1. Introduction

Western boundary currents (WBCs) are the western branch of the subtropical ocean gyres, which are swift, narrow, and energetic flows (Hu et al. 2015). The WBC extensions are among the most eddy-rich regions of the global ocean, showing a significant increase in mesoscale eddy activity of 2%–5% per decade (Martínez-Moreno et al. 2021). The WBCs and eddies can exchange energy, vorticity, and momentum through eddy–mean flow interactions, influencing the local large-scale circulation and eddy activity (Chen et al. 2014). The transfer of energy from the mean flow to eddies through barotropic, baroclinic, and mixed instability processes leads to eddy formation and shedding (Macdonald et al. 2016; Vallis 2017). In turn, the energy transferred from the eddies back to the mean flow through rectification and topographic steering processes (Mata et al. 2006; Kuo and Chern 2011; Witter and Chelton 1998) can feed the mean flow. A quantitative description of the oceanic energy cycle among different energy reservoirs is of critical importance for improving our understanding of the ocean general circulation and dynamical process of a current system (von Storch et al. 2012), particularly in the eddy-rich WBC regions.

The East Australian Current (EAC) is the WBC of the South Pacific Subtropical Gyre and flows southward along the east coast of Australia, with strong kinetic energy in the core of the EAC jet (von Storch et al. 2012; Feng et al. 2016; Sloyan et al. 2016; Bull et al. 2018; Li et al. 2021). After the EAC separates from the coast (Godfrey et al. 1980), typically at around 31°–33°S (Cetina-Heredia et al. 2014), it bifurcates into two branches (Tilburg et al. 2001): the EAC eastern extension and the EAC southern extension (Oke et al. 2019a,b), and anticyclonic eddies shed from the main jet (Nilsson and Cresswell 1980; Marchesiello and Middleton 2000; Oke and Middleton 2000). The EAC eastern extension flows eastward toward New Zealand, and the EAC southern extension continues to flow southward toward Tasmania (Ridgway and Dunn 2003). It has been shown that the EAC can separate at any latitude along its path (Cetina-Heredia et al. 2014; Kerry and Roughan 2020; Li et al. 2022b), forming an energetic mesoscale eddy field (Everett et al. 2012), with the highest eddy kinetic energy (EKE) occurring between 33.1° and 36.6°S (Li et al. 2021).

To investigate the eddy shedding process in the EAC, previous studies examined the energy conversion terms from mean available potential energy (MPE) to eddy available potential energy (EPE) through baroclinic instabilities and from mean kinetic energy (MKE) to EKE through barotropic instabilities (Bowen et al. 2005; Mata et al. 2006; Bull et al. 2017). These earlier studies were based on model output with coarse horizontal resolution (>20 km), which is insufficient to resolve the mesoscale process, hence they show different dynamical mechanisms. For example, Bowen et al. (2005) proposed that anticyclonic eddies shed from the EAC jet mainly due to the barotropic instability of the mean flow, but Mata et al. (2006)
and Bull et al. (2017) suggested that the generation of eddies is characterized by mixed barotropic and baroclinic instabilities, with barotropic energy conversion being dominant. Recently, based on a long-term (22 yr), high-resolution (2.5–6 km) model simulation, Li et al. (2021) demonstrated that the barotropic instability is the primary source of EKE, and the decay of cyclonic eddies can convert EKE back into MKE in some regions (~27°–28°S and ~30.5°–31.5°S). Previous studies mainly focus on the sources of EKE; however, little is known about the eddy–mean flow interactions in the EAC system.

Energetics analysis is an effective method for investigating the eddy–mean flow interaction by quantifying the energy exchange between the time-mean large-scale circulation and time-varying mesoscale flows. It has been widely used to study the eddy–mean flow interactions among the major WBCs of the global ocean, such as in the Gulf Stream (Kang and Curchitser 2015; hereafter KC15), the Kuroshio (Yang and Liang 2016, 2018; Yan et al. 2019, 2022), the Brazil Current (Magalhães et al. 2017; Brum et al. 2017), and the Agulhas Current (Halo et al. 2014; Tedesco et al. 2022). These studies systematically investigated the energetics evolution of four of the five major WBCs and their associated eddies. However, unlike the other four WBCs, the quantitative three-dimensional description of the energy exchange between the EAC and mesoscale eddy reservoirs has never been investigated in the EAC system.

The objective of this study is to present the first detailed investigation into the three-dimensional structure of the eddy–mean flow interactions and energy budget in the EAC system. We perform the energetics analysis based on a 24-yr (1998–2021) high-resolution (0.1° × 0.1°) reanalysis and examine four energy reservoirs (MKE, EKE, MPE, and EPE) and the energy conversion terms among them. We conduct our analysis in three key regions identified for their dynamical regimes: the EAC jet, the typical EAC separation region, and the EAC southern extension. This paper is structured as follows: section 2 provides the theoretical framework; section 3 describes the observations and the numerical-model simulation; section 4 presents the detailed analysis of eddy–mean flow interactions; the main findings are summarized and discussed in section 5.

2. Diagnostic framework

a. Governing equations

Following the framework of KC15, the derivation of the governing equations is based on the Reynolds-averaged Navier–Stokes equations using the hydrostatic and Boussinesq approximations, along with the continuity and scalar transport equations, which can be written as

\[
\frac{\partial u}{\partial t} + u \cdot \nabla u - f v = - \frac{1}{\rho_0} \frac{\partial p}{\partial x} + \mathcal{F}_u + \mathcal{D}_u, \tag{1}
\]

\[
\frac{\partial v}{\partial t} + u \cdot \nabla v + f u = - \frac{1}{\rho_0} \frac{\partial p}{\partial y} + \mathcal{F}_v + \mathcal{D}_v, \tag{2}
\]

\[
\frac{\partial C}{\partial t} + u \cdot \nabla C = \mathcal{F}_C + \mathcal{D}_C, \tag{3}
\]

\[
\frac{\partial p}{\partial z} = -\rho g, \quad \text{and} \quad \nabla \cdot u = 0, \tag{4}
\]

where \(u = (u, v, w)\) is the velocity vector, \(f\) is the Coriolis frequency, \(\rho_0 = 1025 \text{ kg m}^{-3}\) is the constant part of the density \(\rho\), \(p\) is the pressure, \(g\) is the gravitational acceleration, and \(\mathcal{F}\) and \(\mathcal{D}\) represent the forcing and horizontal diffusive terms, respectively. Here \(C\) can be temperature \(T\) and salinity \(S\), then the density can be calculated from the equation of state \(\rho = \rho(T, S, Z)\), which is given by

\[
\rho(x, y, z, t) = \rho_i(z) + \rho'_i(x, y, z, t), \tag{6}
\]

where \(\rho_i\) is a predefined reference density. It is chosen to be the area average of the time-mean density that is a constant at a given depth, and \(\rho_i\) is the perturbation density. Following von Storch et al. (2012), we can derive the density transport from the temperature \(T\) and salinity \(S\) transport in Eq. (3) and the equation of state. Applying the density decomposition, Eq. (6) yields

\[
\frac{\partial \rho_i}{\partial t} + u \cdot \nabla \rho_i = \frac{\rho_0}{g} N^2 w + \mathcal{F}_\rho + \mathcal{D}_\rho, \tag{7}
\]

where the buoyancy frequency \(N^2\) is defined by

\[
N^2 \equiv -\frac{g}{\rho_0} \frac{\partial \rho_i}{\partial z}, \tag{8}
\]

b. Energy definitions

To obtain the mean flow and eddy energy equations, all the time-varying variables are decomposed as \(\Phi(x, y, z, t) = \Phi(x, y, z) + \Phi'(x, y, z, t)\). Here overbar and prime denote the time mean and the deviation from the time mean, and \(\Phi\) can be \(u, v, w, p, \) and \(\rho\).

MKE and EKE are defined as

\[
\text{MKE} = \frac{1}{2} \rho_0 (u^2 + v^2) \quad \text{and} \quad \text{EKE} = \frac{1}{2} \rho_0 (w^2 + \nu^2). \tag{9}
\]

MPE and EPE are defined as

\[
\text{MPE} = \frac{\rho'_0}{2\rho_0} \frac{\rho'_0}{N^2} \quad \text{and} \quad \text{EPE} = \frac{\rho'_0}{2\rho_0} \frac{\rho'_0}{N^2}. \tag{10}
\]

Applying the variable decomposition to the perturbation density \(\rho_i\), we find

\[
\rho'_i = (\rho - \rho_i) - (\rho - \rho_i) = \rho - \rho = \rho'; \tag{13}
\]

therefore, \(\rho'_i\) is independent of the reference density \(\rho_i\).
c. Energy budget equations

The MKE budget equation with its sources, sinks, and energy term conversions can be derived by multiplying the momentum equations [Eqs. (1) and (2)] by \( \rho_0 u' \) and \( \rho_0 v' \), respectively, then taking the time average of their sum. Similarly, the EKE budget equation can be derived by multiplying the momentum equations [Eqs. (1) and (2)] by \( \rho_0 u'' \) and \( \rho_0 v'' \), respectively, then taking the time average of their sum.

The MPE budget equation can be obtained by multiplying the density transport equation [Eq. (7)] by \( \rho \beta \rho_0 N^2 \), then taking the time average. Similarly, the EPE budget equation can be obtained by multiplying the density transport equation [Eq. (7)] by \( \rho \beta \rho_0 N^2 \), then taking the time average.

The energy budget equations for MKE, EKE, MPE, and EPE are detailed in Table 1.

The energy budget equations can be obtained by multiplying the momentum equations [Eqs. (1) and (2)] by \( \rho_0 u'' \) and \( \rho_0 v'' \), respectively, then taking the time average of their sum.

Table 1. The eddy–mean flow interaction terms used in this study.

<table>
<thead>
<tr>
<th>Term</th>
<th>Mathematical form</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>KmKc</td>
<td>(-\rho_0 (u''u'\cdot \nabla u + v''v'\cdot \nabla v))</td>
<td>MKE ( \rightarrow ) EKE conversion rate due to eddy momentum flux</td>
</tr>
<tr>
<td>PeKe</td>
<td>(-\rho_0 \nabla \cdot (u''u' + v''v'))</td>
<td>EPE ( \rightarrow ) EKE conversion rate due to vertical eddy density flux</td>
</tr>
<tr>
<td>PmKm</td>
<td>(-\rho \beta \rho_0 N^2 u''v')</td>
<td>MPE ( \rightarrow ) MKE conversion rate due to vertical mean density flux</td>
</tr>
<tr>
<td>PmPe</td>
<td>(-\frac{\rho_0^2 N^2}{\rho_0^2 N^2} \nabla \cdot (u''u' + v''v'))</td>
<td>MPE ( \rightarrow ) EPE conversion rate due to horizontal eddy density fluxes</td>
</tr>
<tr>
<td>NLKE</td>
<td>(-\rho_0 \nabla \cdot (u''u' + v''v'))</td>
<td>EKE ( \rightarrow ) MKE kinetic energy-conversion rate due to nonlocal eddy–mean flow interactions</td>
</tr>
<tr>
<td>NLPE</td>
<td>(-\frac{\rho_0^2 N^2}{\rho_0^2 N^2} \nabla \cdot (u''u' + v''v'))</td>
<td>EPE ( \rightarrow ) MPE potential energy-conversion rate due to nonlocal eddy–mean flow interactions</td>
</tr>
</tbody>
</table>

\[
\frac{\partial \text{MKE}}{\partial t} \text{unsteadiness} = -\frac{\rho_0^2 N^2}{\rho_0^2 N^2} \nabla \cdot (u''u' + v''v') + \frac{\rho_0 \beta \rho_0 N^2 u''v'}{D_f},
\]

\[
\frac{\partial \text{EKE}}{\partial t} \text{unsteadiness} = -\frac{\rho_0^2 N^2}{\rho_0^2 N^2} \nabla \cdot (u''u' + v''v') - \frac{\rho_0 \beta \rho_0 N^2 u''v'}{D_f},
\]

\[
\frac{\partial \text{MPE}}{\partial t} \text{unsteadiness} = -\frac{\rho_0^2 N^2}{\rho_0^2 N^2} \nabla \cdot (u''u' + v''v') + \frac{\rho_0 \beta \rho_0 N^2 u''v'}{D_f},
\]

\[
\frac{\partial \text{EPE}}{\partial t} \text{unsteadiness} = -\frac{\rho_0^2 N^2}{\rho_0^2 N^2} \nabla \cdot (u''u' + v''v') - \frac{\rho_0 \beta \rho_0 N^2 u''v'}{D_f},
\]

where \( u_H \) is the horizontal velocity vector; \( \rho_0 \) and \( \rho' \) are the reference pressure and perturbation pressure that are related to \( \rho_0 \) and \( \rho' \), respectively. The unsteadiness terms on the left-hand side of Eqs. (14)–(17) denote the temporal change rates of MKE, EKE, MPE, and EPE, respectively. On the right-hand side, the terms \( \text{PW} \), \( \text{DF} \), \( \text{F} \), and \( D \) represent the energy redistribution rates through pressure work, advection, forcing effects, and turbulent diffusivity, respectively. The energy exchanges between the mean flow and the eddy fields are influenced by different energy reservoirs and the oceanic external energy have been illustrated in KC15 and Yan et al. (2019). In this study, the atmospheric forcing and dissipation terms are not explicitly evaluated, because we focus on the eddy–mean flow interaction terms as listed in Table 1.

The definitions of local and nonlocal eddy–mean flow interactions were introduced by Chen et al. (2014) and discussed in Chen et al. (2016) and Yan et al. (2019). The nonlocal eddy–mean flow interaction terms NLKE and NLPE are shown to connect the MKE and EKE interactions with the external ocean energy, where NLKE (NLPE) represents the energy conversion of EKE \( \leftrightarrow \) MKE (EPE \( \leftrightarrow \) MPE; Chen et al. 2016; Yan et al. 2019). KC15 considered these terms as the mean energy flux divergences of the cross kinetic energy (NLKE) and available potential energy (NLPE). If the volume integrals of the divergence forms (NLKE and NLPE) are negligible, the eddy–mean flow interaction is called local, because almost all the energy released from the mean flow is converted to eddy energy in the same region. For a fixed, nonclosed ocean region, their magnitudes are not negligible, hence part of the energy released from the mean flow is conveyed outside of the domain instead of being used to sustain the local-eddy energy growth in the same region.

3. Data and methods

a. Satellite observations

Satellite observations, including absolute geostrophic current velocity and geostrophic current velocity anomalies, are
obtained from Archiving, Validation, and Interpretation of Satellite Oceanographic Data (AVISO; Ducet et al. 2000), which are distributed by the Copernicus Marine Environment Monitoring Service (https://marine.copernicus.eu). Here we use AVISO+ daily data, which have a horizontal resolution of 0.25° x 0.25° and span from January 1998 to December 2021.

b. Model data and validation

To investigate the three-dimensional energetics structure of the eddy–mean flow interactions in the EAC, in this study, we use the daily output from the 2020 version of the Bluelink Reanalysis (BRAN2020) (Chamberlain et al. 2021). BRAN2020 is an ocean reanalysis that combines observations with an eddy-resolving, near-global ocean general circulation model, which is the latest version of the Bluelink Reanalysis. BRAN2020 has a horizontal resolution of 0.1° x 0.1° and 51 vertical layers, with a 5-m vertical resolution down to 40 m and a 10-m vertical resolution to 200 m. The model output is a realistic reconstruction of mesoscale upper-ocean dynamics around Australia (Chamberlain et al. 2021). Based on BRAN2020, we calculate energy reservoirs and energy conversion terms over the period of 1998–2021.

To illustrate the performance of BRAN2020 in representing the EAC and associated mesoscale eddy fields, we show the spatial distributions of surface MKE and EKE from AVISO observations and BRAN2020. The EAC forms at approximately 15°S in the south Coral Sea and flows poleward along Australia’s southeast coast. The main core of the EAC originates at around 24.5°S and separates from the coast at 32.5°S (Figs. 1a,b), with one branch flowing eastward and the other continuing to flow southward. Although the surface MKE along the EAC path in BRAN2020 is weaker than the AVISO observations (Fig. 1c), the locations and separation latitudes of the EAC jet in BRAN2020 are consistent with that in the AVISO observations. The spatial distributions of BRAN2020 surface EKE also agree well with the AVISO observations (Figs. 1d,e), with the highest surface EKE in the EAC typical separation region (32.5°–35.8°S) where anticyclonic eddies shed from the main jet. However, the BRAN2020 surface EKE is stronger than the AVISO observations in most regions (Fig. 1f), particularly in the EAC typical separation region and

Fig. 1. Spatial distribution of surface MKE from (a) AVISO observations and (b) BRAN2020 over 24 years (1998–2021). The dark gray vectors in (a) and (b) indicate surface geostrophic velocities. (c) Differences of surface MKE between AVISO observations and BRAN2020. (d)–(f) As in (a)–(c), but for the EKE.
the EAC southern extension. We suspect this is a result of the increased resolution in BRAN2020 compared to AVISO.

We acknowledge that there may be uncertainties in the BRAN2020 fields introduced through the data assimilation process. To quantify the impact on our calculations, we also calculated the energy reservoirs and energy conversion terms from a free-running model output Ocean Forecasting Australian Model, version 2017 (OFAM2017), which has no data assimilation (Oke et al. 2013). This model uses the same free-running ocean model as BRAN2020 but covers a shorter period (1994–2016) and has data assimilation. These results are presented and compared below (e.g., Fig. 2).

c. Energy calculations

It is noted that the energy terms MPE, EPE, and three related energy conversion terms PmKm, PmPe, and NLPE depend on the choice of reference stratification. By examining the sensitivity of energy analysis results to different $\rho_R$ profiles, KC15 found that EPE and PmPe are slightly affected by the choice of $\rho_R$, because of their similar structures and fairly constant volume-integrated values. Following KC15 and Yan et al. (2019), in this study, we choose $\rho_R$ as the horizontal average over the whole EAC region (24°–40°S, 145°–165°E) in Fig. 2 for the entire 24-yr simulation period. We then evaluate the four energy terms (MKE, EKE, MPE, EPE), as well as six eddy–mean flow interaction terms (KmKe, PmKm, NLKE, PmPe, PeKe, NLPE) as shown in Table 1. The detailed horizontal and vertical distribution of these terms in the EAC system are presented in the following section.

d. Key dynamical regions

Here we focus on three key regions along the EAC path identified using dynamical reasoning: the EAC jet region (EAC jet; red box in Fig. 2a), the EAC typical separation region (EAC eddy; purple box in Fig. 2a), and the EAC southern extension region (EAC southern extension; orange box in Fig. 2a). The EAC eddy is located within the EAC typical path.
separation region, with a similar range of latitudes to those in Oke et al. (2019b) and Li et al. (2021), which encompasses the region of the highest EKE in the EAC system. North of the EAC eddy, the EAC jet region captures the core of the EAC jet, with a focus on the variability of the mean flow upstream. South of the EAC eddy, the EAC southern extension region covers both the southward flow of the EAC southern extension and eddy activity south of the EAC typical separation region. We did not explore the EAC eastern extension as identified by Oke et al. (2019a) here; however, the variability in this region could form the basis for future work.

4. Results

a. Energy reservoirs

As shown in previous studies (Kerry and Roughan 2020; Li et al. 2021), large EKE is confined within the upper 450 m. A depth of 1000 m has been chosen to study the eddy–mean flow interactions in the other WBC regions, such as in the Gulf Stream (KC15), the Kuroshio (Yang and Liang 2016; Yan et al. 2019), and the Brazil Current (Brum et al. 2017); here we choose the 1000-m depth to capture the main dynamics of the eddy–mean flow interactions in the EAC system. We first examine the spatial distributions of the energy reservoirs in the three key dynamics regions from BRAN2020. Figure 2 shows the depth-integrated energy terms (MKE, EKE, and EPE) over the upper 1000 m. Along the EAC path, the energy terms exhibit nonuniform distribution. In the EAC jet, strong MKE is confined within a narrow band along the shelf edge from 24.5° to 32.5°S (Fig. 2a). The EAC separates from the coast at around 32.5°S and bifurcates into the eastward and southward flows. MKE decreases rapidly south of the separation latitude. In addition, we can also find relatively weak MKE in the EAC eastern extension.

In the EAC separation region, EKE is the highest and much greater than MKE in the EAC jet, implying that the EAC jet sheds eddies when it separates from the coast around these latitudes (Fig. 2b). This high-EKE region is consistent with a previous study from a higher-resolution regional-model simulation (Li et al. 2021). EKE decreases sharply in the EAC southern extension. Upstream of 32.5°S, EKE is the weakest along the EAC path. This structure of EKE has also been shown in previous studies (Feng et al. 2016; Kerry and Roughan 2020; Li et al. 2021). The horizontal distribution of depth-integrated EPE in the study region is similar to that of EKE but with a smaller magnitude (Fig. 2c). Compared to BRAN2020, the free-running model OFAM2017 has a much stronger MKE in the EAC jet (Fig. 2d) but weaker EKE (Fig. 2e) and EPE (Fig. 2f) in the EAC system. However, the horizontal distributions of energy reservoirs have very similar patterns in these two model outputs (Fig. 2).

The horizontal distributions of MKE, EKE, and EPE at three reference depths (50, 200, and 500 m) are similar to that integrated over the upper 1000 m (Figs. 2, 3) but decrease in magnitude with depth. These energy terms are the strongest at the surface (50 m), where we can find strong MKE and EPE but weak EKE in the EAC jet (Figs. 3a–c). In the EAC eddy and EAC southern extension, EKE is much larger than MKE and EPE. At 200 m, MKE, EKE, and EPE become weaker, but we can still see large EKE and EPE in the EAC eddy (Figs. 3d–f). At 500 m, these energy terms decrease dramatically and are smaller than 50, 80, and 70 J m⁻³ in the EAC jet, the EAC eddy, and the EAC southern extension (Figs. 3g–i), respectively.

To examine the vertical distributions of the energy reservoirs, we calculate the profiles of energy reservoirs in the EAC jet, eddy, and southern extension from the surface to 1000 m. In the EAC jet, although there is a small bump within the pycnocline at around 150–200 m in EPE, all energy reservoirs decrease with depth (Fig. 4a). Compared to the kinetic energy, the available potential energy is larger in the surface but smaller in the deep layer. Above 286 m, EPE is the strongest term; however, below this depth, it is much smaller than the other terms. We find strong surface EPE within the upper 65 m, which is larger than MKE and EKE. As the mean flow dominates this region, we find stronger MKE than EKE in the top 325 m. However, EKE is larger than all the other terms below 325 m.

Eddies dominate the EAC eddy region, as shown in Fig. 4b, where EKE and EPE are much larger than MKE and MPE, implying that most energy is stored within the eddy field. Both MKE and EKE decrease with depth gradually, but MPE and EPE have two peaks: one located in the surface and the other at 230 m, which is similar to the vertical structures in the Kuroshio (Yan et al. 2019) and Gulf of Mexico (Maslo et al. 2020). Both MPE and EPE have a minimum at around 100 m. In the top 30 m, EPE is the largest, but EKE is much larger than the other terms below the 500 m.

In the EAC southern extension, MKE and EKE also decrease with depth gradually, with EKE larger than MKE over the whole profile (Fig. 4c). Among the four energy terms, MKE is the weakest above 700 m. MPE is larger than the other terms above 325 m. In the eddy field, EPE is larger than EKE above 56 m but is much smaller than EKE below this depth. We also find a minimum of EPE at around 100 m.

To illustrate the meridional distribution of energy terms through the water column, we show the vertical profile of the zonal-mean MKE, EKE, and EPE averaged between the 200 m isobath and 154.5°E along the EAC path (Fig. 5). In the EAC jet, MKE has two peaks within the upper 200 m (Fig. 5a). The first peak is between 25° and 26.5°S, and the second one is between 28° and 30.5°S. The surface MKE decreases as the EAC flows poleward, with a value less than 50 J m⁻³ south of 33°S. The strong MKE in the top layer is consistent with previous observations from a mooring array at 27°S from 2012 to 2013 (Sloyan et al. 2016).

The strongest EKE dominates the EAC eddy regions over the upper 325 m and extends through the EAC separation region from 32° to 37°S (Fig. 5b). North of 32°S, EKE becomes weaker in the EAC jet. Strong EPE is confined within a shallow layer (<75 m) along the whole EAC path (Fig. 5c). In addition, we also find strong EPE in the subsurface layer (155–325 m) in the EAC eddy, consistent with the double-peak structure of the area mean vertical EPE profile in this region in Fig. 4b.
b. Energy conversions

In this section, we examine the energy conversions among the four energy reservoirs. We first show spatial distributions of the depth-integrated energy conversion terms (\(K_{mK_e}\), \(P_{eK_e}\), \(NLKE\), \(NLPE\), \(P_{mK_m}\), and \(P_{mP_e}\)) over the upper 1000 m (Fig. 6). Along the EAC path, we find two strong, narrow, positive \(K_{mK_e}\) bands, with one located between 29.5° and 30.5°S and the other between 32° and 33.5°S (Fig. 6a). Positive \(K_{mK_e}\) indicates that eddies can drain kinetic energy from the mean flow to drive a shedding event, particularly in the EAC eddy. It is worth noting that we also find two small regions with negative \(K_{mK_e}\) values, implying an inverse energy cascade from EKE to MKE (Yan et al. 2019). The first is located north of 26°S, and the other between 27° and 28.5°S.

Regions of negative \(K_{mK_e}\) are regions of eddy decay (Gula et al. 2015), which indicates eddies return kinetic energy and momentum to the mean flow. In contrast, the energy conversion from EPE to EKE (\(P_{eK_e}\)) through baroclinic instability (Fig. 6b) is much weaker than that from MKE to EKE (\(K_{mK_e}\)) through barotropic instability, implying that the
barotropic instability is the main source of EKE in the EAC system. Negative PeKe can also be found in the EAC return flow region (154.5°–156°E, 33°–34°S), suggesting that eddies convert EKE to EPE around this region. These horizontal patterns of KmKe and PeKe are consistent with previous studies from higher-resolution-model simulations (Li et al. 2021, 2022b) that investigated extreme events.

The energy conversion from MPE to MKE (PmKm) is weak in the majority of the EAC system (Fig. 6c) except north of 26°S, but the energy conversion from MPE to EPE (PmPe) is strong along the EAC path (Fig. 6d), consistent with results from high-resolution global ocean models (von Storch et al. 2012; Chen et al. 2014). This indicates that most energy stored in MPE is converted to EPE instead of MKE. The strongest PmPe is between 29° and 35.5°S, where the baroclinic instability facilitates the available potential energy transfer from the mean flow to the eddy field. The spatial distribution of PmPe is also consistent with a previous study (Bull et al. 2017) and is linked to the baroclinic instability of the Tasman Sea (Sloyan and O’Kane 2015). As described in KC15, Magalhães et al. (2017) and Yan et al. (2019), there are two pathways for eddies to draw kinetic energy from the mean flow: MKE → EKE and MPE → EPE → EKE. The KmKe term directly transfers MKE to EKE through barotropic instability. PmPe and PeKe provide an indirect route of EKE conversion through baroclinic instability.

Through nonlocal eddy–mean flow interactions, there are two energy conversion pathways for the energy to be transferred from the eddy field to the mean flow: EKE → MKE and EPE → MPE. The NLKE term suggests that part of MKE converted from (to) local EKE is transported to (from) eddies in other regions (Yan et al. 2019). NLPE also represents the nonlocal eddy–mean flow interactions but for the available potential energy. As shown in a global modeling study (Chen et al. 2014), we also find negative NLKE along the EAC path from 24° to 36°S (Fig. 6e), indicating that nonlocal energy conversion from MKE to EKE. There also exists two positive-NLKE bands south of 32°S, where nonlocal eddy–mean flow interactions contribute to the energy conversion from EKE to MKE. The first narrow, positive NLKE band is located inshore of the negative NLKE band, and the second one is in the EAC return flow region. For the NLPE pattern, we only find strong nonlocal available potential energy conversion in the EAC upstream (north of 27°S) and the EAC eddy (Fig. 6f). Compared to BRAN2020, similar horizontal distributions of energy conversion terms are found in the free-running model OFAM2017 (Figs. 6g–l) but with smaller magnitude in most regions.

In the vertical, the kinetic energy conversions (KmKe and NLKE) between the mean flow and the eddy field (MKE ↔ EKE) keep the same horizontal structure with their strength decreasing from the surface to 500 m (Figs. 7a–c,m–o). PmKm also has similar spatial distribution with strong energy conversions north of 32°S, and its magnitude decreases with depth from 50 to 500 m (Figs. 7g–i). Although PeKe has a similar horizontal pattern at 50, 200, and 500 m, its strength peaks at 200 m (Figs. 7d–f).

The horizontal distributions of available potential energy conversions (PmPe and NLPE) between the mean flow and the eddy field (MPE ↔ EPE) vary with depths (Figs. 7j–l,p–r), which is also consistent with the results in the Gulf Stream (KC15) and Kuroshio (Yan et al. 2019). At 50 m, we can find positive PmPe along the EAC path, with a very narrow strip near the shelf in the EAC upstream (Fig. 7j). East of this narrow strip, large negative PmPe is observed between 24° and 32°S, implying that the eddies return available potential energy to the mean flow in this region. At 200 and 500 m, positive PmPe is confined within two narrow strips along the EAC.
path and the path of the EAC return flow (Figs. 7k–l). The strongest energy conversion from MPE to EPE through baroclinic instability can be found in the EAC eddy at 200 m. NLPE exhibits a positive–negative band structure between 24° and 33°S at 50 m, but positive NLPE dominates the region south of 33°S (Fig. 7p). However, at the depths of 200 and 500 m, we can only find strong NLPE in the EAC typical separation region, with positive values near the shelf and negative values in the EAC return flow (Figs. 7q,r).

To better understand the energy conversions in the three subdomains, we further examine the vertical structure of the six energy conversion terms in the upper 1000 m. In the EAC jet (Fig. 8a), the energy conversion occurs within the upper 600 m. KmKe and PeKe are positive through the whole profile, indicating the energy source of EKE through barotropic instability (MKE → EKE) and baroclinic instability (EPE → EKE; Fig. 8a). We can also find positive PmKm (MPE → MKE) within the upper 550 m, with a peak at 75 m. The PmPe shows the largest energy conversion from MPE to EPE between 125 and 255 m, with a maximum value of \( \sim 4 \times 10^{-4} \) W m\(^{-2}\). However, in the top 40 m, it is negative, indicating an inverse energy conversion from EPE to MPE. For the nonlocal eddy–mean flow energy conversion terms, negative NLKE in the upper 1000 m suggests an energy conversion of MKE → EKE through nonlocal eddy–mean flow interactions. In contrast, the strong negative NLPE only dominates the upper 150 m, with positive values below. This suggests that the available potential energy transfers from the mean flow to the eddy field in the upper layer (0–150 m) through nonlocal eddy–mean flow interactions, but there is an inverse energy conversion of EPE → MPE below 150 m due to nonlocal eddy–mean flow interactions.

In the EAC eddy (Fig. 8b), all the energy conversion terms are positive within the upper 550 m except NLKE, which is negative in the upper 150 m, implying that nonlocal eddy–mean flow interactions contribute to the energy conversion from MKE to EKE in this region. Compared to KmKe and PeKe in the EAC jet, these two terms are much stronger here. In addition, KmKe is about two times larger than PeKe in the upper 285 m, suggesting that barotropic instability is the main source of EKE in the EAC eddy region. This result is consistent with a previous study from a regional high-resolution (free running) simulation (Li et al. 2021). PmKm is the weakest energy conversion term over the whole profile, and strong positive PmPe dominates the energy conversion with a peak at 220 m. This

![Image](image-url)
suggests that the mean flow releases most available potential energy to the eddy field through baroclinic instability. Nonlocal eddy–mean flow interactions contribute to the inverse energy conversion of EPE → MPE, which decreases with depth and extends deeper to around 400 m.

Energy conversion terms in the EAC southern extension (Fig. 8c) are on average an order of magnitude smaller than in the other two regions. However, energy conversion related to EPE (PeKe, PmPe, and NLPE) dominates the EAC southern extension (Fig. 8c). Compared to KmKe, which is weakly...
positive and decreases with depth, PeKe is stronger over the whole profile, implying that (although weak) baroclinic instability is the main source of EKE in the EAC southern extension. Similar to that in the EAC eddy, PmKm is also very weak in the EAC southern extension, particularly in the top 150 m, suggesting no energy conversions between MPE and MKE. Most available potential energy is converted from mean flow to the eddy field, as shown in the dominant PmPe over the upper 600 m. Positive NLKE in the upper 400 m shows that eddies from other regions transfer EKE to MKE in the EAC southern extension. In contrast, most nonlocal inverse available potential energy conversion of EPE \( \rightarrow \) MPE is confined within the upper 140 m but with negative NLPE below this layer.

To further examine the vertical energy conversion structures along the EAC path, we zonally average the six energy conversion terms within the three regions shown in Fig. 2a. Strong positive KmKe is confined within the upper 400 m in the EAC jet and EAC eddy north of 36°S, except for two small negative KmKe regions in the EAC upstream (Fig. 9a). One is between 24.5° and 26°S and the other between 27° and 28.5°S. In contrast, PeKe is almost positive along the whole EAC path but with a much weaker magnitude (Fig. 9b). This further demonstrates that barotropic instability is the main source of EKE in the EAC jet and EAC eddy.

In the EAC jet, PmKm in the upper 400 m shows alternating positive–negative patterns north of 31°S (Fig. 9c). The available potential energy conversion (PmPe) of MPE \( \leftrightarrow \) EPE within the depth of 50–400 m exhibits positive values between 26° and 36°S (Fig. 9d), which is the strongest among all energy conversion terms. In the top surface layer (<50 m), however, we also find an inverse energy conversion from EPE to MPE north of 32°S (negative PmPe).

The energy conversion profiles of available potential energy and kinetic energy between the mean flow and the eddy field due to nonlocal eddy–mean flow interactions have different patterns along the EAC path. North of 34°S, strong negative NLKE dominates the upper 400 m (Fig. 9e). However, the NLKE in the upper 300 m is positive between 34° and 36°S. This suggests nonlocal eddy–mean flow interactions transfer EKE to MKE north of 34°S. However, south of 34°S, the energy conversion is from MKE to remote EKE through nonlocal eddy–mean flow interactions. In the EAC upstream, we can find strong negative NLPE in the upper 150 m north of 32°S (Fig. 9f), with weak positive values in the subsurface (150–400 m). In the EAC eddy, strong positive NLPE dominates the upper 400 m, implying an inverse available potential energy conversion of EPE \( \rightarrow \) MPE between 32° and 36°S.

We further examine four energy reservoirs and six energy conversion terms integrated over the upper 1000 m along the EAC path. In the EAC jet, the kinetic energy and available potential energy in the mean flow are much larger than those in the eddy field between 24° and 31°S, with MPE the largest among four energy reservoirs (Fig. 10a). In the EAC eddy and extension region, EKE and EPE are much larger than MKE and MPE, with EKE dominant between 32° and 38°S.

As shown in Fig. 10b, the depth-integrated energy conversion terms have similar meridional distributions to Fig. 9. KmKe is negative within the latitudes of 24.5°–26°S and 27°–28.5°S, but it is much larger than PeKe and is the main source of EKE between 29° and 35°S. PeKe is positive and weak along the EAC path, but it is larger than KmKe and contributes to the eddy growth south of 35°S. PmKm is positive in most latitudes, indicating energy conversion from available potential energy to kinetic energy in the mean flow. Among all the energy conversion terms, PmPe is positive and the largest...
in almost the whole EAC path. The energy conversion of kinetic energy due to nonlocal eddy–mean flow interactions is from MKE to EKE north of 34°S and from EKE to MKE between 34° and 36.5°S. Additionally, nonlocal eddy–mean flow interactions also contribute to the energy conversion of available potential energy from MPE to EPE north of 31.5°S and from EPE to MPE between 31.5° and 34.5°S.

c. Energy budget

In this section, we show the eddy–mean flow energy budgets by examining the volume-integrated energy reservoirs and energy conversion terms in three subdomains along the EAC path (Fig. 11). More energy is contained in available potential energy than kinetic energy in the EAC jet (Fig. 11b). The largest energy reservoir is MPE (6.06 PJ), followed by EPE (2.68 PJ), MKE (2.42 PJ), and EKE (2.28 PJ), respectively. The ratio of MKE to MPE is 40% in the mean flow, but EKE and EPE are comparable in the eddy field with a ratio of 85% (EKE/EPE). The energy conversion rate of EKE through barotropic instability (MKE → EKE) is 1.31 GW. The baroclinic instability provides another indirect energy conversion pathway for EKE: MPE → EPE → EKE. Although the energy conversion rate from MPE to EPE is large (7.03 GW), eddies release less energy from available potential energy to kinetic energy with a transfer rate of 1.17 GW from EPE to EKE, which is smaller than that from MKE to EKE. The ratio of baroclinic to barotropic contribution to EKE production (PeKe/KmKe) is 89% in this region. As the leading energy reservoir, MPE is the energy source, which also transfers energy to MKE with a rate of 1.27 GW and to EPE in other
regions with a rate of 0.81 GW. The mean flow also transfers MKE to EKE in the other regions with a rate of 2.41 GW through nonlocal eddy–mean flow interactions.

In the EAC eddy (Fig. 11c), the eddy fields contain much larger kinetic energy and available potential energy than the mean flow. The ratio of MKE to EKE and MPE to EPE are only 13% and 20%, respectively. EKE (8.58 PJ) is much larger than EPE (6.78 PJ), MPE (1.36 PJ), and MKE (1.09 PJ). The ratio of PeKe to KmKe is 64%, implying that barotropic instability dominates the EKE production in this region, with an energy conversion rate of 5.22 GW from MKE to EKE. Similar to that in the EAC jet, the baroclinic conversion of MPE → EPE → EKE also contributes to EKE production. However, the energy gain rate of EKE from EPE (3.33 GW) is only about one-third of that from MPE to EPE (11.08 GW). The mean flow can release part of its available potential energy to the kinetic energy with an MPE → MKE conversion rate of 0.32 GW. Nonlocal eddy–mean flow interactions convert a small amount (0.08 GW) of MKE to EKE in other regions but contribute to the inverse energy conversion of EPE → MPE with a rate of 1.90 GW.

The energy reservoir in the eddy field is also very large in the EAC southern extension (Fig. 11d). EKE (9.58 PJ) is the leading energy reservoir, followed by MPE (8.90 PJ), EPE (6.69 PJ), and MKE (0.53 PJ). The ratio of MKE to EKE drops to 6%, but the ratio of MPE to EPE increases up to 133%. The energy conversion rate of MKE → EKE through barotropic instability decreases dramatically to 0.25 GW. In contrast, the energy conversion rate of EPE → EKE grows to 2.91 GW, implying that baroclinic instability dominates EKE production in the EAC southern extension. Compared to the EAC jet and EAC eddy, the MPE → EPE conversion rate of 3.14 GW is relatively smaller. Similarly, the energy conversion rate of MPE → MKE is also small, with a value of 0.21 GW. Nonlocal eddy–mean flow interactions provide inverse energy conversion pathways of EKE → MKE and EPE → MPE, with conversion rates of 0.47 and 0.26 GW, respectively.

d. Synthesis

In the horizontal, strong MKE is confined within a narrow band between 24.5° and 32.5°S in the main core of the EAC, while high EKE and EPE dominate the EAC eddy and EAC southern extension. We show that eddies drain energy from the mean flow to grow through two pathways: MKE → EKE and MPE → EPE → EKE. Strong barotropic instability dominates EKE production in the EAC jet and EAC eddy north of 36°S, while baroclinic instability dominates EKE production in the EAC southern extension. Negative KmKe is also found in two small regions (24.5°–26°S and 27°–28.5°S), implying inverse energy conversion of kinetic energy from the eddy field to the mean flow. PmPe is the largest among the six energy conversion terms, indicating strong energy conversion from MPE to EPE through baroclinic instability between 29° and 35.5°S. Nonlocal eddy–mean flow interactions also play a role in the energy conversion between the mean flow and the eddy fields. NLKE exhibits negative values along the EAC path from 24° to 36°S, indicating the energy conversion from MKE to EKE in other regions. Positive NLKE is also found within two narrow bands south of 32°S in the inshore of the negative NLKE band and the EAC return-flow regions. The strong nonlocal available potential energy conversion is confined within the EAC upstream (north of 27°S) and the EAC eddy.
In the vertical, the energy is mainly stored in the upper 500 m. MKE and EKE keep the same horizontal structures with their strength decreasing dramatically with depth. However, the strongest EPE is confined within the upper 75 m along the whole EAC path, with another peak in the subsurface layer (155–325 m) in the EAC eddy. Overall, the horizontal distributions of the kinetic energy conversions $\text{MKE} \leftrightarrow \text{EKE}$ ($K\text{mKe}$ and $\text{NLKE}$) and $\text{MPE} \leftrightarrow \text{MKE}$ ($P\text{mKm}$) have similar patterns over the whole water column, but their magnitudes decrease with depth. Strong positive $P\text{mKm}$ is confined within the top 300 m north of 32°S. The energy conversion of $\text{EPE} \leftrightarrow \text{EKE}$ ($P\text{eKe}$) also has a uniform horizontal structure but peaks in the subsurface layer, particularly between 100 and 300 m in the EAC southern extension. The horizontal structures of available potential energy conversions ($P\text{mPe}$ and $\text{NLPE}$) between the mean flow and the eddy field (MPE ↔ NLPE) vary with depths in the EAC jet. Negative $P\text{mPe}$ and $\text{NLPE}$ dominate the surface 50- and 150-m-layer north of 32°S, respectively. Below the negative surface $P\text{mPe}$ and $\text{NLPE}$, strong positive values extend deeper to 400 m. $P\text{mPe}$ is the strongest below 50 m among the six energy conversion terms, which peaks at around 217 m in the EAC jet and EAC eddy but decreases with depth in the EAC southern extension.

Regions with large energy reservoirs correspond to strong energy conversions from the mean flow to the eddy field. In the horizontal, EKE and EPE in the EAC eddy are much stronger than the other regions (Figs. 2, 3), with strong kinetic energy conversion ($K\text{mKe}$) and potential energy conversion ($P\text{mPe}$) from the mean flow to the eddy field in this region (Figs. 6, 7). In the vertical, EKE is constrained within the upper 450 m (Fig. 5b), where $K\text{mKe}$ is also stronger than the lower layers (Fig. 9a), and EPE peaks in the subsurface layer (155–325 m) within the strong $P\text{mPe}$ depth of 50–400 m (Fig. 9d).

For the volume-integrated energy reservoir and energy conversions, the energy is mainly stored in available potential energy instead of kinetic energy in the EAC jet. The ratio of MKE/MPE and EKE/EPE is 40% and 85%, respectively. The energy conversion rate of MKE $\leftrightarrow$ EKE through barotropic instability is 1.31 GW, which is larger than the baroclinic instability conversion (EPE $\leftrightarrow$ EKE) of 1.17 GW. In the EAC eddy, most energy is contained in the eddy fields instead of the mean flow. The ratio of MKE/EKE and MPE/EPE is

![Schematics of the volume-integrated eddy–mean flow energy budget in the upper 1000-m layer over the three subdomains indicated in Fig. 2a. Energy reservoirs are in units of petajoules (PJ = 10^15 J) and energy-conversion terms are in units of gigawatts (GW = 10^9 W). (a) The definition of each term. Arrows represent the corresponding energy transfer direction.](image-url)
13% and 20%, respectively. The barotropic instability dominates the EKE production, with an energy conversion rate of 5.22 GW from MKE to EKE. Similarly, the energy reservoir in the eddy field is also very large in the EAC southern extension, with EKE the leading energy reservoir (9.58 PJ). The ratio of MKE to EKE drops to 6%, and the energy conversion rate of MKE → EKE decreases to 0.25 GW. In contrast, baroclinic instability is the primary source of EKE, with an energy conversion rate of 2.91 GW from EPE to EKE. The energy conversion between kinetic energy and available potential energy in the EAC system has similar magnitudes with that in the Kuroshio and Ryukyu Current regions (Yan et al. 2019, 2022).

5. Discussion

This study is the first to systematically investigate the detailed spatial structure of the eddy–mean flow interactions and energy budget along the EAC path on the basis of an eddy-resolving long-term (1998–2021) model simulation. Following the existing theoretical framework (KC15; Chen et al. 2014), we examined the three-dimensional structures of four energy reservoirs (MKE, EKE, MPE, and EPE) and six energy conversion terms (KmKe, PeKe, PmKm, PmPe, NLKE, and NLPE). Then, we present the characteristics of the eddy–mean flow energy distributions and conversions within three chosen subdomains (EAC jet, EAC eddy, and EAC southern extension). We find that both local and nonlocal eddy–mean flow interactions exist in the EAC system, with inhomogeneous horizontal distributions.

While we have presented the first systematic eddy–mean flow study in the EAC, our results are in broad agreement with previous studies in the other WBCs. The energy reservoirs and conversion rates have complex horizontal and vertical structures, but with the same order of magnitude as those in the Gulf Stream (KC15), Kuroshio, and Ryukyu Current (Yan et al. 2019). For example, the barotropic conversion is the main source of EKE in the EAC jet and EAC eddy, whereas baroclinic conversion dominates EKE production in the EAC southern extension. The double-peak structure in the EPE profile has also been shown in the Kuroshio and Ryukyu Current regions (Yan et al. 2019) as well as the Gulf of Mexico (Maslo et al. 2020). We note our methodology is potentially more robust than that used in the Brazil Current, where the density is assumed to be a function of the temperature only (Magalhães et al. 2017; Brum et al. 2017). It is known that the EAC is weaker but more eddying, with a high ratio of EKE/MKE east of the main jet. The high EKE in the EAC system is comparable with that in the other WBCs; further study is needed to investigate EKE variability in five major WBCs in the global ocean.

Our results, using a 0.1° × 0.1° model BRAN2020, show spatial distributions of kinetic energy components (MKE and EKE). The spatial distribution of MKE is also consistent with satellite observations in Figs. 1a and 1b, which is a better representation than that of the lower-resolution climate model used by Bull et al. (2020), implying that eddy-resolving resolution (0.1°) is needed to represent the EAC well. Additionally, our identified EKE sources (KmKe and PeKe) are mainly in agreement with results from a high-resolution regional-modeling study (Li et al. 2021, 2022b) that looked at extreme events. Compared with previous results obtained from coarser-horizontal-resolution studies (Bowen et al. 2005; Mata et al. 2006; Bull et al. 2017), our eddy-resolving model simulation provides a more realistic representation of the EAC and associated mesoscale processes, allowing us to better understand the eddy–mean flow interactions in the EAC. We suggest that eddy-resolving resolution (<10 km) is required to better represent mesoscale variability in the WBCs and improve our understanding of eddy–mean flow interactions.

In this study, we chose to use the data-assimilating model BRAN2020, as our validation showed that it did a good job of representing MKE and EKE variability in the system. Although the model fields in BRAN2020 are more realistic than OFAM2017 (a free-running model) due to assimilation of surface data, we acknowledge that it also has some limitations. For example, because of the possible uncertainties introduced by assimilating observations, momentum or mass is not conserved. However, the comparisons between BRAN2020 and OFAM2017 show that the spatial distributions of energy reservoirs and energy conversion terms are similar (e.g., Fig. 2). This gives us confidence that assimilating observations in BRAN2020 may have less impact on the results in this study. We also recognize that data-assimilating models have been used for similar studies previously, e.g., Yang and Liang (2018, 2019). Additionally, spatial averaging within our three key dynamic regions has the disadvantage that the size of each box influences the magnitude of the values averaged within the box. However, within each box, the relative relationships between terms hold true. This issue is not unique to our study, and normalizing by box size has not been done in other studies (e.g., KC15; Yan et al. 2019).

Our study extends our knowledge of the three-dimensional structures of energy reservoirs and energy conversions in the EAC region and refines the results of recent studies on the eddy–mean flow interactions in the WBCs. Consistent with regional-model simulations (Li et al. 2021, 2022b), we demonstrate that barotropic instability is the primary source of EKE in the EAC jet and EAC eddy, but baroclinic instability dominates EKE production in the EAC southern extension. However, the results presented here only show the climatological characteristics of the eddy–mean flow interactions. To investigate the interactions between individual mesoscale eddies and the WBCs, such as eddy shedding (Marchesiello and Middleton 2000; Mata et al. 2006; Macdonald et al. 2016; Bull et al. 2017) or the impinging of mesoscale eddies on the WBCs (Li et al. 2020; Yan et al. 2022), we need a time-dependent eddy–mean energy framework. Chen et al. (2016) introduced a time-dependent energy diagram for eddy–mean flow interactions, which has been used to investigate the interactions between westward-propagating mesoscale eddies and the Kuroshio by Yan et al. (2022) and will provide insights into eddy shedding and interactions in future EAC studies.

As suggested by Zhai et al. (2010), the western boundary acts as a “graveyard” for the westward-propagating mesoscale
eddy and provides a significant ocean eddy energy sink in the global ocean. Over most of the EAC system, roughly 88% of mesoscale eddies propagate westward (Pilo et al. 2015). In the EAC upstream, it has been shown that a cyclonic–anticyclonic eddy pair propagated westward to reach and remerge with the EAC between 24° and 28°S (Li et al. 2020). Future work could examine the individual eddy shedding and the interaction between individual westward-propagating mesoscale eddies and the EAC based on an energy analysis framework used in Yan et al. (2022).

Oceanic kinetic energy is dominated by the geostrophic eddy field (Ferrari and Wunsch 2009), and WBCs are hotspots of mesoscale eddies (Martinez-Moreno et al. 2021) and global warming (Wu et al. 2012). In a warming climate, WBCs are shifting poleward (Yang et al. 2016, 2020) and transporting more mass and warm water into the high-latitude regions. This will increase the barotropic and baroclinic instability in the WBC extensions, resulting in increased eddy shedding and ocean warming, as shown in the EAC southern extension (Li et al. 2022b). Eddy-rich regions are showing a significant increase in mesoscale variability during the past decades (Martinez-Moreno et al. 2021). Investigating the trends of EKE sources from barotropic (KmKe) and baroclinic (PeKe) instability is crucial for understanding the dynamics of increasing EKE and ocean warming in the WBC extensions. This present work lays the foundation for us to now investigate the variability and trends in the WBCs as per Li et al. (2022a).

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