

Baroclinic instability and transient features of mesoscale surface circulation in the Black Sea: Laboratory experiment

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[1] The circulation in the Black Sea is characterized by a strong basin-wide current along the shore in the cyclonic direction (the Rim Current). Satellite and field data demonstrate that this circulation is subject to mesoscale variability in the form of meanders, eddies, and filaments. The unstable cyclonic boundary current was modeled in a new series of laboratory experiments on a rotating platform using a scaled model of the Black Sea. The dynamical similarity of the important dimensionless control parameters including the normalized Rossby deformation radius, the Rossby number, and the Ekman number was satisfied in the experiments. The results demonstrate the development of the baroclinic instability due to freshwater discharge imitating the river inflow in the Black Sea. The typical wavelength of the baroclinic instability observed in the experiments is analogous to that observed in the satellite images of the Black Sea when compared to characteristic dimensions of the basin. The cyclonic boundary current in the laboratory model is dynamically similar to the Rim Current. Persistent transient features of the circulation of the Black Sea, such as the so-called Batumi Eddy and the Sevastopol Eddy as well as other features, were reproduced in the experiments when the background rotation rate of the system was varied.

INDEX TERMS: 4243 Oceanography: General: Marginal and semienclosed seas; 4520 Oceanography: Physical: Eddies and mesoscale processes; 4512 Oceanography: Physical: Currents; *KEYWORDS:* baroclinic instability, stratified/rotating fluid, Rim Current, mesoscale eddies, particle image velocimetry

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1. Introduction

[2] Laboratory modeling can be considered an effective tool for studies of the dynamics of the Black Sea in addition to field experiments and numerical simulations. Geographical features of the Black Sea allow one to model it in a small-scale laboratory experiment observing the similarity of a number of important dimensionless governing parameters. The Black Sea is a nearly enclosed basin (Figure 1) having limited exchange with the Mediterranean through the narrow Bosphorus Strait. The net outflow from the Black Sea through the Bosphorus is approximately $300 \text{ km}^2 \text{ yr}^{-1}$ [Unluata *et al.*, 1990] which constitutes 0.06% of the total volume of the Black Sea. The sea is elongated in the East-west direction with the aspect ratio of approximately 3:1. The Black Sea is relatively narrow in its central part between the Crimean peninsula and Anatolian coast where the minimum distance is 260 km. The limited extent of the sea in the latitudinal direction allows us in most cases to exclude the effect of the variation of the Coriolis parameter with latitude from consideration of the dynamical features of the circulation. The Black Sea is a deep basin (maximum depth 2246 m, average depth 1300 m) with a

narrow shelf and a steep continental slope except in the northwestern part of the sea where the shelf occupies a very broad region. In the northwestern part of the Black Sea the shelf is over 200 km wide with the depth ranging from 0 to 100 m. In other parts of the sea it has a depth of less than 100 m and a width of 2.2 to 15 km. Near the Caucasian and Anatolian coasts the shelf is only a narrow intermittent strip.

[3] The hydrological structure of the Black Sea is characterized by a very stable stratification. A simplified description of the stratification can be summarized as follows. A thin upper layer of 40–50 m and of a low salinity of approximately 18 psu is due to the continuous supply of fresh water by major rivers in the western part of the sea. Most of the inflow comes from four major rivers; namely the Danube, the Dniester, the Dnieper and the Southern Bug. The average total annual discharge into the Black Sea is 300 km^3 per year [Unluata *et al.*, 1990], which constitutes approximately 0.06% of the total volume of the Black Sea. The stratification is especially pronounced along the coast in the boundary current [e.g., Oguz and Besiktepe, 1999] called Rim Current [Oguz *et al.*, 1992] transporting fresh water around the sea in a cyclonic direction. This basin-scale current is also referred to as the Main Black Sea Current in Russian literature.

[4] The results of numerical modeling by Kourafalou and Stanev [2001] also indicate that a so-called Coastal Low

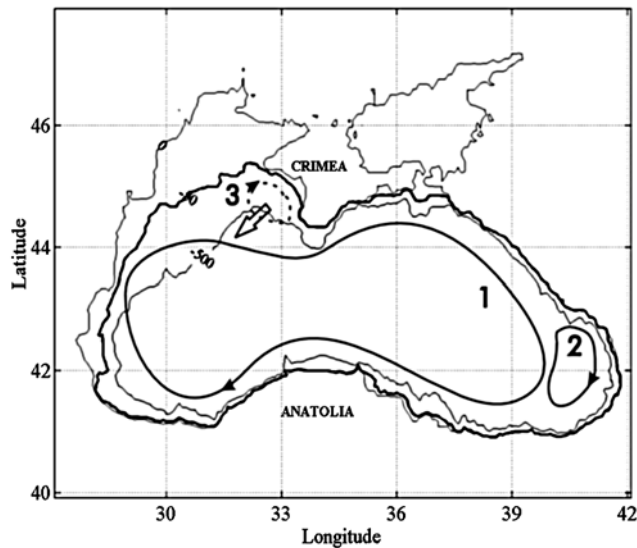


Figure 1. Bathymetry and the sketch of the main features of the circulation of the Black Sea: 1, Rim Current; 2, Batumi Eddy; and 3, Sevastopol Eddy. The arrow indicates the general direction of migration of the Sevastopol Eddy.

Salinity Band is formed because of combined river input. The rest of the sea can be effectively considered as a denser water mass of salinity in excess of 20 psu. This two-layer stratified system allows one to use a straightforward approach to modeling the hydrological structure of the Black Sea in the laboratory.

[5] The general circulation of the Black Sea is characterized therefore by a basin-scale cyclonic boundary current [e.g., Neumann, 1942; Bogatko *et al.*, 1979]. Two interconnected large-scale cyclonic gyres are formed in the interior of the western and eastern parts of the basin because of the narrowing in the central part of the sea. Persistent or recurrent features of this basin-wide circulation are also anticyclonic eddies along the coast. Some “taxonomy” of these features of the surface circulation of the Black Sea is provided by Oguz *et al.* [1993]. Some features are particularly worth noting in the context of the experimental results reported herein. One large anticyclonic eddy occupying the southeastern corner of the Black Sea is called Batumi Eddy. It is formed by the recirculation to the right of the Rim Current. The current separates from the coast in this region and crosses the sea toward the northern shore at approximately 40°E. Another persistent anticyclonic eddy (Sevastopol Eddy) is located west of the tip of the Crimean peninsula. It is similarly located to the right of the main jet of the Rim current which separates from the coast following the continental slope at this region. According to Ginzburg *et al.* [2002b] the Sevastopol Eddy often migrates slowly in the southwestern direction (arrow in Figure 1). Both of these eddies exhibit significant variability during the year. It can be clearly seen in the geostrophic velocity maps deduced from the TOPEX/Poseidon altimeter data [see Korotaev *et al.*, 2001, Figure 9; Korotaev *et al.*, 2003, Figures 7 and 12–13] that the Batumi Eddy starts to appear in winter and is most strong in spring while in summer and fall it is undistinguishable. Moreover, in summer and fall the separation of the jet from the northern shore rather than

from the southern shore can be observed. This can result in a reversal of the circulation in the region of location of the Batumi Eddy although the reversed circulation is weaker than the circulation associated with the Batumi Eddy. The origin of the Batumi Eddy is still a subject of debate and its existence is sometimes attributed to the surface freshwater forcing associated with the intensification of precipitation toward the eastern coast of the Black Sea. Herein we will argue that the Batumi Eddy is a transient feature of the circulation occurring as a result of the separation of the boundary current due to variations of the intensity of the general circulation. The Sevastopol Eddy is subject to even stronger variability. In fact the identity of this eddy is artificial to large extent. Satellite imagery of this region of the sea often reveals two smaller anticyclones or even anticyclones accompanied by cyclonic eddies [Ginzburg *et al.*, 2000]. This combination constitutes a vortex dipole or mushroom-like current. Numerous recent observations [e.g., Fedorov and Ginzburg, 1992; Ginzburg, 1994, 1995; Ginzburg *et al.*, 2000; Afanasyev *et al.*, 2002; Ginzburg *et al.*, 2002a, 2002b] using satellite imagery demonstrate significant mesoscale variability of the entire circulation system. The observed mesoscale features of the circulation include meanders, closely spaced anticyclonic and cyclonic eddies, dipoles and filaments. These hydrodynamical structures are also typical features of any quasi-two-dimensional turbulent flow [e.g., Voropayev and Afanasyev, 1994]. It is especially worth noting that regular arrays of meanders are often observed along the southern coast between 30°E and 40°E [e.g., Oguz and Besiktepe, 1999, Figure 8; Ginzburg *et al.*, 2000, Figure 1; Afanasyev *et al.*, 2002, Figure 5]. These meanders are likely due to the baroclinic instability of the Rim Current modified by the coastal features in this region. Similar instability is also observed at the northern shore of the Black Sea. The temporal and spatial characteristics of the mesoscale variability in the Black Sea as well as dynamical processes involved are yet to be fully understood. It is important to study these flows not only because of their many practical connections such as the understanding of exchange between the shelf region and the interior of the sea, but also because such flows often reveal the influence of fundamental hydrodynamics interactions.

[6] The major mechanisms that force cyclonic circulation in the Black Sea are buoyancy flux due to river input and wind stress. The importance of the relative contributions of these two mechanisms is not completely clear. The buoyancy flux alone can provide the required cyclonic circulation according to the theoretical and experimental analysis by Bulgakov *et al.* [1996a, 1996b]. Recent estimates [Efimov and Shokurov, 2002; Efimov *et al.*, 2002], however, show that the seasonal variability of the circulation system is correlated with the vorticity of the wind over the sea. The wind fields are of a larger spatial extent than that of the Black Sea. The annual cycle of wind vorticity follows a simple harmonic law such that the cyclonic vorticity prevails in winter while the anticyclonic vorticity is persistent in summer. The amplitudes of the cyclonic and anticyclonic peaks are slightly different such that the annual average value is positively signed (cyclonic) and is approximately 10^{-6} s^{-1} . The magnitude of peaks reaches 3–4 times of the average value. It is also worth noting that river discharge also follows an annual cycle with the maximum value

occurring in May and the minimum in October. The seasonal variability of the discharge is significant. The difference between the peak and the mean value constitutes approximately 75% of the mean [Kourafalou and Stanev, 2001]. The overall intensity of the circulation in the Black Sea also exhibits a strong seasonal variation. It attenuates in summer to fall and intensifies in winter to spring [Korotaev *et al.*, 2001]. The Rim Current jet is clearly observed in winter and spring while during summer months the meso-scale eddy variability is so large that it masks the Rim Current such that it can only be defined in terms of statistically defined transport. The temporal evolution of kinetic energy of the surface geostrophic circulation derived from the TOPEX/Poseidon altimeter data [see Korotaev *et al.*, 2001, Figure 10] is characterized by a strong peak in January/February which can be associated with atmospheric forcing and weaker peak in May which is probably due to the intensified river discharge. The variability of the kinetic energy can be as high as 70% of the mean value.

[7] In recent years numerous attempts have been made to model different dynamical aspects of the circulation of the Black Sea in numerical simulations [e.g., Oguz and Malanotte-Rizzoli, 1996; Staneva *et al.*, 2001; Stanev and Staneva, 2000; Beckers *et al.*, 2002; Stanev and Beckers, 1999]. Laboratory experiments on this subject however are relatively few. Bulgakov *et al.* [1996b] considered the process of development of quasi-stationary circulation induced by buoyancy fluxes in a rotating basin. It was demonstrated that the slow injection of fresh water at the surface and saltier water at an intermediate depth results in the formation of a cyclonic circulation at the surface with a countercurrent at an intermediate depth. A similarity of a number of control parameters including the Rossby and Ekman numbers was achieved in the experiments. The formation of the stationary circulation was observed on a significant timescale of several hours which was mainly controlled by the timescale of viscosity. The addition of a simple coastline in the form of two convex plates in the circular tank allowed the authors to show the formation of two macro gyres. The issue of variability of the general cyclonic circulation was considered in laboratory experiments by Zatsépin *et al.* [2002]. The cyclonic circulation in a circular tank was forced by a freshwater source at the surface. It was observed that the flow was stable initially when the value of the Burger number which was defined as the baroclinic Rossby deformation radius normalized by the characteristic size of the basin, was high enough. After some significant time period the upper layer was formed over the entire surface area and the value of the Burger number became lower. The flow began meandering eventually filling with eddies the entire area of the basin.

[8] In the new series of experiments reported herein, we follow in general the approach proposed by Bulgakov *et al.* [1996b] and Zatsépin *et al.* [2002], which includes forcing the circulation by a buoyancy source. The present study is focused on the modeling of the unstable peripheral boundary current within a scaled model of the Black Sea. We will show that the laboratory model correctly reproduces the main features of the circulation system including meanders and mesoscale eddies occurring because of the finite amplitude development of the baroclinic instability of the boundary current.



Figure 2. Sketch of the experimental setup.

[9] Seasonal variations of river inflow or wind stress cause variations of the intensity of the circulation. We reproduce these transient effects by varying the rotation rate of the platform in the second series of our experiments. The slow down of the background rotation corresponds to the intensification of the cyclonic circulation in the laboratory basin while the spin-up of the platform models the attenuation of the circulation. The results of these experiments demonstrate the occurrence of the transient features typical for the circulation in the Black Sea. We believe that specific features of the geometry of the coastline are important for the formation of some distinct features of the circulation, namely the big hook-shaped meanders, Batumi and Sevastopol eddies. The laboratory experiments described in this paper demonstrate in particular that Batumi and Sevastopol eddies are transient features which occur because of the separation of the boundary layer in the eastern part of the sea and at the tip of the Crimean peninsula. Complete dynamical similarity of laboratory flows and the flows in the Black Sea was satisfied in our experiments with respect to the normalized Rossby deformation radius, the Rossby number and the Ekman number.

[10] In the following sections of this paper, the laboratory setup, visualization and measuring techniques that we employ in our experiments are described in section 2, while section 3 contains the results and analysis of the experiments. Section 3 also contains an analysis of the main control parameters of the flow and the dynamical similarity between the laboratory flows and the flows in the Black Sea. We conclude with a discussion of our results.

2. Laboratory Apparatus and Technique

[11] Our experiments were carried out in a rectangular Plexiglas tank of dimensions 64×64 -cm mounted on a rotating table to reproduce the effects of the Earth's rotation (Figure 2). A 2D scale model (15.2 km in 1 cm) of the Black Sea made from Styrofoam was placed into the tank along the diagonal. The shape of the model reproduces the shape of the 50 m isobar (Figure 1). The maximum longitudinal dimension of the model was 75.5 cm. The tank was rotated about a vertical axis through its center in the counterclockwise direction. The rotation rate Ω was varied between 1.55 s^{-1} and 3.1 s^{-1} (period $T = 2-4$ s). The tank itself was filled with a salt water of salinity $S = 15.00-18.75\text{‰}$ (density $\rho = 1012-1015 \text{ kg m}^{-3}$) with a working depth of 7 cm. Fresh water was supplied through a thin glass tube from a Mariotte siphon, which allowed us to maintain a constant flux. A

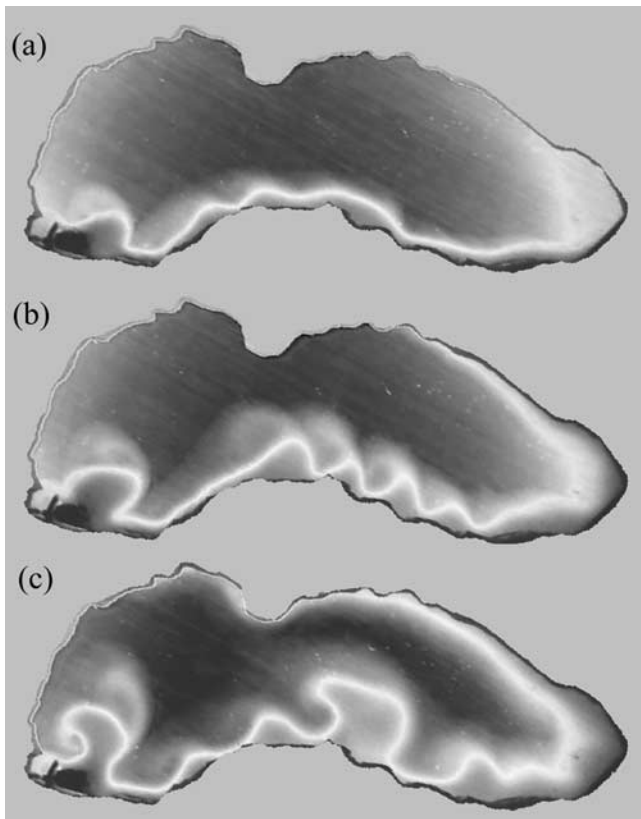


Figure 3. Sequence of video frames that shows the typical evolution of the boundary current and baroclinic instability: (a) $t = 36$, (b) 75, and (c) 143 s. Visualization is by thymol blue. Rotation rate $\Omega = 1.6 \text{ s}^{-1}$. See color version of this figure at back of this issue.

typical value of flux in our experiments was 4.5 g s^{-1} . The wedge-shaped nozzle filled with a porous material was fixed at the end of the glass tube to reduce the turbulence generated by the fluid inflow. The wedge was submerged just below the surface of the salt water in the “western” part of the sea. The fresh water flowing horizontally in the cyclonic direction, gradually forms a very thin wedge-formed layer along the periphery of the sea.

[12] At the beginning of each experiment the tank was rotated until a state of a solid body rotation was established. The supply of fresh water was then started and the following evolution of the flow was documented. In some experiments the effects of the spin-up or spin-down was simulated. For this purpose the rotation rate of the tank was varied after the circulation in the tank was established (flow completed the closed loop around the periphery of the sea). The tank was either accelerated or decelerated gradually during a time period of $5-10 T$. The rotation rate was varied typically by 10–13%.

[13] The freshwater current was made visible by dyeing the fluid with the pH indicator thymol blue. The thymol blue technique [e.g., Baker, 1966; Voropayev and Afanasyev, 1994] utilizes the color change of thymol blue indicator molecules in the presence of a local concentration of base ions. In its neutral state, the solution of thymol blue is orange-yellow in color. By adding a small quantity of base solution, the fluid obtains a dark blue color permitting a

visualization of the flow and providing a good contrast for photography. After each experiment it took only a few minutes for the diffusive chemical reaction with the acidic ambient fluid (an acid was added to the fluid in the tank) to restore the working fluid to its original yellow color. The fluid was illuminated by a diffuse light source from below. A video camera was mounted above the tank on the turntable so that video recordings were obtained in the rotating frame. The camera provides a frame rate of 30 fps and resolution 720×576 pixels.

[14] The horizontal velocity and vorticity fields in the flow were measured using a PIV technique. A description of the method and general technique is given by Fincham and Spedding [1997] and Pawlak and Armi [1998]. Small plastic pellets of a mean size of approximately $2 \times 2 \text{ mm}$ were seeded on the surface of the fluid to provide flow tracers for the PIV in addition to color contrast.

3. Experimental Results and Interpretation

[15] In what follows we will focus successively upon the evolution of the baroclinic instability in the laboratory basin as well as upon the transient processes involved in the eddy formation during spin-up or slow down of the circulation.

3.1. Baroclinic Instability

[16] A series of experiments has been performed for different values of the rotation rate of the platform. In all

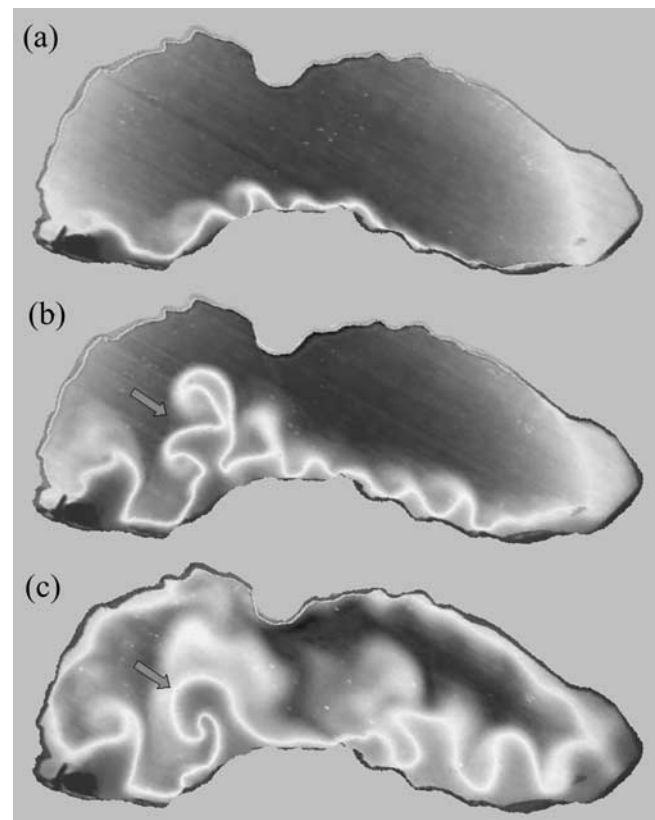


Figure 4. The same as in Figure 3 but for rotation rate $\Omega = 2.1 \text{ s}^{-1}$: (a) $t = 9$, (b) 72, and (c) 274 s. The arrows indicate the process of pairing of eddies (Figure 4b) and the formation of a big hook-shaped meander (Figure 4c). See color version of this figure at back of this issue.

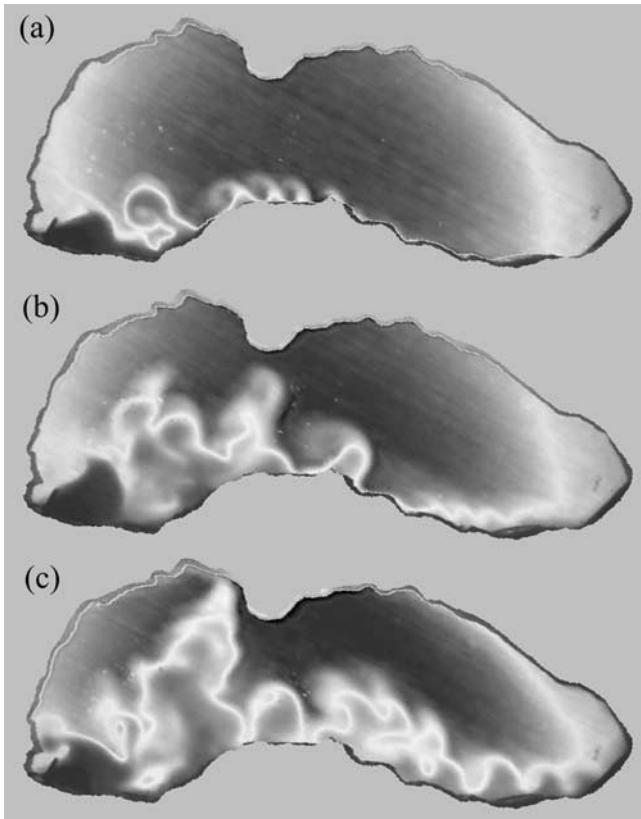


Figure 5. The same as in Figure 3 but for rotation rate $\Omega = 2.6 \text{ s}^{-1}$: (a) $t = 29$, (b) 110, and (c) 205 s. See color version of this figure at back of this issue.

of our experiments, the development of the meanders, which are typical of baroclinic instability, was observed. Immediately after the source of fresh dyed water starts, the narrow boundary current forms and propagates in a cyclonic direction following the coastline (Figures 3–5). The current becomes unstable and forms meanders which grow and separate from the current forming mesoscale eddies. Interesting events of pairing of eddies can be observed during the finite amplitude stage of evolution of the instability (Figure 4b). These events increase the wavelength of the instability twofold. However, after the eddies separate, the instability of the boundary current develops again with the same typical wavelength. The development of instability can be observed both along the “southern” shore and “northern” shore of the sea. Separated eddies eventually fill the interior of the basin forming a typical pattern of a quasi-two-dimensional turbulent flow. Striking similarities between the laboratory flow and the real flow in the Black Sea can be observed in particular in the region of the flow which corresponds to the southern coast between 30 and 33°E . A regular array of relatively small-scale meanders (Figures 4a and 5a) is often observed in satellite imagery (Figure 6). The development of large hook-shaped meanders was also documented in this region (e.g., meander M6 in Figure 8 by *Oguz and Besiktepe* [1999]). Since cyclonic vorticity is located at the left-hand side of the meander while anticyclonic vorticity is located at the right-hand side, these meanders can also be interpreted as mushroom-formed currents [e.g., *Ginzburg et al.*, 2000, Figure 1]. The labo-

ratory flow forms very similar features (Figure 4c), which gives an indication that some particular features (most likely the curvature) of the coastline are important for the formation of these flows.

[17] Considering the experiments in the sequence from small to larger rotation rates it will be observed that the wavelength of the instability decreases. Linear theory gives that the most unstable wavelength λ is proportional to the Rossby radius R_d of deformation

$$\lambda = c R_d,$$

where c is the dimensionless coefficient of the order of unity. The baroclinic Rossby radius of deformation is defined as

$$R_d = \sqrt{\frac{g\Delta\rho h}{\rho f}}$$

for the two-layer fluid. Here g is the gravitational acceleration, ρ is the density of the upper layer, $\Delta\rho$ is the density difference between the layers, h is the thickness of the upper layer and $f = 2\Omega$ is the Coriolis parameter. The well known result for a linearly stratified fluid gives for example the value of the coefficient c approximately equal to 3.9 [*Eady*, 1949] (Note, that in the case of a linearly stratified fluid characterized by the Brunt-Vaisala frequency N , the Rossby radius of deformation is $R_d = Nh/f$). The results of measurements of the wavelength for different values of rotation rate and accordingly R_d are shown in

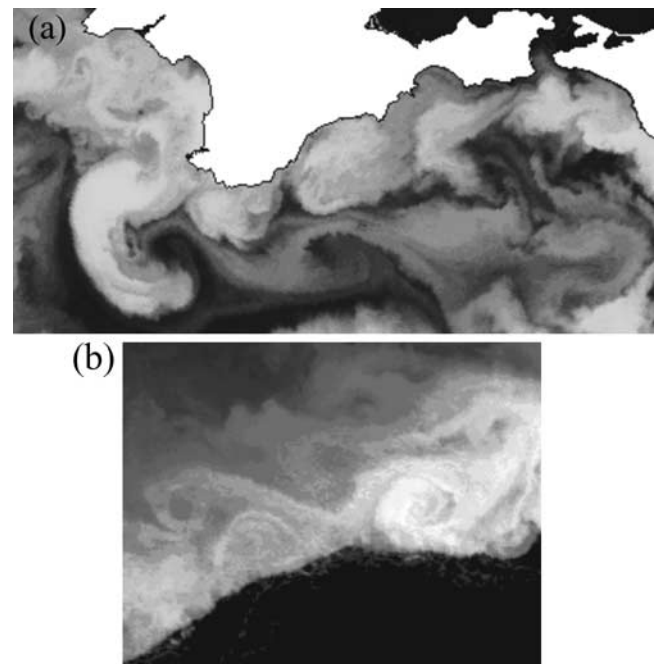


Figure 6. Typical satellite imagery (NOAA IR) of the baroclinic instabilities in different regions of the Black Sea: (a) Crimean peninsula and (b) Anatolian coast between 31° and 33°E . Images courtesy of S. V. Stanichny and D. M. Soloviev.

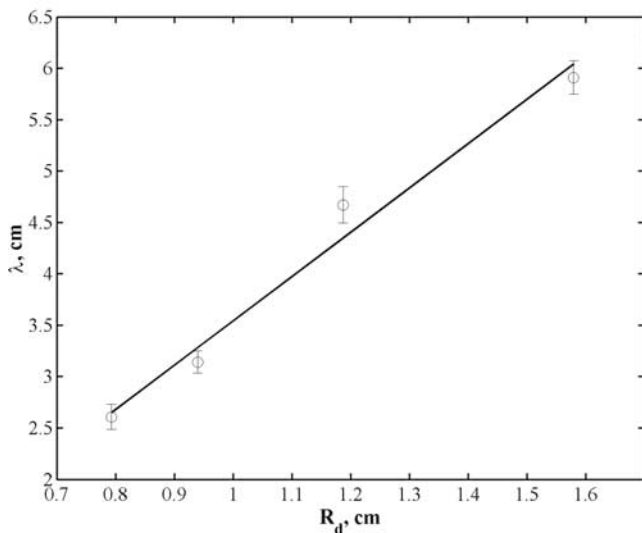


Figure 7. Variation of the wavelength of baroclinic waves with the Rossby radius of deformation. Solid line is the result of linear regression.

Figure 7. To estimate R_d the values of the thickness h of the upper layer is required. These values were estimated from the experimental images of the flows by measuring the surface area of the boundary current for different times. Since the value of the flux rate q is known one can easily estimate the vertical extent of the fresh layer by dividing the total volume of the layer for given time by its surface area. The mean value $h = 2.0 \pm 0.2$ cm was obtained in our experiments. Linear regression then gives the value of the coefficient $c = 4.3 \pm 0.4$ which is in close agreement with theory.

3.2. Control Parameters

[18] An important issue that allows us to make the quantitative comparison of the major characteristics of our laboratory flows with that in the Black Sea is the dynamical similarity. We have achieved similarity with respect to a number of control parameters. The natural scale of the baroclinic motions is represented by the Rossby radius of deformation. Taking the thickness of the boundary current $h = 100\text{--}200$ m [e.g., *Oguz and Besiktepe*, 1999] and the salinity difference $\Delta S = 3\text{‰}$ one can obtain the value of the Rossby radius for the Black Sea to be $R_d = 15\text{--}20$ km. The Rossby radius normalized by the scale of the sea $L = 300$ km, gives the dimensionless parameter $R_d/L = 0.05\text{--}0.07$ which characterizes the relative size of baroclinic motions with respect to the size of the basin. One can also interpret this parameter as a ratio of the distance covered by long baroclinic waves per one rotation of the system to the size of the basin. The appropriate value of the length scale for the laboratory basin is $L = 20$ cm while the Rossby radius varies between 0.8 and 1.6 cm. This gives $R_d/L = 0.04\text{--}0.08$ for the laboratory flows. Thus there is a complete similarity between the normalized wavelength of the instability or the scale of mesoscale vortices in the laboratory and in the Black Sea. Since the laboratory basin is a scale model of the sea, the size of the eddies with respect to the typical size of the coastal features is also similar. Direct measurements of the wave-

length of the instability in the Black Sea using satellite imagery (e.g., Figure 6) gives $\lambda = 70\text{--}80$ km. Comparing these values with the estimates for the Rossby radius of deformation one obtains $c = 4\text{--}4.5$ which is in agreement with the results of our experiments. It is interesting to note that the normalized width of the boundary current W/L was also similar to that in the Black Sea. In the laboratory $W = 2.5\text{--}5$ cm that gives $W/L = 0.13\text{--}0.25$. In the Black Sea the width of the Rim Current can be estimated to be $W = 40\text{--}80$ km which gives the similar range of $W/L = 0.13\text{--}0.27$. This fact however, is just another consequence of the similarity of the Rossby radius of deformation.

[19] The Rossby number is defined as

$$Ro = \frac{U}{fL},$$

where U is a typical velocity, gives the ratio of the vorticity of the flow to the background vorticity. Taking the typical values of the velocity in the Rim Current jet to be $U = 30\text{--}80$ cm s⁻¹ we obtain $Ro = 0.01\text{--}0.02$ for the basin-sized circulation. The speed of the boundary current for the laboratory flow was measured in the experiments with seeding particles. The speed varies between $U = 2$ cm s⁻¹ in the vicinity of the source along the “southern” shore and $U = 1$ cm s⁻¹ along the “northern” shore. Accordingly the value of the Rossby number varies in the range $Ro = 0.01\text{--}0.03$. The similarity of the values of the Rossby number in the laboratory and in the Black Sea can also be interpreted in terms of the normalized time T which gives the amount of days required for the current to complete a full circle around the sea. This timescale is proportional to $1/Ro$. The estimates give $T = 60\text{--}90$ days for both the laboratory and the Black Sea. It is also useful to introduce the local Rossby number $Ro_l = \frac{U}{f_l l}$, where l is the size of the mesoscale eddies. For the laboratory flows $l = 4\text{--}10$ cm which gives $Ro_l = 0.04\text{--}0.12$. Similar values of Ro_l were obtained for the mesoscale eddies in the Black Sea from the direct calculation of the velocity field of the surface circulation using the satellite data [*Afanasyev et al.*, 2002]. Thus the values of the Rossby number are identical for the laboratory flows and the flows in the Black Sea. Therefore the dynamical regime of vortices is similar. In particular the fact that the Rossby number is small indicates that the vortices are in to a large extent geostrophic balance.

[20] A further important dimensionless parameter is the Ekman number

$$Ek = \frac{\nu_z}{f h^2},$$

where ν_z is the vertical viscosity. This parameter characterizes the damping of eddies due to Ekman pumping. The vorticity in the eddy will decay exponentially with the characteristic timescale

$$T_E = \frac{2}{f E^{1/2}}.$$

It is difficult to estimate the Ekman number for the flows in the sea because the vertical viscosity is unknown. Using the value $\nu_z = 1$ cm² s⁻¹ [*Zatsepin et al.*, 2002] we obtain

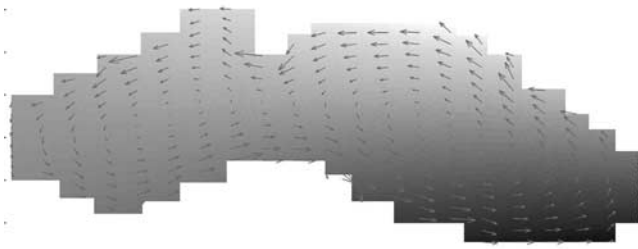


Figure 8. Irrotational velocity field (arrows) in the rotating coordinate system obtained from the numerical solution of the Laplace equation for the velocity potential. Shading represents the variation of the velocity potential.

$Ek = 10^{-4}$. In the laboratory flow, the vertical exchange of momentum is provided by molecular viscosity which gives the value of the Ekman number $Ek \approx 6 \times 10^{-4}$. The damping rate is therefore slightly higher for the laboratory flows. The timescale T_E is then approximately equal to 20 s or 5 laboratory “days”.

3.3. Transient Flows

[21] The second series of experiments we performed were directed at the investigation of transient effects occurring when the circulation in the Black Sea varies because of seasonal changes of the river input or the atmospheric forcing. Suppose the cyclonic wind forcing becomes stronger over a period of say one month. This will cause the appropriate change in the vorticity of the interior of the basin. Strictly speaking the total vertical vorticity is always zero because of the no-slip conditions at the boundaries. The cyclonic circulation in the major part of the basin therefore becomes more intense. The vorticity (velocity shear) in the relatively narrow anticyclonic boundary layer also becomes stronger. The increase of the anticyclonic wind forcing on the other hand will cause the opposite effect, the attenuation of the cyclonic circulation. It is difficult to model the wind forcing in the laboratory because such a forcing cannot be easily controlled and measured. Another way to model the relative changes of the circulation in the basin is to vary the rotation rate of the platform. The slow down of the platform will correspond then to the intensification of the cyclonic circulation while the spin-up of the platform will model the attenuation of the circulation. It is straightforward then to describe the initial motion of water in the basin using simple theory. When the boundaries of the basin start rotating with respect to the water at rest the water does not follow the rotation of the basin but it only undergoes an irrotational displacement with respect to the boundaries of the basin. In the laboratory coordinate system at rest, this displacement can be described by the velocity potential φ given by the solution of the Laplace equation for the particular basin. The free slip conditions in terms of velocity should be imposed on the boundaries performing solid body rotation. This solid body rotation is described by the relation of the form $V \propto r$, where V is the azimuthal velocity and r is the polar radius. The velocity field $\vec{U} = \nabla\varphi$ can then be transformed into the rotating coordinate system by subtracting the solid body rotation, $\vec{U}_\Omega = \vec{U} - V$. The resulting velocity field is demonstrated

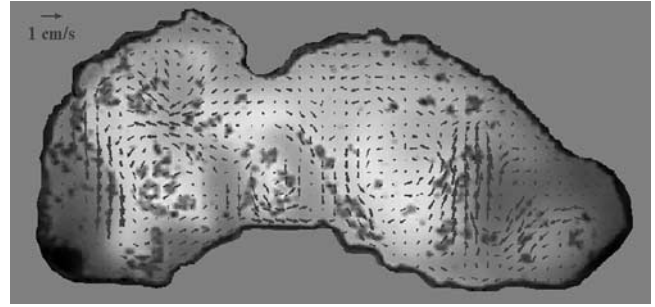


Figure 9. Experimental image of the flow with tracer particles during the slow down of the rotating platform. Rotation rate is decreased from $\Omega = 1.8$ to $\Omega = 1.6 \text{ s}^{-1}$ during 10 revolutions of the platform. Velocity field (arrows) is obtained by PIV method.

in Figure 8. This velocity field represents a simple circulation pattern with two macro gyres occurring because of the narrowing in the middle of the basin. The real flows however are subject to no-slip boundary conditions which result in formation of the boundary layer with vorticity of the opposite sign. The dynamics of the boundary layer will produce further interesting effects and in particular the separation of the boundary layer. We believe that the process of the separation of the boundary layer is responsible for the formation of the Batumi and Sevastopol eddies in the Black Sea as well as for the effect of the reversal of the circulation in the region of Batumi eddy. These processes can be illustrated in the simple experiments (Figures 9 and 10). Figure 9 demonstrates the flows resulting from the slow down of the platform from $\Omega = 1.8$ to 1.55 s^{-1} during 10 laboratory “days”. The slow down was performed when the boundary current was established all around the coastline. These conditions therefore correspond to the intensification of the circulation in the entire basin when the peripheral jet current is well formed. Further development of the flow is characterized by the formation of two typical features. The first one is the separation of the boundary current from the “northern” shore in the “eastern” part of the sea. The recirculation in the extreme eastern part of the sea is cyclonic which is opposite to that of the Batumi eddy. We believe that this circulation pattern corresponds to the fall circulation in the Black Sea according to the geostrophic velocity maps deduced from the TOPEX/

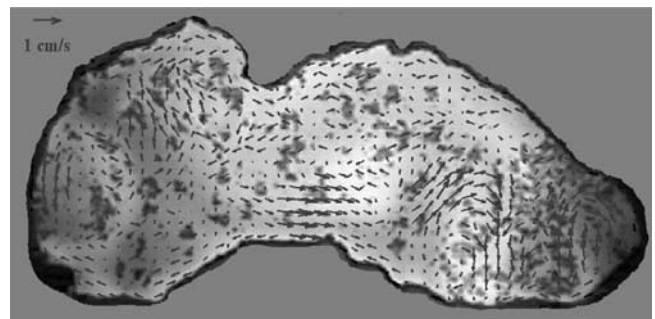


Figure 10. The same as in Figure 9 but when the source of fresh water was switched off before the slow down of the platform.

Poseidon altimeter data [see Korotaev *et al.*, 2001, Figure 9d; Korotaev *et al.*, 2003, Figure 6F]. It is interesting that in the same picture by Korotaev *et al.* [2001] the Sevastopol eddy is most intense compared to other seasons. The anticyclonic eddy can be also observed in the region where the boundary current separates from the tip of the Crimean peninsula in the laboratory flow. Figure 10 demonstrates a typical pattern of the circulation occurring in a similar experiment with the slow down of the platform. In contrast to the previous experiment however the boundary current was initially very weak (the source was switched off). In this case the separation occurs from the “southern” shore and the resulting recirculation corresponds to that in the Batumi eddy [see Korotaev *et al.*, 2001, Figure 9b]. Thus there are obvious similarities between certain features of the circulation in the Black Sea and in the laboratory caused by the separation of the boundary current. These features are transient in a sense that they occur because of the variation of the global circulation in the basin.

4. Conclusions

[22] The laboratory experiments described herein provide clear evidence that baroclinic instability is an important dynamical feature of the circulation in the Black Sea. The results demonstrate the occurrence of the cyclonic peripheral jet current, which develops according to the general theory described by the thermal wind equations. This main current system then becomes unstable and forms typical meanders and mesoscale eddies which eventually fill the interior of the basin forming a typical pattern of quasi-two-dimensional turbulent flow. It is interesting to consider a mechanism of intensification or attenuation of the global circulation in the Black Sea. It is known that variations in the intensity of the circulation occur because of variations of the freshwater input by rivers and the variation of wind forcing. The transfer of vertical vorticity to the interior of the basin occurs differently in these two cases. When the intensity of the boundary current varies the interior of the basin is not immediately affected. The perturbation to the circulation is localized in the narrow peripheral region of the width of the order of the Rossby radius of deformation. Baroclinic instability, however, provides an effective mechanism of transfer of cyclonic vorticity into the interior of the basin. Cyclonic eddies form at the left-hand side of the unstable boundary current, while anticyclonic eddies form at the right-hand side near the boundary. The cyclonic eddies then grow and penetrate the interior, contributing to its overall cyclonic circulation. Anticyclonic vorticity on the other hand remains at the boundary and forms the boundary layer. We believe that the formation of the anticyclonic boundary layer is due to this mechanism provided by baroclinic instability rather than because of the no-slip boundary condition and horizontal transfer of vorticity by viscosity. The coefficient of the turbulent horizontal exchange of momentum however can be introduced here to account for this effect. This is widely used in numerical models that are often too coarse to resolve the small-scale instability. In contrast to this indirect transfer of vorticity by cyclonic eddies, the wind forcing transfers vorticity directly to the entire basin. To simulate this effect to some extent we varied the rotation rate of the platform, thus varying the relative

vorticity of the fluid. Although there are certain similarities between the transient eddies in the Black Sea and in the laboratory flows, the mechanism of generation of anticyclonic vorticity in the boundary layer due to the no-slip lateral boundary condition and the transfer of vorticity by molecular viscosity can be important for the laboratory flows. Thus it is difficult to provide any quantitative comparison between the resulting separation of the boundary layer in our experiments where rotation rate was varied and the separation of the Rim current in the Black Sea. Further experiments that can clarify this mechanism are clearly required and are currently under way.

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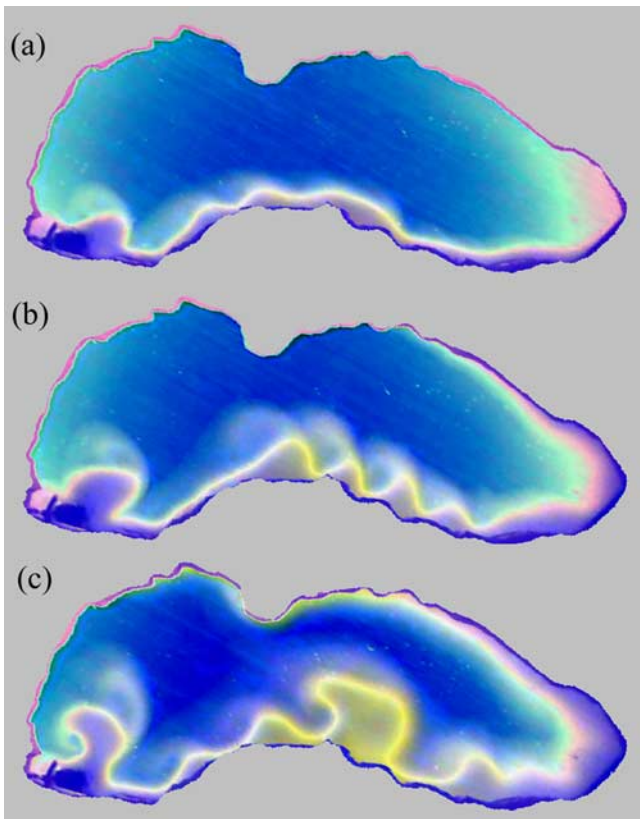


Figure 3. Sequence of video frames that shows the typical evolution of the boundary current and baroclinic instability: (a) $t = 36$, (b) 75, and (c) 143 s. Visualization is by thymol blue. Rotation rate $\Omega = 1.6 \text{ s}^{-1}$.

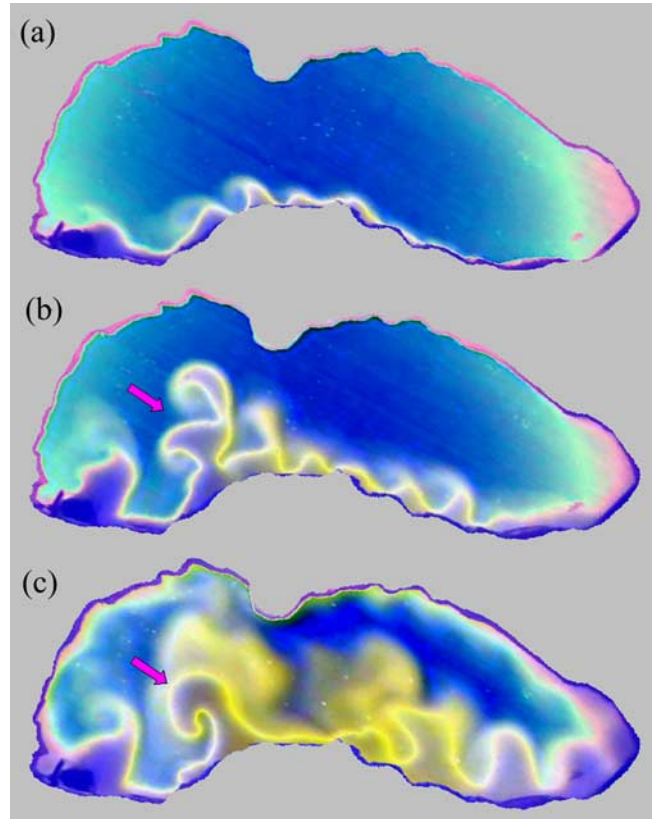


Figure 4. The same as in Figure 3 but for rotation rate $\Omega = 2.1 \text{ s}^{-1}$: (a) $t = 9$, (b) 72, and (c) 274 s. The arrows indicate the process of pairing of eddies (Figure 4b) and the formation of a big hook-shaped meander (Figure 4c).

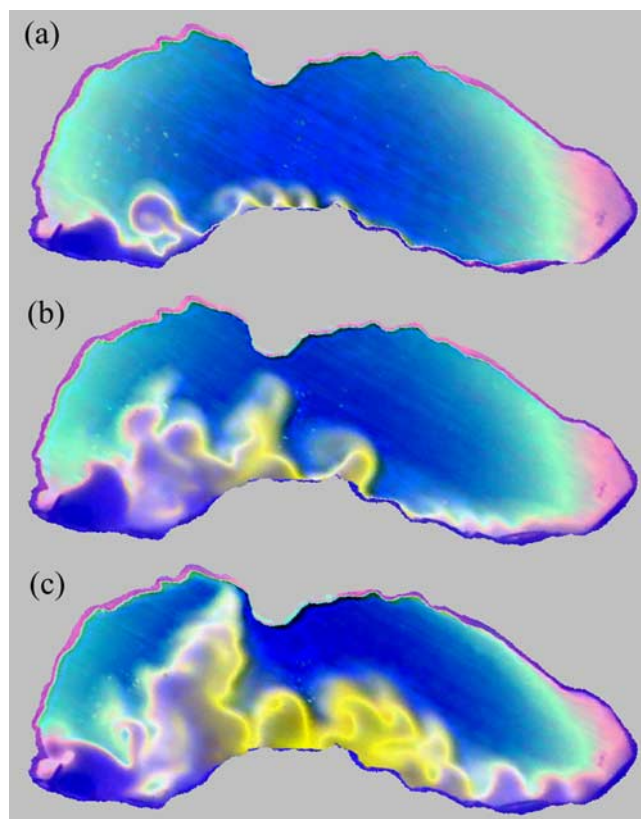


Figure 5. The same as in Figure 3 but for rotation rate $\Omega = 2.6 \text{ s}^{-1}$: (a) $t = 29$, (b) 110, and (c) 205 s.