Mesoscale variability in the northeastern tropical Pacific: Forcing mechanisms and eddy properties

Jun-Hong Liang,1 James C. McWilliams,1 Jaison Kurian,1 François Colas,1 Peng Wang,1 and Yusuke Uchiyama1

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The generation mechanisms and properties of the mesoscale eddies in the northeastern tropical Pacific (NETP) are studied using a series of numerical solutions and satellite observations. The spatial and temporal resolution of mountain wind jets over the Gulfs of Tehuantepec and Papagayo are essential for an accurate modeling of the regional mesoscale variability. Three previously proposed eddy generation mechanisms are the local transient wind forcing, the combined low-frequency wind and boundary forcing, and the remote equatorial Kelvin wave forcing. In our model, the transient wind-forcing was represented by wind fields with synoptic variability, and the remote equatorial Kelvin wave forcing by 5-day open boundary conditions with interannual variability. Solutions with and without high-frequency forcings are contrasted to evaluate the contributions of the three mechanisms. The combined low-frequency wind and boundary forcing is the primary eddy forcing mechanism in the NETP. In the Tehuantepec region, the high-frequency wind-forcing contributes more to the mesoscale variability than the remote equatorial Kelvin wave forcing, while in the Papagayo region, their contributions are comparable. Eddies in the Tehuantepec and Papagayo regions are larger in both amplitude and size, and are more likely to deflect equatorward than eddies in the rest of the NETP. The maximum temperature anomaly of eddies is at around 50 m depth. Eddies with lifetimes >6 weeks are more likely anticyclonic, while eddies with lifetimes <6 weeks are more likely cyclonic. The anticyclone-dominance for large-amplitude long-lived eddies is the combined consequence of wind-driven asymmetric dipole spin-up and the evolutionary fragility of large-amplitude cyclones.


1. Introduction

The northeastern tropical Pacific (NETP), defined as the Pacific ~5°N–18°N and 120°W to the coast of Central America, plays an important role in global climate (El Niño Southern Oscillation (ENSO)), weather (hurricane genesis), and local fishery industry [Wyrtki, 2006; Wang and Fiedler, 2006]. The mean state and variability of the NETP are strongly modulated by three powerful wind jets over the Gulfs of Tehuantepec, Papagayo, and Panama, mostly from mid-fall to spring. These strong wind jets funnel through three narrow mountain gaps in the Central American cordillera and are forced by either cold surges from the North American continent or by trade winds from the Caribbean Sea [Chelton et al., 2000]. They are stronger and more frequent in winter than in summer. Regional circulation and thermocline structure conform to the Sverdrup relation and are strongly correlated with the strength of the mean wind jets [Kessler, 2002, 2006; Xie et al., 2005]. The annual cycle of sea surface temperature (SST) in the Gulfs of Tehuantepec and Papagayo is influenced by the gap outflow over the two gulfs [Sun and Yu, 2006]. Seasonal dynamics of sea surface salinity at the eastern Pacific off Panama has been shown to be modulated by wind jet over the Gulf of Panama [Alory et al., 2012]. There is strong variability in the wind jets at synoptic timescales. Nearshore oceanic responses to the high-frequency wind events include the spin-up of asymmetric eddies [McCreary et al., 1989; Trasviña et al., 1995; Trasviña and Barton, 2008], the decrease in SST [Clarke, 1988; Barton et al., 1993; Trasviña et al., 2003; Barton et al., 2009], and the enhancement of surface nutrients and biological production [McClain et al., 2002; Pennington et al., 2006].

On an intraseasonal timescale, satellite altimetric data reveal the existence of two bands of strong mesoscale
variability off the coast of Central America in the NETP due to nonlinear eddies from the Gulfs of Tehuantepec and Papagayo (Figure 1, top) [Giese et al., 1994]. One originates from the Gulf of Tehuantepec and extends southwestward to around 115°W 10°N; and the other one originates from the Gulf of Papagayo and extends to the west of 95°W. The Tehuantepec eddies first move southwestward and then join the same track along 11°N where the Papagayo eddies propagate westward. It is also observed that there is a preference for anticyclonic eddies over cyclonic eddies in these two regions of high eddy activity [e.g., Palacios and Bograd, 2005]. These eddies transport coastal nutrient-rich water to the open ocean [Samuelsen and O’Brien, 2008] and were recently shown to disperse deep-sea products from hydrothermal vents in the East Pacific Rise [Adams and Flierl, 2010]. There have been a few mechanisms proposed for the genesis of Tehuantepec and Papagayo eddies [Willett et al., 2006]. The most obvious possibility is that positive wind curl on the left flank of the wind jets through the mountain gaps spins up cyclonic eddies and negative wind curl on the right flank of the wind jets spins up anticyclonic eddies. On the other hand, the shallowness of the local thermocline suppresses upwelling and the associated cyclonic eddies, which leads to asymmetric dipoles with stronger anticyclonic eddies [McCreary et al., 1989]. There is, however, generations of eddies that are not associated with any synoptic gap wind events [Hansen and Maul, 1991; Zamudio et al., 2006; Liang et al., 2009]. This leads to two other explanations of the generation mechanism. The first are the barotropic and baroclinic instabilities of the mean ocean currents [e.g., Willett et al., 2006; Farrar and Weller, 2006], which are part of the large-scale circulations and are modulated by low-frequency wind. The second one is the instability of coastal currents triggered by passing poleward propagating coastal Kelvin waves [Zamudio et al., 2006]. Poleward propagating coastal Kelvin waves are mainly initiated when eastward-propagating Equatorial Kelvin waves hit the America Continent. They induce strong horizontal and vertical shear flows and trigger barotropic and baroclinic instabilities during their passage. The eddy generation mechanisms are schematically illustrated in Figure 1 (bottom).

Figure 1. (top) A Central America ROMS domain. Also shown in the figure is a color map of 90-day high-passed root-mean square sea level anomaly (cm) in this region from AVISO altimetric data. Three arrows indicate, from north to south, three mountain gaps behind the Gulfs of Tehuantepec, Papagayo, and Panama, respectively. The black box delimits computational domain with dashed lines delineating open boundaries. (bottom) A schematic showing the generation mechanisms of eddies in the Northeastern Tropical Pacific.

In this study, we assess the importance of different eddy generation mechanisms by analyzing a series of solutions from the Regional Ocean Modeling System (ROMS) forced by surface and lateral boundary conditions of different spatial resolution and temporal variability. The necessary forcing conditions for realistically reproducing regional mesoscale variability are evaluated by comparing the solutions with altimeter observations. We also seek to characterize eddy properties (size, amplitude, geographic distribution, and vertical structures) in this region. The rest of the paper is organized as follows: section 2 describes the way ROMS was configured for the NETP; section 3 presents the results, discusses the roles of different eddy generation mechanisms, and analyzes eddy properties; and section 4 are conclusions.

2. Data and Methods

2.1. Regional Ocean Model

The numerical model used in this study is the Regional Ocean Modeling System (ROMS), which solves the three-dimensional hydrostatic primitive equations in vertical hybrid z-sigma [Lemarie et al., 2012] and horizontal curvilinear coordinates with innovative algorithms for advection, mixing, pressure gradient, vertical-mode coupling, time stepping, and parallel efficiency [Shchepetkin and McWilliams, 2005]. A configuration with a horizontal resolution of 10 km (400 × 620 grid points) encompasses a domain from 22°S to 35°N and from the coast of the American continent to 140°W, with open-boundary conditions at its western and alongshore edges (Figure 1, top). The grid resolution (~10 km) is much smaller than the Rossby deformation radius in this region (>50 km) [see Chelton et al., 1998, Figure 6] and is, therefore, capable
The three open boundaries of the ROMS model were forced by temperature, salinity and velocity fields interpolated from the Simple Ocean Data Assimilation (SODA) data between 1999 and 2008 [Carton and Giese, 2008]. Both the 5-day interannual data and the monthly climatological (long-term monthly mean) data were used. Equatorial Kelvin waves, which can trigger eddy generation in the NETP, are preserved in the 5-day interannual data, but are filtered out in the monthly climatological data. The boundary condition is a mixed radiative-relaxation parameterization [Marchesiello et al., 2001; Mason et al., 2010]. The Flather boundary condition was imposed on the 2D momentum equations, and the Orlanski radiative condition was imposed for 3D fields. A sponge layer along the open boundaries was also set up to damp outgoing eddies and waves.

Three different wind products were used. The first two are publicly available: the QSCAT/NCEP blended wind [Militij et al., 2004] and the Scatterometer Climatology of Ocean Winds (SCOW) [Risien and Chelton, 2008]. The QSCAT/NCEP blended wind product blends QSCAT scatterometer wind and NCEP reanalysis from August 1999 to December 2008. It is daily at a 0.5° x 0.5° spatial resolution. The SCOW wind product is a monthly climatology at a 0.25° x 0.25° spatial resolution based on QSCAT Scatterometer wind from September 1999 to October 2009.

The mountain gaps are narrow, in particular, the Chivela Pass where the Tehuantepec wind funnels through, is only some 40 km (~0.4°) wide. Therefore, the SCOW wind on a spatial grid of 0.25° x 0.25° resolves the mountain gap wind jets better than the QSCAT/NCEP blended wind on a spatial grid of 0.5° x 0.5°. Figure 2 shows the wind curl in the SCOW product and the wind curl difference between the SCOW product and the climatology from the QSCAT/NCEP blended wind product in winter when the wind jets are strongest. The climatological wind curls from the two wind products are similar except in the two wind jet regions. The winter wind curl climatology in the QSCAT/NCEP blended wind product is up to 70% weaker than in the SCOW product over the Gulf of Tehuantepec. However, the SCOW product does not contain synoptic wind events, which have been suggested to play an important role in generating mesoscale eddies. To have the best spatial and temporal resolution in the wind-forcing, we developed a corrected daily wind product based on both the QSCAT/NCEP daily wind product and the SCOW product. The new wind field has the same climatology as the SCOW product and has synoptic wind events. The wind stress field for the Tehuantepec wind in the corrected QSCAT/NCEP blended wind is prepared as follows:

1. The daily Tehuantepec wind index was defined as the daily blended QSCAT/NCEP wind in the offshore direction averaged over the nearshore region in front of the mountain gap (from 15°N to the coast and from 96°W to 94°W).
2. The climatological monthly wind stress difference in the Gulf of Tehuantepec between the SCOW wind product and the blended QSCAT/NCEP wind product was defined as the typical Tehuantepec wind field for each month. The region of the typical Tehuantepec wind field is delimitated by the black line in Figure 2a. Outside of the region, the typical Tehuantepec wind field decays with the distance from the boundary following a Gaussian filter with standard deviation of 20 km so that no artificial wind curl was created at the boundaries of the region.
3. The typical Tehuantepec wind field was added to the blended QSCAT/NCEP daily wind product with a weight. The weight is proportional to the Tehuantepec wind index and ensures that the climatological wind stress and curl equal those in the SCOW in the region.
4. Similar procedures were carried out for Papagayo wind. The new daily wind product is called the corrected blended QSCAT/NCEP wind product in this paper. The spatial and temporal resolutions of the wind jets in the corrected blended QSCAT/NCEP wind product are the best among the three wind products.
5. Heat fluxes from COADS climatology [da Silva et al., 1994] were used, and a relaxation to Pathfinder climatological SST [Casey et al., 2010] was imposed following the parameterization of Barnier et al. [1995]. To prevent salinity drift, we also imposed a relaxation to the COADS sea surface salinity.
The abbreviated names for runs forced by different combinations of surface and lateral boundary forcings are listed in Table 1. Simulations forced by climatological conditions were integrated for 16 years with initial conditions interpolated from the SODA data sets. Simulations forced by interannual surface and lateral boundary conditions were restarted from the solutions forced by the corresponding climatological conditions, and were integrated from August 1999 to December 2008 when both the SODA and the blended wind data are available. The first four years of solutions were discarded as spin-up.

2.3. Data Sets

To assess the realism of the model results, satellite and reanalysis data sets were used. Weekly sea level anomaly (SLA) data between 1999 and 2008 on a 1/3° × 1/3° grid came from the Ssalto/Duacs multimission altimeter gridded sea level anomaly product (http://www.aviso.oceanobs.com/en/data/product-information/duacs/index.html), which merge data from up to four satellites [Pascual et al., 2006]. Sea surface temperature from 1999 to 2008 on a 0.25° × 0.25° grid originated from the Tropical Rainfall Measuring Mission Microwave Imager (TMI) SST product (http://www.ssmi.com). The mean seasonal sea surface height (SSH) on a 0.25° × 0.25° grid was downloaded from http://oceanwatch.pifsc.noaa.gov. The CSIRO Atlas of Regional Seas (CARS) climatological mean ocean temperature on a 0.5° × 0.5° grid was downloaded from http://www.marine.csiro.au/dunn/cars2009.

3. Results and Discussion

3.1. Annual Cycle of the NETP

The regional geostrophic circulation can be inferred from SSH maps. Figures 3a, 3d, 3g, and 3j show the observed mean seasonal cycle of SSH. A domain mean in each season was removed for better visual effects. This will not change the circulation pattern, while the thermosteric effect is largely eliminated. The SSH map agrees with the map of dynamic height shown in Kessler [2006, Figure 7]. Two distinct features in this region are the Tehuantepec Bowl (TB) west of the Gulf of Tehuantepec (“bowl” means a depression of the thermocline and an elevation of the ocean surface; and “dome” refers to the opposite situation) and the Costa Rica Dome (CRD) west of the Gulf of Papagayo [Kessler, 2006]. The TB is the strongest in winter and almost disappears in summer, while the strength of the CRD is less variable with seasons. This is mainly because the Tehuantepec wind has a stronger seasonal cycle than the Papagayo wind, and the

<table>
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<td>SCBC</td>
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<td>S5BD</td>
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<td>SCCD</td>
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<td>S5CC</td>
<td>SODA 5-day</td>
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Each name has four letters. The first two letters indicate the open boundary conditions: “SC” means SODA climatology, and “S5” means SODA interannual data updated every 5 days. The third letter indicates the wind product used (S: SCOW; B: blended QSCAT/NCEP wind; and C: corrected blended QSCAT/NCEP wind). The last letter indicates whether the wind is daily (D) or climatological (C).

Figure 3. Mean-seasonal sea surface height (cm) in (a–c) January, February, and March (JFM); (d–f) April, May, and June (AMJ); (g–i) July, August, and September (JAS); and (j–l) October, November, and December (OND). The left column is the satellite observed mean SSH anomaly, the middle column is solutions of run SCCD, and the right column is solutions of run SCSC. The two black dashed lines in Figure 3a delineate 12°N and 9°N.
strength of the TB and the CRD highly correlates with the seasonal strength of the wind jets over the respective gulfs, respectively. In winter, there are two anticyclonic cells off the coast of the central America, one north [Brenes et al., 2008] and one south [Chaigneau et al., 2006] of the CRD. All these features are captured in runs S5CD and SCSC (Figure 3). The close agreement of the two solutions indicates that the high-frequency variability in surface and lateral boundary forcing does not influence the mean seasonal circulations. All four solutions forced by the QSCAT/NCEP blended wind (runs SCBC, SCBD, S5BC, and S5BD) predict weaker TB and CRD due to the weaker wind jets (not shown here). This also confirms the conclusion drawn by Kessler [2002, 2006] that the mean and seasonal circulations in the NETP are determined by low-frequency wind.

Figure 4 shows the maps of SST from satellite data and from runs S5CD and SCSC. The ocean surface is substantially cooler along the two wind paths than in the surrounding areas during fall and winter. The cooling is underestimated in the solutions probably due to the fact that the wind jets in the surface forcing are under-resolved and wind-driven mixing is consequently weaker. By examining different solutions, we again see little difference in the seasonal mean SST between solutions with and without high-frequency interannual variability in surface and open boundary conditions. Alexander et al. [2012] show that there is a significant SST difference between El Niño and La Niña years, and the SST difference can be reproduced in solutions forced with 5-day interannual open boundary conditions but not in solutions forced by climatological open boundary conditions. The close agreement between the two solutions shown in Figure 4 is because the SST contrast due to ENSO is averaged out. Similar to the comparison of SSH, SST signals produced by wind jets are further underestimated when the wind climatology is weaker (runs SCBC, SCBD, S5BC, and S5BD).

3.2. Mesoscale Variability

Mesoscale variability is studied using high-frequency SLA from both altimetric data and ROMS solutions and velocity fields from ROMS solutions. The high-frequency fields were obtained as follows: For each grid point, a temporal mean and a raw seasonal cycle smoothed by a 30-day running mean were first removed to obtain a non-seasonal anomaly. After that, a high-pass filter was applied so that any variability with periods longer than 90 days, such as ENSO events, was essentially removed [Palacios and Bograd, 2005].

3.2.1. Mean and Seasonal Cycle

Figure 6 shows the standard deviation of the high-frequency SLA from model runs forced by different surface and lateral boundary conditions, and from satellite altimetric data. The spatial patterns of the two bands of strong mesoscale variability emanating from the Gulfs of Tehuantepec and Papagayo are reproduced in all solutions. However, the strengths of mesoscale variability within the two bands are under-predicted to different degrees in all solutions. Among all runs, run SCBC under-predicts the mesoscale variability most (Figure 6a) because the forcing for this run has relatively low spatial resolution and does not contain high-

Figure 5 displays the zonal hydrographic structures at 12°N and 9°N from run S5CD, run SCSC, and the CARS climatology. These two latitudes, delineated by two dashed lines in Figure 3a, are chosen since 12°N crosses the TB, and 9°N crosses the CRD. The simulated subsurface temperature profiles between the two runs are alike. This confirms that the mean ocean state is not influenced by the addition of high-frequency forcing in the NETP. The surface mixed layer depth is less than 50 m at both latitudes. The slight thermocline shoaling at (110°W 12°N) and doming at (90°W 9°N) are reproduced in the solutions. Compared with observations, the simulated thermocline is slightly diffused.
frequency temporal variability. With increasing spatial and temporal resolutions in surface and lateral boundary conditions, the predicted mesoscale variability approaches to the observed variability. The combination of a corrected daily wind and 5-day interannual open boundary condition is the most realistic forcing, and the solution using this forcing (Run S5CD, Figure 6e) is consequently the closest to the observations. Outside the two strong mesoscale variability bands, in particular along 15°N, there is more mesoscale variability in the solutions than in the observations. One of the possible sources of eddies along 15°N is the Acapulco eddies originating from the coast of Mexico [Zamudio et al., 2001]. By contrasting Figures 6c and 6d with Figure 6b, we can see that daily wind-forcing contributes slightly more to the eddy activity along 15°N than 5-day interannual lateral boundary forcing.

[21] Figure 7 displays the seasonal cycle of mesoscale variability in the Tehuantepec and Papagayo regions, as well
as quantitative comparisons between different solutions and altimetric observations. The standard deviation of the high-frequency SLA was averaged over the regions delimited by the black boxes in Figure 6f, and was defined as the strength of mesoscale variability in the regions. Mesoscale variability exhibits a strong seasonal cycle in both regions. In the Tehuantepec region, it is strongest in winter and weakest in summer. In the Papagayo region, it is also strongest in winter, and weakest in both summer and fall. Based on altimetric observations, mesoscale variability during winter is 60% stronger than during summer in the Tehuantepec region and during summer and winter in the Papagayo region. Consistent with the results in Figure 6, the observed mesoscale variability is best reproduced in run S5CD. In the Tehuantepec region, the S5CD run under-predicts observed mesoscale variability by 13% in winter and over-predicts observed mesoscale variability by 6% in summer. In the Papagayo region, run S5CD under-predicts observed mesoscale variability by 3% to 17% in different seasons.

### 3.2.2. Forcing Mechanisms

The two bands of strong mesoscale variability are mainly the combined consequence of three different forcing mechanisms: (1) the local high-frequency wind-forcing; (2) the combined low-frequency wind and boundary forcing; and (3) the remote equatorial Kelvin wave forcing. The importance of the three mechanisms can be understood by a quantitative comparison of the standard deviation of the high-frequency SLA in different runs shown in Figure 7.

Run S5CD was forced by the most realistic wind and open boundary conditions. Its solution is closest to observations and is therefore taken as the control run. Run SCBC includes neither the local transient wind-forcing nor the remote equatorial Kelvin wave forcing. It reproduces 68% to 80% of the mesoscale variability in run S5CD for Tehuantepec region and 62% to 90% for Papagayo region in different seasons. The surface and lateral forcings in runs SCBC and S5CD have the same climatological mean. This implies that the combined low-frequency wind and boundary forcing is the most important forcing mechanism for mesoscale variability in the NETP. Run SCBC is also forced by climatological wind and open boundary conditions, but the wind forcing used in run SCBC has weaker wind jets than in run SCCC because its spatial resolution is lower (Figure 2). Currents driven by weaker wind jets are less spatially intensified and less unstable. Compared with run SCCC, mesoscale variability in run SCBC is 5% to 7% lower in the Tehuantepec region and 8% to 19% lower in the Papagayo region in different seasons. Because wind jets are still under-resolved in the forcing for S5C due to the spatial resolution, run S5CD still underestimates the observed mesoscale variability in the two regions. Without the transient wind forcing, run S5C under-predicts mesoscale variability by 7% to 20% in the Tehuantepec region and by 1% to 12% in the Papagayo region in different seasons.

Without the remote equatorial Kelvin wave forcing, the S5CD run under-predicts mesoscale variability by 6% to 12% in the Tehuantepec region and by 2% to 13% in the Papagayo region in different seasons. In the Tehuantepec region, the high-frequency local atmospheric forcing contributes more to eddy activity than the remote equatorial Kelvin wave forcing. In the Papagayo region, the importance of the two forcing mechanisms is comparable. Remote Kelvin wave forcing not only modulates eddy activities in Tehuantepec and Papagayo region, but also eddy activities in other regions along the coast of America [Zamudio et al., 2006, 2007, 2008; Echevin et al., 2011; Belmadani et al., 2012].

The respective roles of local wind-forcing and instability on eddy generation are further analyzed by examining some terms of the eddy kinetic energy budget. The energy conversion terms can be calculated as [Marchesiello et al., 2003],

$$FmKm = \frac{1}{\rho_0} \left( \overline{\partial u_t} + \overline{\partial v_t} \right)$$

(1)

$$FeKe = \frac{1}{\rho_0} \left( \overline{w^2} \frac{\overline{\partial u}}{\partial x} + \overline{w^2} \frac{\overline{\partial v}}{\partial y} + \overline{w^2} \frac{\overline{\partial w}}{\partial z} + \overline{v w} \frac{\overline{\partial u}}{\partial x} + \overline{w w} \frac{\overline{\partial v}}{\partial y} + \overline{v w} \frac{\overline{\partial w}}{\partial z} \right)$$

(3)

$$PeKe = \frac{g}{\rho_0} \left( \overline{w''} \right)$$

(4)

where $FmKm$ is the total wind work on ocean currents and is largely the energy input into the mean current from low-frequency gap winds; $FeKe$ is the eddy kinetic energy (EKE) generation due to transient wind, and is the eddy spin-up by transient wind events in this study; $KmKe$ is the energy conversion between mean currents and eddies, and indicates barotropic instability when it is positive; $PeKe$ is the energy conversion between available potential energy and EKE, and indicates baroclinic instability when it is positive; $u$, $v$, and $w$ are zonal, meridional, and vertical velocities; $g$ is
The eddy kinetic energy budget terms calculated by Equations (1) to (4) in the text for the (top) Tehuantepec and (bottom) Papagayo regions.

Figure 8. The eddy kinetic energy budget terms calculated by Equations (1) to (4) in the text for the (top) Tehuantepec and (bottom) Papagayo regions.

gravity; \( \tau \) is wind stress; and \( () = \overline{()} + ()' \) with ()' the high-frequency component of a variable ()

[25] Figure 8 shows the averaged seasonal energy budget terms for run S5CD in the Tehuantepec and the Papagayo regions delimited in Figure 6f, respectively. Only the local EKE generation terms in the EKE budget are shown in Figure 8. Both boundary fluxes and EKE dissipation are required to close the EKE budget, but are not shown here. These budget terms show similar seasonal variability as the strength of mesoscale variability shown in Figure 7. The total wind work (\( FmKm \)) is the largest in fall and winter for the Tehuantepec region and in winter for the Papagayo region. Both barotropic (\( KmKe \)) and baroclinic (\( PeKe \)) instabilities are also the strongest during the same seasons, because the stronger wind jets drive more unstable currents. The magnitudes of \( KmKe \) and \( PeKe \) are comparable, which implies a mixed baroclinic/barotropic eddy generation process. The transient wind work (\( FeKe \)) is the largest in fall for both Tehuantepec and Papagayo, in agreement with the strongest enhancement of eddy variability from run SCCD to run SCCC shown in Figure 7. The magnitude of \( FeKe \) is smaller than the sum of \( KmKe \) and \( PeKe \), which, from an energy budget perspective, confirms the conclusion drawn from Figure 7 that eddies are mostly generated by instability of the mean seasonal circulations, not directly by high-frequency wind events.

3.3. Eddy Properties

[26] To study the eddy properties in the NETP, we applied an automated eddy detection and tracking method [Kurian et al., 2011] to both satellite altimetric data and the solutions from run S5CD as this run statistically agrees the best with observations. An eddy is identified if a closed contour of the 90-day high-passed SLA conforms to a set of criteria for its shape, amplitude, and size. These criteria are: (1) The closed contour is nearly circular; (2) Its radius is from 15 km to 250 km for the ROMS solution and from 50 km to 250 km for the altimetric data, with the maximum radius (250 km) considerably larger than the maximum Rossby deformation radius in this region (150 km); (3) the SLA magnitude monotonically increases toward the center with a minimum 1 cm core to edge difference. Eddies are tracked from one time step to the next by finding the nearest eddies at consecutive solution or altimetry outputs (5 days apart for ROMS solution and 7 days apart for altimetric data) and comparing their properties (amplitude, size, and location) (see Chelton et al. [2011] and Kurian et al. [2011] for details).

3.3.1. Size, Amplitude, Geographic Distribution, and Vertical Structures

[27] Figure 9 displays eddy properties from satellite altimetric data and run S5CD. There are a comparable number of large-size (\( R > 70 \) km) eddies in the ROMS solution and the altimetric data. There are significantly more small-size (\( R < 70 \) km) eddies in the ROMS solution than in the altimetric data because the ROMS solution has a better spatial resolution (\( 1/10^\circ \times 1/10^\circ \)) than the altimetric data (\( 1/3^\circ \times 1/3^\circ \)). Small-size eddies are more likely cyclonic, while large-size eddies are more likely anticyclonic. The cyclone dominance for small-size eddies is also found in California Current System [Kurian et al., 2011] and the Peru Chile Current System [Colas et al., 2011]. A distinct difference between the eddy statistics for the NETP and for the global ocean is the cyclone-to-anticyclone ratio when the eddy amplitude is large (\( A > 10 \) cm). The cyclone to anticyclone ratio is significantly larger than unity for long-lived large-amplitude eddies in the southern hemisphere, and the cyclone to anticyclone ratio is close to unity for eddies of similar properties in the northern hemisphere [see Chelton et al., 2011, Figure 9]. In the NETP, there is a strong anticyclone dominance for eddies of amplitude larger than 10 cm (Figure 9f). The mechanism for the anticyclone dominance in the NETP will be discussed in section 3.3.2.

[28] Because there is a general agreement in eddy statistics between run S5CD (Figure 9) and altimetric data, we will proceed to present results from run S5CD. Figure 10 displays the number of coherent cyclonic and anticyclonic eddies with a lifetime of at least 4 weeks. There are more cyclonic eddies than anticyclonic eddies in total, however, there are more long-lived (lifetime longer than 6 weeks) anticyclonic eddies than cyclonic eddies. Figure 11 shows the trajectories and birth places of eddies with lifetimes larger than 8 weeks. Eddies detected from altimetric data also have similar geographic distribution (not shown). In agreement with results in Figure 10, eddies of these lifetimes are more likely anticyclonic. There are two clusters of eddies along the two bands of strong regional mesoscale variability originating from the Gulfs of Tehuantepec and Papagayo. There are only one anticyclonic eddy with a lifetime larger than 8 weeks from the Gulf of Panama in 6 years. This is consistent with previous studies that show Panama eddies are short-lived [e.g., Willett et al., 2006]. Outside the two strong eddy variability bands, substantial eddy generation and propagation also occur. It has been long recognized that most of the open ocean is baroclinically unstable [e.g., Robinson and McWilliams, 1974]. Both anticyclonic and cyclonic eddies propagate westward. 56% of anticyclonic eddies deflect equatorward while 57% cyclonic eddies deflect poleward. The different preferential zonal deflection for eddies of different polarity in the NETP is consistent with global eddy statistics [Chelton et al., 2007, 2011] and is a combined consequence of the \( \beta \) effect and eddy self-advection [McWilliams and Flierl, 1979]. Eddies in the
Tehuantepec and Papagayo regions are more likely to deflect equatorward than in the rest of the NETP. 76% of the anticyclonic eddies and 55% of the cyclonic eddies deflect equatorward in these two regions. Strong offshore currents with an equatorward component are driven by the gap winds, and the advection by these currents contributes to eddy equatorward deflection in the two regions. Maps of shorter-lived eddies (lifetimes smaller than 8 weeks) show similar geographical patterns, except that there are more cyclonic eddies than anticyclonic eddies (not shown here).

To study the vertical structure of eddies, we constructed composite vorticity and temperature maps over individual long-lived (life >8 weeks) eddies (Figures 12 and 13). The anomaly for a field at a given time and depth level is

Figure 9. Cumulative eddy number per snapshot with respect to (a) eddy radius R and (d) amplitude A, eddy number distribution per snapshot with respect to (b) R and (e) A, and cyclone to anticyclone ratio with respect to (c) R and (f) A. Altimeter data is plotted with dashed lines, and run S5CD is plotted with solid lines.

Figure 10. Cumulative number of coherent eddies per year with a life longer than 4 weeks in run S5CD.

Figure 11. The tracks (lines) and origins (solid points) of (top) anticyclonic and (bottom) cyclonic eddies with a life longer than 8 weeks in 6-year solutions of run S5CD.
found by removing the horizontal average of the field over a box of 250 km × 250 km centered around the eddy. Both anticyclonic and cyclonic eddies have their maximum vorticity anomaly at the surface (Figure 12). Anticyclonic eddies are stronger and penetrate deeper than cyclonic eddies. Eddies in the Tehuantepec and Papagayo regions are larger in size and relative vorticity (strength) than eddies in the rest of the regions in the NETP. The maximum temperature anomaly associated with the eddies is at around 50 m (Figure 13), which is the depth of the thermocline in the NETP. The maximum temperature anomaly at thermocline has also been observed in cyclonic eddies in the eastern South Pacific ocean [Chaigneau et al., 2011]. It is slightly shallower in the Papagayo region, as thermocline shoals in that region. The depth of the maximum temperature anomaly associated with eddies in the NETP is shallower than in the California Current System (approximately 100 m) [Kurian et al., 2011] and in the Peru Chile Current System (approximately 100 m for cyclonic eddies and 400 m for anticyclonic eddies) [Chaigneau et al., 2011].

### 3.3.2. Polarity Asymmetry

Figure 14 shows the mean strength (averaged vorticity) and number of long-lived eddies (life >8 weeks) for different geographic regions defined in Figure 6f and for different seasons. The number of long-lived Tehuantepec anticyclonic eddies is twice that of cyclonic eddies in fall and winter. In spring and summer, the numbers of long-lived Tehuantepec anticyclonic eddies and cyclonic eddies are comparable. The average strength of Tehuantepec eddies in fall and winter is higher than in spring and summer. The number of long-lived Papagayo anticyclonic eddies is more than twice that of cyclonic eddies in all seasons and the average strength of long-lived Papagayo eddies is higher than long-lived eddies in Tehuantepec region and other regions. Outside the two regions, the anticyclone dominance is not evident.

Two mechanisms have been previously proposed for the anticyclone dominance (see Willett et al. [2006] for a review). Both of these mechanisms refer to wind-driven spin-up of asymmetric dipoles with a stronger anticyclone due to the shallowness of the thermocline in the Gulfs (the thermocline in the Gulfs of Tehuantepec and Papagayo is around 30 m). Using a 1.5-layer model, McCreary et al. [1989] showed that vertical mixing entrains thermocline water, which is shallow in this region, to the surface, and inhibits the strengthening of cyclonic eddies. Thomas and Rhines [2002] proposed that Ekman transport at finite Rossby number ($Ro = \zeta / f$ with $\zeta$ the relative vorticity and $f$ the planetary vorticity) enhances/weakens Ekman pumping on the anticyclonic/cyclonic side of a dipole. This effect forms a positive feedback to the preferential spin-up of anticyclones. The wind-driven spin-up of asymmetric
circulation has been previously observed [e.g., Trasviña et al., 1995] and the two mechanisms are relevant. Because considerable number of eddies in the Tehuantepec and Papagayo regions are generated by current instability, not by wind-driven eddy spin-up (Figure 8) and both previously stated mechanisms are relevant during wind-driven eddy spin-up, we propose the theory given by Graves et al. [2006], which applies during eddy propagation, as likely important. Graves et al. [2006] show that cyclonic eddies with finite Rossby number and small Burger number (Bu = Rd/R with Rd the first baroclinic Rossby deformation radius and R the eddy radius) are more easily dissipated under an ambient strain field by neighboring eddies and mean flows. The preferential destruction of strong cyclonic eddies and the consequent anticyclone dominance have been observed in laboratory flows [e.g., Perret et al., 2006]. In order to assess the relevance of this theory for eddies in the Tehuantepec and Papagayo regions, we examined short-lived large-amplitude eddies that have a life shorter than 10 days, a radius larger than 50 km, and a relative vorticity \( \zeta > 0.8f \) in the two regions. The corresponding Rossby number (Ro) of these eddies is larger than 0.8, and the corresponding Burger number (Bu) is smaller than one because the first baroclinic Rossby deformation radius \( R_d \) in the NETP is between 50 km to 100 km [see Chelton et al., 1998, Figure 6]. The finite Rossby number (Ro > 0.8) and small Burger number (Bu ≤ 1)
falls in the regime for preferential destruction of cyclonic eddies according to the theory by Graves et al. [2006]. There is a strong polarity asymmetry for short-lived large-amplitude eddies in the two regions. On average, there are 9.6 and 4.6 short-lived large-amplitude eddies per year in the two regions, respectively. There are only 0.5 short-lived large-amplitude anticyclonic eddies per year in the Tehuantepec region, and no such anticyclonic eddies in the Papagayo region. The existence of considerable amount of short-lived large-amplitude eddies indicates that evolutionary fragility of cyclonic eddies plays an important role in the anticyclone dominance for large-amplitude long-lived eddies in the NETP.

4. Conclusions

[32] We present regional ocean modeling solutions of the northeastern tropical Pacific (NETP) with the objective of clarifying the respective contributions of three different eddy generation mechanisms, i.e., the combined low-frequency wind and boundary forcing, the high-frequency wind-forcing, and the remote equatorial Kelvin wave forcing. The latter two forcing mechanisms can be represented by surface and open boundary conditions with high-frequency interannual variability, respectively. For the modeling of NETP, added difficulty is the narrow mountain gaps in the Central America that strong wind jets funnel through. A daily wind product with corrected gap winds is developed based on both the blended QSCAT/NCEP daily wind at a 0.5° × 0.5° grid and scatterometer climatology of ocean wind at a 0.25° × 0.25° grid.

[33] Through a systematic analysis of 10 solutions forced by different combinations of surface and lateral boundary conditions, we show that the mean seasonal ocean state is not sensitive to high-frequency surface and open boundary conditions. The regional mesoscale variability depends on the spatial and temporal variability of wind and open boundary. By comparing numerical solutions with AVISO sea level anomaly data, we find that the run forced by corrected daily wind and 5-day interannual open boundary condition is closest to the real mean state and variability of the ocean. The combined low-frequency wind and boundary forcing is the most important eddy generation mechanism, and accounts for more than 68% to 80% mesoscale variability in the Tehuantepec region and 62% to 90% mesoscale variability in the Papagayo region. Without the local high-frequency wind-forcing, mesoscale variability is under-estimated by 7% to 20% in the Tehuantepec region, and by 1% to 12% in the Papagayo region in different seasons. Without the remote equatorial Kelvin wave forcing, mesoscale variability is under-estimated by 6% to 12% in the Tehuantepec region, and by 2% to 13% in the Papagayo region in different seasons. These results also stress the importance of high-resolution wind and open boundary conditions in a numerical model in reproducing the realistic mesoscale variability of the NETP.

[34] An eddy identification and tracking algorithm was applied to both AVISO sea level anomaly data and ROMS solutions. Eddies in the Tehuantepec and Papagayo regions are more likely to deflect equatorward than eddies in the rest region of the NETP because eddies in these two regions are advected by offshore currents that have a strong equatorward component. Eddies in the two regions are also larger in amplitude and size than eddies in the rest of the NETP. Temperature anomaly associated with eddies in the NETP is at around 50 m, shallower than that with eddies off the coasts of California and Peru/Chile. Eddies with lives shorter than 6 weeks are more likely cyclonic, while eddies with lives longer than 6 weeks are more likely anticyclonic. Besides previously proposed preferential anticyclone generation mechanisms due to the shallow thermocline, the preferential destruction of strong cyclonic eddies at finite Rossby number and small Burger number under ambient deformation is also important for the anticyclone dominance among long-lived large-amplitude eddies in the NETP.

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References


Lemarie, F., J. Kurian, A. F. Shchepetkin, M. J. Molemaker, F. Colas, and J. C. McWilliams (2012), Are there inescapable issues prohibiting the use of true-following coordinates in climate models?, Ocean Modell., 42, 57–79.


