Strong Eddy Kinetic Energy Anomalies Induced by Baroclinic Instability in the Southwest Region of the Kerguelen Plateau, East Antarctic

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Abstract

Eddy activities are particularly prominent in the Southern Ocean due to the instabilities of the Antarctic Circumpolar Current (ACC), which plays a critical role in energy transport of the global ocean. The Indian sector of the Southern Ocean is not only a typical eddy-rich region with strong Eddy Kinetic Energy (EKE) and associated energy conversions among different energy reservoirs (kinetic energy and potential energy of the eddy and mean flow), but also events of extreme EKE. In this study, a systematic energetics analysis framework is employed to examine the notable anomalies of an intensified EKE event observed in the southwest region of the Kerguelen Plateau in 2017 based on a reanalysis product. The EKE anomaly existing at all depths emerges in April, reaches its peak during the austral winter, and persists into the following summer. Energetics analysis indicates that the strong anomalous EKE is primarily determined by baroclinic instability, with distinct governing mechanisms at the surface and in the internal ocean. The anomalous intrusion of warm Circumpolar Deep Water intensifies the baroclinic energy conversion in the subsurface, which contributes to the observed EKE anomalies. Moreover, the anomalous strong wind-induced Ekman pumping serves to amplify the lifting of isopycnals, which enhances the baroclinic instability and subsequently intensifies the EKE anomalies. This study sheds new light on underlying mechanisms governing local polar dynamics and provides insights into the intricate interaction between ocean dynamics and energy distribution in the Antarctic.

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Key Points

• The subpolar region to the southwest of the Kerguelen Plateau is characterized by anomalous strong Eddy Kinetic Energy (EKE) in 2017.

• The strong regional anomalies in EKE can be primarily attributed to baroclinic instability, with inverse barotropic energy conversion.

• Baroclinic instability is mainly caused by anomalous intrusion of Circumpolar Deep Water, particularly at depths between 500-2000 meters.
Abstract

Eddy activities are particularly prominent in the Southern Ocean due to the instabilities of the Antarctic Circumpolar Current (ACC), which plays a critical role in energy transport of the global ocean. The Indian sector of the Southern Ocean is not only a typical eddy-rich region with strong Eddy Kinetic Energy (EKE) and associated energy conversions among different energy reservoirs (kinetic energy and potential energy of the eddy and mean flow), but also events of extreme EKE. In this study, a systematic energetics analysis framework is employed to examine the notable anomalies of an intensified EKE event observed in the southwest region of the Kerguelen Plateau in 2017 based on a reanalysis product. The EKE anomaly existing at all depths emerges in April, reaches its peak during the austral winter, and persists into the following summer. Energetics analysis indicates that the strong anomalous EKE is primarily determined by baroclinic instability, with distinct governing mechanisms at the surface and in the internal ocean. The anomalous intrusion of warm Circumpolar Deep Water intensifies the baroclinic energy conversion in the subsurface, which contributes to the observed EKE anomalies. Moreover, the anomalous strong wind-induced Ekman pumping serves to amplify the lifting of isopycnals, which enhances the baroclinic instability and subsequently intensifies the EKE anomalies. This study sheds new light on underlying mechanisms governing local polar dynamics and provides insights into the intricate interaction between ocean dynamics and energy distribution in the Antarctic.
Plain Language Summary

The Indian sector of the Southern Ocean is a region known for its spatiotemporal variability often referred to as jets and eddies. Eddy Kinetic Energy (EKE) is widely used to measure the kinetic energy as the difference between the total kinetic energy and the kinetic energy of mean currents. This study finds an anomalous event of significant increases in EKE in the southwest region of the Kerguelen Plateau in the Southern Ocean in 2017. We apply a systematic energetics analysis framework to a reanalysis product to investigate the processes responsible for the observed anomalous event. The results suggest that the main cause for the event was the anomalous intrusion of warm water masses in the upper and deeper ocean layers, which led to the increases in density gradients and then intensified the energy conversion from available potential energy to EKE. Moreover, the change in wind pattern has an impact on the variations of EKE in the upper ocean. This study provides a better understanding of energy conversions and underlying mechanisms for EKE in polar regimes.

Keywords

Eddy Kinetic Energy; Baroclinic Instability; Circumpolar Deep Water; Antarctic Circumpolar Current; Polar Dynamics
1. Introduction

The Southern Ocean is a critical region for the oceanic uptake of carbon and heat. It exhibits substantial ocean-atmosphere momentum exchanges and is a typical region with eddy-mean flow interaction [Morrow et al., 1994; Orsi et al., 1995; Chen et al., 2014; Rintoul, 2018]. In the Southern Ocean, high levels of eddy activities are associated with the jets and fronts of the Antarctic Circumpolar Current (ACC) [Thompson, 2008; Frenger et al., 2015], which is a dominant eastward-flowing large-scale circumpolar current [Sokolov and Rintoul, 2009]. Several significant ocean fronts that align with the axes of ACC jets actively interact with topographic features and mesoscale eddies. The circumpolar eddy dynamics and variability have a profound impact on global air-sea interactions and thermohaline circulation [Gille, 1994; Hughes and Ash, 2001; Thompson, 2008; Fu et al., 2010; Hogg et al., 2015; Rintoul, 2018; Hogg et al., 2022].

The Indian sector of the Southern Ocean is a typical eddy-rich region with various energy and mass transport [Sparrow et al., 1996; Shi et al., 2002]. The Kerguelen Plateau (KP), located in the middle of the Indian sector, is one of the most prominent topographic features around the polar current region, exerting a substantial influence on the ACC [Webb, 1993; Morrow et al., 1994; Bestley et al., 2020]. In the southwest of the KP, the ACC extends meridionally from the northwest, reaching its southernmost point of 65°S (Figure 1). A cyclonic sub-polar gyre, the Prydz Bay Gyre (PBG), was detected near the Southern Boundary (SB) of the ACC between 60° and 80°E [Smith et al., 1984; Nunes Vaz and Lennon, 1996; Heywood et al., 1999]. It is located to the west of the Princess Elizabeth Trough (PET), a topographic gap between the KP and the Antarctic continent [Orsi et al., 1995; Heywood et al., 1999]. The interaction of currents and gyres in this region gives rise to multiscale eddies, which play a crucial role in energy and momentum transport in the circumpolar region. These multiscale disturbances have significant impacts on the local...
ecosystem, highlighting the importance of understanding their dynamics and interactions with surrounding flows [Swadling et al., 2010; Williams et al., 2010; Mou et al., 2021].

The Southern Antarctic Circumpolar Current Front (SACCF) and the SB pass through the southern KP. It was suggested that the SACCF is steered by the topography of the KP, causing a horizontal shear between the eastward ACC and westward-flowing Antarctic Slope Current (ASC) [Meijers et al., 2010]. Additionally, it is an important upwelling region associated with the atmospheric Antarctic Divergence (AD) in the south of the ACC, which is a meteorological zone mirrored in the ocean properties between the northward and southward Ekman transports due to the westerlies and easterlies [e.g., Foldvik and Gammelsrod, 1988]. The upwelling induced by Ekman transports draws warm Circumpolar Deep Water (CDW) into the surface waters. Characterized as a salty, warm water mass in the Southern Ocean, CDW is forced across the shelf break into Prydz Bay, where it plays a crucial role in mixing processes at the continental margin [Whitworth III et al., 1985; Williams et al., 2016; Liu et al., 2017; Thompson et al., 2018]. Eddies and turbulence actively facilitate mixing along and across isopycnals in this region [Wakatsuchi et al., 1994; Rintoul, 2018].
Figure 1. Schematic of bathymetry with major topography features and main currents in the Indian sector of the Southern Ocean (colored part in the inset), East Antarctica. The light grey lines indicate the isobath of 2000 m from the ETOPO1 bathymetry dataset. The historical position of the Southern Boundary (SB, white dashed line) of the ACC, Southern Antarctic Circumpolar Current Front (SACCF, white dot-dashed line), Polar Front (PF, green solid line), and Subantarctic Front (SAF, white solid line) from Orsi et al. [1995] is as shown. The schematic of the Antarctic Slope Current (ASC, yellow solid line) from Orsi et al. [1995] and the Prydz Bay Gyre (PBG) region (dark blue dashed line) from Heywood et al. [1999] are shown. The gap in the topography between the Kerguelen Plateau and the Antarctic continent (85°E, 63°-66°S) is the Princess Elizabeth Trough [Heywood et al., 1999]. The study region is indicated by the light green box in the figure.

Eddy Kinetic Energy (EKE) is widely utilized as a crucial component of the kinetic energy associated with eddies, encompassing all transient motions [Martinez-Moreno et al., 2019]. In the Southern Ocean, EKE produces a strongly heterogeneous distribution influenced by the interplay between wind forcing, topography, and mean flow [Morrow et al., 2010]. Previous studies have proposed a substantial increase in EKE within the Southern Ocean in recent decades [Hogg et al., 2015; Martinez-Moreno et al., 2019; Martinez-Moreno et al., 2022], while a recent analysis of EKE trends in smaller regions in the Southern Ocean
suggested that the changes in EKE are not uniformly distributed as previously implied, and
significant EKE increase only downstream of the Campbell Plateau [Hogg et al., 2015; Zhang et al., 2021]. Numerous studies have focused on analyzing EKE to comprehend large-scale
physical processes in the ACC region [Hughes and Ash, 2001; Meredith and Hogg, 2006; Trani et al., 2014; Hogg et al., 2022]. Most of these investigations have concentrated on
downstream of large topographic barriers characterized by significant EKE, particularly in
the KP area, based on satellite observations or numerical modeling [Morrow et al., 1994; Morrow et al., 2010; Trani et al., 2014; Rosso et al., 2015; Zhang et al., 2021; Cai et al., 2022; Shi et al., 2023]. The interactions between the ACC and subpolar gyres under the wind
impact in different high-latitude regions have received significant attention due to their
impacts on biological diversity and productivity in recent years. A quantitative assessment of
the energy budget focused on the lee of significant topographic features in a realistic model
was performed and the relative importance of localized energy conversion compared to the
energy conversion across the entire ACC region was estimated [Matsuta and Masumoto, 2023]. The results demonstrated that the westerlies can locally supply sufficient energy to
initiate baroclinic instability in the Indian and Pacific sectors of the ACC. In the central
Pacific sector, the interannual variation of EKE in the upper ocean layer has revealed that
wind stress impacts the variation through both baroclinic and barotropic pathways [Fu et al., 2023]. However, the Indian sector remains poorly explored.

A significant event of strong EKE that occurred in 2017 was observed in the confluence
of SACCF and PBG region during the austral winter in the present study. Previous studies
have concentrated on the anomalies in 2016-2017 in the Antarctic. Antarctic sea ice extent
has been suggested to decline dramatically from September 2016, culminating in a record low
by December in the austral summer, and coincided with anomalously warm surface waters
surrounding most of Antarctica [Stuecker et al., 2017; Turner et al., 2017; Meehl et al., 2019;
The rapid decrease of sea ice extent was attributed to sustained ocean hydrographic changes and easterly wind anomalies. The anomalous warming in the southern Indian Ocean was observed accompanied by pronounced low chlorophyll levels in Prydz Bay [Meehl et al., 2019; Sabu et al., 2021]. Notably, the EKE anomaly occurred following this regional warming. Analyzing the hydrography and dynamical processes during this specific period could provide insights into underlying mechanisms and potential connections with climate variability and oceanic changes. The reanalysis products of GLORYS12V1 data and ERA5 data were employed to examine the regional patterns of EKE in all ocean layers from the perspective of energetics analysis and to explore the causes of the anomalous event.

2. Data and Methods

The reanalysis data acquired from the Global Ocean Reanalysis and Simulation (GLORYS12V1) product were used to investigate the time-varying energetics in this study, limited by the scarcity of in-situ observation. This product is the Copernicus Marine Environment Monitoring Service (CMEMS) global ocean eddy-resolving (1/12° horizontal resolution, 50 vertical levels) reanalysis covering the altimetry (1993 onward), which has been used to analyze energetics in the Southern Ocean [Fu et al., 2023]. Utilized monthly and daily variables include sea surface height, current velocity, potential temperature, and practical salinity in all vertical levels, from 1993 to 2020.

To evaluate the performance of the reanalysis data in the study region, we compared the climatology and yearly averaged geostrophic Eddy Kinetic Energy ($EKE_g$) from satellite altimetry observations with the reanalysis result. The daily sea surface height (SSH) product with 0.25° × 0.25° spatial resolution during 1993-2020 was utilized to investigate $EKE_g$. The
gridded Level-4 product from CMEMS were constructed by merging TOPEX/Poseidon, Jason-1/2, ERS-1/2, GFO, CryoSat-2, HY-2A, Altika, and ENVISAT mission data. Monthly mean wind data were obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 reanalysis fields for the period 1993-2020. They were used to understand the possible mechanisms influencing circulation patterns and eddy activities. The spatial resolution is 0.25° × 0.25°.

The wind stress is derived from

\[ \boldsymbol{\tau} = \rho_a C_D |\boldsymbol{V}_w| \boldsymbol{V}_w, \]

where \( \boldsymbol{\tau} \) is the vector wind stress, \( \rho_a \) is the density of air approximately equal to 1.22 kg m\(^{-3}\), \( C_D \) is the drag coefficient of wind on seawater approximately equal to 1.5×10\(^{-3}\), and \( \boldsymbol{V}_w \) is vector wind velocity in m s\(^{-1}\).

The Ekman transport divergence is given by

\[ \nabla \cdot U_E = \partial / \partial x (\tau^{(y)}/(\rho f)) - \partial / \partial y (\tau^{(x)}/(\rho f)) = k \cdot \nabla \times (\boldsymbol{\tau}/\rho f), \]

where \( U_E \) is the vector Ekman transport, \( f \) is the Coriolis constant, \( \tau^{(x)} \) and \( \tau^{(y)} \) are x- and y-components of wind stress, respectively, \( k \) is the unit vector in the vertical direction, and \( \nabla \) is the gradient operator. Therefore, in the Southern Hemisphere (\( f < 0 \)), upwelling into the Ekman layer results from negative wind stress curl, and downwelling results from positive wind stress curl. Upwelling is sometimes referred to as Ekman suction.

Energetics analysis has been commonly used to reveal regional dynamic mechanisms. It’s an effective approach to investigating the variability of a current system [e.g., Lorenz, 1955; Ivchenko et al., 1997; von Storch et al., 2012; Chen et al., 2014; Rieck et al., 2015; Kang et al., 2016; Dong and Zhou, 2022]. In this study, we employ the energetics analysis framework
developed by Kang and Curchitser [2015] to explore the possible mechanism of an anomalous EKE event within the study area.

Following Kang and Curchitser [2015], for a given time-mean state $T_0$, the velocity $u = (u, v)$ is decomposed into its time-mean $\bar{u}$ and time-varying $u'$ parts, where $\bar{()}$ and $(')$ represent the time mean and deviation of a variable, respectively. The total density can be expressed as follows:

$$\rho(x, y, z, t) = \rho_r(z) + \rho_a(x, y, z, t),$$  

where the reference density $\rho_r$ is the time-mean and spatial-mean density, which is a constant at a given depth $z$. The perturbation density $\rho_a$ is the difference between the density and reference value. The value $\rho_0 = 1000 \text{ kg m}^{-3}$ is the constant part of $\rho_r$.

A comparison of selections of the buoyancy frequency $N$ is conducted. The sensitivity test of reference stratification on energetics analysis indicated that the regional constant $N$ at a given depth emphasizes the coastal impacts. Thus, $N$ is defined by

$$N^2 \equiv -\frac{g}{\rho_0} \frac{d\rho_r}{dz}.$$  

The Mean Kinetic Energy (MKE), Eddy Kinetic Energy (EKE), Mean Potential Energy (MPE), and Eddy Potential Energy (EPE) are given respectively,

$$\text{MKE} = \frac{1}{2} (\bar{u}^2 + \bar{v}^2),$$  

$$\text{EKE} = \frac{1}{2} (u'^2 + v'^2),$$  

$$\text{MPE} = \frac{g^2 \rho_a^2}{2 \rho_0^2 N^2},$$  

$$\text{EPE} = \frac{g^2 \rho_a^2}{2 \rho_0^2 N^2}.$$
where \( \bar{u} \) and \( \bar{v} \) are the means of zonal and meridional velocity components, \( u' \) and \( v' \) are the anomalies of zonal and meridional velocity components, and \( g \) is the gravity constant. To unify the computation, all these energy terms are divided by the density \( \rho_0 \), thus the units of them are \( m^2s^{-2} \) (hereafter expressed as \( \text{cm}^2s^{-2} \)). Kang and Curchitser [2017] evaluated different decompositions of KE, and demonstrated that only with an orthogonal decomposition the physically consistent MKE and EKE could represent the KEs of the mean flow and eddies precisely. Hence, we choose the time-mean state \( T_0 = 1 \) month in this study in order to examine the seasonal variability of the energy terms. With such definitions, the MKE and EKE represent the monthly averaged KEs of the mean flow (monthly mean flow) and eddies (monthly varying flow), respectively. Physically, they measure the contributions of the actual perturbations that persist longer and shorter than a month, respectively.

The energy conversions between the mean flow and eddies are mainly due to the barotropic instability (i.e., barotropic conversion term, hereafter BT term) and baroclinic instability (i.e., baroclinic conversion term, hereafter BC term and CE term) following Kang and Curchitser [2015]. The conversions can be quantitatively evaluated as follow:

\[
\text{MPE} \rightarrow \text{EPE}: \quad \text{BC} = -\frac{g^2}{\rho_0^2 \bar{N}^2} \bar{\rho}_a' \bar{u}' \cdot \nabla \bar{\rho}_a,
\]

\[
\text{EPE} \rightarrow \text{EKE}: \quad \text{CE} = -\frac{g}{\rho_0} \bar{\rho}_a' \bar{w}',
\]

\[
\text{MKE} \rightarrow \text{EKE}: \quad \text{BT} = -[u'u' \cdot \nabla \bar{u} + v'v' \cdot \nabla \bar{v}],
\]

where \( w \) is the vertical velocity calculated by the continuity equation based on horizontal velocity \( u \) and \( v \). \( \bar{w} \) and \( w' \) are time-mean and time-varying parts of \( w \). The EKE generation attributes to barotropic and baroclinic instabilities, represented by the conversion terms BT and CE, respectively.
To utilize GLORYS12V1 reanalysis data in the study, data validation is performed before the analysis. The geostrophic eddy kinetic energy ($EKE_g$) can be derived from sea surface height (SSH) anomalies [Qiu et al., 2018], which are used based on satellite altimetry data:

$$EKE_g = \frac{1}{2} \left[ \left( \frac{g \partial \eta'}{f \partial y} \right)^2 + \left( \frac{g \partial \eta'}{f \partial x} \right)^2 \right],$$

(12)

where $g$ is gravitational acceleration, $f$ is the Coriolis parameter, and $\eta'$ is the SSH anomalies from the monthly mean.

The time series and spatial patterns of time-mean surface $EKE_g$ are shown in Figure 2. The satellite observation cannot measure sea level beneath sea ice at all, so the time series is the EKE averaged among the area north of south latitude of 65 degrees. The spatially averaged results (Figure 2a) based on satellite altimeter data and reanalysis data exhibit consistent changes with a significant correlation coefficient of 0.95. The spatial distributions also show similar patterns and close magnitudes (Figures 2b and 2c), with relatively high values in the windward of the KP, and the south where the ACC flow through the PET. The results confirm the reliability of the reanalysis data. Moreover, the $EKE_g$ is weak in the coastal area due to the lack of satellite observation, which is unrealistic, and satellite data cannot provide information in the vertical water column. The reanalysis data we used has a more comprehensive imprint for the kinetic energy field of the whole region. Besides, the reanalysis product has a higher spatial resolution to depict the characteristics of eddies.
244
245 Figure 2. (a) Time series of the yearly area-mean $EKE_g$ (40°-80°E, 52°-65°S), (b) spatial distribution of climatology derived from satellite altimeter data and (c) reanalysis data (cm$^2$s$^{-2}$).

246
247 To describe the ocean dynamics, water mass definition is necessary to analyze the intrusion of warm water. Following Meijers et al. [2010] and Guo et al. [2022], the Circumpolar Deep Water with neutral density variable $\gamma_n$ (kg m$^{-3}$) is defined in the thresholds of $28.03 < \gamma_n < 28.27$. The neutral density is calculated from potential temperature and practical salinity. Its anomaly is the difference between monthly neutral density in 2017 compared to the multiyear average between 2010-2020 with the results in 2017 removed in averaging.
3. Results

The sequence of area-mean EKE for 1993-2020 reveals notable interannual variations (Figure 2). It peaks in 2004 and 2017, with the latter year exhibiting a particularly pronounced increase, and indicates an elevated level of variation starting from 2013. The variation is presumed to be influenced by the westerlies and large-scale atmospheric patterns. Notably, the EKE in 2017 reached its peak within the two-decade period. The spatial distribution reveals a prominent pattern in the southwest region of the KP. Annual cycles of surface kinetic energy (MKE and EKE) based on reanalysis data are illustrated in Figure 3. EKE shows less seasonal variation with relatively high values in austral autumn, while MKE is strong in summer. Spring, summer, autumn, and winter used in this study refer to seasons in the southern hemisphere (e.g., the austral summer is December, January, and February). The horizontal distribution of climatology of EKE (Figure 3c) is strongly constrained by regional topography on a large scale. The high values focus on the downstream of plateaus, such as the KP and Crozet islands, and they decrease as the ACC is seasonally weaker in summer.

The seasonal cycles of MKE and EKE suggest distinct anomalies between 2017 and climatology (Figures 3a and 3b). The annual cycle of MKE peaks in March, and is relatively weak in autumn and winter, while in 2017 it increased consistently until August. The annual cycle of EKE is strong in austral autumn Abnormally, the EKE in 2017 is much higher than in other years. It is significantly anomalous in winter, which is over two times the multiyear average. The surface averaged result of EKE (Figure 3d) shows an unusually high-eddy energy region of 65°-80°E, 60°-65°S, where the ACC flows between Antarctica and the KP.
Figure 3. Annual cycle of area-mean surface MKE (a) and EKE (b) for climatology (1993-2020) and 2017 over the region of 40°-80°E, 52°-72°S (units: cm² s⁻²). (c) Horizontal distribution of multiyear averaged EKE and in 2017 (d). Dashed red boxes in (c) and (d) indicate the area-mean region. Black lines mark the 3000-m and 4000-m depth contours from the ETOPO1 bathymetry dataset. The light grey lines indicate the isobath of 2000 m.
The spatial distribution of surface monthly mean EKE of 2017 is illustrated in Figure 4. The distinct high-energy eddies appeared in the southwest region of the KP (~66°45’ S) from April. It seems to propagate from east to west in austral winter, lasting until the next year. Moreover, the anomalous strong EKE exists from the surface to the deep layer, shown as in Figure 5a. The three-dimensional (longitude-latitude-depth) structure of EKE reflects the strong eddy activities in both surface and deep layers. EKEs at different depths exhibit high values in the anomalous region. Comparing the meridional (latitude-depth) transects of monthly MKE and mean EKE between the anomaly year (2017) and multiyear average (Figures 5b-5e), the anomalies of kinetic energy in 2017 are prominent. High values of MKE are observed in the Fawn Trough and the south side of the KP. Strong anomalies of EKE and MKE are both distinct on the south side, nearly 64°S (Figures 5b and 5c).
Figure 4. Spatial distribution of monthly mean surface EKE (cm$^2$ s$^{-2}$) in 2017. (a-l) show January to December. The mainly anomalous EKE region focused on is indicated by the dashed red box (60°-80°E, 60°-65°S).

Figure 5. (a) Three-dimensional (longitude-latitude-depth) structure of EKE (cm$^2$ s$^{-2}$) in June 2017, when the integrated EKE in the anomalous region was the strongest in the event. The latitude-depth transects are the 75°E of MKE (b and c) and mean EKE (d and e) in June of 2017 and the multiyear average (denoted by the red transect in (a)).

Previous studies have highlighted the importance of barotropic and baroclinic instabilities as the primary sources of EKE. Energetics analysis is performed to investigate the energy conversion processes contributing to the EKE growth in the selected anomaly region, denoted by the dashed red boxes in Figure 4. Monthly averaged area-mean of MKE, EKE, and Eddy Potential Energy (EPE) in the anomaly region are considered (Figure 6a), with these results representing the integrated densities within the upper 500 meters of the water column. The EKE growth was initiated in March and peaked in June, following the peak of EPE in April. In June and August, MKE exhibited high values, indicating strong kinetic energy during the winter. Their spatial distributions from April to July are shown in
The kinetic energy (EKE and MKE) was strong in winter, demonstrating the dominance of kinetic energy, while the EPE weakened after May.

To further analyze the contributions to EKE growth, the depth-integrated energy conversion rate densities (upper 500 m) are calculated, based on Equations 9-11 as described in the methods. All peaks of energy conversion (BC: MPE → EPE, CE: EPE → EKE, and BT: MKE → EKE) are observed in May (Figure 6b), preceding the strongest EKE anomaly (Figure 6a). 60°-80°E averaged depth-integrated energy conversion rate densities are illustrated in Figure 8. Baroclinic energy conversions (BC and CE) exhibit positive values (Figures 8a and 8b). It is observed that strong baroclinic conversion occurred starting from April, with values exceeding 5×10^8 m^2 s^-3. Both BC and CE propagated southward over a distance of about 1.5° (~170 km) from April to November, while the barotropic energy conversion (BT) shows negative values with southward propagation (Figure 8c).

Figure 6. Time series of monthly mean depth-integrated (upper 500 m) energy densities (MKE, EKE, and EPE, unit: cm^2 s^-3) (a) and energy conversion rate densities (unit: m^2 s^-3) (b) averaged over the selected subregion in 2017, the dashed red box indicated in Figure 4.
Figure 7. Spatial distribution of upper 500 m integrated EPE (a), EKE (b), and MKE (c) densities (unit: cm$^2$ s$^{-2}$) in the subregion from April to July in 2017.
Figure 8. Hovmöller diagrams of 60°-80°E averaged upper 500-m integrated energy conversion rate density (unit: m$^2$s$^{-3}$) in Equation 9-11 in 2017, (a) BC: MPE $\rightarrow$ EPE, (b) CE: EPE $\rightarrow$ EKE, and (c) BT: MKE $\rightarrow$ EKE.

According to the results of three-dimensional EKE in Figure 5, it is evident that EKE remains robust in the deeper ocean, experiencing minimal weakening in comparison to the surface. Our investigation encompasses energetics analysis across all ocean layers. Vertical profiles of averaged energy and energy conversion rates for all layers during May 2017 are provided in Figure 9. Both MKE and EKE exhibit similar patterns with relatively less variation from the surface to the deep layers, whereas EPE shows a peak at the surface, followed by a decline within the upper 50 meters, and then a rapid increase in the upper 1000 m (Figure 9a). This pattern is similar to the energy conversion of MPE to EPE (Figure 9b). EPE and the baroclinic conversion of MPE to EPE, as well as EPE to EKE, exhibit particularly notable intensities within the depth range of the Circumpolar Deep Water (CDW), approximately between 500 and 2000 meters.
Figure 9. Vertical profile of energy (a) and energy conversion (b) averaged over the subregion (60°E, 60°-65°S) in May 2017 (unit: m² s⁻³). Four typical layers are indicated by the dashed magenta lines at depths near 50 m, 500 m, 1000 m, and 2000 m, respectively.

To explore the underlying mechanisms of anomalous EKE variability, the isopycnals of neutral density within the upper 2000 m, along with their anomalies compared to multiyear averages are illustrated in Figure 10, where the baroclinic energy conversions were distinct (Figure 9b). The first isopycnal near the surface indicates the upper boundary of the CDW. Isopycnals in the southwest sector of the KP deviated considerably from the climatological values, indicated by the black and magenta curves (the left panels in Figure 10). The neutral densities show significantly positive anomalies in the coastal region (the right panels in...
Figure 10, particularly during the period of most pronounced baroclinic energy conversion in May exhibited in Figures 6b, 8a, and 8b.

Figure 10. The latitude-depth transects of neutral density ($\gamma_n$, kg m$^{-3}$) and its anomaly at 75°E in March (a and b), April (c and d), May (e and f), and June (g and h) in 2017. The black curves represent isopycnals of neutral density in 2017 for the transects, and the magenta curves represent the multiyear average of 2010-2020. The isopycnals of 28.03 kg m$^{-3}$ indicate the upper boundary of the CDW.
The meridionally integrated averages of CE (baroclinic energy conversion of EPE → EKE) in different layers are shown in Figure 11. CE is comparatively weak in the surface layer, and it diminishes below the approximate depth of 2000 m (Figure 11e), transitioning from strong positive values. Moreover, the active baroclinic conversion is associated with the robust EKE anomaly during the period spanning from April to July across all depths. Similar patterns are reflected in the horizontal distribution of energy, as illustrated in Figure 12. Both the MKE and EKE extend consistently throughout the water column displaying minimal fluctuations (the middle and right panels in Figure 12). In contrast, EPE experiences notable enhancement within the depth range of the CDW, as shown in the first column of Figures 12b and 12c, indicating its greater concentration in this area.
Figure 11. Hovmöller diagrams of baroclinic energy conversion rates (unit: m² s⁻³) of EPE to EKE (the CE term in Equation 10), which are 60°-80°E integral averages of different layers in 2017, near 50 m, 300 m, 1000 m, 2000 m, and 3500 m, respectively.
Figure 12. Horizontal distribution of EPE, EKE, and MKE (unit: cm$^2$ s$^{-2}$) in four typical layers (a-d) in May 2017, as Figure 10 shows, which are indicated by the dashed magenta lines at depths near 50 m, 500 m, 1000 m, and 2000 m, respectively.

Moreover, $65^\circ$-$80^\circ$E meridional averaged monthly wind-induced Ekman pumping velocities $W_{ek}$ in the region between $60^\circ$-$72^\circ$S in March-May are depicted in Figure 13. The results in 2017 show obvious positive anomalies compared with the multiyear average (Figure 13a). The monthly Ekman pumping velocity in $70^\circ$S, denoted by the dashed grey line in Figure 13a, is shown in Figure 13b. There are two distinct peaks in April and October, with the former one having impacts on the anomalous event.
Figure 13. (a) 65°-80°E meridionally averaged monthly Ekman pumping velocity $W_{ek}$ (m s$^{-1}$, positive: upward) in the region between 60°-72°S in March-May. (b) Meridional averaged Ekman pumping velocity $W_{ek}$ in 70°S of multiyear mean and 2017, denoted by the dashed grey line in (a).

4. Discussion

4.1. Primary Energy Source for the EKE Anomaly Event

Based on the energetics analysis, energy conversions correspond well with the variations of eddy energy, and the responses of EKE show a time lag after a substantial buildup of potential energy (Figures 6 and 7). Baroclinic energy conversions (BC and CE) exhibit positive values before the emergence of the EKE anomaly, representing their contributions to the anomalous EKE. It is implied that Mean Potential Energy (MPE) delivers energy into eddies, resulting in the enhancement of EPE. Subsequently, EKE receives energy from EPE, while barotropic conversion contributes to the reduction of EKE.
While the ACC is well-known for its contribution of energy to the subpolar region through barotropic conversion, our analysis within the specific study region reveals an inverse conversion pattern with negative barotropic conversion (BT in Figures 6b and 8c). The regional energy cascade operates differently compared to the broader ACC. Here, it's the baroclinic conversion that predominantly influences the energy input, involving the conversion from available potential energy to kinetic energy through baroclinic processes, instead of barotropic energy conversion contributing to the energy input. Furthermore, the negative southward propagation of the BT highlights that the barotropic conversion influences the mean flow after strong energy disturbances. These interactions between eddies and the mean flow result in distinct energy conversion patterns. Consequently, the pronounced anomalous EKE observed during the winter months can be attributed to robust baroclinic energy conversion, making it the primary factor driving the enhancement of EKE in this specific region.

4.2. Possible Mechanisms for the Strong Baroclinic Energy Conversion

In the southwest region of the KP, there is a notable steepening of isopycnals from March 2017 (Figure 10b), particularly during May when baroclinic energy conversion is most pronounced (Figures 6b, 8a, and 8b). The flattening of isopycnals is demonstrated to indicate the release of potential energy and the occurrence of baroclinic instability [Rintoul, 2018; Cai et al., 2022]. The anomalies observed in isopycnals lead to vigorous baroclinic instability, which aligns remarkably with the period of notable baroclinic energy conversion from EPE to EKE (CE, Figure 11). The energy input to EKE is concentrated within the depth range of the CDW, corresponding with the vertical distribution depicted in Figure 9b (denoted by the red line).

The intrusion of anomalous warm CDW plays a pivotal role in steepening the isopycnals, particularly in the anomalous region. Consequently, Baroclinic instability is initiated,
accompanied by the restoration of isopycnals, where the baroclinic pathway originates. This intensified baroclinic instability facilitated the conversion from MPE to EPE, subsequently culminating in the generation of EKE. As a result, the patterns of EKE exhibit intensely positive anomalies at the surface layer and in the internal ocean.

4.3. Impacts of Wind Changes

Another pronounced phenomenon is that the depth of the upper boundary of the CDW is distinctly shallower than the normal situation, as indicated by the isopycnal of 28.03 kg m\(^{-3}\) in Figure 10. Previous studies have proposed that the CDW intrusion into Prydz Bay (PB) during austral autumn and winter is significantly influenced by the wind patterns north of the shelf break from January to May [e.g., Guo et al., 2022]. During the summer of 2017, unusual wind patterns were suggested to have occurred in PB, which even resulted in strong advection of warmer waters towards the shelf region in January [Meehl et al., 2019; Wang et al., 2019; Sabu et al., 2021]. In the present study, changes in the wind field during the period are revealed to strengthen regional Ekman divergence, leading to anomalous strong Ekman pumping, particularly in the southern coastal area (Figure 13a). The wind-induced Ekman pumping velocities from March to May in the anomaly region significantly exceeded the multiyear average (Figure 13b), further promoting the upwelling of CDW. That facilitated the development of meridional density gradients, amplifying the lifting of isopycnals near the coast. Consequently, the baroclinic energy conversion was intensified, ultimately resulting in the observed anomalies in EKE. In summary, these processes contributed to the heightened generation of eddies and enhancement of eddy energy of the system.

Collectively, our findings contribute significantly to the understanding of energy dynamics and transformation mechanisms in the region. Previous studies predominantly focused on the baroclinic instability induced by wind forcing [e.g., Wu et al., 2017; Matsuta and Masumoto, 2023], while this study emphasizes the important role played by currents in
the interior ocean. Despite other Antarctic regions also experienced positive anomalies in spatially averaged EKE during the same year, they did not exhibit distinctive phenomena observed in our study area. We speculate that the variations in EKE may be influenced by large-scale climate modes, and these differences could be attributed to the combined effects of ocean currents, topography, and other unique characteristics specific to our study region. Future research endeavors could further explore the feedback mechanisms operating in polar regions.

5. Conclusions

In this study, a systematic energetics analysis framework is employed to examine the notable anomalies of an intensified EKE event observed in the southwest region of the Kerguelen Plateau in 2017 based on a reanalysis product. The EKE anomaly existing at all depths emerges in April, reaches its peak during the austral winter, and persists into the following summer. Our results indicate that the anomalously high-intensity EKE during this period predominantly results from baroclinic instability, with its primary source being the available potential energy. Potential mechanisms have been proposed to elucidate the processes occurring in both the upper and deeper ocean layers, and we emphasized the energetics dynamics at depth. The intrusion of anomalous warm Circumpolar Deep Water intensifies the baroclinic energy conversion, which contributes to the EKE anomalies. And anomalous strong wind-induced Ekman pumping serves to amplify the lifting of isopycnals, which also intensifies the baroclinic instability. Thus, the powerful baroclinic energy pathway ultimately results in a substantial increase in regional EKE. Our study sheds new light on the underlying mechanisms governing local polar dynamics and provides insights into the intricate interaction between ocean dynamics and energy distribution in the Antarctic.
We have analyzed the underlying mechanisms of eddy dynamics, and a possible physical process of EKE responding to changes in wind patterns is proposed. It is important to note that we have primarily focused on the oceanic domain. The intrusion of warm CDW in the ocean interior is emphasized to be the primary factor leading to the strong anomalies in EKE. Further investigations would be necessary to explore how regional mesoscale eddy fields respond to large-scale atmospheric patterns, and if these patterns have impacts on the intrusion of CDW. We call for high-resolution air-sea coupled models in the subpolar region to gain a more comprehensive understanding of regional dynamics and their ecological implications in the Antarctic.
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Data Availability Statement


Thompson, A. F. (2008), The atmospheric ocean: eddies and jets in the Antarctic Circumpolar Current, *Philosophical Transactions of the Royal Society*


