The Bifurcation of the North Equatorial Current in the Pacific*

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ABSTRACT

A new climatology using historical temperature and salinity data in the western Pacific is constructed to examine the bifurcation of the North Equatorial Current (NEC). Integrating dynamically calculated circulation from the sea surface to 1000 m and combining it with surface Ekman transport, it is shown that the bifurcation of the NEC occurs at the southernmost position (14.8°N) in July and the northernmost position (about 17.2°N) in December. This annual signal lags behind the seasonal meridional migration of the zero zonally integrated wind stress curl line by 4–5 months but corresponds pretty well with the local Ekman pumping associated with the Asian monsoon winds. The bifurcation latitude of the NEC is depth dependent. On the annual average, it shifts from about 13.3°N near the surface to north of 20°N at depths around 1000 m. There is a time lag of 1–2 months from the sea surface to the subsurface (300–700 m) for the annual cycle. Below 700 m, the bifurcation of the NEC approaches as far north as 22°N during the northeast monsoon (November–January), and as a result an anomalous transport of subtropical water is shown to flow equatorward along the western boundary. The bifurcation of the NEC below 700 m becomes unrecognizable when the prevailing wind is from the southwest (June–August).

1. Introduction

The western equatorial Pacific is a crossroads for water masses formed at middle and high latitudes (Fine et al. 1994), in which low latitude western boundary currents play a pivotal role (McCreary and Lu 1994; Lu and McCreary 1995; Lukas et al. 1996). In the Northern Hemisphere, the westward flow of the North Equatorial Current (NEC) splits as it encounters the Philippine coast, feeding the poleward-flowing Kuroshio and the equatorward-flowing Mindanao Current (MC). An indicator of the partition of the NEC mass, heat, and salt transport between the Kuroshio and the MC is the bifurcation latitude of the NEC, which is involved in determining how much subtropical water bends equatorward to flow into the equatorial region via the MC and how much turns poleward to return to the subtropics via the Kuroshio.

For the long-term mean it is easy to show from the Sverdrup theory that the bifurcation of the NEC should occur at the zero zonally integrated wind stress curl line at 14.6°N (Fig. 1), though this latitude varies slightly among different wind products (e.g., Kessler and Taft 1987; Wajsowicz 1999). The steady Sverdrup theory, however, masks the variable interactions and exchanges of water masses between oceanic gyres, and therefore is not sufficient to describe the actual bifurcation latitude of the NEC. Surface wind forcing changes both in time and space, and these changes exert a particularly large impact on the bifurcation latitude of the NEC both by local (Asian monsoon winds) and remote effects (Rossby waves generated by basinwide winds).

Another important issue that the Sverdrup theory does not accommodate is the depth dependence of the subtropical gyre circulation. The bifurcation latitude of the NEC is observed at a mean latitude of about 13°N near the surface (Nitani 1972; Toole et al. 1988, 1990), but it shifts northward with depth, approaching as far north as 20°N at depths around 800 m (Qu et al. 1998, 1999). A manifestation of this northward shift is the appearance of the Luzon Undercurrent (LUC) flowing southward beneath the Kuroshio (Qu et al. 1997), by which a significant amount of the low-salinity North Pacific Intermediate Water is advected into the equatorial ocean (Talley 1993; Bingham and Lukas 1994; Qu et al. 1997).

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The appearance of the LUC has been linked with the basinwide circulation of the North Pacific subtropical gyre that contracts to the north with increasing depth (Reid and Arthur 1975; Reid 1997; Qu 2001).

Without temporally continuous and spatially extensive measurements, a comprehensive study of the NEC bifurcation latitude has been impossible, given that the flow field in the tropical western Pacific is highly variable and populated with various eddies and waves. Over the past decade, numerical models have become useful tools in synthesizing observations and analyzing variability of the ocean. Using results from a high-resolution, reduced-gravity model, Qiu and Lukas (1996, hereafter referred to as QL96) provided the first picture on the seasonal excursion of the NEC bifurcation latitude. According to their model results, the seasonal bifurcation of the NEC occurs at the northernmost position in October and the southernmost position in February. But, to the best of our knowledge, no observational confirmation has been published so far. Due to the limited vertical structure and the absence of the Indonesian Throughflow of their model, the situation in the intermediate ocean remains unknown.

This study is intended to construct a new climatology of temperature and salinity similar to that of Levitus (1982, 1994), using all available historical data in the western North Pacific, but focusing on the structure of the low-latitude western boundary currents. Dictated by the need to have a single mapping scale for the entire global ocean, the objective analysis used in preparing the Levitus climatology involves smoothing over 700 km, and this results in oversmoothing of important mean structures near the western boundary where zonal scales are short (Qu et al. 1999). Without this constraint, we are able to grid the data at 0.5° with a smoothing e-folding scale of about 150 km (see section 2), giving significantly better resolution of the narrow western boundary currents. The new climatology, as will be shown below, resolves most of the detailed nontransient phenomena identified from the individual cruise data and has a reasonable representation of the NEC bifurcation in the western Pacific.

The results of this study are presented in the following sections. In section 2, we describe the data and methods of analysis. In section 3, we show the vertically integrated circulation. In section 4, we examine the vertical structure of the western boundary currents and the depth dependence of the NEC bifurcation latitude. In section 5, we discuss the mechanisms that determine the seasonal excursion of the NEC bifurcation latitude. Results are summarized in section 6.

2. Data and method of analysis

The data used for this study consist of all temperature, salinity, and dissolved oxygen concentration profiles at observed levels recorded on the CD-ROMs of the World Ocean Database 1998 of NOAA/NESDIS/NODC from the region 0°–30°N, 120°–165°E. We first select the data by dropping those profiles that were flagged as “bad” or as not passing the monthly, seasonal, and annual standard deviation checks (Levitus 1982, 1994). Then, we remove those profiles with obviously erroneous records (e.g., temperature higher than 10°C or salinity lower than 33.5 psu below 800 m) and those profiles that extend shallower than 100 m, simultaneously eliminating coastal stations. Some of the early observations are of poor quality, and extreme outliers are not uncommon in some areas, requiring extensive hand editing to remove.

The statistics of the data used for the present study is shown in Table 1. Most of the 198,597 temperature profiles (Fig. 2a) are from expendable bathythermograph (XBT) measurements and confined within 500 m of the sea surface, with only 45,616 extending deeper than 500 m, 23,860 deeper than 800 m, and 13,793 deeper than 1200 m. Though smaller by a factor 6.7 near the surface (Fig. 2b), the number of salinity observations is comparable with that of temperature observations in the upper intermediate layers. The number of oxygen profiles is somewhat smaller (18,010), about 2/3 of which extend deeper than 800 m (Table 1). The spatial distributions of the temperature and salinity profiles used for this study in two opposite seasons (December–February and June–August) are shown in Fig. 3, and the situation is essentially the same for the other two seasons, except for a bias in the density of sampling.

<table>
<thead>
<tr>
<th></th>
<th>Total (≥100 m)</th>
<th>≥500 m</th>
<th>≥800 m</th>
<th>≥1200 m</th>
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<tbody>
<tr>
<td>Temperature</td>
<td>198,597</td>
<td>45,616</td>
<td>23,860</td>
<td>13,793</td>
</tr>
<tr>
<td>Salinity</td>
<td>29,525</td>
<td>22,301</td>
<td>18,702</td>
<td>12,663</td>
</tr>
<tr>
<td>Oxygen</td>
<td>18,010</td>
<td>13,552</td>
<td>11,858</td>
<td>8,418</td>
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toward summer. At 800 m, for example, the numbers of observations for the four seasons are 5747, 5118, 8500, and 4495 for temperature; 4524, 3728, 7074, and 3376 for salinity; and 3294, 2465, 3928, and 2171 for oxygen.

The temperature, salinity, and oxygen data from individual profiles are first interpolated onto a 10-dbar uniform pressure series using cubic spline. Then, considering that there are at least 6.7 times as many temperature profiles as salinity and oxygen profiles, we grid the temperature, salinity, and oxygen data in slightly different ways. For temperature, the data in the upper 500 m are averaged in a $0.5^\circ \times 0.5^\circ$ grid for each month regardless of the year of observations. Below 500 m, data coverage is relatively sparse, and a three-month-running average is applied, that is, monthly mean temperature is derived from observations in three overlapping months (January–February–March; February–March–April, etc.). For salinity and oxygen, the 3-month running average is applied to the entire water column from the surface down to 1200 m.

The upper ocean is best sampled in the northwestern part of the region studied, where the number of samples is usually larger than five at each grid cell and can be as large as several tens. In regions of sparse sampling, we choose a variable horizontal radius to include at least five samples at each grid cell. The use of variable radius gives better resolution of the narrow western boundary currents, where its typical values for temperature, for example, are $0.3^\circ$ at 100 m, $0.6^\circ$ at 800 m, and $0.9^\circ$ at
1200 m. This radius is somewhat larger in the interior ocean, namely east of 140°E, often exceeding 1.0° at 800 m and 1.5° at 1200 m. The gridded monthly data are then smoothed using a two-dimensional Gaussian filter, with $e$-folding scales of 1 month and 1.5° longitude and latitude.

The smoothed temperature and salinity fields are finally converted to dynamic heights, from which geostrophic velocities are determined. While deeper observations are available at some locations and seasons, the number of observations decreases rather rapidly below 1200 dbar (Qu et al. 1999). To optimize uniformity of the database, we select the reference level at 1200 dbar. For the inshore grids where water depth is shallower, the properties at deeper levels are extrapolated linearly from their nearby offshore grids.

Standard deviations are also estimated and used to edit the mean fields. If a property from an individual profile deviates from the grid mean by a value three times larger than the standard deviation, it is excluded, and the mean and standard deviation are recalculated. The spatial distributions of temperature and salinity standard deviations, though not shown, are chiefly characterized by east–west oriented contours. Typical surface temperature standard deviation is 0.5°C, ranging from 0.3°C near the equator to 0.8°C north of 20°N. Temperature standard deviation is largest at depths of the thermocline around 100 m, where its typical value exceeds 1°C. It decreases with depth below the thermocline, and on the regional average, falls below 0.5°C at 500 m and 0.2°C at 800 m. Salinity standard deviation at the surface is higher (~0.15 psu) near the equator, but it decreases toward the north, falling below 0.1 psu at about 15°N. This trend is reversed below the thermocline. At 500 m, for example, the typical salinity standard deviation ranges from 0.02 psu south of 10°N to 0.07 psu north of it. Oxygen standard deviation at 800 m is of the order 0.1 ml L$^{-1}$ in most part of the Tropics, but can be as large as 0.2 ml L$^{-1}$ in the central subtropical gyre.

The uncertainty of dynamic height cannot be evaluated from individual profiles directly because many are shallower than 1200 dbar. Instead, it is evaluated from temperature and salinity standard deviations. Assuming that a positive temperature deviation always corresponds to a negative salinity deviation and then integrating vertically their contributions from each individual depth to 1200 dbar, we obtain a typical dynamic height standard deviation ranging from 15 dyn cm at 100 m to 1.5 dyn cm at 800 m. Thus the standard errors of the mean dynamic height field, defined as the standard deviations divided by the square root of the number of measurements, are of order 5 dyn cm at 100 m and 0.5 dyn cm at 800 m based on 5–10 independent samples at each grid cell. These values might be overestimated because temperature and salinity deviations are not always negatively correlated. In an extreme case, where they are positively correlated, as is the
3. Vertically integrated circulation

a. Mean state

Depth-integrated (0–1000 m) dynamic height, \( P = \frac{1}{g} \int_{1000m}^{0} D \, dz \), provides an overview of the geostrophic circulation in the upper ocean (Fig. 4), where \( g \) is the acceleration due to gravity and \( D \) represents the dynamic height relative to 1200 dbar. Given depth-integrated dynamic heights \( P \) at any two points \( A \) and \( B \), the geostrophic volume transport between these two points, \( Q_{AB} \), can be determined by

\[
Q_{AB} = (P_A - P_B)g/f,
\]

where \( f \) is the Coriolis parameter.

The westward NEC splits at the western boundary (Fig. 4): its two branches (i.e., the Kuroshio and MC) close the interior Sverdrup circulations of the subtropical gyre in the north and the tropical gyre in the south. The division between the two gyres (i.e., the NEC bifurcation) occurs around 15.4 N near the western boundary. If surface Ekman transport is considered, this latitude moves to 15.2 N, suggesting that, despite the presence of baroclinic processes, inertial effects, and locally wind-driven fluctuations, Sverdrup theory provides an useful estimate (14.6 N) for the mean bifurcation latitude of the NEC in the western Pacific (Fig. 1).

Based on 5–10 independent samples in each grid cell and assuming dynamic height errors at different depths are all positively correlated, an uncertainty of order 20 m² is obtained in the mean field of depth-integrated dynamic height. However, if we assume that dynamic height errors at different depths are uncorrelated, this uncertainty would be reduced by a factor 10. With such an uncertainty ranging between 2 and 20 m², most of the large-scale phenomena presented here (e.g., Fig. 4) are representative. Although there is no easy way to quantify the uncertainty in the bifurcation latitude, its location and seasonal excursion as shown below are consistent with the large-scale circulation, and this increases our confidence in the significance of our estimates.

b. Seasonal variation

Monthly mean depth-integrated dynamic heights are presented in a smaller region near the Philippine coast (5°–25°N, 120°–140°E) to better illustrate the structure of the western boundary currents (Fig. 5). In the south, the flow field is dominated by a cyclonic circulation centered at 6°–8°N off Mindanao. This cyclonic circulation, often referred to as the Mindanao Dome (MD; Masumoto and Yamagata 1991), is fully developed in December/January, when the northeast monsoon prevails (Fig. 6). It decays during the rest of the year with the diminishing of local Ekman pumping combined with the westward propagation of downwelling Rossby waves excited by the northeast trade wind farther estward near 160°E (Masumoto and Yamagata 1991; Tözuka et al. 2002). In the north, water tends to recirculate as part of the subtropical gyre; its southern boundary is defined by the location of the NEC bifurcation at the Philippine coast.

Given that the western boundary currents presented in this study (Fig. 5) are considerably weaker and wider than what we have known from synoptic measurements presumably as a result of smoothing, we define the NEC bifurcation latitude to be the meridional velocity averaged within a 5°– instead of a 2°-longitude band as previously used by QL96 off the continental slope is zero. At the Luzon strait (18.5°–22°N), where western boundary is disconnected, the average is made from 120° to 125°N. Our calculation shows that the annual signal of the NEC bifurcation latitude is insensitive to the selection of longitude bands in the range between 2° and 5°, but its amplitude (maximum–minimum) tends to increase by up to 30% with a selection near the larger end of this range, reflecting the wide spread signal of the western boundary currents in this climatology.

The annual march of the NEC bifurcation is evident in Fig. 5. It occurs at the southernmost position (14.6°N) in July and the northernmost position (17.8°N) in November (Fig. 7, top). This annual signal will be modified if the contribution of surface Ekman transport, whose typical values within the 5°-longitude band are 1.5 Sv (1 Sv = 10⁶ m³ s⁻¹) (northward) in winter and −0.5 Sv (southward) in summer, is considered. Here, we see that the Ekman transport associated with the northeast monsoon (October–December) pushes the NEC bifurcation southward by up to 1°, while its northward movement forced by the southwest monsoon (June–August) is relatively small. Adding the contribution from the Ekman transport reduces the peak-to-peak seasonal vari-
Fig. 5. Monthly depth-integrated (0–1000 m) dynamic height (m^2) relative to 1200 dbar. The asterisks indicate the location of the NEC bifurcation.

Fig. 6. Same as Fig. 5 but for wind stress curl (10^{-8} \text{ N m}^{-2}). The heavy dashed lines represent zero zonally integrated wind stress curl.
the local wind stress curl has a maximum (<1 × 10^{-8} N m^{-2}) in November and a minimum (<1 × 10^{-8} N m^{-2}) in May/June (Fig. 7, bottom), which is almost in phase with the seasonal excursion of the NEC bifurcation latitude.

4. Depth dependence of the circulation

a. Mean state

The mean dynamic height and geostrophic flow (Fig. 8) clearly demonstrate the northward shift of the NEC at increasing depth. Near the sea surface (0–100 m), the NEC is well confined within the latitude band between 8° and 16°N, and bifurcates as it encounters the western boundary at 14.2°N. This bifurcation latitude is significantly affected by surface Ekman current. If we assume, for example, that Ekman current is uniformly distributed in the upper 100 m, the bifurcation near the sea surface (0–100 m) will move to 13.3°N, about 0.9° farther southward than that obtained from the geostrophic circulation alone.

At 200 m, the NEC becomes broader, with the northern boundary reaching at least 22°N, and as a consequence, its bifurcation occurs about 2° farther northward than at the sea surface. At 400 m, the NEC flows entirely north of 12°N, leaving a broad area of almost no motion to the south. At 600 m, there is a dynamic height minimum (<51 dyn cm) centered at about 12°N. North of it, the NEC flows westward with a maximum speed exceeding 3 cm s^{-1} at 18°–20°N; south of it, a narrow eastward flow is present along 9°–11°N. A similar pattern is shown at 800 m, except that the MD identified in the shallower waters has completely disappeared at this depth. Instead, an anticyclonic circulation characterized by a local dynamic height maximum (>32 dyn cm) appears southeast of Mindanao, through which water of South Pacific origin intrudes northward along the western boundary (Qu et al. 1999).

The velocity section along 130°E shows the vertical structure of the NEC as it enters the Philippine Sea (Fig. 9). At about 10°N, the near-surface westward flow associated with the NEC exceeds 20 cm s^{-1}. The core of maximum velocity moves toward the north with increasing depth, approaching 18°N at depths below 300 m. The North Equatorial Countercurrent flows eastward between 3° and 8°N, forming the southern flank of the MD.

Upon reaching the western boundary, the NEC bifurcates into the northward-flowing Kuroshio and the southward-flowing MC and LUC. Although the narrow western boundary currents are significantly weaker in this study compared with synoptic measurements (e.g., Lukas et al. 1991; Qu et al. 1998), as a result of averaging and smoothing, their basic structure is well resolved in the present climatology. At 9°N, a southward flow associated with the MC is dominant in the upper 700 m, with a velocity core of about 14 cm s^{-1} located at about 50 m (Fig. 10). The Mindanao Undercurrent (MUC; Hu...
et al. 1991; Lukas et al. 1991) stands out as two velocity cores. The deeper one, lying at 800–900 m, is weaker and closer to the coast, and the shallower one is somewhat offshore. This velocity structure shows a remarkable agreement with that from repeat hydrographic observations reported by Qu et al. (1998). Similar structure is seen at 11°N, except that the velocity core of the MC tends to be deeper along the northern section. At 13°N, surface velocity drops to near zero, and the core of southward flow occurs at about 300 m. The Kuroshio starts to appear as a northward surface flow around 15°N, overlying the southward-flowing LUC that extends from about 200 m to at least 1000 m. At 19°N, the maximum speed of the Kuroshio exceeds 10 cm s\(^{-1}\) at about 50 m, while the LUC appears as a weak southward flow only at depths below 700 m.

The bifurcation latitude of the NEC, by definition, is the place where the western boundary currents reverse. Meridional velocity averaged within a 5°-longitude band off the Philippine coast shows that the bifurcation of the NEC occurs at about 14°N near the surface (Fig. 11). This latitude shifts to the north with increasing depth, extending north of 20°N at 800–1000 m. Below the MC, the northward flow is confined basically to the south of 15°N.

b. Seasonal variation

The circulation near the surface for each individual month contains essentially the same pattern as that shown in Fig. 8. Further inspection of the anomalous field, however, shows considerable discrepancies among different seasons, and these discrepancies seem to correspond with local Ekman pumping (Fig. 6). In winter, when the northeast monsoon prevails, strong positive Ekman pumping produces an anomalous cyclonic circulation over a large part of the Philippine Sea (Fig. 12). This situation is reversed in summer. As the southwest monsoon develops, local Ekman pumping reaches...
its seasonal minimum (Fig. 6), and thus generates an anomalous anticyclonic circulation in much of the region studied.

The circulation in the intermediate layers is generally weak (<3 cm s⁻¹). Its seasonality is apparent even in the monthly mean velocity fields (Fig. 13). At 800 m, the NEC has moved to the latitudes north of 18°N. South of this latitude, a narrow eastward flow is present at about 10°N during most seasons of the year. Two pathways can be identified that contribute to this eastward flow. One is the anticyclonic circulation off Mindanao, through which water from the South Pacific may be advected northward along the coast of Mindanao. Part of this water mass appears to be carried offshore before heading eastward along 9°–11°N. Another contribution is from the NEC through the deep extension of the LUC (Fig. 13). From November to January, when the northeast monsoon develops, the LUC reaches its maximum strength, and part of the NEC water is transported southward along the western boundary to feed into the eastward flow at about 10°N. This does not seem to be the case during the southwest monsoon season. From June to August, the deep part of the LUC becomes unrecognizable, with no apparent southward flow along the Philippine coast below 700 m (Fig. 14).

Water property distributions provide independent evidence for the monsoon-related circulations. In the months of November–January, when the northeast monsoon prevails, water of eastern subtropical origin with O₂ < 1.8 ml L⁻¹ and 34.3 < S < 34.5 psu (Reid 1965; Bingham and Lukas 1994) is seen extending all the way toward the western boundary at depths around 800 M (Fig. 15). Upon approaching the Philippine coast, part of this water mass turns southward via the LUC and can be traced continuously to the southern tip of Mindanao (Bingham and Lukas 1995), despite considerable modification of properties as a result of mixing. In the months of June–August, when the prevailing wind is from the southwest, this water mass is basically east–
west oriented, with its extreme properties centered at 18°–20°N (Fig. 15). There is little indication that this water mass extends farther southward than 14°N during this period of the year.

The seasonal cycle of the NEC bifurcation is depth dependent (Fig. 16). Near the sea surface (<100 m), the dynamically calculated circulation suggests a southernmost bifurcation (13.4°N) in June and a northernmost bifurcation (14.8°N) in November. As we progress to the deeper levels, this bifurcation trends northward, approaching 17.3°N in August and 20.9°N in January at depths around 700 m.

Below 700 m, the bifurcation of the NEC reaches at least 22°N from November to January, but becomes unrecognizable from June to August (Fig. 14). In fact, during the latter period of time, the weak MUC appears to merge with the deep extension of the Kuroshio, possibly providing a direct pathway for the Antarctic Intermediate Water (AAIW) to leak into the subtropical North Pacific.

5. Some thoughts on the forcing mechanisms

Before proceeding to the conclusions, we discuss in this section the mechanisms that determine the seasonal bifurcation of the NEC. The theoretical background of the bifurcation has been presented by QL96, and only a brief summary is presented here. In the sense of linear dynamics, the variability of large-scale, low-frequency circulation in the ocean is essentially governed by a combination of local Ekman pumping and remotely forced Rossby waves (Meyers 1979). This simple model, for the long-term average, yields the Sverdrup re-
Fig. 14. Same as Fig. 11 but for monthly mean velocity in Jul and Dec.

Fig. 15. Salinity (psu) and oxygen concentration (ml L\(^{-1}\)) at 800 m in Jul and Dec. Areas with oxygen concentration <1.8 ml L\(^{-1}\) are shaded.
lation is that the NEC bifurcation is small compared with the annual migration of the zonally integrated wind stress curl line. The present results show that the amplitude of the seasonal excursion of the NEC bifurcation latitude is only about half of that of the annual migration of the zonally integrated wind stress curl line, giving support to the QL96 conclusion.

We note, however, that in addition to the difference in amplitude, there is a phase lag of 4–5 months between the seasonal bifurcation of the NEC and the annual migration of zero zonally integrated wind stress curl line. This result differs from QL96. One possible explanation for this difference is that the QL96 result includes ageostrophic flow and applies only to the surface ocean.

Here, we emphasize the importance of local Ekman pumping associated with the monsoonal winds in determining the seasonal bifurcation of the NEC. In the months of November–December, for example, the local wind stress curl in the tropical western Pacific is usually larger than $10 \times 10^{-8}$ N m$^{-2}$, and can be as large as $30 \times 10^{-8}$ N m$^{-2}$ near the coast of Luzon (Fig. 6). This large positive wind stress curl produces an anomalous cyclonic circulation in the Philippine Sea (Figs. 12 and 13), whose southward component near the western boundary causes the NEC bifurcation to occur at a higher latitude. During the southwest monsoon, on the contrary, the weak positive/negative wind stress curl produces an anomalous anticyclonic circulation (Figs. 12 and 13), and its northward component near the western boundary results in a shift of the NEC bifurcation to its southernmost position.

Another process that might be important in modulating the bifurcation latitude of the NEC is the equatorward-propagating coastal Kelvin waves (Lukas 1996). To the extent that linear dynamics dominates, annual, westward-propagating Rossby waves generated at midlatitudes should reflect at the western boundary into equatorward-propagating coastal Kelvin waves and eastward-propagating short Rossby waves. These equatorward-propagating coastal Kelvin waves may alter the circulation pattern of the western boundary at lower latitudes and consequently the bifurcation latitude of the NEC. Lukas’s work also pointed out the potential importance of the eastward-propagating short Rossby waves, but Qiu and Lukas’s (1996) reduced gravity model does not support this idea. This has to be investigated further by research.

In addition to the above, we note that the ocean process within the marginal seas may also play a role in determining the seasonal bifurcation of the NEC. In the southern hemisphere, it is often believed that the presence of the Indonesian throughflow, a component of the circulation around Australia–Papua New Guinea as suggested by Godfrey’s (1989) “Island Rule,” augments the region of equatorward western boundary current, thus producing a bifurcation farther to the south (Qu and Lindstrom 2002). The situation seems to be reversed in the Northern Hemisphere, where the circulation around the Philippines tends to push the bifurcation toward the equator (Metzger and Hurlburt 1996; Qu et al. 2000). In a 1.5-layer reduced-gravity model forced by climatological wind, Metzger and Hurlburt (1996) found that this equatorward movement can be up to several degrees, but its coherence with the fluctuation of the South China Sea circulation is not understood. We will leave this problem for a future study using results from high-resolution general circulation models.

6. Summary and discussion

Based on a new climatology derived from historical temperature and salinity data, this study provides a detailed description of the seasonal variation and depth distribution of the NEC bifurcation in the western Pacific. The results are summarized as follows.

Near the sea surface (0–100 m), the mean bifurcation of the NEC occurs at about 14.2$^\circ$N. Adding surface Ekman transport moves this latitude southward to about 13.3$^\circ$N. Below the sea surface, the NEC bifurcation latitude shifts with depth, reaching as far north as 20$^\circ$N at depths around 800 m. A manifestation of this northward shift is the appearance of the LUC flowing southward beneath the Kuroshio. A subsurface northward countercurrent also exists along the coast of Mindanao, representing the influence of South Pacific sources, but its northward extension is confined primarily to the south of 15$^\circ$N.
A combination of the vertically integrated (0–1000 m) geostrophic circulation with surface Ekman transport indicates that the seasonal bifurcation of the NEC occurs at the southernmost position (about 14.8°N) in July and the northernmost position (about 17.2°N) in December. This annual signal is smaller by a factor of at least 2 in amplitude than that of the annual migration of the zero zonally integrated wind stress curl line, supporting the QL96 conclusion that the integral effect of Rossby waves on the NEC bifurcation latitude is reduced by phase cancellation.

In contrast to the QL96 model results, we found that the seasonal bifurcation of the NEC lags behind the annual migration of the zero zonally integrated wind stress curl line by 4–5 months but corresponds pretty well with the local Ekman pumping. This result suggests that the Asian monsoon might play a role in determining the seasonal bifurcation of the NEC. Two processes are likely involved. One is by the directly wind-driven Ekman transport. Our preliminary estimate shows that this process may account for up to 20% of the seasonal variability in the NEC bifurcation latitude. The second process is associated with the anomalous circulation forced by local Ekman pumping, which tends to displace the NEC bifurcation farther northward in winter and farther southward in summer. We are currently conducting a set of numerical experiments to further examine these two processes.

The seasonal excursion of the NEC bifurcation latitude is found to be depth dependent. The bifurcation determined from geostrophic circulation at the subsurface (300–700 m) lags behind by 1–2 months compared with that in the shallower waters. Below 700 m, the LUC approaches its maximum strength in November–January, when the northeast Asian monsoon prevails, and as a consequence, a significant amount of subtropical water is transported toward the equator along the western boundary. During the southwest monsoon, the weak northward flow underlying the MC (i.e., the MUC) appears to be connected with the deep extension of the Kuroshio.

In addition to the local monsoonal winds, the remotely forced westward-propagating Rossby waves, and equatorward-propagating coastal Kelvin waves, as previously suggested by Lukas (1996), we also emphasize the potential importance of the South China Sea circulation, through which the circulation around the Philippines may be affected. A separate study to investigate this problem using results from general circulation models is under way.

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