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Thermohaline staircases in a Caribbean eddy and mechanisms for staircase formation

Julio M. Morell[a], Jorge E. Corredor[a], William J. Merryfield[b,*]

[a]*Department of Marine Sciences, University of Puerto Rico, P.O. Box 908, Lajas, PR 00667-0908, USA*
[b]*Canadian Centre for Climate Modelling and Analysis, Meteorological Service of Canada, University of Victoria, P.O. Box 1700, Victoria, BC, Canada V8W 2Y2*

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Abstract

The structure of a cyclonic eddy in the eastern Caribbean was observed by Caribbean Vorticity Experiment cruise CaVortEx I in August 2003. Prominent thermohaline staircases are evident in profiles of temperature and salinity at locations that appear to correlate with the presence of lateral property gradients and shear within the eddy, although such a connection is less than definitive due to the coarseness of horizontal sampling. These observations are examined in light of predictions from two theories for staircase formation. Aspects of the data are found to be consistent with each, raising the possibility that both mechanisms are operating.

Keywords: Salt fingers; Double diffusion; Finestructure; Oceanic eddies; CDT observations

1. Introduction

Thermohaline staircases are ocean regions where temperature T and salinity S vary vertically in a step-like manner. These structures are associated with double-diffusive instability in the form of diffusive convection where T and S increase with depth, or salt fingering where T and S decrease with depth (Schmitt, 1994). The most prominent salt-fingering staircase occupies much of the mid-thermocline in the western tropical North Atlantic, in a substantial region bordered roughly by 50°–60°W and 10°–18°N where conditions are particularly favorable for salt fingering due to the flow of relatively cool and fresh Antarctic Intermediate Water and Atlantic Central Water (Bub and Brown, 1996) beneath warmer and more saline Subtropical Underwater. This structure is often called the C-SALT staircase after an extensive observing campaign conducted there in the mid-1980s (Schmitt et al., 1987).

Abbreviations: Caribbean Sea

*Corresponding author. Tel.: +1 250 363 8263; fax: +1 250 363 8247.
E-mail address: bill.merryfield@ec.gc.ca (W.J. Merryfield).

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Although the C-SALT region is usually viewed as being bounded to the west and separated from the Caribbean Sea by the Lesser Antilles near 60°W, staircases have been observed farther west, within the Caribbean. For example, Lambert and Sturges (1977) described a staircase in the northeast Caribbean centered near 500 m depth in the vicinity of 65°10′W, 17°40′N.

In August 2003 Caribbean Vorticity Experiment cruise CaVortEx I was undertaken to provide a north–south transect of a prominent eddy in the eastern Caribbean that satellite imagery revealed to be interacting with the Orinoco River plume, or ORP (Fig. 1). In contrast with observations of Lambert and Sturges (1977), which found staircases at each location surveyed within a small region, a striking aspect of the physical structure of this eddy was the presence of well-defined staircases in the depth range of 400–600 m within the flanks of the eddy but the absence of such structures within the eddy core and at the eddy periphery (Corredor et al., 2004).

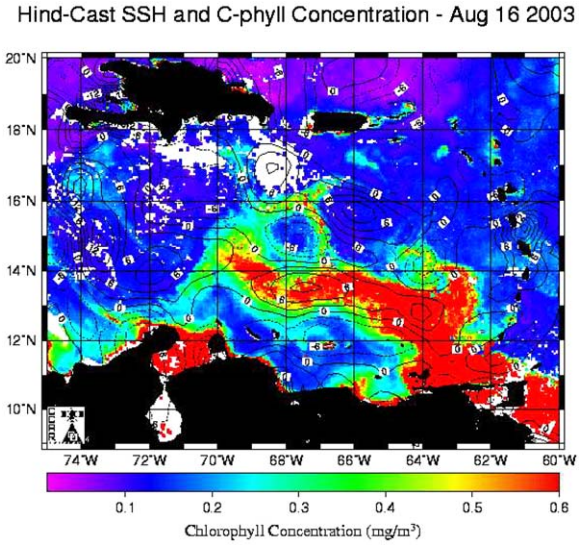

Fig. 1. Chlorophyll concentration (colors) and sea-surface height anomalies (contours labeled in cm) in the eastern Caribbean on August 16, 2003. The center of the cyclonic eddy traversed during CaVortEx I lies in the near 15°N, 67°50′W in a region of negative sea-surface height anomaly. The Orinoco River plume corresponds to the large region of elevated chlorophyll concentration lying mainly southward and eastward of the eddy. (Image obtained from the Colorado Center for Astrodynamics Research at the University of Colorado, Boulder.)

In this paper, the CaVortEx I staircase observations are examined in greater detail. Because the observed heterogeneity of step properties with horizontal location and depth potentially provides clues as to the conditions under which staircases form, the observations are analyzed in the context of two proposed scenarios for staircase formation, that staircases arise through the growth of double-diffusive intrusions (Merryfield, 2000), and that staircases arise through an instability of the vertical flux-gradient relations for salt fingering (Radko, 2003, 2005). The former mechanism requires lateral T and S gradients to operate, whereas the latter can occur under laterally uniform conditions.

2. CaVortEx I

Observations at sea and modeling experiments show that meso-scale eddy dynamics result in enhancement of vertical and horizontal fluxes promoting mixing in the water column. Much attention has focused on the role of "eddy pumping" in transporting nutrients to the euphotic zone through the uplifting of density surfaces (e.g., Williams and Michael, 1998 and references therein). Sub-mesoscale processes, such as ageostrophic upwelling (Martin and Richards, 2001) and slumping of horizontal density gradients (Ferrari and Boccaletti, 2004), also can play an important role.

While Lagrangian drifter studies (Molinari et al., 1981) and analysis of satellite-based sea-surface height topography (Andrade and Barton, 2000; Carton and Chao, 1999; Murphy et al., 1999; Pratt and Maul, 2000) have revealed the existence of a complex eddy field in the Caribbean Sea, studies of the internal structure of Caribbean eddies have been lacking. The Caribbean Vorticity Experiment (CaVortEx) is an ongoing research effort for the in situ characterization of the optical, biogeochemical and physical structure, and dynamics of Caribbean eddies. Cruise CaVortEx I intercepted a cyclonic eddy traversing the east-central Caribbean and obtained a detailed vertical