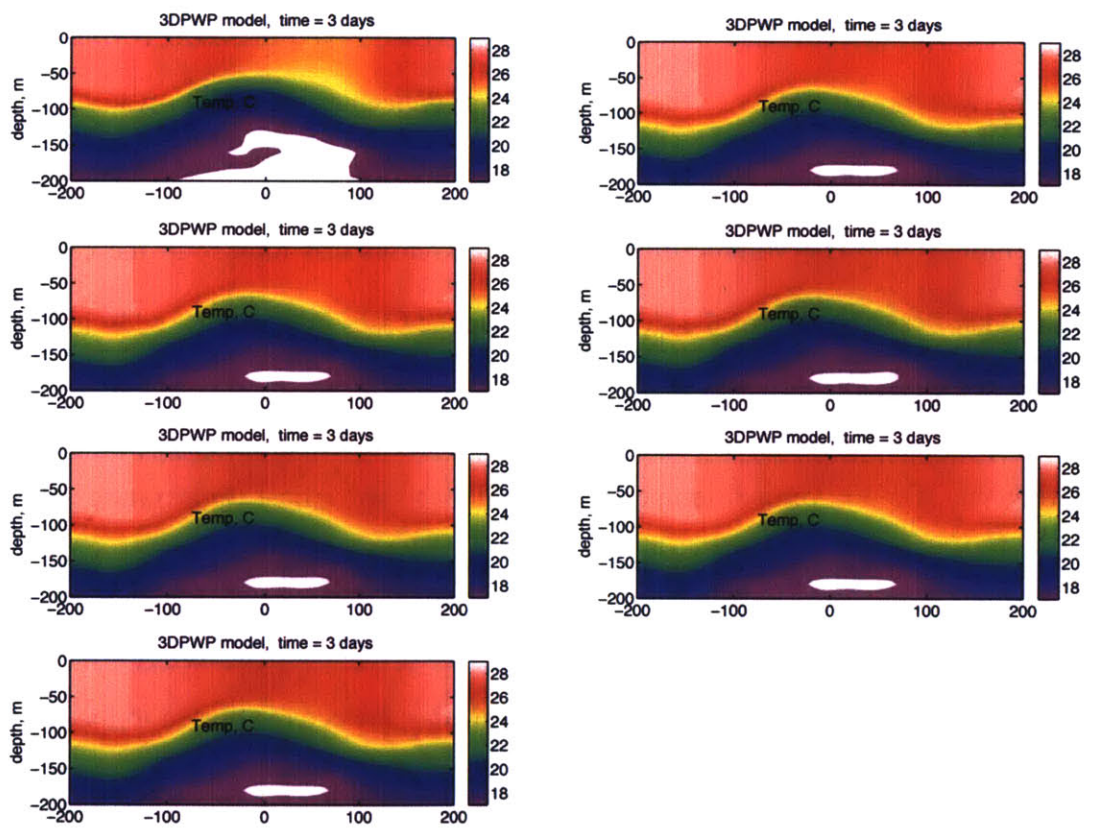
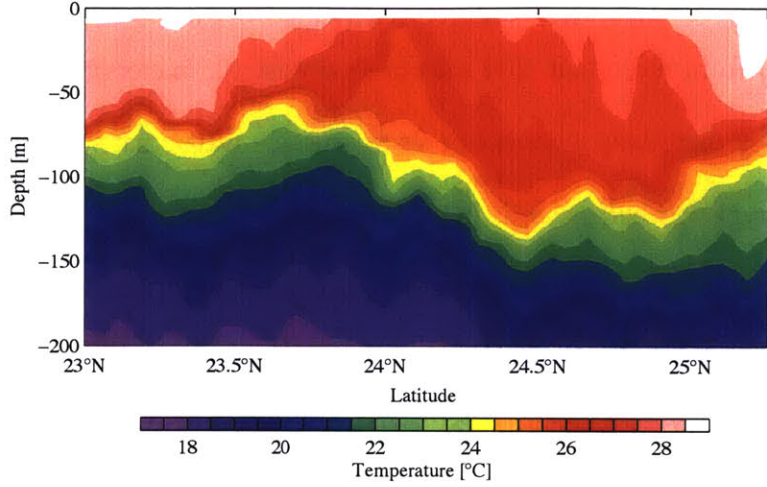


Figure 5 – Vertical temperature profiles sliced three days after the storm passed. From left to right and top to bottom: (a) profile taken from the Revelle, (b) vertical temperature profiles from 3DPWP with no eddy, (c) centered eddy, (d) eddy left a half storm radius from center, (e) eddy right a half storm radius from center, (f) eddy left one storm radius from center, (g) eddy right one storm radius from center, (h) eddy left one and one half storm radii from center.

In the case of no eddy there was a large downwelling that can be observed in Figure 5 which extended from more than 200 meters to almost 125 meters below the sea surface. In all other cases there was a pocket of warm-surface water that was still retained three days after the typhoon had passed, but the volumes of these pockets was significantly smaller than the volume of the pocket in the no eddy case. These vertical temperature profiles all differ from the profile taken by the Revelle in that all have this warm-surface water pocket at a depth of approximately 175 meters.

The addition of an eddy to the model drastically reduced the volume of this warm pocket. As the eddy was moved further to the right or left of the center, this warm-water pocket decreases in volume and then rapidly re-expands to the size and shape of the warm-water pocket in Figure 5b. The volume of this pocket decreases less rapidly in the cases in which the eddy lies to the left of the storm track than the cases in which the eddy is to the right of the storm track.

Comparing the 3DPWP vertical temperature profiles to the vertical temperature profile taken from the Revelle we can see that the 3DPWP was better able to approximate temperature profiles of Typhoon Fanapi when an ocean eddy is added. There does not appear to be a significant difference, however, in whether the eddy is placed to the left or right of the storm track in the cases in which the eddy is within 1.5 to 2 storm radii from the typhoon track's center. After the eddy was placed 2 or greater storm radii to the right there is no difference from the no eddy case. After two storm radii to the left, although the model provides a better approximation than the no eddy case, these cases did not

provide as a close a match to the Revelle's vertical temperature profile as the cases in which the eddy is between 0.5 and 2 storm radii to the left of center. The cases in which the eddy was greater than 2 storm radii left of center produced a significantly different vertical temperature profile than the no eddy case, but did not predict observed profile well.

The changes in the vertical temperature profiles made by the introduction of an ocean eddy can more clearly be illustrated by Figure 6. The vertical temperature profiles shown in Figure 6 are the temperature differences between the vertical temperature profile of the no eddy case and those in Figures 5 c-h. In all graphs there was a general cooling of the isotherm when an ocean eddy is present while the underlying layer is warmed. Initially the isotherms, in the cases with an eddy, were over a degree warmer than the no eddy case and gradually warm as the eddy moves further off the center of the typhoon track.

Most of the cooling that occurred in the cases in which there was an eddy was in the isotherm and extended in a column to the surface directly below the storm track. As can be seen in Figure 6 the main difference between the vertical temperature profiles in the cases in which an ocean eddy was added to the right and those with an eddy to the left of the storm track is that the shallower, cold water was mixed upward in the cases with an eddy to the right of the storm track. The vertical temperature profiles in the model were still warmer when an eddy was present to the right of the storm track and there was an underlying layer that was warmer than in the no eddy case; however, the temperature profiles are slightly colder in the case of eddies to the right of the storm track than in the case of eddies to the left by 0.2 to 0.3°C.

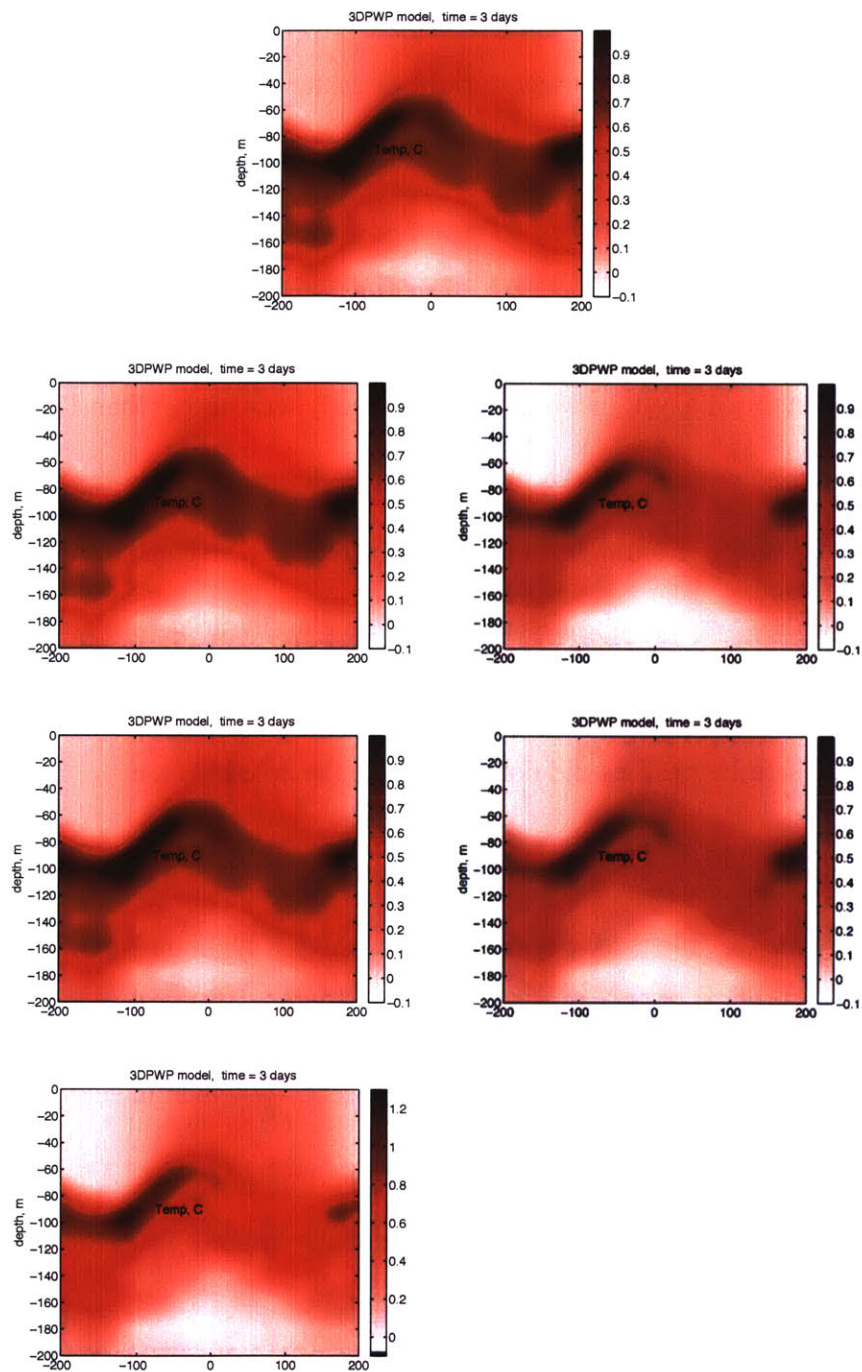


Figure 6 – From left to right and top to bottom vertical temperature profile differences between the no ocean eddy case and an ocean eddy (a) centered, (b) one half a storm radius left of track center, (c) one half a storm radius right of track center, (d) one storm radius left of track center, (e) one storm radius right of track center, (f) one and a half storm radii left of track center all sliced three days after the storm passage

We also ran trials with the 3DPWP for eddies up that were up to 3 storm radii to the right and left of center. In the case of trials to right of center where the eddy was greater than 1 storm radii off center we found that SST and vertical temperature and salinity profiles did not differ from the no eddy case. These results are to be expected for ocean eddies that are to the right (north) of westward tracking Pacific tropical cyclones.

For the trials with the 3DPWP in which the ocean eddy was further than 1.5 storm radii to the left of the typhoon track we did not include the figures. In the cases which had an eddy between 1.5 and 3 storm radii to the left of center, the SST and vertical temperature and salinity profiles were not significantly different than the trial with an eddy 1.5 storm radii to the left of center. For trials with eddies greater than three radii left of center, temperature and salinity profiles did not differ from the no eddy case.

We also examined vertical salinity profiles from the 3DPWP and compared them with a profile taken by the Revelle three days after the passing of typhoon Fanapi. These graphs can be seen in Figure 7. The salinity profiles do not differ significantly or, in most of the cases, at all from each other when an eddy was present. Whether an eddy was to the left, right, or centered on the storm track seems to have had no effect in the 3DPWP model. The salinity profile in the case with no eddy did differ slightly from the cases in which there was an eddy present and the no eddy case more closely resembled the observed vertical salinity profiles. The no eddy case was fresher in the upper 75 m than the case with an eddy present by 0.05 to 0.1 PSU. The difference between how well the no eddy case and cases in which an eddy was present was not significant enough, however, to

conclusively determine if an eddy was needed in the model for the case of Typhoon Fanapi.

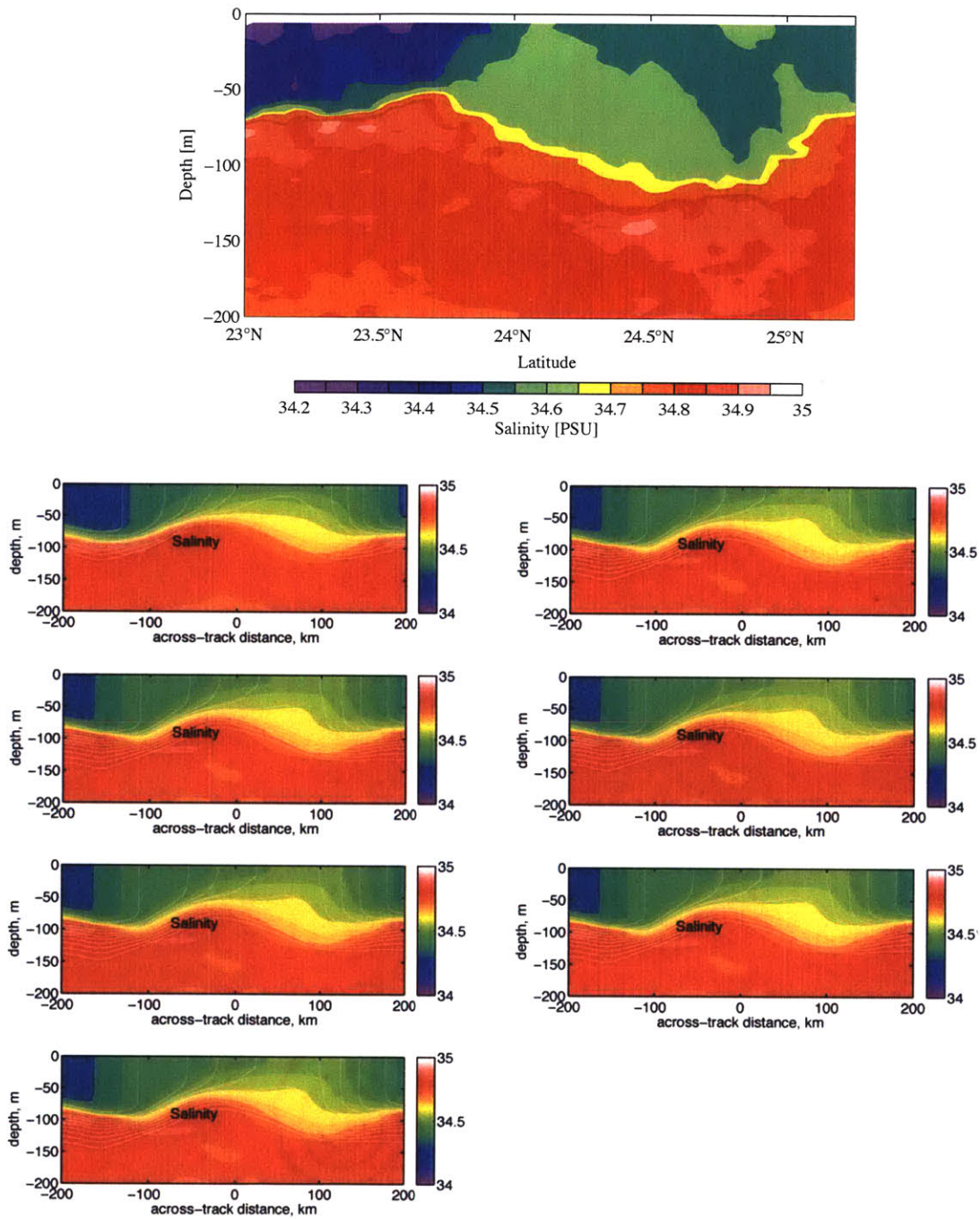


Figure 7 – Vertical salinity profiles sliced three days after the storm passed. From left to right and top to bottom: (a) profile taken from the Revelle, (b) vertical salinity profiles from 3DPWP with no eddy, (c) centered eddy, (d) eddy left a half storm radius from center, (e) eddy right a half storm radius from center, (f) eddy left one storm radius from center, (g) eddy right one storm radius from center, (h) eddy left one and one half storm radii from center.

The sea surface temperatures from each case ran for the 3DPWP are shown in Figure 8. From these graphs the only difference that can easily be seen was that the no eddy case has cold wake with an interior temperature of 25°C or less that was longer and more persistent than the cases with an eddy. The more illustrative graphs are in Figure 9. These graphs are the differences of the no eddy SST results from the model and each of the six cases with an eddy. In these graphs the warmer tail ends of the cases with an eddy are clearly visible and show a SST increase of a degree or more on the storm track. The shape, area, and temperature of the track SST, however, was not dependent on the placement of the eddy along the storm track.

Another feature of interest in Figure 9 were the warmed bands of surface water to the left and right of the track. The most these bands warmed the SST was 0.3°C and decreased in warming from there. These bands were cooler than the no eddy case. In the case of the centered eddy the bands were symmetric about the track. As the eddy was moved to the right or left the bands decreased in area and temperature on the side of the track opposite the eddy. The temperature of the bands on the same side of the track as the eddy in the cases in which the eddy was to the left of the storm track, however, increased slightly in temperature compared with the centered eddy case, but not in area. This trend continued until 2.5 to 3 storm radii from center. The warm bands to the right of the storm track were almost completely faded once the eddy was moved left of center.

In the cases in which the eddy was to the right of center the warm bands on the left of the track faded with the distance of the eddy from the center; however, unlike in the case of

the eddies left of center, the bands to the right of the track did not increase in temperature or area. The bands to the right of the track actually decreased rapidly in temperature and size compared with the cases with an eddy to the left of center. When an eddy was placed to the right of center the bands on either side of the track quickly cooled with eddy distance from center and when the eddy was placed within two storm radii to the right of the storm track the SST mirrored the no eddy case.

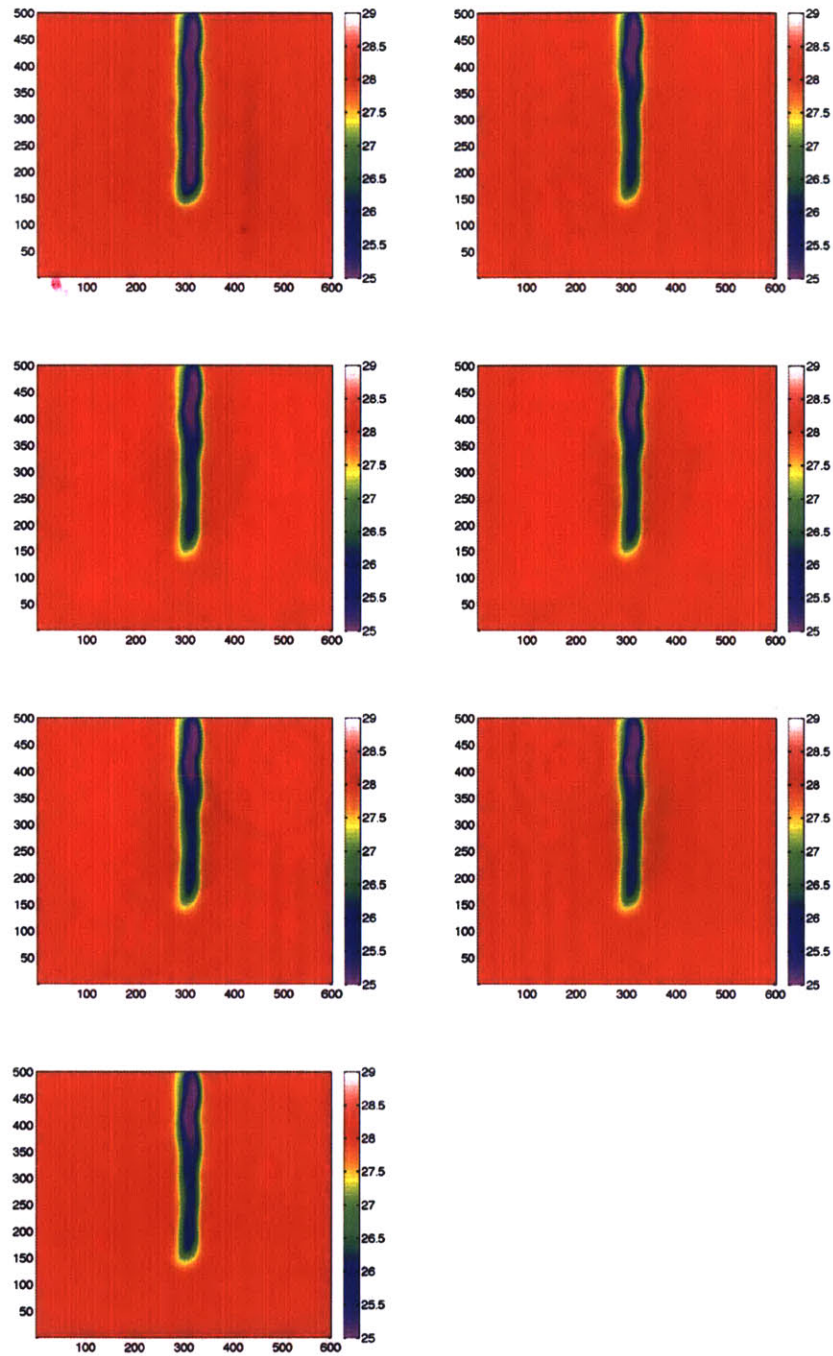


Figure 8 – Sea surface temperature three days after the storm passed from 3DPWP. From left to right and top to bottom: (a) no eddy, (b) centered eddy, (c) eddy left a half storm radius from center, (d) eddy right a half storm radius from center, (e) eddy left one storm radius from center, (f) eddy right one storm radius from center, (g) eddy left one and one half storm radii from center.

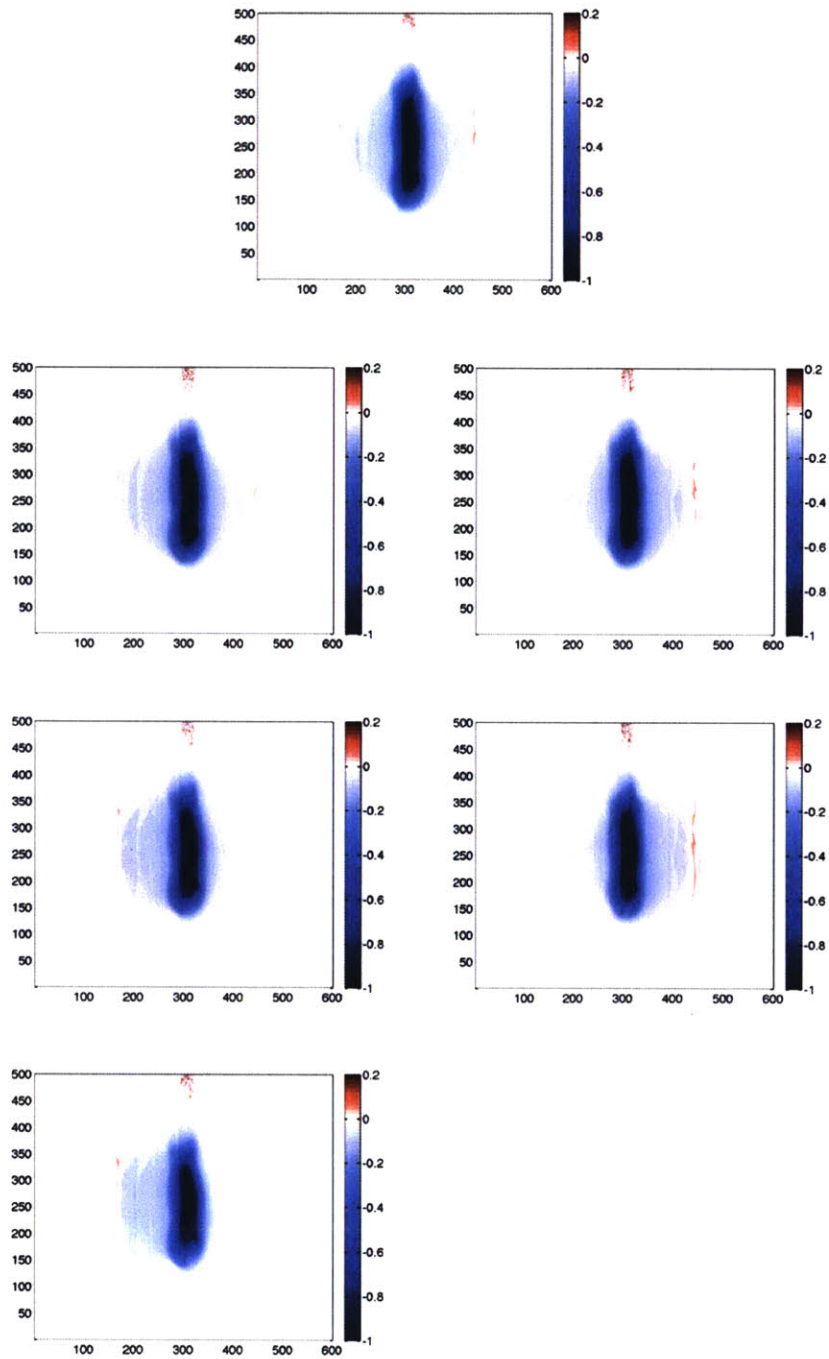


Figure 9 – From left to right and top to bottom sea surface temperature differences between the no ocean eddy case and an ocean eddy case (a) centered, (b) one half a storm radius left of track center, (c) one half a storm radius right of track center, (d) one storm radius left of track center, (e) one storm radius right of track center, (f) one and a half storm radii left of track center all three days after the storm passage

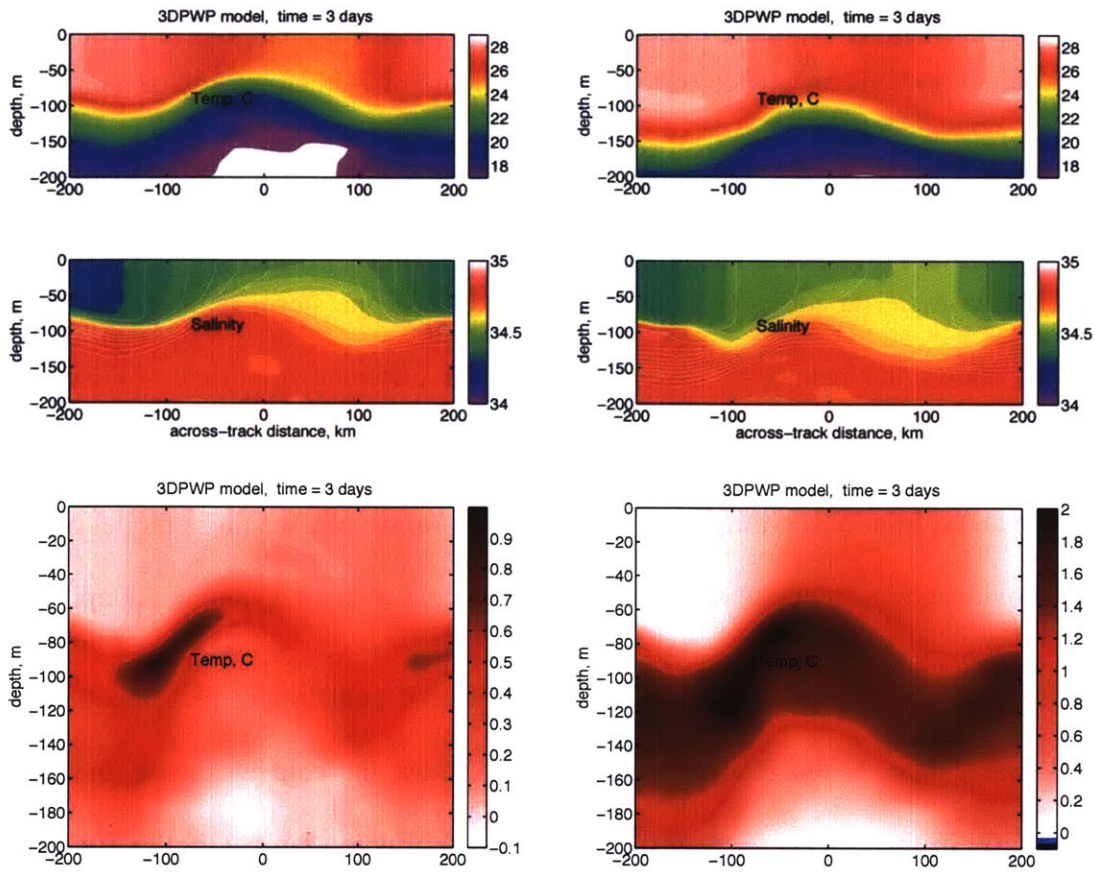


Figure 10 – 3DPWP model outputs for with an amplitude of isotherm displacement of 15 m (left column) and 60 m (right column) time sliced three days after the storm has passed with an eddy located one storm radius left of center: vertical temperature profile for (a) half amplitude and (b) twice amplitude, vertical salinity profiles for (c) half amplitude and (d) twice amplitude, and difference in vertical temperature profiles for the no eddy case and (e) Figure 5a and (f) Figure 5b.

We also ran trials to observe the effects of eddy strength on ocean mixing. The trials we ran had half of (15 m) and twice (60 m) the amplitude of isotherm displacement of the originally eddy. The eddies in both case still had the same half width as the eddies in previous trials, 170 km, and all other inputs for the 3DPWP model were kept the same as in previous cases. The eddies in both cases were placed one storm radii left of center. Figure 10 shows the results of these two cases for different amplitudes of isotherm displacement. Comparing the vertical temperature and salinity profiles in Figure 10a-d with those taken from observations in Figures 5a and 7a, we can see these model outputs did not provide a more accurate representation of the cold wake of Typhoon Fanapi.

In Figure 10a, for an eddy with half the amplitude of isotherm displacement of the original cases, there is too much cooling directly below the cold wake and the warm pocket at 200 m that was present in the no eddy case was too large. Figure 10e better illustrates this difference, the vertical temperature profile differs from the no eddy only in a cooler 20 m oscillating band moving between 60 and 100 m, which does not match well with the Revelle profile. The salinity profile in Figure 10c for this eddy was also fresher in the column below the storm track than the profile taken by the Revelle.

The vertical temperature and salinity profiles in Figures 10b and 10d, for an eddy with twice the amplitude of isotherm displacement, also did not compare well with those in Figures 5a and 6a. The entire upper 200 m was much warmer than the no eddy case, as can be seen in Figure 10f, and was much warmer the profile by the Revelle. The temperature differences were twice as high in Figure 10f as those in Figures 6a and 6b.

The graphs in Figure 10 were created by using a value of half (15 m) and twice (60 m) the observed amplitude of isotherm displacement (30 m) that was used in the original trials. Comparing those graphs with those from Figures 5, 6, and 7, we can see that the 3DPWP model better models Typhoon Fanapi when the amplitude of isotherm displacement, and hence eddy strength, is closer to the amplitude observed by the Revelle.

Conclusions

In this work we used a version of the 3D Price-Weller-Pinkel model to study the interaction between a tropical cyclone with a cold-core ocean eddy. Although there have been several studies that have focused on modeling Atlantic tropical cyclones with the 3DPWP model, there have been none focusing on the model's ability to describe those in Pacific. We have used observations and data taken during the 2010 Impact of Typhoons on the Ocean in the Pacific (ITOP) and, specifically, those observations relevant to Typhoon Fanapi to compare with the model outputs.

In order to study the 3DPWP model's ability to describe Pacific tropical cyclones with the added effect of ocean eddies we compared vertical temperature and salinity profiles taken from the cold wake of Typhoon Fanapi by the Revelle. We compared the observed profiles with model outputs first with no eddy present and then with cold-core ocean eddies of the same size as the eddy that Fanapi encountered.

From the vertical profiles of temperature shown in Figure 5 in the no eddy case, we found that three days after the passing of the hurricane there was still a large pocket of warm surface water, above 28°C, that extends up from below 200 m and a column of cooler water below the hurricane track that was approximately 24°C. By adding an eddy to the model, whether to the left or right of the track, the warm surface water pocket almost vanishes. The column of water below the track was also warmed by 2–4°C, which can be more clearly seen in Figure 6, and this temperature change was comparable to what was

observed by the Revelle. From Figure 6 we can also see there was an overall warming of water above 150 m by the introduction of an eddy and a cooling of water below 150 m because of the vertical displacement of the isotherms by the eddy. In the case of representing vertical temperature profiles after Typhoon Fanapi, the profiles more closely resemble the observations when an eddy is added.

Although the eddy that Typhoon Fanapi encountered was approximately one storm radii to the left of the typhoon track, we could not determine if an eddy placed in the model at this location was better able to model the ocean's response to Typhoon Fanapi than an eddy placed at other locations within a radius of 1.5 storm radii. We can say that when an eddy was less than 3 storm radii to the left of the track or 1.5 radii to the right the model produced significantly different vertical temperature profiles than when no eddy was added and these profiles better modeled the observed vertical temperature than when no eddy was present.

In the case of SST we can see from Figure 8 that the most obvious difference when an eddy was added was the warming of the cold wake after three days. The core of the cold wake in the no eddy case was 28°C for 350 km while the 28°C core of the cold wake only extended 100 km and then warmed to 26°C or greater for the remainder of the cold wake. The SST in the model cases with eddies produced an overall warmer SST compared with no eddy case. The cold wake SST did not differ between cases when the eddies were centered, to the right or to the left of the storm track, but the SST of the cases with an eddy 1.5 storm radii to the right of center or greater were the same as the no eddy case.

A more subtle difference in SST were warmed bands to the left and right of the storm track when the eddy was centered. These bands were 0.2°C warmer than the SST in the no eddy case. As the eddy was shifted to the right or left of center the warm bands shifted to the same direction as the eddy. The bands faded more quickly with distance from track center when the eddy was to the right. These bands, in all cases, were caused by the crests of the isotherms in the model breaching the ocean surface.

The salinity profiles between the case of no eddy present and those of eddies centered or to the left or right of center did not differ significantly. The column of water directly below the storm track was slightly fresher in the no eddy case and overall the upper 75 m were slightly fresher than in the cases with an eddy present. There was no difference in salinities between the cases in which the eddy was to the left or right of the storm track. We cannot say in this study that adding an eddy to the model improves the ability of the model to represent the change in the ocean salinity field in the cold wake of Typhoon Fanapi.

There are several more features that would be of interest to examine in relation to Typhoon Fanapi and the 3DPWP model. Although we examined the effects of cold-core eddies in ocean mixing after a typhoon, we did not study the effects of warm core eddies. Fanapi also paused for a brief period on the 16th and 17th of September at the bend in the track before turning west that can be seen in Figure 2. We also did not examine the effect on ocean mixing of such a pause in a tropical cyclone track with or without an eddy present or the effect of two eddies on opposing sides of the typhoon track, which was the

case with Fanapi. None of these three cases have been studied and could all be examined with modifications to the 3DPWP model.

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