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A Laboratory Study of Formation of "The Warm Core" in the East Sea of Korea

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In a laboratory model the response of the boundary layer flow over topography is studied in a rotating sliced cylinder by employing the source-sink analogy with Ekman layer dynamics. The boundary layer flow is produced by two different fluid. In the first experiment homogeneous fluid is used both for the source and the working fluid of the container. In the second experiment a denser fluid is used for the source with the same working fluid. For the homogeneous western boundary layer flow both the northward and the southward flow were affected by the topography(ridge) to produce a cyclonic motion near the ridge. When woughward moving heavy boundary flow of slower speed and the northward moving faster flow were present at the same time, the splitting of southward flow and the separating of the northward flow were observed with a cyclonic motion at the ridge. The most important factor that influence production of the cyclonic motion has been turned out to be the presence of the topography in the western boundary layer. In particular the role of the southward moving heavy flow over the interior flow pattern was found to be very significant.

1. Introduction

The existence of a warm-water sector in the vicinity of the Ulreung-Do can be easily identified from the horizontal distributions of water temperature at the depth of 150*m*(Na, 1988). This warm-water sector (following the shape of its vertical extent it is called "the warm core"), however, does not always exist over that particular site. For example the monthly distribution of the water temperature at the depth of 150*m* of the year 1979 (Fig. 1) shows that the warm core is not located at fixed position.

The site of the warm core may be due to the convergence of warm surface water driven by the wind (Na, 1988) or due to the geostrophic adjustment of the East Korea Warm Current(EKWC) as it separates from the coast. But the latter explanation may not be reasonable since the warm core existed during the month when there was no branching of the Tsushima current or no EKWC was present (Fig. 2). Another possible candidate responsible for the formation of the warm core could be the lower layer motion or the North Korea current flowing southward as well as its interaction with the EKWC. If we regard the East Sea as two-layered ocean, then even weaker motion in the lower layer several times thicker than the upper layer could drive the shallow upper-layer in motions via interfacial stresses. This postulation does not exclude the case of the lower layer motion driven by the upper layer. However, our present interest lies in the formation of the warm core. Several numerical models on the circulation in the East Sea have not revealed any types of the temperature fields having warm core in the vicinity of the Ulreung-Do (Yoon, 1982, 83, Sekine, 1987). They were rather upper-layer driven flows in terms of influx and outflux at the boundaries. Laboratory simulations of the circulation in a basin like the East Sea (the Sea of Japan) may require careful application of relevant geophysical parameters into the experimental apparatus. For example, we have to decide whether β-effect or topographic effect is important in vorticity dynamics of the upper-layer motions in the two-layer ocean. For a weaker low-layer motion, it could be generated by either the wind-stress exerted on the northern half of the East sea (low-layer water) or the thermohaline effect, the motion will feel the bottom topography such that the topographical influence will appear in the upper-layer motion due to interfacial stress. If we have a cyclonic motion that is induced by either the topographic effect or the North Korea Current flowing southward, the upper-layer may adjust itself such a way that the interface must be lowered to increase the height of the water column, in other wards, to conserve potential vorticity and consequently to form a warm core.

By choosing appropriate parameters, a laboratory analogy with a gross feature of the motions in the East sea could be established. Therefore, the purpose of this paper is to examine the role of the external parameters such as wind-stress, lower layer motion and the bottom topography to the mechanism of the warm core formation in terms of the flow pattern of the upper layer motion. Particulary we have emphasized the effects of the denser boundary flow over the ridge on the upper layer motion. Unfortunately the mechanism or the dynamics

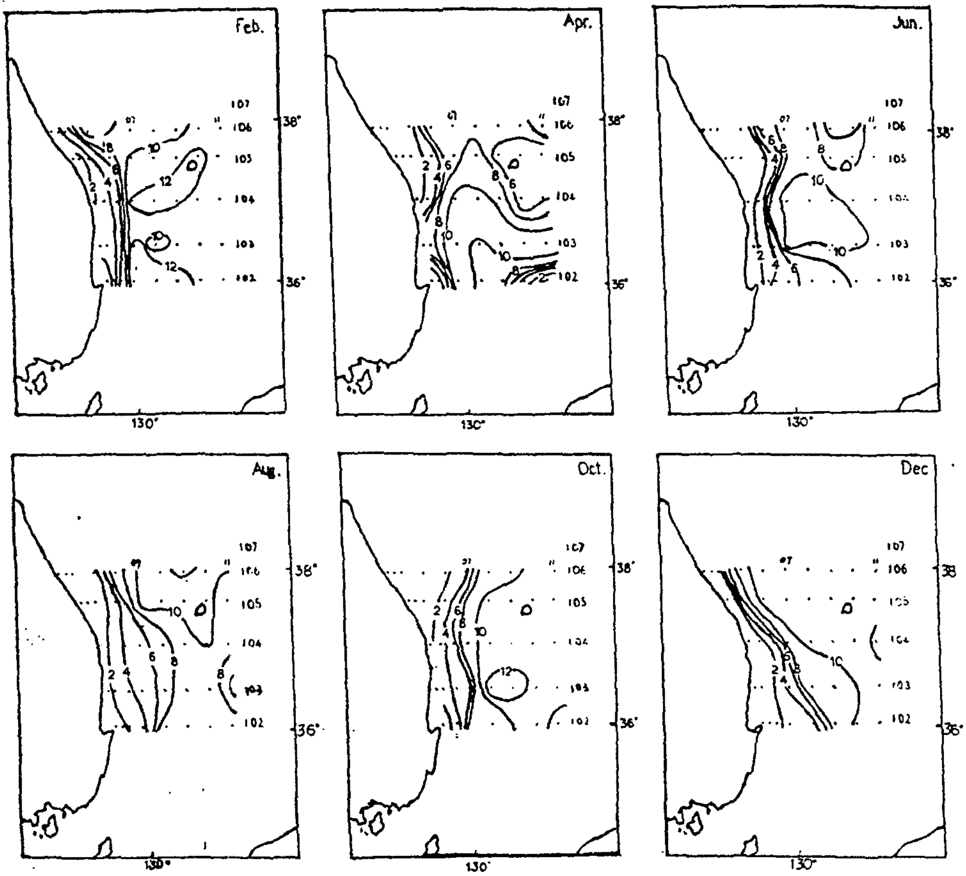
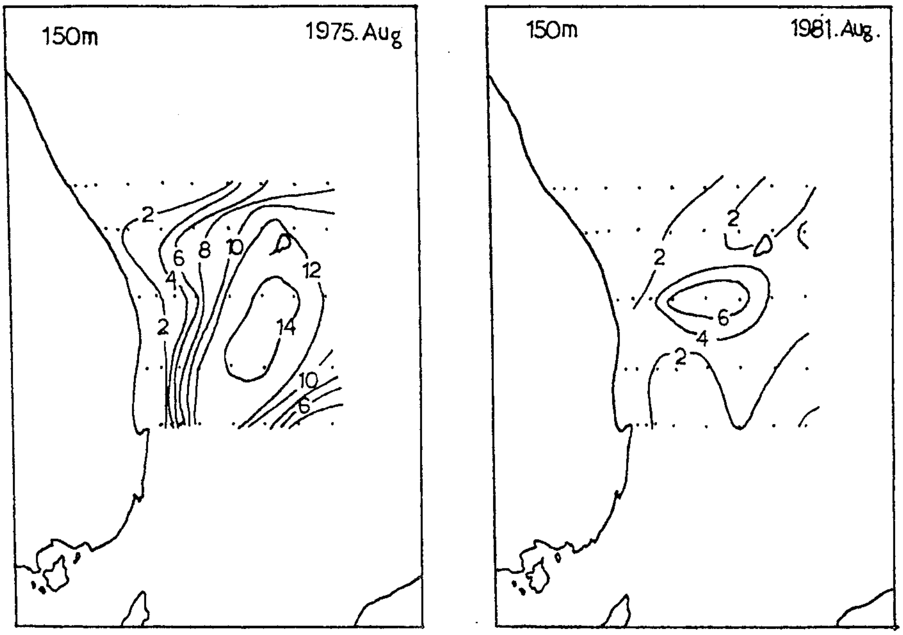


Fig. 1. Monthly distribution of the water temperature at the depth of 150*m* of the year 1979.



(a) (b)

Fig. 2. Temperature field at 150*m* in august 1975(a) and 1981(b). (a) indicates the existence of the warm core without the presence of the EKWC.

of the North Korea Current is not available except rough estimates of its path along the western boundary of the East sea. Therefore we assume that the North Korea Current flows southward feeling the bottom topography. In this case the existence of the topographic feature such as the protuberance may affect its path (Fig. 3). For this purpose, laboratory experiments have been done by using the rotating cylindrical container with the topography such as the ridge.

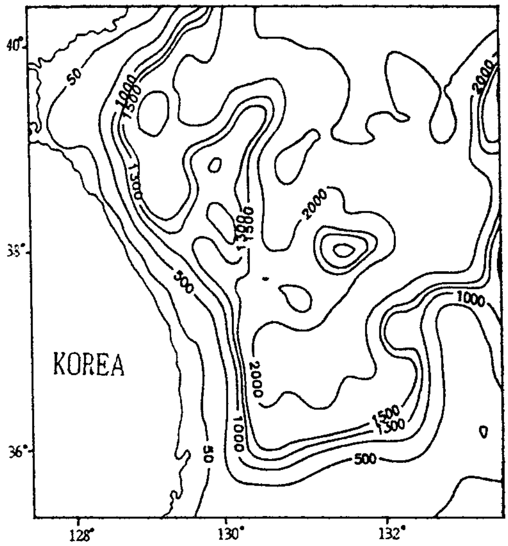


Fig. 3. Bottom topography of the East Sea showing the protuberance around the Wonsan bay.

2. Vorticity equation of source-sink flow in a rotating container

The Ekman layer suction or pumping due to the horizontal variation of the wind stress at the sea surface can be simulated by a suitable source-sink flow in a laboratory model (Kuo and Veronis, 1971). For the source flow which is analogous to the cyclonic wind field at the surface, fluid can be injected through the rim boundary at the sloping bottom (β-effect) of the cylindrical container. The source fluid will smear into the interior of the working fluid via sidewall boundary layers and it will push the water column upward thus produces divergent Ekman layer at the surface. In this way we can produce a boundary layer flow(or western boundary layer flow) that interacts with topography and lower-layer motion. If we make a topography over the sloping bottom, then it will show a controlling influence on the flow pattern. To examine all the imposed effects on the flow pattern we should have at least the governing vorticity equation for the interior flow in the cylindrical container (Fig. 4) to determine the magnitudes of the external parameters.

In a rotating cylindrical coordinate (r, θ, z), the vertical velocities at the top and the bottom boundaries can be easily obtained by the kinematic boundary conditions and so-called the Ekman layer compatibility condition. If we define E $[=\frac{\nu}{2\Omega H^2}]$ as the Ekman number and Ro $[=\frac{U}{2\Omega L}]$ as the Rossby number with ν is the kinematic viscosity, Ω is the uniform angular velocity and H and L are the depth and the radius of the cylinder respectively, the quasi-geostrophic vorticity equation is

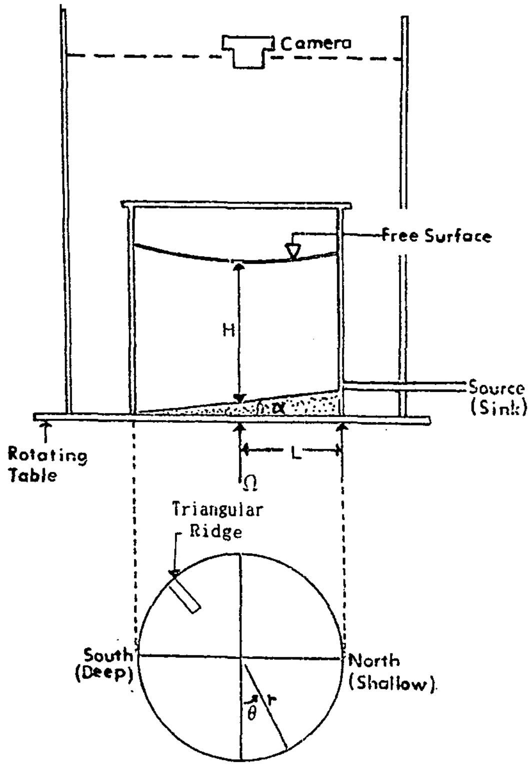


Fig. 4. Geometary for the cylindrical tank with sliced bottom.

$$\mathrm{Ro}\frac{d}{dt}(\nabla^2 P) = -\frac{\partial P}{\partial \theta} + \frac{2\xi}{F} - \frac{E^{1/2}}{2F}\nabla^2 P - \left(\frac{\partial P}{\partial r}\sin\theta - \frac{1}{r}\cdot\frac{\partial P}{\partial \theta}\cos\theta\right)\frac{\tan\alpha}{2F} \qquad (1)$$

where

$$\frac{d}{dt} = \frac{\partial}{\partial t} - \frac{1}{2r}\cdot\frac{\partial P}{\partial \theta}\frac{\partial}{\partial r} + \frac{1}{2r}\cdot\frac{\partial P}{\partial r}\cdot\frac{\partial}{\partial \theta},$$

$$\nabla^2 = \frac{1}{r}\frac{\partial}{\partial r}r\frac{\partial}{\partial r} + \frac{1}{r^2}\cdot\frac{\partial^2}{\partial \theta^2},$$

$F=\frac{\Omega^2 L}{g}$ Froude number, and tanα is the slope of the bottom. The time rate of change of the surface elevation due to the influx from the source is $\xi[=\frac{\partial \xi}{\partial t}]$.

We have assumed the geostrophic interior motions with

$$2v = \frac{\partial P}{\partial r} \text{ and } -2u = \frac{1}{r}\frac{\partial P}{\partial \theta} \qquad (2)$$

In equation(1), the linearized free surface condition and the source fluid of the same density as the working fluid have been assumed Moreover when the topography h(r, θ) is introduced over the sloping bottom, as additional term must be included in the RHS of the equation(1) as

$$\left[-\frac{1}{r}\frac{\partial P}{\partial \theta}\frac{\partial}{\partial r} + \frac{1}{\partial r}\frac{\partial P}{\partial r}\frac{\partial}{\partial \theta}\right]h(r,\theta) \qquad (3)$$

where

$$\varepsilon = \frac{h}{H} << 1$$

From the vorticity equation it is shown that the sign of ξ clearly determines the Ekman layer dynamics via suction or pumping.

Here we have to examine the Rossby number in terms of the influx-induced velocity field and the new Ro is given by

$$R_O = \frac{\xi}{2\Omega L E^{1/2}}$$

and R_O remains small as far as the order of the magnitude of ξ is close to that of $E^{1/2}$ or $O(\xi) \sim O(E^{1/2})$.

To keep both the β-effect and the topographic effect comparable in magnitude we have

$$O\left[\frac{\tan\alpha}{F}\right] \sim O(\varepsilon)$$

Eventually we keep the magnitudes of the terms as $O(\xi) \sim O(E^{1/2}) \sim O(\tan\alpha) \sim O(F)$ in order to reflect the overall effects caused by those external forcing. By setting the magnitudes of each terms in comparable size except R_O which is always kept small the non-linearity can be excluded.

3. Experimental Apparatus and Methods

A cylindrical shape of the plexiglass tank with inner radius of 9.3*cm* was placed on a horizontal turntable with its vertical axis coincident with the rotating axis(Fig. 5.). To avoid any thermal fluctuations due to the changes of the room temperature, the tank was placed within the square tank filled with a constant temperature fluid(Fig. 6). A metal turntable rotated counter-clockwise, and the rotation rate was changed by a frequency-controlled a.c. motor. The bottom of the tank has a sliced-shape to simulate the β-effect and also a topography that is located on top of the sliced bottom is introduced near the western boundary to examine the response of the flow. For flow visualization a pH-indicator technique described by Baker(1966) was used for both the working fluid within the tank and the external fluid that is pumped into the tank as the source flow. A triple-tube(150*ml*) syringe pump was used for injecting or withdrawl fluid into or from the tank. The pump mechanism consists of a threaded drive block travelling along a rotating screw shaft connected to a d.c. motor of which speed is controlled by a variable d.c. power supply. The injection and the withdrawl of the fluid could be achieved by changing the polarity of the d.c. power supply, i.e., by the reversal of the direction of rotation of the motor. This method was used to simulate a different wind forcing(or change of sign of the curl of the wind stress). Once the external fluid is injected into the tank the fluid flows in through the narrow gap along the rim of the circular bottom. The size of gap is about one tenth of one milimeter which is much less than the thickness of the sidewall Ekman layer. In case of injecting a denser fluid into the tank to simulate the source-driven and the lower-layer driven motion a point source located at the northern edge was used. A 35*mm* camera as well as a VCR was mounted on a stationary frame vertically above the tank with a stop watch placed next to the tank. In this way photographs could be taken after the dye lines produced and swept off the wire at any time to compute the observed velocity of the flow. In this experiment our main concern was the observation of the 'western' boundary layer flow that is influenced by (1)wind-driven boundary flow (2)bottom topography (3)denser low-layer motion (4)combined effects of two or three. All theses effects are introduced after we achieved the working fluid spun up.

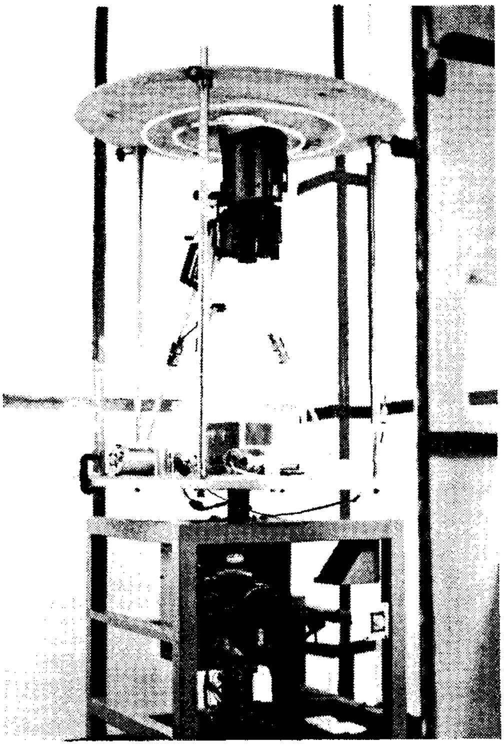


Fig. 5. Experiment Apparatus.

4. Experimental Results and Discussion

4.1. Boundary layer flow over topography(homogeneous fluid)

The "Western boundary" layer flow could be produced easily in a cylinder with the sliced bottom by introducing a source(southward moving western boundary layer flow) and a sink(northward moving western boundary layer flow). An arbitary shape of barrier(topography) was placed within the region where the boundary layer flow existed. We have employed two different ridges. One was a triangular ridge(4.5*cm* long, 0.7*cm* wide,

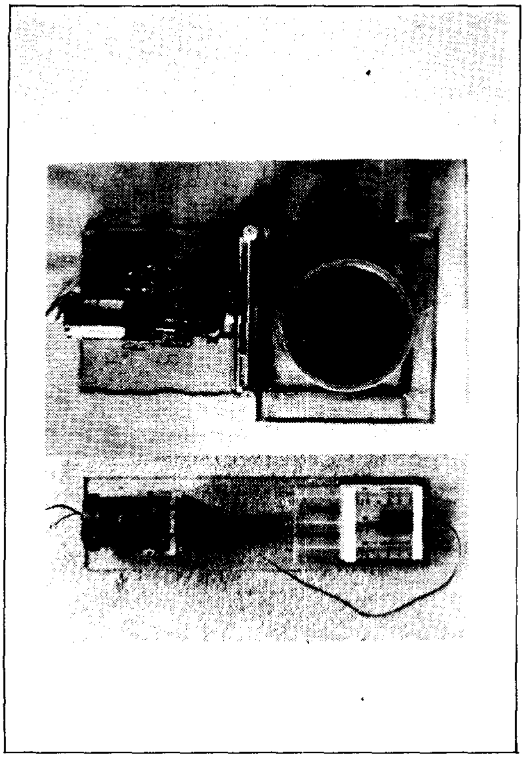


Fig. 6. Theremaly insulated cylindrical tank and the sylinge pump.

0.7*cm* high) and a circular ridge of 3*cm* in diameter, 0.7*cm* in height. Both ridges were placed at the western boundary about 45 degree south-west from the north pole. Fig. 7. shows the flow pattern over the circular ridge for both the source and the sink driven boundary layer flows. In both cases the ridge is blocking the flow such that roughly over the ridge a cyclonic(sink-driven) and a anticyclonic (source-driven) flows were generated. In fact this type of quasi-geostrophic flow over topography has been the subject of theoretical discussions(Hart, 1977) in that the zonal influence produces anticyclonic vortices over rise and cyclonic vortices over depression. In particular the northward moving boundary flow was forced to leave the boundary and produce a cyclonic flow near the ridge. Both the source and the sink-driven flow show the Sverdrup(1947) balance in β-plane, that is, a uniform northward(southward) flow in the interior. When the triangular ridge was introduced the overall flow patterns have not been changed compared to those of the circular ridge(Fig. 8). However, in this case besides the occurance of two vortices (two cylonic vortices for source, two anticyclonic vortices for sink) a small scale cyclonic motion occurs over inner edge(toward interior) of the ridge for the northward flowing boundary current. The behavior of the flow over the topography can ben easily explained in terms of the conservation of the potential vorticity. The presence of the protuberance results in decrease of the moving column of the water and accordingly it will decrease the relative vorticity in such a way that the flow tends to move anticyclonically. So far we have observed the behavior of the boundary flow when it is blocked by the topography in homogeneous model. It must be emphasized that the topographical effect on the boundary flow could produced a cyclonic motion around the ridge. In a two-layer model with no free surface the change of vorticity in the upper-layer is proportional to the changes in interface height (Hart, 1972). In other words, where the motion is cyclonic the interface is lowered and it may be very favorable for formation of the warm core.

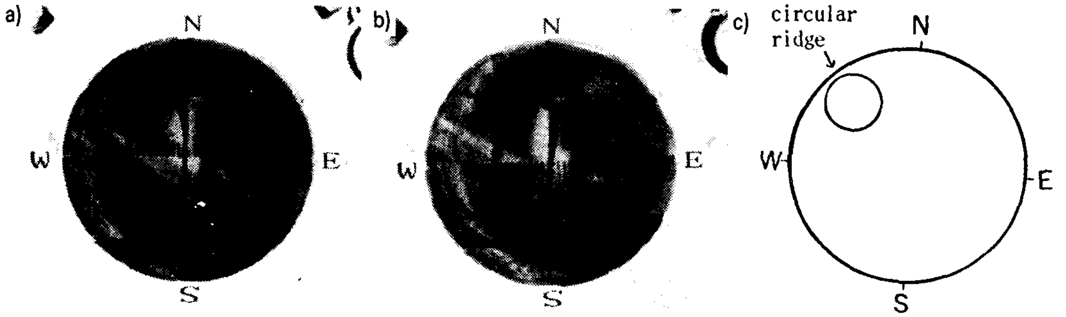


Fig. 7. Source-sink flow over a circular ridge. a) source flow b) sink flow c) uniform sink(source) around the rim at the bottom. Ro=1.2×10^{-3}.

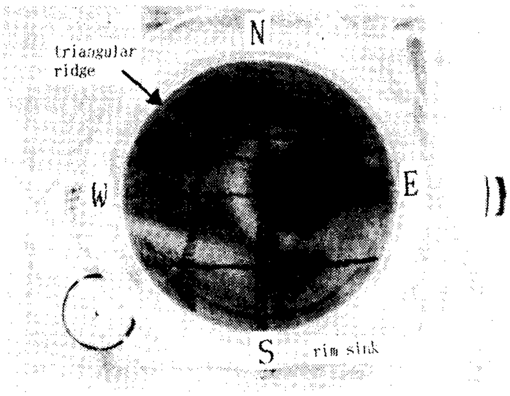


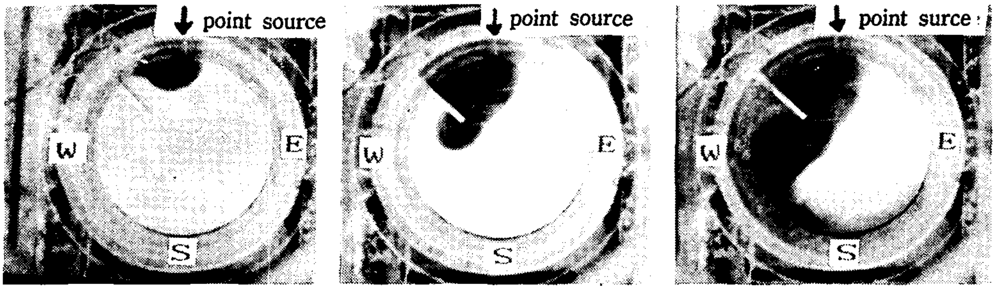
Fig. 8. Sink-driven boundary layer flow over a triangular ridge. Ro=1.2×10^{-3}.

4.2. Boundary layer flow over topography (a denser source driven flow)

From a point source of denser fluid [$\frac{\Delta\rho}{\rho}\sim O(10^{-2})$] that was located at the north pole(the shallowest point in the tank) the colored fluid was pumped into the interior(Fig. 9). The source flow was deflected to the right due to the Coriolis effect and moved along the western boundary until it was blocked by the triangular ridge. Then it swung around and kept its path along the boundary. From the observation the thickness of the colored-dense fluid was less than 1*mm* all over the bottom. The corresponding bottom Ekman-layer thickness was calculated to be about 1*mm*. When the denser fluid was introduced, the interior flow pattern was close to the one shown in the Fig. 10. In this figure the thymol blue solution of higher density was pumped into for visualization of the upper-layer motion. The pattern is very similar to the one driven by source in homogeneous fluid. Therefore, as far as the upper-layer motion is concerned the denser source does not produce any appreciable changes in the Sverdrup balance except in the southern interior where horizontal motions are weak. Over the interior edge of the topography a strong shear in horizontal velocity is clearly shown(Fig. 10) and this produces a cyclonic vortice that has been appeared in case of the homogeneous flow(Fig. 8). It should also be noted that the Fig. 10 was taken long after the denser source was introduced, i.e., about 10 minuits after the initial pumping. For comparison, the last picture of the Fig. 9 is corresponding to the Fig. 10.

4.3. Source(denser) and Sink flow over topography

The denser source fluid was pumped into the interior while the lighter fluid was withdrawn from the tank. The pumping rate was 0.03*ml*/sec and the rate of withdrawl was 0.1*ml*/sec such that the overall flow pattern resembled that of sink-driven motion(Fig. 11). Over the eastern half of the tank southward uniform flow of the Sverdrup balance is observed. However the western boundary layer flow has been changed dramatically. A large votice occupies the interior and two cyclonic vortices appear in north and south of the ridge. Small anticyclonic vortice exists south of the ridge. In spite of the sink-driven motion, the northward moving western boundary layer flow can not exist within the boundary. Rather it separates from the western boundary and flows into the interior. It is also interesting to observe the splitting of the southward flow over the ridge such that the one flows northward to form an anticyclonic vortice and the other southward flows to meet with the northward moving boundary flow. It is also observed that, like previous two cases, at the inner edge of the ridge a strong shear in velocity eventually produced a cyclonic motion. In this experiment the effects of the denser source flow of weaker strengh on the western boundary layer turns out to be quite important in determination of the path of the flow. Unfortunately the present denser source flow does not simulate so called stratified model. However, as far as the stratification is not so strong to choke off the Ekman suction(pumping) velocity, the physical process which causes the zonal correction is significantly affected by the even weak source-driven motion. The most significant observation is that there always exists a cyclonic motion near the inner edge of the ridge regardless of changes in external forces. This type of cyclonic motion eventually provides the favorable condition for the formation of warm core by lowering the interface over that particular site.



Time 1 Time 2 Time 3

Fig. 9. A denser source flow over triangular ridge.

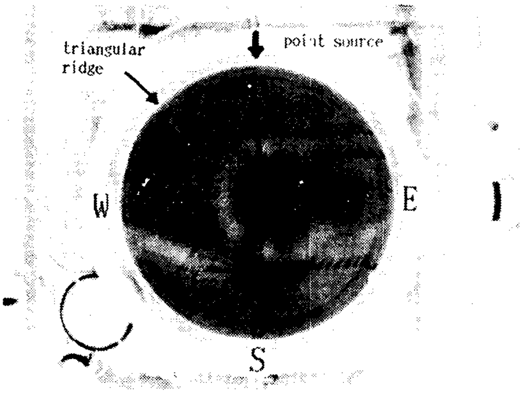


Fig. 10. Flow pattern of the interior motion with denser source.

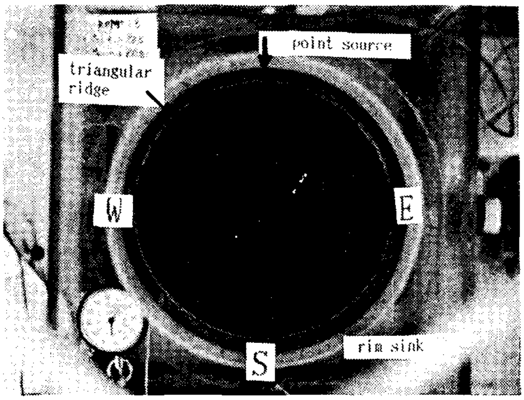


Fig. 11. Source-sink driven flow over triangular ridge.

5. Conclusion

Laboratory model of the response of the boundary layer flow over topography is studied. The boundary layer flow was produced in a rotating sliced cylinder by employing the source-sink analogy with the Ekman suction(pumping). The topographical effect on the homogeneous boundary layer flow was such that over the interior part of the ridge there always exists a cyclonic motion that may play important role in the formation of the warm core in two layer ocean. When heavier fluid is pumped in the creeping flow within the bottom Ekman layer produces the Sverdrup type interior motion and it also produces a cyclonic motion over the same site as in the case of the homogeneous flow. In order to study the role of the southward flow of heavy water and the interaction with the northward moving boundary flow, a denser source with weaker flux rate compared to the uniform sinking flux rate was introduced. The interior motion still reflected the Sverdrup balance with some modification in flow path, while the western boundary flow was forced to leave and thus separated before it reached western wall. The southward moving western boundary flow was observed together with the cyclonic motion at the inner edge of the ridge. Therefore the topographical effects and the presence of the southward boundary layer flow affect the path of the northward western boundary layer flow in such a way that over the interior site close to the inner edge of the ridge a cyclonic motion occurs. This cyclonic motion could be interpreted as a favorable mean of the formation of the warm core by lowering the interface of the two layer ocean. For the verification two-layer model with lower layer driven motion should be examined in a laboratory model.

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