

## Geophysical Fluid Mechanics group: overview

From ocean currents and atmospheric circulation to the flow of pollutants in urban areas and the interaction between sediments and coastlines, fluid mechanical processes play a vital role in the physical world we inhabit. The reports in this section highlight the diversity of challenges and opportunities in understanding and modeling geophysical flow phenomena. Advancing our knowledge of fluid dynamics in geophysical contexts is essential for developing sustainable and effective solutions to these pressing environmental and public health challenges.

In urban settings, understanding fluid flow around structures and the dispersion of pollutants is critical for designing healthier cities. Effective emergency response to contaminant releases requires competent fast-response models that are cheaper and faster than established turbulence simulation techniques such as Reynolds-averaged Navier-Stokes or large-eddy simulation (LES). Fradera-Soler *et al.* show that building-induced horseshoe vortices, which are not captured by state-of-the-art fast-response models, can have a profound effect on plume dispersion around buildings, with acute sensitivity to upstream release location. The authors also articulate and demonstrate a novel Lagrangian framework for analyzing the time-dependent nature of contaminant release. Given the intrinsic complexity of urban flows, real-world measurements must play a crucial role in monitoring and response. Vishwasrao *et al.* introduce a machine learning approach for optimizing sensor placement in urban environments. Using diffusion models for sparse data reconstruction, their approach enables more efficient monitoring of urban wind flows, with applications in pollution tracking and microclimate management.

Several studies in this collection address fluid dynamics in rivers, coastal environments, and the sea floor. In these settings, fluid interactions with sediments play pivotal roles. The complexity of these particle-laden turbulent flows poses significant challenges for modeling and simulation. Even when sediments remain stationary on riverbeds, properly capturing the interaction between the porous flow within the bed and the turbulent flow above it poses problems for standard LES methodologies. Fust *et al.* introduce a variable-width volume filtering technique with a force-correction scheme to obtain accurate interfacial drag forces in LES of flow over permeable beds. Their methodology improves drag force predictions by accounting for porosity variations across interface regions, contributing to more robust simulations of groundwater and surface water interactions. Once lifted, sediment particles interact with turbulence in complex ways, for example, forming particle clusters driven by turbulent fluctuations, with implications for a wide range of coastal processes such as coral reef life cycles. Chan *et al.* developed an algorithm to quantify how noncohesive sediment clusters evolve and break up in turbulent flows. Their findings elucidate similarities and differences between the turbulent breakup of sediment clusters and that of eddies and bubbles. Further from the shore, sloping seabeds are fertile ground for dangerous and destructive underwater avalanches of sediment known as turbidity currents (gravity currents driven by the suspension of fine particles). Leonelli *et al.* report the results of particle-resolved simulations of turbidity currents interacting with erodible sediment beds. They demonstrate an effective simulation methodology for incorporating the simultaneous effects of a fine mud suspension ( $\sim 10 \mu\text{m}$ ) with much larger sand particles ( $\sim 1 \text{mm}$ ). Their simulation framework

provides a promising platform for studying lab-scale turbidity currents while providing valuable insight and data for the development of modeling techniques for full-scale gravity currents. More generally, gravity currents occur in a wide variety of geophysical settings, including atmospheric transport of wildfire smoke in addition to underwater turbidity currents. This interaction between detailed simulations and lower-fidelity models for gravity currents is addressed by the multifidelity approach of Lu *et al.* to gravity currents. They combined (low-fidelity) numerical solutions of shallow-water equations with high-fidelity direct numerical simulation (DNS) data using machine learning to reduce computational demands while modeling of fluid flow over varying terrain.

The dynamics of kinetic and potential energy over a vast range of scales in the ocean has enormous implications for understanding and modeling Earth's climate. Global models with  $\sim 25$  km resolution can capture some mesoscale eddies, but current approaches severely underpredict their kinetic energy. Perezhogin *et al.* demonstrate that this situation can be improved by using the Germano-based dynamic procedure commonly used with LES. Their results bring clarity to the role of grid resolution and filter-to-grid ratio in controlling the accuracy of mesoscale eddy simulations.

Air-sea interactions are another crucial aspect of ocean energetics. Wu and Hwang's DNS capture the influence of wave-induced stresses on wind-wave interactions. They offer a path toward a deeper understanding of turbulence structure in the atmospheric boundary layer over the open ocean, with potential applications in both climate modeling and wind energy production. The dissipation of kinetic energy, and its association with mixing processes involving available potential energy, is an absolutely crucial aspect of stratified oceanographic flow physics. Bottom topography generates internal waves ( $\sim 100$  m) which can break down into turbulent hot spots of mixing and dissipation. Lewin *et al.* show how the interaction of internal waves with horizontal shear leads to the development of intense turbulence and mixing. Their ensemble of simulations demonstrated the sensitivity of mixing efficiency to the wavelength and orientation of the incident internal wave, as well as the relative strength of the stratification and horizontal shear.