

1 **Dynamics of the Southeast Indian Ridge storm track evaluated using a wave**
2 **activity flux framework**

3 Alexis Johnson Exley^{a,c} Kathleen Donohue,^a Xiaobiao Xu,^b

4 ^a *University of Rhode Island*

5 ^b *Florida State University*

6 ^c *Woods Hole Oceanographic Institution*

7 *Corresponding author:* Alexis Johnson Exley, alexis.exley@whoi.edu

8 ABSTRACT: Regions of elevated eddy kinetic energy (EKE) downstream from topographic ridge
9 systems of the Southern Ocean are analogous to atmospheric storm tracks. Typically investigated
10 using a 3-dimensional wave activity flux framework, dynamics of storm tracks are primarily
11 governed by energy transfers between the mean and eddy field. Here, three years of high-resolution
12 numerical model output is used to diagnose these eddy-mean field interactions and the physical
13 mechanisms responsible for initiating and maintaining the Southeast Indian Ridge storm track in
14 the Southern Ocean. Background dynamics are found to be primarily governed by the vertical wave
15 activity flux, corresponding to the baroclinic conversion of energy. This term suggests ubiquitous
16 baroclinic growth across the domain but largely enhanced in the crest of the standing meander.
17 Temporal variability in array averaged EKE however is found to be dominated by the horizontal
18 wave activity flux terms, corresponding to the barotropic conversion of energy. This variability is
19 event driven and, when decomposed into synoptic storm track case studies, shown to be analogous to
20 atmospheric downstream development, a process by which wave-train like propagation is sustained
21 by barotropic growth, flux and decay of energy in the along stream direction. Anomalously large
22 local increases in EKE are attributed to an extremely extended meander which obstructs the typical
23 propagation of these barotropic perturbations. These major events are compared to an atmospheric
24 omega block and hypothesized to significantly increase eddy heat and tracer fluxes and therefore
25 play a sizable role in the eddy driven arm of the Southern Ocean overturning circulation.

26 **1. Introduction**

27 The Southern Ocean plays an essential role in the global overturning circulation by redistributing
28 heat, carbon and other climate relevant tracers between the interior and surface ocean (Bryan
29 and Lewis 1979; Speer et al. 2000). Driven by the divergence of wind induced Ekman transport
30 and buoyancy forcing, adiabatic upwelling of dense, deep waters is primarily accomplished along
31 steeply sloped isopycnals which outcrop within the Antarctic Circumpolar Current (ACC) (Rintoul
32 et al. 2001; Olbers et al. 2004). Available potential energy stored in these titled isopycnals is
33 released by baroclinic instabilities which generates a vigorous mesoscale eddy field. Below the
34 surface layers, eddies facilitate a preferentially poleward transport of fluid across ACC fronts which
35 directly opposes the northward Ekman transport, and feeds the lower limb of the Southern Ocean
36 overturning circulation (Sloyan and Rintoul 2001; Hallberg and Gnanadesikan 2006).

37 This critical return limb of the overturning does not occur ubiquitously around the Southern
38 Ocean but is instead concentrated to localized regions where topographic ridge systems destabilize
39 the mean flow of the ACC (e.g. Sallée et al. 2011; Abernathey and Cessi 2014; Youngs and Flierl
40 2023). In these hot spots of energetic eddy activity, conservation of potential vorticity requires
41 ACC streamlines to deflect equatorward and consequently converge, further steepening isopycnals
42 and increasing horizontal velocity shear. Bathymetry shoaling to the right of the flow in the
43 Southern Hemisphere has a stabilizing effect on the flow (Chen and Kamenkovich 2013; Chen
44 et al. 2015). It inhibits downgradient baroclinic conversion until fluid parcels navigate away from
45 the ridge resulting in regions of enhanced eddy activity downstream from six major topographic
46 ridge systems of the Southern Ocean (Figure 1). In these regions, Rossby waves are generated and
47 arrested by the eastward mean flow to form standing (stationary) meanders. Local eddy fluxes and
48 diffusivities (Thompson and Sallée 2012; Foppert et al. 2017; Naveira Garabato et al. 2011; Exley
49 et al. 2025) are observed to be around an order of magnitude larger within these meanders and
50 collocated with increased upwelling (Barthel et al. 2022; Tamsitt et al. 2017) and enhanced vertical
51 velocities (Dove et al. 2021), highlighting the outsized impact of these hotspots on the Southern
52 Ocean circulation.

53 These topographically controlled dynamics of the ACC are analogous to atmospheric storm
54 tracks, well documented features of enhanced eddy kinetic energy (EKE) (Williams et al. 2007).
55 Storm tracks in the atmosphere are persistent, weather generating mid-latitude features, most
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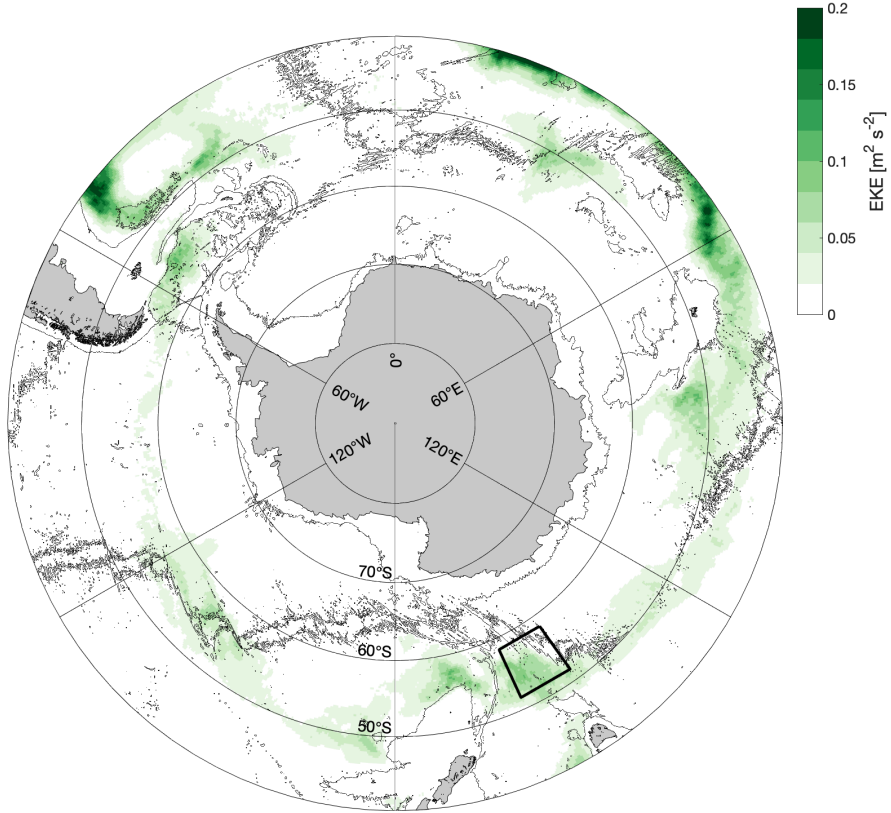


FIG. 1. Time mean sea surface eddy kinetic energy (EKE) from 15 years of mapped sea surface height altimeter data. The Southeast Indian Ridge domain is outlined in black. Bathymetry is contoured at 3000 and 6000 meters.

commonly associated with orographically induced stationary meanders of the background flow (Simmons and Hoskins 1979; Lee and Mak 1996). Dynamics of atmospheric storm tracks are primarily concerned with energy transfers between the mean and eddy field. They are typically characterized by baroclinic growth of an initial perturbation at the expense of the mean flow followed by a downgradient flux which acts to sustain the track away from its genesis region. Consequently, storm tracks initiate in regions of enhanced baroclinicity but elevated values of EKE are observed further downstream.

Atmospheric and oceanic storm tracks share a number of defining characteristics and recent work has drawn parallels between the underlying dynamics (Williams et al. 2007; Bischoff and Thompson 2014; Chapman et al. 2015; Foppert 2019). Most notably, energetic regions of the Southern Ocean

are well known to exhibit the spatial displacement of baroclinically unstable hotspots from peak values of EKE that exemplifies atmospheric storm tracks. Additionally, topographic interactions with the background flow act to localize storm tracks and, in both the atmosphere and ocean, baroclinic instability is thought to be the primary driver of eddy variability. Storm track eddies also have a characteristic life cycle in the ocean that parallels that in the atmosphere, growing within the meander and subsequently decaying further downstream.

There are however, notable differences between atmospheric and oceanic storm tracks. Length scales of transient eddies in oceanic storm tracks are significantly smaller than those in the atmosphere. This is an important distinction between oceanic and atmospheric dynamics as it may impact pathways of energy exchange from the background flow (Chen et al. 2016). Additionally, eddy propagation in Southern Ocean storm tracks is less structured than in the atmosphere with nearly negligibly phase speeds (Klocker et al. 2012; Klocker and Abernathey 2014). Recent work has also suggested that barotropic (or mixed barotropic-baroclinic) instabilities may play a non-negligible role in oceanic storm tracks (Youngs et al. 2017; Barthel et al. 2017; Foppert 2019; Constantinou and Hogg 2019). While atmospheric storm tracks may provide a useful framework to understand these energetic regions of the Southern Ocean, the systematic differences highlighted here underscore why well-documented atmospheric dynamics do not necessarily translate to the oceanic regime. These distinctions highlight the need for autonomous studies of the dynamics governing oceanic storm tracks.

The most defining characteristic of both atmospheric and oceanic storm tracks is the spatial offset between baroclinicity and EKE. In the atmosphere, this phenomenon has been attributed to a sustaining mechanism coined downstream development (Simmons and Hoskins 1978; Orlandi and Chang 1993; Orlandi and Sheldon 1995). This framework suggests that subsequent to growth of the initial baroclinic perturbation, energy from the original eddy is transported downstream by ageostrophic fluxes of geopotential anomaly. As this eddy decays, fluxes sustain the growth of a second eddy further downstream. This process is repeated until energy eventually dissipates at some distance downstream from the initial perturbation. This mechanism is responsible for a characteristic pattern of sequential growth and decay of adjacent troughs and ridges and has been observed in the atmosphere to play a significant role in the development of large weather systems (Danielson et al. 2006).

98 Many studies have documented a displacement between elevated baroclinicity and peak EKE in
99 the Southern Ocean (e.g. Abernathey and Cessi 2014; Bischoff and Thompson 2014; Thompson
100 and Garabato 2014; Foppert et al. 2017; Yung et al. 2022) but none have conclusively identified a
101 mechanism responsible. Proposed mechanisms include: 1) the downstream advection of eddies,
102 and consequently EKE, away from their development region (Yung et al. 2022), 2) a flux of
103 pressure perturbations analogous to atmospheric downstream development (Chapman et al. 2015),
104 3) barotropic instabilities generated downstream from baroclinic (Barthel et al. 2017; Youngs et al.
105 2017; Foppert 2019) and 4) a time delay, proportional to eddy turnover time, between instability
106 processes and EKE generation in which PE is first transferred into large scale eddies before
107 cascading to smaller scales before eventually converting to EKE (Chen et al. 2016). In this work,
108 we aim to explore the viability of mechanisms 2 and 3 by quantifying energy transfer between the
109 mean and eddy field.

110 In the Southern Ocean, transfer dynamics between the mean flow and eddies have traditionally
111 been explored within energy budget frameworks (Lorenz 1955; Bleck 1985). These methodologies
112 however are hindered by the temporal and spatial averaging required and, at best, provide a long
113 term, time mean perspective of a Southern Ocean domain average. These uncertainties can be
114 avoided by adopting a wave activity flux framework. Heavily used in atmospheric studies, the wave
115 activity flux is an energy conservation law that allows for similar insights to energy budgets but
116 each of the terms are uniquely defined and directly associated with a physical process of interest to
117 oceanic storm track dynamics. Namely, the terms associated with eddy buoyancy and momentum
118 fluxes are consistent with energy transfer between the mean and eddy field, and terms proportional
119 to eddy streamfunction anomalies represent an ageostrophic flux of geopotential (Takaya and
120 Nakamura 2001).

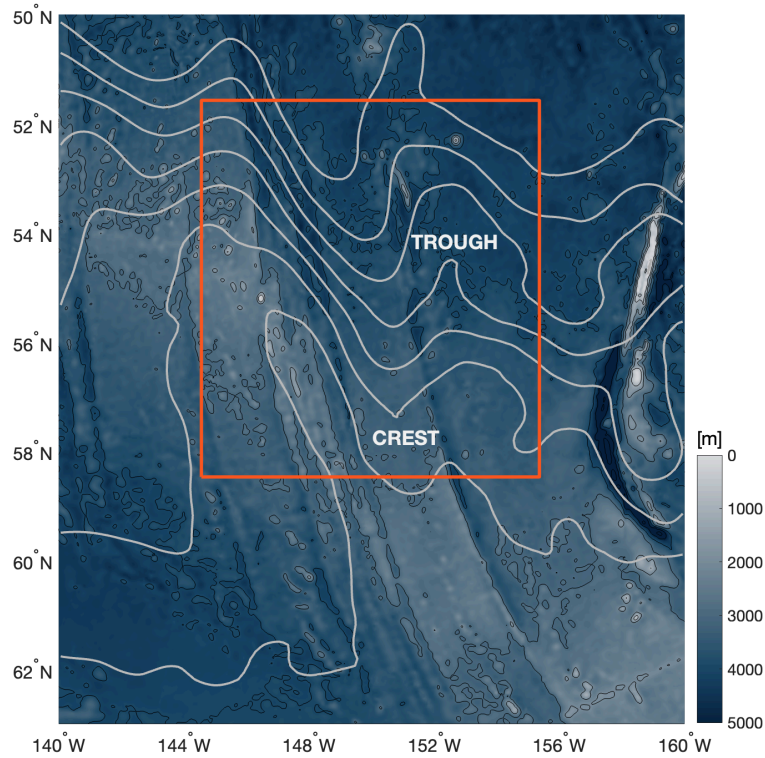
121 The wave activity flux was first formulated to diagnose the transfer of wave energy as air flows
122 over mountain ridges (Eliassen and Palm 1961). It was derived for a zonally averaged mean
123 flow which makes it preferable for diagnosing the relative importance of heat and momentum
124 fluxes but, in this form, does not represent eddy propagation for a zonally non-uniform flow like
125 the ACC. Plumb (1985) built on this work to define a three-dimensional wave activity flux that
126 can diagnose propagation of transient eddies within a zonally asymmetric flow. This updated
127 wave activity ensures phase independence by time averaging but requires no spatial averaging.

128 Phase independence is required to identify the underlying, persistent patterns and energy flows
129 that are not influenced or obscured by the oscillatory nature of wave phases. To generalize these
130 previous versions of the wave activity to be applicable for either stationary or migratory small
131 amplitude quasigeostrophic disturbances on a zonally variable flow, Takaya and Nakamura (2001)
132 formulated a new phase independent conservation law. This wave activity is a linear combination
133 of wave energy and wave enstrophy which ensures the phase independence without the need for
134 any temporal or spatial average.

135 Two previous studies have employed the wave activity flux framework of Takaya and Nakamura
136 (2001) to document storm track dynamics in the Southern Ocean. Chapman et al. (2015) use a
137 primitive equation model with idealized topography to investigate the development and maintenance
138 of storm tracks downstream from baroclinically unstable regions. They provide evidence to suggest
139 that eddies grow downstream from the ridge in response to energy conversion from the mean to
140 eddy potential field. As eddies grow, energy is fluxed further downstream by an ageostrophic
141 geopotential flux which is associated with EKE growth. This is analogous to the downstream
142 development theory of Orlanski and Sheldon (1995). Foppert (2019) builds on this work using
143 observations from an array of current and pressure recording inverted echo sounders in Drake
144 Passage. She proposes a mechanism by which an initial perturbation grows through baroclinic
145 instability. During growth, the meander strengthens, increasing its curvature and ageostrophic flow
146 within trough and crest axes. The steepening meander increases the horizontal velocity shear which
147 facilitates an eddy momentum flux and barotropic instability, of similar magnitude and, collocated
148 with the initial baroclinic perturbation.

149 We build upon previous work to investigate dynamics of eddy-mean interactions in the Southeast
150 Indian Ridge (SEIR; Figure 2), a documented hotspot of eddy fluxes in the Southern Ocean
151 (Thompson and Sallée 2012; Thompson and Garabato 2014; Meijer et al. 2022; Exley et al. 2025).
152 Mechanisms of eddy growth and maintenance are diagnosed in a wave activity flux framework
153 using output from a global simulation based on the HYbrid Coordinate Ocean Model (HYCOM).
154 The goal of this work is to investigate patterns of the wave activity flux in a high-resolution
155 ocean model where the temporal evolution of relevant dynamics can be addressed with realistic
156 topography and on a larger spatial scale than possible with observations. Specifically, we aim to
157 address the viability and interplay of a mixed instability and diagnose the physical mechanisms

158 responsible for the spatial displacement of EKE. The wave activity flux framework as well as the
 159 application in global HYCOM is discussed in section 2. In section 3 the results of the time mean
 160 fields are presented and in section 4 synoptic case studies are used to illustrate time dependent
 161 dynamics. In section 5 these results are compared against well documented atmospheric processes
 162 and the physical mechanisms of oceanic storm tracks diagnosed in this work are contextualized
 163 with previous studies. We conclude in section 6.



164 FIG. 2. Time mean sea surface height contours, obtained from the satellite altimetry record, overlaid on
 165 bathymetry of the Southeast Indian Ridge. The crest and trough, which are associated with anticyclonic and
 166 cyclonic curvature, respectively, are labeled. Orange box indicates the study domain.

2. Data and Methods

a. Global Simulation Based on HYCOM

The numerical outputs used in this study are from a global ocean simulation based on the HYbrid Coordinate Ocean Model (HYCOM, Bleck 2002; Chassignet et al. 2003). The simulation, as part of a global ocean model comparison effort (see Chassignet et al. 2020, for configuration details), is integrated using the atmospheric reanalysis JRA55-do (Tsujino et al. 2018). The model domain covers the global ocean with a horizontal resolution of $1/12^\circ$, or ~ 5 km, for the area of interest in this study ($52^\circ\text{S} - 58^\circ\text{S}$ and $145^\circ\text{E} - 155^\circ\text{E}$; Figure 2 orange box). The vertical coordinate in HYCOM is isopycnic in the stratified ocean interior and dynamically transitioned to fixed pressure levels in the surface mixed layer and/or unstratified seas. The simulation has 36 layers in the vertical, which is interpolated onto a 10-m vertical grid in the analysis. Three years of daily mean model outputs (2018 - 2020) are used in this study.

This HYCOM simulation was selected due to its strong correspondence with satellite SSH data and *in situ* observations in Drake Passage. The model was found to accurately reproduce SSH variability associated with ACC fronts (Xu et al. 2020). Additionally, a detailed examination of the modeled vertical structure of ACC transport was conducted and showed excellent agreement with the directly measured SADCp profile (Firing et al. 2011) and repeat hydrographic sections (Cunningham et al. 2003; Firing et al. 2017). The model also effectively captured near-bottom mean flow and eddy kinetic energy along the cDrake section. The combination of high horizontal resolution, adaptive grid and comparable deep energy demonstrates that this HYCOM run is well-suited to diagnose eddy flux processes in the ACC.

b. The Wave Activity Flux Framework

An extension of the traditional Eliassen-Palm flux (Eliassen and Palm 1961), the following is a description of the wave activity flux framework formulated by Takaya and Nakamura (2001). Several assumptions are made in order to extend the wave activity conservation from a zonally uniform to a zonally varying background flow like the ACC. Namely, the background flow is assumed nearly unforced and varies significantly slower and at much larger spatial scales than the eddies or perturbations. Eddy phase speed is also assumed constant in the direction of the background flow. Although these assumptions may break down in topographic regions of the ACC,

previous work has been successful applying this framework and formulating impactful conclusions in non-linear regimes (Danielson et al. 2006; Chapman et al. 2015; Foppert 2019). For the following, time mean quantities (90-day low pass filtered) and corresponding deviations (the eddy term) are denoted by overbars and primes, respectively such that $a = \bar{a} + a'$. Vector quantities are bolded and superscripts indicate their directional components, $\mathbf{W} = [W^x, W^y, W^z]$, while subscripts indicate partial derivatives.

The wave activity flux, as derived by Takaya and Nakamura (2001), is a conservation law formulated, without averaging in time or space, for small amplitude, quasigeostrophic eddies or waves on a zonally varying background flow:

$$\frac{\partial M}{\partial t} + \nabla \cdot \mathbf{W} = D \quad (1)$$

where M is the wave activity density, a linear combination of EPE, EKE and eddy enstrophy. $\mathbf{W}$ is a 3-dimensional flux of wave activity and D is any nonconservative dissipation term. The wave activity, $M = \rho(A + E)/2$ includes a term proportional to eddy enstrophy, $A = 0.5q'^2/\nabla_H \bar{q}$, and a total eddy energy term normalized by eddy phase speed, $E = (\text{EPE} + \text{EKE})/(|\bar{\mathbf{u}} - c_p|)$. $\bar{q}$ and q' are the mean and eddy component of the quasigeostrophic potential vorticity. Both the eddy enstrophy and energy (when zonally averaged) terms are related to a pseudomomentum, the second order mean momentum that a wave or eddy could add to or subtract from the mean background flow. The introduction and linear combination of these two terms ensures phase-independence without the need for time or spatial averaging, a requirement to represent phase averaged statistics. This allows M and $\mathbf{W}$ to be diagnosed locally along the wave or eddy.

When the wave and mean flow are both conserved, in the absence of diabatic forcing, $D = 0$ and the eddy flow will increase at the expense of the mean flow when $\partial M/\partial t > 0$ and $\nabla \cdot \mathbf{W} < 0$. In other words, the eddy field, M , will grow (decay) in response to wave activity flux convergence (divergence) which is associated with an increase (decrease) in wave activity density.

The quantity $\mathbf{W}$ is the wave activity flux, a sum of the stationary and propagating flux components such that, $\mathbf{W} = \mathbf{W}_s + M\mathbf{C}_u$. The propagating component contains the local eddy phase speed, $\mathbf{C}_u = c_p \cdot \bar{\mathbf{u}}/|\bar{\mathbf{u}}|$, which is in the direction of the mean flow and assumed constant. One of the major challenges when applying this framework is the requirement for a priori knowledge of the eddy phase speed which can introduce large errors when attempting to close the wave activity budget.

The stationary component, $\mathbf{W}_s$, is identical to the flux term derived in Takaya and Nakamura (1997) and can be expanded as:

$$\mathbf{W}_s = \rho \begin{bmatrix} W^x \\ W^y \\ W^z \end{bmatrix} = \frac{\rho}{2|\bar{\mathbf{u}}|} \left\{ \begin{array}{l} \bar{u}(\psi_x'^2 - \psi'\psi_{xx}') + \bar{v}(\psi_x'\psi_y' - \psi'\psi_{xy}') \\ \bar{u}(\psi_x'\psi_y' - \psi'\psi_{xy}') + \bar{v}(\psi_y'^2 - \psi'\psi_{yy}') \\ \frac{f^2}{N^2} [\bar{u}(\psi_x'\psi_z' - \psi'\psi_{xz}') + \bar{v}(\psi_y'\psi_z' - \psi'\psi_{yz}')] \end{array} \right\} \quad (2)$$

where $\rho = 1035 \text{ kg m}^{-3}$, f is the local Coriolis parameter, N^2 is the mean buoyancy frequency and ψ is the geostrophic streamfunction which is related to geostrophic velocity as $(u_g, v_g) = (-\psi_y, \psi_x)$ and can be approximately calculated from the geopotential as $\psi f = \phi_b$. Each term in $\mathbf{W}_s$ represents a physical process associated with eddy generation or wave packet propagation. Relevant terms to this study will be discussed below. For a more in-depth description, Takaya and Nakamura (2001) provides a detailed physical interpretation of the individual terms in $\mathbf{W}_s$ from an atmospheric perspective while Chapman et al. (2015) takes an oceanographic approach by associating each term to diagnostics used in more traditional energy budget diagrams.

The first and third terms of the horizontal and vertical components in $\mathbf{W}_s$ are described by Takaya and Nakamura (2001) as being related to the meridional transport of momentum and buoyancy, respectively, in the direction opposite to the group velocity due to eddy fluxes. Following the notation of Foppert (2019), we refer to these terms as the $\mathbf{W}_{\text{eddy}}$ terms:

$$\mathbf{W}_{\text{eddy}} = \frac{\rho}{2|\bar{\mathbf{u}}|} \left\{ \begin{array}{l} \bar{u}(\psi_x'^2) + \bar{v}(\psi_x'\psi_y') \\ \bar{u}(\psi_x'\psi_y') + \bar{v}(\psi_y'^2) \\ \frac{f^2}{N^2} [\bar{u}(\psi_x'\psi_z') + \bar{v}(\psi_y'\psi_z')] \end{array} \right\} \quad (3)$$

where the horizontal and vertical terms are analogous to the Reynolds stress and eddy buoyancy fluxes, respectively, which appear in the mean momentum and buoyancy budgets and represent the transfer of energy and momentum between the mean flow and eddy field.

Takaya and Nakamura (2001) show that the divergence and convergence of the wave activity flux vector indicate regions where wave packets are emitted and absorbed, respectively. Specifically, a positive divergence of the horizontal eddy terms $\nabla \cdot \mathbf{W}_{\text{eddy}}^H = \left[\frac{\partial \mathbf{W}_{\text{eddy}}^x}{\partial x}, \frac{\partial \mathbf{W}_{\text{eddy}}^y}{\partial y} \right] > 0$, corresponds to a local decrease in wave activity, reflecting a net export of eddy energy from the region. This typically implies a source of wave activity and thus local generation of eddies that radiate downstream. For

example, Takaya and Nakamura (2001) show that within a baroclinic wave packet, a region of strong horizontal divergence, or the wave source region, indicates conversion of energy from the mean flow to the propagating disturbances. Conversely, convergence of $\mathbf{W}_{\text{eddy}}^H$ corresponds to accumulation of wave activity and absorption of energy by the mean field. As the wave activity is a conserved quantity, in the absence of forcing or damping, divergence implies a source of wave activity and local eddy generation. By analogy to Reynolds stress conversion terms, this typically occurs when energy is transferred from the mean flow to eddy field in a downgradient momentum flux through shear production and represents barotropic conversion from MKE $\rightarrow$ EKE.

Similarly for the $\mathbf{W}_{\text{eddy}}^z$ terms, by use of the hydrostatic relation, $\psi'_x \psi'_z = f^{-1}(v'_g b')$ which is a measurement of the eddy buoyancy flux and appears in energy diagrams as conversion between mean and eddy potential energy reservoirs. The $\mathbf{W}_{\text{eddy}}^z$ terms therefore correspond to eddy buoyancy fluxes that represent baroclinic conversion between MPE $\leftrightarrow$ EPE. Because $f < 0$ in the Southern Ocean, a positive (negative) vertical wave activity flux is associated with downgradient (upgradient) flux of momentum and therefore poleward (equatorward) eddy buoyancy flux.

For perturbations propagating on a zonally uniform flow, the linearized quasigeostrophic equation for meridional momentum (in the zonal direction) can be approximately rearranged as $\psi'_{xx} = v'_x \approx -f u_a / (\bar{u} - c)$. It follows that $-\psi' \psi'_{xx} = \phi' u_a / (\bar{u} - c)$. Similar arguments can be made for the meridional and vertical directions. The second and fourth terms in $\mathbf{W}_s$ can therefore be approximated as an ageostrophic flux of geopotential anomaly related to the rate of work done by pressure in the direction of the phase speed. Again, following notation of Foppert (2019), we refer to these as the $\mathbf{W}_{\text{ageo}}$ terms:

$$\mathbf{W}_{\text{ageo}} = \frac{\rho}{2|\bar{\mathbf{u}}|} \left\{ \begin{array}{l} \bar{u}(-\psi' \psi'_{xx}) + \bar{v}(-\psi' \psi'_{xy}) \\ \bar{u}(-\psi' \psi'_{xy}) + \bar{v}(-\psi' \psi'_{yy}) \\ \frac{f^2}{N^2} [\bar{u}(-\psi' \psi'_{xz}) + \bar{v}(-\psi' \psi'_{yz})] \end{array} \right\} \quad (4)$$

This study uses spatial and temporal patterns of the stationary wave activity flux and eddy energy to diagnose the physical mechanisms governing eddy fluxes in the SEIR storm track. We focus on $\mathbf{W}$ rather than attempting to close the local wave activity budget as the assumptions made when formulating the conservation law may not be entirely accurate in the nonlinear regime of the ACC, potentially giving rise to large uncertainties. We also assume the propagating component of

the wave activity flux is significantly smaller, and therefore negligible, compared to the stationary component (i.e. $\mathbf{W} = \mathbf{W}_s$) (Klocker et al. 2012; Klocker and Abernathey 2014). Regardless of these assumptions, we believe patterns presented below effectively illustrate the dynamics governing the SEIR storm track.

c. Application in HYCOM

Three years of daily HYCOM output spanning about 52°S – 58°S and 145°E – 155°E (Figure 2) was used to formulate the wave activity flux. Each output file is a daily mean field that includes sea surface height, temperature, salinity, zonal and meridional velocity, pressure and density. Variables are transformed from their original hybrid density/pressure grid onto a regular 10 meter grid. A 90-day temporal low pass filter is applied to each quantity of the three year time series and taken as the mean field. Prime quantities are defined as the deviation from the 90-day low pass filter following a standard Reynolds decomposition. We consider these as the transient eddy quantities. The cutoff period of 90 days is consistent with Foppert (2019) and has been shown to accurately separate the eddy field from the mean flow in the Southern Ocean (Phillips and Rintoul 2000).

Pressure anomalies are calculated by considering both the baroclinic and barotropic contribution to sea surface height. The contribution from changes in the density profile, or the baroclinic contribution, is calculated as a geopotential anomaly, a function of the temperature and salinity profile relative to 3000 meters. The choice of 3000 meters was made to reference as close to the bottom as possible while including the majority of the meander region. This choice eliminates the ridge from the study. The barotropic, or mass-loading, contribution is the input from small perturbations in the deep pressure field. The following equation is used to calculate the pressure anomalies at 3000 meters:

$$\eta'_{\text{tot}} = \frac{\phi'_{0-3000}}{g} + \frac{P'_{3000}}{\rho_b g} \quad (5)$$

where $\rho_b = 1050 \text{ kg m}^{-3}$ is a deep reference density and g is the gravitational acceleration. The total geostrophic streamfunction anomaly can then be calculated as the sum of the 3000-meter referenced baroclinic streamfunction and the reference streamfunction:

$$\psi' = \psi'_{bcb} + \psi'_{ref} = \frac{\phi'_{0-3000}}{f} + \frac{P'_{3000}}{\rho f} \quad (6)$$

where $\rho = 1035 \text{ kg m}^{-3}$. Eddy potential energy (EPE) and EKE are also calculated from daily HYCOM output. EPE is a function of the buoyancy field and here calculated from the vertical derivative of the streamfunction anomaly, $\text{EPE} = 0.5 \left(\frac{f\psi'_z}{N} \right)^2$. Similarly, EKE is calculated from the geostrophic streamfunction anomaly, $\text{EKE} = 0.5(\psi'^2_x + \psi'^2_y)$. All of the above terms are calculated as an average between 500 and 1000 meters depth. This depth average ensures the mixed layer is excluded from the analysis while capturing the most active layers of eddy variability.

3. Results: Time Mean Patterns

The three-year mean wave activity flux and energy terms, averaged between 500 and 1000 meters in depth, are shown in Fig. 3. Time-averaged sea surface height contours, representative of ACC streamlines, illustrate a prominent standing meander in the lee of the ridge. This meander, analogous to an arrested Rossby wave, has a wavelength of approximately 300 – 500 km. It exhibits greater curvature in the northernmost streamlines compared to the southern ones, where the flow follows a more direct path through the study domain after initial deflection by the topography. The persistence and spatial coherence of the standing meander may be influenced by additional bathymetric features downstream of the Southeast Indian Ridge. A second, smaller ridge is located slightly downstream near 152°W, followed by the Macquarie Ridge even further downstream, near 158°W (Fig. 2). These sequential ridge systems likely constrain jets of the ACC, contributing to the relatively consistent structure of the standing meander over time.

In the horizontal, time mean wave activity flux vectors are overlaid on the horizontal magnitude, $|\mathbf{W}^H|$, and the divergence of the horizontal terms, $\nabla \cdot \mathbf{W}^H$ (Fig. 3 A&B, respectively). While the magnitude of the horizontal terms is closely related to the spatial patterns of Reynolds stress and therefore turbulent momentum flux, the divergence illustrates regions of local eddy generation and energy conversion from the mean state into the eddy field. The largest values of $|\mathbf{W}^H|$ are found leading into the trough of the standing meander ($\sim 54^\circ\text{S}$). Note that meander crests are associated with anticyclonic curvature and are therefore always poleward deviations in a zonal current (labeled in Fig. 2). Smaller, localized peaks are found in the immediate lee of the ridge ($\sim 52.5^\circ\text{S}$) and within the crest of the standing meander ($\sim 56^\circ\text{S}$).

Divergence is largest leading into the crest of the standing meander, suggesting this is a region where energy is being emitted and thus locally generated by strong horizontal velocity shear,

consistent with mean-to-eddy energy conversion through barotropic instability (Fig. 3B). Closer inspection of the time resolved divergence field reveals that this region exhibits consistently positive divergence throughout the study period (not shown). Exiting the crest, just downstream from the peak divergence, is a region of persistent convergence. This pattern of divergence leading into convergence also appears near the crest axis, where the $|\mathbf{W}^H|$ is largest. The pattern is smaller in magnitude than in the trough axis and somewhat masked where the divergence was not able to be resolved in a large region centered on $\sim 53^\circ\text{S}$, 151°E due to the central differencing used for the divergence calculation.

The mean vertical component of the wave activity flux, $\mathbf{W}^z$, is positive across nearly the entire domain (Fig. 3C). This reflects a nearly ubiquitous baroclinic conversion of energy from the mean state to the eddy field. Maximum values are found in the crest of the standing meander, collocated with the persistent divergent feature of the horizontal terms ($\sim 56^\circ\text{S}$). The vertical component however is notably more diffuse, with maximum values spanning the entire crest, without being confined to either upstream or downstream the axis as with the divergent term.

Vertically averaged, time mean EKE (Fig. 3D), EPE (Fig. 3E) and sea surface height standard deviation, H^* (Fig. 3F) are compared against horizontal and vertical patterns of the wave activity flux. EKE and EPE are components of the wave activity density, M , and have been used as indicators for baroclinic growth and eddy fluxes. Sea surface height standard deviation has also been used as a proxy for eddy heat flux (Foppert et al. 2017). Maximum values of EPE are about three times as large as maximum values of EKE and peaks are not collocated in space. EPE shares a number of spatial similarities with both $|\mathbf{W}^H|$ and $\mathbf{W}^z$. Most strikingly, EPE has a large peak in the same location as $|\mathbf{W}^H|$, leading into the trough of the meander ($\sim 54^\circ\text{S}$). A few localized peaks are collocated with $|\mathbf{W}^H|$ as well. A broad region of elevated EPE is also found near the crest of the meander, corresponding to the region of enhanced $\mathbf{W}^z$ and horizontal divergence.

In contrast, time mean EKE patterns (Fig. 3D) are mostly distinct from spatial patterns of $|\mathbf{W}^H|$, $\nabla \cdot \mathbf{W}^H$, and $\mathbf{W}^z$. EKE peaks just east of the EPE and $|\mathbf{W}^H|$ maximum but not necessarily in the mean along-track downstream direction. Another peak, of similar magnitude, is found on the easternmost side of the domain where time mean streamlines converge in the lee of the standing meander. This appears to be a region of strong $\mathbf{W}^H$ convergence but positioned on the very edge of the study domain, just upstream from Macquarie ridge, makes it challenging to draw any

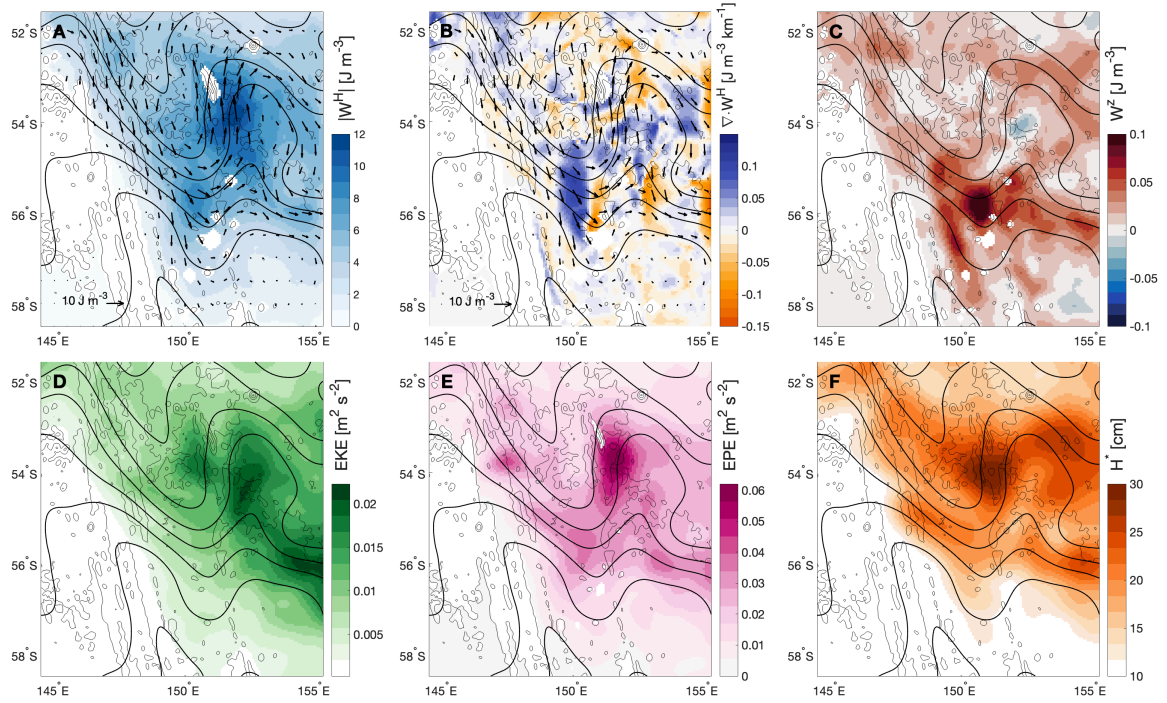


FIG. 3. Three year time means of wave activity flux terms . (A) horizontal wave activity flux magnitude, $|\mathbf{W}^H|$ (B) divergence of the horizontal wave activity flux, $\nabla \cdot \mathbf{W}^H$ (C) vertical wave activity flux, $\mathbf{W}^Z$, (D) EKE, (E) EPE, and (F) sea surface height standard deviation, H^* . Time mean quantities are calculated from the daily mean HYCOM fields and, with the exception of H^* , are all averaged between 500 and 1000 meters. Arrows overlaid on the horizontal terms (A & B) represent the horizontal wave activity vectors plotted at every half-degree. The corresponding three year mean sea surface height is contoured every 0.2 meters in black. Bathymetry is contoured every 1000 meters in gray. Gaps in the wave activity flux terms and EPE are associated with regions where the geostrophic streamfunction anomaly cannot be calculated because the water column depth is less than 3000 meters. Gaps are larger in the divergence plot due to the central differencing required.

conclusions. Minimum values of EKE are found near the crest, where maximum values of $\mathbf{W}^Z$ and $\mathbf{W}^H$ divergence are located, reinforcing the understanding that EKE peaks downstream from regions of energy growth. Time mean sea surface height standard deviation (Fig. 3F) largely reflects patterns of EPE however a local peak corresponding to EKE on the easternmost side of the domain is observed in addition to another peak exiting the meander trough.

4. Results: Synoptic Storm Tracks

An advantage of utilizing the wave activity flux framework over a more traditional energy budget is the ability to diagnose time dependent dynamics within the numerical model. Recall that the version of HYCOM selected for this study is a free running, non-assimilating model based entirely on underlying physics. We therefore do not expect it to reproduce specific events but believe it is well suited to represent eddy statistics (event dates will not correspond to altimetry record). EKE is compared against that of the wave activity flux components in Fig. 4 such that terms are averaged across the study domain and evaluated daily. Fig. 4 C&D illustrate the divergence terms where in panel C, divergence and convergence are isolated by masking out negative and positive values, respectively, from the divergence field to produce separate time series. The full divergence is illustrated in panel D.

Large temporal variability is identified in all terms but most significantly in the EKE (Fig. 4A) and horizontal wave activity time series (Fig. 4 B blue line and C&D), which appear to be closely related. Both are characterized by large maxima around January, 2019 and January, 2021. A number of smaller peaks are found throughout the three year time span with a majority concentrated between January, 2019 and January, 2020. The strong temporal correlation between the $\mathbf{W}^H$ terms and EKE suggests that these peaks are event driven processes associated with shear instabilities and the redistribution of momentum.

The divergent and convergent components of the horizontal time series (Fig. 4C) are isolated and examined separately to demonstrate that both peak simultaneously in time, suggesting that energy growth and decay occur concurrently across the domain. These peaks coincide with maxima in both $|\mathbf{W}^H|$ and EKE, suggesting that time periods of strong eddy activity are characterized by intensified energy redistribution. When the divergent and convergent components are not separated, their opposing signs largely cancel out, obscuring the energetic events. Notably, divergence is consistently slightly larger in magnitude than convergence, implying a net gain of energy within the eddy field.

Domain averaged $\mathbf{W}^Z$ is almost always positive throughout the three year study period, suggesting large scale conversion from the mean to eddy field. Temporal variability is higher frequency than that of $\mathbf{W}^H$ and EKE. $\mathbf{W}^Z$ exhibits less temporal correlation to the other components but occasionally peaks during event time periods. For example, the large event at the end of the time series appears

400 to have some correlation to both the horizontal and vertical flux terms. However, in contrast, the
401 event in January, 2019 appears to be largely driven by the horizontal terms.

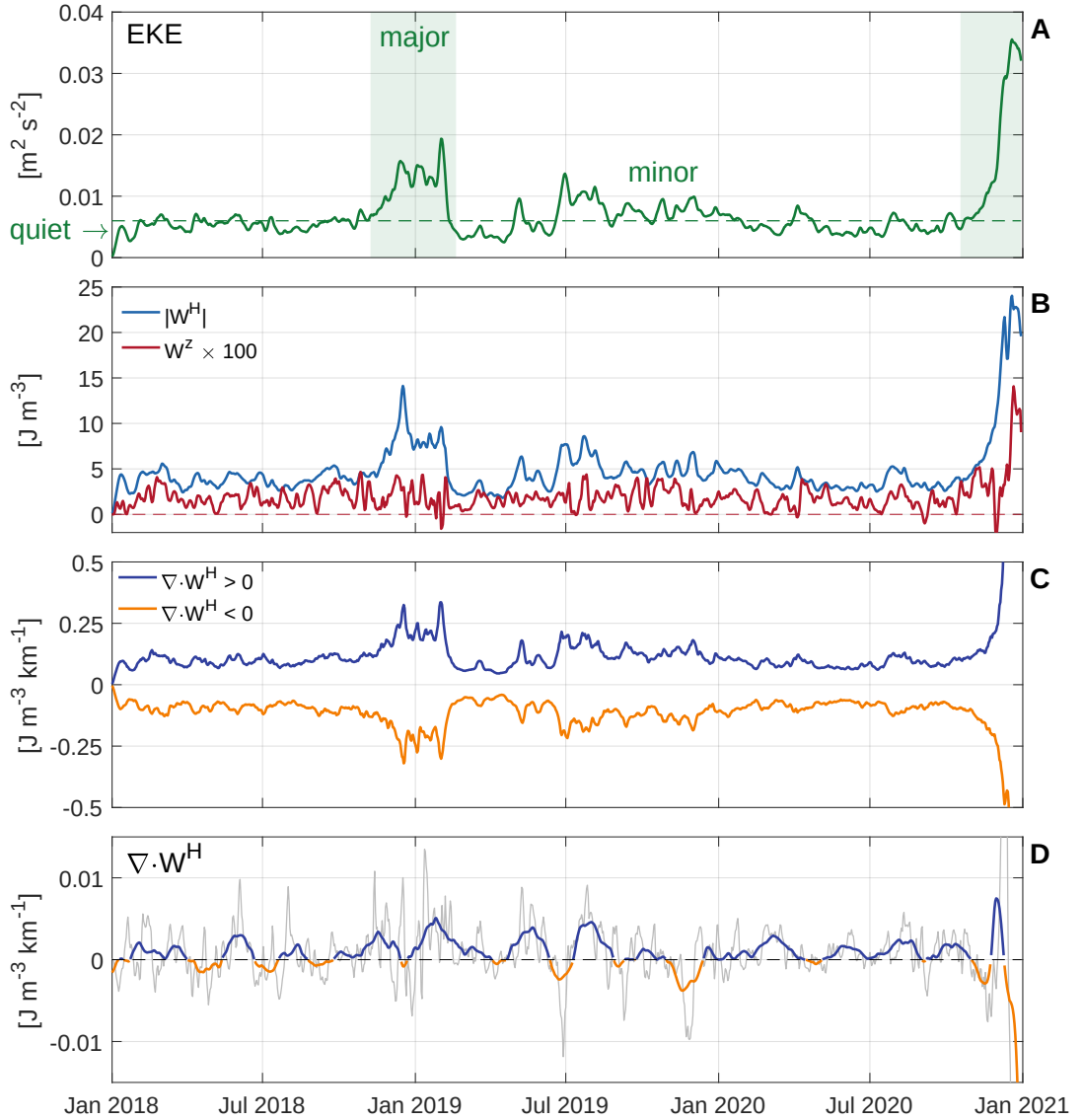


FIG. 4. Daily, domain averaged EKE (A) and wave activity flux components (B, C & D). (B) $|\mathbf{W}^H|$ in blue and $\mathbf{W}^z$ (multiplied by 100) in red. (C) spatially averaged divergence (green) and convergence (pink) of the horizontal wave activity components, each isolated by masking out negative and positive values, respectively, from the divergence field to produce separate time series representing only divergent (positive) and convergent (negative) contributions. (D) full divergence, including both positive and negative values, representing the net divergence of the horizontal wave activity vectors. In panel A, the dashed green line represents the EKE = .007 m²s⁻² which delineates quiet time periods from events. In panel B, the dashed red line represents $\mathbf{W}^z = 0$ which delineates energy conversion from the background flow to the eddy field ($\mathbf{W}^z > 0$) from the reverse ($\mathbf{W}^z < 0$).

410 The three year time series is separated into event driven synoptic storm track sections and
411 compared against a composite mean field of background or quiet time periods. Background time
412 periods are defined as those with $EKE < .006 \text{ m}^2\text{s}^{-2}$ (Fig. 4 top: dashed green line). Results
413 presented below were found to be insensitive to this threshold. Minor events are time periods
414 where $EKE > .006 \text{ m}^2\text{s}^{-2}$ but excludes the two highlighted events in January, 2019 and 2021 (Fig.
415 4), which are classified as major events.

416 *a. Background Dynamics*

417 A composite mean of the quiet time periods is used to illustrate background dynamics of the SEIR
418 storm track. Here, background is used to describe time periods exclusive of events, or significant
419 peaks in EKE. The composite background field is composed of days in which the domain average
420 $EKE < .006 \text{ m}^2\text{s}^{-2}$. Approximately 30% of the three years of model data were considered quiet
421 time periods and used for this composite background mean field (Fig. 5: top row). Here, the
422 horizontal wave activity terms are separated into eddy and ageostrophic components where the
423 divergence of the eddy terms are plotted in color and the ageostrophic terms are represented by
424 vector arrows (Fig. 5B). Monthly averages have been taken during January, February and March of
425 2018 (Fig. 5: bottom row) as these months have consistently low EKE and are used to demonstrate
426 that spatial patterns are dependent on the structure of the meander.

427 During the quiet, or background, time periods, spatial patterns of the horizontal and vertical wave
428 activity flux terms are similar to each other and have similarities to the mean field (Fig. 5A&B). $\mathbf{W}^z$
429 is positive nearly everywhere but maximum values are found within the first crest of the standing
430 meander ($\sim 56^\circ\text{S}$). Similar to the mean fields, $\nabla \cdot \mathbf{W}_{\text{eddy}}^H$ illustrates strong divergence leading into
431 the first crest followed by a region of convergence on the downstream side of the crest axis. This
432 pattern is somewhat repeated leading into the trough, divergences, of smaller magnitude, are found
433 leading into the trough axis while convergences are found exiting the trough.

440 Similar to the 3-year mean fields, EKE (Fig. 5A&B) shows very little correlation to patterns
441 of the wave activity terms. EKE is at a minimum in the crest of the standing meander, starts to
442 increase in magnitude around 152°E and continues to increase in magnitude until peaking where
443 streamlines converge as they leave the study domain. While ageostrophic flux vectors are generally

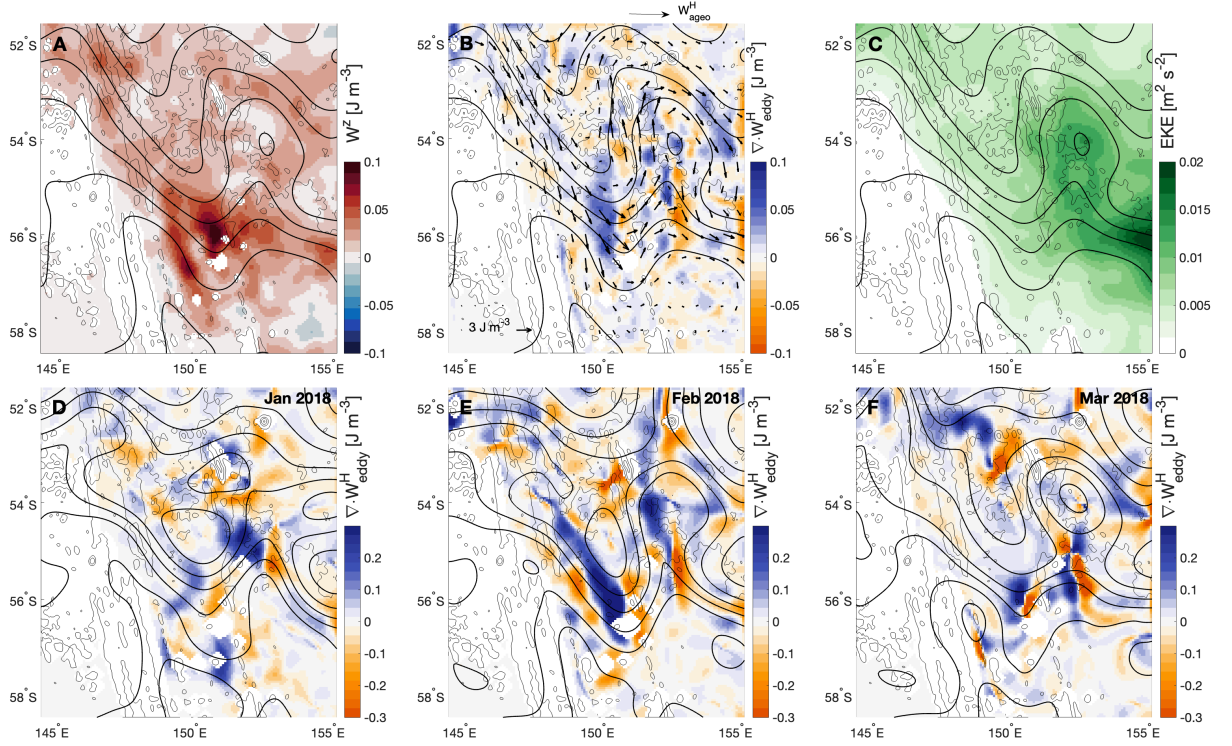


FIG. 5. Top: Composite mean fields during quiet time periods of (A) W^z , (B) $\nabla \cdot \mathbf{W}^H_{\text{eddy}}$ and vectors of $\mathbf{W}^H_{\text{ageo}}$ and (C) EKE. Bottom: monthly averages of $\nabla \cdot \mathbf{W}^H_{\text{eddy}}$ during (D) January, (E) February and (F) March of 2018. The entirety of these months are considered quiet time periods. Corresponding composite mean sea surface height in contoured every 0.2 meters in black. Bathymetry is contoured every 1000 meters in gray. Holes in the wave activity flux terms are associated with regions where the geostrophic streamfunction anomaly cannot be calculated because the water column depth is less than 3000 meters

aligned in the downstream direction, there is little evidence to suggest that, in this scenario, this ageostrophic flux is sustaining energy growth so far downstream.

Composites during months without any events, January, February and March of 2018 (Fig. 5: bottom row), are used to illustrate that patterns of $\nabla \cdot \mathbf{W}^H_{\text{eddy}}$ are persistent but depend on the structure of the meander. Namely, regions of strong divergence upstream from and leading into the crest/trough axis followed by regions of strong convergence downstream from the crest/trough axis. This pattern is observable in the first crest of the mender in both the 3-year mean (Fig. 3B) and the background composite (Fig. 5B) because, we hypothesize, this first crest of the standing meander is extremely stationary, remaining locked in place near $\sim 150.5^\circ\text{E}$ at all times. It does appear that more intensified meanders will also intensify the magnitude of the divergence and convergences

such as in February 2018 (Fig. 5E). Downstream, the trough of the meander is far more active, and divergence and convergence hot spots will be modified depending on the location and intensity of the trough axis. For example, in January 2018, the meander is in a more retracted state and peaks in $\nabla \cdot \mathbf{W}_{\text{eddy}}^H$ are concentrated to a much smaller region and located further south compared to the subsequent month when the meander is far more extended (Fig. 5D&E, respectively).

Figure 6 schematically illustrates the background patterns of both the horizontal and vertical components of wave activity flux that are not tied to transient events. Divergence and convergence of the horizontal wave activity terms, $\mathbf{W}_{\text{eddy}}^H$ are indicated by purple and orange circles, respectively. The vertical component $\mathbf{W}^Z$, is overlaid along ACC jets of the standing meander and is uniformly positive, but notably intensified within the crest of the stationary meander. Regions of horizontal divergence are located upstream from crest/trough axes while regions of horizontal convergence are located downstream from crest/trough axes. These divergence and convergence patterns are more variable within the first trough, where the ACC jets exhibit less stability, compared to the more consistent structure near the crest. The bathymetry likely plays a critical role in anchoring this first crest between two ridges, potentially explaining the uniquely persistent divergence observed that could be unique to the SEIR region.

b. Minor Event

The temporal evolution of a single minor storm track event is documented in Fig. 7. During this month-long time period, which just precedes the first major event, the storm track is characterized by a large, relatively extended, standing meander. The northernmost streamlines constitute the primary meander, while the interior streamlines facilitate a more direct route across the SEIR region. The southernmost streamline formulates an independent meander which appears much less energetic than the primary meander. During this particular event, energy develops and is fluxed along the interior streamlines, translating directly across the domain as opposed to along the meander. Other minor events that were observed at different time periods will translate energy around the meander, or most commonly, along both pathways simultaneously. This time period is chosen as it most clearly and cleanly illustrates the dynamics that transpire during minor events.

The development and flux of energy during this minor event is demonstrated at four time steps during the month long period. The horizontal wave activity flux term is decomposed into its eddy

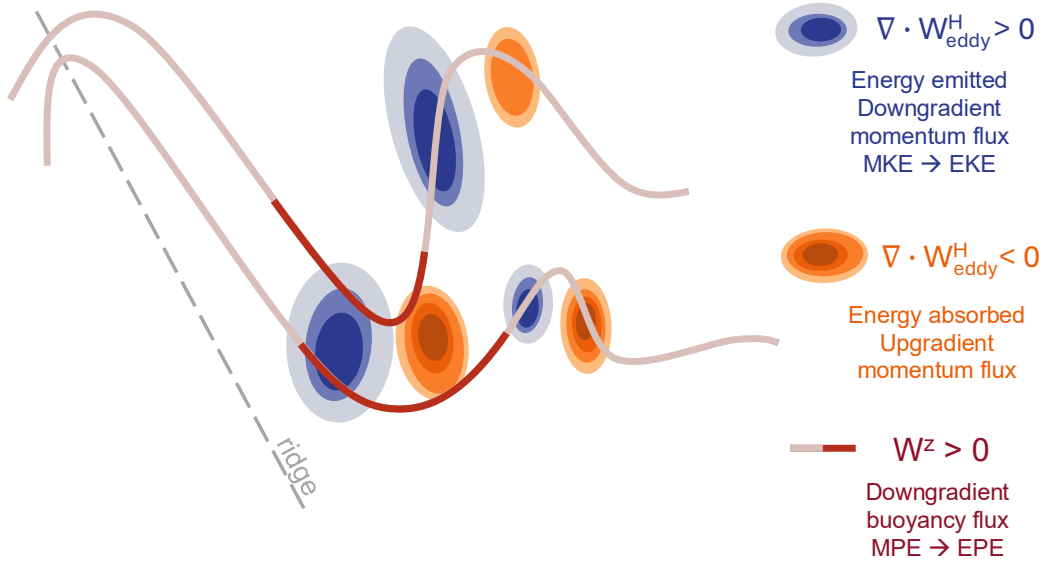


FIG. 6. Schematic illustrating patterns of $\mathbf{W}_{\text{eddy}}^H$ and W^z that occur during non-event time periods and are considered background dynamics. Purple regions indicate where the $\mathbf{W}_{\text{eddy}}^H$ field diverges and orange regions indicate where the $\mathbf{W}_{\text{eddy}}^H$ field converges. The W^z patterns are overlaid in red on streamlines of the meander. Darker colors indicate larger magnitudes. The idealized location of the ridge is indicated by the gray dashed line.

and ageostrophic components (Fig. 7 top) such that $\nabla \cdot \mathbf{W}_{\text{eddy}}^H$ is illustrated in color and $\mathbf{W}_{\text{ageo}}^H$ vector arrows are overlaid. The divergence terms are compared against the vertical wave activity flux (Fig. 7 middle) and energy terms (Fig. 7 bottom). Each column of Fig. 7 represents a single time step at 7 day intervals from September 11 to October 2, 2018.

In the horizontal (Fig. 7 top), a pattern of wave-train like energy growth, emission and subsequent convergence emerges. At the start of this minor event, a perturbation develops in the northwest corner of the domain, as streamlines propagate off the topography. This perturbation is characterized by a secondary, smaller meander of wavelength ~ 200 km, embedded within the larger meander. This secondary meander exhibits strong alternating divergences and convergences of $\mathbf{W}_{\text{eddy}}^H$ as the perturbation propagates through the storm track. Specifically, regions of strong divergence are localized near, or just slightly downstream from, the axes of this secondary meander. Just downstream, between meander axes, are regions of strong convergence. Ageostrophic flux vectors emit from the divergent peaks and presumably act to transport recently generated energy further downstream, into convergent peaks, in the direction of the background flow. This wave-train

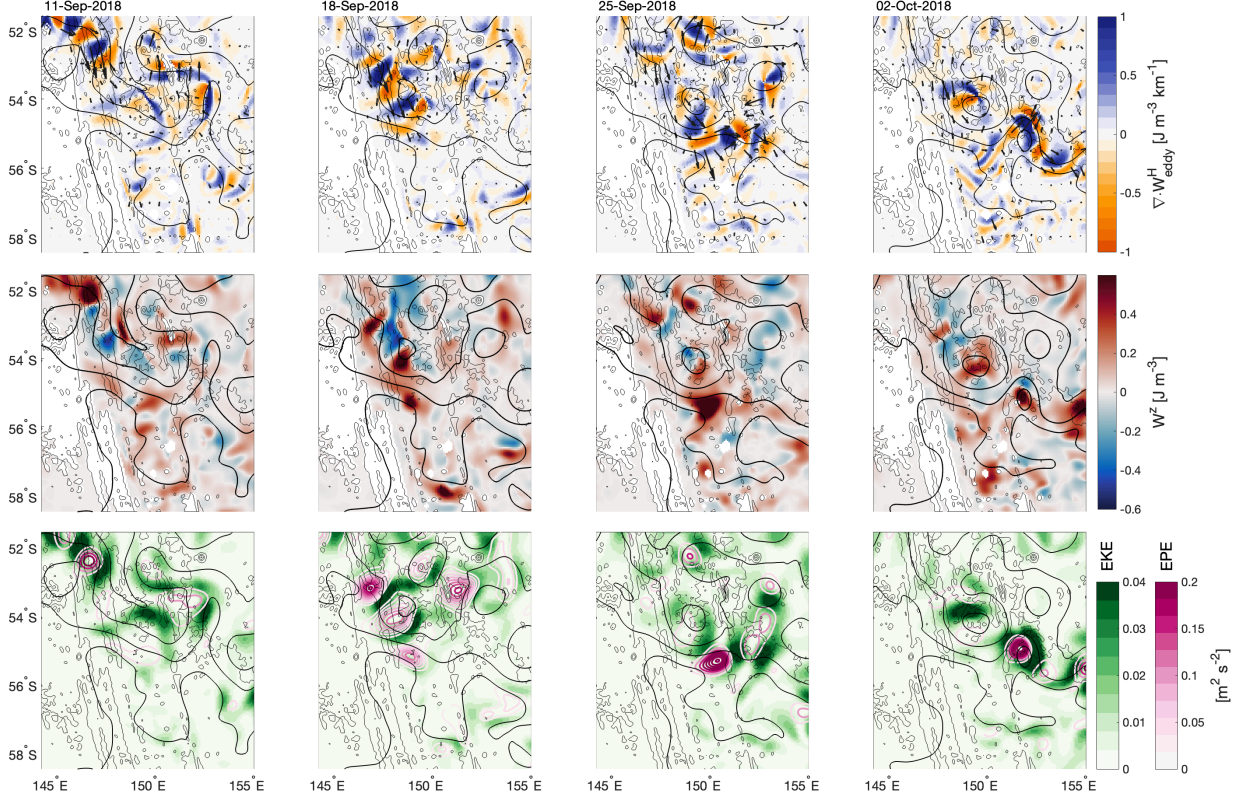


FIG. 7. A case study illustrating the temporal evolution of a minor event from September 11 – October 2, 2018.

Each column is a single time step at 7 day intervals. The horizontal wave activity flux (top) is decomposed into eddy and ageostrophic components such that the divergence of $\mathbf{W}_{\text{eddy}}^H$ is plotted in color while the ageostrophic vectors are superimposed in black and plotted at every half degree. The vertical wave activity flux term, $\mathbf{W}^z$ is in the middle row and eddy energy terms are on the bottom. Eddy energy is separated into EKE (green filled contours) and EPE (pink open contours). Daily mean sea surface height is contoured every 0.4 meters in black. Bathymetry is contoured every 1000 meters in gray.

like feature of alternating divergence and convergence propagates through the storm track as the original hot spot of energy decays and another forms further downstream suggesting an evolution through the transmission of wave energy.

Associated with these hot spots of $\nabla \cdot \mathbf{W}_{\text{eddy}}^H$ are localized peaks in $\mathbf{W}^z$, the vertical component of the wave activity flux (Fig. 7 middle). $\mathbf{W}^z$ appears to be positive and relatively enhanced in the regions where alternating divergent and convergent peaks characterize these secondary meanders. However, peaks of $\mathbf{W}^z$ are typically not aligned with peaks of $\nabla \cdot \mathbf{W}_{\text{eddy}}^H$ and can grow, decay and

propagate independently. The ageostrophic horizontal flux does not systematically emanate away from $\mathbf{W}^z$ maxima to support an adjacent downstream growth of eddy energy as does for $\mathbf{W}_{\text{eddy}}^H$. In contrast, regions of enhanced ageostrophic flux can sometimes be collocated with regions of large negative $\mathbf{W}^z$ values, indicating energy loss from the eddy field. Additional $\mathbf{W}^z$ peaks of similar magnitude can also be found isolated from the hot spots of horizontal wave activity flux.

Energy terms, EKE and EPE, however are strongly linked to the horizontal wave activity flux terms (Fig. 7 bottom). Regions of horizontal wave activity divergence coincide with pronounced peaks in EPE, while convergent regions align with local maxima in EKE. This spatial configuration suggests a barotropic energy conversion mechanism in which energy is extracted from the mean flow in divergence zones, where it then accumulates as EPE. Energy is then effectively radiated downstream via the ageostrophic flux that becomes intensified within the axes of the secondary meander. As this energy converges, it is converted into kinetic form, sustaining local peaks in EKE. This phasing, with EPE aligned with divergence and EKE aligned with convergence, is consistent with a wave-mediated energy transfer process in which eddies are generated upstream and intensify downstream through a combination of barotropic growth and wave energy propagation. These patterns and propagation sequence are illustrated schematically in Fig. 8A.

537 *c. Major Event*

The temporal evolution of the horizontal wave activity flux terms during the major event centered around January 2019 is documented in Fig. 9. During this four month long event (November, 2018 – February, 2019), the typical translation of alternating divergence and convergence propagating through the SEIR storm track region is obstructed due to a deeply extended meander. This orientation of the meander establishes a blocking pattern that forces energy to remain trapped, recirculating around the interior closed sea surface height contours over a number of months, locally increasing EKE (Fig. 4). This blocking pattern is illustrated schematically in Fig. 8B.

The extended meander is formed in early November. Spatial patterns of the horizontal wave activity flux terms resemble the minor events. Eddy energy is generated at the expense of the mean flow and simultaneously fluxed downstream where it converges and is transferred into EKE, illustrated by alternating patterns of divergence and convergence of $\mathbf{W}_{\text{eddy}}^H$. In contrast to the minor event documented in Fig. 7, this event is characterized by energy flux along the equatorward

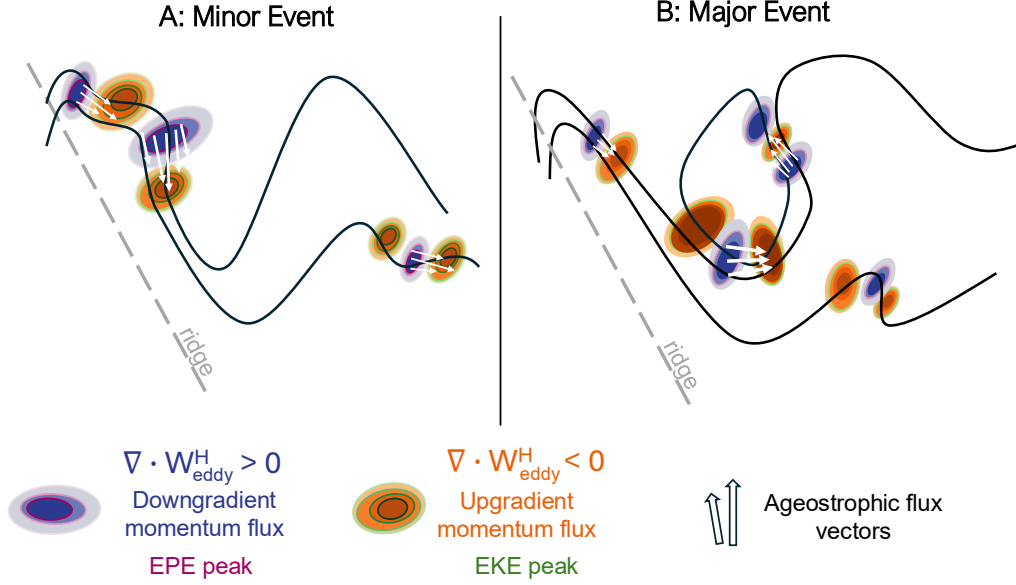
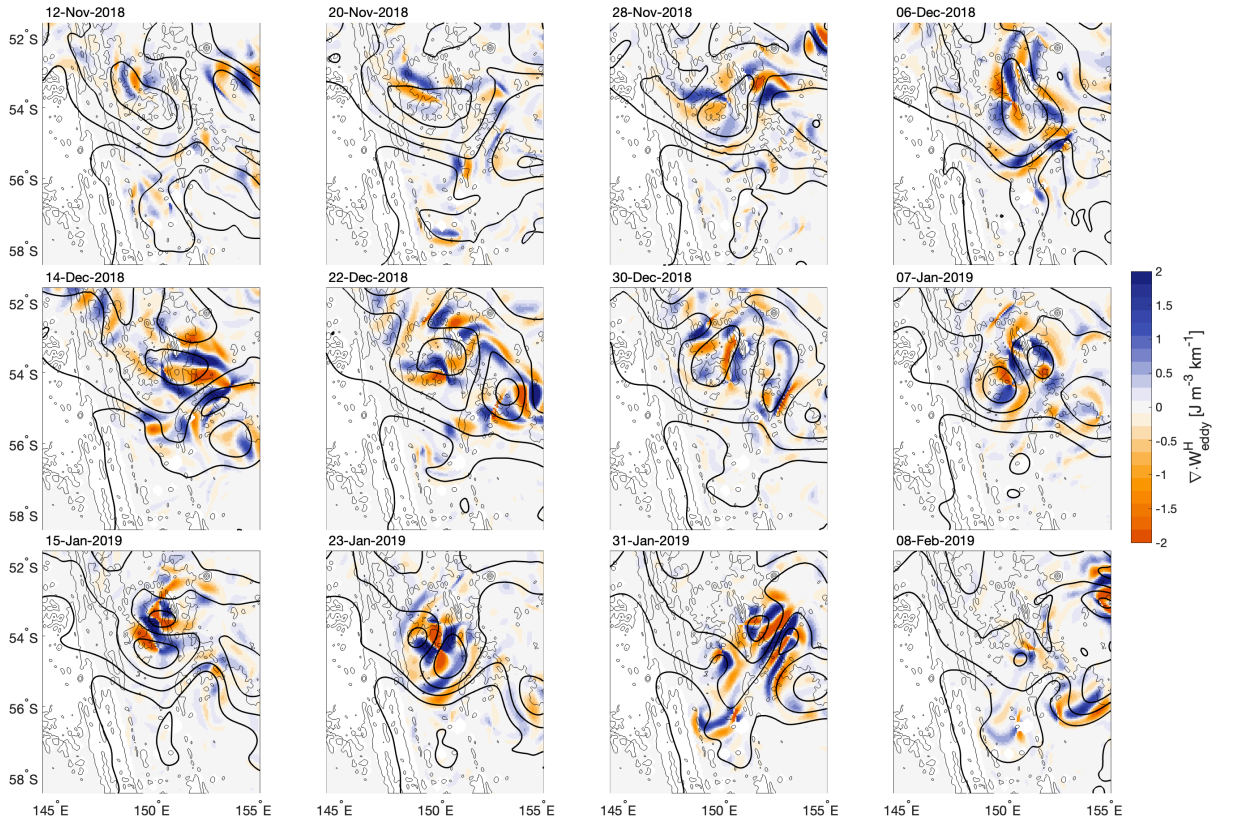


FIG. 8. A simplified schematic illustrating wave activity flux during a minor (A: left) and major (B: right) event. Closed purple contours outlined in pink represent hot spots of divergence, namely $\nabla \cdot \mathbf{W}_{\text{eddy}}^H > 0$ and collocated peaks in EPE. Closed orange contours outlined in green represent hot spots of convergence, namely $\nabla \cdot \mathbf{W}_{\text{eddy}}^H < 0$ and collocated peaks in EKE. White arrows illustrate the horizontal ageostrophic fluxes, $\mathbf{W}_{\text{ageo}}^H$. Black lines are representative of the ACC streamlines or jets of the standing meander. Dashed gray line indicates the topographic ridge.

streamlines and thus around the meander. However, due to the extended configuration, these perturbations are obstructed from eastward translation and forced to recirculate around the closed cyclonic ring in the center of the meander. By the end of November, a second perturbation of energy growth and subsequent flux develops leading into the trough of the meander. At this point, an anticyclonic ring has separated from the trough of the primary meander and it appears as if this perturbation could continue to flux eastward. However, the ring quickly reattaches and this second energy growth hot spot is forced to recirculate into the center of the meander.

In early December, the two energy hot spots being fluxed cyclonically around the center of the meander converge together, rapidly increasing the magnitude of EKE and $\mathbf{W}_{\text{eddy}}^H$ divergences/convergences (Figure 9: Dec. 14). The meander is detached again and some energy is able to escape and translate eastward while the meander is in this temporarily retracted state. Subsequently however, the meander reattaches and energy is fluxed north before being recirculated

562 into the interior again. At the end of December, an anticyclonic ring briefly forms to the east of the
 563 cyclonic ring, within the second (downstream) wavelength of the meander. Some energy is gener-
 564 ated and fluxed around this anticyclonic ring however by the middle of January, the energy hotspots
 565 have converged again. Energy continues to grow, dramatically increasing the magnitude of $\mathbf{W}_{\text{eddy}}^H$
 566 while continuously recirculating in the center of the meander. At the beginning of February, the
 567 meander recedes and the trough moves slightly eastward, allowing this wave-train of divergences
 568 and convergences to break from the blocking pattern and finally escape along streamlines.



569 FIG. 9. Major event case study illustrating the temporal evolution from November, 2018 – February, 2019.
 570 Each panel represents a single time step at 8 day intervals illustrating the divergence of the horizontal eddy wave
 571 activity flux terms, $\nabla \cdot \mathbf{W}_{\text{eddy}}^H$. For visual purposes, the ageostrophic flux vectors are omitted however the pattern
 572 flux from regions of divergence to regions of convergence, in the along-stream direction, holds during blocking
 573 events. Daily mean sea surface height is contoured every 0.4 meters in black. Bathymetry is contoured every
 574 1000 meters in gray.

General patterns of EKE, EPE and $\mathbf{W}^Z$ (not shown) in relation to $\nabla \cdot \mathbf{W}_{\text{eddy}}^H$ are consistent with that of the minor event case study (Figure 7). EPE maxima are spatially collocated with hot spots of energy conversion from the background to eddy field, represented by divergences in the $\mathbf{W}_{\text{eddy}}^H$ field, and strong ageostrophic flux vectors. EKE peaks are spatially collocated with convergences and accumulation of wave activity. EKE rapidly grows with both the magnitude of the horizontal wave activity terms and the $\nabla \cdot \mathbf{W}_{\text{eddy}}^H$, as illustrated in Fig. 4. Broad regions of positive $\mathbf{W}^Z$ correspond to $\mathbf{W}_{\text{eddy}}^H$ divergences/convergences but growth and decay occurs in a manner and pattern independent of $\mathbf{W}_{\text{eddy}}^H$. Additionally, the vertical component does not exhibit the same consistent growth as the horizontal components during this blocking event and large positive growth is typically accompanied by comparably large negative sinks. This suggests energy from both momentum and buoyancy pathways is being rapidly exchanged between the eddy and background fields during these large events but both pathways supply a net gain in energy to the system and therefore both contribute to the large peaks in EKE observed in Fig. 4 during the major events.

5. Discussion

The wave activity flux framework, originally formulated for atmospheric storm tracks by Takaya and Nakamura (2001), is used here to diagnose the dynamics of eddy-mean field interactions in the SEIR region of the Southern Ocean. It is used as an alternative to the energy budget diagnostics traditionally employed in oceanographic studies as it allows for direct and unique interpretation of terms related to the conversion and flux of energy. Specifically, $\mathbf{W}_{\text{eddy}}$ terms correspond to energy conversion between the mean flow and the eddy field while $\mathbf{W}_{\text{ageo}}$ is concerned with ageostrophically induced energy fluxes that can translate energy downstream from generation sites.

These terms can be further decomposed to diagnose the contribution from both barotropic and baroclinic instability pathways. The barotropic pathway, which directly converts MKE to EKE through eddy momentum fluxes in response to strong horizontal velocity shear, is represented by the horizontal wave activity flux terms. Diagnosing the divergence of these horizontal wave activity flux terms, $\nabla \cdot \mathbf{W}_{\text{eddy}}^H$, identifies energy source and decay regions that describe the feedback between the mean state and eddy field. The baroclinic pathway, which initially converts APE

to EPE through a downgradient horizontal buoyancy flux across the background mean field, is represented by the magnitude and sign of the vertical wave activity flux terms $\mathbf{W}^z$.

a. Baroclinic or Barotropic Instabilities?

A striking feature of the background fields and individual case studies is the presence of both large positive peaks of $\mathbf{W}^z$ and strong divergences of $\mathbf{W}^H$ in the lee of the ridge, often associated with the first crest of the standing meander. This points to a mixed but independent baroclinic-barotropic instability regime downstream from the Southeast Indian Ridge.

Consistent with many studies that have diagnosed energy budgets in the southern ocean (e.g. Matsuta and Masumoto 2023; Matsuta et al. 2024; Wu et al. 2017), the baroclinic terms tend to be more persistent and, when averaged temporally, can dominate the energy conversion terms. This is illustrated by the composite mean fields which show positive values of $\mathbf{W}^z$ across the array (Figs. 3 & 5), as well as by the time series in which $\mathbf{W}^z$ averaged spatially at each time point, remains positive throughout the record (Fig. 4B). However, consistent with the findings of Matsuta and Masumoto (2023), who identifies the SEIR region as uniquely characterized by a mixed instability in which the barotropic pathway accounts for approximately 40% of EKE generation, we demonstrate that the barotropic pathway is non-negligible and can play a significant role in Southern Ocean storm track dynamics, especially during event driven time periods.

In the time mean and during composite background time periods, a region leading into the crest of the standing meander is consistently characterized by strong divergence of $\mathbf{W}^H$, indicating a source region of wave activity where energy is converted from the mean flow, likely through barotropic conversion associated with horizontal velocity shear. These regions of divergence are typically accompanied by an area of relatively strong convergence, suggesting that emitted eddy energy is absorbed locally, a pattern consistent with energy transfer from the eddy field back into the mean flow. However, during more than 70% of the temporal record, the spatially averaged divergence terms exceed the convergence (Fig. 4D), indicating a small, especially in comparison to the barotropic field, but notable net gain of energy from the mean field.

The barotropic pathway becomes more significant however, during event driven periods, when spatially averaged EKE increases above the background threshold. The elevated values in EKE consistently correspond to elevated values in the horizontal wave activity terms whereas the vertical

terms typically remain relatively stable, often with no discernible peaks (Fig. 4). As in the mean, elevated values of horizontal divergence are accompanied by elevated convergences however the divergences are consistently larger suggesting that even a small net transfer of energy along the barotropic pathway can result in a large gain in EKE. This points to a potentially critical role for barotropic dynamics in shaping and sustaining the storm track during event driven periods.

It is during these event driven time periods where wave-train like features of alternating $\mathbf{W}^H$ divergence and convergence propagate through the storm track. These divergences and convergences are associated with spatial patterns of EKE and EPE, respectively, further suggesting that energy generation is more tightly linked to the barotropic pathway, especially in an event-like configuration of the storm track. This wave-train like propagation through the storm track is analogous to downstream development and discussed in more detail in the subsequent section.

The finding that the barotropic energy conversion pathway is non-negligible especially during event driven periods is consistent with the results of Youngs et al. (2017), who used an idealized channel model of the ACC to demonstrate that barotropic instabilities become increasingly important as the meander develops and horizontal shear intensifies. In their simulations, both barotropic and baroclinic instabilities are identified in the same locations, just upstream of the first crest of the standing meander, consistent with our observed region of collocated strong positive values of $\mathbf{W}^Z$ and spatial divergences of $\mathbf{W}^H$. However, their temporal analysis did not reveal the propagating wave-train like disturbances captured here. It is also possible that the prominence of barotropic energy conversion documented here is unique to the SEIR region, potentially due to the influence of local bathymetry. This is consistent with Matsuta and Masumoto (2023) who used a general circulation model to examine energy pathways within a Lorenz energy cycle framework. They found that while EKE downstream of most Southern Ocean ridge systems is generated almost entirely by baroclinic conversion, in the SEIR region baroclinic conversion is suppressed and barotropic instability contributes significantly to EKE generation.

b. EKE Offset

Numerous studies have observationally documented a spatial offset between locations of baroclinic instability and localized hot spots of EKE, which typically occur 100 - 500 km further downstream (e.g. Foppert 2019). Conclusively linking this offset to a physical mechanism of

energy flux or time delay has been challenging however and remains an open question. Here, we address these mechanisms using the wave activity flux framework, which provides information on both the baroclinic and barotropic energy pathways. We split our discussion into two parts: patterns of EKE in the background state, when the baroclinic pathway dominates and patterns of EKE during events, when the barotropic pathway dominates.

During the background periods, EKE is elevated along the eastern edge of the study domain, downstream from the standing meander, where streamlines converge again (Fig. 5C). Notably, this region of peak EKE is not spatially aligned with local maxima in either the baroclinic or barotropic energy conversion terms. In contrast, $\mathbf{W}^z$ and divergence of $\mathbf{W}^H$ exhibit local peaks upstream, leading into the crest of the first meander, where EKE begins to grow in the along-stream direction. This suggests that neither the baroclinic nor the barotropic pathways alone can account for the observed spatial pattern of EKE in the background state. Another possible explanation for this displacement is energy transport via the ageostrophic flux. However, this term also peaks near the crest of the meander and diminishes further downstream where EKE is the largest. This spatial structure makes it unlikely that the ageostrophic flux alone is responsible for the observed offset in EKE.

Of previously proposed mechanisms, this leaves two possibilities: either EKE is rapidly advected downstream from its generation site (Yung et al. 2022) , or there exists a time lag between the onset of instability and the full development of EKE due to a cascade to smaller eddies (Chen et al. 2016). While we do not explicitly resolve either mechanism in this study, we hypothesize that they are not mutually exclusive or dynamically distinct and may act in concert to produce the displaced EKE maxima observed in the background fields. This points to non-local sources of energy in the background state of the Southern Ocean, consistent with Chen et al. (2014), who found that in these regions, along with western boundary extensions, energy is exported long distances and can influence mean flow far from its original generation site.

In contrast to the background state, during event driven periods, local peaks in EKE are closely aligned with strong divergences in $\mathbf{W}^H$, suggesting that EKE is being generated by barotropic instabilities redistributing energy from the mean flow to the eddy field. This alignment indicates that, during energetic events, the displacement between baroclinically unstable regions and EKE maxima can be attributed to a closer relationship with the barotropic field than previously under-

stood. The apparent offset reflects a shift in the dominant energy pathway rather than a physical separation between energy input and eddy growth.

Additionally, event periods are marked by patterns of sequential energy growth, flux and decay that are characteristic of downstream development (Orlanski and Chang 1993). In the atmosphere, downstream development is a well documented process in which a region of baroclinic growth leads to energy formation which then becomes a source of energy for further development downstream. This occurs through the transfer of energy by ageostrophic motions, allowing disturbances to propagate along the mean flow, through a chain of successive energy conversions, to amplify disturbances further downstream. This creates a spatial and temporal sequence of growth and decay that reinforces and sustains the storm track.

Consistent with this mechanism, our analysis reveals that within smaller, secondary meanders embedded in the larger standing meander, there are localized hot spots of $\mathbf{W}^H$ divergence located between the crest and trough of the secondary meanders, coinciding with local maxima in EKE. Within the axes themselves, extending from the divergence peaks, we find strong ageostrophic flux vectors oriented in the downstream direction, indicating that barotropic energy locally generated is quickly being transported away from its generation site. Between subsequent axes, regions of $\mathbf{W}^H$ convergence are identified suggesting that energy is being converted back into the mean field. This spatial pattern suggests a repeating wave train-like structure: energy is generated upstream of the meander axes, transferred downstream through enhanced ageostrophic motion within the curvature of the axes, and partially converted back to the mean field on the downstream side. The residual energy that is not lost to the mean continues propagating and contributes to the formation of the next energy center further downstream. Together, these interactions help to sustain a chain of downstream development, effectively maintaining the storm track during energetic events. These processes are illustrated schematically in Fig. 8 (left side).

Here, we find that downstream development in the SEIR region is closely linked to the barotropic energy pathway, in contrast to the atmosphere where downstream development is typically associated with baroclinic processes. Although relatively large positive values of $\mathbf{W}^Z$ are present near the propagating features (Fig. 7), patterns of EKE are much more tightly linked to the structure of the barotropic field. Therefore, during event driven periods, any observed offset between regions of baroclinic instability and EKE maxima can be attributed to both a larger influence from

721 the barotropic energy conversion terms and also to ageostrophic fluxes that are responsible for
722 transporting energy and sustaining the storm track, in a mechanism analogous to downstream
723 development. The relative role of barotropic and baroclinic instabilities and relationship to EKE
724 however should be further addressed both observationally and in other topographic regions of the
725 Southern Ocean.

726 *c. Dynamics and Altimetry Comparison of the Block*

727 Major events are characterized by the growth and decay patterns of barotropic downstream
728 development which become arrested due to a deeply extended meander and forced to recirculate
729 around the interior closed sea surface height contours (Fig. 8: right side). During this recirculation,
730 perturbations are essentially blocked from translating eastward and continue to extract energy from
731 the mean flow, primarily along the barotropic conversion pathway, resulting in extremely elevated
732 values of EKE. This blocking pattern is similar to an atmospheric omega block, a weather pattern
733 characterized by a poleward high-pressure system flanked by two equatorward lows. Omega blocks
734 are persistent patterns and lead to prolonged periods of stable weather in high-pressure regions
735 while flanks experience more unsettled conditions. The persistence of omega blocks occurs because
736 the high-pressure system becomes cut off from the steering currents. These currents, which would
737 typically act to dislodge the blocking pattern, diverge around the high pressure system, isolating it
738 from the mean flow and allowing it to remain stationary for an extended period of time.

739 There exists a significant body of research pertaining to the dynamics and detection of atmo-
740 spheric blocks due to their impact on weather systems. However, the mechanisms governing the
741 onset of blocking are still poorly understood. In many cases, blocking occurs when a quasistation-
742 ary meander amplifies to obstruct the eastward propagation of transient waves or eddies. Nakamura
743 and Huang (2018) describe blocking dynamics as akin to a traffic jam in the jet stream. Just as
744 a highway has a limited capacity for traffic, the jet stream has a limited capacity for meandering.
745 When this is exceeded, a traffic jam ensues in response to a slowdown of the eastward wind (cur-
746 rent) speed. This leads to a convergence of wave activity flux and a rapid accumulation of density,
747 triggering block formation. This process mirrors the blocking patterns observed in this study and
748 underscores the role of stationary meanders in block formation. Consequently, it is not surprising
749 that atmospheric blocks often originate near mountain ridges (Charney and DeVore 1979; Tung

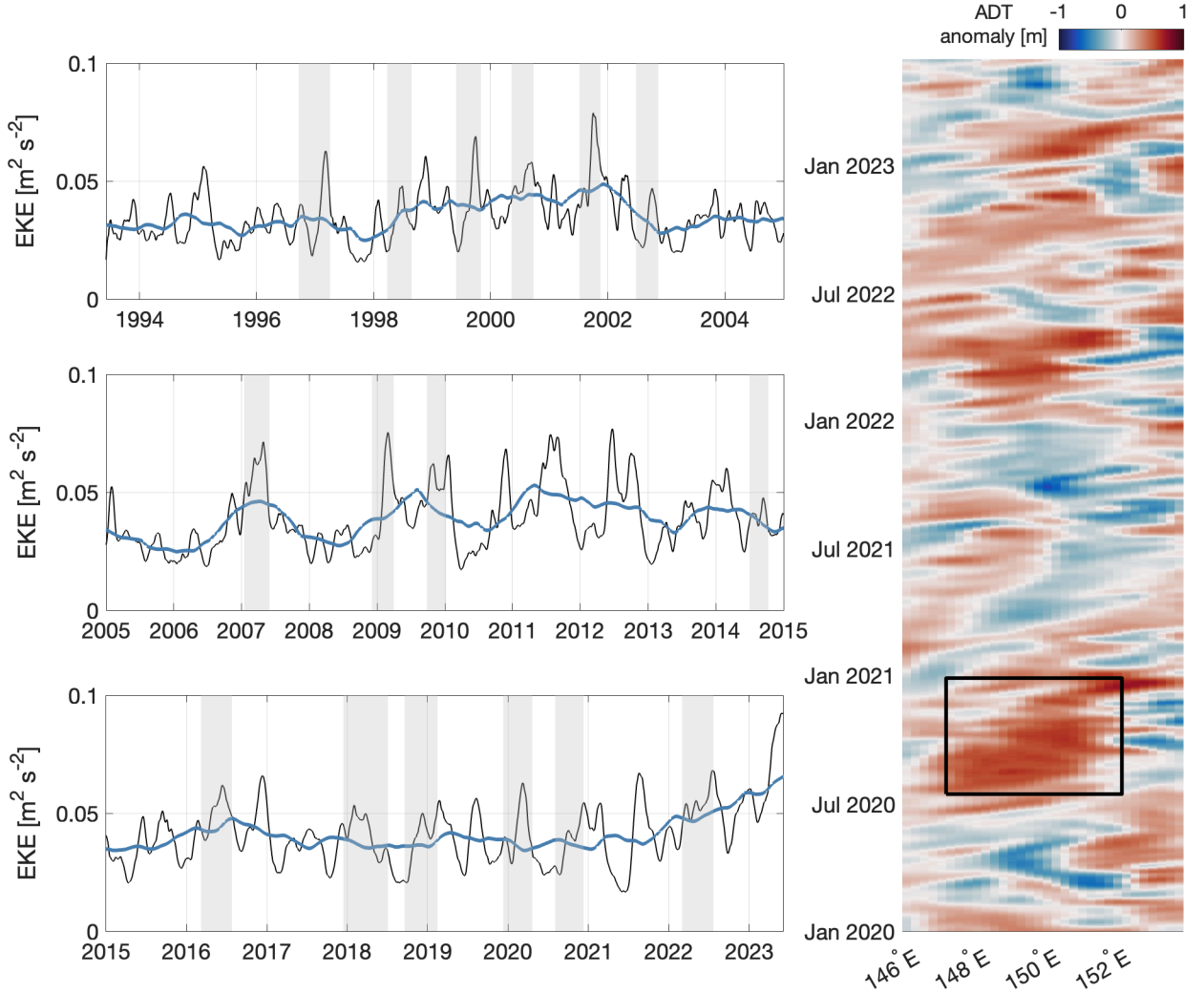
750 and Lindzen 1979; Luo 2005) and, once formed, tend to remain intact for a longer duration (Nar-
751 inesingh et al. 2020). Typically, a block is released when accumulated wave activity translates
752 downstream in the form of a stationary Rossby wave train however the mechanisms governing the
753 release of a blocking event are also not well resolved.

754 While the dynamics documented here appear analogous to atmospheric blocking patterns, there
755 are some discrepancies as well. Namely, in the atmosphere, blocks remain in place for 5 – 10 days
756 which is significantly shorter than the approximately 3 month long event observed in the SEIR
757 region. While we expect oceanic time scales to be longer than those in the atmosphere, 3 months
758 is still significantly larger than the 4 – 6 weeks more typical of oceanic time scales.

759 To explore this discrepancy, justify the atmospheric comparison and confirm the existence of
760 these features independent from the numerical model, we look to 30 years of satellite altimetry in the
761 SEIR region. Gridded at 0.25° resolution, absolute dynamic topography (ADT) and geostrophic
762 velocities are obtained from Copernicus Marine Service (<https://doi.org/10.48670/moi-00148>).
763 Blocking events are classified in the 30 year record as positive ADT anomalies that are stationary
764 and persistent for an extended period of time as identified from a Hovmöller across 53°S (Fig. 10
765 right side black box). Events identified from the Hovmöller are subsequently confirmed using the
766 daily sea surface height fields. Within the 30 year record, 16 blocking events are identified. Each
767 blocking event is highlighted by a gray shaded region in Fig. 10 (left side). Consistent with our
768 HYCOM analysis, these blocking events persist, on average, for about five months and range in
769 length from two to ten months. They are not evenly distributed in time and tend to occur more
770 frequently during prolonged periods of elevated EKE.

771 In contrast to the HYCOM-derived EKE between 500 - 1000 meters (Fig. 4), surface EKE peaks
772 associated with blocking events are not distinguishable from synoptic peaks that occur throughout
773 the time series (Fig. 10 left side). In other words, blocking events cannot be simply identified
774 as the major peaks in domain averaged EKE. Blocking events are slightly more anomalous in the
775 array averaged ADT² time series (proxy for EPE - not shown) however neither term can be used in
776 isolation to identify blocking events. Additionally, composite fields of EKE during each blocking
777 time period present a much different pattern than what was observed in HYCOM (not shown).
778 While HYCOM-derived EKE tends to peak in the center of the high pressure system, altimetry
779 suggests maximum values of EKE are more commonly found further downstream and along the

780 perimeter of the local high. Finally, while outside the scope of this work, we want to highlight
 781 the significant increase in EKE from 2020 to the end of the time series (mid-2023) resulting in
 782 the largest EKE values throughout the 30 year record. It is conceivable this increase illustrates
 783 an uptick in the eddy driven arm of the Southern Ocean overturning circulation however a more
 784 detailed analysis of long term variability will be needed to address this possibility.



785 FIG. 10. Identification of blocking events using 30 years of satellite altimetry. Left: Domain averaged EKE
 786 plotted as a 30-day running mean (black) and 360-day running mean (blue). Gray shaded regions indicate time
 787 periods that have been identified as blocking events. Right: Hovmöller of absolute dynamic topography anomaly
 788 at 53°S. Black box highlights a blocking event that occurred from July 2020 - December 2020.

789 Given that these storm track blocking events are recurrent and persistent features of the SEIR
790 region, it is reasonable to assume they may have significant implications for mixing and heat
791 transport. We hypothesize that during these events, huge quantities of fluid are exchanged across
792 fronts resulting in large local eddy heat fluxes and tracer diffusivities. Relatively warm water
793 may be temporarily confined to the center of the recirculating high pressure anomaly, impacting
794 local air-sea interactions. Additionally, as strain and curvature in the flow increases, submesoscale
795 gradients and enhanced filamentation likely result from strong vertical velocities on the periphery
796 of the block. These processes could locally impact nutrient supply to the surface, carbon subduction
797 and ventilation of the thermocline.

798 *d. The Big Picture*

799 The results presented here build on and expand our understanding of Southern Ocean storm track
800 dynamics by prior observational and modeling efforts. In particular, using a primitive equation
801 model with idealized topography, Chapman et al. (2015) highlighted the role of topographically
802 anchored standing meanders in modulating storm track variability, showing that EKE is not uni-
803 formly distributed but rather concentrated downstream of major bathymetric features. By utilizing
804 the wave activity flux framework, they propose a southern ocean storm track characterized by inten-
805 sified buoyancy gradients within the first few wavelengths of the meander. The resulting baroclinic
806 instability is the primary driver of energy conversion from the mean flow field to the EPE field and
807 is followed by a rapid conversion to EKE which increases in the along stream direction. Energy
808 is subsequently transported downstream by the ageostrophic flux of geopotential which maintains
809 the storm track, and thus EKE, well downstream from the baroclinically unstable region.

810 Observational work by Foppert (2019) similarly documented a systematic spatial offset between
811 regions of eddy heat flux and EKE maxima in Drake Passage. Once again deploying the wave
812 activity, this work confirms a vertical eddy momentum flux associated with baroclinic instability
813 however also documents horizontal eddy momentum fluxes associated with the barotropic pathway.
814 She demonstrates that enhanced values of vertical and horizontal wave activity flux are collocated in
815 both space and time, suggesting a mixed instability that occurs and intensifies jointly. Additionally,
816 Foppert (2019) finds that time mean fluxes are largest within the first half wavelength of the
817 meander immediately in the lee of the ridge, a shorter spatial scale than Chapman et al. (2015)

originally proposed. While Foppert (2019) does find that the ageostrophic fluxes dominate the horizontal wave activity terms, the spatial extent of the array limits the identification of downstream development and maintenance of the storm track away from the energy conversion sites.

The findings presented here confirm previously established dynamics, update existing paradigms, and enhance our understanding of the physical mechanisms governing storm track dynamics in the SEIR region of the Southern Ocean. Like Foppert (2019), we identify a clear role for the horizontal eddy momentum fluxes in redistributing energy between the mean and eddy field. While these fluxes are not negligible in the background, their importance and relative contribution becomes elevated during event driven time periods when local maxima of EKE are identified. We also find that fluxes are largest within the first half wavelength of the meander immediately in the lee of the ridge, however this is complicated by the geometry of the meander in which the crest is the extremely stable in space and time while the trough is far more variable, likely a consequence of the local bathymetry.

Foppert (2019) identifies a recurring dynamical signature in the Drake Passage characterized by elevated values of both horizontal and vertical eddy wave activity fluxes, $\mathbf{W}_{\text{eddy}}^H$ and $\mathbf{W}_{\text{eddy}}^Z$ respectively, just downstream from the ridge crest. This is followed by a local intensification of the ageostrophic flux, associated with the downstream transport of energy and a corresponding local maxima in EPE. The ageostrophic flux accumulates energy even further downstream, resulting in a second peak of $\mathbf{W}_{\text{eddy}}^H$ associated with locally elevated EKE. In the present study, the broader model domain allows us to resolve propagating features across a larger portion of the storm track, revealing alternating regions of $\mathbf{W}_{\text{eddy}}^H$ divergence and convergence consistent with downstream development. We find that ageostrophic flux vectors radiate outward from local divergence peaks, regions associated with elevated EPE, and feed into adjacent convergence zones where EKE is enhanced. This suggests a similar energy cycle to that inferred from observations, where baroclinic and barotropic growth near the meander crest generates EPE, which is then redistributed by ageostrophic motions and ultimately converted into EKE downstream. While Foppert (2019) was limited in spatial extent, our findings generally support and extend her proposed mechanisms, highlighting a propagating storm track structure. These findings emphasize the importance of accounting for the temporal evolution of Southern Ocean storm tracks to fully diagnose the interactions and energy exchanges that govern their behavior.

e. *The Caveats*

We should note that despite the strong correspondence between HYCOM simulations and observational data in Drake Passage (Xu et al. 2020), observations of deep energy in the SEIR region suggest near-bottom mean flow and EKE is not as well represented in this region. Specifically, the magnitude of EKE is found to be weaker in the model than in the observations (not shown). This may bias model results toward the barotropic pathway and de-emphasize the role of the baroclinic terms. However, these observational findings are preliminary and based only on a single year of data. More data will be available in the future to compare against HYCOM in the SEIR region. Additionally, due to the nonlinearities associated with these high amplitude blocking anomalies, assumptions made when deriving the wave activity flux certainly break down within the block. The wave activity might therefore be an inappropriate framework to diagnose relevant dynamics.

6. Conclusions

In this study, the wave activity flux and eddy energy terms are diagnosed in the SEIR sector of the Southern Ocean. These terms are calculated at each time step from 3 years of free-running, high-resolution numerical model output. Each term presented here is averaged between 500 – 1000 meters in the water column. The 3 year mean fields are compared against a composite mean of the non-event time periods and synoptic storm track case studies. The vertical fluxes highlight the role of ubiquitous baroclinic conversion that is amplified in the first crest of the standing meander and dominates in the background and mean fields. The horizontal fluxes confirm that barotropic processes however are non-negligible, especially during event driven time periods when horizontal shear intensifies and perturbations propagate through the storm track. This work emphasizes the intimate link between each diagnostic and illustrates their collective role in governing Southern Ocean storm tracks.

An advantage of utilizing the wave activity flux framework is that it allows for a temporal diagnostic of terms relevant to the energy budget. This Southern Ocean storm track is found to be characterized by a series of events that are analogous to atmospheric processes but here, driven by the barotropic pathway as opposed to the baroclinic. Typical events resemble dynamics of downstream development, a phenomenon in which eddy energy is fluxed downstream to feed adjacent energy centers which sustains EKE through the storm track. This process can help to

877 explain the spatial offset that has been observed between baroclinically unstable regions and EKE,
878 specifically during these event driven time periods. When these events become obstructed from
879 translating eastward by an extended meander, dynamics resemble that of an atmospheric block,
880 namely convergence of wave activity flux and a rapid accumulation of energy.

881 These findings have significant implications for how the ACC is represented in earth and climate
882 models. Many of these models rely on parameterizations that assume eddy energy is generated
883 locally through baroclinic processes (Gent and McWilliams 1990), often neglecting the role of
884 the barotropic arm. The results presented here suggest that barotropic energy conversion, while
885 likely episodic in nature, can drive the development and propagation of eddies through the storm
886 track during energetic time periods. This nonlocal and event driven behavior is unlikely to be well
887 captured by coarse-resolution models, which lack the spatial and temporal resolution required, or by
888 traditional eddy parameterizations, which do not account for shear driven instabilities. As Jansen
889 and Held (2014) highlight and attempt to resolve, many commonly used eddy parameterization
890 assume a steady state balance between energy input and dissipation and fail to represent the
891 energetic intermittency and upscale energy transfers that can be critical to storm track dynamics.
892 This work highlights the need for parameterizations that are energetically consistent and capable
893 of capturing both the generation and redistribution of eddy energy. Accurately representing these
894 dynamics in climate simulations will be key for fully diagnosing and predicting the eddy driven
895 arm of the Southern Ocean overturning circulation.

896 Particularly important will be predicting the response of the eddy driven arm of the Southern
897 Ocean overturning to strengthened westerlies. While the baroclinic response has been the focus
898 of numerous studies, the barotropic response remains less understood. For example, Thompson
899 and Garabato (2014) used an eddy-resolving GCM to show that standing meanders mediate eddy-
900 mean flow interactions, effectively buffering isopycnal steepening through vorticity adjustments
901 and seabed momentum dissipation, without requiring uniform increase in eddy activity across
902 all longitudes. Similarly, Matsuta et al. (2024) demonstrated that intensified westerlies steepen
903 isopycnal slopes and strengthen eddies which absorb excess wind energy, effectively limiting full
904 acceleration of the mean flow. While these studies highlighted the role of the baroclinic response,
905 Wu et al. (2017) showed that all eddy energy reservoirs, including those associated with the
906 barotropic arm, tend to increase under stronger westerlies, while the fundamental energy pathways

907 remain unchanged. In this context, our results suggests that propagating barotropic disturbances
908 may become more frequent or more intense in a future with enhanced wind forcing. If the observed
909 uptick in EKE (Fig. 10) is primarily linked to the barotropic arm of the energy cycle, then it is
910 plausible that this pathway could scale with wind strength in a manner similar to, or even exceeding
911 the baroclinic pathway. Understanding this response will be critical for predicting how storm tracks
912 and eddy mean flow interactions evolve under a changing climate.

913 Resolving these dynamics, especially in the context of an evolving climate, remains a formidable
914 challenge however. As mentioned, partitioning these energy pathways in eddy resolving numerical
915 models is not trivial and increasing model confidence requires extensive high resolution observa-
916 tions in extremely harsh environments. Coarse temporal resolution altimetry products are likely
917 to miss the the transient, propagating features identified in this work and are additionally not
918 well suited to resolve horizontal shear or ageostrophic motions. While SWOT offers a promising
919 increase in spatial resolution, the temporal coverage remains insufficient to fully capture the event
920 scale variability identified here. A distributed network with both bottom and vertical measurements
921 could potentially offer both the temporal and spatial resolution required to better constrain these
922 barotropic processes, however would be costly and regionally limited. As such, new observational
923 strategies that integrate satellite, in-situ and perhaps Lagrangian measurements will be essential to
924 verify and extend these findings.

925 An accurate representation of the Southern Ocean circulation in ocean and climate models
926 requires realistic parameterizations of eddy driven fluxes in these energetic regions. This requires a
927 holistic understanding of the system and all the processes responsible for creating and transporting
928 energy. This work underscores the challenges we face to accurately reproduce these time dependent
929 dynamics and their large scale implications. Future work might consider the onset, frequency, and
930 duration of these blocking events as well as their occurrence in other energetic regions of the ACC. It
931 is possible this system is unique due to the orientation of the topography which facilitates eddy heat
932 fluxes across the full breadth of the ACC. Ultimately, quantifying the contribution of these events
933 on the large-scale overturning circulation will be essential for a comprehensive understanding of
934 the system and how it might respond to future change.

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938 *Data availability statement.* The HYbrid Coordinate Ocean Model output is publicly avail-
939 able and can be accessed from the HYCOM data server. The specific dataset ana-
940 lyzed in this work is available at <https://data.hycom.org/pub/xbxu/GLBb0.08/SEIR/> and can
941 be accessed by request to X.X. The mapped altimetry SSH product can be found at
942 https://data.marine.copernicus.eu/product/SEALEVEL_GLO_PHY_L4_MY_008_047/description.

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