Trends of the Pathways and Intensities of Surface Equatorial Current System in the North Pacific Ocean

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ABSTRACT

An ensemble of ocean reanalysis products is utilized to quantify the long-term tendencies of pathways and along-pathway transports of the three surface equatorial currents (North Equatorial Current, North Equatorial Countercurrent, and northern branch of the South Equatorial Current) in the North Pacific Ocean during the period of the 1900s–2000s. This study uses 12 ocean reanalysis products in the ensemble for the period after the 1960s, while only 2 Simple Ocean Data Assimilation (SODA) products are taken into consideration for the period prior to 1960s. The analyses indicate that the three currents in the western (eastern) Pacific Ocean have more southern (northern) mean central positions and tend to move southward (northward) over the past 100 years. All three currents have weakening tendencies, with the exception of the North Equatorial Current having intensified in the western Pacific Ocean. The Sverdrup dynamics, which directly relates the wind-driven circulation in the interior ocean to wind stress curl and Earth rotation, can be applied to simply address the long-term changes of intensities and pathways of the three surface currents in the tropical North Pacific Ocean.

1. Introduction

Across the tropical North Pacific Ocean, the North Equatorial Current (NEC) and northern branch of the South Equatorial Current (SECN) flow to the west at 10°-20°N and 0°-5°N, respectively, while the North Equatorial Countercurrent (NECC) travels eastward in between (Fig. 1). The three zonal-flowing currents form the major circulation system in the surface layer of the tropical North Pacific Ocean. The equatorial current system plays an important role in redistributing heat, salt, and water mass not only in the tropical Pacific Ocean but also on a global scale (Wyrtki 1979; Donohue and Wimbush 1998; Johnson et al. 2002; Richards et al. 2009; Masunaga and L’Ecuyer 2011). It controls the distributions of biogeochemical tracers underlying the current system as well (Kimura et al. 2001; Christian et al. 2004; Messié and Radenac 2006).

Because the concentration of carbon dioxide (CO₂) in the atmosphere has been increasing steadily since the industrial revolution, global-warming-related variation has been the most important issue in the research community of climate change. Besides temperature increasing in the atmosphere and at land and sea surfaces being proposed, temperature change in the subsurface ocean and other global-warming-related environmental changes in the ocean (such as sea level, salinity, water masses, circulation, and biogeochemistry) were also noticed in the research community (Cess and Goldenberg 1981; Levitus et al. 2005; Gouretski and Koltermann 2007; Bindoff et al. 2007). Among others, changes of temperature and sea level have been more extensively investigated because the long-term observational temperature and sea level data are more easily obtained and collected. Therefore, studies on long-term changes of water masses, circulation, and biogeochemistry are very rare.

Based on observations of in situ field surveys and moorings, satellite remote sensing, and numerical simulation, variability of the Pacific NEC, NECC, and SECN has been extensively explored on broad time scales from days to decades (e.g., Wyrtki 1974; Wyrtki and Kilonsky 1984; Philander et al. 1987; Halpern et al. 1988; McPhaden 1996; Qiu and Lukas 1996; Bonjean and Lagerloef 2002; Johnson et al. 2002; Vecchi and Soden 2007; Kashino et al. 2009; Qiu and Chen 2010, 2012; Hsin and Qiu 2012a,b; Hu and Hu 2014; Hu et al. 

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2015). To date, literature related to the impact of global warming on the upper-layer wind-driven circulation in the tropical Pacific Ocean is still limited. By analyzing outputs of the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) models, Vecchi and Soden (2007) suggested that the South Equatorial Current (SEC) on the equator slows down in a warming climate. Based on the altimetry sea surface height data, Qiu and Chen (2012) investigated multidecadal changes of the NEC and NECC in the western Pacific Ocean and showed that the two currents intensified in the two decades after 1993, while they weakened during the two decades before 1993. Hu and Hu (2014) further confirmed the increasing trend of the NEC transport, based on 16-yr (1993–2008) shipboard Acoustic Doppler Current Profilers measurements along the longitude of 137°E. Chen and Wu (2012) analyzed the bifurcation latitude of the NEC based on the Simple Ocean Data Assimilation (SODA) version 2.2.4 and found that the NEC bifurcation latitude moved to the south over the past 60 years as a result of a southward shift of wind stress curl at 10°–20°N leading the strengthening of the Kuroshio at its origin. Utilizing the same SODA product, Zhai et al. (2014) explored the long-term change of bifurcation latitude of the South Equatorial Current (SBL) in the South Pacific over 1950–2010 and concluded that the SBL has a southward tendency of 0.02° yr⁻¹, which is compatible with the southward tendency (0.024° yr⁻¹) of bifurcation latitude of the NEC.

In view of this, studies concerning the long-term changes of the equatorial currents are still lacking. This study aims to evaluate the long-term trends of the central positions and intensities of the NEC, NECC, and SECN across the tropical North Pacific Ocean by means of an ensemble of 12 ocean reanalysis products spanning periods of at least 50 years. The remaining part of this paper is structured as follows. Data and quantities used in this paper are described in section 2. Section 3 evaluates the 12 ocean reanalysis products in comparison with observational data. Results and discussions are given in section 4, and conclusions are in section 5.

2. Data and methodology

a. Ocean reanalysis products

Many ocean reanalysis products are freely available online from various sources. This study uses 12 ocean reanalysis products spanning periods of at least 50 years, and details about each of them are summarized in Table 1 (spatial resolution, source, reference, basic ocean model, data used for assimilation, and forcing data) and Fig. 2 (temporal coverage). The spatial resolution and temporal coverage differ from one product to the other, with a temporal coverage mostly from the beginning of the 1960s to the end of 2000s (except for the SODA224 and SODASI2, which are available since 1900). All the products are monthly and linearly interpolated on a 1° × 1° grid.

As summarized in Table 1, products used are not based on the same three-dimensional primitive numerical model, data used for assimilation, and atmospheric forcing. Some examples are given below. The ECMWF Ocean Reanalysis System 3 (ORAS3) is based on the Hamburg Ocean Primitive Equation Model (HOPE), assimilated with temperature and salinity profiles and satellite altimetry sea level anomaly, and forced by daily fluxes of ERA-40 from 1959 to 2002 and the ECMWF operational numerical weather prediction (NWP) after 2002. In the new generation of the ECMWF ORAS4, its basic ocean model was changed to the Nucleus for European Modelling of the Ocean (NEMO), version 3.0. The usage of surface fluxes was also changed. Daily
surface fluxes from ERA-40 and ERA-Interim were used for 1958–88 and 1989–2009, respectively. After 2010, ORAS4 was driven by fluxes of the operational ECMWF atmospheric analysis. In addition, GECCO is based on the Massachusetts Institute of Technology General Circulation Model (MITgcm; http://mitgcm.org/), the series of SODA products are derived based on the Parallel Ocean Program (POP: http://soda.tamu.edu/), and the basic ocean model of the Data Assimilation System of the Korea Institute of Ocean Science and Technology (DASK14) is the fourth version of the Modular Ocean Model (MOM4; Griffies et al. 2004). More detailed information about these products can be found in Table 1.

Before estimating long-term trends of pathways and intensities of the NEC, NECC, and SECN in the North Pacific Ocean from these reanalysis products, I validate them with observational flow field, including the mean spatial pattern of surface currents at the depth of 10 m from Argo floats (Asia-Pacific Data-Research Center; http://apdrc.soest.hawaii.edu/) and the upper-layer currents measured by moorings of the Tropical Atmosphere/Ocean/Triangle Trans-Ocean Buoy Network (TAO/TRITON; http://www.pmel.noaa.gov/tao/) array. The Argo-flat-derived mean surface currents were averaged over the period of 2001–10 and gridded at a 1° spatial resolution. There are 7 acoustic Doppler current profilers (ADCPs) and 36 current meters (CMs) implemented by the TAO/TRITON array. The seven ADCPs measured flows in the upper layer of 0–400 m after 1988; six of them were stationed along the equator and one was implemented at 8°N, 128°W. Also, there are 36 CMs equipped in the latitudinal range of 8°S–9°N, which measured currents in the 0–300-m range after 1979. The distribution of CMs is denser in the western (12 in the west of 160°E) and eastern (22 in the east of 140°W) equatorial Pacific Ocean and sparse in between (only 2 CMs). In addition, to further validate the reliability of the two SODA products (SODA224 and SODASI2) in the period before the 1960s with limited observations, comparison of sea level anomaly between the two SODA products and six tidal gauge stations (Malakal, Yap, Guam, Kwajalein, Johnston, and Christmas Islands; http://uhslc.soest.hawaii.edu/), which spanned periods from 1940s–60s to the present, in the tropical Pacific is also performed.

b. Quantities

1) Central position of a current

As in Johnson et al. (2002) and Hsin and Qiu (2012b), the central position $Y_{CM}$ of a zonal flow in the surface layer is calculated by performing a weighted average based on the zonal velocity—that is, integrating the zonal velocity meridionally over the latitudinal range of the flow and vertically from the surface down to the bottom of the flow (i.e., a density level). The definition of $Y_{CM}$ is expressed as follows:

$$Y_{CM}(x,t) = \frac{\int_{z=0}^{Z_b} \int_{y=Y_N}^{Y_S} yu(x,y,z,t) \, dy \, dz}{\int_{z=0}^{Z_b} \int_{y=Y_N}^{Y_S} u(x,y,z,t) \, dy \, dz}, \quad (1)$$

where $x$, $y$, $z$, and $t$ are the longitude, latitude, depth, and time; $Y_N$, $Y_S$, and $Z_b$ are the northern, southern, and lower limits of integration, respectively; and $u$ is the zonal velocity, with $u$ set to zero if in the direction opposite to the flow of interest (i.e., positive $u$ is set to zero for the NEC and SECN, and negative $u$ is for the NECC).

Based on the horizontal distribution of mean surface zonal velocity (at 15 m; Fig. 1) and vertical sections of zonal velocity (Fig. 3) across the equatorial Pacific Ocean, the latitudinal limits of integration ($Y_N$, $Y_S$) are chosen as (20°, 8°N), (10°, 2°N), and (5°N, 0°) for the NEC, NECC, and SECN, respectively. Chosen bands overlap to take into account meridional migrations of the three currents in time. The northern and southern limits for the NECC are the same as those in Hsin and Qiu (2012a, b), and the southern limit of SECN is defined at the equator (same as that in Johnson et al. 2002). No information is found in the literature for other limits ($Y_N$ and $Y_S$ for the NEC and $Y_N$ for the SECN). Therefore, a sensitivity test with variant latitudinal bands for the three currents is further carried out to examine whether those limits are suitable for the calculation in this study (figure not shown).

In the sensitivity test, the mean NEC center moves to the north as the northern limit is shifted from 20° to 25°N, especially in the western Pacific, while the position does not change significantly as the southern limit is shifted from 8° to 6°N. This is because the anticyclonic recirculated flows from the northeast or the westward flow of eddies (in the subtropical countercurrent area) exist in the north of the NEC and may contaminate the calculation of the NEC center, especially in the western Pacific. No significant changes of the NECC and SECN centers are found as different latitudinal bands are adopted. The outcome concludes that the chosen limits of (20°, 8°N), (10°, 2°N), and (5°N, 0°) are proper to calculate the $Y_{CM}$ of the NEC, NECC, and SECN, respectively.

As shown in the vertical sections of zonal velocity at 150°E, 180°, 150°W, and 120°W in the equatorial North Pacific Ocean (Fig. 3), a constant depth may not be suitable for serving as the bottom of the three equatorial currents because their vertical extents vary...
<table>
<thead>
<tr>
<th>No.</th>
<th>Name and resolution ((x, y, z)^b)</th>
<th>Source and reference</th>
<th>Ocean model</th>
<th>Data used for assimilation</th>
<th>Forcing data</th>
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<tbody>
<tr>
<td>1</td>
<td>DASK14 ((1, 1/3 \sim 1, 50))</td>
<td>Data Assimilation System of Korea Institute of Ocean Science and Technology <a href="http://apdrc.soest.hawaii.edu/datadoc/dask14.php">link</a>; Kim et al. (2015).</td>
<td>Modular Ocean Model version 4 (MOM4)</td>
<td>Temperature and salinity profiles ((T/S)) from World Ocean Database (WOD) and Korea Research Organizations; SST from HadISST (1947–81) and OISST (after 1981); sea surface height anomaly (SSHA) from AVISO (Sep 1992–2012).</td>
<td>Fully coupled based on GFDL Climate Model version 2.1 (CM2.1).</td>
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<tr>
<td>2</td>
<td>ECDA-V31 ((1, 1/3 \sim 1, 50))</td>
<td>GFDL Ocean Data Assimilation Experiment v3.1 <a href="http://data1.gfdl.noaa.gov/">link</a>; Chang et al. (2013).</td>
<td>MOM4</td>
<td>(T/S) from WOD, NOAA/Global Temperature and Salinity Profile Programme (GTSPP) and Argo drifters (after 2000); SST from HadISST (1960–80) and OISST (after 1981); winds, air temperature, and surface pressure from NCEP reanalysis.</td>
<td>Fully coupled based on GFDL CM2.1.</td>
</tr>
<tr>
<td>3</td>
<td>ESTOC ((1, 1, 46))</td>
<td>Estimated state of ocean for climate research version 02b <a href="http://www.godac.jamstec.go.jp/estoc">link</a>; Osafune et al. (2015).</td>
<td>MOM3</td>
<td>(T/S) from WOD, NOAA-GTSPP, and Argo drifters; SSHA from AVISO.</td>
<td>Surface momentum, sensible, long-/shortwave radiative, and freshwater fluxes from 6-hourly NCEP reanalysis; latent heat flux from OISST.</td>
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<td>4</td>
<td>GECCO ((1, 1, 23))</td>
<td>German ECCO, an extension of ECCO <a href="http://www.icdc.zmaw.de/easy_init_ocean.html">link</a>; Köhl and Stammer (2008).</td>
<td>MITgcm</td>
<td>(T/S) from WOCE, TAO moorings, ARGO drifters, World Ocean Atlas (WOA) and global XBT/mechanical bathythermograph (MBT) dataset; SSHA from tide gauge stations, ERS-1 and -2, and TOPEX/Poseidon; surface flow from drifters; SST from Reynolds and TMI SST.</td>
<td>Surface fluxes from NCEP reanalysis; winds from ERS/NSCAT/QuikSCAT scatterometers.</td>
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<tr>
<td>5</td>
<td>GECCO2 ((1, 1/3, 50))</td>
<td>An extension of GECCO <a href="http://www.icdc.zmaw.de/easy_init_ocean.html">link</a>; Köhl (2015).</td>
<td>MITgcm</td>
<td>(T/S) from EN3 database and WOA09; SSHA from AVISO; mean dynamic topography from GOCO geoid model; SST from HadISST and AMSRE SST.</td>
<td>Surface fluxes from NCEP reanalysis.</td>
</tr>
<tr>
<td>6</td>
<td>GEOS5-ODAS4 ((0.5, 0.5, 40))</td>
<td>GEOS integrated Ocean Data Assimilation System version 4 of NASA GMAO <a href="http://gmao.gsfc.nasa.gov">link</a>; Vernieres et al. (2012).</td>
<td>MOM4</td>
<td>(T/S) from EN3 database and TAO moorings; SSHA from AVISO; SST from Reynolds SST (after 1982) and CMIP5 SST (before 1982).</td>
<td>Fully coupled based on GEOS-5 atmospheric general circulation model.</td>
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<td>No.</td>
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<td>7</td>
<td>ORAS3 (1.4, 0.3~1.4, 29)</td>
<td>ECMWF Ocean Reanalysis System 3 (<a href="http://www.icdc.zmaw.de/easy_init_ocean.html">http://www.icdc.zmaw.de/easy_init_ocean.html</a>); Balmaseda et al. (2008).</td>
<td>HOPE</td>
<td>T/S from EN3 database; SSHA from AVISO; SST from ERA-40 (1959–82) and weekly OISST (after 1982).</td>
<td>ERA-40 daily fluxes (1959–2002) and ECMWF operational Numerical Weather Prediction fluxes (after 2003).</td>
</tr>
<tr>
<td>11</td>
<td>SODA224 (0.5, 0.5, 40)</td>
<td>SODA version 2.2.4 (<a href="http://soda.tamu.edu/">http://soda.tamu.edu/</a>); Giese and Ray (2011).</td>
<td>POP 2.1</td>
<td>T/S from WOD, TAO moorings, and Argo drifters; SST from COADS 2.5.</td>
<td>Surface winds from NOAA/CIRES 20CRv2 ensemble mean.</td>
</tr>
<tr>
<td>12</td>
<td>SODAS12 (0.5, 0.5, 40)</td>
<td>SODA version si.2 (<a href="http://soda.tamu.edu/">http://soda.tamu.edu/</a>); no available reference.</td>
<td>POP 2.1</td>
<td>T/S from WOD, TAO moorings, and Argo drifters; SST from COADS 2.5 with HadISST bucket corrections.</td>
<td>Surface winds from 18 NOAA/CIRES 20CRv2 ensemble members.</td>
</tr>
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*a Specified as (degree, degree, number of levels).*
zonally. Instead, the density surface of 26 $\sigma_\rho$ can be a proper choice of the lower integral limit for the NEC and NECC in the Pacific Ocean (Johnson et al. 2002; Hsin and Qiu 2012b). Following the definition of Johnson et al. (2002), the 26 $\sigma_\rho$ density surface is also chosen as the lower integral limit for the SECN. To avoid the interference from the eastern and western boundaries of Pacific Ocean, $Y_{CM}$ values of the NEC, NECC, and SECN are quantified in the zonal ranges of 130°E–120°W, 130°E–115°W, and 170°E–100°W, respectively (dashed frames in Fig. 1).

2) ALONG-PATHWAY INTENSITY OF A CURRENT

Following the central position of a current expressed in Eq. (1), intensity INT of this current is defined as follows:

$$ INT(x,t) = \int_{z=z_0}^{z_0+100} \int_{Y_{CM}+W}^{Y_{CM}-W} u(x,y,z,t) \, dy \, dz, \quad (2) $$

where $W$ is half of the mean width of the current, and other variables are the same as those in Eq. (1). Based on the horizontal distribution and vertical sections of zonal velocity (Figs. 1 and 3), $W$ can in general be set to 5° for the NEC and 4° for the NECC and SECN. For the southern limits of the NECC and SECN, different criteria are used. The southern limit of the NECC is set to 2°N when $Y_{CM} - W < 2°N$ [similar to Hsin and Qiu (2012a,b), who calculated the along-pathway intensity of NECC across the Pacific Ocean]. Same as that defined in Johnson et al. (2002), the southern limit of SECN is set to 0 when $Y_{CM} - W < 0°$. In addition, different widths are also tested in Eq. (2) to further examine whether the widths of 5°, 4°, and 4° are proper in the calculation (figure not shown). The result shows that a larger change is found in the western NEC (due to the existence of the anticyclonic recirculated flows from the northeast or the westward flow of eddies in the north of the NEC), and changes in the remaining NEC and the whole NECC and SECN are unobvious. In the western NEC, the change becomes smaller when $W$ is greater than 5°. Therefore, the widths of 5°, 4°, and 4° are suitable for the NEC, NECC, and SECN in Eq. (2) according to the vertical sections of zonal velocity (Fig. 3) and the result of a sensitivity test.

3. Evaluation of ocean reanalysis products

Because ocean reanalysis products adopted in this study are downloaded from variant sources in the world and based on a variety of numerical ocean models, data...
used for assimilation, and forcing data, performance of these datasets are diverse as a matter of course. Therefore, comparing these datasets with observational data is needed in this study to evaluate their performances. Also, comparisons are focused on upper-ocean flow field in the equatorial area of Pacific Ocean, which is set up as the studied area.

As shown in Fig. 4a, the Taylor diagram (Taylor 2001) compares the mean spatial pattern of zonal velocity at the depth of 10 m in the equatorial Pacific Ocean between the Argo-drifter-derived data and 12 ocean reanalysis products. The correlation coefficients $R$ of mean spatial patterns of zonal velocity in all products are greater than 0.75 with the centered root-mean-square differences (RMSDs) less than 0.15 m s$^{-1}$. The standard deviations (STDs) of zonal velocity in all products (including the ARGO-drifter-derived zonal velocity) range from 0.1 to 0.25 m s$^{-1}$. Among the 12 products, the SODA216, ORAS4, and PEODAS are the best three products with $R$ higher than 0.9 and RMSD lower than 0.07 m s$^{-1}$, whereas the SODASI2, GECCO, and DASK14 have worse performances with $R$ lower than 0.8 and RMSD higher than 0.1 m s$^{-1}$. To take the temporal variation of zonal flow into consideration, comparisons of time series of upper-layer zonal velocity measured by the moored ADCPs and CMs of the TAO/TRITON array are performed. Most of the products have correlation coefficients higher than 0.8 with RMSD less than 0.25 m s$^{-1}$, except that the DASK14, ESTOC, GECCO, and GECCO2 have smaller correlation coefficients of 0.7–0.8 and greater RMSD of up to 0.35 m s$^{-1}$ (Figs. 4b,c).

Evaluations are further made by comparing mean pathways and along-pathway intensities of the three equatorial currents at the depth of 10 m derived from the Argo-drifter-derived data to those derived from the 12 ocean reanalysis products. The result shows that the mean pathways of the three equatorial currents at 10 m derived from most of the products are well consistent with ($R > 0.7$ and RMSD < 1) those derived from the ARGO-drifter-derived data (Fig. 5).

As to the intensity, most of the products have very good performances in the NEC (Fig. 6a; $R > 0.7$ and RMSD < 40 000 m$^2$ s$^{-1}$). However, the correlation coefficients drop down to below 0.5 (and even negative values) in the NECC (Fig. 6b). The low correlation of mean zonal distribution of the surface NECC intensity between the ocean reanalysis products and observation is because the observational mean surface NECC intensity near the sea surface has a complicated zonal distribution (Fig. 1), which cannot be well resolved by most of the ocean reanalysis products. Instead of monotonic eastward decreasing of intensity similar to
the surface NEC and SECN, the mean surface NECC weakens from ~130°E to the date line and strengthens again from the date line to the east. The performance of intensities in the SECN becomes better again (Fig. 6c; $R > 0.5$).
Correlation coefficients of sea level anomalies between the six tidal gauge stations in the equatorial Pacific and the two 100-yr SODA products (SODA224 and SODASI2) are calculated to further check the reliability of the two products in the period prior to the 1960s. Correlation coefficients listed in Table 2 are derived from the monthly time series (nonsmoothed) and 1.5-yr running-averaged time series (smoothed), respectively. All correlation coefficients pass the 99% significance level, and most of the correlation coefficients are greater than 0.5, except for the nonsmoothed time series at the Johnston station. When the 1.5-yr running average is adopted, most of the correlation coefficients become higher (except for the Guam Station, which is still high), indicating the low-frequency fluctuations in the equatorial Pacific are better presented in the two SODA products. This fact further demonstrates that the two SODA products can well capture the fluctuations of sea surface height at least after the 1940s.

The comparisons presented above indicate that most of the products available online and adopted in the present study can well reproduce the equatorial currents in the North Pacific Ocean, especially in terms of their pathways. Although the performance of the NECC intensity is not as good as others, correlations of central position of the surface NECC between the ocean reanalysis products and observation are quite good (most are higher than 0.8; Fig. 5b). Thus, it is still worthy to explore the long-term change of the NECC intensity to provide a reference for the climate research community.

### 4. Results and discussion

#### a. Mean pathways and along-pathway transports of NEC, NECC, and SECN

Based on Eq. (1), the central positions of the three equatorial surface currents in the North Pacific Ocean are derived and shown in Fig. 7. Averaged over the 12 ocean reanalysis products, the mean NEC centralizes at ~13.5°N to the west of the date line and shifts northward to ~14.5°N in the region 150°–130°W (black line in Fig. 7a). The mean position of the NEC agrees well with the past findings. The surface NEC was observed at a mean latitude of about 13°N in the western Pacific Ocean (Nitani 1972; Qiu and Joyce 1992; Qu and Lukas 2003), and it has a southward-moving tendency as it flows toward the west (Bonjean and Lagerloef 2002). The STD of the NEC central position among the 12 products ranges from 0.25° to 0.5° (black dashed line in Fig. 7a).

As revealed in Fig. 7b, the NECC center is located at ~5°N in the western Pacific Ocean. It shifts to the north when it flows eastward and reaches the northernmost position of ~6.5°N at 130°W in the eastern Pacific Ocean. Afterward, it moves southward to the east of 130°W. The STDs among the 12 products are smaller (~0.4°) in the western and central Pacific Ocean and larger (~0.6°) in between. As the SECN flows westward, its center shifts northward from ~2°N at 100°W, reaches the northernmost position near 125°W, and moves to the south afterward (Fig. 7c). Its STD is larger in the central Pacific (~0.5°) and becomes smaller toward the western coast of America. The evolutions of the zonal change of mean positions of the three currents are consistent with the past observations (Bonjean and Lagerloef 2002; Johnson et al. 2002; Hsin and Qiu 2012a).

Following the mean central positions of the NEC, NECC, and SECN, the mean along-pathway transports of the three currents are derived from the 12 products and depicted in Fig. 8. The transports of the three currents show different zonal tendencies. The transport of the westward-flowing NEC (in the 12 products and their ensemble average) increases monotonously from ~10 Sv (1 Sv = 10^6 m^3 s^-1) in the eastern Pacific Ocean to ~35 Sv in the western Pacific Ocean (Fig. 8a). The STD among the 12 products also shows a westward increasing tendency from ~1.5 to ~3 Sv. In the eastward-flowing NECC, the mean transport decreases gently from ~26 to ~22 Sv to the west of 150°E, keeps a
constant of ~22 Sv within 150°E–160°W, and decreases rapidly from less than 20 to ~10 Sv to the east of 160°W (black solid line in Fig. 8b), in good agreement with the depth-integrated NECC transport suggested by Johnson et al. (2002). Larger STD of the NECC (>6 Sv; 2 times greater than STD in the NEC) occurs to the west of ~150°W because of larger discrepancies showing up in the two SODA products (SODA224 and SODAS12; black dashed line in Fig. 8b). The zonal distribution of mean transport of the westward-flowing SECN reveals a maximum of ~12 Sv in the vicinity of 140°W and decreases to ~8 Sv toward both sides (Fig. 8c). Larger STD also takes place in the central Pacific Ocean because of the larger difference among the 12 products.

The above zonal tendencies of the vertically integral transports of the NECC and SECN have been proposed by Johnson et al. (2002) based on cross-sectional CTD and ADCP measurements across the tropical Pacific Ocean in the period of 1985–2000. Thus, the ensembles of the 12 products well reproduce the mean positions and intensities of the NEC, NECC, and SECN, although mean along-pathway intensities of the NECC at the depth of 10 m are not well resolved in most of the ocean reanalysis products because of the complicated zonal distribution of the NECC near the sea surface (Figs. 1 and 6b).

b. Trends of pathways of NEC, NECC, and SECN

To explore the trends of the NEC, NECC, and SECN in the western, central, and eastern Pacific Ocean, anomalies of central positions of the three currents averaged over the longitudinal bands of 140°–160°E, 180°–160°W, and 140°–120°W are calculated based on the 12 ocean reanalysis products. (For the SECN, time series are only calculated in the central and eastern Pacific Ocean.) Because this study aims at exploring the long-term trends.
of the three equatorial currents in the North Pacific Ocean, a running smoother with a 5-yr window is adopted here for all monthly time series of anomalous central positions and intensities. Ensembles of 5-yr running-averaged time series of anomalies of central positions and intensities are then obtained from all the 12 products for the period after the 1960s and from the two SODA products (SODA224 and SODASI2) for the period before the 1960s (black dashed curve in Figs. 9 and 10). Afterwards, linear trends are derived separately for the whole duration from the 1900s to 2000s (blue dashed line in Figs. 9 and 10) and for the period after 1960 (red solid line in Figs. 9 and 10).

As depicted by the blue dashed lines in Figs. 9a–c, the trends of the NEC central position in the period of the 1900s to 2000s were $-0.0039$, $-0.0013$, and $0.0073^\circ\text{yr}^{-1}$ in the western, central, and eastern Pacific Ocean, respectively. This result indicates that the NEC has a southward-/northward-moving tendency in the western/eastern Pacific Ocean over the past 100 years, while the tendency of NEC meridional movement is not obvious in the central Pacific Ocean. The trends of NEC in the central and eastern Pacific Ocean became insignificant after the 1960s (red solid line in Figs. 9b,c), while the NEC in the western Pacific remained an obvious southward-moving trend of $-0.0037^\circ\text{yr}^{-1}$ (red solid line in Fig. 9a).

In the NECC (Figs. 9d–f), the central position in the 1900s to 2000s tended to move to the south in the western and central Pacific Ocean with a trend of $-0.0025^\circ\text{yr}^{-1}$ and to the north in the eastern Pacific Ocean with a trend of $0.0017^\circ\text{yr}^{-1}$. After the 1960s, the whole NECC tended to shift southward and the NECC in the western Pacific Ocean had a much larger moving rate of $-0.01^\circ\text{yr}^{-1}$. In the whole analyzed period of the 1900s to 2000s, the center of the westward-flowing SECN tended to shift to the north across the entire Pacific Ocean ($0.0045^\circ\text{yr}^{-1}$; blue dashed line in Figs. 9g,h). During the 1960s to 2000s, the SECN...
kept the northward-moving tendency at a reduced northward-moving rate of $-0.0003^\circ \text{yr}^{-1}$.

In summary, all three of the currents had southward-moving and northward-moving tendencies in the western and eastern Pacific Ocean, respectively, during the 1900s to 2000s. However, no consistent tendencies of pathways are found among the three currents in the central Pacific Ocean (i.e., northward movement for the SECN but southward movement for the NEC and NECC). Different scenarios of trends among the three currents occur when the shorter analyzed period of the 1960s to 2000s is considered. The pathways of the NEC in the western Pacific Ocean, the NECC in the western and central Pacific Ocean, and the SECN in the central and eastern Pacific Ocean kept the same tendencies over the past 50 years (1960s to 2000s) as those over the past 100 years (1900s to 2000s). Estimated trends for other pathways become insignificant when the shorter period is considered.

As revealed in the mean pathways (Figs. 1 and 7), the three currents have more southern/northern positions in the western/eastern Pacific Ocean. In combined consideration of the zonal distribution of the mean pathways and the corresponding trends in the 1900s to 2000s, the three currents with a more southern (northern) position in the western (eastern) Pacific Ocean tended to move to the south (north). This outcome indicates that the zonal skews of positions of the three equatorial currents in the North Pacific Ocean have been getting sharper in the past 100 years.
c. Trends of along-pathway intensities of NEC, NECC, and SECN

Based on Eq. (2) and adopting the same processes of smoothing and composite, the linear regression lines of along-pathway intensities of the three equatorial currents in the western, central, and eastern Pacific Ocean are derived accordingly. As shown by the blue dashed lines in Figs. 10a–c, the NEC intensified at a rate of 0.025 Sv yr$^{-1}$ in the western Pacific Ocean and weakened at a rate of -0.041 Sv yr$^{-1}$ in the rest of the area during the whole analyzed period (1900s-2000s). When the analyzed period of 1960s-2000s is taken into account (red solid line in Figs. 10a–c), the intensities of the NEC in the whole Pacific kept the same tendencies as those derived from the whole analyzed period (i.e., strengthening in the western Pacific Ocean and weakening in the central and eastern Pacific Ocean) but had smaller values of slope.

As revealed in Figs. 10d–f, significant decreasing tendencies of NECC intensities took place in the whole Pacific Ocean during both analyzed periods of the 1900s to 2000s and the 1960s to 2000s. However, the decreasing rates slowed down for the period of the 1960s to 2000s, especially in the western and central Pacific Ocean where the decreasing rates in the 1900s to 2000s were about 3 times larger than those in the 1960s to 2000s ($-0.2$ vs $-0.07$ Sv yr$^{-1}$). The SECN weakened consistently across the whole Pacific Ocean during the 1900s to 2000s (Figs. 10g,h). However, a larger spatial difference of weakening trends existed between the central and eastern Pacific Ocean; that is, the decreasing rate in the central Pacific Ocean ($-0.044$ Sv yr$^{-1}$) was about 6 times larger than in the eastern Pacific Ocean ($-0.0071$ Sv yr$^{-1}$). The trend of SECN intensity in the central Pacific Ocean became unobvious after 1960s, while the weakening tendency in the eastern Pacific Ocean flattened slightly.
Comparing the long-term tendencies (1900s to 2000s) of intensities among the three surface equatorial currents, different magnitudes of changing rates are found in the western, central, and eastern Pacific Ocean. In the western and central Pacific Ocean, changing rates of the intensities of the NECC were much larger (5–10 times) than those of the NEC and SECN. In the eastern Pacific Ocean, changing rates of intensities of the NEC and NECC were on the same order while that of the SECN was rather small. In addition, the changing rates of the three currents’ intensities were greater in the central Pacific Ocean than on the two sides. This condition reversed in the period of the 1960s to 2000s; that is, the decreasing/increasing rates of the three currents’ intensities in the central Pacific Ocean reduced or became insignificant. It is noteworthy that all three equatorial currents have weakened in the past 100 years except for the NEC intensifying in the western Pacific Ocean.

d. Possible dynamical processes

As summarized in Fig. 11, the longitudinal deflection of central positions of the three surface Pacific equatorial currents has been getting larger and larger, while their intensities (besides the NEC in the western Pacific Ocean) have been weakening in the past 100 years (solid bars). When the shorter period of the 1960s to 2000s is considered to estimate the linear trends, fewer than half (8/18; hollow bars) of the estimated trends are significant (i.e., passing the 95% confidence level of a Student’s t test). Therefore, possible dynamical processes leading to the long-term tendencies of positions and transports of the Pacific equatorial currents are explored only for the period of the 1900s to 2000s in this section.

In the surface layer of ocean, the wind variability is the major force driving the surface currents. This fact has been proposed in the investigations of decadal tendency of the NEC in the western Pacific Ocean (Chen and Wu 2012; Qiu and Chen 2012) and global-warming-related change of the SEC on the equator (Vecchi and Soden 2007). In addition, the upper-ocean circulation in the interior ocean can be simply explained by the Sverdrup dynamics (Sverdrup 1947), in which the upper-ocean transport in the interior ocean is directly related to wind stress curl and Earth rotation (i.e., Coriolis effect). Therefore, analyses based on the Sverdrup relationship are performed to explain how winds regulate the surface currents in the tropical North Pacific Ocean.

Based on the 2° × 2° monthly wind stress curl of NOAA/CIRES Twentieth Century Reanalysis, version 2c (http://www.esrl.noaa.gov), Fig. 12a compares the Sverdrup streamfunctions averaged temporally over the periods of 1901–50 (shading with black contour) and 1961–2010 (white contour) in the tropical North Pacific Ocean, while the corresponding zonal Sverdrup transports are shown in Fig. 12b. In a Sverdrup streamfunction map, a zonal zero contour with a positive (negative) value in the south denotes where the maximal velocity of a westward-flowing (eastward flowing) current is located. In the tropical North Pacific Ocean, there are two zonal zero contours; one follows the latitude of ~16°N, and another is located between 3° and 7°N (Fig. 12a). The northern one follows roughly the main stream of the NEC, while the southern one agrees well with the main stream of the NECC. Comparing the two zero contours between the two periods of the 1900s to 1940s (shading with black contour) and the 1960s to 2000s (white contour), slight differences are found. The northern zero contour was almost parallel to the latitude of 16°N during the 1900s to 1940s, whereas the contour moved southward (northward) in the western (eastern) Pacific Ocean during the 1960s to 2000s. The southern zero contour during the 1900s to 1940s was located at ~4°N in the western Pacific Ocean and shifted to the north of ~6°N in the eastern Pacific Ocean. This zero contour during the latter period migrated significantly to the south in the western and central Pacific Ocean and remained at ~6°N to the east of 120°W.

As revealed in Fig. 12b, the zero contour of zonal Sverdrup transport at ~10°N denotes the border of a westward-flowing current (i.e., the NEC) in the north and an eastward-flowing current (i.e., the NECC) in the south. This zero contour in the western/eastern Pacific
Ocean was also located at a more southern/northern latitude in the 1960s to 2000s (white contour) than in the 1900s to 1940s (black contour). This fact further demonstrates the meridional migration of the positions of the westward-flowing NEC and eastward-flowing NECC. Near the equator, a zonal zero contour was able to be found at 1°–2°N in the central Pacific Ocean during the 1900s to 1940s but disappeared during the 1960s to 2000s, indicating that the northward movement of the SECN seems not to be simply supported by the Sverdrup dynamics.

To clarify whether the Sverdrup dynamics can explain the long-term change of intensities of the surface currents in the tropical North Pacific Ocean, the difference of zonal Sverdrup transports between the periods of the 1900s to 1940s and the 1960s to 2000s (the latter minus the former) is depicted in Fig. 13a. In the anomalous zonal Sverdrup transport map, a positive value in an eastward-flowing (westward-flowing) current is indicative of strengthening (weakening) of this current in the latter period. Along the mean pathway of the westward-flowing NEC (red curve), negative values appear in the western Pacific Ocean and positive values appear elsewhere, showing that the NEC was strengthened (weakened) by the zonal Sverdrup transport in the western (central to eastern) Pacific Ocean. South of the NEC, negative values occupy the full eastward-flowing NECC (green curve) area and positive values appear in most of the westward-flowing SECN (blue curve) area, implying that the two currents are weakened by the change of wind stress curl in the tropical North Pacific.

Additionally, the linear trend of zonal Sverdrup transport over the past 100 years is further estimated in Fig. 13b to demonstrate the reliability of the above argument concluded from the anomalous zonal Sverdrup transports between the 1900s to 1940s and the 1960s to 2000s. Positive trend in an eastward-flowing (westward flowing) current shows that the current has been strengthening (weakening) over the past 100 years. It is obvious that spatial pattern of Fig. 13b is similar to that of Fig. 13a because trend can be estimated by Sverdrup transport difference per years. Positive trend appears in most of the westward-flowing NEC area, except for the western Pacific Ocean where a negative trend occurs. The eastward-flowing NECC and westward-flowing SECN areas are filled with negative and positive trend, respectively. Therefore, the estimated linear trend of zonal Sverdrup transport supports again the long-term change of intensities of the three Pacific equatorial currents. The outcomes shown in Figs. 12 and 13 conclude that the Sverdrup dynamics is valid for addressing

Fig. 12. (a) Sverdrup streamfunction (Ψ; Sv) and (b) zonal Sverdrup transport (\(M_x = \partial \Psi/\partial y\); m² s⁻¹) averaged over the periods of the 1900s to 1940s (shading with black contour) and the 1960s to 2000s (white contour). The wind data are the 2° × 2° monthly wind product of the NOAA/CIRES Twentieth Century Reanalysis version 2c (http://www.esrl.noaa.gov).
the long-term change of both central positions and intensities of the equatorial currents in the North Pacific Ocean over the past 100 years with an exception of the SECN center.

5. Concluding remarks

In this study, the tendencies of central positions and along-pathway transports of the North Equatorial Current, North Equatorial Countercurrent, and the northern branch of South Equatorial Current in the tropical North Pacific Ocean have been quantitatively explored by means of an ensemble of 12 ocean reanalysis products. These 12 products are provided by various institutions and are produced based on different ocean general circulation models, data used for assimilation, and surface flux products. Before utilizing upper-ocean flow field in these products to investigate the variability of the three Pacific equatorial currents, the 12 products are validated with the TAO/TRITON mooring data and Argo-drifter-derived surface velocity, and the sea level anomalies in the two 100-yr SODA products are further compared with those at the six tidal gauge stations for the period prior to the 1960s (from the 1940s to the present).

Revealed in the ensemble central positions, the mean pathways of the three currents in the tropical North Pacific Ocean are deflective zonally with more southern/northern positions in the western/eastern Pacific Ocean. The trends of central positions and along-pathway intensities are summarized in Fig. 11. The analyses show that the central positions of the equatorial currents in the western Pacific Ocean had southward-moving tendencies during the past 100 years while those in the eastern Pacific Ocean had tendencies of moving northward. The result also indicates the zonal deflection of the equatorial currents’ pathways has been getting larger over the past 100 years.

As to the trends of along-pathway intensities during the 1900s to 2000s, consistent weakening tendencies occurred over the three equatorial currents except for the strengthened North Equatorial Current in the western Pacific Ocean. The long-term changes of pathways and intensities are ascribed to the variability of wind stress curl in the equatorial Pacific Ocean and can be explained by the Sverdrup dynamics. It has to be

Fig. 13. (a) Difference between zonal Sverdrup transports (m$^2$ s$^{-1}$) between the 1900s to 1940s and the 1960s to 2000s (the latter minus the former) and (b) linear trend (m$^2$ s$^{-1}$ yr$^{-1}$) of zonal Sverdrup transport over the period of 1901–2010. The wind data are the 2° × 2° monthly wind product of NOAA/CIRES Twentieth Century Reanalysis v2c (http://www.esrl.noaa.gov). The red, green, and blue curves depict the mean central positions of the NEC, NECC, and SECN, respectively. In (b), light-blue shading denotes the area where its trend passes the Student’s $t$ test with the confidence level of 95%.
noted that the ensemble consists of only two ocean reanalysis products for the period prior to the 1960s because of the limited availability of ocean reanalysis products, leaving a question about the statistical reliability. Thus, it is worthy to revisit/reexamine the long-term changes of these currents in the future when more ocean reanalysis products spanning longer periods (at least 100 years) are available. The outcome brought out from this preliminary study can be helpful not only in understanding the long-term changes of the Pacific equatorial currents in the past 100 years but also in validating the outputs of climate models for the community of climate research.

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