

1 Internal Tides–Cyclonic Eddy Interaction and Intermodal 2 Energy Pathways: Evidence from 3-km NEMO-AMAZON36 3 Simulations

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14 **Abstract.** The interaction between internal tides (ITs) and mesoscale features plays a key role in ocean energy
15 dissipation. Understanding how IT energy is transformed in energetic western boundary regions remains a central
16 challenge, particularly in regions of vigorous mesoscale activity.

17 To this aim, we apply vertical mode decompositions to the high-resolution (3 km) simulations during September-
18 December 2015. This study shows that the IT vertical mode and the precise point of IT-eddy encounter determine
19 whether the IT energy propagates freely, deviates, or is trapped, and how topography and coherent eddies
20 synergistically scatter energy between baroclinic modes off the Amazon shelf.

21 Three representative interaction cases, each captured in a separate 25 hour snapshot, were examined: undisturbed
22 propagation until crossing the Ceará Rise seamount, interaction with a cyclonic eddy (CE) core, and interaction
23 with a CE eastern edge. The principal findings establish two points.

24 First, an IT response (propagation, deviation or scattering) is dually controlled by its vertical mode, and the
25 mesoscale encounter location along with the associated background conditions (currents and stratification). In the
26 absence of a strong eddy, the Mode-1 IT propagates as a coherent beam with a long propagation range (O (1100
27 km)). In the presence of a strong CE, however, the IT beams are disrupted, preventing sustained long-range
28 transmission. Within the eddy core, the Mode-1 IT is coherently refracted northward ($\sim 35^\circ$ relative to its
29 northeastward incident direction) while maintaining high energy fluxes exceeding 200 W m^{-1} . At the CE edge,
30 Mode-1 is diffracted into two distinct branches, with one propagating northward ($\sim 39^\circ$) and the other eastward
31 ($\sim 35^\circ$). In contrast, the IT higher modes are highly susceptible to blocking and trapping: Mode-2 energy, despite
32 initial amplitudes comparable to Mode-1, is strongly blocked at the CE-seamount interface, while Mode-3 remains
33 weak (below 200 W m^{-1}) and less propagative.

34 Second, intermodal energy transfer is governed by a hierarchical synergy between the seamount and CE's
35 background flow. In the absence of an eddy, the seamount drives a forward energy cascade (O ($10^{-8} \text{ W m kg}^{-1}$))
36 from the Mode-1 IT to higher modes. In contrast, in the presence of a CE, the CE's strong horizontal shear triggers

37 a competing inverse energy cascade ($O(10^{-8} \text{ W m kg}^{-1})$) from the background flow to the IT modes. This
38 interaction is critical for the extreme damping of Mode-2 and explains the observed redistribution of energy fluxes.
39 These results provide mechanistic insight into the fate of IT energy in complex oceanic environments and advance
40 understanding of multi-scale ocean dynamics.

41 **1 Introduction**

42 Internal tides (ITs)—internal waves at tidal frequencies—are generated when barotropic tides interact with
43 topography, forcing vertical displacements of the stratified water column (Garrett and Kunze, 2007; Kelly and
44 Nash, 2010; Buijsman et al., 2012; Zhao, 2014; Chen et al., 2022). They enhance turbulent mixing and influence
45 deep-water circulation (Wunsch and Ferrari, 2004; Kunze, 2017).

46 High-mode ITs, characterized by short wavelengths and large vertical shear, typically dissipate near their
47 generation sites (Vic et al., 2019; Koch-Larrouy et al., 2015; Kouogang et al., 2025). In contrast, low-mode ITs
48 propagate thousands of kilometers, redistributing tidal energy and acting on open-ocean mixing (Zhao, 2017;
49 Alford et al., 2019; Wang et al., 2021; Kouogang et al., 2025). During their propagation, ITs can interfere with
50 other tidal beams (e.g., tidal beams from other sources), interact with oceanic flows (e.g., subtidal currents,
51 mesoscale eddies) and topography (e.g., seamounts, ridges), generating nonlinear internal solitary waves (ISWs)
52 (Pereira et al., 2007; Zhang et al., 2014; Kelly and Lermusiaux, 2016; Wang et al., 2021; Xu et al., 2021; Wang
53 et al., 2024; Li et al., 2024). Low-mode ITs can be scattered into higher modes by bathymetric roughness (Johnston
54 and Merryfield, 2003; Mathur et al., 2014). These multiscale interactions cause IT incoherence and nonstationary,
55 challenging satellite detection (Zaron and Egbert, 2014; Savage et al., 2020).

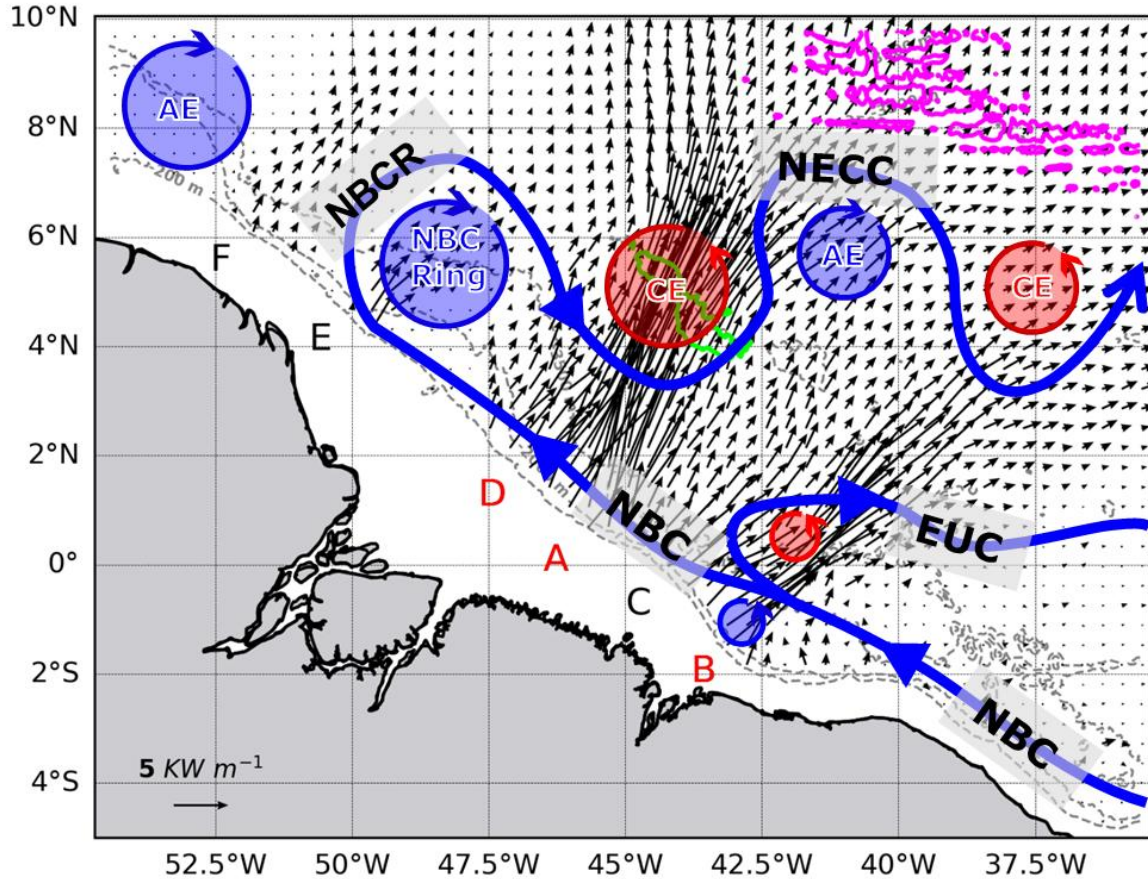
56 Mesoscale eddies (MEs)—comprising both anticyclonic (AEs) and cyclonic (CEs) types—often possess
57 horizontal scales comparable to those of low-mode ITs. This scale similarity allows MEs to alter oceanic
58 stratification and currents, thereby influencing IT generation, propagation, and inter-modal energy redistribution
59 through processes such as scattering, refraction, trapping, and damping (Dunphy and Lamb, 2014; Clément et al.,
60 2016; Dunphy et al., 2017; Guo et al., 2023; Wang and Legg, 2023). MEs can enhance or weaken the topography
61 scattering of ITs, causing spatial divergence (Li et al., 2024). Low-mode ITs can also be refracted or trapped by
62 background currents like the looping and leaping Gulf Stream (Duda et al., 2018; Kelly and Lermusiaux, 2016;
63 Kelly et al., 2016), Kuroshio (Cao et al., 2022; Xu et al., 2021; Chen et al., 2022) and Brazil Current (Pereira et
64 al., 2007), changing their direction of propagation (Huang et al., 2018). Scattering by topography and background
65 circulation to higher modes can redistribute energy toward more dissipative pathways (Lahaye et al., 2020; Fan
66 et al., 2024).

67 Although the IT responses to background circulation (stratification, currents, and eddies) are well-documented on
68 seasonal and interannual timescales (Pereira et al., 2007; Nash et al., 2012; Tchilibou et al., 2020, 2022), their
69 variability at shorter, daily timescales remains less explored. On seasonal timescales, it becomes difficult to
70 distinguish variations in IT responses (e.g., incoherence, trapping, and deviation), particularly those induced by
71 changes in submesoscale and mesoscale activity, and background shear. Analyses at daily timescales could better
72 capture the specific background conditions that most strongly modulate the fate of ITs. Our study addresses this
73 issue by investigating the rapid variability of IT responses to MEs off the Amazon shelf.

74 The region off the Amazon shelf is a dynamic region with a strong western boundary current (North Brazil
75 Current, NBC), receiving large amounts of freshwater from the Amazon and Para Rivers. The area is also marked

76 by high mesoscale activity (MEs), and the presence of seamounts, ITs, and ISWs (Fig. 1). The NBC flows
77 northwestward, exhibiting a seasonal double retroflexion eastward, a first one into the North Equatorial Counter-
78 Current (NECC) at about 5–8° N near 50° W, and a second one into the Equatorial Undercurrent (EUC) in winter–
79 spring (Didden and Schott, 1993). Shear instabilities within these currents and their interaction with the Amazon
80 slope generate the CEs and AEs (NBC rings) in this region (Fratantoni and Glickson, 2002; Barnier et al., 2001;
81 Silva et al., 2009). From August to December (ASOND), mean currents and eddy kinetic energy (EKE) are
82 stronger, and the pycnocline is deeper and weaker than during the March-to-July (MAMJJ) season (Aguedjou et
83 al., 2019; Barbot et al., 2021; Tchilibou et al., 2022). Generated at multiple sites (A to E, Fig. 1) along the Amazon
84 shelf break (Tchilibou et al., 2022; Assene et al., 2024; Magalhaes et al. 2016), ITs from the most energetic sites
85 (A and D, Fig. 1) can either propagate over long distances or interact with other processes to potentially
86 disintegrate into ISWs, which have been observed via in situ measurements (Brandt et al., 2002), SAR imagery
87 (Magalhães et al., 2016), MODIS (De Macedo et al., 2023), and SWOT data (Goret et al., 2026). This makes the
88 region an ideal laboratory for studying the tidal variability of IT responses during the propagation of tidal flux.
89 Using numerical modeling, Tchilibou et al. (2022) reported that the M2 coherent baroclinic tidal flux propagates
90 more northward during MAMJJ in the region off the Amazon shelf. During ASOND, however, it becomes
91 incoherent—branching and deviating near 6°N—due to strong interactions with MEs and background currents off
92 the Amazon shelf. This variability in flux behavior (e.g., free propagation, refraction, branching) during ASOND
93 may result from the interaction of the coherent flux with MEs, sheared currents (e.g., NECC), changes in
94 stratification, topography (e.g., Ceará Rise seamount, Mid-Atlantic ridge; Fig. 1), other internal wave sources, or
95 coupled processes.

96 Motivated by the complex mesoscale interplay off the Amazon shelf, we investigate the fate of IT within this
97 dynamic environment at daily timescales from the realistic model outputs. Specifically, we examine whether ITs
98 propagate freely, are deviated, or become trapped by mesoscale features. We further determine whether these
99 outcomes depend on the vertical modes of ITs, or the location of the ME encounters together with its associated
100 background conditions (currents and stratification), distinguishing, for instance, between interactions at a CE core
101 versus its edge. Finally, we explore the synergistic roles of topography (e.g., Ceará Rise seamount) and CEs in
102 governing modal energy transfers.



103
 104 **Figure 1.** Internal tide generation and propagation, and regional circulation off the Amazon shelf. Key IT
 105 generation sites (A–F) are marked along the shelf break slope, with the three primary sites (A, B, D) highlighted
 106 in red. The associated M_2 baroclinic energy flux, represented by black arrows, is the 25-hour mean depth-
 107 integrated flux from the September-December (SOND) 2015 period. The schematic background circulation
 108 includes the North Brazil Current (NBC), its retroflection (NBCR), North Equatorial Countercurrent (NECC), and
 109 Equatorial Undercurrent (EUC) (solid blue lines). Mesoscale eddies are indicated by cyclonic (CEs, red circles)
 110 and anticyclonic eddies (AEs, blue circles), the latter including the NBC Ring. Topography, from the NEMO-
 111 AMAZON36 model, is detailed with the 200 m and 2000 m isobaths (grey lines) and specific features outlined by
 112 their 3500 m isobath (Ceará Rise seamount: green contour; Mid-Atlantic ridge: magenta contour).

113 2 Methodology

114 2.1 High-resolution numerical model: AMAZON36

115 We use outputs from the Nucleus for European Modelling of the Ocean (NEMO) model v4.0.2 (Madec et al.,
 116 2019), specifically the AMAZON36 configuration (Assene et al., 2024). This high-resolution ($1/36^\circ$, ~ 3 km)
 117 model is designed for the western tropical Atlantic (54.7° W– 35.3° W, 5.5° S– 10° N) and features 75 vertical
 118 layers, with 23 levels in the upper 100 m. The 3 km horizontal resolution provides approximately 30–60, 20–28,
 119 and up to 17 grid points per wavelength for Mode-1, Mode-2, and Mode-3 M_2 IT in the Amazon region,
 120 corresponding to horizontal wavelengths of ~ 90 – 180 km, ~ 60 – 85 km, and up to ~ 50 km, respectively (Tchilibou
 121 et al., 2022). This resolution ensures that all three modes are well resolved and accurately represents the

122 topography critical to their generation and propagation from the Amazon shelf break (Assene et al., 2024). The
123 latter detailed more about the AMAZON36 configuration parameters.

124 The model simulations span 11 years, from January 2005 to December 2015, and provides three-dimensional daily
125 and hourly outputs. This dataset has previously been used to study IT interactions with background currents and
126 stratification, as well as IT impact on the ocean thermal structure (Assene et al., 2024; Kouogang et al., 2025).

127 For this study, we focus on the period from September to December (SOND) 2015, when stronger mean currents
128 and EKE contribute to more incoherent ITs (Tchilibou et al., 2022). To analyze the rapid variability of IT
129 responses to MEs like CEs, we examine 25-hour segments, from hourly outputs, within the entire SOND season.

130

131 **2.2 Internal Tides and Mesoscale Activity**

132 Our analysis for each 25-hour window of AMAZON36 outputs during the SOND period involves several steps:
133 extracting the M2 IT constituent, separating the barotropic and baroclinic components, projecting the baroclinic
134 components onto vertical modes, extracting MEs and characterizing their properties, and examining the mean
135 background current pattern and topographic features.

136

137 **2.2.1 Undecomposed IT Energy equations**

138 First, to examine the variability of IT responses to MEs, we explore all 25-hour snapshots of IT energy flux from
139 the AMAZON36 output during the SOND period. Following the method of Kelly et al. (2010), barotropic and
140 baroclinic tidal constituents were separated. This separation is performed directly by the NEMO model to ensure
141 accuracy, providing the total energy for all resolved propagation modes at a given tidal frequency (Tchilibou et
142 al., 2022). Our analysis focuses solely on the M2 harmonic, the dominant tidal constituent in this region (Gabioux
143 et al., 2005; Fassoni-Andrade et al., 2023).

144 The energy budget for IT can be expressed from the following equations (Wang et al., 2016; Buijsman et al., 2012;
145 Kerry et al., 2013; Tchilibou et al., 2022; Siyanbola et al. 2024):

146

$$147 \nabla_h \cdot \mathbf{F} + D + R = C \quad (1)$$

148

149 In contrast to energy budgets decomposed into vertical modes, we refer to these as the undecomposed IT energy
150 equations. Here, $\nabla_h \cdot \mathbf{F}$ is the divergence of the depth-integrated energy flux, $\mathbf{F} = (F_x, F_y)$ the energy flux vector,
151 C represents the depth-integrated barotropic-to-baroclinic energy conversion, and D is the depth-integrated energy
152 dissipation term. The term R includes the energy tendency term, implicit horizontal dissipation, wave-mean flow
153 and wave-wave interaction terms, and other offline computation errors. $\nabla_h = (\partial/\partial x, \partial/\partial y)$ is the horizontal gradient
154 operator.

155 In the following, a particular attention is given to depth-integrated and time-averaged energy flux term \mathbf{F} , which
156 was defined as (Tchilibou et al., 2022; Assene et al. 2024):

157

$$158 [\mathbf{F}_{bc}, \mathbf{F}_{bt}] = \left[\int_{-H}^{\eta} \mathbf{u}_{bc} p_{bc} dz, \mathbf{u}_{bt} p_{bt} \right], \quad (2)$$

159

160 where $\mathbf{u} = (u, v)$ is the horizontal baroclinic tidal velocity vector, and p the tidal pressure. Here, the subscripts bt
 161 and bc denote barotropic and baroclinic components, respectively. η is the sea surface height and H is the seafloor
 162 depth.

163

164 2.2.2 Projection of IT Motions Onto Vertical Modes

165 Second, to investigate whether the IT responses to MEs is mode-dependent and to examine potential inter-modal
 166 energy transfer, we project the M_2 tidal constituent onto a set of vertical modes for selected 25-hour snapshots
 167 that capture ME-induced IT responses. This selective approach substantially reduces the computational cost
 168 associated with processing high-resolution 3D data for all 25-hour windows during the SOND period.

169

170 Vertical Mode Decomposition

171 For each selected snapshot, we first extract the M_2 harmonic via harmonic analysis. Although performing
 172 harmonic fits over short (25-hour) segments may introduce frequency leakage from nearby tidal constituents (e.g.,
 173 S_2 , N_2 , and K_2) into the M_2 signal, this effect is expected to be small in our case because the tidal regime is
 174 strongly M_2 -dominated, accounting for more than 70% of the total tidal energy (e.g., Gabioux et al., 2005;
 175 Tchilibou et al., 2022; Fassoni-Andrade et al., 2023). This approach is consistent with previous studies that have
 176 successfully applied harmonic analysis to similarly short records to resolve semidiurnal constituents (e.g., 17–29
 177 h M_2 tidal observations in Waterhouse et al., 2018), demonstrating that dominant semidiurnal tides can be reliably
 178 estimated from short-duration data.

179 We then decompose the M_2 tidal currents and pressure using a locally computed set of vertical modes. This
 180 method provides a more accurate separation of barotropic and baroclinic tides than simpler approaches (Kelly,
 181 2016; Lahaye et al., 2020; Lahaye et al., 2024; Siyanbola et al. 2024).

182 The vertical modes are obtained by solving the standard Sturm-Liouville eigenvalue problem at each horizontal
 183 grid point, using the local mean stratification profile (based on the time-mean buoyancy frequency, $\overline{N^2}$), and
 184 assuming a flat bottom, a free surface, horizontally homogeneous stratification, and no background flow (Gerkema
 185 and Zimmerman, 2008; Bella et al., 2024):

186

$$187 \quad \partial_z \left(\frac{\partial_z \Phi_n}{N^2} \right) + \frac{\Phi_n}{c_n^2} = 0, \quad (3)$$

188

189 with the boundary conditions:

$$190 \quad \partial_z \Phi_n = 0 \text{ at } z = -H, \text{ and } g \partial_z \Phi_n + \overline{N^2} \Phi_n = 0 \text{ at } z = \bar{\eta}, \quad (4)$$

191

192 where ∂_z denotes the partial derivative in z -direction, Φ_n is the horizontal velocity/pressure eigenfunction for
 193 mode n , c_n is the modal phase speed and g is the acceleration due to the gravity. The associated vertical
 194 velocity/buoyancy eigenfunction, φ_n , is given by:

195

$$196 \quad \partial_z \varphi_n = \Phi_n, \text{ and } \partial_z \Phi_n = -\frac{\overline{N^2}}{c_n^2} \varphi_n. \quad (5)$$

197 It should be noted that the flat-bottom assumption could represent a limitation for higher-mode projections near
 198 steep topography such as the Ceara Rise seamount. The errors associated with this approximation are expected to
 199 be of a few percent for the dominant low modes (Kelly, 2016).

200 The vertical modes satisfy the orthogonality condition (Kelly, 2016; Lahaye et al., 2024; Bella et al., 2024):

201

$$202 \int_{-H}^{\bar{\eta}} \Phi_m \Phi_n dz = H \delta_{mn}, \quad (6)$$

203

204 where δ_{mn} is the Kronecker delta and $\bar{\eta}$ is the time-averaged sea surface height.

205 We solved Equation 3 for the first 11 modes ($n = 0, 1, \dots, 10$) at each grid point, where $n = 0$ represents the
 206 barotropic mode. In this study, the analysis of energy flux focuses primarily on the first three baroclinic modes
 207 ($n = 1, 2, 3$), which are the most dynamically significant at the model’s resolution (~ 3 km). These three baroclinic
 208 modes account for 96.2% (33.2%), 96.8% (37.9%), and 97.2% (26.3%) of the total baroclinic energy flux (relative
 209 to the combined baroclinic and barotropic flux) in the NE, CEC, and CEE cases, respectively. They therefore
 210 capture the dominant share of the baroclinic energy, supporting their use as the basis of our analysis.

211 The horizontal velocity \mathbf{u} and pressure p fields are projected onto these modes to obtain the depth-independent
 212 modal amplitudes:

213

$$214 [\mathbf{u}_n(\mathbf{x}, t), p_n(\mathbf{x}, t)] = \frac{1}{H} \int_{-H}^{\bar{\eta}} [\mathbf{u}(\mathbf{x}, z, t), p(\mathbf{x}, z, t)] \Phi_n(\mathbf{x}, z) dz, \quad (7)$$

215

216 with $\mathbf{x} = (x, y)$ denoting the horizontal direction.

217 The full 3D structure of \mathbf{u}_n fields for each mode can be reconstructed as (Li et al., 2024):

218

$$219 \mathbf{u}_n(\mathbf{x}, z, t) = \mathbf{u}_n(\mathbf{x}, t) \Phi_n(\mathbf{x}, z) \quad (8)$$

220

221 Modal Energy Budget

222 To analyze the inter-modal energy transfer/scattering and redistribution, we examine the terms of the modal
 223 energy budget of a given mode interacting with physical features such as topography and mesoscale flow (Fan et
 224 al., 2024; Bella et al., 2024; Kelly, 2016; Kelly and Lermusiaux, 2016):

$$225 \nabla_h \cdot \mathbf{F}_m + D_m + \Psi_m = \sum_n (C_{mn} + A_{mn} + H_{mn} + V_{mn} + B_{mn}). \quad (9)$$

226 Here:

- 227 • C_{mn} is the nonlinear scattering (from mode $m > 0$ into mode n) of energy by topography and stratification.
- 228 • A_{mn} represents the advection of the ITs by the background flow and MEs.
- 229 • H_{mn} and V_{mn} represent the effect of the horizontal and vertical shear of the background flow, respectively.
- 230 • $\mathbf{F}_m = H p_m \mathbf{u}_m$ is the depth-integrated and time-averaged baroclinic energy flux for mode n .
- 231 • B_{mn} consist of the three-way interaction term and the horizontal gradient of the buoyancy field.
- 232 • Ψ_m consists of the energy tendency terms.

233 • D_m is the dissipation term of modal energy budget, which also includes interactions with unresolved modes,
 234 other physical dissipation processes leading to local dissipation (Alford & Zhao, 2007), and other offline
 235 computation errors.

236 A previous seasonal-scale study by Bella et al. (2024) found the nonlinear coupling terms C_{mn} , A_{mn} , H_{mn} , and
 237 V_{mn} to be dominant across the North Atlantic basin. For our investigation on a daily timescale, a preliminary
 238 analysis identified C_{mn} and H_{mn} as the dominant terms in our study region. We therefore focus on estimating
 239 these dominant couplings terms as defined by Bella et al. (2024):

240

$$241 \quad C_{mn} = \langle H p_m \mathbf{u}_n \cdot T_{nm} - H p_n T_{mn} \cdot \mathbf{u}_m \rangle, \quad (10)$$

242

$$243 \quad H_{mn} = \langle -H (U_{mn}^v \mathbf{u}_n) \cdot \mathbf{u}_m \rangle, \quad (11)$$

$$244 \quad \text{With } T_{mn} = \frac{1}{H} \int_{-H}^{\bar{\eta}} \Phi_m \nabla_h (\Phi_n) dz, \quad (U_{mn}^v)_{ij} = \frac{1}{H} \int_{-H}^{\bar{\eta}} \Phi_m \Phi_n \frac{\partial \bar{U}_{h,i}}{\partial x_j} dz.$$

245

246 Here, the angle bracket $\langle \cdot \rangle$ denotes the average over a M2 tidal period, $\bar{U}_h = (\bar{U}, \bar{V})$ is the time-averaged total
 247 horizontal velocity vector. $\frac{\partial \bar{U}_{h,i}}{\partial x_j}$ is the tensor.

248 The modal horizontal kinetic energy (HKE_n) of M2 IT is estimated as (Kelly et al., 2012; Fan et al., 2024):

249

$$250 \quad HKE_n = \frac{\rho_0 H}{2} \langle u_n^2 + v_n^2 \rangle, \quad (12)$$

251 where ρ_0 is the reference density.

252

253 **Symmetric–Antisymmetric Separation of Nonlinear Coupling Terms**

254 The energy transfer matrices—including topographic scattering (C_{mn}) and (H_{mn})—are decomposed into
 255 symmetric and antisymmetric components, following the established methodology (Savage et al., 2020; Bella et
 256 al., 2024). For any general transfer matrix (X_{mn}), the standard mathematical definitions are: the antisymmetric
 257 component, $X_{mn}^A = \frac{1}{2} (X_{mn} - X_{nm})$, and the symmetric component, $X_{mn}^S = \frac{1}{2} (X_{mn} + X_{nm})$.

258 The antisymmetric component, X_{mn}^A , represents the internal reallocation of energy—specifically, the scattering
 259 or transfer of energy among the various IT vertical modes. Critically, this process conserves the total energy of
 260 the IT field, as it analytically redistributes energy across the system modes and spatial scales without introducing
 261 a net gain or loss. For instance, the term C_{mn} is inherently antisymmetric and thus provides a canonical reference
 262 for conservative internal energy transfer.

263 Conversely, the symmetric component, X_{mn}^S , describes the net energy exchange between the IT and the low-
 264 frequency background flow. When integrated in a basin, this component acts as a source or sink for the IT system,
 265 quantifying the total energy gained from or lost to the slowly varying circulation (Bella et al., 2024).

266 The direction of energy transfer is interpreted from the sign of the matrix elements. Considering a specific mode
 267 m:

268 • For the full matrix X_{mn} , a negative value indicates a net forward transfer of energy from mode m to mode n,
 269 while a positive value indicates a net backward transfer from mode n to mode m;

- For the antisymmetric component X_{mn}^A , a negative value signifies a forward transfer from mode m to mode n of the IT field, and a positive value signifies a backward transfer;
- For the symmetric component X_{mn}^S , a negative value indicates a forward transfer from mode- m IT to the mode- n background flow, whereas a positive value indicates energy is transferred from the mode- n background flow to mode- m IT.

275

276 2.2.3 Eddy detection and structure

277 Third, to investigate whether the IT responses to MEs depend on the eddy encounter location, including the
 278 associated background conditions (currents and stratification), we detected and characterized eddies from 25-hour
 279 mean snapshots of AMAZON36 output during the SOND period.

280 The mesoscale activity in this region during the 2015 ASOND period was previously assessed by Tchilibou et al.
 281 (2022). Their analysis, which compared the model's surface EKE with satellite data, showed reasonable agreement
 282 in both the spatial pattern and amplitude of the mean EKE, especially in regions dominated by the NECC.

283 Eddies were identified in our model outputs using the Okubo-Weiss parameter (W), chosen for its ability to detect
 284 coherent vortices on specific isopycnal surfaces or depths (Okubo, 1970; Weiss, 1991; Kurian et al., 2011; Xu et
 285 al. 2019). The W parameter is defined as:

286

$$287 W = S_n^2 + S_s^2 - \zeta^2, \quad (13)$$

288

289 where the normal strain (S_n) and shear strain (S_s), and the relative vorticity (ζ) are:

290

$$291 S_n = \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}, \quad S_s = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}, \quad \zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}. \quad (14)$$

292

293 Regions where rotation ($W < 0$) dominates over strain ($W > 0$) indicate potential eddy cores.

294 The detection of eddies on selected isopycnal surfaces (between 23 and 27 kg m^{-3} isopycnals) following the
 295 procedure of Kurian et al. (2011) and Xu et al. (2019). First, the W fields were smoothed using a 50 km \times 50 km
 296 half-power filter to suppress small-scale noise. For each 25-hour mean snapshot, we then applied a constant
 297 threshold of $W_0 = -3 \times 10^{-11} \text{ s}^{-2}$ to isolate vorticity-dominated regions ($W < W_0$). Closed contours corresponding
 298 to $W = W_0$ were identified, and each contour was subjected to a series of quality control criteria to be classified
 299 as an eddy: a shape error (deviation from a fitted circle) of less than 50%, a mean azimuthal velocity greater than
 300 5 cm s^{-1} , and a radius larger than 50 km.

301 For each identified eddy, its thickness was defined as the vertical extent of its W_0 contours, and its center location
 302 was defined as the centroid of the closed W_0 contour. Detected eddies were classified as cyclonic or anticyclonic
 303 based on the sign of their potential vorticity anomaly (PVA, positive for CEs and negative for AEs; Fig. 2a).

304

305 To analyze the eddy dynamical structure, we used the framework of rescaled potential vorticity (PV_r). This method
 306 filters out high-frequency wave noise to isolate the balanced mesoscale signal. The PV_r is derived from the
 307 classical Ertel (1942) potential vorticity, rescaled by a reference stratification at rest, $\rho^*(z)$, following the approach
 308 of Morel et al. (2023, 2019) and subsequent studies (e.g., Delpech et al., 2020; Aguedjou et al., 2021; Ernst et al.,
 309 2023).

310 Its expression is:

311

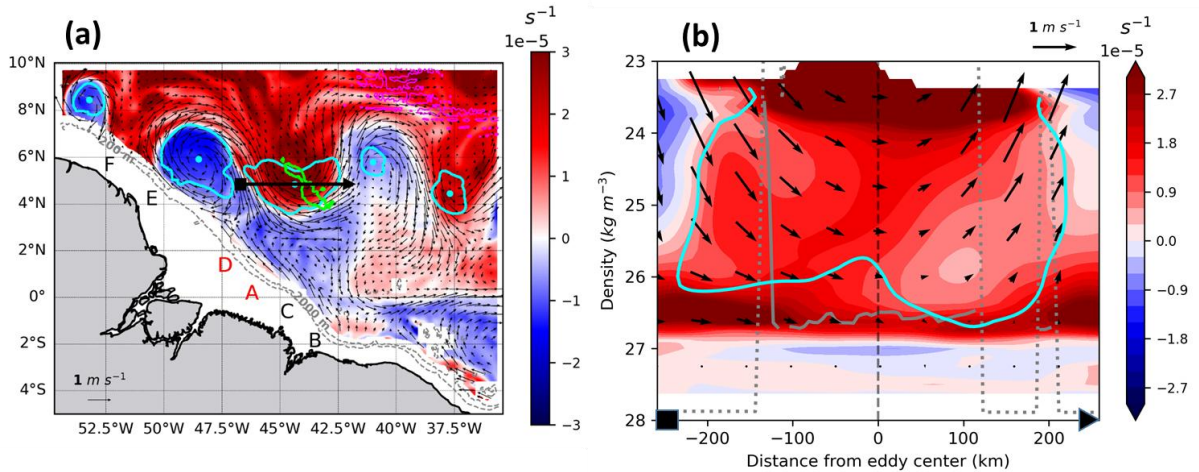
$$312 \quad PV_r = -(\nabla \cdot \mathbf{U} + f) \cdot \nabla \mathbf{Z}(\rho) = \nabla \cdot [(\nabla \cdot \mathbf{U} + f) \nabla \mathbf{Z}(\rho)], \quad (15)$$

313

314 where \mathbf{Z} is a rescaling function defined by $(\rho^*) = z$. ρ^* is defined by the adiabatically rearranged state of minimum
315 potential energy, following the concept of Lorenz (1955) as formalized by Nakamura (1995) and Winters and
316 D'Asaro (1996). ρ is the potential density and f , the local Coriolis parameter. An eddy dynamical core is then
317 identified by its anomaly from the background planetary vorticity, $PVA = PV_r - f$, within a layer bounded by two
318 isopycnals.

319

320 To distinguish subsurface eddies from surface-intensified ones, we classified them based on the isopycnal level
321 of their core of PVA. Following the method of Kouogang et al. (2025), we used the base of the pycnocline (defined
322 by $\sim 26.5 \text{ kg m}^{-3}$ isopycnal) as the boundary of the lower pycnocline depth. Eddies with their PVA core on
323 isopycnals less dense than 26 kg m^{-3} were classified as surface-intensified eddies (Fig. 2b), while those with their
324 core on denser isopycnals ($> 26.5 \text{ kg m}^{-3}$) were classified as subsurface-intensified eddies as formalized by
325 Aguedjou et al. (2021) in the tropical Atlantic Ocean. This classification scheme was applied to all eddies detected
326 during the SOND period. This study focuses specifically on these surface-intensified eddies.



327

328 **Figure 2.** Detection and vertical structure of a representative ME (17 September 2015). (a) PVA (color shading)
329 averaged within the $23\text{--}25.5 \text{ kg m}^{-3}$ isopycnal layer ($\sim 50\text{--}160 \text{ m}$ depth). Panel (a) shows detected eddy edges
330 (cyan contours), eddy centroids (cyan dots), and mean background currents (black arrows) along the 24 kg m^{-3}
331 isopycnal. (b) Vertical cross-section of PVA along the transect in (a) (black arrow), passing through the core of a
332 CE. The transect endpoints are marked by a square (start) and triangle (end). The vertical dashed black line
333 indicates the eddy centroid, black arrows show the CE-associated currents, and grey lines mark the upper (dotted)
334 and lower (solid) thermocline limits. PVA and mean background currents fields were smoothed using a $50 \text{ km} \times$
335 50 km half-power filter to suppress small-scale noise. Topography is detailed with the 200 m and 2000 m isobaths
336 (grey lines) and specific features outlined by their 3500 m isobath (Ceará Rise seamount: green contour; Mid-
337 Atlantic ridge: magenta contour).

338

339 3 Results

340 In order to examine the variability of IT responses to MEs, particularly to CEs, we first present three representative
341 cases of interactions between the (non-modal) baroclinic energy flux of the M2 IT and the detected eddy fields,
342 identified from all 25-hour mean snapshots during SOND 2015. We then analyze the IT's vertical mode responses,
343 focusing on the encounter location of the fluxes — originating from the most energetic generation sites A and D
344 — with a CE along their path, and examine the potential modal energy transfer and redistribution.

345

346 3.1 Variability of IT responses to MEs: three distinct cases

347

348 Following the method described in Sects. 2.2.1 and 2.2.3 (Eqs. (1)-(2) and (13)-(15)), we identified three distinct
349 cases from the SOND 2015 period for analysis, each occurring near a spring tide maximum to ensure comparably
350 high tidal energy levels (Fig. 3). This setup minimizes the influence of tidal variability, allowing us to isolate the
351 eddy-induced effects. Although the tidal forcing is not strictly identical across the three cases, the differences in
352 tidal amplitude remain small (less than 18%) and are therefore considered secondary compared to the large
353 contrasts in mesoscale conditions between the cases.

354 Figure 4 illustrates in the three relevant cases, the M₂ baroclinic energy flux, and MEs detected and their polarity
355 given by the sign of PVA. The three selected cases are located in a region shaped by two major topographic
356 features: the Ceará Rise seamount (~500 km from sites A and D; between 4°N–6°N, 45°W–42.5°W), with an
357 amplitude (h_{\max}) of ~1000 m and a width (w_{\max}) of ~100 km, and the Mid-Atlantic Ridge (~1100 km from sites A
358 and D). Each case was selected to highlight distinct IT responses:

- 359 • No-Eddy case (NE, 24 November 2015): Energy flux from the primary generation sites (A and D) propagated
360 freely, crossing the seamount and reaching the ridge. A similar pattern was observed from site B (Fig. 4a);
- 361 • Cyclone Eddy Center case (CEC, 17 September 2015): Energy flux from sites A and D was refracted into a
362 single beam at the core of a CE positioned (4.9° N, 44.4° W) above the seamount. Separately, flux from the
363 less energetic site E was also refracted into a single beam, emanating from the center of a nearby AE (centered
364 at 5.9° N, 48.5° W) (Fig. 4b);
- 365 • Cyclone Eddy Edge case (CEE, 29 September 2015): Energy flux from sites A and D was diffracted into
366 multiple beams at the eastern edge of a CE located (5.3° N, 45.0° W) on the northern flank of the seamount
367 (Fig. 4c).

368 Across the three selected cases, the analysis of the background conditions (stratification and currents) along a
369 transect following the IT paths from sites A and D reveals strong background currents ($>1.0 \text{ m s}^{-1}$, Fig. 5). In the
370 NE case (Figs. 5a,d), these currents are dominated by their cross-transect component (Fig. 5a), associated with
371 the NBC near the Amazon shelf-break and with the NECC near the seamount. In the eddy cases, the background
372 currents at the CE encounter location differs between cases: in the CEC case (Figs. 5b,e), the currents have both
373 cross- and along-transect components, whereas in the CEE case (Figs. 5c,f), they are dominated by their along-
374 transect component (Fig. 5f). In both eddy cases, the currents at the CE encounter location are associated with the
375 coupled NECC/CE flow. Away from the CE encounter location and the seamount, the background currents exhibit
376 a strong along-transect component associated with the NECC coupled with circulation from a nearby small AE.
377 Regarding background stratification, the buoyancy frequency gradient (∇N^2 , Appendix A, Fig. A1) along the IT
378 paths from sites A and D shows strong signatures ($O(10^{-8} \text{ m}^{-1} \text{ s}^{-2})$) localized near topographic features (seamount

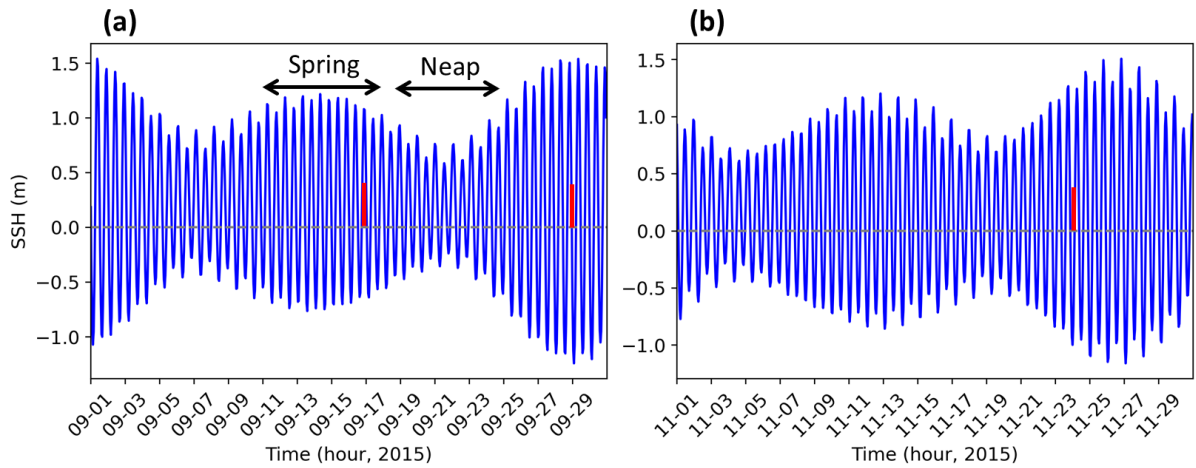
379 and ridges). At the CE encounter and seamount locations in the eddy cases, the horizontal stratification gradient
 380 is also similarly strong, except in the CEC case where it is quasi-uniform (Appendix A, Fig. A1). The strong
 381 background stratification is associated with the NECC in the NE case and with the coupled NECC/CE in the CEC
 382 case. Overall, the key distinction between the eddy cases lies not only in where the IT beam encounters the eddy
 383 (eddy core vs. eddy edge), but also in the associated background conditions (currents and stratification).

384 It should be noted that the eddy core/center and eddy edge are defined as regions where $r/R \approx 0$ and $r/R \approx 1$,
 385 respectively, where r is the distance from the eddy centroid and R is the radius of maximum velocity. This
 386 geometric difference in the CE encounter location leads to markedly different energetic behavior, as discussed
 387 below.

388 In this study, the three cases are qualitatively distinguished by the presence or absence of a CE, and, when a CE
 389 is present, by the geometry of the IT–CE intersection.

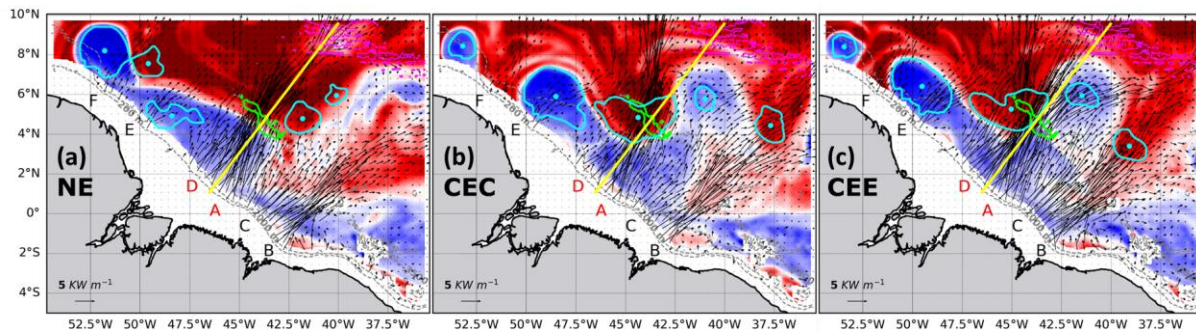
390

391 To determine whether the IT response patterns depend on the IT's vertical structure or on the eddy encounter
 392 location, we focus on the IT response to CEs and project the energy flux into vertical modes (Sect. 2.2.2). This
 393 approach enables us to examine the specific response of each vertical mode to the CE and potential modal energy
 394 redistribution and transfer resulting from these interactions.



395

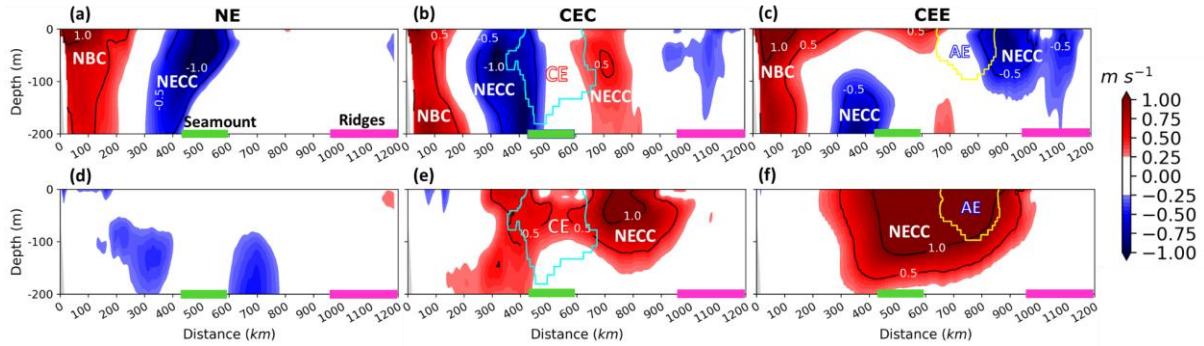
396 **Figure 3.** Sea surface height (SSH) from AMAZON36 simulations (station location: 1.29° N, 46.34° W) in (a)
 397 September and (b) November 2015. Red bars denote the three case study dates, and black arrows mark the spring-
 398 neap tidal cycle.



399

400 **Figure 4.** Depth-integrated M2 total baroclinic energy flux (black arrows) and isopycnally-averaged PVA (color
 401 shading), for the (a) NE, (b) CEC, and (c) CEE cases. All fields are 25-hour mean snapshots. The PVA is averaged
 402 within the 23–25 kg m⁻³ density layer (approximately 50–160 m). Detected eddies along the 24 kg m⁻³ isopycnal

403 are overlaid, with edges (cyan contours) and centroids (cyan dots). The respective dates are 24 November 2015
 404 (a), 17 September 2015 (b), and 29 September 2015 (c). The transects (yellow lines) highlight the most energetic
 405 energy flux pathways considered, originating from sites A and D. These transects are identical across all three
 406 cases to facilitate direct comparison. Topography is detailed with the 200 m and 2000 m isobaths (grey lines) and
 407 specific features outlined by their 3500 m isobath (Ceará Rise seamount: green contour; Mid-Atlantic ridge:
 408 magenta contour).



409 **Figure 5.** Vertical structure of the mean background current velocity in the upper 200 m, shown along transects
 410 defined on the IT propagation paths from sites A and D (Fig. 4). The cross-transect (panels a–c) and along-transect
 411 (panels d–f) components of current velocity are shown for the NE (a, d), CEC (b, e), and CEE (c, f) cases. In
 412 panels (a–c), positive (negative) values indicate flow oriented approximately northwestward (southeastward). In
 413 panels (d–f), positive (negative) values indicate flow oriented approximately northeastward (southwestward).
 414 Notable topographic features are outlined by colored rectangles (seamount: green; ridges: magenta). Panels (b),
 415 (c), (e), and (f) also show the detected eddy edges for AE (yellow) and CE (cyan).

418 3.2 IT Responses to CEs

419
 420 Following the method described in Sect. 2.2.2 (Eqs. (3)-(12)), we separately analyze the first three vertical modes
 421 of the M2 IT in the three cases.

423 3.2.1 NE Case: IT without Eddy

424
 425 We first analyse the tidal energy diagnostics for the NE case to establish an eddy-free propagation baseline.
 426 Figures 6a-c maps the energy flux propagation and HKE for the first three modes, revealing distinct patterns for
 427 each one.

428 Mode-1 energy propagation is highly dominant. The fluxes, generated from sites A and D, constructively form a
 429 notably coherent beam that converges and propagates northeastward ($\sim 37^\circ$ azimuth) for over 1100 km with
 430 minimal deviation (Fig. 6a). This long-distance propagation maintains a relatively constant HKE of 150–200 J
 431 m^{-2} , with a wavelength (λ_1) estimated between 90–125 km. In contrast, the Mode-2 flux propagates a significantly
 432 shorter distance (500–600 km, λ_2 : 60–85 km) and terminates abruptly at the seamount (Fig. 6b). Mode-3 forms no
 433 coherent beams but appears as scattered patches extending only 50–100 km (λ_3 : 35–50 km; Fig. 6c). Along their
 434 respective beams, Mode-1 and Mode-2 exhibit stronger energy flux amplitudes ($>200 \text{ W m}^{-1}$) compared to Mode-
 435 3 ($<200 \text{ W m}^{-1}$). The spatial distribution of these modal energy fluxes is consistent with the vertical structure of

436 the corresponding baroclinic velocity profiles (Appendix B, Figs. B1–B2). A sharp Mode-2 damping is clearly
437 visible over the seamount, while Mode-3 energy appears trapped over the seamount and ridge where the Mode-1
438 flux diminishes, suggesting that topographic features drive scattering to higher vertical modes.

439

440 To quantitatively assess the mechanisms responsible for this energy loss, we compute intermodal energy transfer
441 terms (Eqs. (9)-(11)) and map only the dominant terms in Figures 5d-o. These dominant terms, of order of
442 magnitude comparable ($O(10^{-8} \text{ W m kg}^{-1})$), are topographic scattering term (C_{mn} , Eq. (10)), and the horizontal
443 shear term (H_{mn} , Eq. (11)) of background flow. They then are separated into its antisymmetric and symmetric part
444 for the analysis. All other background flow-induced energy transfer terms, such as advection and vertical shear,
445 are negligible in comparison ($O(10^{-10} \text{ W m kg}^{-1})$; figures not shown).

446

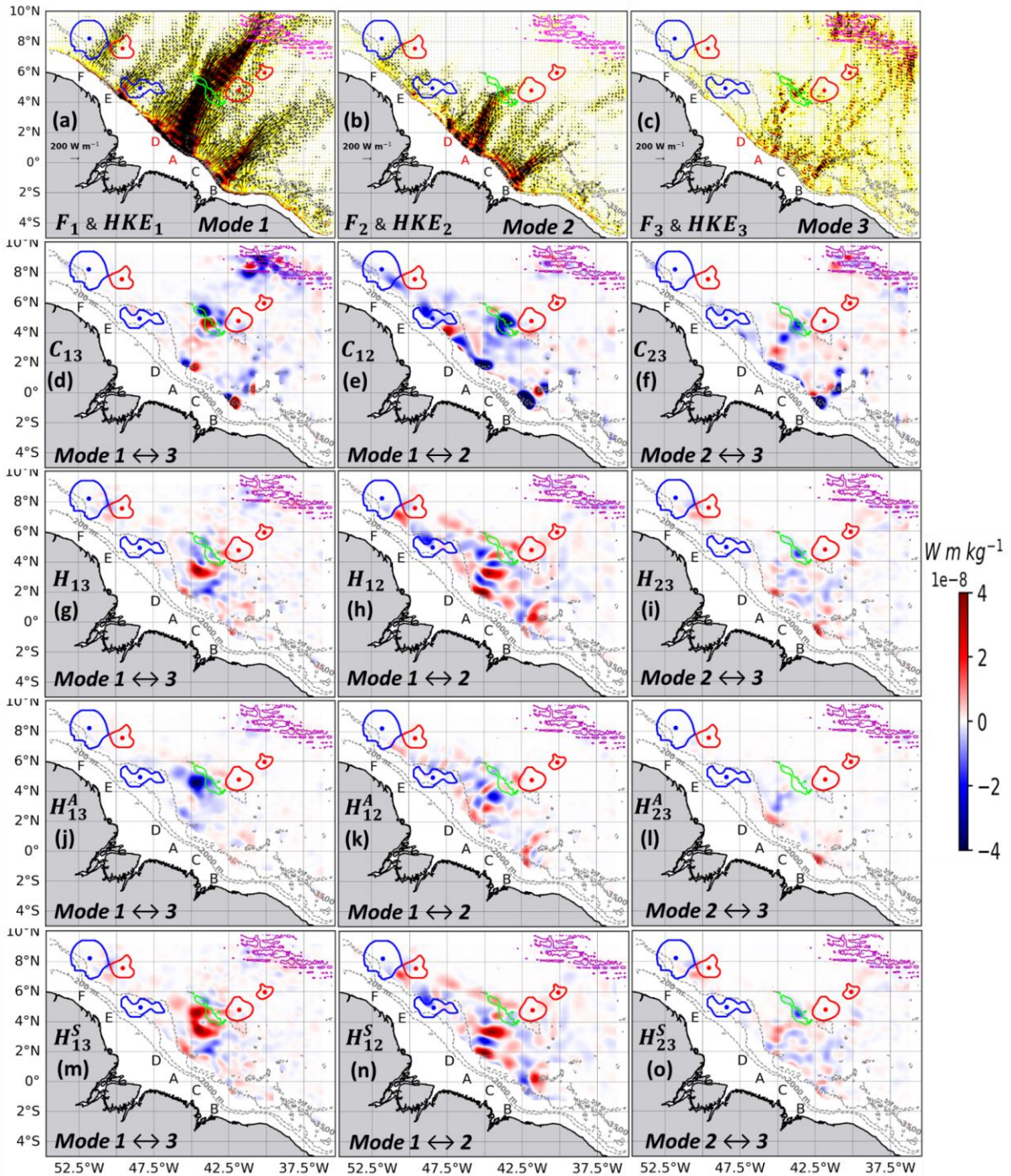
447 The analysis reveals a primary pathway of intermodal energy transfer driven by topographic scattering term (C_{mn}),
448 which is antisymmetric by construction. Along the IT path from generation sites A and D, a dominant forward
449 energy cascade ($|C_{mn}| \sim 4 \times 10^{-8} \text{ W m kg}^{-1}$) occurs near major bathymetric features—the shelf break and seamount.
450 Specifically, energy is sequentially transferred from Mode-1 to Mode-2 IT for C_{12} (Fig. 6e, blue patches), and
451 then from Mode-2 to Mode-3 IT for C_{23} (Figs. 6f, blue patches). For C_{13} , however, energy exchanges between
452 Mode-1 and Mode-3 IT are bidirectional—energy is both lost and gained—and spatially confined to the vicinity
453 of topographic features (Fig. 6d, blue and red patches). This could stem from the background conditions,
454 particularly the notable effect of the horizontal stratification gradient in the coupling term C_{mn} (Appendix A, Fig.
455 A1), or the influence of shear in the background flow (NBC, NECC), the effect of which is discussed in detail
456 below.

457

458 Decomposing the horizontal shear term H_{mn} (Figs. 6g–i) into its antisymmetric (Figs. 6j–l) and symmetric (Figs.
459 6m–o) components shows that its net influence ($|H_{mn}| \sim 4 \times 10^{-8} \text{ W m}^{-1} \text{ kg}^{-1}$) is more due to the symmetric part.
460 This latter facilitates energy exchanges between the background flow and the IT modes along the IT path from
461 the most energetic sites. Indeed, before the seamount, the symmetric terms H_{12}^S and H_{13}^S are both strongly
462 dominant in their net effect, while H_{23}^S is weakly dominant in H_{23} . In this region, energy is strongly transferred
463 from the Mode-2 and Mode-3 background flow to the Mode-1 IT (Figs. 6m,n, red patches). Over the seamount,
464 the symmetric part of H_{mn} becomes notable. Here, energy transfers are weak overall, but a notable transfer occurs
465 from the Mode-2 IT to the Mode-3 background flow (Fig. 6o, blue patches).

466

467 In essence, in the NE case, coherent energy flux from sites A and D converges and propagates until encountering
468 major topographic features (seamounts and ridges). While Mode-1 IT energy propagates over long distances with
469 amplitudes exceeding 200 W m^{-1} , the higher modes behave differently. Mode-2 IT energy, despite having a
470 comparable amplitude to Mode-1, is effectively damped. In contrast, the weaker Mode-3 IT energy ($< 200 \text{ W m}^{-1}$)
471 becomes trapped by the topography. The interaction with topographic features, potentially enhanced by the
472 background flow, triggers significant intermodal energy transfer on the order of $10^{-8} \text{ W m}^{-1} \text{ kg}^{-1}$. This transfer is
473 governed by two primary mechanisms: 1) topographic scattering drives a dominant forward energy cascade
474 through the IT modes (Mode-1 \rightarrow Mode-2 \rightarrow Mode-3), and 2) the horizontal shear of the background flow
475 facilitates a direct energy scattering from the Mode-2 and Mode-3 background flow to Mode-1 IT.



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Figure 6. Tidal energy diagnostics for the NE case on 24 November 2015, averaged over a M2 tidal period. Panels (a–c) show the depth-integrated M2 baroclinic energy fluxes (F_m ; black arrows) and horizontal kinetic energy (HKE_m ; color shading) for (a) mode-1 (F_1 , HKE_1), (b) mode-2 (F_2 , HKE_2), and (c) mode-3 (F_3 , HKE_3). Panels (d–f) present the effects of topographic scattering and stratification (C_{mn} ; color shading) for (d) C_{13} , (e) C_{12} , and (f) C_{23} . Panels (g–i) show the net component of horizontal shear induced by the mean background flow (H_{mn} ; color shading) for (g) H_{13} , (h) H_{12} , and (i) H_{23} . Panels (j–l) show the antisymmetric component of this horizontal shear (H_{mn}^A ; color shading) for (j) H_{13}^A , (k) H_{12}^A , and (l) H_{23}^A . Panels (m–o) show the symmetric component of horizontal shear (H_{mn}^S ; color shading) for (m) H_{13}^S , (n) H_{12}^S , and (o) H_{23}^S . All panels include the detected eddy edges (closed contours) and eddy centroids (dots) for anticyclones (blue) and cyclones (red). Topography is shown using the 200 m and 2000 m isobaths (grey contours), with specific features highlighted by the 3500 m isobath (seamount:

487 green contour; Mid-Atlantic Ridges: magenta contour). The C_{mn} and H_{mn} fields were smoothed with a Gaussian
488 filter ($\sigma = 7$ grid points) to aid interpretation. It should be noted that the colorbar range is saturated in panels to
489 enhance the visibility of energy transfer features.

490

491 3.2.2 CEC Case: IT Encountering a CE Core

492

493 We next examine IT responses when the energy flux from sites A and D encounter the core of a surface-intensified
494 CE (CEC case, Fig. 2b). The CE, centered at 4.9° N, 44.4° W above the localized mid-seamount, has a radius of
495 157 km, maximum velocity 1.35 m s^{-1} , and a core bounded by $23\text{--}25.5 \text{ kg m}^{-3}$ isopycnals extending $\sim 150 \text{ m}$
496 within the pycnocline.

497

498 Prior to interaction, the incident mode-1 IT energy fluxes converge and interfere. Upon encountering the CE core,
499 this energy is refracted into a single beam (Fig. 7a), which emanates from the eddy center and propagates
500 northward at approximately 35° from their northeastward incident direction. Both incident and refracted beams
501 maintain comparable HKE of $150\text{--}200 \text{ J m}^{-2}$ (Fig. 7a), though the refraction process locally confines the energy,
502 leading to a reduction in HKE ($25\text{--}50 \text{ J m}^{-2}$) in the northwestern lee of the eddy. Concurrently, the Mode-2 IT
503 energy flux is blocked at the southern edge of the CE and seamount (Fig. 7b), while Mode-3 appears as scattered
504 patches in the regions where Mode-2 is trapped (Fig. 7c), indicating active intermodal energy scattering. As in the
505 NE case, Mode-1 and Mode-2 IT exhibit higher energy flux amplitudes ($>200 \text{ W m}^{-1}$) along their beams than
506 Mode-3 ($<200 \text{ W m}^{-1}$) (Figs. 7a-c). The vertical structure of the along-transect baroclinic velocity further supports
507 these results (Appendix B, Figs. B1, B3).

508

509 An analysis parallel to that conducted for the NE case identified the topographic scattering term (C_{mn}) and the
510 horizontal shear term (H_{mn}) of the background flow as the dominant mechanisms responsible for the active energy
511 scattering observed.

512

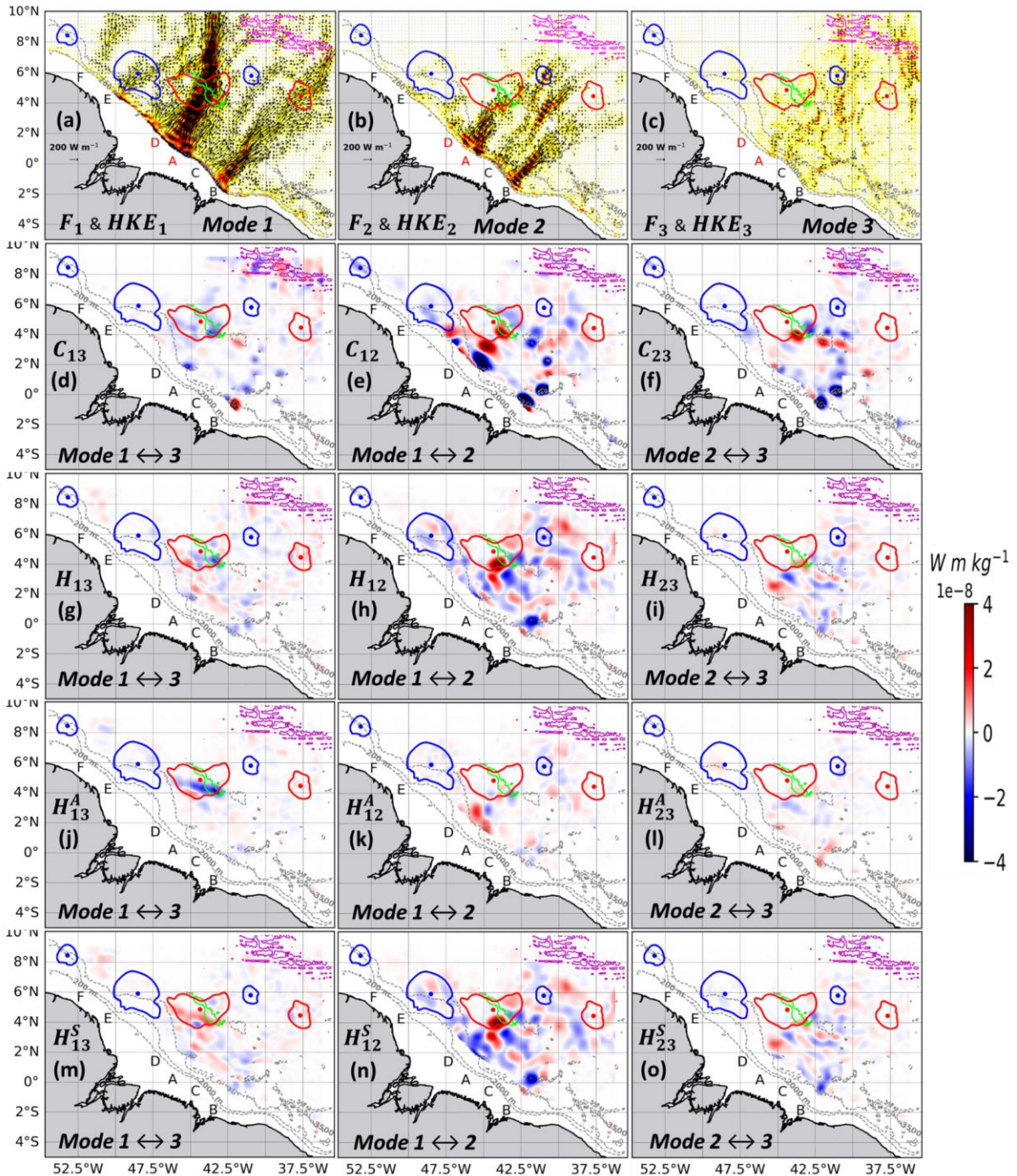
513 The analysis of the term C_{mn} in the CEC case reveals a distinct coupling pattern modulated by the CE core in
514 conjunction with the seamount along the IT path from sites A and D. A dominant forward energy transfer ($|C_{mn}|$
515 $\sim 4 \times 10^{-8} \text{ W m kg}^{-1}$) from Mode-1 to Mode-2 occurs near the shelf break for C_{12} (Fig. 7e, blue patches), consistent
516 with the NE case (Fig. 6e). A significant shift occurs near the southern edge and core of the CE, where a dominant
517 backward energy transfer is observed (with the exception of Mode-1 to Mode-3 IT). Here, energy is sequentially
518 gained by Mode-1 from Mode-2 for C_{12} (Fig. 7e, red patches near the southern edge and core of the CE) and by
519 Mode-2 from Mode-3 for C_{23} (inverse cascade, Fig. 7f, red patches), while energy is simultaneously lost from
520 Mode-1 to Mode-3 for C_{13} (direct forward transfer, Fig. 7d, blue patches). These patterns could be due to either
521 the horizontal stratification gradient in the coupling term C_{mn} associated with the CE (Appendix A, Fig. A1), or
522 shear in the background flow (NECC/CE).

523

524 Analysis of the background flow horizontal shear term (H_{mn}) shows that its magnitude ($|H_{mn}| \sim 4 \times 10^{-8} \text{ W m}^{-1}$
525 kg^{-1}) is comparable to the topography scattering term as in NE case. In the CEC case, along the energy flux from
526 sites A and D, the net effect of H_{mn} (Figs. 7g-i) is primarily due to its symmetric part (Figs. 6m-o), except for term

527 H_{13} . Between the shelf break and the southern edge of the CE, both the symmetric terms H_{12}^S and H_{23}^S are both
528 strongly dominant in their net effect. In this region, energy is both lost and gained between the Mode-1 IT and the
529 Mode-2 background flow, and between the Mode-2 IT and the Mode-3 background flow (Figs. 7n,o, blue patches).
530 This bidirectional transfer is spatially confined to this region and more pronounced between the Mode-1 IT and
531 the Mode-2 background flow, a pattern also present in the NE case (Figs. 6h,n). Near the CE center and seamount,
532 the terms H_{13}^A and H_{13}^S weakly combine to form H_{13} (Fig. 7j,m, blue and red patches), while H_{12}^S and H_{23}^S both
533 remain dominant in their net effect. These patterns coincide with the region where energy fluxes are deflected.
534 Here, energy transfer is stronger for H_{12}^S than for H_{23}^S . Specifically, the background flow loses energy to the IT
535 modes: the Mode-2 background flow energizes the Mode-1 IT (Fig. 7n, red patches), and the Mode-3 background
536 flow energizes the Mode-2 IT (Fig. 7o, red patches). These overall patterns indicate a deflection of Mode-1 and
537 Mode-2 IT, and provide strong evidence for a dominant energy pathway from the background flow to the IT
538 modes driven by horizontal shear. This latter is coupled with direct forward energy transfer between IT modes
539 driven by topographic scattering previously observed.

540
541 In summary, in the CEC case, the interaction with the CE core dictates distinct fates for IT modes. Mode-1 IT
542 from sites A and D is not freely propagating but is primarily refracted into a single northward beam. In contrast,
543 Mode-2 IT is blocked, and Mode-3 IT is scattered at the eddy edge and seamount. Energy flux amplitudes for
544 Modes 1 and 2 exceed 200 W m^{-1} along their beams, whereas Mode-3 remains below this threshold. This
545 interaction facilitates a significant energy transfer ($O(\sim 10^{-8} \text{ W m kg}^{-1})$) governed by a complex interplay of two
546 mechanisms: 1) a dominant backward energy cascade, where horizontal shear transfers energy from the Mode-3
547 background flow to Mode-2 IT, and from the Mode-2 background flow to Mode-1 IT; and 2) a forward scattering,
548 where topography directly transfers energy from Mode-1 to Mode-3 IT.



549
550 **Figure 7.** Tidal energy diagnostics for the CEC case (17 September 2015), following the format of Fig. 6.

551
552 **3.2.3 CEE Case: IT Encountering a CE Edge**

553
554 Finally, we assess IT interactions with the edge of a surface-intensified CE centered at 5.3° N, 45.0° W (radius
555 143 km, maximum velocity 1.23 m s⁻¹, core bounded by 23–25.5 kg m⁻³ isopycnals extending ~100 m above the
556 pycnocline).

557
558 This interaction yields a different kinematic response. The incident Mode-1 energy fluxes from sites A and D
559 converge and, at the eddy edge, clearly diffract into two distinct beams (Fig. 8a): one propagating northward

560 (~39°) and the other eastward (~35°) relative to their northeastward incident direction. The northward-refracted
561 beam maintains high HKE (150–200 J m⁻²), while HKE is sharply reduced (25–50 J m⁻²) in the northeast lee of
562 the CE (Fig. 8a). Separately, the eastward-refracted beam, less energetic (HKE <100 J m⁻²) than the northward
563 beam, passes near the eastern edge of a small AE. Mode-2 flux is sheared at the CE edge with limited directional
564 change (Fig. 8b), and Mode-3 becomes trapped along the northeastern CE edge and near the ridge (Fig. 8c).
565 Consistent with previous cases, Mode-1 and Mode-2 exhibit higher energy flux amplitudes (>200 W m⁻¹) than
566 Mode-3 (<200 W m⁻¹), and the energy flux patterns is supported by the vertical structures of the baroclinic velocity
567 (Appendix B, Figs. B1, B4).

568

569 As in prior cases, the analysis identified topographic scattering (C_{mn}) and horizontal shear (H_{mn}) of the background
570 flow as the two dominant mechanisms driving intermodal scattering in the CEE case.

571

572 The analysis of the term C_{mn} reveals a pattern modulated by the CE edge and seamount along the IT path from
573 sites A and D. A dominant forward energy transfer ($|C_{mn}| \sim 4 \times 10^{-8} \text{ W m kg}^{-1}$) from Mode-1 to Mode-2 for C_{12}
574 (Fig. 8e, blue patches) and from Mode-1 to Mode-3 IT for C_{13} (Fig. 8d, blue patches) occurs near the shelf break.
575 Near the eastern edge of the CE and the southern flank of the seamount, inter-modal IT energy transfers —
576 between Mode-1 and Mode-2 IT, and between Mode-2 and Mode-3 IT — are both strong and bidirectional (i.e.,
577 forward and backward transfers coexist; Figs. 8e,f, blue and red patches), and remain spatially confined to this
578 region. An exception is the Mode-1 to Mode-3 IT transfer (Fig. 8d), which is weak in this area.

579 These overall patterns indicate that the CE edge inhibits the forward energy cascade observed in the NE case and
580 instead initiates a dual mechanism: a potential flow shear-induced energy transfer between the background flow
581 (NECC/CE) and IT modes, and a topographically-driven energy scattering between IT modes.

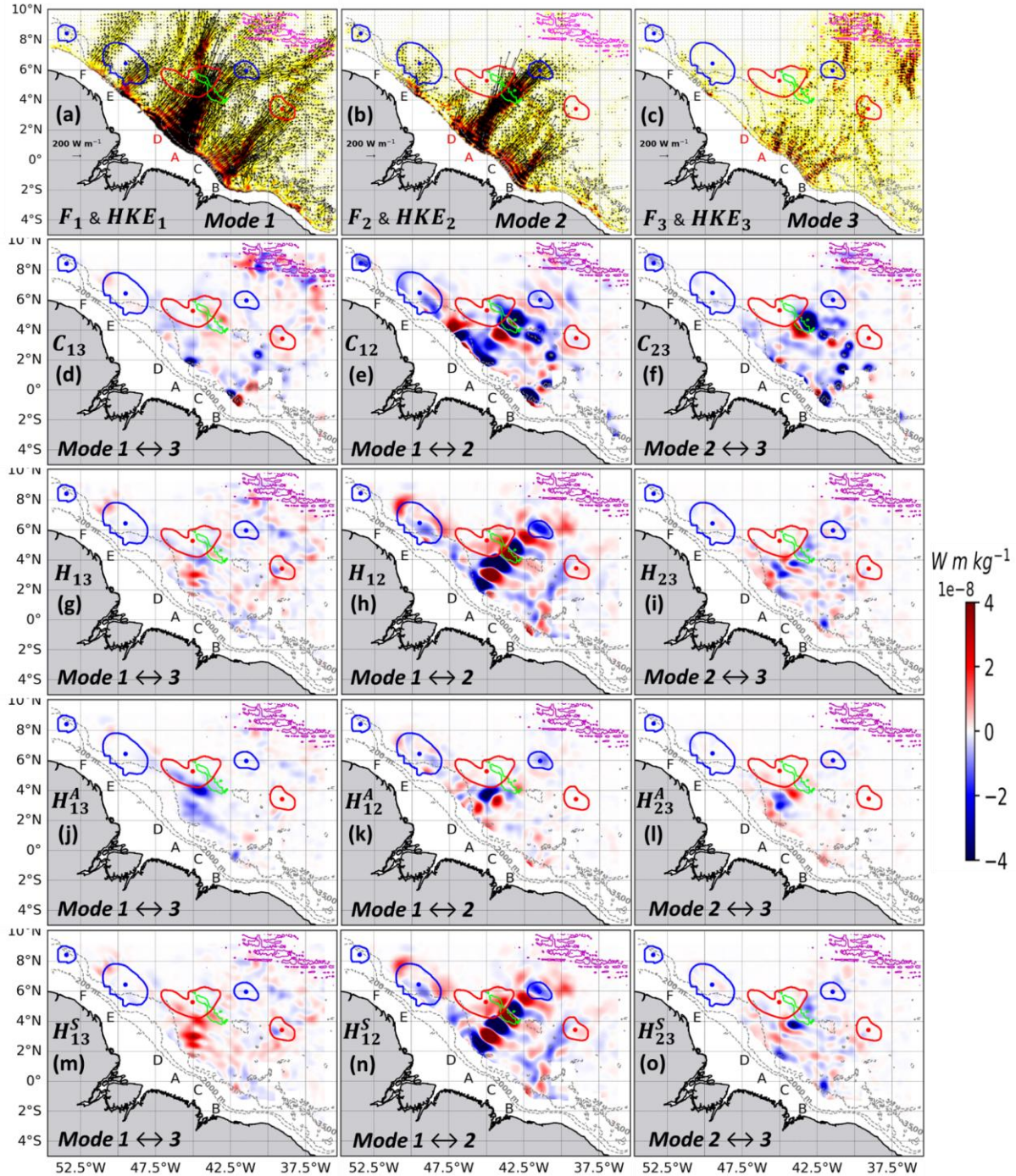
582

583 As in previous cases, the horizontal shear term (H_{mn}) in the CEE case is of comparable magnitude ($|H_{mn}| \sim 4 \times$
584 $10^{-8} \text{ W m}^{-1} \text{ kg}^{-1}$) to the topographic scattering term. The net effect of H_{mn} (Figs. 8g-i) is primarily dominated by
585 its symmetric part (Figs. 8m-o), except for term H_{13} . Along the IT path from sites A and D, terms H_{12}^S and H_{23}^S
586 are both strongly dominant in their net influence, while H_{13}^A and H_{13}^S weakly combine to form H_{13} (Figs. 8g,j,m)
587 — a pattern also present in the CEC case (Figs. 7g,j,m). The energy transfer pattern along this path is characterized
588 by alternating bands of energy loss and gain (blue and red patches), reflecting bidirectional transfers between the
589 background flow and IT modes. These alternating bands are particularly striking and spatially extended for H_{12}^S
590 (Figs. 8h,n). They are distinct from those observed in the previous cases, appearing both upstream and downstream
591 of the seamount and near the eastern CE edge. These patterns could result from an interference structure associated
592 with the IT field. For H_{23}^S , however, forward energy transfer dominates: the Mode-2 IT energizes the Mode-3
593 background flow near the CE edge (Fig. 8o, blue patches), coinciding with the region where energy fluxes are
594 deflected. These overall patterns provide strong evidence for a dominant energy pathway between the background
595 flow and IT modes driven by horizontal shear, coupled with a topographically-driven energy transfer between IT
596 modes.

597

598 In summary, in the CEE case, upon interacting with the CE edge, each IT mode meets a distinct fate. Mode-1 IT
599 from sites A and D splits into two energetic beams, propagating northward and eastward with energy fluxes

600 exceeding 200 W m^{-1} . In contrast, Mode-2 IT is sheared apart, while Mode-3 IT is scattered by the eddy edge and
 601 seafloor topography, its energy flux remaining below 200 W m^{-1} . During this encounter, a significant energy
 602 transfer ($\sim 10^{-8} \text{ W m kg}^{-1}$) occurs through dual mechanism distinct from that observed in the CEC case: 1) a
 603 dominant bidirectional energy transfer between the background flow and the IT modes (Mode-1 \leftrightarrow Mode-2 \leftrightarrow
 604 Mode-3) driven by horizontal shear, which can act to suppress the topographically-driven downscale energy, and
 605 2) a bidirectional energy transfer between the IT modes driven by topographic scattering.



606
 607

Figure 8. Tidal energy diagnostics for the CEE case (29 September 2015), following the format of Fig. 5.

608 4 Discussion

609 This study investigated the fate of M₂ IT energy on the Amazon shelf during the high EKE period of SOND 2015.
610 We addressed three questions: (1) Does the IT propagate freely, deviate, or become trapped by mesoscale features?
611 (2) Do these outcomes depend on the IT vertical mode, or on the location of the ME encounters (CE core vs. edge)
612 along with the associated background conditions (currents and stratification)? (3) What are the synergistic roles
613 of topography and CEs in governing modal energy transfers? By projecting energy flux into vertical modes and
614 performing intermodal energy transfer terms, we dissected these interactions more deeply.

615 616 4.1 The Variable Fate of Internal Tides: Free Propagation, Deviation, and Trapping

617
618 Our results show that the fate of IT energy is not uniform but is dictated by interactions with mesoscale features,
619 affecting the intensity and distribution of energy flux. The NE case established a baseline of efficient, long-range
620 propagation, where the Mode-1 energy flux maintained amplitudes exceeding 200 W m⁻¹ along a coherent beam
621 for over 1100 km. This free propagation aligns with previous studies (e.g., Xu et al., 2016; Fan et al., 2024) and
622 confirms Mode-1's characteristic as a freely propagating IT (Zhao et al., 2010). Its path is governed by Snell's
623 law (Small, 2001; Zhao, 2014), with minimal Coriolis constraint (f) near the equator ($f/\omega_{M2} \ll 1$, with ω_{M2} the M₂
624 tidal frequency), shifting steering mechanisms to wave–current and wave–stratification interactions. The stability
625 of the Mode-1 IT beam in background flow is consistent with ray-tracing results, such as those at the Hawaiian
626 Ridge, where typical currents had only slight effects (Rainville and Pinkel, 2006). While high-resolution and
627 idealized simulations suggested reduced Coriolis constraints at low latitudes (Wang et al., 2021; Le Dizes et al.,
628 2025), our realistic simulations advance these findings by forcing nonlinear interactions in a highly complex field.

629
630 In the NE case, the strong background flow—particularly the NECC—moved quasi-perpendicular to the incident
631 Mode-1 IT beams, and the associated stratification was notable over the seamount. The subcritical seamount
632 ($h_{\max}/H \sim 0.2$) acted only as a minor directional obstacle ($\lambda_1/w_{\max} \sim 0.9\text{--}1.25$) for propagating Mode-1 IT, though
633 it could affect higher-order modes intensified near the bottom.

634
635 In contrast, in the eddy cases, the incident Mode-1 IT beams passed through the strong cross-beam and along-
636 beam background flow (NECC/CE) in the CEC and CEE case, respectively. The presence of a CE consistently
637 disrupted free IT propagation, leading to deviation or trapping with distinct energy modulations. The incident
638 Mode-1 IT was deviated into convergent energy beams, creating a zone of reduced energy flux in the lee of the
639 eddy, consistent with processes modeled by Wang and Legg (2023) and Dunphy and Lamb (2014). This reduction
640 in coherent energy flux is strongly supported by in situ observations south of the Azores, which reported a
641 reduction in low-mode IT energy flux during interactions with a surface-intensified eddy (Löb et al., 2020). Across
642 all cases, Mode-3 energy never formed a coherent beam and consistently exhibited the weakest fluxes (<200 W
643 m⁻¹). The most relevant blockage occurred for Mode-2 (with flux amplitude comparable to Mode-1) in the CEC
644 case, where an otherwise energetic mode was completely impeded at the eddy–seamount interface. This
645 vulnerability aligns with global observations that Mode-2 M₂ IT generally has smaller sea surface height
646 amplitudes and shorter propagation distances (O[100 km]) than Mode-1 (Zhao, 2018). MEs thus act as potent
647 filters that selectively dissipate or trap the energy of specific vertical modes.

648 It should be noted that the multi-source interference, observed along the propagation paths of the energy fluxes
649 from sites A and D, could also modify the beam geometry independently of mesoscale activity. In this study, we
650 assume that the contribution of multi-source interference is smaller than that of eddy-induced effects. A more
651 detailed analysis would be required to precisely quantify this contribution.

652

653 **4.2 The Dual Control of IT Response: Vertical Mode and Eddy Encounters**

654

655 A key finding of this study is that the IT responses to an ME is dually controlled by its vertical mode, and the
656 specific location of the eddy encounter and its associated background conditions. Mode-1 IT is robust and long-
657 ranging but susceptible to beam steering, while Mode-2 is far more vulnerable to damping and blocking. Mode-3
658 IT is consistently weak and scattered, behaving as a trapped mode that seldom forms coherent beams. Only Mode-
659 1 IT underwent large-scale deviation by MEs or background flow fields, with energy loss occurring via forward
660 energy transfer at localized, energetic interaction sites (seamount, eddy boundaries). This is consistent with studies
661 showing that remote IT energy is scattered to higher modes at continental margins (Siyanbola et al., 2024; Fan et
662 al., 2024) and with findings that an ME focuses Mode-1 energy flux in specific areas while inducing vertical mode
663 scattering (Dunphy and Lamb, 2014). Our observation of Mode-1 deviation is analogous to the redirection of
664 ISWs by ME fields (Liao et al., 2012; Goret et al., 2026).

665

666 IT beam deviation is sensitive to eddy properties. The direction of deviation depends strongly on eddy polarity,
667 as shown by previous studies (e.g., Huang et al., 2018; Guo et al., 2023; Dunphy et al., 2017; Wang and Legg,
668 2023; Li et al., 2024; Goret et al., 2026). While the present study focuses exclusively on CEs, a qualitative
669 illustration of AE-induced deflection can be glimpsed in the energy flux path emanating from the less energetic
670 generation site E (Fig. 4b: deviation of the energy flux due to an AE core centered at 5.9°N and 48.5°W). While
671 earlier work noted that AE cores speed up Mode-1 propagation and induce clockwise (southward) refraction,
672 whereas CE cores slow it down and induce counterclockwise (northward) refraction, our findings link specific
673 interaction geometries to distinct intermodal energy pathways in a realistic framework. The impact of AEs on
674 intermodal energy pathways remains an important open question. Based on previous studies (e.g., Dunphy and
675 Lamb, 2014; Goret et al., 2026), we can assume that AEs exhibit a symmetric response; however, precise
676 quantification is left for future investigation.

677

678 The distinction between the CEC (core) and CEE (edge) cases reveals that the same CE can impose fundamentally
679 different fates on a passing Mode-1 IT beam. Interaction with the eddy core — where stratification was strong
680 and the CE flow was oriented cross-beam — refracted the incident beam coherently by $\sim 35^\circ$ into a single
681 northward path. In contrast, an encounter at the eddy edge — where stratification was quasi-uniform and the CE
682 flow was oriented along-beam — diffracted the energy into two distinct beams propagating northward ($\sim 39^\circ$) and
683 eastward ($\sim 35^\circ$). This demonstrates that “eddy lensing” is nuanced and sensitive to the radial structure and shear
684 fields of the eddy. Recent SWOT satellite observations corroborate this finding, documenting analogous refraction
685 at an eddy core and diffraction at a western eddy edge within the study region (Goret et al., 2026). Our results
686 provide a mechanistic explanation for incoherent IT signals and variable trapping noted in high-resolution models
687 of the ASOND period in this region (Tchilibou et al., 2022).

688

689 While Mode-1 IT is susceptible to beam steering, higher modes (Mode-2 and Mode-3) are more sensitive to
690 topography and are quickly damped, trapped, and become primary recipients of energy via downscale cascades
691 linked to topographic scattering (Lahaye et al., 2020; Fan et al., 2024; Bella et al., 2024). Our results advance
692 these findings by showing that higher modes are also more sensitive to the presence of a CE in conjunction with
693 a localized seamount. Therefore, the energy scattering from lower to higher IT modes and the trapping of those
694 modes by CE's flow are two linked processes facilitating the IT dissipation (Wang and Legg, 2023).

695

696 This study was limited to surface-intensified eddies. Future work should investigate whether similar IT
697 interactions occur with other ME types, such as deep intrathermocline eddies or complex multi-eddy systems. A
698 key question is whether eddies with thin vertical structures—and thus higher vertical modes—are capable of
699 trapping ITs, which warrants specific examination.

700

701 **4.3 Synergistic Roles of Topography, Background Flow, and CEs in Modal Energy Transfers**

702

703 Our results reveal a complex hierarchy of interactions that governs modal energy transfers, where even without
704 strong MEs, the combined effects of topography and background flow establish a baseline for energy pathways.

705

706 The NE case shows the seamount acts as a critical site for modal scattering, driving a dominant forward energy
707 cascade from Mode-1 to Mode-2 to Mode-3 IT ($\sim 4 \times 10^{-8} \text{ W m kg}^{-1}$). This magnitude of transfer is characteristic
708 of interactions over abrupt topography, consistent with quantifications of energy cascades on continental slopes
709 (Kelly and Nash, 2012). This topographically driven transfer is significantly modulated by background flow
710 (NECC, NBC) through horizontal shear mechanisms of comparable strength, aligning with studies in the North
711 Atlantic concluding that low-frequency flow strongly impacts the IT energy cycle, often transferring energy
712 toward smaller scales (Bella et al., 2024). Background flow shear actively participates in energy exchange,
713 facilitating transfer from the Mode-2 and Mode-3 background flow to the Mode-1 IT before the seamount, and
714 from the Mode-2 IT to the Mode-3 background flow over the seamount. Thus, seamount-topography interaction
715 with background flow creates a dynamic environment for energy redistribution even before considering ME
716 effects.

717

718 Introducing a CE—particularly one co-located with the seamount, as in the CEC case—fundamentally reorganizes
719 the energy transfer landscape. The CE's strong horizontal shear dominates background flow effects and reverses
720 the canonical energy pathway, initiating a dominant inverse energy cascade from background flow to IT modes.
721 This shift from the topographically driven forward cascade observed in the NE case is mediated by horizontal
722 shear, supported by analyses using coupled-mode shallow-water models that emphasize advection terms involving
723 mean flow and buoyancy shear (Kelly et al., 2016). The synergy between the CE and seamount creates competing
724 pathways: topographically driven forward scattering operates concurrently with eddy-driven inverse cascades,
725 leading to complex energy redistribution that explains observed modal blocking and trapping. This aligns with
726 studies detailing how CEs and AEs differently affect topographic scattering (Li et al., 2024) and underscores that
727 cross-scale energy exchange is a key driver in the tropical western Atlantic (Wang et al., 2025).

728

729 The consistent co-location of the CEs and the seamount with the NECC suggests the background conditions—
730 specifically western boundary currents—combined with the position of CE encounters, act to further enhance IT
731 refraction and diffraction. This mechanism is supported by studies in other western boundary currents (Duda et
732 al., 2018; Cao et al., 2022; Xu et al., 2021; Kelly and Lermusiaux, 2016; Chen et al., 2022; Pereira et al., 2007;
733 Kelly et al., 2016). However, fully isolating the individual contributions of the eddy flow from that of the NECC
734 will require a future idealized modelling framework.

735 **5 Conclusion**

736 This study illustrates the complex pathways of M2 IT energy in the region off the Amazon shelf during the period
737 of SOND 2015. By applying vertical mode decomposition to high-resolution NEMO-AMAZON36 simulations,
738 we examined three representative interaction cases: undisturbed propagation until crossing a topography,
739 interaction with a CE core, and interaction with a CE eastern edge. These three cases are schematically represented
740 in the figure 9. For each case, we systematically computed the intermodal energy transfer terms to identify the
741 governing mechanisms.

742

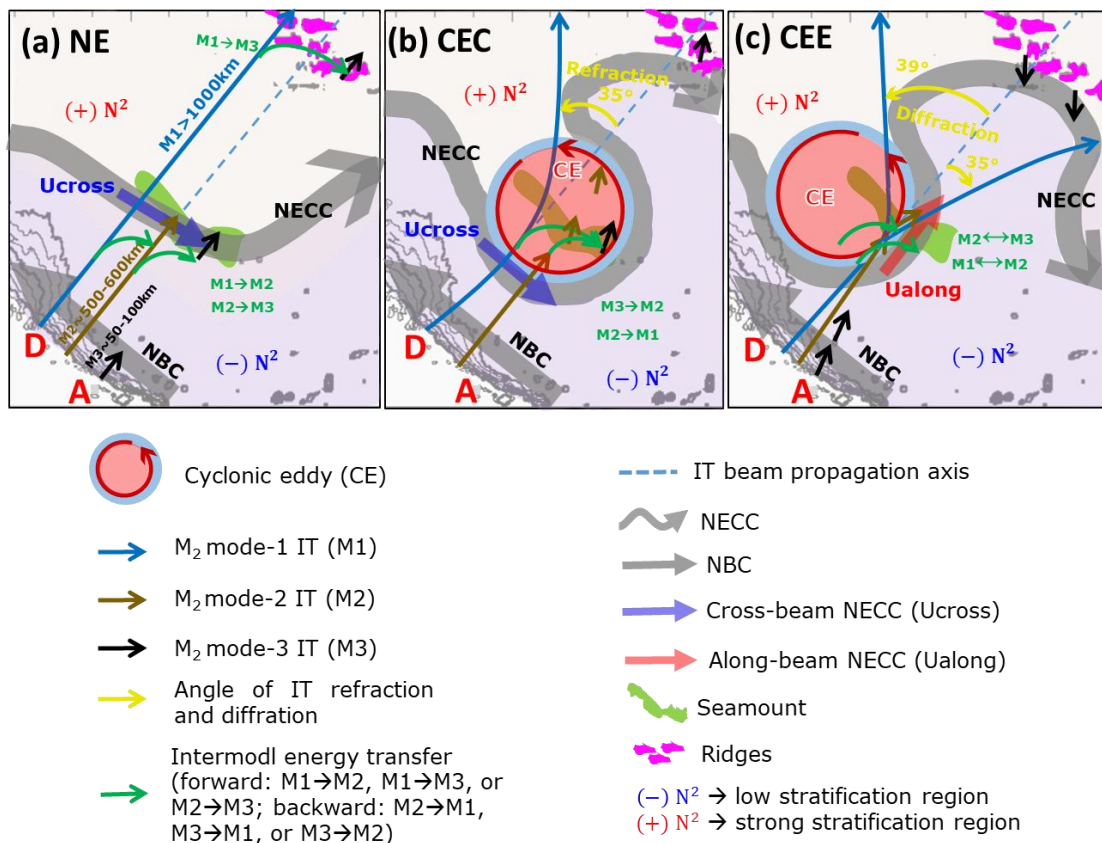
743 The two primary conclusions are as follows:

744 First, the specific response of an IT—whether it propagates freely or deviates—is dually controlled by IT vertical
745 modal structure, and the location of the ME encounters together with its associated background conditions
746 (currents and stratification). In the absence of a strong eddy (NE case, Fig. 9a), Mode-1 IT propagated freely as a
747 long-range coherent beam. It passed through the cross-beam NBC flow, crossed the Ceará Rise seamount, and
748 continued through the cross-beam NECC flow — the latter associated with strong stratification — with little
749 disruption. In contrast, interactions with a CE and its associated currents and stratification consistently disrupted
750 this propagation pattern, leading to refraction, diffraction, or trapping. When the beam encountered the CE core
751 (CEC case, Fig. 9b), where stratification was strong and the CE flow was oriented cross-beam, the Mode-1 beam
752 was coherently refracted northward by approximately 35° while maintaining high energy fluxes ($>200 \text{ W m}^{-1}$).
753 At the eddy edge (CEE case, Fig. 9c), however, where stratification was quasi-uniform and the CE flow was
754 oriented along-beam, the beam instead underwent diffraction: its energy split into two distinct beams propagating
755 northward ($\sim 39^\circ$) and eastward ($\sim 35^\circ$). Higher modes were particularly susceptible to trapping; Mode-2 energy
756 flux—despite an amplitude comparable to Mode-1—was completely blocked and trapped at the eddy-seamount
757 interface, while Mode-3 energy remained weak ($<200 \text{ W m}^{-1}$), scattered and less blocked. This weaker and more
758 spatially diffuse signature of mode 3, in contrast to the clearly blocked mode 2, likely reflects local generation
759 near the seamount and/or a loss of coherence induced by the overlying eddy, and deserves future investigation.

760

761 Second, the redistribution of energy via intermodal transfers is governed by a hierarchy of synergistic interactions
762 between the seamount and the background flow of the eddy. In the NE case, the seamount drives a dominant
763 forward energy cascade from Mode-1 to higher modes ($O(10^{-8} \text{ W m kg}^{-1})$), a process modulated by the
764 background flow's horizontal shear. The presence of a CE colocated with the seamount fundamentally reorganizes
765 this dynamic. The CE's strong horizontal shear initiates a dominant inverse energy cascade from the background

766 flow to the IT modes, directly competing with the ongoing topographic forward cascade. This specific synergy is
 767 crucial for explaining the extreme blocking of Mode-2 and the complex redistribution of energy fluxes observed.
 768
 769 Nonetheless, the region is shaped by a complex, co-located interplay of forces—including the NECC, MEs (CEs
 770 and AEs), and the topographic features—making it challenging to fully isolate their individual effects on ITs in
 771 our realistic simulations. Limiting our analysis to three case studies reflects the primarily qualitative nature of our
 772 approach. A natural next step would be to extend it toward more quantitative results by conducting composite
 773 analyses over a larger set of eddy-IT interaction cases. Grouping configurations by eddy position relative to the
 774 seamount, for instance, would allow the IT responses to mesoscale variability to be characterized in a statistically
 775 robust way. In addition to statistical analyses, to disentangle and quantify the specific contributions of each
 776 mesoscale feature with greater precision, future work should also employ idealized modelling frameworks. Such
 777 an approach is essential for isolating the deterministic impacts of mesoscale flow and advancing toward a
 778 predictive understanding of IT energy pathways in complex oceanic environments.
 779 Finally, it should be noted that the use of flat-bottom vertical modes in the vicinity of steep topography represents
 780 a limitation of our analysis, particularly for diagnosing higher-mode energy transfers near the seamount. Future
 781 work employing topography-aware modal decompositions would help refine these results and provide a more
 782 accurate representation of IT energetics.



783
 784 **Figure 9.** Schematics summarizing the fate of propagating M2 IT from generation sites A and D on the Amazon
 785 shelf-break. The panels correspond to the three analyzed cases: (a) NE, (b) CEC, and (c) CEE. The diagram
 786 highlights the key dynamic IT responses—inter-modal scattering, refraction, and diffraction—resulting from
 787 interaction with mesoscale structures, emphasizing the pronounced effects of CEs. The specific IT response is

788 dually controlled by its vertical mode, and the CE encounter location along with the associated background
789 conditions. Furthermore, intermodal energy scattering is governed by a hierarchical synergy between the seamount
790 and the CE's background flow.

791

792 **Data availability**

793 The AMAZON36 simulations are available upon request by contacting the corresponding author.

794

795 **Authors contributions**

796 Funding acquisition: AKL, XC and MA. Conceptualization and methodology: FK, AKL and XC. Performing
797 simulations: FA and GM with the assistance of AKL. Data processing: FK. Formal analysis: FK with interactions
798 from all co-authors. Preparation and writing of the manuscript: FK with contributions from all co-authors.

799

800 **Competing interests**

801 The contact author has declared that none of the authors has any competing interests.

802

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817

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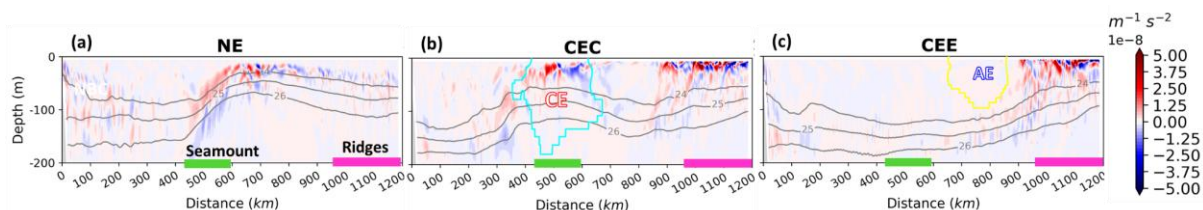
1114 Appendix

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1116 Appendix A: Horizontal Stratification Gradients Along IT Paths

1117 To evaluate the background stratification in the NE, CEC, and CEE cases, we computed the horizontal
1118 stratification gradient (∇N^2) along the transect defined on the IT propagation paths from sites A and D (Fig. 4).

1119 The horizontal stratification gradient was strong near the topographic features (seamount and ridges; Figs. A1a-
1120 c) and the CE core (Fig. A1b), but quasi-uniform near the CE edge (Fig. A1c).



1121

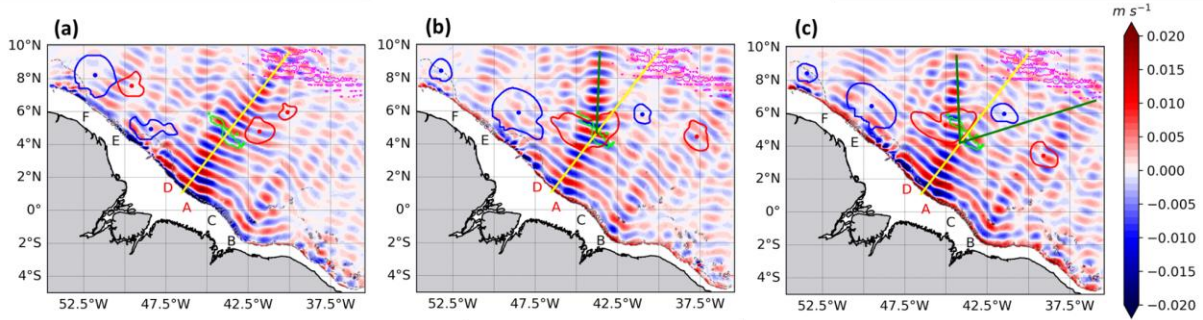
1122 **Figure A1.** Horizontal stratification gradients (∇N^2) in the upper 200 m, shown along transects defined by the IT
1123 propagation paths from sites A and D (Fig. 4), for the (a) NE, (b) CEC, and (c) CEE cases. Color shading indicates
1124 the gradient magnitude. Notable topographic features are outlined by colored rectangles (seamount: green; ridges:
1125 magenta). Panels (b) and (c) also show the detected eddy edges for AE (yellow) and CE (cyan). All panels show
1126 selected potential density isopycnals (24–26 $kg\ m^{-3}$, grey contours).

1127

1128 Appendix B: M₂ Tidal Beam Dynamics

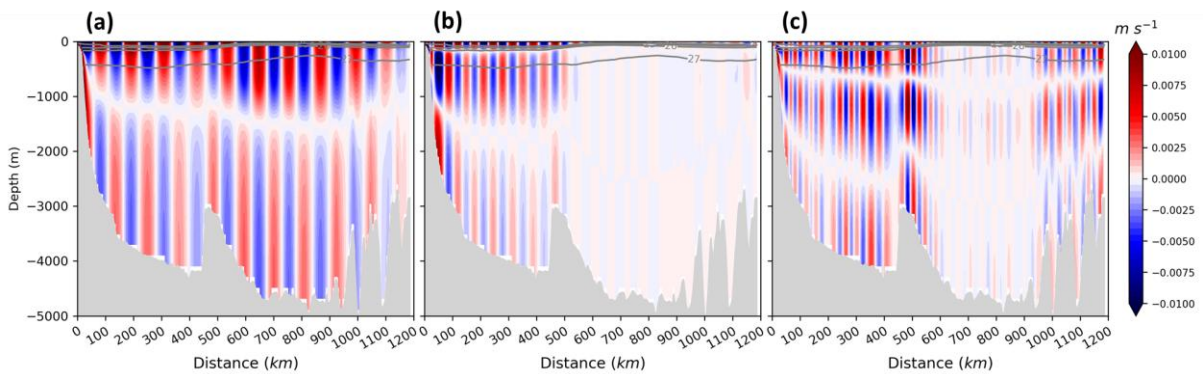
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1130 To better determine whether the response of ITs to MEs, specifically CEs, is governed more by the IT's vertical
1131 structure or by the CE's properties and location, we analyzed the M₂ baroclinic velocity field. Following the
1132 methodology in Sect. 2.2.2, we projected the velocity field into vertical modes and defined transects along
1133 different IT beams for the NE, CEC, and CEE cases (Fig. B1): the northeastward incident beam (yellow) from
1134 sites A and D, northward refracted beams from CE center (green), and diffracted beams (northward and eastward)
1135 from CE edge (green). We then decomposed the modal velocities into along- and cross-transect components. The
1136 transect along the incident tidal beam was identical in all three cases to enable a direct comparison. Our analysis
1137 focused on the more energetic along-transect component, as shown in Figs. B2-B4. The vertical structure of this
1138 velocity component was found to be coherent with the modal M₂ energy flux patterns in all analyzed cases.



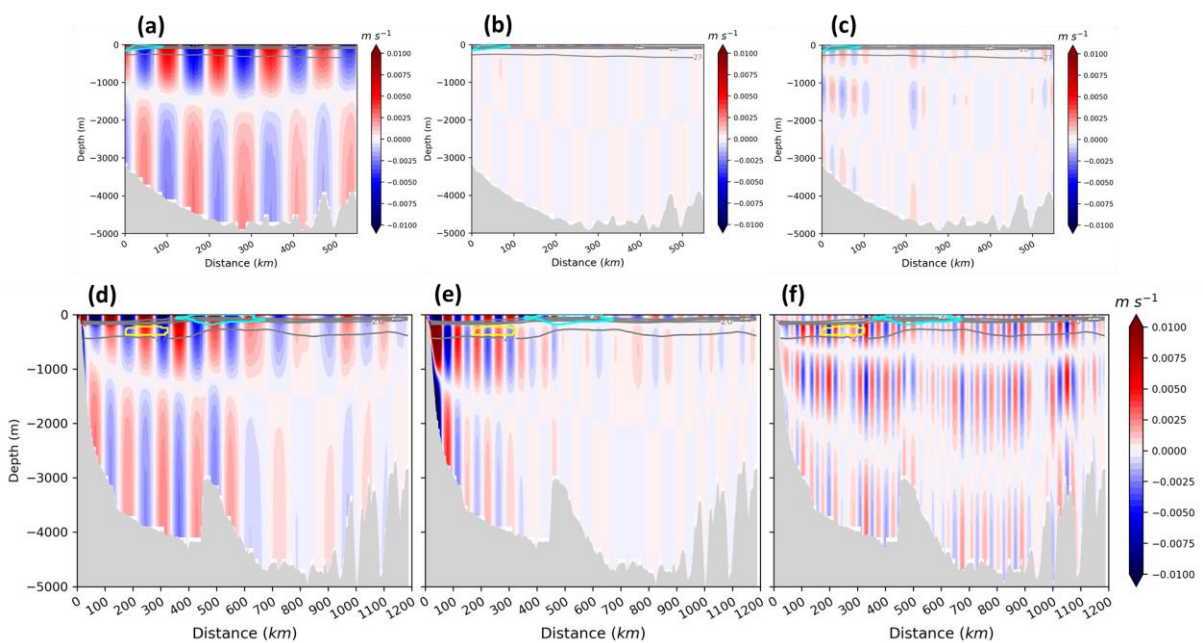
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Figure B1. Horizontal propagation of mode-1 M2 IT beams. Snapshots (at $t = 6$ h) of meridional baroclinic velocity for the (a) NE, (b) CEC, and (c) CEE cases. The corresponding dates are 24 November 2015, 17 September 2015, and 29 September 2015, respectively. All panels include defined transects along different IT beams: the northeastward incident beam (yellow lines) from sites A and D, northward refracted beams from CE core (solid green line), and diffracted beams (northward and eastward) from CE edge (solid green lines). Detected eddy edges (closed contours) and centroids (dots) for AE (blue) and CE (red) are also shown.



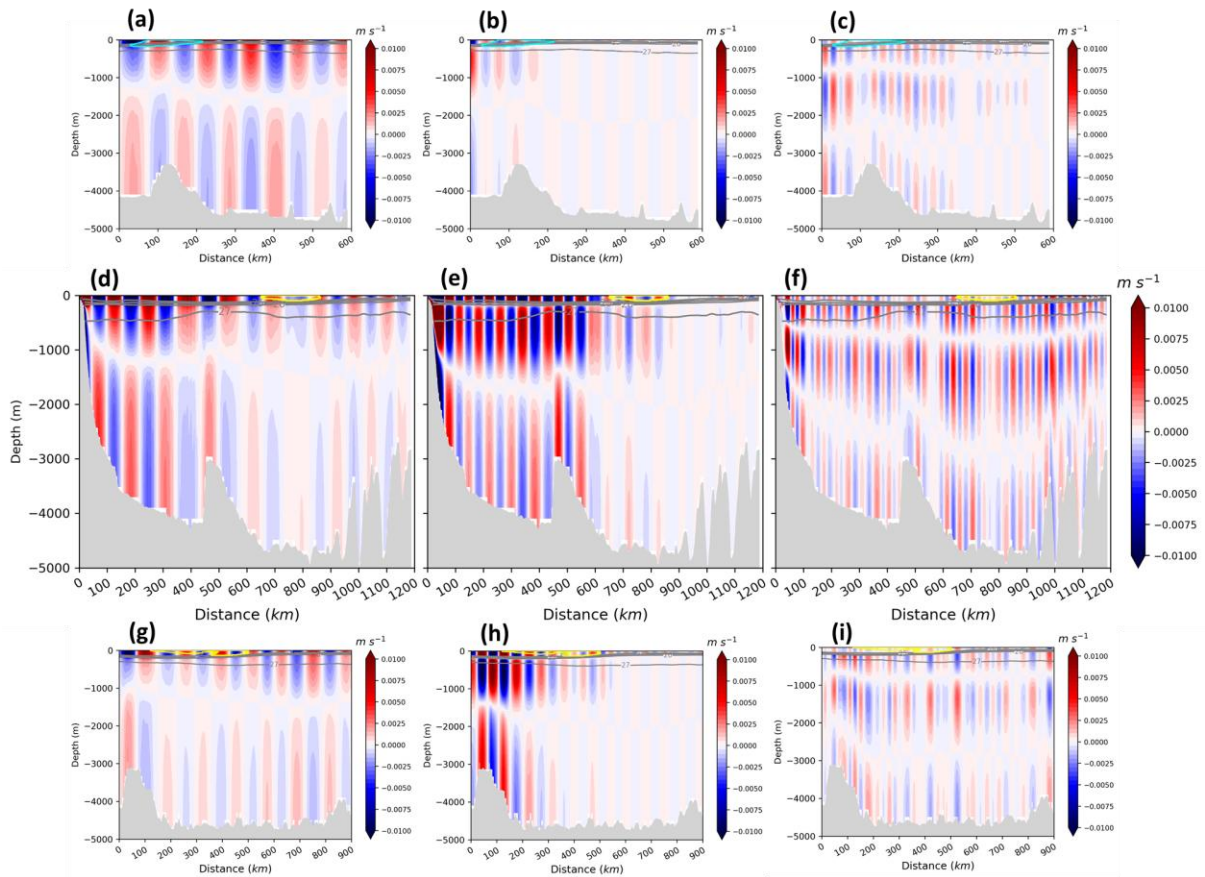
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Figure B2. Vertical structure of the first three M2 IT modes in the NE case. Snapshots ($t = 6$ h on 24 November 2015) of the along-transect baroclinic velocity component for modes 1 (a), 2 (b), and 3 (c) along the northeastward incident beam. All panels include selected potential density isopycnals ($23\text{--}27$ kg m^{-3} , grey contours), and the seafloor topography (grey shading).



1151

1152 **Figure B3.** Vertical structure of the first three M2 IT modes in the CEC case. Snapshots ($t = 6$ h on 17 September
 1153 2015) of the along-transect baroclinic velocity component for modes 1 (a, d), 2 (b, e), and 3 (c, f) along different
 1154 beams: the northward diffracted beam (a-c) and the northeastward incident beam (d-f). All panels include detected
 1155 eddy edges for AE (yellow) and CE (cyan), selected potential density isopycnals ($23\text{--}27\text{ kg m}^{-3}$, grey contours),
 1156 and the seafloor topography (grey shading).



1157 **Figure B4.** Vertical structure of the first three M2 IT modes in the CEE case. Snapshots ($t = 6$ h on 29 September
 1158 2015) of the along-transect baroclinic velocity component for modes 1 (a, d, g), 2 (b, e, h), and 3 (c, f, i) along
 1159 different beams: the northward diffracted beam (a-c), the northeastward incident beam (d-f), and the eastward
 1160 diffracted beam (g-i). All panels include detected eddy edges for AE (yellow) and CE (cyan) eddies, selected
 1161 potential density isopycnals ($23\text{--}27\text{ kg m}^{-3}$, grey contours), and the seafloor topography (grey shading).
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