Subduction Driven by Mesoscale Front Evolution and Submesoscale Cyclonic Eddy Generation

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Key Points:

- Frontogenesis, submesoscale instabilities, and frontal decay analyzed in a high resolution simulation.
- A mesoscale front cascaded into submesoscale cyclonic eddies (SCEs), forming a subduction area at the periphery of the cyclones.
- Downwelling at the SCEs periphery was driven by eddy-induced frontogenesis, with 3D helical-spiral parcel transport patterns.

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Abstract

Mesoscale and submesoscale features with Rossby and Richardson numbers near unity indicate a breakdown of geostrophic balance. This gives rise to ageostrophic flows that drive circulation across density gradients and produce vertical motions, transporting heat and biogeochemical tracers below the mixed layer. During winter 2022, high-resolution multiplatform in situ observations and realistic numerical simulations captured the evolution of mesoscale and submesoscale features in the northwestern Mediterranean Sea. A mesoscale front in the Balearic Sea was observed progressing from intensification to decay, culminating in the formation of two submesoscale cyclonic frontal eddies (SCEs). These formed as the front elongated and interacted with a mesoscale ridge, illustrating the dynamic interplay between mesoscale and submesoscale processes. The front intensified due to strain-induced frontogenesis. A strong down-front wind event triggered submesoscale instabilities and the nonlinear Ekman effect, enhancing vertical motions through an ageostrophic secondary circulation and contributing to restratification. As the front weakened, isopycnal slopes flattened, and energy cascaded toward smaller scales, forming the SCEs. This energy transfer was primarily driven by submesoscale instabilities, with additional contributions from centrifugal and gravitational instabilities. A Lagrangian analysis revealed that horizontal parcel transport was dominated by mesoscale circulation, while vertical displacements were controlled by submesoscale processes. The evolving SCEs exhibited a three-dimensional helical-spiral recirculation pattern, promoting vertical transport. Submesoscale eddy-induced frontogenesis drove subduction into the mixed layer, intensified by submesoscale instabilities and guided by downward-sloping isopycnal surfaces at the eddy periphery.

Plain Language Summary

In 2022, a multidisciplinary experiment in the Balearic Sea combined multiplatform in-situ observations with high-resolution numerical simulations to investigate the evolution of an oceanic front. The study focused on analyzing the energy transfer to submesoscale cyclonic eddies (SCEs) and understanding their impact on subduction processes from the ocean surface to the interior. The evolution of the front was characterized by two key phases: (i) an intensification driven by frontogenetic processes, and (ii) a subsequent decay under conditions favorable for overturning instabilities, triggered by a down-front wind event. These dynamics enhanced vertical motion through an across-front ageostrophic secondary circulation, contributing to the restratification of the upper ocean. Following the wind event, the front decayed and fragmented into smaller-scale structures, leading to the formation of SCEs along its edges. The formation of SCEs was associated with the frontal decay, as well as with centrifugal and gravitational instabilities, which transferred energy from the mesoscale front to the SCEs. These eddies exhibited a three-dimensional helical-spiral recirculation pattern that facilitated the vertical transport of water parcels. Submesoscale eddy-induced frontogenesis, coupled with associated instabilities, drove subduction along outcropping isopycnals at the periphery of the SCEs.

1 Introduction

The subduction driven by oceanic mesoscale and submesoscale processes in the mixed layer enhances vertical velocities (Mahadevan, 2016), facilitating the downward transport of water parcels from the surface into the ocean interior below the mixed layer. This process plays a critical role in the transport of heat (Su et al., 2018), buoyancy, and biogeochemical tracers (Ruiz et al., 2019; Uchida et al., 2019; Freilich, 2021). Mesoscale and submesoscale processes drive ubiquitous density fronts, eddies, and elongated filaments in the ocean's mixed layers (Chelton et al., 2011, 2019). Mesoscale structures, characterized by horizontal scales of 10–100 km and lasting several weeks, are strongly dom-