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Research Article

Keywords: Ocean Stratification, Hemispheric Asymmetry, Baroclinic Mode, Wind Energy Input, Eddy Kinetic Energy

Posted Date: September 23rd, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10664712/v1>

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Hemispheric Differences in Ocean Stratification and Surface Energy Pathways Under Climate Change

by

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Abstract

Global ocean stratification is intensifying under climate change, yet the hemispheric asymmetry of this transformation and its impact on the ocean's mechanical energy cycle remain insufficiently understood. Here we analyze multi-decadal temperature-salinity profiles alongside satellite observations to quantify changes in the first baroclinic mode phase speed, reduced gravity, and surface layer thickness, assessing their influence on wind energy input. Our results reveal a pronounced hemispheric asymmetry: the Tropical Ocean and Northern Hemisphere exhibit severe upper-layer compression, trapping mechanical energy near the surface and suppressing down-scale energy transfer. Conversely, the subpolar Southern Ocean maintains a stable baroclinic structure, acting as a mechanical sink where intensified wind-work fuels enhanced eddy kinetic energy. These findings reshape understanding of global ocean dynamics and energy pathways, with implications for climate system responses and projections.

Significance Statement

The ocean's role in storing and distributing mechanical energy under climate change is critical yet uncertain. This study uncovers a fundamental hemispheric asymmetry in ocean structural responses, demonstrating that stratification intensifies energy trapping in the Tropical and Northern Hemisphere oceans, while the Southern Ocean remains mechanically resilient through eddy-driven energy venting. This divergence alters the global ocean's mechanical energy balance, informing future climate modeling and projections.

Keywords

Ocean Stratification; Hemispheric Asymmetry; Baroclinic Mode; Wind Energy Input; Eddy Kinetic Energy

46 1. Introduction

47 The global ocean plays a crucial role in regulating the Earth's climate by acting as a thermal
48 and mechanical flywheel. It absorbs more than 90% of the excess heat generated by human activities,
49 such as greenhouse gas emissions [1]. This significant increase in heat, combined with changes in
50 freshwater flow, is causing rapid changes in the ocean's density patterns. Ocean stratification has
51 intensified globally in recent decades, with an estimated increase of roughly 0.8% per decade in the
52 upper 2,000 meters since the 1960s [2]. However, while global measurements provide a general
53 understanding of these changes, they often overlook important spatial variations. The distinct
54 atmospheric conditions and different shapes of the Northern and Southern Hemisphere ocean basins
55 suggest that the restructuring of the water column may be uneven [3]. It is crucial to understand this
56 asymmetry in order to accurately map how the ocean processes and distributes energy in a changing
57 climate.

58 The primary mechanism driving the three-dimensional circulation of the global ocean is the
59 interaction between wind stress and the ocean surface [4]. The wind imparts mechanical energy,
60 which is then split into two distinct pathways: work done on the time-mean circulation (W_{MKE}) [5]
61 and work done directly on, or converted into, the time-varying mesoscale eddy field (W_{EKE}) [6]. This
62 energy input is mediated by the ocean's vertical density structure [4-6]. Stratification not only
63 determines the depth over which wind momentum is distributed within the turbulent boundary layer,
64 but also governs the characteristic speeds and spatial scales of baroclinic waves through the first
65 internal mode phase speed (c_1) [7].

66 Under the effects of global warming, the upper ocean has experienced significant alterations,
67 such as widespread freshening and warming. As a result, there has been an overall increase in global
68 stratification [3]. However, the specific spatial adjustments of this stratification, particularly how it
69 impacts the continuous vertical modes and transforms them into dynamically active layers, are not
70 well comprehended. Traditional metrics, such as the buoyancy frequency (N^2), only offer insight into
71 localized vertical gradients and fail to fully capture the dynamic changes in the water column that
72 determine the phase speeds of planetary waves and the depth of the active upper layer [7].

73 In this study, we utilize a two-layer description of the water column, mathematically
74 constrained by the continuous Sturm-Liouville equation, to map the global evolution of the phase
75 speed of the first baroclinic mode, the reduced gravity across the main pycnocline, and the effective
76 surface layer thickness from 1960 to 2022. While the ocean possesses infinite vertical degrees of
77 freedom, global current meter observations and altimetric analyses confirm that horizontal kinetic
78 energy and sea surface height variations across most of the world ocean are dominated by the
79 barotropic and first baroclinic modes [8-11]. This concentration of energy justifies the reduction of
80 the continuous system into an equivalent two-layer structure to isolate bulk kinematic shifts [10]. By

cross-examining these structural shifts with trends in satellite-derived Mean Kinetic Energy (MKE), Eddy Kinetic Energy (EKE), and their corresponding wind-work terms (W_{MKE} and W_{EKE}), we identify a meridional asymmetry: low latitudes and the Northern Hemisphere exhibit a buoyancy-dominated, energy-compressing regime, while the subpolar Southern Ocean maintains a contrasting eddy-saturated, mechanically resilient equilibrium. This approach directly addresses the gap in understanding how hemispheric differences in ocean structure regulate the global energy cycle.

2. Results

2.1 Meridional Asymmetry in Baroclinic Vertical Architecture

The multi-decadal evolution of the global ocean's internal structure reveals a significant hemispheric asymmetry. Over the baseline period of 1960-2022, there has been a widespread positive trend in the phase speed of the first baroclinic internal mode (c_1) across most of the global ocean (see Figure 1a) [3,12]. However, this acceleration is not consistent across all regions. While there are marked increases in the equatorial band (15°S-15°N) and in both the subtropical and subpolar gyres of the Northern Hemisphere (15°N-75°N), the subpolar Southern Ocean (75°S-45°S) stands out as the main exception, with neutral to slightly negative long-term changes.

To investigate the mechanical forces driving the observed changes in c_1 , we utilize a simplified two-layer framework to represent the continuous vertical stratification. This approach mathematically separates the effects of the vertical density difference (reduced gravity, g') and the geometry of the upper layer (equivalent surface layer thickness, H_1) through a constrained optimization routine. The resulting changes in c_1 are then described by the relationship $c_1 \approx (g'H_1)^{1/2}$.

The global linear trends of these decomposed parameters reveal the structural source of the wave speed acceleration. The increase of c_1 outside the Southern Ocean is driven by a globally coherent surge in reduced gravity g' (Figure 1b). This sharpening of the density gradient across the base of the primary pycnocline is most severe in the equatorial Pacific and Atlantic basins, as well as the cores of the subtropical gyres. In these regions, the equivalent surface layer thickness H_1 exhibits a systematic, statistically significant, shoaling trend (Figure 1c).

The regional time-series (Figure 2) illustrate the detailed historical development of this structural polarization. Prior to the late 1980s, the spatially averaged anomalies of c_1 , g' , and H_1 remained consistent within coherent, multi-decadal ranges across all latitudes examined, reflecting natural background climate variability. However, after approximately 1990, the latitudinal time-series begin to diverge. The Tropical Ocean (Figure 2, represented by yellow lines), as well as the subtropical (magenta lines) and subpolar zones (green lines) of the Northern Hemisphere, experience a sustained increase in g' accompanied by a steady decrease in H_1 . This increase in g' is significantly greater than the decrease in H_1 , resulting in an overall positive trend in c_1 .

115 In contrast, the subpolar Southern Ocean (75°S–45°S, shown in blue lines) shows consistent
116 structural stability over the entire 62-year period. The integrated regional anomalies for c_1 , g' , and
117 H_1 display almost no significant long-term trends since the 1960s. Although the high-resolution trend
118 map (Figure 1c) reveals localized variations within the Southern Ocean, such as a noticeable
119 deepening of H_1 in the northern edge of the Antarctic Circumpolar Current (45°S–55°S) balanced by
120 a shallowing further south (60°S–75°S), the overall average across the broad subpolar region remains
121 stable.

122 The complete breakdown of these decadal linear trend slopes, corresponding standard errors,
123 and non-parametric statistical significance parameters across all five macro-meridional zones is
124 compiled and presented in Extended Data Table 1.

125 2.2 *Spatial Patterns and Co-Evolution of Mechanical Energy Budgets*

126 The observed variations in the baroclinic vertical architecture (c_1 , g' , H_1) are not simply static
127 indicators of ocean warming; rather, they actively reshape global ocean energetics. The value of c_1
128 determines the baroclinic Rossby radius of deformation, and its geographically asymmetric trends
129 fundamentally alter the threshold for baroclinic instability within the mean flow. In this context, wind
130 stress acts as the primary mechanical forcing that modulates both the upper-layer geometry H_1 and
131 the momentum injected into the mean currents. However, the interplay between altered stratification
132 and wind forcing governs the efficiency of energy conversion from the mean state into eddy fields.

133 The structural polarization documented in the ocean's baroclinic vertical architecture co-
134 evolves with highly contrasting regional trends in surface mechanical energy and wind momentum
135 injection over the satellite altimetry era (1993–2022). In the low-to-mid latitudes and the Northern
136 Hemisphere, where the upper ocean has experienced significant structural compression, the long-term
137 linear trends of EKE (Figure 3c) and W_{EKE} (Figure 3d) remain subdued, fragmented, or even declining
138 [13]. While localized areas of increased W_{MKE} (Figure 3b) can be seen in the extensions of western
139 boundary currents, they do not lead to a widespread corresponding increase in the background eddy
140 fields.

141 The subpolar Southern Ocean presents the inverse dynamic signature, characterized by an
142 intense coupling between wind forcing and upper-ocean kinetic energy. Within the 75°S–45°S
143 circumpolar belt, the robust, invariant baseline of c_1 , g' , and H_1 (Figure 2) coexists with large, highly
144 significant positive trends in MKE, (Figure 3a), EKE (Figure 3c), W_{MKE} (Figure 3b), and W_{EKE} (Figure
145 3d). The spatial averages of these energy metrics (Figure 4) show that the long-term expansion of the
146 Southern Ocean eddy field (Figure 4c, blue line) and its corresponding mechanical wind-work input
147 (Figure 4d, blue line) together represent the most prominent linear signal in the global ocean energy
148 budget.

149 Superimposed upon these multi-decadal regional trends, the spatial averages of the energy
150 metrics (Figure 4) reveal prominent interannual variations that are globally synchronous. Most
151 notable are the massive, sharp, high-amplitude spikes in global EKE (Figure 4c) and W_{EKE} (Figure
152 4d) centered precisely around the years 1997–1998 and 2015–2016. These global energetic pulses are
153 heavily pronounced within the Tropical band (Figure 4d, yellow line), where the curves temporarily
154 surge several standard deviations above the background mean before returning rapidly to the long-
155 term multi-decadal baseline.

156 3. Discussion

157 3.1 Wave-Kinematic Feedbacks and Global Climate Teleconnections

158 The widespread increase of c_1 across low-to-mid latitudes and the Northern Hemisphere leads
159 to fundamental changes in the ocean's internal wave dynamics. Since the phase speed of the first
160 baroclinic mode determines the velocity of large-scale internal waves, an increase in c_1 alters the
161 timescales over which signals are transmitted across major ocean basins. Along the equatorial
162 waveguide (15°S–15°N), the propagation speed of non-dispersive baroclinic Kelvin waves is exactly
163 equal to c_1 [14]. The observed multi-decadal increase in c_1 means that these waves, which transport
164 mass and heat through downwelling and upwelling motions, cross the Pacific and Atlantic basins
165 more rapidly. This acceleration may influence the development and decay phases of the El Niño-
166 Southern Oscillation (ENSO), potentially affecting the timing and evolution of global atmospheric
167 teleconnections [15,16].

168 In the extra-tropical and mid-latitude domains, this structural alteration triggers an even more
169 pronounced wave feedback. The phase speed of long baroclinic Rossby waves (c_R) scales
170 quadratically with the internal mode speed via the relation: $c_R = -\beta \cdot R_d^2 = -\beta \cdot c_1^2 / f^2$ where $\beta = df/dy$ with
171 f the Coriolis parameter, and R_d is the first internal Rossby radius of deformation [7]. Because Rossby
172 wave phase propagation is a function of c_1^2 , the observed structural adjustments trigger a non-linear,
173 squaring acceleration of the speed at which mid-latitude oceans adjust to shifting atmospheric wind
174 stress curl anomalies. The extra-tropical oceans may be becoming more responsive to shifting
175 atmospheric wind stress curl anomalies due to structural changes in baroclinic wave speeds.

176 3.2 Energy Trapping Mechanics vs. Eddy-Saturated Venting

177 This global wave acceleration modifies how the ocean balances horizontal energy transport
178 against vertical mixing. The simultaneous increase in c_1 and the sharpening of g' , along with a
179 reduction in H_1 , create a pronounced mechanical barrier at low-to-mid latitudes. This barrier restricts
180 the downward transfer of mechanical energy imparted by surface winds to the mean or eddy current
181 fields, so that more energy is either dissipated locally, converted into mesoscale features, or

182 transported horizontally by planetary waves. As a result, the vertical and horizontal distribution of
183 mechanical energy in the ocean is significantly altered.

184 The enlargement of the Rossby radius shifts the dominant length scales of ocean variability
185 toward larger, more stable wave architectures, enabling localized wind energy inputs to be efficiently
186 swept away as radiating wave energy before they can destabilize the local water column [17].
187 Concurrently, the sharp density variation across the thinned surface layer acts as a vertical barrier,
188 increasing the local Burger number (i.e. $Bu = (R_d/L)^2$ with L the horizontal length scale) and stabilizing
189 the horizontal flow against medium-scale baroclinic shears [6,12]. This structural compression may
190 influence the distribution of available potential energy (APE) near the surface and affect the
191 downward transmission of near-inertial and internal wave energy [18]. The wind's mechanical work
192 may become increasingly confined to a thinning surface volume, potentially influencing upper-ocean
193 warming and the transmission of momentum to the deep ocean [19].

194 The subpolar Southern Ocean presents the inverse physical regime, with stable baroclinic
195 structure and increased eddy activity that may facilitate the dissipation of mechanical energy. Within
196 the Antarctic Circumpolar Current (ACC) channel, the continuous and intensified input of mechanical
197 energy by the shifting Southern Hemisphere Westerlies does not accumulate as a localized change in
198 vertical stratification or layer thickness [20,21]. Because the background baroclinic architecture (c_1 ,
199 g' , H_1) is dynamically anchored by intense buoyancy forcing and deep wind-driven upwelling [22,23],
200 the system cannot form a surface buoyancy trap. Instead, the massive wind energy input drives lateral
201 velocity shears that trigger baroclinic instability [12,17]. This instability continuously converts the
202 wind-generated MKE into EKE [24]. These eddies release the potential energy stored in the tilted
203 isopycnals of the ACC through an enhanced upward and poleward eddy buoyancy flux [21,25]. This
204 mechanism may facilitate the dissipation of excess mechanical energy through structural
205 transformations and contribute to the maintenance of the subpolar Southern Ocean's baroclinic
206 structure [26].

207 3.3 *Climate Forcing Extremes and Super-El Niño Signatures*

208 The sharp EKE and W_{EKE} spikes observed in 1997–1998 and 2015–2016 highlight a critical
209 intersection where transient climate extremes temporarily bypass these slow, multi-decadal structural
210 regimes. During these Super-El Niño events, the catastrophic breakdown of the equatorial Pacific
211 trade winds and the subsequent global atmospheric teleconnections drastically alter wind stress curl
212 fields worldwide [15,27]. In the Tropical zone, W_{EKE} experiences sudden, high-amplitude pulses.
213 Mechanically, the rapid propagation of downwelling equatorial Kelvin waves during these events
214 may displace the shallow pycnocline and influence localized vertical velocity shears [28].

215 The abrupt deposition of wind energy during these events excites intense local baroclinic and
216 barotropic instabilities, manifesting as the observed global EKE peaks [8]. The fact that these spikes

217 are short-lived and rapidly return to the background multi-decadal baseline suggests that while
218 transient atmospheric extremes can temporarily supercharge the ocean's eddy field, the long-term
219 energetic pathways may be influenced by the slowly evolving, asymmetric baroclinic modifications
220 shown in Figure 2.

221 3.4 *Implications for Global Ocean Models and Earth System Projections*

222 This structural polarization carries critical implications for state-of-the-art Earth System
223 Models (ESMs) used to project future climate scenarios. Most current climate simulations utilize grid
224 resolutions of $1^\circ \times 1^\circ$, which are unable to resolve the internal Rossby radius of deformation,
225 particularly at mid-to-high latitudes where R_d shrinks to less than 20 km [7]. Consequently, these
226 models oversimplify vertical mixing and symmetric eddy-viscosity closures (such as standard Gent-
227 McWilliams schemes) that apply uniform damping coefficients worldwide [25]. This bias may lead
228 to errors in projections of global ocean heat content distribution, deep carbon sequestration pathways,
229 and the rate of decline of the abyssal overturning circulation [28,29]. Embedding this dual-regime
230 framework, differentiating between buoyancy-dominated energy traps and mechanically regulated
231 eddy sinks, into next-generation climate models appears a priority to reduce uncertainties in global
232 warming projections.

233 4. **Conclusion**

234 Our analysis illustrates that global climate change is actively polarizing the ocean into two
235 distinct mechanical regimes. These contrasting mechanisms are conceptually synthesized and
236 summarized in Figure 5. At low-to-mid latitudes and across the Northern Hemisphere, a buoyancy-
237 driven regime dominates: warming and freshening compress the upper ocean structure, sharpening
238 the pycnocline interface (g') and forcing it upward (H_I) [3,30]. This structural stiffening, traps
239 mechanical energy in a shallow surface layer and restricts deep baroclinic conversions [4,18].
240 Conversely, the subpolar Southern Ocean operates as a mechanically regulated regime. Protected by
241 vigorous upwelling and an intense, eddy-saturated circulation, it maintains a remarkably stable
242 baroclinic structure, absorbing and dissipating shifting wind energy inputs via an enhanced mesoscale
243 eddy field [21,22,26]. This meridional polarization carries profound implications for the closure of
244 the global ocean energy budget and the pathways of climate change propagation. The widespread
245 acceleration of the first internal mode phase speed (c_I) across the Tropics and the Northern
246 Hemisphere is expected to alter basin-scale adjustment timescales. Because c_I dictates the velocity
247 of equatorial Kelvin waves and sets the quadratic scaling of mid-latitude baroclinic Rossby waves,
248 the modern ocean is adjusting to atmospheric wind anomalies at an accelerated rate. For example, in
249 the tropical Pacific, the increase in c_I is expected to alter the characteristic scales and evolution of the
250 El Niño-Southern Oscillation. Concurrently, the horizontal expansion of the Rossby radius of

deformation enables the rapid, radiative transport of wind-imparted energy toward western boundaries and coastal margins, favoring horizontal wave propagation over localized vertical mixing.

Interestingly, the increase in c_I , which is linked to the rise in g' and the decrease in H_I , leads to a higher Burger number, making surface currents more stable in terms of baroclinic instability. This mechanism is expected to reduce the transfer of energy from the surface to deeper layers of the ocean. This process restricts the energy injected by the wind to a thinning upper layer of the water column choking the mechanical energy supply required to sustain abyssal mixing and maintain the global overturning circulation [19,28].

In contrast, the Southern Ocean's capacity to preserve its baroclinic baseline through eddy-saturated venting may play an important role in the dissipation of mechanical energy and the maintenance of its vertical structure.

Current state-of-the-art Earth System Models, which frequently suffer from coarse grid resolutions and rely on overly simplistic vertical mixing parameterizations, may fail to resolve this critical structural polarization. Correcting these potential biases and embedding this dual-regime energy-trapping and eddy-dissipative framework into next-generation climate projections is vital to accurately forecasting future ocean heat uptake, marine ecosystem stability, and global carbon sequestration feedbacks [29].

5. Material and Methods

5.1 Data

Vertical profiles of ocean temperature and salinity for the period 1960–2022 were obtained from the Institute of Atmospheric Physics, Chinese Academy of Sciences (IAP-CAS) gridded product, which features a $0.5^\circ \times 0.5^\circ$ horizontal resolution and 41 vertical depth levels extending from the surface to 2000 meters [30].

Monthly global geostrophic current velocities were derived from altimetric absolute dynamic topography data for the period of January 1993 to December 2022, obtained from the Archiving, Validation, and Interpretation of Satellite Oceanographic (AVISO) facility. These data have a spatial resolution of $0.25^\circ \times 0.25^\circ$ and were decomposed into mean and eddy components. The slowly varying component of the circulation (mean component), referred to as $\mathbf{u}_M$, was defined as the 36-month median filtered value of the geostrophic current ($\mathbf{u}$), i.e.

$$\mathbf{u}_M(\mathbf{x}, t_l) = \frac{1}{K+1} \cdot \sum_{k=-K/2}^{K/2} \mathbf{u}(\mathbf{x}, t_{l+k}) \quad l = K/2 + 1 \dots N - K/2$$

where $K = 36$ months. The eddy component, $\mathbf{u}_E$, was calculated as the difference between the total circulation ($\mathbf{u}$) and the mean circulation ($\mathbf{u}_M$), i.e. $\mathbf{u}_E = \mathbf{u} - \mathbf{u}_M$. The mean and eddy component of the

283 circulation were used to compute the mean flow (MKE) and eddy (EKE) kinetic energy as $K_M =$
 284 $|\mathbf{u}_M|^2/2$ and $K_E = |\mathbf{u}_E|^2/2$.

285 Global monthly wind data were provided by the Copernicus Climate Change Service (C3S).
 286 Copernicus wind data consist of global maps of the zonal and meridional component of the surface
 287 wind with a spatial resolution of $0.25^\circ \times 0.25^\circ$. The wind stress was calculated from surface wind
 288 components using the standard formula $\boldsymbol{\tau} = \rho_{air} \cdot c_D \cdot (v_x^2 + v_y^2)^{1/2} \cdot \mathbf{v}$, where $\mathbf{v} = (v_x, v_y)$ is the surface wind,
 289 ρ_{air} is the air density at the ocean surface (taken as 1.2 kg/m^3) and c_D is the drag coefficient, taken as
 290 $1.2 \cdot 10^{-3}$ if $(v_x^2 + v_y^2)^{1/2} < 11 \text{ m/s}$ and $[0.49 + 0.065 \cdot (v_x^2 + v_y^2)^{1/2}] \cdot 10^{-3}$ if $(v_x^2 + v_y^2)^{1/2} \geq 11 \text{ m/s}$ [31]. This
 291 drag coefficient is generally accurate for wind speeds up to 25 m/s. However, in severe storm
 292 conditions where wind speeds exceed 25 m/s, saturation effects may cause c_D to stabilize or even
 293 decrease [32]. In these situations, the description of c_D discussed in [31] may not be applicable. It
 294 should be noted that this study uses monthly wind data, which rarely captures wind events with
 295 intensities higher than 25 m/s. In Figure S.1 of the Supplementary Material, we show the percentage
 296 of points where monthly ERA5 data captures wind speeds between 11 m/s and 25 m/s, as well as
 297 speeds higher than 25 m/s. It is evident that the number of events captured by the monthly ERA5
 298 wind data set with speeds between 11 m/s and 25 m/s is always less than 2%. Additionally, the ERA5
 299 data set does not capture any events with a monthly mean wind speed greater than 25 m/s throughout
 300 the entire observation period. This demonstrates that the chosen form for c_D is accurate for this study.

301 Wind stress and the mean and eddy components of the geostrophic current field were used to
 302 compute the work done by the wind on the mean (W_{MKE}) and eddy (W_{EKE}) circulation using the
 303 standard formulations [5]:

$$\begin{aligned} 304 \quad W_{MKE} &= \boldsymbol{\tau} \cdot \mathbf{u}_M \\ W_{EKE} &= \boldsymbol{\tau} \cdot \mathbf{u}_E \end{aligned}$$

305

306 5.2 Sturm-Liouville Formulation

307 The phase speed of the vertical baroclinic modes is dictated by the continuous stratification
 308 profile. The vertical structure function $\phi(z)$ and the corresponding phase speed c for the internal modes
 309 are governed by the standard Sturm-Liouville equation subject to rigid-lid boundary conditions [7]:

310

$$\begin{aligned} 311 \quad \frac{d}{dz} \left(\frac{1}{N^2(z)} \frac{d\phi}{dz} \right) + \frac{1}{c^2} \phi(z) &= 0 \\ 312 \quad \left. \frac{d\phi}{dz} \right|_{z=0} &= 0; \quad \phi(z)|_{z=-D} = 0 \end{aligned}$$

313

314 where $N^2(z) = -(g/\rho_0) \cdot (d\rho/dz)$ is the buoyancy frequency, g is gravitational acceleration, ρ_0 is the
 315 reference ocean density, and D is the local bottom depth. This second-order differential equation was

solved numerically at each grid point using an eigenvalue solver to isolate the primary eigenvalue, yielding the long-term evolution of the first internal mode phase speed (c_1) [7].

5.3 Constrained Two-Layer Fitting

To map the continuous stratification into an operationally distinct two-layer vertical architecture, the observed continuous density profiles $\rho(z)$ were modeled using an idealized step-function:

$$\rho_{ideal} = \begin{cases} \rho_1 & \text{for } -H_1 \leq z \leq 0 \\ \rho_2 & \text{for } -D \leq z < -H_1 \end{cases}$$

where ρ_1 and ρ_2 represent the average upper and lower layer densities, and H_1 represents the equivalent surface layer thickness. The optimization routine fits this step function to the observed profile by minimizing the vertical density mismatch. Crucially, the optimization is strictly constrained to reproduce the exact phase speed c_1 derived from the continuous Sturm-Liouville equation, enforcing the operational identity:

$$c_1 = \sqrt{g' \frac{H_1 \cdot (D - H_1)}{D}} \approx \sqrt{g' H_1}$$

where $g' = g \cdot (\rho_2 - \rho_1) / \rho_0$ defines the reduced gravity across the layer interface. This dual constraint prevents mathematical ambiguity, mapping all changes in continuous stratification directly onto physically interpretable shifts in layer sharpness (g') and layer depth (H_1).

Data Availability

Original monthly T-S data were made available by the Institute of Atmospheric Physics (IAP) of the Chinese Academy of Sciences (CAS) and can be downloaded at the following web site

<http://www.ocean.iap.ac.cn/pages/dataService/dataService.html?navAnchor=dataService>

Altimeter products used in this research are available to registered users from the AVISO database and can be downloaded at

ftp://ftp-access.aviso.altimetry.fr/climatology/global/delayed-time/monthly_mean

Original ERA5 wind data can be downloaded from the Copernicus data archive by registered users at

<https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels-monthly-means?tab=overview>

Code Availability

Codes used in this research are available upon reasonable request.

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404 wave states and wind speeds. *J. Phys. Oceanogr.* **43**, 1589-1610 (2013).
405

406 **Funding**

407 The authors declare that no direct funding, grants, or financial support from any public,
408 commercial, or non-profit sector was received for the research, authorship, and/or publication of this
409 article.

410 **Author Contributions**

411 All the authors contributed equally to the work. G.L.E.B. and S.C. proposed the original idea.
412 G.L.E.B and E.N. designed the research. All authors contributed to analyze the data and to interpret
413 the results. G.L.E.B. and C.E.C. provided the figures. G.L.E.B. wrote the initial version of the
414 manuscript, S.C., E.N., C.E.C. and M.S. provided corrections and comments.

415 **Competing Interests**

416 The authors declare no competing interest.

417 **Extended Data Displays**

418 **Extended Data Table 1.** Decadal trend statistics for vertical baroclinic parameters across distinct
419 meridional domains (1960–2022). Compiled linear trend slopes, associated standard errors, and non-
420 parametric statistical significance parameters calculated across five macro-meridional bands.
421 Statistical metrics are provided for the first internal mode phase speed (c_1), the reduced gravity (g'),
422 and the equivalent surface layer thickness (H_1). Trend values represent median slopes normalized per
423 decade. Uncertainties define the standard error bounds of the robust Theil-Sen estimator. Bold values
424 highlight statistically significant trends evaluated via two-tailed non-parametric Mann-Kendall tests
425 at the 95% confidence level ($p < 0.05$). Insignificant near-zero trends across the 75°S–45°S belt
426 quantify the invariant structural baseline of the subpolar Southern Ocean.

Extended Data Table 1 | Regional Multi-Decadal Trends in Baroclinic Architectural Parameters (1960–2022)

Meridional Latitudinal Domain	c_1 Trend ($\text{m s}^{-1} \text{dec}^{-1}$)	p-value (c_1)	g' Trend ($10^{-3} \text{ m s}^{-2} \text{dec}^{-1}$)	p-value (g')	H_1 Trend (m dec^{-1})	p-value (H_1)
Subpolar Southern Ocean (75°S–45°S)	-0.002 ± 0.003	0.542	+0.005 ± 0.008	0.612	+0.08 ± 0.15	0.684
Subtropical Southern Ocean (45°S–15°S)	+0.024 ± 0.004	0.001	+0.114 ± 0.015	0.001	+1.24 ± 0.22	0.002
Tropical Ocean (15°S–15°N)	+0.086 ± 0.007	< 0.001	+0.482 ± 0.032	< 0.001	-3.85 ± 0.31	< 0.001
Subtropical Northern Hemisphere (15°N–45°N)	+0.053 ± 0.005	< 0.001	+0.291 ± 0.021	< 0.001	-2.12 ± 0.24	< 0.001
Subpolar Northern Hemisphere (45°N–75°N)	+0.031 ± 0.004	0.002	+0.145 ± 0.018	0.001	-1.05 ± 0.19	0.003

**Note: Linear trends are computed using a robust Theil-Sen median estimator and normalized per decade. Uncertainties represent standard errors of the slope estimator. Statistical significance evaluated via non-parametric Mann-Kendall tests. This table was created on July 2, 2026 using MATLAB release 2018a on a machine running Ubuntu 18.04.06 LTS.*

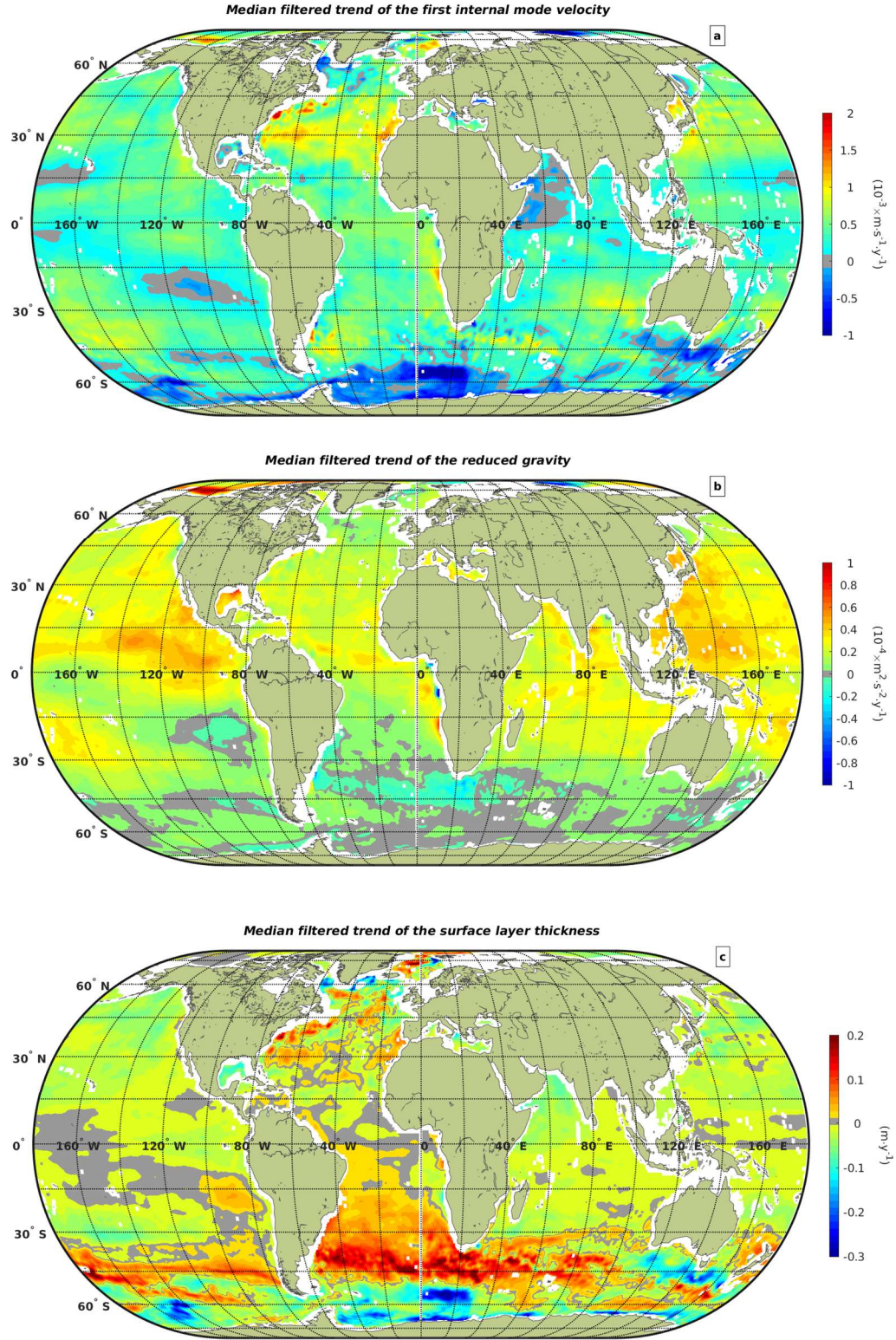
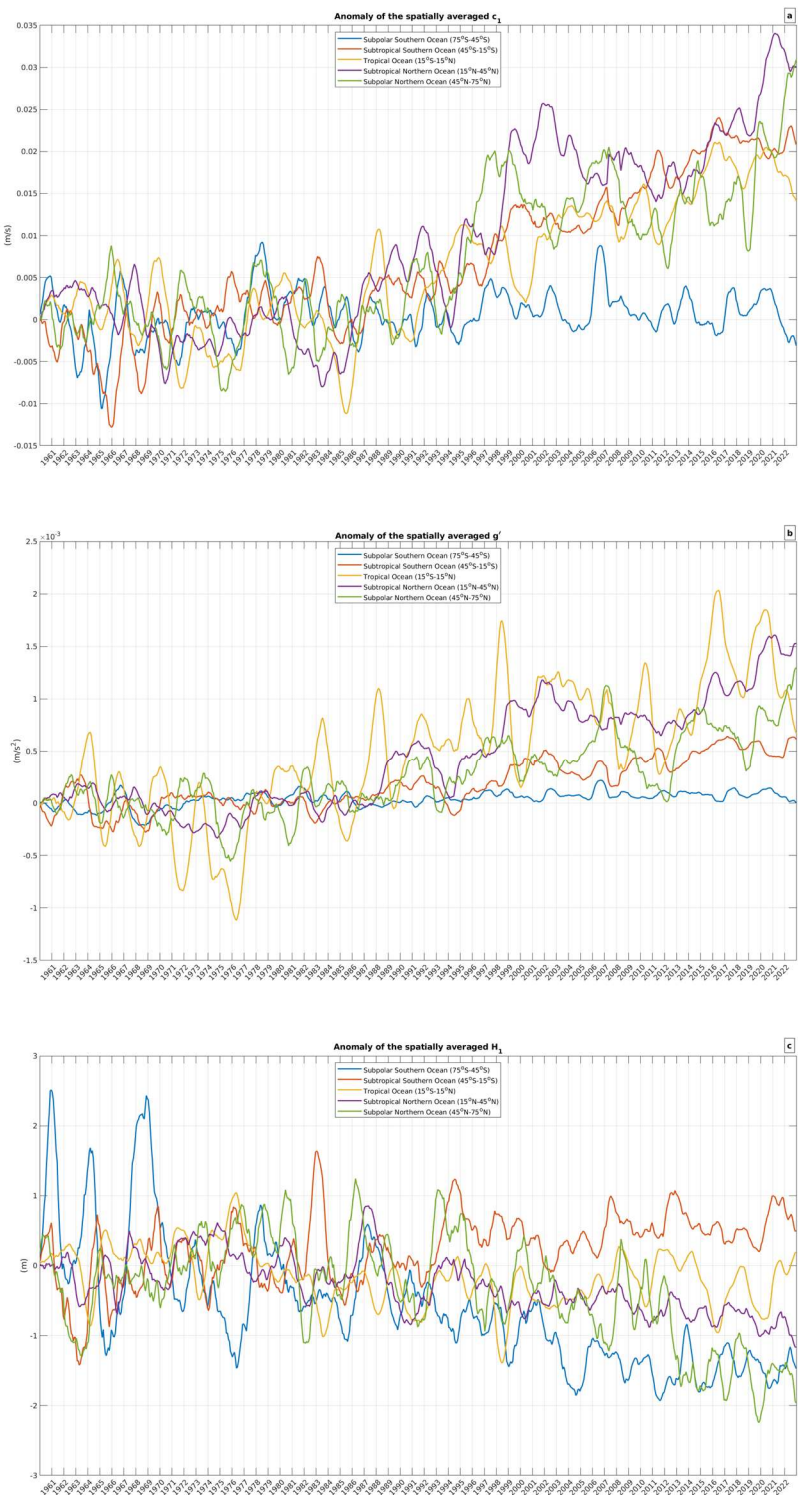


Figure 1. Long-term linear trends in global ocean baroclinic vertical structure (1960–2022). a) Spatial distribution of the linear trend in the phase speed of the first baroclinic internal mode. b) Linear trend in reduced gravity. c) Linear trend in the equivalent surface layer thickness. Layer architecture parameters in b and c are derived by fitting continuous historical vertical density profiles with an idealized two-layer step function, strictly constrained to reconstruct the continuous eigenvalues derived in a. Grid-point thermodynamic fields are calculated from the CAS-IAP gridded temperature and salinity product over the 62-year baseline. Hatching denotes trend significance at the 95% confidence level evaluated via non-parametric Mann-Kendall testing.



438
439 **Figure 2.** Multi-decadal regional trajectories of ocean baroclinic architecture. Anomalies of spatial
440 averages over five macro-meridional zones mapping the temporal evolution of: a) first internal mode
441 phase speed, b) reduced gravity, and c) equivalent surface layer depth. Colored lines isolate specific
442 meridional bounds: 75°S–45°S (blue; subpolar Southern Ocean), 45°S–15°S (red; subtropical
443 Southern Hemisphere), 15°S–15°N (yellow; Tropical Ocean), 15°N–45°N (magenta; subtropical
444 Northern Hemisphere), and 45°N–75°N (green; subpolar Northern Hemisphere). Time series are
445 derived from the CAS-IAP thermodynamic dataset (1960–2022) with anomalies relative to the long-
446 term climatological mean.

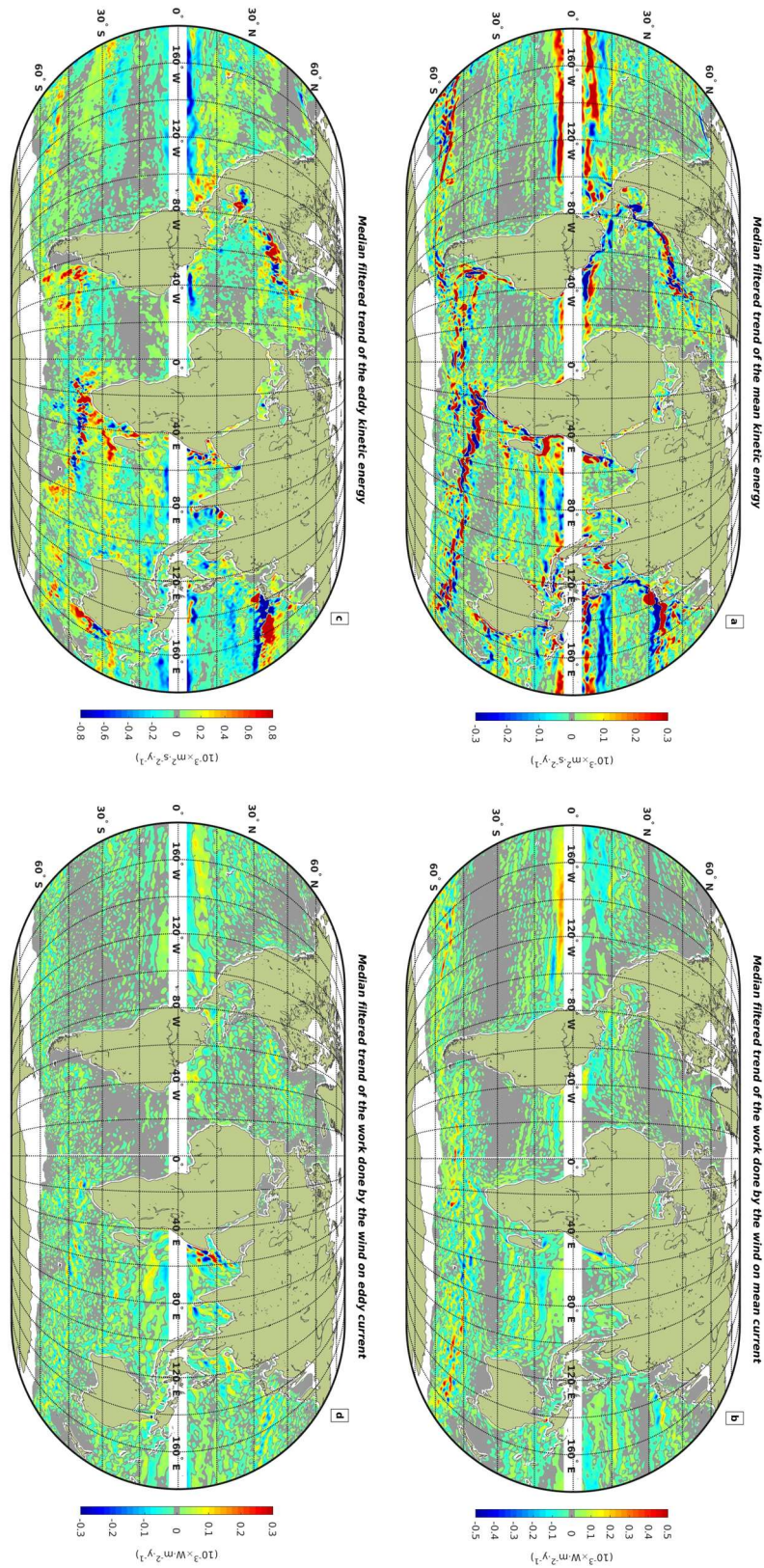


Figure 3. Spatial trends in surface mechanical energy and wind-work parameters (1993–2022). a) Linear trend in Mean Kinetic Energy (MKE) derived from time-mean satellite geostrophic velocity baselines. b) Linear trend in the mechanical work executed by the surface wind stress vector on the mean circulation. c) Linear trend in Eddy Kinetic Energy (EKE) capturing transient mesoscale fluctuations. d) Linear trend in the mechanical work executed by the wind stress anomaly vector directly onto the time-varying eddy current field.

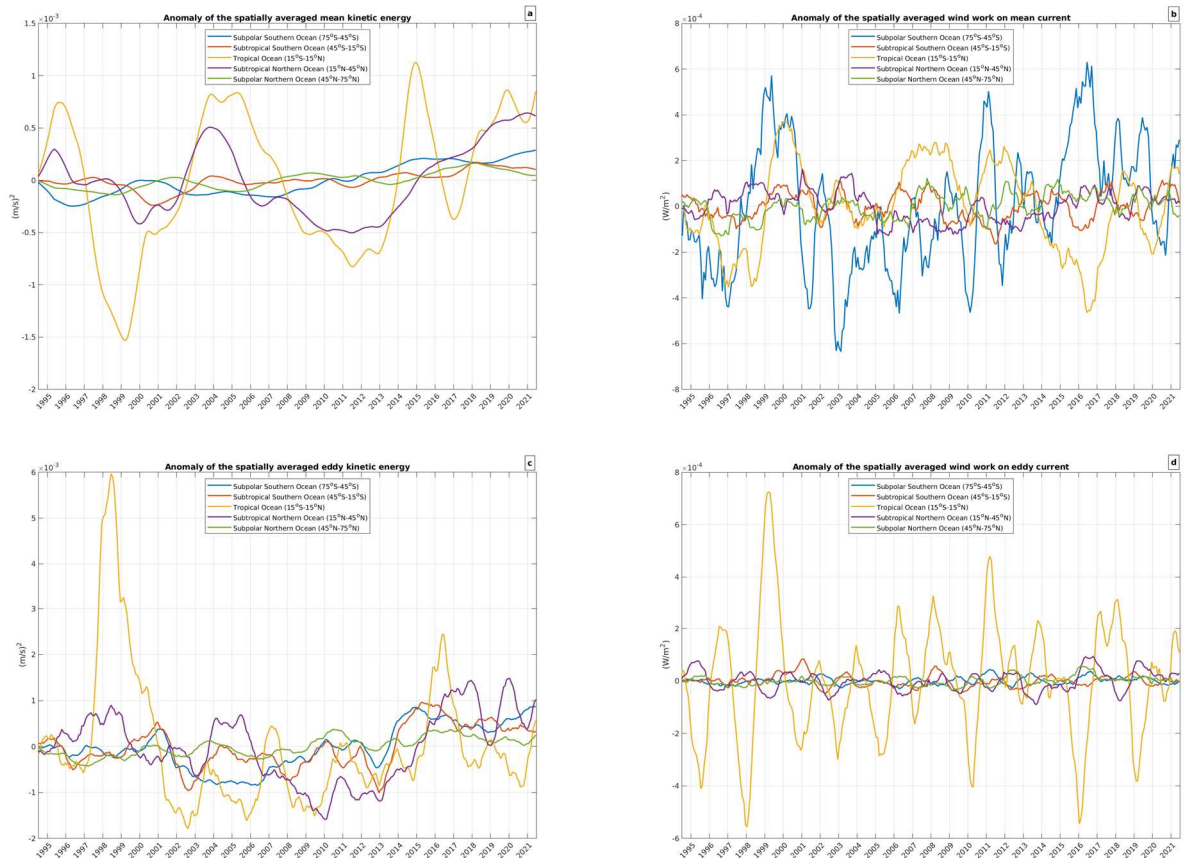


Figure 4. Temporal co-evolution of regional mechanical energy budgets and wind inputs. Spatial averages isolating interannual-to-decadal variations across the five designated meridional bands for a) Mean Kinetic Energy, b) mean wind-work, c) Eddy Kinetic Energy (EKE), and d) eddy wind-work. Line color assignments match the regional framework established in Figure 2 (75°S–45°S, blue; 45°S–15°S, red; 15°S–15°N, yellow; 15°N–45°N, magenta; 45°N–75°N, green). Prominent, high-amplitude globally synchronous spikes in c) and d) centered on 1997–1998 and 2015–2016 highlight transient mechanical supercharging tied directly to extreme Super-El Niño climate modes.

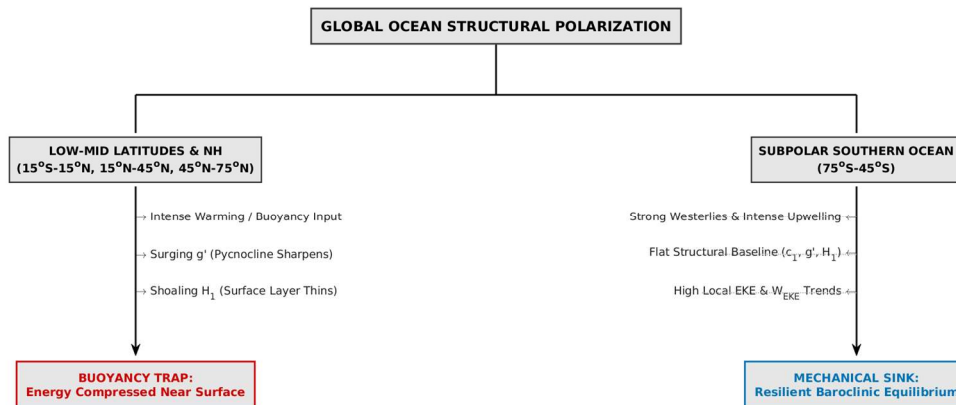


Figure 5. Schematic framework of global ocean structural polarization and mechanical energy pathways. Conceptual flowchart synthesizing the localized, climate-driven divergence in baroclinic vertical structures and subsequent wind-coupling pathways. Anthropogenic thermodynamic forcing polarizes the global system into two distinct mechanical branches: a low-to-mid latitude and Northern Hemisphere regime (left) dominated by severe buoyancy-driven upper-layer compression (surging g' , shoaling H_1) creating an energy-trapping surface "buoyancy trap"; and a subpolar Southern Ocean regime (right, 75°S – 45°S) maintaining an invariant structural baseline (c_1 , g' , H_1) where intensified Westerly wind forcing is mechanically vented via lateral shear, baroclinic instability, and eddy-saturated dissipation pathways into a resilient "mechanical sink".

Supplementary Files

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