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Review

Gravity currents in oceanic and estuarine systems: A comprehensive review [version 2]

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ABSTRACT

Global ocean dynamics involve the large-scale flow and circulation of the world's oceans, which are essential for regulating heat distribution, sequestering carbon, recycling nutrients, and influencing global weather patterns. Of particular interest in this review paper is the interaction between counterflowing currents, which frequently occur in estuaries and deep-sea environments, and have significant implications for oceanic and estuarine dynamics. When counterflowing currents, including but not limited to gravity currents, develop within the same region and encounter each other, these interactions lead to complex flow dynamics characterized by fronts, eddies, and intense turbulence, which in turn initiate vertical nutrient transport and mixing processes. In addition to affecting both regional and global thermohaline circulation, these interactions play an important role in turbulent mixing, sediment dynamics, and biological productivity. By synthesizing existing studies on counterflowing currents interactions, this paper explains the complex processes that control these phenomena and their significance in oceanic and estuarine environments. We highlight relevant gaps in existing knowledge and suggest future research approaches to advance the understanding of these important oceanic processes.

KEYWORDS

Ocean dynamics, gravity currents, flow interactions, turbulent mixing, upwelling.

1 Introduction

The global ocean is a vast and dynamic system that supports marine biodiversity and plays a significant role in nutrient cycling and the Earth's climate (Sala et al., 2021; Deng, 2024; Johnson and Lynam, 2020). Consequently, changes in ocean dynamics can significantly influence global weather patterns, sea levels, and ecosystem resilience, highlighting the need for a deeper understanding of global ocean dynamics. In recent decades, advancements in observational technology, such as satellite remote sensing, autonomous underwater vehicles, and high-resolution models, have improved the ability to study oceanic processes on both regional and global scales. While this paper focuses in part on gravity currents that develop when dense flows propagate into lighter ambient fluids driven by horizontal hydrostatic pressure gradients (Benjamin, 1968; Simpson, 1997; Borden & Meiburg, 2013; He et al., 2017), it also considers other major oceanic currents, including western boundary currents, to provide a broader understanding of current interactions in both estuarine and open-ocean settings. Gravity currents are important in the formation and modification of deep-ocean water masses in both the Southern Ocean and certain areas of the Northern Hemisphere (Gordon et al., 2009). In the ocean, these currents form when dense water masses in marginal seas or coastal shelves experience intense evaporation, surface heat loss, or brine rejection from sea-ice formation (Legg et al., 2009). The dense water masses subsequently flow down the continental slope as a gravity current, mixing with other water masses. In estuaries, the propagation of salt wedges along the estuary floor is also considered as estuarine gravity currents. Similarly, river plumes, which are rich in nutrients and fine sediments, flow into the coastal ocean as gravity currents (Nash & Moum, 2005). Generally, sediment-laden gravity currents can either propagate along the seabed as turbidity currents, flow at the surface as river plumes (as shown in Figure 1), or travel along the interface of a stratified water column as intrusive gravity currents (Cortés et al., 2014; Monaghan, 2007).

Estuarine and oceanic turbidity currents are described as sediment-laden gravity currents that arise from density differences produced by suspended particles and sustained by turbulence (Cantero et al., 2012; Fukuda et al., 2023; Liu et al., 2023; Nomura et al., 2002; Reece et al., 2024; Wahab et al., 2022). These sediment-laden gravity currents propagate through submarine canyons, sculpting the deep-sea landscape and transporting significant quantities of terrigenous materials, mainly sediments and organic carbon into the deep sea (Paull et al., 2018; Liu et al., 2023; Talling et al., 2007; 2022). The destructive and unpredictable nature of turbidity currents makes direct field measurement challenging. Consequently, important flow characteristics, such as velocity, thickness, sediment concentration, and grain size, are typically investigated through laboratory experiments (Han et al., 2023; He et al., 2022), numerical simulations (He et al., 2019; 2021), or inferred from turbidite deposits in the deep sea (Kneller and Baranney, 1995). Generally, gravity currents consist of a head with a protruding nose, followed by a more homogeneous body that contains most of the dense fluid (Meiburg & Kneller, 2010; Salinas et al., 2021). The evolution and hydrodynamic characteristics of gravity currents are influenced by factors such as the bottom topography, the density difference, and obstacles along the flow path of the current (He et al., 2025a). Studies have described the turbulent structure of gravity currents, demonstrating that while both saline and turbidity gravity currents share similar turbulent structures, the presence of suspended sediments introduces additional dynamic complexity in turbidity currents (Cossu & Wells, 2012; Kneller et al., 1999; Islam & Imran, 2010).

Oceanic gravity currents are common across the global oceans (Rétif et al., 2024), with a prominent example being the cold, dense water formed on the continental shelf around Antarctica. This dense water descends the continental slope as a gravity current, contributing to

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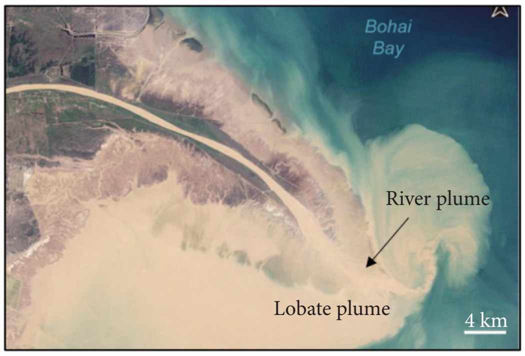

Fig. 1 Yellow River plume, China. Reproduced with permission from Shanmugam, 2019, © Elsevier Ltd. 2019.

the formation of abyssal waters and ultimately producing Antarctic Bottom Water (Gordon et al., 2009; Aoki et al., 2020; Han et al., 2024; Orsi et al., 1999) (see Figure 2). Oceanic gravity currents play an important role in ocean stratification and contribute to the redistribution of water masses, heat, and salinity as part of the global overturning circulation (Fukuda et al., 2023; Almansi et al., 2020; Willebrand et al., 2001). In addition to transporting suspended matter and dissolved gases, they also carry nutrients, carbon-based particles, contaminants, and pollutants from continental shelf regions to the deep ocean (Liu et al., 2023; Condie, 1995; Talling et al., 2023; Baringer & Price, 1997). The dynamic characteristics of large-scale oceanic gravity currents are complex and governed by a combination of factors, including density difference, bottom topography, and the Earth's rotation (He et al. 2025b). Depending on the origin, these currents are commonly quasi-steady and can flow for extended periods, ranging from days to months. Earth's rotation has a significant influence on large-scale oceanic gravity currents. Over long timescales, their flow may approach a geostrophic balance, where the Coriolis force balances the horizontal pressure gradient force (Wirth, 2009).

Interaction between counterflowing currents has been reported in oceanic and estuarine systems. As shown in Figure 3, the nature of these interactions is influenced by the difference in density between the interacting gravity currents. When their densities are similar, the interaction tends to be more balanced (i.e., symmetric), while a greater difference in densities can result in more asymmetric interactions, often accompanied by complex dynamics such as enhanced mixing. Although seabed sedimentary deposits have provided evidence of interactions between turbidity currents on the ocean floor, as stated by Simpson (1997), the details of the mechanisms and dynamic processes involved in the interaction have not been fully described. In the global ocean, deep water masses such as Antarctic Bottom Water (AABW) and North Atlantic Deep Water (NADW) occupy the deep ocean basins, where they form the lower limb of the global thermohaline circulation and contribute significantly to large-scale ocean circulation patterns (Brix and Gerdes, 2003). Orsi et al. (1999) described the interaction between two major oceanic bottom waters, noting that when they first meet, the less dense northern water is displaced upward from the ocean floor by the colder southern bottom water flowing northward. This vertical stratification plays an important role in the meridional overturning circulation. Due to the significant role of oceanic gravity currents in large-scale circulation

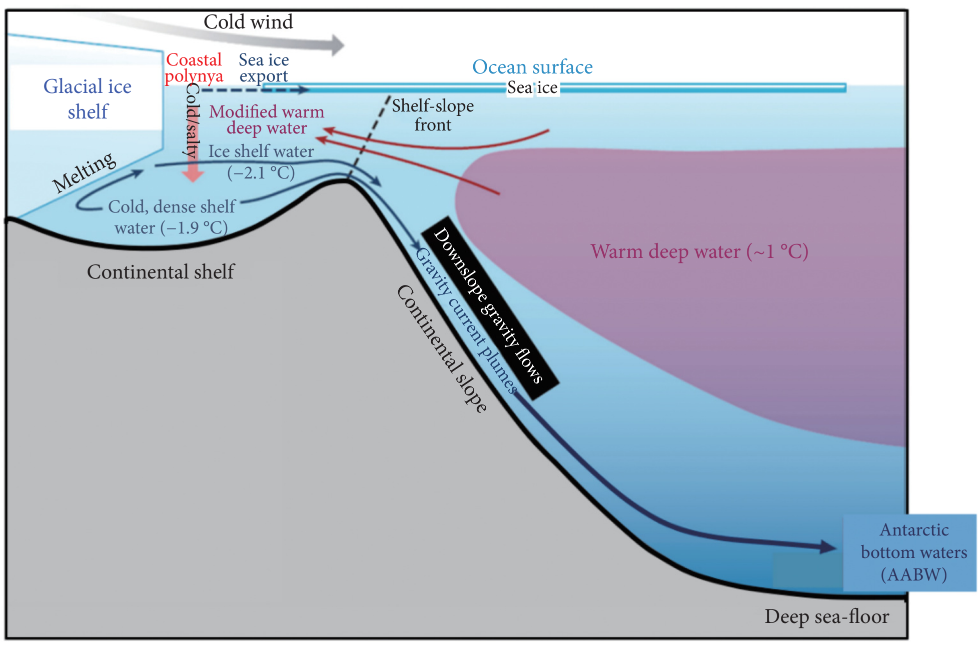

Fig. 2 Schematic of Antarctic bottom water (AABW) flowing as a gravity current on the continental slope. Reproduced with permission from Shanmugam, 2021, © Elsevier Ltd. 2021.

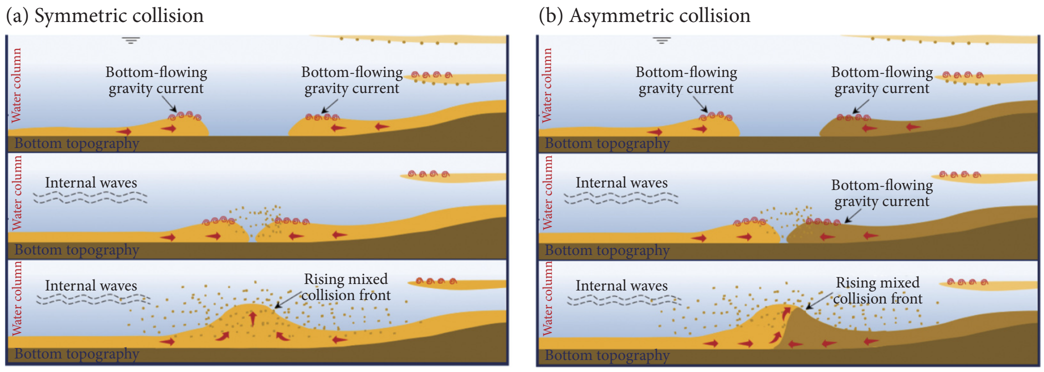

Fig. 3 The schematic representation of (a) a symmetric collision between currents of equal density and (b) an asymmetric collision between currents of unequal densities, with the shaded current in (b) representing the denser current.

patterns, stratification, global climate, and marine ecosystems productivity, understanding these interaction mechanisms is important for improving predictions of long-term climate variability and changes in ocean stratification and biogeochemical cycles.

Estuaries are biologically rich transition zones where riverine freshwater meets and mixes with saline ocean water (Geyer, 2004), resulting in frequent interactions between counterflowing currents. Therefore, understanding these interaction processes is important for predicting biodiversity shift, and efficiently managing aquatic resources. While increased turbulence and biological activity have been observed in estuarine and oceanic confluences where counterflowing currents occur (Chelton et al. 1990; Provost & Le Traon 1993), insufficient field observations have hindered a comprehensive understanding of their complex flow dynamics. This paper provides a comprehensive review of the available studies on the interaction and mixing process of counterflowing gravity currents, emphasizing their implications in oceanic and estuarine systems. In the remaining part of this paper, Section 2 presents case studies of collision and interactions between two oceanic currents. Section 3 discusses the implications of these interactions, while Section 4 presents concluding remarks and recommendations for future studies.

2 Interactions between two currents in estuarine and oceanic systems

2.1 Interactions involving bottom-flowing gravity currents

Bottom-flowing gravity currents, including dense overflows and turbidity currents, play an important role in deep-ocean nutrient cycling and sediment transport along the seabed. Consequently, the complex interactions between these currents can lead to merging, splitting, or the formation of secondary flows, depending on factors such as the density differences between the individual currents, seafloor topography, and oceanic forcing. It has been established that the interaction between counterflowing gravity currents can generate intense turbulence and mixing, with influence on sediment dynamics, nutrient availability, and biological productivity in adjacent waters. For instance, when a rapidly flowing current encounters a slower current, turbulence is generated at the confluence zone, leading to increased mixing and sediment resuspension. Sediment resuspension due to shear-induced turbulence is well documented in both estuarine and deep-sea environments. When such interactions occur, the currents would deflect or alter their trajectories, with implications for sediment deposition patterns and stratigraphy. Understanding the interactions between bottom-flowing gravity currents is important for explaining variations in global ocean dynamics, as these currents influence local ecosystems as well as regional and global circulation patterns.

Within the global ocean dynamics, gravity currents are a broad class of flows with a wide range of environmental applications, including thermohaline circulation (Fukuda et al., 2023). Driven by differences in temperature and salinity, the AABW and the NADW constitute important components of the global thermohaline circulation (Figure 4). AABW forms primarily in the Weddell and Ross Seas through sea-ice formation (brine rejection) and cascades downslope as a gravity current. It accounts for about 30%–40% of the deep global ocean volume (Bowen et al., 2021; Ohshima et al., 2013; Silvano et al., 2020), and plays an essential role in the circulation of the deep. Characterized by extremely low temperatures and high salinity, AABW ventilates the abyssal ocean, influencing the oceanic carbon cycle, biological productivity, and heat storage (Han et al., 2024). As presented in Figure 4, the NADW is formed in the North Atlantic when surface waters lose buoyancy due to cooling and increased salinity, leading to deep convection and sinking into the deep ocean (Muschitiello et al., 2019; Weijer et al., 2022). Primary formation regions include the Labrador and the Nordic Seas, where intense winter cooling destabilizes the water column. The Denmark Strait Overflow Water (DSOW), which is the deepest component of the lower NADW, is formed by the dense water overflowing the Denmark Strait sill between Greenland and Iceland (Fröhle et al., 2022), and it feeds the deep western boundary current that transports NADW southward. Garrison and Ellis (2015) present a simplified view of thermohaline circulation in the Atlantic, in which surface water becomes dense and sinks in both the northern and southern polar regions.

The abyssal zone of the Atlantic Ocean, which contains NADW and AABW, has been extensively studied because of its several important roles, including supplying oxygen and redistributing nutrients in the deep ocean (Johnson, 2008; Matsumoto, 2017). Their formation and relative proportion influence the supply and quantity of important nutrients available in the deep-sea ecosystem (Howe et al., 2016). At low latitudes, the two bottom water masses first meet and interact (Brix & Gerdes, 2003; Orsi et al., 1999; Berglund et al., 2023), with the colder AABW underlying the NADW in line with the schematic representation by Talley (2013) in Figure 5 below. The NADW, thereafter, flows southward at intermediate depths. Although there has been considerable research on the interaction between oceanic gravity currents, those involving bottom-flowing gravity currents have received less attention due to the remote seafloor location and the technical difficulties associated with direct in situ observations at great depths. For these reasons, an in-depth understanding of

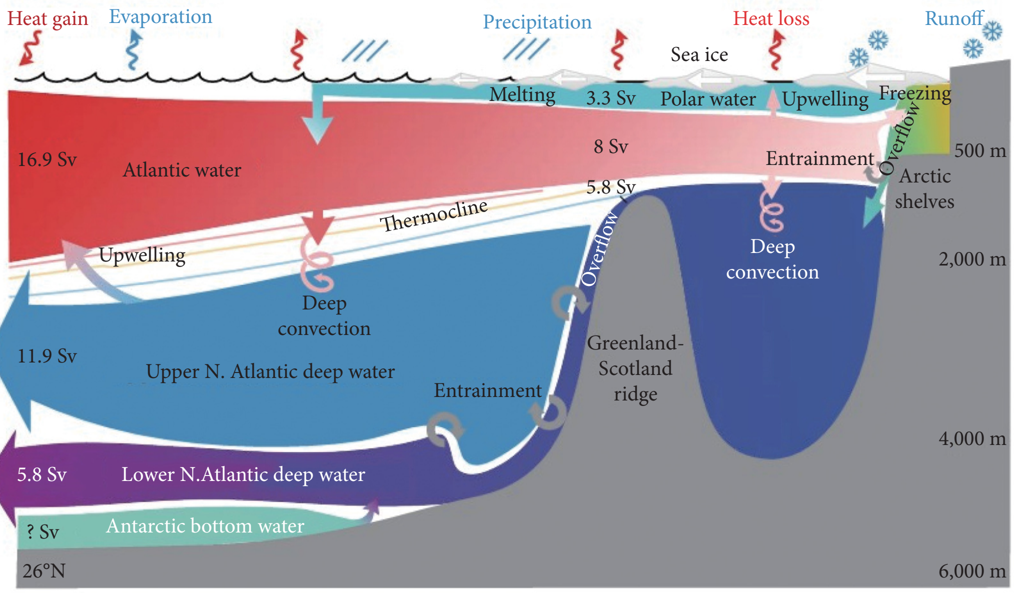

Fig. 4 Schematic of the overturning circulation in the North Atlantic and Arctic Mediterranean (Adapted from Weijer et al., 2022 under CC BY 4.0 License).

these interaction processes primarily relies on experimental and computational models, which have provided valuable insight into the dynamics of interacting geophysical flows.

Recent advances in computational fluid dynamics and controlled laboratory experiments have improved the ability to model these complex interactions, providing valuable insights into the collision dynamics of counterflowing gravity currents under varying environmental conditions. Simpson (1997) experimentally studied the interaction between counterflowing bottom-flowing gravity currents, where an upward motion of the collision front was observed, followed by the formation of two bore-like currents spreading in opposite directions. Shin (2001) examined the velocity and height of the emerging bore-like currents and further developed a theoretical model that predicts the post-collision speed of the bore-like current. Van der Wiel et al. (2017) explored how the height and density difference between gravity currents affects the collision dynamics and revealed that both symmetric and asymmetric interactions led to a vertical motion of the collision front. Zhong et al. (2018) conducted an in-depth analysis of the interaction between symmetric (i.e., same density) counterflowing gravity currents and showed typical collision dynamics presented in Figure 6 below. They demonstrated that counterflowing gravity currents have little or no influence on each other while being sufficiently spaced apart (Figure 6(a)). As the two currents flow into proximity prior to collision, their horizontal velocities decrease at the collision point due to mutual influence on each other; thus, the increasing pressure between the colliding currents results in an upward motion of ambient fluid between the two currents (Figure 6(b)). During the interaction, the collision front is vertically displaced as a fraction of the kinetic energy of the gravity currents is

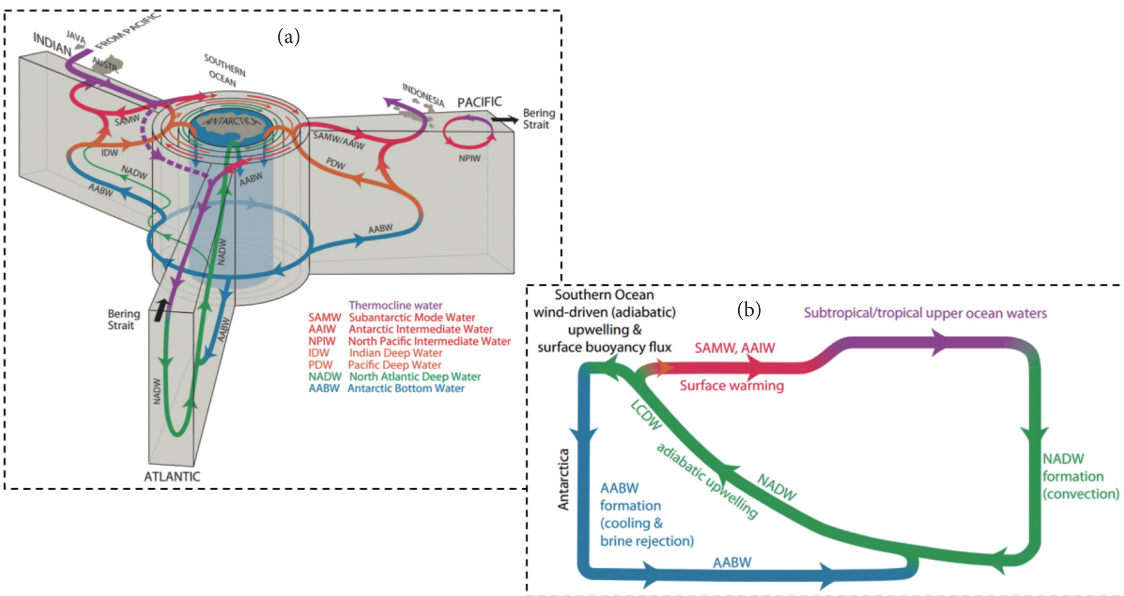

Fig. 5 (a) Diagrammatic representation of the overturning circulation from a Southern Ocean viewpoint. (b) Two-cell diagram highlighting the NADW and AABW cells. Reproduced with permission from Talley 2013, © The Oceanography Society 2013.

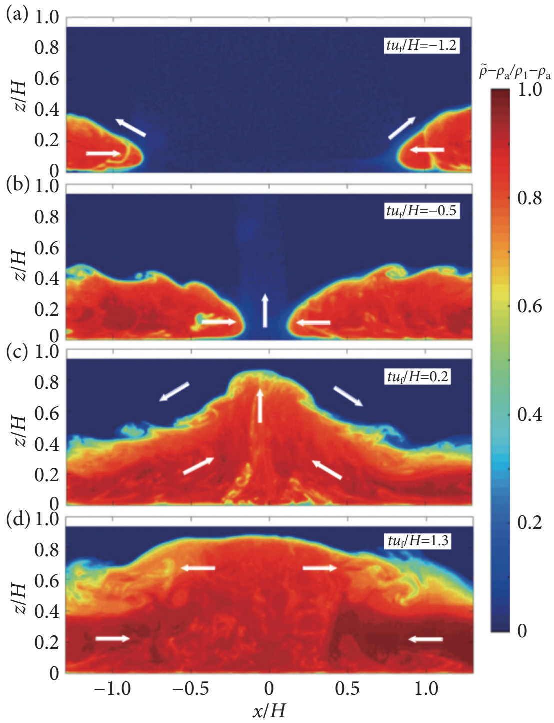

Fig. 6 Density field demonstrating the collision dynamics of same density currents with the white arrows indicating the flow direction. Reproduced with permission from Zhong et al., 2018, © Cambridge University Press 2018.

converted into potential energy, while another fraction is dissipated through turbulence (Figure 6(c)). The vertical velocity at the collision boundary decreases as the displaced collision front approaches its maximum rise height. Finally, the dense fluid collapsed and produced bore-like currents that propagated away from the collision point (Figure 6(d)). Okon et al. (2021) focused on the vertical motion of the displaced fluid, showing how the density difference between the colliding currents influences the collision dynamics.

Using numerical simulations, Cafaro & Rooney (2018) illustrate that the interface angle between the colliding currents depends on their density ratio, highlighting the significance of baroclinic vorticity in the dynamics of colliding density currents. Kokkinos & Prinos (2022) observed a consistent energy loss of approximately 17% from the initial energy of the system during collision, which indicates substantial energy dissipation during the interaction process. Kokkinos and Prinos (2023) observed that the differences in the initial heights of gravity currents could also influence the maximum rise height of the collision front. Dai et al. (2023) observed that vortices contributed to the mixing process and the generation of turbulent kinetic energy during the interaction process. Their study provided a comprehensive assessment of the energy budget, including the total energy equation as well as the equations for mean flow and turbulent kinetic energy. Okon et al. (2024) noted that the rate at which the interface length increases is determined by the buoyancy ratio of the colliding currents. They further indicated that the height of the rising fluid can exceed twice the depth of the colliding currents, even across a range of density ratios. Experimental and numerical models have provided valuable insights into the flow patterns, collision dynamics, and interactive mechanisms of counterflowing gravity currents, improving the present understanding of the collision phenomenon.

2.2 Interactions involving surface-flowing plumes

Plume-to-plume collision represents an important but insufficiently studied process in oceanic and estuarine dynamics. When a river discharges into the sea, it forms buoyant plumes that transport suspended and dissolved materials offshore (Horner-Devine et al., 2015; Masunaga et al., 2016). From a hydrodynamic perspective, river or estuarine plumes, which are transported as buoyancy-driven gravity currents (Horner-Devine & Chickadel, 2017; Mendes et al., 2021; Seena et al., 2022), usually develop as thin stratified layers that extend offshore near the river mouths. As presented in Figure 7, river plumes, which often evolve as gravity-driven flows, are essential components of estuarine circulation and play significant roles in the transportation of freshwater and terrigenous materials, including sediments, nutrients, and contaminants, from land to the sea (Dagg et al., 2004; Geyer et al., 2004; Gong et al., 2019; 2020; Hu et al., 2023; Ren et al., 2020; Warrick & Farnsworth, 2017). Their formation, structure, and dispersion are influenced by several environmental factors and force balances, all of which significantly influence the transport and fate of sediments, nutrients, and pollutants in coastal waters (Allahdadi et al. 2017; Pullen & Allen 2000; Horner-Devine et al. 2009; MacCready et al. 2009; Spicer et al. 2022; Chen et al., 2009; Horner-Devine et al., 2006; Kastner et al. 2018; Nehama & Reason, 2021; Tilburg et al., 2011; Rogowski et al., 2014; Seena et al. 2019). River plumes have been documented in various coastal and estuarine areas worldwide (Flores et al., 2022; Piñones et al., 2005; Gaston et al., 2006; Tarya et al., 2015). Compared to those from large rivers, plumes originating from small rivers and multi-inlet estuaries often exhibit unique characteristics, including frequent interactions and mixing with adjacent plumes (Warrick & Farnsworth, 2017; Mertes & Warrick, 2001). While individual plumes have been extensively studied (Chant et al., 2008; Hickey et al., 2010; Denamiel et al., 2013), the dynamics of their interactions, particularly in regions with multiple river mouths, remain poorly understood.

Although observational studies indicate that neighboring plumes could come into contact, collide, overlap, and mix (Mertes and

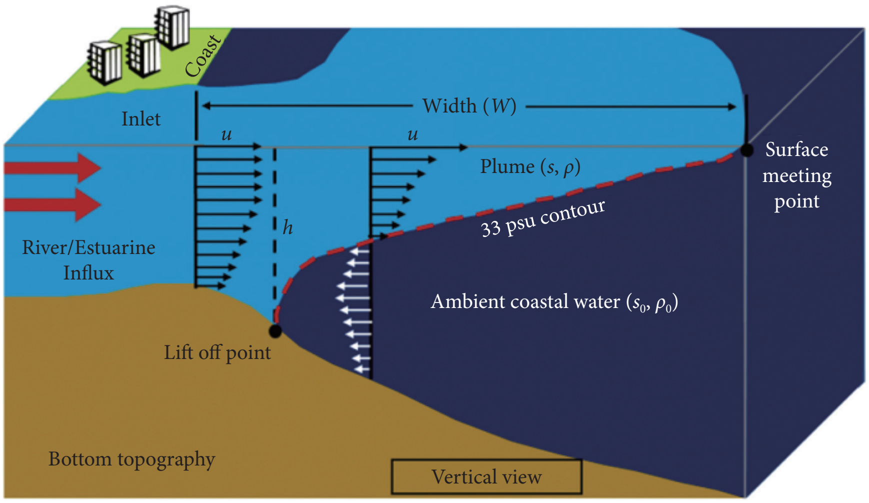

Fig. 7 Diagrammatic representation of offshore spreading of the plume over the ambient coastal water. Reproduced with permission from Seena et al., 2019, © The Author(s) 2019.

Warrick 2001; Warrick and Fong 2004; Saldías et al. 2012), the specific processes and mechanisms by which these interactions occur have not been extensively described. Warrick & Farnsworth (2017) reported that plume-to-plume collisions are common in coastal waters characterized by multiple rivers flowing in close proximity. Such interactions significantly affect the spreading and mixing dynamics of neighboring river plumes. Mendes et al. (2016) observed that river plumes create horizontally propagating density fronts, which can generate internal waves as the flow transitions from supercritical to subcritical conditions. Kourafalou (1999) noted that the northern river plumes in the Adriatic Sea restricted the northward expansion of the Po River plume. Field studies in the Black Sea and model studies focused on the Pearl River Delta provide additional evidence that plume-to-plume interactions can significantly influence plume dynamics (Osadchiev and Korshenko, 2017; Gong et al., 2019). Osadchiev and Zavialov (2020) explained that when small plumes collide and merge, the mixing intensity within the small plumes will decrease while their alongshore spreading becomes intensified. This indicates that interactions among smaller plumes can significantly influence their dynamics and the distribution of transported materials (Menders et al., 2016). Despite their importance, relatively few field studies have documented real-world plume interactions (Saldías et al., 2012; Menders et al., 2016; Warrick et al., 2007).

Warrick & Farnsworth (2017) addressed this gap by developing a two-dimensional hydrodynamic model of frontal plume collisions using hydrostatic simulations and geophysical scaling to classify various types of plume collisions and associated flow patterns across different environments. A three-dimensional hydrodynamic model was also used to analyze the fundamental variations in plume spreading patterns between coastlines with a single river and those with several rivers. Figure 8 presents a time series of salinity, temperature, and velocity at 4-minute intervals, capturing the collision of two symmetrical plume fronts with equal salinity and thickness approaching each other. Before and during the collision, the results demonstrate symmetrical water characteristics and velocities around

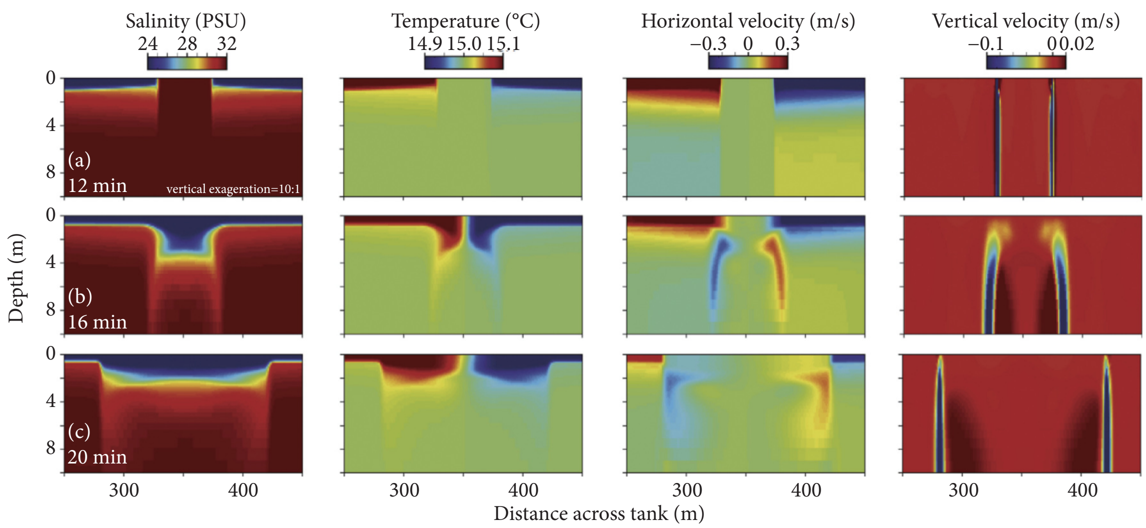

Fig. 8 Time series of salinity, temperature, and velocities for the tank model, illustrating the collision of two plume fronts at 4-minute intervals. Results are shown at (a) 12 minutes, (b) 16 minutes, and (c) 20 minutes after model initiation. Reproduced with permission from Warrick & Farnsworth, 2017, © Elsevier Ltd. 2017.

the collision point. At the post-collision phase, bores developed along the lower interfaces of the plumes, showing horizontal convergences and downwelling velocities comparable to those of the plume fronts, although with reduced magnitudes (Figures 8(b) and 8(c)). Temperature data further revealed a reversal in flow direction after the collision, as the bores transported plume waters back toward their respective sources (Figures 8(b) and 8(c)). The findings indicate that coastal areas characterized by large numbers of small rivers are more prone to plume collisions, which greatly impact the dispersion and fate of river systems. Several collision types, such as reflection, subduction, and occlusion, were observed to be determined by the differences in colliding plume densities and thickness. Overall, the results emphasize the need for further research to improve our understanding of plume interactions in complex coastal systems.

Gong et al. (2019) present a detailed analysis of the interactions between multiple small river plumes in the Pearl River Estuary (PRE) during winter, a time characterized by reduced river flow and dominant downwelling-favorable winds, illustrating that baroclinic effects were the prevailing feature. Their findings indicated that in winter, the river plumes in the Pearl River Estuary are highly developed, resulting in significant interactions. Both plumes, located downstream and upstream, exerted mutual influence on each other, with interactions dominated by both barotropic and baroclinic factors. Hu et al. (2023) examined the frontal collision of river plumes by comparing hydrostatic and non-hydrostatic numerical models. While previous studies mainly depended on hydrostatic models, which have constraints in accurately representing flow structures, Hu et al. (2023) advanced their research by conducting an in-depth analysis using both hydrostatic and non-hydrostatic simulations to better understand the dynamics of plume collisions. Their results demonstrate that non-hydrostatic simulation results corroborate field observations, especially regarding flow structures. These models further revealed that bore-like structures developed at the back of the plume front, emphasizing their impact on the development and the entrainment at the interface. Their studies objectively re-examined the present categorization of plume collisions, clarifying the fundamental dynamics and types of collisions under non-hydrostatic conditions. They further examined the characteristics of dynamic pressure and identified it as an important factor in the formation and evolution of vortex structures.

During the collision, hydrostatic simulations demonstrate a two-layer dynamical structure in the collision region, as shown in Figures 9(a) and 9(b), where the structure is primarily governed by horizontal advection with minimal or no vertical flow. The uppermost layer consists of a surface flow (F_S), whereas the subsurface layer exhibits a set of horizontally opposing flows (F_1 and F_2). Hu et al. (2023) explained that when colliding plumes have different densities, the direction of the surface flow is determined by the less dense plume, whereas for plumes with equal density, it depends on the denser plume. The relative magnitudes of F_1 and F_2 in the subsurface layer is affected by the velocities of the plume fronts before collision. The flow pattern described here provides a clear explanation for the changes in plume shape observed in hydrostatic simulations. Specifically, the surface flow F_S plays a significant role in the formation of the intrusive mass of the lighter plume and the interaction between the two plumes. Conversely, non-hydrostatic simulations provide a more comprehensive and complete representation of the collision process. In addition to the horizontal two-layer structure seen in hydrostatic cases, these simulations capture additional complex features, including large-scale vortices and the entrainment processes initiated by plume interaction. In the initial phases of a frontal collision, the descending vertical velocities of the head vortices from both plumes converge, forming a hump-like structure near the collision point (Figure 9(c)). Upon the collapse of this hump, two new vortices and an intrusive mass are generated (Figure 9(d)). Density distribution and dynamic pressure at the pre-collision, collision, and post-collision stages are presented in Figure 10.

3 Implications of counterflowing oceanic currents interaction

The interaction between counterflowing currents, including but not limited to gravity-driven flows, plays a significant role in shaping physical and ecological processes in estuarine and oceanic environments. These interactions influence the development of oceanic fronts, enhance biological productivity, drive turbulent mixing, and affect sediment transport. A well-known example is the convergence of the

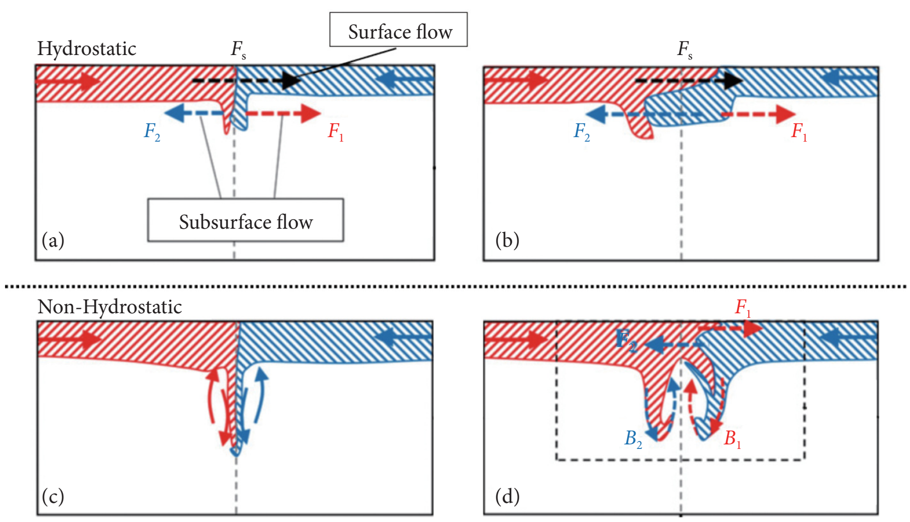

Fig. 9 Schematic of the flow patterns during collision. (a) and (b) Hydrostatic results; (c) and (d) non-hydrostatic results. Reproduced with permission with permission from Hu et al., 2023, © AIP Publishing 2023.

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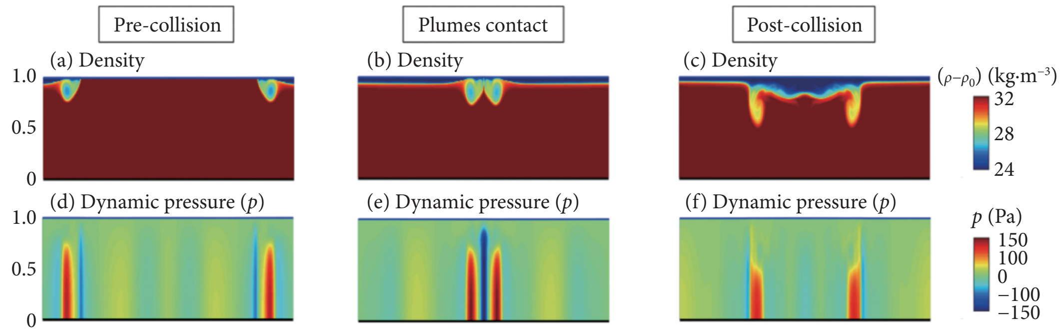

Fig. 10 (a)–(c) The distributions of density, (d)–(f) dynamic pressure. Reproduced with permission from Hu et al., 2023, © AIP Publishing 2023.

Brazil and Malvinas currents, two major western boundary currents that transport subtropical and subantarctic waters. As highlighted by Orúe-Echevarría et al. (2019), this collision is one of the most prominent regional features in the global ocean. Piola and Matano (2001) further documented the formation of extensive eddy fields resulting from this interaction. The specific implications of counterflowing currents' interaction in both estuarine and oceanic environments are discussed below.

3.1 Role of counterflowing currents interaction in the formation of fronts

Studies have shown that interaction between counterflowing oceanic currents initiates oceanic fronts, which usually serve as a dynamic region of upwelling and downwelling that facilitates the vertical exchange of inorganic and organic materials (Matano et al., 2010; Ruiz et al., 2019; Yabe et al., 2024). An important example is the front, which develops from the interaction of the northward-flowing Gulf Stream and the southward-flowing Labrador Current. This front is characterized by strong temperature and salinity gradients with instabilities that manifest as meanders and eddies (Meinen & Luther, 2016; Neto et al., 2021; Jutras et al., 2023). Moreover, shelf waters from the Mid-Atlantic Bight (MAB) and the South Atlantic Bight (SAB) often collide year-round on Cape Hatteras' continental shelf and slope, creating significant along-shelf gradients in thermohaline properties across the Hatteras Front (Savidge et al., 2013; Savidge & Austin, 2007; Savidge & Bane, 2001; Savidge & Savidge, 2014). Furthermore, apart from the respective impacts of bathymetry and density, the displacement of the Hatteras Front in relation to bathymetry has an impact on water export. Savidge & Savidge (2014) stated that fluctuations in the Gulf Stream and wind variability influence the motion of the Hatteras Front. Following the significant temperature-salinity (T-S) contrasts between the two shelf water masses and their constant convergence near Cape Hatteras, the Hatteras Front is present year-round, a phenomenon that has been established for many years.

One of the world's strongest open-ocean fronts, which is the Brazil-Malvinas Confluence, is generated due to the southward-flowing Brazil Current and the northward-flowing Malvinas Current colliding along the western boundary of the Argentine Basin (Orúe-Echevarría et al., 2021; Wainer et al., 2000). The interaction between these two currents occurs offshore from the mouth of the Rio de la Plata, resulting in an area of high mesoscale variability (Matano et al., 2010). It has been documented that the head-on collision leads to the separation from the western boundary, generating a broad, quasi-stationary meander that reaches south to around 45°S (Piola & Matano, 2001). The instabilities resulting from the interaction between western boundary currents trigger distinct mesoscale features, including eddies (Lentini et al., 2002). These features and the mesoscale instabilities of the Brazil Current and the Malvinas Current dominate the dynamics of the confluence region, significantly influencing the local climate and biological environment (Garzoli & Simionato, 1990). Another important example in the North Pacific is the confluence of the warm Kuroshio Current and the cold Oyashio Current (Itoh et al., 2022; Joh et al., 2023; Kida et al., 2015). This has led to the formation of a front at the surface and at depth, significantly influencing the oceanography and marine ecology of the region. Within the North Pacific Oceanic Frontal Zone, the Kuroshio-Oyashio Extension region is characterized by significant sea surface temperature gradients over the Oyashio Extension and a pronounced sea surface height gradient over the Kuroshio Extension.

In estuaries, the interaction between freshwater outflow and saline seawater generates estuarine fronts, which are often visibly turbid due to the high sediment load carried by the river. These estuarine fronts serve as transition zones between freshwater and saltwater and often exhibit strong gradients in temperature, salinity, and other hydrodynamic properties. Largier (1993) noted that the generation of internal waves in frontal regions is driven by the collapse of mixing zones and temporal variations in forcing, while dissipation occurs through the breaking of shoaling pycnoclines and instabilities caused by excessive interfacial shear. Although the energy stored in estuarine fronts may contribute little to the overall mechanical energy budget, the potential energy available during relaxation flows, when active forcing reduces, can play an important role in determining water quality. Due to the complex oceanic conditions and associated technical difficulties, laboratory and numerical experiments have been used to gain valuable insights into front formation at confluence regions. Van der Wiel et al. (2017) experimentally demonstrated that asymmetric collisions produce a tilted front, where the denser current undercuts the less dense one, similar to estuaries, where denser seawater flows beneath less dense river water. Cafaro & Rooney (2018) numerically demonstrated that the characteristics of fronts produced at the collision region mainly depend on the density difference between the colliding currents, as often observed in estuaries, where the freshwater from a river mixes and interacts with the salty water from the ocean.

It is noteworthy that the formation of fronts resulting from counterflowing currents converging and interacting is important for the transport and dispersion of pollutants, as these fronts can trap pollutants, sediments, and nutrients, thereby influencing their distribution in coastal and open marine systems. For this reason, understanding how the collision process influences these fronts is essential for effectively managing aquatic ecosystems and resources, especially in addressing pollution challenges. To this end, continued investigation into the dynamics of counterflowing currents and their contribution to front formation will be necessary for predicting changes in marine ecosystems and designing appropriate management strategies to minimize the negative impacts of pollution in front-affected regions. Section 3.2 describes the vertical displacement caused by counterflowing current interactions and its role in biological productivity.

3.2 Role of counterflowing currents interaction in biological productivity

Interactions between counterflowing oceanic currents significantly enhance biological productivity in regions where these counterflowing water masses meet. This is because frontal dynamics and secondary circulation mixing at the interfaces of counterflowing currents can upwell nutrient-rich deep waters to the euphotic surface, boosting primary productivity and supporting marine ecosystem functioning (Ferrari et al., 2017; Xing et al., 2024; Vélez-Belchí and Tintoré, 2001). Studies have shown that some of the most productive open-ocean regions occur at oceanic confluences, where interactions between counterflowing currents drive vertical nutrient transport that supports phytoplankton production and creates biological hotspots (Lévy, 2003; Rodríguez et al., 2001). For instance, the Brazil-Malvinas Confluence (BMC) generates an oceanic front and the upwelling of nutrients, thereby promoting a rich biodiversity in the region. Yabe et al. (2024) noted the consistent flow of nutrients upwelling around a biological hotspot at the confluence region of the quasi-stationary jet and the Oyashio in the western North Pacific. They revealed that nutrients were transported to the euphotic zone at the confluence of the two currents, facilitated by ageostrophic secondary circulation across the frontal structure separating them. The interaction between Kuroshio Extension and Oyashio has been noted to induce the development of eddies and fronts (Itoh & Yasuda, 2010), which may influence biological production by facilitating the vertical mixing of nutrients from the subsurface to the euphotic zone (Kimura et al., 2000). In another study, Wang et al. (2022) attributed the significant abundance of haptophytes in the mixed water area to the mixing mechanisms linked to nutrient dynamics in frontal systems, where eutrophic Oyashio water interacts with Kuroshio water. The biologically rich frontal structure of oceanic confluences has been noted as an important fishing area (Yasuda, 2003). This assertion has been corroborated by Ruiz et al. (2019), who confirmed that oceanic fronts allow vertical nutrient transport to the surface waters for primary productivity.

In estuarine environments, the interaction between counterflowing gravity currents enhances biological productivity by redistributing nutrients, and establishing productive feeding grounds, thereby creating rich, diverse ecosystem that are important to ecological health. Largier (1993) asserted that the proliferation of plankton might be attributed to either in situ formation at the front or passive convergent transfer towards the front. Irrespective of whether the higher phytoplankton biomass at the front results from in situ production or aggregation, this concentration can facilitate secondary production, subsequently attracting higher organisms in the aquatic food chain. Although the effects of fronts on plankton at the surface have been extensively studied, the effect of basal fronts on benthic productivity has received less attention. Vertical mixing is an important process in estuarine dynamics, controlling the exchange of water and particles between river and coastal waters (Tu et al., 2019; Uncles et al., 2006). Enhanced mixing at the estuarine front increases the availability of nutrients, which in turn boosts primary production and overall ecosystem productivity. This is evidence in the Chesapeake Bay, the largest estuary in the United States, where the meeting of nutrient-rich freshwater and saltier coastal waters creates stratification that influences nutrient trapping and redistribution, enhancing primary production (Muhling et al., 2018). The Mississippi River serves as the primary source of freshwater, sediments, and organic matter in the Gulf of Mexico (Schiller et al., 2011). The higher nutrient availability in the Gulf of Mexico, resulting from the interaction between the freshwater discharge of the Mississippi River and the saltwater Gulf waters, supports phytoplankton, which constitute the basis of the food web, thereby supporting a highly productive plume estuarine front.

Laboratory and numerical experiments have demonstrated that the interaction between counterflowing currents initiates strong vertical motion and intense mixing along the collision boundary (van der Wiel et al., 2017; Zhong et al., 2018; Okon et al., 2021; Cafaro & Rooney, 2018; Kokkinos & Prinos, 2022; 2023; Dai et al., 2023). The vertical motion is greatly influenced by the interaction of vorticity dynamics at the leading edge of colliding currents, especially when the collision occurs between counterflowing bottom currents with different densities. When bottom currents of contrasting densities collide, the uneven vortex distribution at the collision boundary of asymmetric currents initiates a complex interaction where the less dense bottom current is lifted above the denser current (Agra & Nof, 1993; de Carvalho Ferreira & Keer, 2017; Orsi et al., 1999), creating stratification and contributing to the overall circulation pattern. Orsi et al. (1999) cited the displacement of the less dense northern water from the bottom after colliding with AABW. Limeburner et al. (2005) noted a clear transition zone between the bottom-flowing AABW and the overlying NADW at depths of 4000–4200 m. Dai et al. (2023) demonstrated through numerical simulations that when counterflowing gravity currents collide, the fronts become distorted, leading to vertical stretching of the pre-existing vorticity. This process generates a series of vertical vortices that extend throughout the fluid column along the interface.

3.3 Role of counterflowing currents interaction in turbulent mixing

The interaction between counterflowing oceanic currents generates turbulence that enhances mixing and affects ocean stratification, nutrient distribution, and overall ocean dynamics. This turbulence facilitates the exchange of heat, salinity, and nutrients between water masses, while also producing eddies and vortices that promote both vertical and horizontal transport. Oceanic fronts, driven by strong flow motion and intensified turbulent mixing, significantly influence the dynamics of the local ocean (D'Asaro et al., 2011; Ogawa et al., 2015). They act as important sites for both the vertical transport of heat and nutrients into the ocean interior and enhanced air-sea exchange of heat and momentum (Ferrari, 2011; Xing et al., 2024). Given that turbulence is a fundamental mechanism that drives the mixing process by increasing the diffusion and mixing of different fluid layers through turbulent and irregular fluid motions, its analysis is important to fully understand the complex mixing dynamics during the collision phase. While Song et al. (2024) identified small-scale turbulent mixing as a possible energy source for the upwelling of deep waters in the abyssal ocean, Orúe-Echevarría et al. (2023) discussed its importance in modifying the water mass, salinity distribution, and as a component of the global overturning circulation. Currents interaction generates turbulence that intensifies the vertical and horizontal mixing of water masses, as observed in areas such as the Brazil-Malvinas Confluence in the South Atlantic, where it generates eddies and dynamic features that further mix nutrient-rich cold waters with warmer waters (Orúe-Echevarría et al., 2023; Artana et al., 2019; de Souza et al., 2019; Roget et al., 2023).

When freshwater and saltwater currents flow in counterflowing directions within an estuary, their interaction results in the generation of shear forces and turbulence, with the denser saltwater flowing beneath the less dense freshwater (Geyer, 2004). Estuarine fronts are frequently characterized by substantial turbulence and mixing caused by the shear between counterflowing currents, which affects the distribution of nutrients, sediment dynamics, and overall productivity of the estuarine environment (Farmer et al., 2002; MacDonald & Geyer, 2004). The Columbia River Estuary experiences turbulence due to the interaction between riverine freshwater and oceanic saltwater. This turbulence is characterized by the formation of eddies and mixing zones, which can impact sediment transport and water quality. Notably, increased mixing and turbulence can influence phytoplankton distribution and abundance, affecting the structure and function of the entire food chain.

Experimental and numerical simulations have also demonstrated that the interaction between counterflowing gravity currents initiates intense turbulent activities (Dai et al., 2023; Zhong et al., 2018), which are accompanied by strong mixing depending on the buoyancy ratio between the colliding currents. Okon et al. (2024) noted that turbulent kinetic energy increases from relatively small values in the current body to relatively large values around the interface of the two colliding currents. Kokkinos & Prinos (2022) elaborate on the spatial distribution of turbulence in the front zones, noting that regions with high turbulence levels are associated with increased mixing. In another study, Kokkinos and Prinos (2023) asserted that turbulence is sustained despite a reduction in mixing after the maximum vertical displacement phase. Turbulence is significantly increased during the collision, which is essential for energy dissipation and mixing. They found that approximately 20% of the system's energy was dissipated during mixing, emphasizing the important role of turbulence in the dynamics of interaction between gravity currents. Significantly, when gravity currents collide, mixing occurs at the collision front, and the symmetry of the collision determines the extent of mixing. Dai et al. (2023) numerically confirmed the formation of vertical vortices by geometric distortions of the fronts leading to turbulence. These vortices play an important role in mixing and energy dynamics, explaining the mechanisms behind the energetic nature of oceanic confluence regions (Chelton et al., 1990; Provost & Le Traon, 1993).

3.4 Role of counterflowing currents interaction in sediment dynamics

The interaction between counterflowing currents generates turbulence that resuspends sediments from the bed into the water column, facilitating their widespread distribution and the potential formation of sediment plumes. Interestingly, the magnitude and direction of these currents greatly influence the distribution of suspended sediments, controlling their deposition sites and subsequent interactions with benthic ecosystems. Interactions between counterflowing oceanic currents generate complex flow patterns that play a significant role in shaping seafloor topography. For instance, where a strong current meets a weaker one, sediment may be eroded from the seabed, while deposition occurs in calmer downstream locations. These processes can modify the bottom topography, promoting the formation of sedimentary features. Sediment dynamics influenced by counterflowing current interactions have significant impacts on benthic ecosystems because sediment resuspension can reduce light penetration and nutrient distribution, thus affecting primary productivity and the resilience of the ecosystem. As global ocean dynamics change in response to climate change and other factors, continued research into the role of counterflowing currents' interaction in sediment dynamics will be essential for understanding and managing the complexities of marine ecosystems.

In tidal estuaries, which receive sediment from marine and fluvial sources, hydrodynamic processes often interact to trap sediment within estuarine channels and intertidal flats, leading to the formation of estuarine turbidity maxima (Burchard et al., 2018; Grasso et al., 2018; 2021; de Nijs et al., 2012). This could affect sediment transport processes, deposition, erosion, and sorting, thereby influencing the morphology, habitat development, and biological functioning of estuaries. Observational studies conducted in recent decades have provided valuable insight into sediment dynamics in estuaries, particularly on the formation of the estuarine turbidity maximum (ETM) in the region of freshwater and saltwater interaction (Eidam et al., 2021). Enhanced deposition along the estuary front, frequently caused by flocculation of fine particles at the interface between freshwater and seawater, can result in the buildup of hazardous pollutants in sediments. Estuaries are often characterized by net sediment accumulation due to hydrodynamic trapping processes. Geyer (2004) explained that when suspended sediment and particles from a river flow into the estuary, they interact with the saline front propagating shoreward. In contrast to freshwater, which flows above the saline layer, the suspended sediment settles from the surface layer into the denser, saline water flowing along the bed and becomes trapped. Over time, this process can contribute to long-term sediment accumulation, potentially increasing turbidity and reducing depth in some estuaries.

Estuarine fronts, like those found in San Francisco Bay, frequently serve as sediment-trapping zones where the interaction of riverine freshwater and oceanic saltwater promotes depositional regions, which in turn contribute to the formation of mudflats and marshes, when other environmental conditions are favorable. Riverine flow, resuspension, and the development of an estuary turbidity maximum are factors that modify particulate dynamics in the Chesapeake Bay (Moriarty et al., 2021). The interaction between freshwater inflows and tidal seawater in the Chesapeake Bay region can lead to significant erosion and sediment transport in certain regions, depending on the local hydrodynamic conditions, thereby affecting the stability of the estuarine bottom and modifying its topography. In the Gulf of Mexico, sediment sorting is influenced by the interaction between riverine and marine currents. The Yangtze River Estuary has experienced notable morphological changes attributable to the interaction between freshwater discharge and tidal currents, and human activities. These changes include the formation of new sedimentary structures and alterations in sediment deposition patterns. Resuspended sediments, driven by turbulent currents, impact sediment fluxes in coastal regions, such as the Mississippi River Delta. A detailed analysis of the mechanisms underlying sediment trapping resulting from these interactions has not yet been fully understood and could represent a promising direction for experimental and numerical studies, particularly due to the limitations of field observations.

4 Conclusions and recommendations

The collision and interaction between counterflowing oceanic currents play an essential role in determining the dynamics of oceanic systems. By considering both estuarine and oceanic environments, the paper provides a comprehensive understanding of the mechanisms driving the collision dynamics. These interactions lead to the development of thermohaline fronts, turbulence, eddies, and vertical displacements, which substantially influence ocean circulation, sediment transport, and nutrient cycling. Case studies provide evidence of the significant effects of these phenomena on both regional and global scales. While significant progress has been made in understanding the interaction between counterflowing oceanic currents, studies of the interaction between bottom-flowing gravity currents remain an emerging research direction. This review has identified important open questions and research gaps for future research, as presented below:

i. Although laboratory and numerical studies of colliding gravity currents have advanced considerably, long-term in situ monitoring in oceanic and estuarine regions where gravity currents interact or collide remains limited. However, oceanic and estuarine fronts are well recognized as areas of strong vertical motion, nutrient upwelling, and enhanced biological productivity. Future studies should prioritize field campaigns that deploy advanced observational systems, including moored profilers, autonomous underwater vehicles, and satellite remote sensing. These research efforts could target estuarine turbidity maxima and river plume convergence regions to measure vertical velocities, turbulent fluxes, density structure, mixing efficiency, and sediment transport during collision events. Field observations that capture variability across temporal and spatial scales are relevant to understanding vertical exchange and nutrient fluxes within frontal zones. Such datasets are also necessary to validate numerical predictions and to inform the development of parameterizations for operational ocean forecasting and ecosystem models.

ii. Most existing literature on the numerical simulation of colliding gravity currents relies on idealized two-dimensional or hydrostatic models that neglect several important physical mechanisms. Future numerical modeling should shift toward fully three-dimensional, non-hydrostatic approaches such as Large Eddy Simulation (LES) or Direct Numerical Simulation (DNS). These methods can resolve baroclinic vorticity generation, turbulent kinetic energy (TKE) budgets, and energy cascades at submesoscales during current collisions. To capture the full range of collision dynamics observed in estuaries and coastal oceans where fronts drive vertical exchange, advanced models should include Coriolis effects, ambient stratification, realistic bathymetry, and variable buoyancy ratios. Incorporating these features into the model will improve estimates of eddy diffusivity and mixing efficiency, thereby supporting the development of more accurate parameterizations for regional ocean and climate models.

iii. Recent experimental studies show that asymmetries in density, height, or sediment concentration can significantly alter the post-collision dynamics of interacting currents, including bore propagation, vertical uplift, and mixing efficiency. In reality, most estuarine and oceanic flows are asymmetric, particle-laden, and characterized by varying buoyancy ratios and non-Newtonian characteristics. For these reasons, future experimental research should move beyond symmetric, small-scale lock-exchange configurations to adopt large-scale, stratified flume experiments that capture realistic estuarine and shelf conditions. These should include erodible beds, suspended sediment feedbacks, and even complex topography. Such experiments can help reveal how buoyancy ratios, sediment properties, and frontal dynamics govern collision-driven vertical transport, which in turn affects nutrient cycling, benthic–pelagic interactions, and the stability of submarine infrastructure. Moreover, incorporating natural forcing mechanisms, such as tidal oscillations or cross-shelf flows, would further enhance the practicality and applicability of these studies.

iv. Interactions between counterflowing gravity currents are not merely hydrodynamic phenomena; they also play a significant role in ecological productivity, sediment redistribution, and the formation of turbidites. Besides, frontal zones where oceanic currents converge often serve as biological hotspots, as they promote nutrient upwelling into the euphotic zone. Therefore, future research could combine high-resolution hydrodynamic modeling with biogeochemical tracers and sediment transport simulations to better quantify the ecological and engineering consequences of collision phenomena. Developing frameworks that connect small-scale collision dynamics observed in laboratory and numerical studies to large-scale circulation and ecological outcomes in natural systems will be especially valuable. Moreover, research collaboration among physical oceanographers, modelers, and ecologists will be essential to translate physical processes into ecosystem-scale predictions, particularly as climate change alters the frequency and intensity of frontal systems. Such interdisciplinary approaches can improve predictive capacity for coastal resilience planning and marine spatial management.

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

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