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Shelf Bathymetric Roughness Controls Mixing of the Persian/Arabian Gulf Outflow and Arabian Sea OMZ Ventilation

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Abstract

Hypersaline overflows from Marginal seas contribute to global ocean circulation and climate variability. The Persian/Arabian Gulf (P/AG) contributes dense, saline, oxygenated deep outflow into the Arabian Sea's Oxygen Minimum Zone (OMZ). Here, we present high-resolution hydrographic mapping of the UAE-Oman margin in the northwestern Arabian Sea, integrating CTD profiles, multibeam bathymetry and ROV imagery. The P/AG outflow forms a thin bottom-attached layer that thickens dramatically over the rough, irregular seafloor of the unstable shelf, where dilution and loss of bottom contact occur. Near-bottom salinity, oxygen, and pH decrease systematically downstream in association with enhanced mixing. Distinct benthic assemblages coincide with attached versus detached flow sectors, consistent with differing near-bed hydrodynamic regimes. These observations indicate that bathymetric roughness controls the near-field transformation of the outflow. Because outflow density depends on Gulf warming and evaporation, modest climatic shifts may alter detachment depth, pathway geometry, and intermediate-depth ventilation of the Arabian Sea OMZ.

Short Summary

The Persian/Arabian Gulf exports a dense, salty, oxygen-rich current that helps ventilate the Arabian Sea. Measurements along the northern margin of the Gulf of Oman show that the flow remains thin and attached over smooth seafloor, but thickens, mixes, and detaches over the rough

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terrain of the shelf. These changes affect oxygen delivery and benthic life, and also suggest that climate-driven density shifts may alter their pathways and impacts.

1 Introduction

Marginal seas produce water masses with properties distinct from the open ocean and provide pathways for climate signals to penetrate the ocean interior (Melet et al., 2022). Net evaporation in basins such as the Persian/Arabian Gulf (P/AG), the Mediterranean, and the Red Sea increases salinity and drives dense outflows into adjacent basins. Exchange between marginal seas and the open ocean is often regulated by hydraulic controls, and the resulting overflows undergo strong diapycnal mixing due to bottom friction, turbulence, and entrainment, substantially modifying their properties (Melet et al., 2022; Peters and Johns, 2005; Pratt and Lundberg, 1991).

This study focuses on the Oman–UAE margin of the northeastern Arabian Plate, where the P/AG outflow enters the Gulf of Oman as the northwestern mouth of the Arabian Sea and interacts with a broad continental shelf characterized by strong spatial variability in seafloor morphology. P/AG water is characterized by high salinity, temperature, and comparatively elevated oxygen content (Brewer and Dyrssen, 1985; Yao and Johns, 2010; Swift and Bower, 2003; Font et al., 2024). It exits the Gulf as a dense near-bottom flow through the Strait of Hormuz, entraining ambient water until reaching neutral buoyancy at relatively shallow intermediate depths. The outflow then follows the southern margin of the Gulf of Oman as a gravity-driven current and spreads into the Arabian Sea and the broader Indian Ocean, with its signature traceable as far as the Bay of Bengal (Bower et al., 2000; Jain et al., 2017; Sheehan et al., 2020; Ezam et al., 2010; Prasad et al., 2001).

Dynamical processes within the Gulf of Oman, such as eddy–topography interactions and mesoscale eddy field strain, play a central role in determining the open-ocean signature of P/AG water (L'hégaret et al., 2015; Queste et al., 2018; Vic et al., 2015; L'hégaret et al., 2016; Font et al., 2024). Such eddies can trap and redistribute the outflow, while double-diffusive processes such as salt fingering have been observed beneath the plume in the Arabian Sea (Turner, 1967; L'Hégaret et al., 2021).

The Arabian Sea Oxygen Minimum Zone (OMZ) ranks among the strongest globally, with suboxia spanning much of the intermediate depths in its northern and northeastern sectors, including the

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Gulf of Oman (Rixen et al., 2020; Schmidt et al., 2021). OMZs host distinctive biogeochemical pathways and exert a significant influence on carbon and nitrogen cycling relative to their area, shaping ecosystems through habitat compression and contributing to outgassing of greenhouse gases (Gruber and Galloway, 2008; Hood et al., 2023; Stramma et al., 2010). Nearby source waters, notably P/AG water, are estimated to oxygenate ~35% of the OMZ (Davila et al., 2023). Consequently, it is poised to respond rapidly to variations in P/AG water properties (Ditkovsky et al., 2023; Hood et al., 2023; Lachkar, 2019; Lachkar et al., 2023; Lachkar et al., 2022).

Despite decades of study, key aspects of the near-field transformation of P/AG water remain poorly constrained, including outflow thickness variability, detachment behaviour, bathymetric controls on mixing, downstream oxygen modification, and links between physical structure and benthic communities. Here we present high-resolution observational mapping of the P/AG outflow along the Oman–UAE margin using CTD profiles, multibeam bathymetry, and ROV imagery. The dataset resolves spatial variability in outflow thickness, identifies zones of bottom attachment and detachment, documents downstream oxygen and pH modification, and reveals benthic assemblages consistent with boundary-layer structure.

2 Data and Methods

2.1 Data

This study uses 50 Conductivity–Temperature–Depth (CTD) profiles collected in the Gulf of Oman, offshore Fujairah, between 9 and 18 July 2025 (Fig. 1). Profiles were obtained using a Sea-Bird SBE 19plus V2 SeaCAT CTD (4 Hz). Data were quality-controlled, and only downcast measurements were used because upcast measurements were affected by winch motion. High-resolution multibeam bathymetry was collected using a Kongsberg EM712 system with Seafloor Information System (SIS) software. This bathymetry dataset can be accessed from Abdelmaksoud et al. (2025a).

2.2 Methods

CTD data were processed and visualized using Ocean Data Viewer (ODV; Schlitzer, 2024) and the TEOS-10 GSW MATLAB toolbox (Mcdougall and Barker, 2011). Vertical sections were generated for salinity, temperature, dissolved oxygen, pH, and turbidity. The P/AG water fraction

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(P/AGwf) was calculated following Font et al. (2024) based on the composite-tracer approach of Jenkins (1999). The endpoints used are 1°C and 34.86 g/kg for IODW, 29.56°C and 41.04 g/kg for P/AG water, and 23.45°C and 36.37 g/kg for IOCW, similar to those of Font et al. (2024).

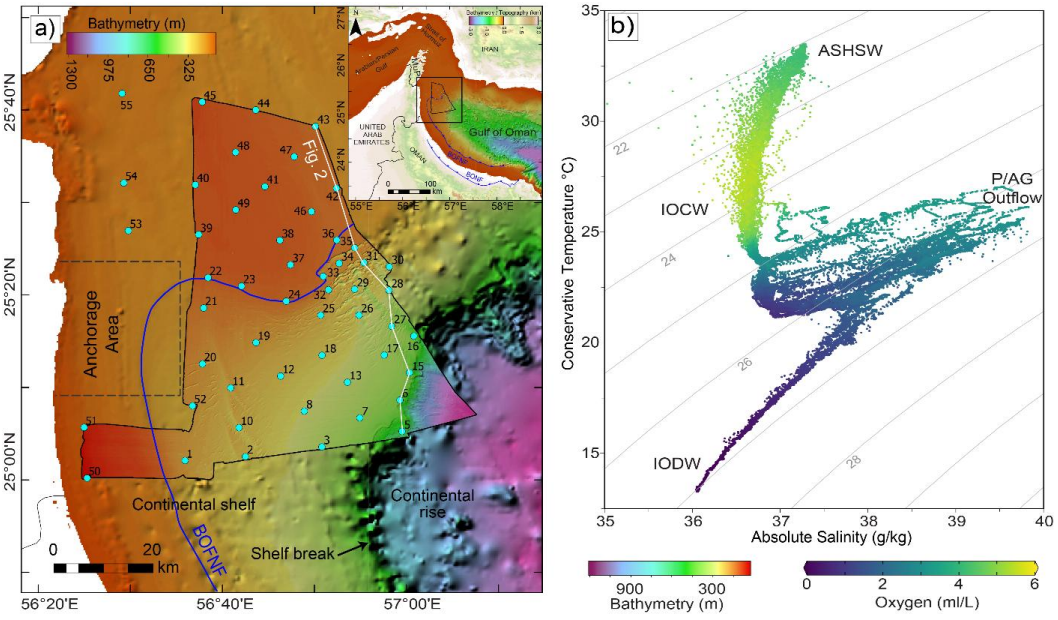

Figure 1. Bathymetry and CTD data. a) A high-resolution multibeam bathymetry of the northwestern Arabian Sea superimposed over regional bathymetry, showing acquired CTD data, with an inset showing the P/AG and the Gulf of Oman as the mouth of the Arabian Sea. b) Absolute salinity versus conservative temperature plot showing four distinct water masses across the water column of the Arabian Sea. BOFNF stands for Batinah Offshore Normal Fault; ASHSW, Arabian Sea High Salinity Water; IOCW, Indian Ocean Central Water; IODW, Indian Ocean Deep Water; P/AG Outflow, Persian/Arabian Gulf Outflow.

Parameter maps were produced for the deepest measurements (~5 m above the seafloor). Additional maps of plume top, bottom, and thickness were derived using a P/AGwf threshold of ≥0.3. This threshold represents water parcels in which P/AG contributes at least 30% of the local mixture and remains a substantial hydrographic component of the outflow. This more conservative threshold excludes weak peripheral P/AG water influence and better isolates the dynamically coherent mixed plume. Whereas core is defined by P/AGwf ≥0.55, corresponding to mixtures in which P/AG water is the dominant water mass component. Turner angle (Tu) and Brunt–Väisälä frequency (N^2) were calculated. ROV imagery was used to assess relationships between benthic

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communities and the outflow, and multibeam bathymetry was analyzed to evaluate topographic controls on plume structure.

3 Results

3.1 Water column stratification in the Gulf of Oman

Four distinct water masses were identified at the mouth of the Gulf of Oman during summer (Fig. 1b). The upper layer, termed Arabian Sea High-Salinity Water (ASHSW), is shallow and characterized by an absolute salinity of ~37.2 g kg^{-1} and temperature of ~33 °C. Indian Ocean Central Water (IOCW) has a salinity of ~36.6 g kg^{-1} and temperature of ~28 °C. The P/AG outflow exhibits very high salinity (37.0–39.8 g kg^{-1}) and moderate temperatures of 20–27 °C. Indian Ocean Deep Water (IODW), the deepest layer, has lower temperatures (~13–20 °C) and salinities (~36.0–37.0 g kg^{-1}). Oxygen concentrations are 4–5 ml L^{-1} in the Arabian Sea High-Salinity Water and 5–6 ml L^{-1} in IOCW. The P/AG outflow shows intermediate values (1.5–3.5 ml L^{-1}), whereas IODW exhibits the lowest oxygen (<1 ml L^{-1}).

3.2 Characteristics and thickness variability of the P/AG outflow

The outflow forms a distinct layer characterized by elevated salinity, temperature, oxygen, and pH (Fig. 2a,b). As the outflow enters the Gulf of Oman, it separates into three lateral sectors. Across the mouth of the Gulf of Oman over relatively flat bathymetry, properties are highest (salinity ~39.0 g kg^{-1}, temperature ~26 °C, oxygen ~3.0 ml L^{-1}, pH ~8.51; Figs. 2a,c,e; 3a–c). Over the shelf of the Arabian Plate, characterized by pockmarks and erosional features, values decrease to ~38.5 g kg^{-1}, ~23.5 °C, ~2.5 ml L^{-1}, and pH ~8.42. Farther south over the lower shelf and upper slope, properties decline further (~37.2 g kg^{-1}, ~22 °C, ~2.0 ml L^{-1}, pH ~8.35). The western extent of the outflow corresponds to bathymetric constraints, with the shallowest occurrence at ~110 m depth. A high-turbidity layer occurs above the seafloor and thickens basinward from ~20 m above the flat shelf to >400 m above the upper slope (Fig. 2a,b). P/AGw_f values reach ~0.7 over the stable shelf and exhibit along-flow lateral variations, largely coincident with the rough, eroded bathymetry. The outflow core and plume are thin over the stable shelf and are disrupted by rough bathymetry (Fig. 2i). The core fades shortly after these flow disruptions. The ratio between roughness height and plume thickness (hr/H) is used as a measure of the dynamical interaction

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between the P/AG outflow plume and the seabed (Fig. 2j). The top of the outflow occurs at depths of 50–100 m above the flat shelf, with a very thin layer that has a thickness of 10–30 m, exhibiting a southeastward deepening and thickness increase (Fig. 3e-f). The upper depth of the P/AG outflow increases up to 170 m in the center, then becomes shallower at the extreme southern portions, reaching ~130–140 m (Fig. 3e). The thickness increases up to 200 m above the lower shelf and upper slope (Fig. 3f).

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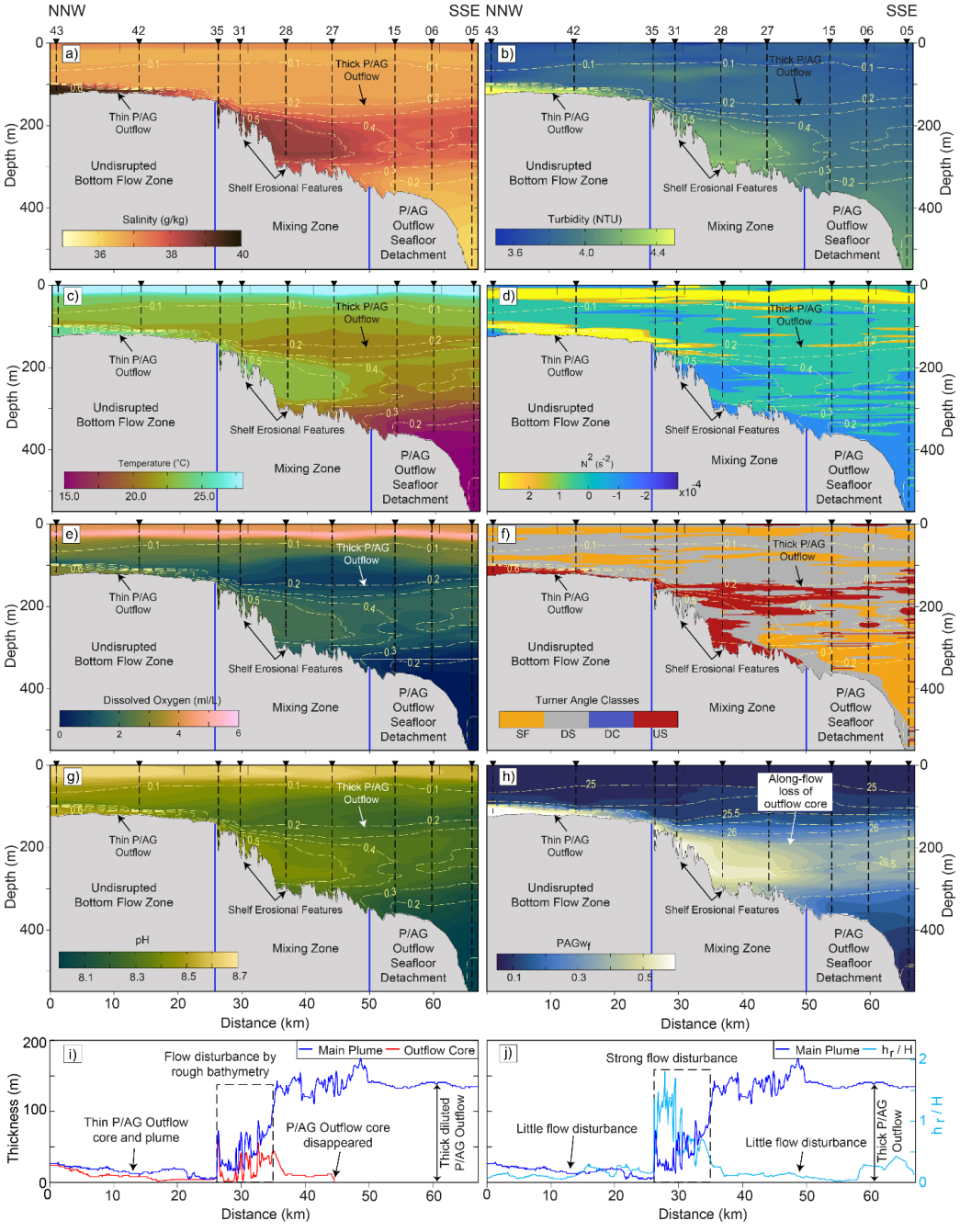

Figure 2: An NNE-SSW CTD transect (along P/AG outflow path) showing P/AG outflow and its relation to the seafloor irregularities. The parameters include salinity (a), turbidity (b), temperature (c), Brunt–Väisälä frequency (d), dissolved oxygen (e), Turner angle (f), pH (g), and P/AGw$_f$ (h). i) Along-transect thickness of the P/AG outflow

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core and main plume. j) The local seabed roughness relative to the height and plume thickness (hr/H), plotted with the plume thickness. a-g are superimposed by P/AGw_f contours, whereas h is superimposed by density contours. SF stands for salt fingering; DS, doubly stable; DC, diffusive convection; US, unstable.

3.3 Benthic evidence for P/AG outflow bottom attachment-detachment

Near-seafloor parameters (Fig. 3a–c) show sharp lateral transitions (salinity 38–36 g kg^{-1}, conservative temperature 25–15 °C, oxygen 3 to <0.5 ml L^{-1}) across the depth range where the outflow shifts from bottom-attached to detached flow. Where the outflow remains attached (Fig. 4c), the seabed consists of exposed or semi-consolidated substrate with little fine-sediment drape, consistent with persistent near-bottom shear and resuspension. At deeper sites where the near-bottom hydrographic signature of the outflow weakens (Fig. 4d), the seafloor is dominated by fine-sediment accumulation beneath a detached outflow layer.

ROV imagery from ~284 m depth (Fig. 4c) shows a conspicuous epibenthic community on hard or firm ground, dominated by sessile suspension feeders. Branching azooxanthellate scleractinian colonies and octocorals are common, with additional scattered epifauna on exposed patches of substrate. This assemblage is consistent with a relatively energetic bottom boundary layer associated with the attached outflow. By contrast, imagery from ~360 m depth (Fig. 4d) shows a flat, soft-sediment seabed with sparse epifauna; tube anemones, consistent with cerianthids, are present and locally abundant. This shift, from coral-bearing hard-substrate assemblages to soft-sediment, cerianthid-dominated assemblages, coincides with the hydrographic transition, providing an independent benthic indicator of attachment and separation of the outflow along the margin.

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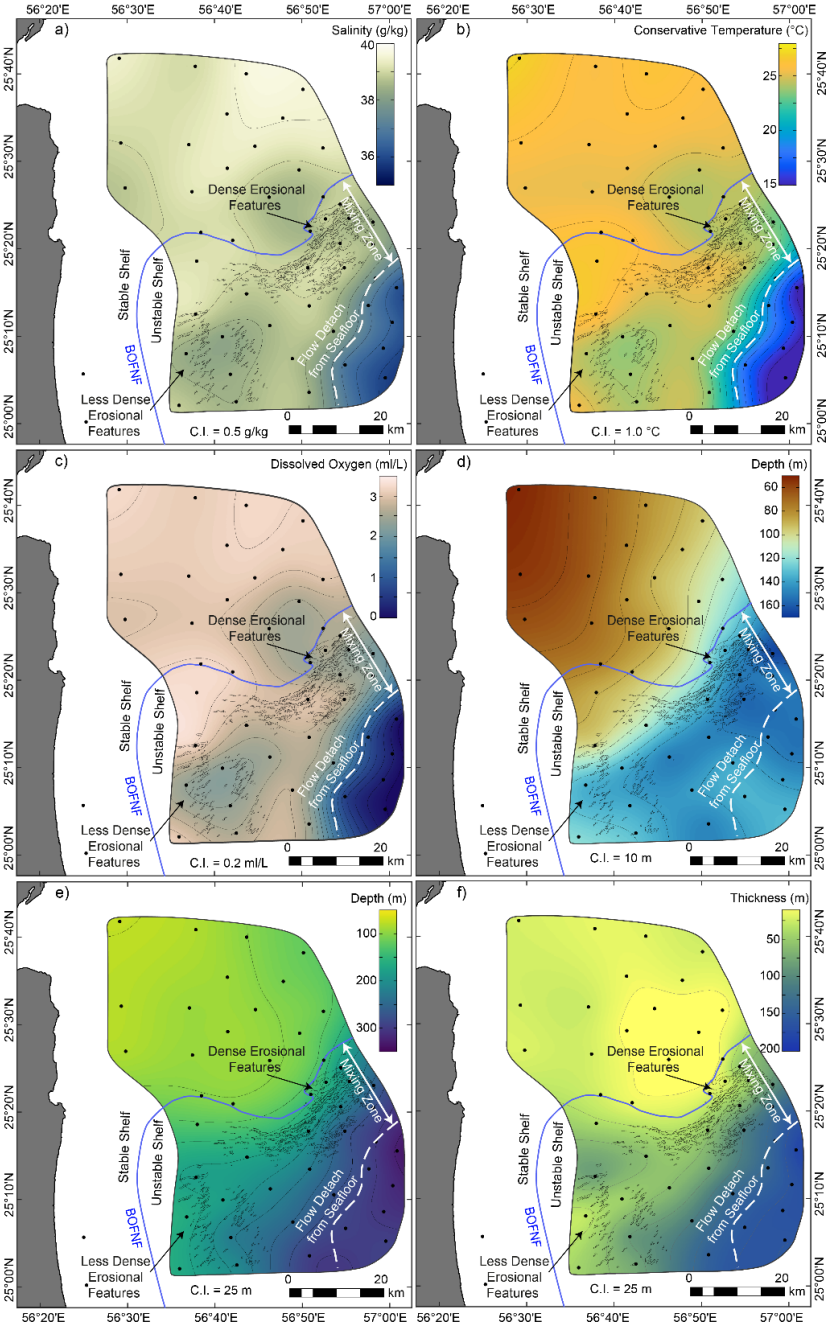

Figure 3: Near-seafloor parameters maps, as well as maps for outflow top depth, bottom and thickness. CTD maps above the seafloor, including salinity, conservative temperature, and oxygen content (a, b, c, respectively). The top, bottom, and thickness variation of the P/AG outflow are also mapped (d, e, f, respectively).

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4 Discussion

4.1 Distribution, mixing, and flow behaviour of the P/AG outflow

Hydrographic CTD measurements in the northwestern Arabian Sea reveal spatial variability in P/AG outflow characteristics. Recently, the continental shelf of the northeastern Arabian Plate margin has been subdivided into two domains: a stable and an unstable shelf, based on the integration of multibeam bathymetry and seismic reflection data (Abdelmaksoud et al., 2026b). The outflow waters exit the Strait of Hormuz, hugging the flat continental stable shelf bathymetry, with a very thin bottom-attached flow of 10-30 m (Figs. 2 and 3). This flow has high salinity, temperature, and density, resulting in negative buoyancy and a compact, coherent core with high P/AGw_f and comparatively little dilution. The flow has a sharp upper interface (high N^2), indicating stable stratification (Fig. 2d). Outflows exiting dense marginal-seas typically begin as thin bottom-attached plumes before being transformed by entrainment (e.g., Bower et al., 2000). At the transition from the stable to the unstable shelf, the abrupt bathymetric shift serves as the initial trigger for flow transformation. This transition marks an abrupt increase in the seafloor depths delimited by a major gravitational collapse, i.e., northern extension of the Batinah Offshore Normal Fault. The outflow suffers from rapid geometric/hydraulic adjustment, increasing in thickness from ~20 m to ~170 m, with localized patches of $N^2 < 0$ occurring in the immediate vicinity of the bathymetric transition/step (Figs. 2d and 3f). This situation is consistent with locally statically unstable stratification and transient density overturning during hydraulic adjustment of the bottom-attached plume across the bathymetric step (Alford et al., 2013; Jalali et al., 2017). This indicates the bathymetric step is dynamically active and likely promotes enhanced turbulent entrainment/mixing at the onset of plume transformation.

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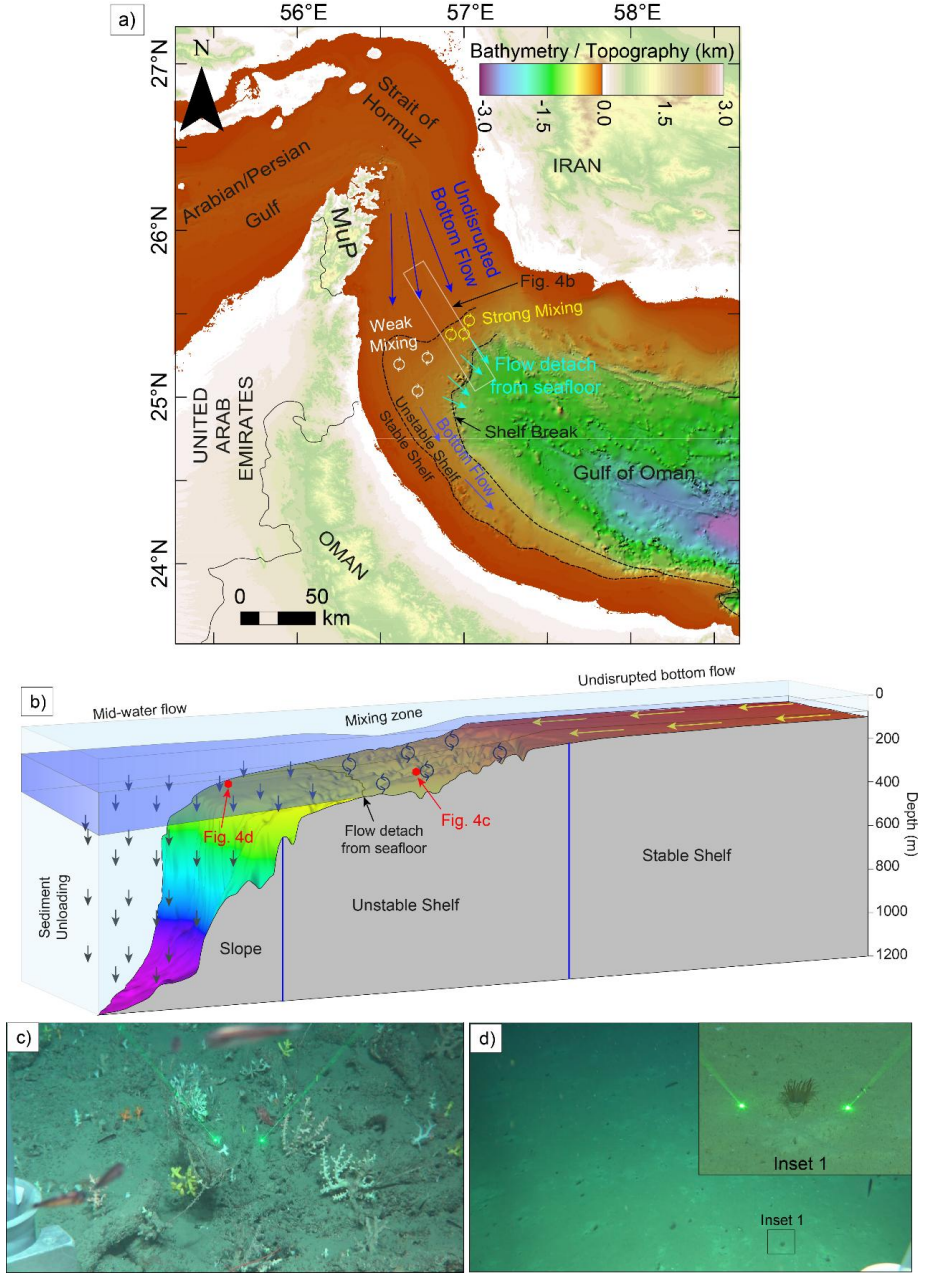

Figure 4: Map and 3D illustration of the outflow behaviour, as well as comparison of benthic communities from the bottom-attached and -detached flow. a) A map illustration of the outflow behaviour of the P/AG outflow relative to the bathymetry. b) A 3D illustration of the P/AG outflow behaviour over the stable shelf, unstable shelf, and upper slope. c and d are photos from ROV dives from the mixing zone and another representing an area where the outflow detached from the seafloor, respectively.

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The unstable shelf has extensive crescent-shaped and elongated pockmarks and irregularities on the seafloor (Abdelmaksoud et al., 2026b; Abdelmaksoud et al., 2025b). Within this domain, the outflow is characterized by lower salinity, temperature, and oxygen content than the undisrupted flow above the stable shelf, with continued plume thickening and weakening of P/AGw_f. The outflow within this domain exhibits disruption, and its compact core eventually fades. There is also a significant reduction of N^2 peak as well as broadening of the interfacial (across the upper plume interface) N^2 stratification, which indicates erosion and weakening of the initially sharp plume to ambient interface. The ambient interface is consistent with sustained interfacial entrainment/mixing, dilution of the dense core, and the development of a thicker, more diffuse interfacial mixing layer. Mechanistically, the roughness effect is expressed in terms of roughness height relative to plume thickness, hr/H. The roughness height relative to the plume thickness increases to >1 immediately after the bathymetric step. Where the roughness elements become a substantial fraction of plume thickness, they enhance form drag, wake generation, and near-bottom turbulence, thereby sustaining entrainment and dilution across the pockmarked shelf sector (Cenedese and Adduce, 2010; Ottolenghi et al., 2017; Özgökmen and Fischer, 2008). This situation is consistent with roughness-enhanced boundary-layer turbulence and hydraulic transitions documented for other marginal-sea overflows (Peters & Johns, 2005; Price, 1997).

Once the P/AG outflow water gains enough buoyancy, it begins to detach from the seafloor above the unstable shelf and to flow at an intermediate level (Fig. 4). The detached flow from the seafloor has lower salinity, temperature, and oxygen content, with the top of the outflow water moving towards shallower depths (Figs. 2 and 3). The intensity of the mixing and dilution of the P/AG outflow changes across the unstable shelf domain. This intensity correlates with the density of seafloor irregularities, with high-mixing zones found within high-density irregularities and vice versa (Fig. 4a).

Over the lower shelf to the upper slope, the near-bottom P/AG outflow signatures weaken strongly, and the P/AGw_f near the seabed becomes small or disappears (Fig. 2h), indicating that the bottom attachment is lost and the plume persists higher in the water column. The outflow transitions into a detached intermediate-depth plume, following from the preceding thickening and dilution across the unstable shelf. The plume lift-off occurs approximately where the pronounced N^2 maximum at the upper plume interface disappears, consistent with erosion of the initially sharp plume to the

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ambient density interface by entrainment and dilution until the bottom-attached gravity current can no longer maintain a clear near-bottom density excess. Farther offshore, the gradual re-establishment of moderate N^2 suggests formation of a new, weaker and broader interface around the detached plume as it adjusts toward its intermediate intrusion/neutral-buoyancy depth (Fig. 2d). The detached intermediate-depth plume/intrusion exhibits continued along-slope propagation, and the maps (Fig. 3) suggest that, throughout the study area, the plume remains organized as a margin following, bathymetrically steered boundary plume/current, with a clear shallow-side/upslope limit imposed by the shelf morphology. Along-path dilution of the intermediate-depth plume within the Gulf of Oman is also evident, with the plume exhibiting P/AGw_f of around 0.4 near the mouth of the Gulf (This study, Fig. 2h), and the value is reduced to less than 0.3 to the south across the Omani Margin (Font et al., 2024).

The outflow results in further erosion and deepening of the seafloor irregularities of the unstable shelf. The outflow water then carries the erosional products and deposits its load directly after detaching from the seafloor above the lower shelf and slope (Fig. 2b). Strong bottom flows over rough bathymetry are known to maintain thick bottom nepheloid layers through resuspension (Mccave, 1986; Gardner et al., 2018). Marine nepheloid layers, particularly bottom nepheloid layers on continental margins, mark loci of active suspension and redeposition driven by energetic near-bed currents (Biscaye and Eittreim, 1977; Gardner et al., 2018).

Previous hydrographic and ADCP observations show that, after exiting the Strait of Hormuz, P/AG water cascades down the continental slope and spreads along the Gulf of Oman margin (Pous et al., 2004). Along the Omani coast, the outflow core occurs at a depth of 200 m with a potential density range of 25.5 – 27 kg/m^3 (Font et al., 2024). Climatological and historical analyses indicate that P/AG water typically equilibrates between approximately 200 and 350 m (Prasad et al., 2001; Swift and Bower, 2003). Observations off Oman document that the P/AG outflow pathway and thermohaline properties vary with the mesoscale field, which can eject boundary water offshore through near-shelf dipoles and lee eddies (L'hégaret et al., 2015). High-resolution simulations and process analyses demonstrate that remotely generated mesoscale eddies interact with the steep slope to generate frictional boundary layers and submesoscale vortices that peel P/AG water from the boundary, thereby enhancing lateral dispersion and dilution (Vic et al., 2015).

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4.2 Oxygen modification along the P/AG outflow path and its impact on the Arabian Sea-OMZ

P/AG outflow brings high-oxygen waters from the Arabian Gulf to the Arabian Sea-OMZ, thereby ventilating the OMZ. Glider observations off Oman directly demonstrate that P/AG water supplies oxygen to the OMZ at intermediate depths, quantifying its ventilation contribution along the slope (Font et al., 2024). Modeling further indicates that changes in Gulf properties can modulate OMZ intensity by altering the density and ventilation potential of exported P/AG water (Lachkar, 2019).

Downstream changes in the oxygen content and pH of the outflow water show consistent dilution and oxygen loss along the continental shelf. Layer fine structure and step-like profiles along transects indicate active mixing above the seafloor. These results provide a high-resolution continuous mapping of P/AG outflow O_2 modification along the continental shelf, linking local mixing intensity to the outflow's potential to ventilate the upper oxycline of the Arabian Sea. Profiles from the Gulf of Oman frequently exhibit step-like thermohaline structure and interleaving consistent with double-diffusive processes that facilitate transformation of P/AG water (Ghazi et al., 2017; Azizpour et al., 2017). The spatial correspondence between P/AG outflow persistence and elevated near-bottom oxygen levels suggests that the upper oxycline is effectively ventilated. Where the shelf-trapped P/AG water layer is strongest and most persistent, near-bottom oxygen is elevated relative to adjacent waters, indicating effective ventilation near the upper oxycline depths (Font et al., 2024; Swift and Bower, 2003). Downstream maps show progressive oxygen reduction along the outflow pathway basinwards, reflecting dilution and consumption (Fig. 6). As mixing intensity varies across the stable-unstable shelf boundary, depending on seafloor roughness, the magnitude and spatial footprint of P/AG outflow ventilation depend on local thickness, attachment state, and mixing intensity.

4.3 Impact of the P/AG outflow on benthic life

Benthic zonation closely follows P/AG outflow attachment behaviour. Where the outflow remains bottom-attached, strong near-bed shear limits fine-sediment accumulation, maintaining exposed or semi-consolidated substrate and enhancing delivery of suspended particles and oxygenated water. Such conditions favor sessile suspension feeders, including corals and other epifauna, consistent

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with the importance of hydrodynamics and substrate availability in deep-water coral ecosystems (Flach et al., 1998; Roberts et al., 2006).

Below the detachment depth, fine sediments dominate and the hydrographic signature weakens, indicating lower-energy, lower-oxygen conditions. Cerianthid tube anemones commonly occur on such soft substrates and can form distinctive assemblages observable in video surveys (Davies et al., 2014; Flach, 2002). The thick nepheloid layer along the lower shelf and slope may further enhance food supply by retaining suspended organic matter, acting as a reservoir redistributed by mixing (Hanz et al., 2019). These patterns provide a biological imprint of boundary-layer dynamics and independently support the hydrographic interpretation of outflow attachment and separation.

4.4 Implications for climate sensitivity of the P/AG outflow

The attachment–detachment thresholds documented here imply that the P/AG outflow's pathway is sensitive to moderate shifts in source-water density, which depends strongly on the Gulf surface temperature and evaporation. Warming in the P/AG would reduce outflow density, alter lift-off depths, modify downstream oxygen delivery, and potentially reorganize benthic zonation along the margin, indicating a climatically sensitive mechanism. Interannual to decadal changes in evaporation and heat content modulate the density contrast across the Strait of Hormuz and, by extension, the strength and properties of the exported outflow (Campos et al., 2020). Numerical experiments indicate that warming within the P/AG reduces outflow density and weakens intermediate-depth ventilation, thereby intensifying and expanding hypoxia in the Arabian Sea OMZ (Lachkar, 2019; Lachkar et al., 2022). Process-resolving simulations and regional syntheses indicate that where and how the outflow leaves the boundary depends on the balance between buoyancy forcing and near-slope mixing (L'hégaret et al., 2015; Vic et al., 2015), so small density reductions favor earlier detachment and enhanced lateral dispersion.

5 Conclusions

High-resolution hydrographic mapping shows that small- to mesoscale seafloor roughness primarily controls mixing, thickening, and detachment of the Persian/Arabian Gulf outflow along the Oman–UAE margin. Enhanced boundary-layer turbulence over irregular bathymetry drives dilution, seabed detachment, and reorganization of the intermediate-depth pathway, affecting

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oxygen delivery and sediment transport. These observations support a bathymetry-first framework in which mesoscale eddies modulate downstream export but are not required to initiate detachment. Because attachment and lift-off depend strongly on source-water density, moderate climatic changes in Gulf heat and evaporation may alter outflow pathways and ventilation of the Arabian Sea oxygen minimum zone.

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Data availability

The bathymetry and CTD profiles are archived at Zenodo repository (Abdelmaksoud et al., 2025a; Abdelmaksoud et al., 2026a). The regional bathymetry and topography dataset is publicly available (GEBCO Compilation Group, 2025).

Code availability

The used TEOS-10 GSW MATLAB toolbox is publicly available (Mcdougall and Barker, 2011). The Ocean Data Viewer (ODV; Schlitzer, 2024) is publicly available.

Author contributions

AA, AHA, and MYA conceptualized the study. AA performed data curation and formal analysis, and wrote the manuscript draft. AHA, MYA, GB, and KS-M reviewed and edited the manuscript.

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Competing interests

The authors declare there are no conflicts of interest for this manuscript.

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