Ocean Modelling 41 (2012) 1–15

Contents lists available at SciVerse ScienceDirect

Ocean Modelling

journal homepage: www.elsevier.com/locate/ocemod

# Generation of the Cape Ghir upwelling filament: A numerical study

Charles Troupin [a,*], Evan Mason [b], Jean-Marie Beckers [a], Pablo Sangrà [c]

[a] Université de Liège, GHER-MARE, AGO, Allée du 6-Août, 17, Sart-Tilman B5a, B4000 Liège, Belgium
[b] Departament d'Oceanografia Física, Institut de Ciències del Mar – CSIC, Barcelona, Spain
[c] Facultad de Ciencias del Mar, Edificio Ciencias Básicas, Universidad de Las Palmas de Gran Canaria, 35017 Las Palmas de Gran Canaria, Spain

ARTICLE INFO

*Article history:*
Received 12 April 2011
Received in revised form 3 July 2011
Accepted 8 September 2011
Available online 5 October 2011

*Keywords:*
Eastern boundary
Canary upwelling system
Upwelling filaments
Potential vorticity
ROMS model

ABSTRACT

Filaments are narrow, shallow structures of cool water originating from the coast. They are typical features of the four main eastern boundary upwelling systems (EBUS). In spite of their significant biological and chemical roles, through the offshore exportation of nutrient-rich waters, the physical processes that generate them are still not completely understood. This paper is a process-oriented study of filament generation mechanisms. Our goal is twofold: firstly, to obtain a numerical solution able to correctly represent the characteristics of the filament off Cape Ghir (30°38′N, northwest Africa) in the Canary EBUS and secondly, to explain its formation by a simple mechanism based on the balance of potential vorticity.

The first goal is achieved by the use of the ROMS model (Regional Ocean Modeling System) with embedded domains around Cape Ghir, with a horizontal resolution going up to 1.5 km for the finest domain. The latter gets its initial and boundary conditions from a parent solution and is forced by climatological, high-resolution atmospheric fields. The modeled filaments display spatial, temporal and physical characteristics in agreement with the available in situ and satellite observations. This model solution is used as a reference to compare the results with a set of process-oriented experiments. These experiments allow us to reach the second objective. The solutions serve to highlight the contributions of various processes on the filament generation. Since the study is focused on general processes present under climatological forcing conditions, inter-annual forcing is not necessary.

The underlying idea for the filament generation is the balance of potential vorticity in the Canary EBUS: the upwelling jet is characterized by negative relative vorticity and flows southward along a narrow band of uniform potential vorticity. In the vicinity of the cape, an injection of relative vorticity induced by the wind breaks the existing vorticity balance. The upwelling jet is prevented from continuing its way southward and has to turn offshore to follow lines of equal potential vorticity.

The model results highlight the essential role of wind, associated with the particular topography (coastline and bottom) around the cape. The mechanism presented here is general and thus can be applied to other EBUS.

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## 1. Introduction

The eastern boundary upwelling systems (EBUS) constitute high-productivity regions of the world ocean (e.g., Ryther, 1969; Durand et al., 1998; Jennings et al., 2001). They are driven by large-scale wind patterns responsible for coastal upwelling, resulting in the increase of nutrient concentration in the surface layers. Sea Surface Temperature (SST) images covering the EBUS reveal the presence of narrow ($\mathcal{O}$(10 km)), elongated ($\mathcal{O}$(100 km)) structures of cool water extending seaward in the upper surface layer ($\mathcal{O}$(100 m)), preferentially located near to coastal irregularities. These structures are called "upwelling filaments", or simply "filaments". Associated with the low temperature signal, high-chlorophyll concentrations are frequently observed through satellite imagery, bearing the important biological activity of filaments.

Filaments were first observed during the late 1970-early 1980s in the California Current System (CCS) through in situ measurements (e.g., Brink, 1983; Brink et al., 1984; Mooers and Robinson, 1984) and remote sensing imagery (e.g., Bernstein et al., 1977; Ikeda and Emery, 1984; Flament, 1985). Intensive surveys were carried out during multidisciplinary projects in the CCS: the Coastal Ocean Dynamics Experiment (CODE, Kosro and Huyer, 1986; Beardsley and Lentz, 1987), the Coastal Transition Zone program (CTZ, Brink and Cowles, 1991; Strub et al., 1991) and the Eastern Boundary Current experiment (EBC, Huyer et al., 1998).

Numerous cruises also took place in the Canary Upwelling system (CUS), with the objective of examining the dynamics of the filaments and studying their effects upon primary production (e.g., Haynes et al., 1993; Hagen et al., 1996; Barton et al., 1998; Barton and Arístegui, 2004; Pelegrí et al., 2005). Remote-sensing

* Corresponding author. Tel.: +32 43662340.
*E-mail addresses:* ctroupin@ulg.ac.be (C. Troupin), emason@icm.csic.es (E. Mason), JM.Beckers@ulg.ac.be (J.-M. Beckers), psangra@dfis.ulpgc.es (P. Sangrà).

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doi:10.1016/j.ocemod.2011.09.001

imagery helped to identify the sites favorable to filaments (e.g., Van Camp et al., 1991; García-Weill et al., 1994; Kostianoy and Zatsepin, 1996; Hernández-Guerra and Nykjaer, 1997).

Different mechanisms have been proposed for the filament generation: interaction of the upwelling jet with the topography (Ikeda and Emery, 1984; Strub et al., 1991; Hagen et al., 1996), baroclinic instability (Ikeda and Emery, 1984), meandering of the equatorward jet (Strub et al., 1991), interaction with a field of synoptic-mesoscale eddies (Mooers and Robinson, 1984; Lutjeharms et al., 1991; Strub et al., 1991; Peliz et al., 2004), influence of the wind (e.g., Kelly, 1986; Hagen et al., 1996; Castelao and Barth, 2007). Pelegrí et al. (2005) proposed that an injection of positive vorticity due to the friction of the flow with the sea floor created the offshore deflection of the jet. Most of the surveys point at coastline or topography irregularities as a responsible factor. Indeed, along the coast of NW Africa, numerous capes (Fig. 1) are frequently affected by filaments: Cape Ghir (Hagen et al., 1996; Pelegrí et al., 2005), Cape Jubi, Cape Bojador and Cape Blanc (Gabric et al., 1993; Karakas et al., 2006).

The combination of high spatial resolution (to capture the filaments) and large domain extension (to reproduce the large-scale oceanic features) required by the filament modeling often implies the use of nesting procedures. Several models have been implemented in the Canary EBUS. Spall (1990) used an eddy-resolving model covering the Canary basin to study the local circulation. With a horizontal resolution close to 35 km, the model could reproduce the main currents. The authors reported problems in the eddy kinetic energy values and in the representation of the Mediterranean water tongue, probably related to the specification of the open boundary conditions. Johnson and Stevens (2000) used a 1/6°-resolution model in a region extending from the north of Portugal to the south of Canary Islands, including the Azores Archipelago and the Strait of Gibraltar. Their simulations were able to generate the Cape Ghir filament and to show that the filament is stronger during the upwelling maximum. Stevens et al. (2000) applied a similar model to the Iberian shelf-slope region and pointed out the need for a enhanced-resolution implementation in order to be able to model the effects of the capes. With a 1/12°-resolution model, Stevens and Johnson (2003) noted that filaments tend to appear at the same locations along the coast: at 25.5°N, 28°N (Cape Juby), 31°N (Cape Ghir) and 33°N, in agreement with satellite observations. However, their modeled filaments were too broad and penetrated too far offshore in comparison with observations.

With a 9 km-resolution model forced by seasonal wind, Batteen et al. (2000) studied the effects of the coastline on the eddy and filament structures in the Canary Current system. Despite using a flat bottom (4500 m depth), they were able to obtain filaments in agreement with field measurements and attached to the main capes. Their experiments underlined the role played by the wind in the generation of filaments and the importance of the coastline to obtain realistic locations. Another process-oriented study was conducted by Batteen et al. (2007) in the same area with a terrain-following, 3 km-resolution model. Filament structures were obtained off Cape Ghir when an iterative topography developed by Martinho and Batteen (2006) was used, while the Gaussian smoothed topography only generated little mesoscale activity.

The peculiarity of the Cape Ghir region was also highlighted by Mason et al. (2011): in their study of the Canary Current, they showed that its variability was related to the propagation of planetary waves, attributed to a temporal variation of the wind stress curl (e.g., Dickinson, 1978; Hagen, 2005), in particular between Cape Sim and Cape Ghir. Another important conclusion from their work is that the Canary Current tends to be insensitive to variability in the Azores Current.

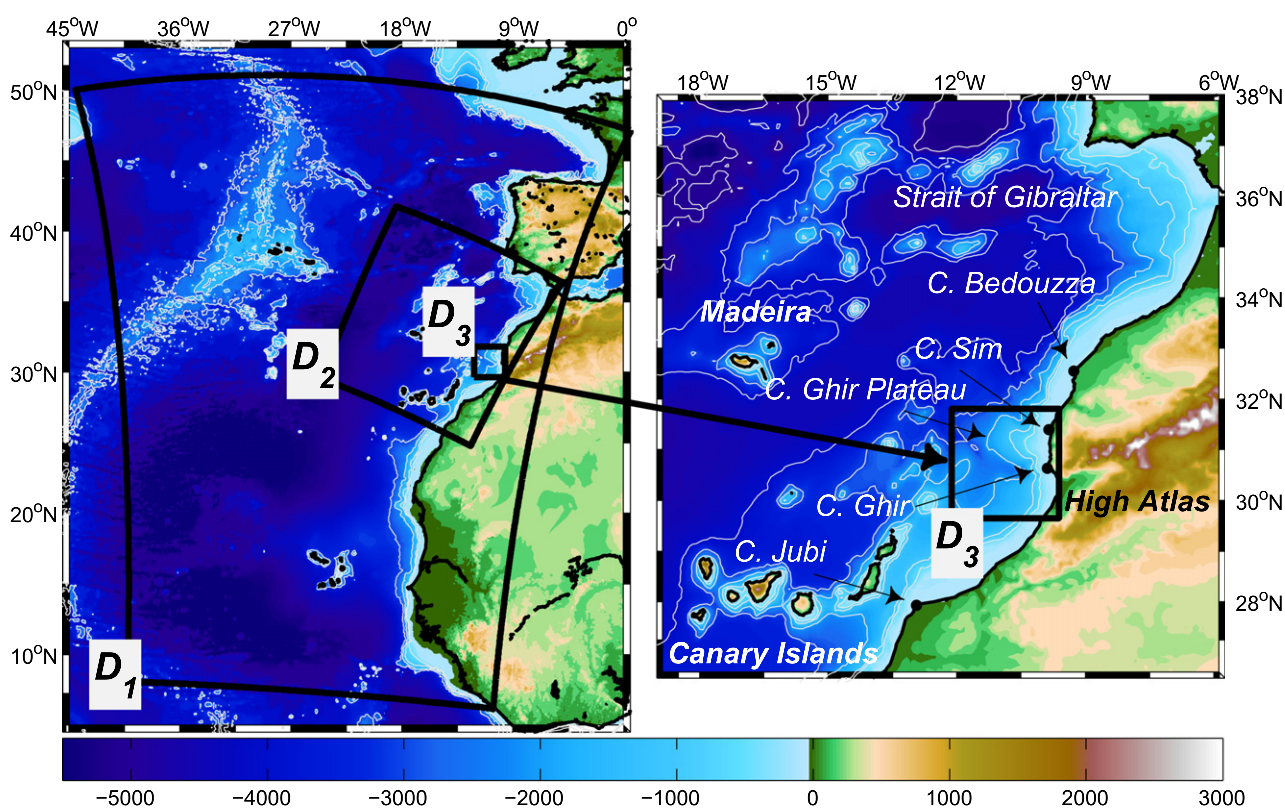


**Fig. 1.** Topography and nested domains (thick black lines) used for the filament modeling, referred to as: the large domain $\mathcal{D}_1$, the intermediate domain $\mathcal{D}_2$ and the small domain $\mathcal{D}_3$. The main topographic features are indicated in the close-up view (right). Isobaths 500, 1000, 2000 and 3000 m (thin white lines) are superimposed on both maps.

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