Frontogenesis and Subsequent Formation of Cold Filaments and Eddies on an Idealized Shelf

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***Abstract* – Cold filaments in the eastern Gulf of Mexico are investigated using a numerical model to simulate the effect of cooling over an idealized shelf. A horizontal density gradient induces an alongshelf current that in time becomes unstable. As these instabilities grow, filaments and later eddies are generated, so that dense water near the coast is exchanged with offshore in an attempt to balance the surface heat loss over the sloping shelf.**

1. INTRODUCTION

During wintertime cooling, satellite observations of sea surface temperature (SST) in the eastern Gulf of Mexico (GoM) reveal organized patterns of alternating warm and cold water extending 40 – 80 km offshore along the West Florida Shelf. The filaments also appear in images of chlorophyll concentration, most likely as an indication of water movement rather than primary productivity. A recent modeling study of the GoM with realistic forcing and topography reproduces these filaments well ([1], Fig. 1).
Observations from the California Current System ([2], [3]) and off the Iberian Peninsula ([4], and references therein) show that filament formation in these regions is closely related to coastal upwelling. Reference [2] used a numerical model to simulate a forced eastern boundary current, and reproduced filaments extending 400-500 km offshore. The filaments then pinched off, forming eddies. Relatively large velocities within the filaments were responsible for a substantial amount of cross-shelf heat transport. The authors found it necessary to include irregularities in the topography in order for filaments to exist and exhibit a realistic behavior.
Reference [3] also successfully reproduced a convincing representation of filaments and eddies along an eastern boundary from numerical experiments. Once again, the California Current System was used for comparison. Their conclusion was that frontal instabilities were the cause of initial, small amplitude disturbances, while larger scale meanders were the result of baroclinic instability. The small-scale features were, however, essentially eliminated when SST was kept constant (neglecting heat loss from the ocean surface prevents the formation of a strong horizontal temperature gradient, and hence frontal instabilities).
The formation of dense water masses in polar regions may produce qualitatively similar features as those observed in the GoM. Reference [5] attempted to simulate a coastal polynya, as a constant buoyancy loss was applied over a semi-circular surface area above a shallow, sloping bottom. Three distinct phases were identified in the resulting flow field; geostrophic adjustment, instabilities and offshore eddy transport. After a certain time, dense water was in this manner effectively transported away from the cooling region. Eventually, the offshore transport balanced the buoyancy loss so that the system was in equilibrium. A more recent study by [6] includes the effect of bottom friction in an otherwise similar environment. In this case, the offshore transport is too weak to balance the surface cooling as the bottom friction retards the eddy propagation, and thus the density continuously decreases throughout the experiment. However, the horizontal density gradient, and therefore the velocities it generates, reaches a statistical equilibrium that compares well with relevant observations.

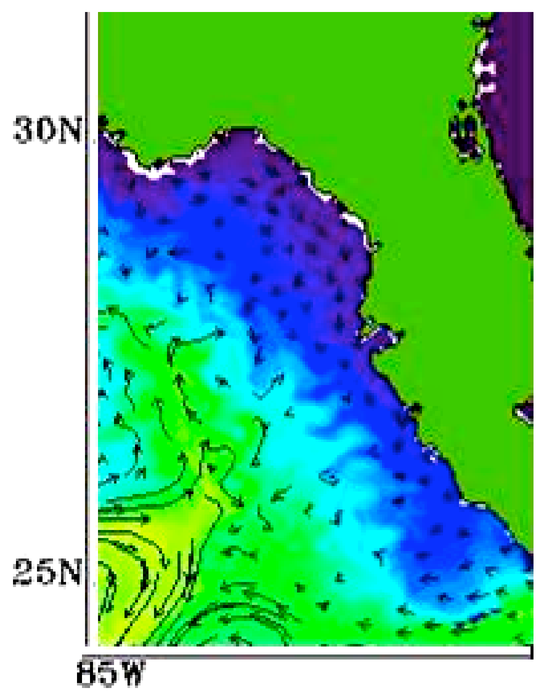

Fig. 1. SST and surface currents in December, simulated with the NCOM. Colder water is represented by darker colors.

2. MODEL

The numerical model used is the Navy Coastal Ocean Model (NCOM), a three-dimensional, hydrostatic, primitive equation ocean model developed at the U.S. Naval Research Laboratory. A detailed description of the model can be found in [7]. The model employs a hybrid sigma / z-level vertical coordinate useful for simulating both shelf and deep ocean domains.

Experiments in this study are performed in a square basin, 320 x 320 km, with a coastline at the eastern boundary. The topography (Fig. 2) depicts an idealized shelf, uniform in the north-south direction with a minimum (maximum) depth of 4 m (1500 m). There are 40 vertical layers; the upper 20 are terrain-following sigma levels while the bottom 20 (below the shelf break at 140 m) are z-levels. The horizontal grid spacing is 2 km.

The surface mixed layer is initially 60 m deep, and has a temperature of 22°C. Further down, the temperature decreases linearly towards the bottom. Periodic boundary conditions are applied at the northern and southern edges of the domain, and at the western boundary the model uses Orlanski radiation [8].

The only forcing of the system is a uniform surface heat loss, which varies between -40 and -70 Wm^{-2} in the different experiments. There are certainly more realistic ways one could force the model, but since the main object is to investigate filaments and eddies resulting from a horizontal density gradient, not the formation of the gradient itself, this "shortcut" may be justified.

The fact that the NCOM uses the hydrostatic approximation is a weakness considering that surface cooling usually results in convection. However, [9] have shown that although non-hydrostatic effects are important in the development of deep convective plumes, these effects are unimportant in relatively shallow water. The shelf depths used in this study are well within this shallow-water limit.

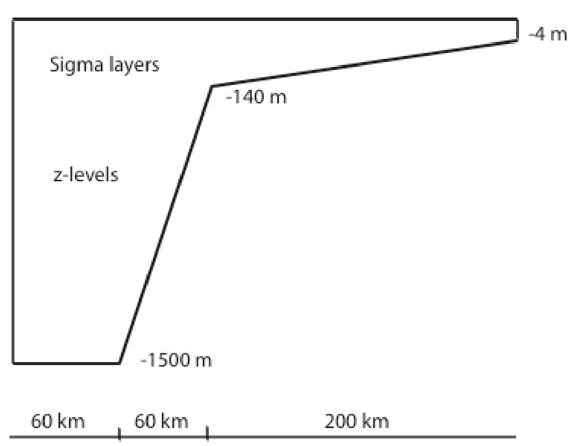

Fig. 2. The idealized shelf topography used in the numerical experiments.

3. MODEL RESULTS

The experiment described in the following was performed using a surface heat flux of –60 Wm^{-2}, starting with a stratified ocean at rest. Salinity was constant throughout the run, so that density was determined by temperature (and pressure) alone. The upper mixed layer was 60 m deep with a temperature of 22°C, so that the water is uniform in a region extending about 80 km offshore. The model run lasted 60 days.

Within the first few days of cooling, a thermal front is generated along the coastline, where the water is shallow and thus most susceptible to the forcing. Isotherms quickly orient themselves vertically, and as the cooling continues, the horizontal density difference increases.

Instabilities start to form after 10 days, as small perturbations in the temperature field. This is most likely due to cold, dense water moving offshore and a balancing surface inflow of warmer, lighter water. The horizontal velocity field is still quite weak, O(0.001 ms^{-1}), and at this time the velocities have a dominant cross-shelf component.

As time progresses and the cooling continues, an equatorward, meandering circulation slowly builds strength. This causes the frontal perturbations to merge with each other, thereby increasing their separation distance and offshore extent. Approaching 25 days into the simulation, mature filaments approximately 20 - 30 km long are conspicuous features in both the temperature and velocity fields (Fig. 3).

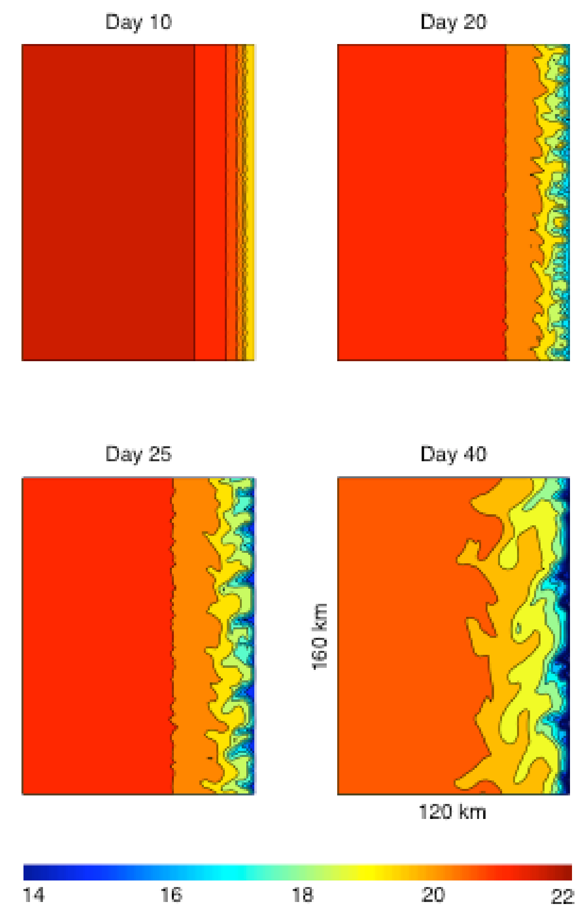

Fig. 3. Snapshots of SST contours on the shelf at days 10, 20, 25 and 40. The horizontal thermal gradient is most intense along the coast, hence this is where the instabilities originate.

Around day 30, cyclonic eddies disengage from the tips of filaments and propagate further offshore. The velocity field at this point displays a north-south alternating pattern of positive and negative relative vorticity (Fig. 4).

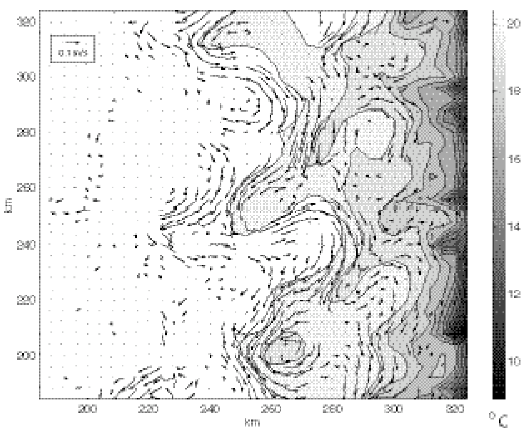

Fig. 4. Snapshot of SST (shading) and surface current (vectors) after 60 days of cooling.

When comparing alongshelf relative vorticity profiles in the upper and lower layers, it is evident that a phase shift occurs when the cold filaments reach a certain size. Initially, the surface and bottom layers exhibit near identical behavior (Fig. 5a), but after approximately 20 days the profiles have been shifted so that a negative anomaly resides above a positive and vice versa (Fig. 5b). During later stages, the surface vorticity field becomes increasingly stronger while the bottom layer, being influenced by friction, seems to reach a maximum relative vorticity after 20 days.

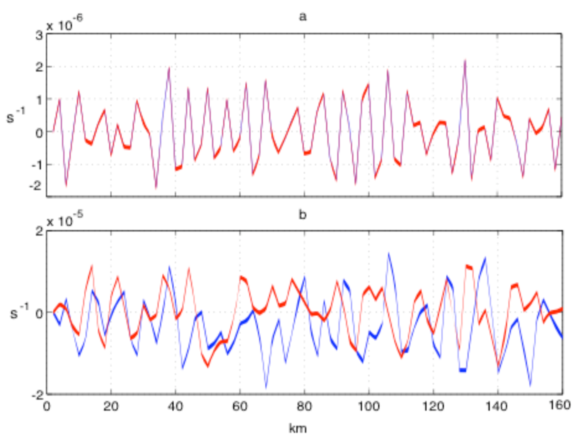

Fig. 5. Relative vorticity at the surface (blue) and bottom (red) calculated along a 160 km long section parallel to the coast. After 10 days (a), the profiles are practically indistinguishable, while clear differences can be seen after 20 days (b).

4. SUMMARY AND DISCUSSION

For clarity, the progression of filament and eddy formation is separated into four stages and discussed individually. These are frontogenesis (4.1), instabilities (4.2), filaments (4.3) and eddies (4.4).

4.1. A primary requirement for the formation of cold filaments along the GoM coast is a horizontal density front created by (wintertime) surface heat loss. This is simulated by applying a uniform surface heat loss to a stratified ocean over an idealized shelf. The cooling is most intense over the shallowest areas, as the deeper regions have larger heat content.

In reality, winds may be an important factor, but since they are predominately northerly during winter the effect would be to enhance the generation of filaments by Ekman transport.

4.2. After the temperature front has been established, it seems the system seeks to restore equilibrium in two ways; columns of dense water begin to move offshore, balanced by an inflow of warmer water. A gravitational force is present due to the sloping bottom, but the shallow water depth in the frontal region does not allow for significant convective motion. Rather, cross-shelf transport is achieved by vertically nearly homogeneous filaments that become increasingly elongated.

After 7-10 days the instabilities are manifest as small perturbations on the front. At the same time, a slow equatorward current has been set up. The current strengthens as the cooling continues, and while following the meandering SST contours it adds a vorticity component to the system. The interactions between vorticity anomalies of opposite sign further increase the extent of the filaments; meanders grow when cyclone - anticyclone pairs propagate offshore (Fig. 6).

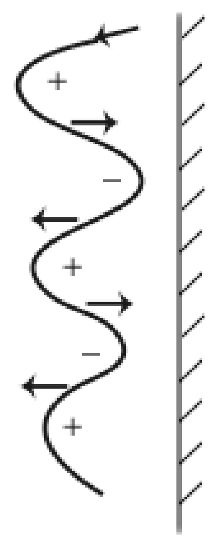

Fig. 6. Sketch of interacting vorticity anomalies in an equatorward meandering current on a sloping bottom.

4.3. 20 days into the model run, the initial small scale disturbances have grown to about 15-20 km, and they show a clear tendency for rapidly stretching offshore while curving southward. The vorticity anomalies at this point exhibit a hetonic structure as seen from Fig. 5, indicative of efficient cross-shelf heat transport [10]. The time span between days 20 - 30 coincides with the fastest offshore movement, where filaments rapidly stretch out to 40-50 km. However, bottom friction eventually retards the lower layer vorticity anomalies, so that heton dynamics become less important compared to the momentum exchange between upper layer vortices. The effect of heton dynamics appears to be an energetic boost to the system to facilitate cross-shelf heat transport.

As vorticity anomalies move offshore, the depth increases and, by conservation of potential vorticity during vertical stretching, so must the relative vorticity. Cyclonic anomalies will in this manner grow stronger, while anticyclones diminish, hence an interacting pair will become dominated by the cyclone. The observed southward curving of the eddy propagation path is therefore ultimately an effect of the sloping bottom (Fig. 7).

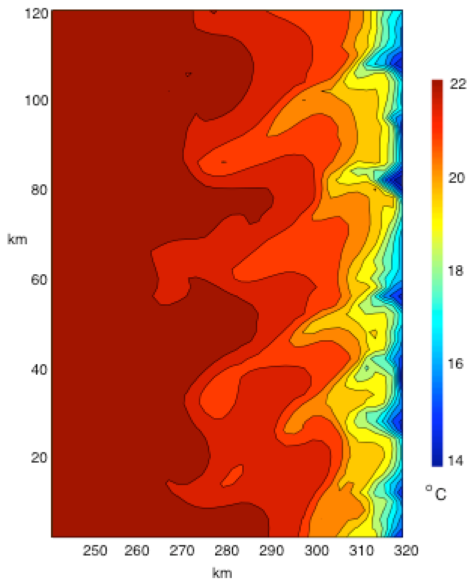

Fig. 7. Snapshot of SST on day 43 of the model run. Filaments curve southward, as they develop positive relative vorticity.

4.4. It is frequently seen from the model results that after 25 – 30 days, cyclonic eddies are formed from the tips of filaments. The eddies continue to propagate southward until they dissipate or merge with other eddies or filaments. The end result is that dense water is carried away from the region of most intense cooling and mixed with lighter water. New filaments and eddies are constantly formed, thus the inner zone of cold water expands offshore. According to [6], a balance between offshore eddy transport and cooling can not be reached when bottom friction is included in the model, however the horizontal density gradient eventually reaches a statistical equilibrium. Future work will reveal whether or not this holds in the current study.

ACKNOWLEDGMENTS

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