OCEANOLOGY, English Translation, VOL. 34, NO. 1, AUGUST 1994
Russian Edition: JANUARY – FEBRUARY 1994

Deep convection in the eastern basin of the Mediterranean Sea

I. F. Gertman

Sevastopol' Department of the State Oceanographic Institute

I. M. Ovchinnikov

The Southern Department of P. P. Shirshov Institute of Oceanology, Russian Academy of Sciences, Gelendzhik

Yu. I. Popov

Odessa Department of the State Oceanographic Institute

Abstract. In February 1990, R/V *Yakov Gakkel'* made detailed observations in the Rhodos cyclonic gyre (RCG). A favorable combination of wintertime climatic and oceanographic conditions allowed the process of deep convection in "the violent mixing phase" to be observed and investigated for the first time. Free convection developed down to the 1000-m depth, while the penetrative convection was traced down to 2000 m and deeper. These observations decisively resolve the problem of participation of the Levantine Basin surface waters in the partial production of the deep water mass of the eastern basin of the Mediterranean Sea, a possibility categorically rejected by the majority of oceanographers. Deep, vigorous wintertime convection in the RCG center destroys the geostrophic balance of forces, and results in the weakening of the RCG and in the breakdown of the cyclonic circulation into several mesoscale vortices with varying direction of motion. The RCG weakens substantially for 2–3 spring months due to active convection, and recovers again only during summer.

Environmental problems of the Mediterranean Sea are in the mainstream of modern studies of this inland basin. Of special importance is the problem of vertical exchange of water masses, particularly the process of deep convection that develops actively in winter across extensive northern shelves and in the centers of cyclonic gyres located along the Mediterranean branch of the polar front. Under these conditions, the winter convection ventilates deep waters, removing many pollutants that tend to accumulate in this vast water mass.

To date, the processes of deep convection have been studied sufficiently well in the north of the western basin of the Mediterranean Sea [*MEDOC Group*, 1970, and many others]; they have been revealed also in the Adriatic [*Ovchinnikov et al.*, 1985; *Zore-Armanda*, 1974]. However, up to the present, these processes remained obscure in the Aegean Sea and in the eastern basin (the Levantine Sea). Sources of the deep water production in the Aegean Sea [*Gertman and Popov*, 1989; *Ovchinnikov et al.*, 1990; *Georgopoulos et al.*, 1988; *Gertman et al.*, 1990a] and in the Levantine Sea [*Gertman et al.*, 1987; *Ovchinnikov et al.*, 1990; *Gertman et al.*, 1990b] were discovered and explored only in the late 1980s. This work is devoted to a detailed investigation of the characteristics of deep convection in the Levantine Sea, because the possibility of development of such a process here surprised many oceanographers.

Since Nielsen's time [*Nielsen*, 1912] and up to the mid-1980s it was commonly believed that the winter cooling in the Levantine Sea is not sufficient for the densification and sinking of surface waters under the high-salinity intermediate layer, and hence the surface waters do not participate here in the deep water mass formation. Accordingly, the opinion prevailed in the literature that the deep waters of this basin are of advective origin exclusively, and consist mainly of deep Adriatic waters with an admixture of Cretan deep water.

Detailed studies of the Mediterranean Sea circulation [*Moskalenko and Ovchinnikov*, 1991; *Ovchinnikov*, 1966; *Ovchinnikov et al.*, 1976] showed that in the Levantine Sea, amidst multiple cyclonic and anticyclonic vortices, the most conspicuous is a strong quasisteady gyre [*Ovchinnikov et al.*, 1976] in the northwestern part of the sea, which we named the Rhodos gyre. In summer this gyre is affected by relatively strong local monsoon-

0001–4370/95/3401–0004$18.00/1

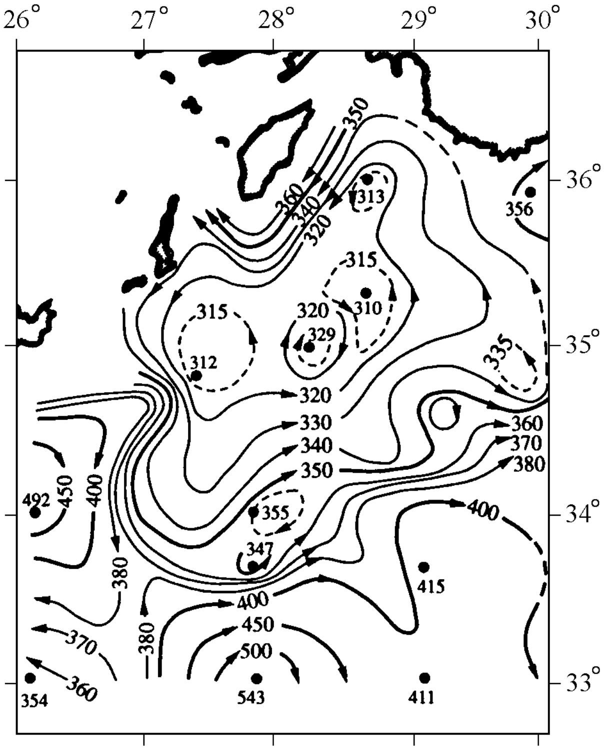


Figure 1. Geostrophic circulation 0/500 dB in the Rhodos survey area based on data of R/V *Yakov Gakkel'* Cruise 36, November 9–26, 1990.

type (etesian) winds from the north, while in winter the gyre is affected by the polar air that invades through the Aegean Sea behind the cyclones that move along the Mediterranean branch of the polar front. Therefore the wind-driven Rhodos Cyclonic Gyre (RCG) is well developed in all seasons, with the surface water in its center always 1.5–2.0 °C colder than the ambient water [*Ovchinnikov et al.*, 1976]. Besides the cooling influence of the atmosphere, the lowered water temperature in the gyre's center is accounted for by the intense upwelling of colder, deeper waters. Therefore the thermal water stratification here is always weakened, whereas the salinity, which decreases with depth, always tends to destabilize the hydrological structure.

Based on these premises, dedicated field studies of the Levantine Sea conducted in March 1977 and February 1982 [*Ovchinnikov*, 1984] showed that the high salinity intermediate layer does not exist in the RCG center. Nonetheless, the winter convection here was still hindered by the weakened thermocline and developed only to the 150–200-m depth. Such a weakly developed convection in both cases could be explained by insufficient cooling (14.72 and 14.94 °C respectively) and densification in the gyre's center. Therefore the local convective processes developed here are of "the preconditioning phase" type [*MEDOC Group*, 1970], being only one of several sources of the Levantine Intermediate Waters (LIW). These waters, which were newly formed in the gyre's center, descended along the pycnocline's dome, acquiring the LIW signatures only at its periphery. Hence, the highly saline intermediate layer clearly cannot exist in the RCG center due to its dynamic peculiarities; therefore there are no obstacles here to the fully developed, deep wintertime convection, as previously believed.

Although the first attempts to find deep convection failed, calculations using the Ivanov [1981] model of the non-stationary thermohaline structure of the upper layer, relative to the winter conditions in the Rhodos gyre [*Ovchinnikov and Plakhin*, 1984], have shown that stronger cooling of the surface waters (down to 14 °C and lower) results in the deep convective mixing in the gyre's center extended to great depths, thus participating in the formation of Levantine Sea Deep Water. Having analyzed the RCG water structure, Anati [1984] pointed out the possibility of deep water production in its center. All these experimental and theoretical premises indicating the possible penetration of deep convection to great depths have been confirmed by the thermohaline analysis of the deep waters of the eastern Mediterranean Sea at the 1000-m and 2000-m levels [*El-Gindy and El-Din*, 1986]. Hence, there are vulnerable places in the Levantine Sea where winter convection penetrates to great depths and where surface waters participate in the formation of the deep water mass.

In mid-March 1987 (R/V *Yakov Gakkel'*), after an intense polar-air outbreak, traces of convection were found in the RCG center that were distinct in temperature and salinity distributions down to the 600–800 m depth, and down to the 1000 m depth judging from the unstable density distribution [*Gertman et al.*, 1987]. However, some peculiarities of the water stratification suggested that the deep convection in the RCG center had moved already to the concluding phase of "the sinking and spreading" of the newly formed waters. This process has been traced in deep layers even one month later. The same phase of deep convection was found here also by R/V *Yakov Gakkel'* in the winter of 1989.

Better understanding of the deep convection processes in the Levantine Sea required location and study of its second, main phase, "the violent mixing" of waters of different origin. For this purpose, an expedition was organized (R/V *Yakov Gakkel'* Cruise 36) in the winter of 1990 to the Eastern Mediterranean, aimed at the investigation of convective processes in the Aegean and Adriatic seas [*Ovchinnikov et al.*, 1990]. A winter convection study in the Levantine Sea was conducted within a 180 × 180 nm area in the northwestern part, south of Rhodos, on February 9–26, 1990; 86 stations were occupied to 2000-m depth, using a 20 nm station spacing.

The weather conditions during the Rhodos survey were determined primarily by two types of synoptic situations. The first one was characterized by enhanced pressure gradients over the Aegean Sea, resulting in northerly winds up to 15–20 m/s and the cooling of the near-surface air down to 10–12 °C. The heat loss in these conditions sometimes reached -20 to $-30\,\mathrm{MJ\,m^{-2}}$ $\mathrm{day^{-1}}$. The other synoptic situation was characterized by a weak-gradient pressure field dominated by westerly winds (6–15 m/s) bringing relatively warm air (13–16 °C). In these conditions, the heat loss of the sea was also negative, reaching though just $-12\,\mathrm{MJ\,m^{-2}}$ $\mathrm{day^{-1}}$. The mean daily heat loss in February was $-15\,\mathrm{MJ\,m^{-2}\,day^{-1}}$.

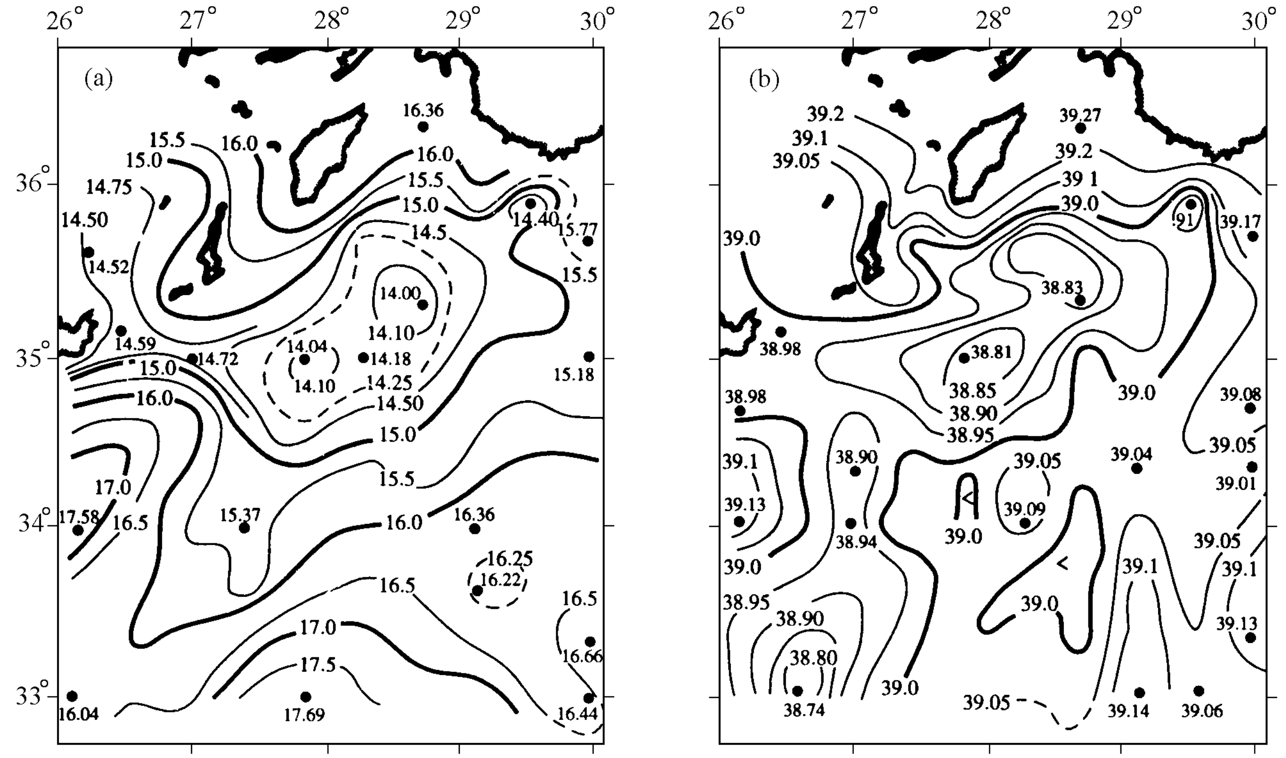
Before analyzing physical fields let us consider the circulation characteristics in the survey area during the observation period. The dynamic topography map 0/500 db (Figure 1) clearly shows the Rhodos cyclonic gyre (RCG) with a divergent zone extending from SW to NE. With dimensions of 160 nm × 170 nm the RCG was nearly circular. However a ring current on the periphery of the gyre, meandered substantially. The external meanders were associated with anticyclonic eddies; cyclonic mesoscale eddies appeared in the internal meanders; a stable anticyclonic eddy was traced in the RCG center. Many winter surveys show that the RCG center shifts insignificantly and its mean position could be characterized as 35° 00′ N, 28° 30′ E.

Maps of oceanographic properties (Figure 2) and a meridional section (Figure 3) show that their values in the RCG center are highly anomalous. The temperature, salinity, and oxygen values are at their maximum at the periphery of the survey area (16.36–17.69 °C, 39.13–39.27 ‰, 5.50 $\mathrm{mL^{-1}}$, respectively), decreasing to the minimum values (14.00–14.04 °C, 38.81–38.83 ‰, 4.89–4.93 $\mathrm{mL^{-1}}$, respectively) in the gyre's center. The distributions of temperature and salinity exhibited two separate local minima, while the oxygen distribution in the gyre's center exhibited three local minima and one local maximum. These anomalies are peculiar because of the lowered salinity, that contributes to the density decrease which in its turn suppresses the development of winter convection. This peculiarity constitutes the principal feature by which the RCG differs from cyclonic gyres in the north of the western Mediterranean [*MEDOC Group*, 1970] and in the south of the Adriatic Sea [*Ovchinnikov et al.*, 1985; *Zore-Armanda*, 1974] where the enhanced salinity in the centers of the gyres contributes to a density increase, thus facilitating the development of convective processes to great depths. However the surface water cooling in the RCG center in the winter of 1990 was so intense that the density reached $29.16\,\mathrm{kg\,m^{-3}}$ (cf. $29.00\,\mathrm{kg\,m^{-3}}$ at the gyre's periphery). The density distribution exhibited three local maxima and one local minimum where the density was as low as $29.02\,\mathrm{kg\,m^{-3}}$. In general, the RCG was marked distinctly by the following isopleths: 15.0 °C, 39.00 ‰, 5.5 $\mathrm{mL^{-1}}$ and $29.0\,\mathrm{kg\,m^{-3}}$. These surface features correlate well with the dynamic topography map for the sea surface; therefore the surface features could be considered induced by the water dynamics in this area. Based on this analysis of the water circulation and other characteristics of the surface layer, it could be concluded that the RCG in the surface layer is a coherent feature.

The main feature of the RCG hydrological structure (Figure 3) is the deep convection in its center (in the coldest and densest, but less salty and less oxygenated spot), at Station No. 158/53, 21.02.90, that extended to the 1000-m depth. A similar convection, but to the 500–700 m depth only, was observed along the divergence zone at two more stations on February 20 and 25. The convective mixing at these three stations in the RCG center results in the formation of a deep depression (down to 500–1000 m) in the pycnocline's dome, oriented SW-NE and reminiscent of a volcanic caldera. The repeated section of February 26–27 along this convective depression shows deep mixing developed no less intensely, reaching again the 500–1250-m depth at three stations. Hence, the deep convection in the RCG in late February of 1990 was quite long-lasting (7–10 days). Judging from two cold-air outbreaks in early March, these convective processes have been developed here for about 10 more days.

A section across the Rhodos gyre (Figure 3) clearly shows another feature of the convective “break-through.” In the upper 200 m layer, the water temperature, salinity and oxygen are characterized by the minimum values relative to the ambient surface waters. During further sinking, the mixed surface water keeps its properties nearly constant; however this water appears as warmer, saltier, and more oxygenated relative to the ambient deep waters. The constancy of the characteristics of the mixed water and its higher density within the “break-through” are evidence that free convection in the RCG center penetrates to the 1000-m depth. This is confirmed by the anomalies in oceanographic properties on maps for the 1000-m level. At the same time, the concave isopleths of hydrographic parameters on the section (Figure 3) and by their anomalies mapped at the 2000-m level suggest that the penetrative convection in the Rhodos gyre reaches the 2000-m depth. This deep penetration of winter convection contributes crucially to the participation of local surface waters in the formation of the Levantine Sea Deep Water mass.

The development of convection down to great depths over a prolonged period (up to 10 days) destroys the geostrophic balance of forces and therefore the circulation under the pycnocline becomes highly complex. Multi-aspect analysis of the dynamics under the pycnocline shows that the entire middle part of the Rhodos gyre (500 m and deeper) is involved in an anticyclonic rotation induced by the water sinking and is of purely thermohaline origin. At the same time, separate cyclonic eddies form at the peaks of the pycnocline's dome remaining around the convective “break-through.” The water fluxes from the outer sides of these eddies are combined into a weak and unstable (intensely meandering) ring current, which represents the remnants of the active cyclonic surface circulation. Hence, the deep winter convection destroys the under-pycnocline RCG structure, and thus predetermines the complex



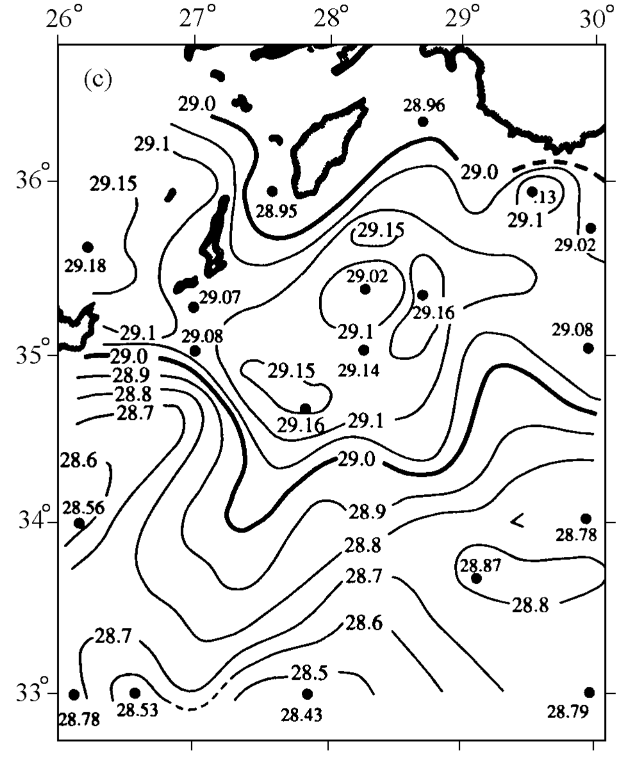
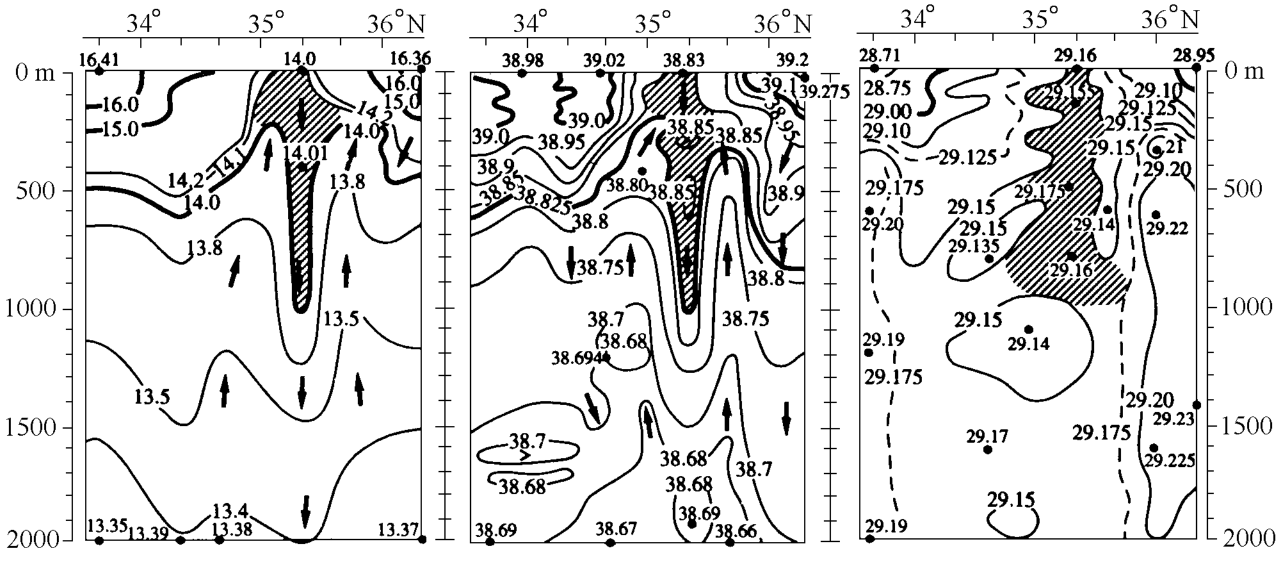


Figure 2. Distributions of temperature (a), salinity (b), and density (c) at the surface of the Rhodos survey area in February, 1990.

mesoscale character of oceanographic fields and dynamic features, which tend to form an ordered system within this gyre.

With cessation in March of winter storm winds, which supported the surface water cyclonic circulation, the Rhodos gyre sharply weakens, being destroyed from within by convection. The gyre recovers anew probably only after 1–2 months when all remnants of the convection disappear completely and the water structure becomes stable. This is likely responsible for the severely weakened RCG observed in the POEM program (March–April 1986) when some anticyclonic movements at the 600 m level were recorded [*Ozsoy et al.*, 1989].

The winter convection in the Levantine Sea is selectively associated with the RCG center due to the decreased heat content of the surface layer here, which is colder and thinner than elsewhere in the sea. Additionally, the low temperature in the source of deep convection persists due to the active upwelling of cold deep waters surrounding the convective "break-through," and markedly affects its upper part (Figure 3). Besides these factors, the still slightly elevated salinity in the gyre's center continues to exert a destabilizing influence on the hydrographic structure, thus relaxing the need for large heat loss required for deep mixing. Therefore the development of deep convection here in winter does not require very large sea-to-air heat losses, as suggested before. The required heat loss is provided by frequent, active polar-air outbreaks. As shown by observations, the mean daily heat losses in February or



(a) (b) (c)

Figure 3. Distribution of potential temperature (a), salinity (b) and density (c) on the meridional section along 28°40′E across the middle of the Rhodos cyclonic gyre, February 13–21, 1990.

March, between -15.0 and $-18.5\,\mathrm{MJ\,m^{-2}\,day^{-1}}$ are sufficient for deep mixing in the RCG. These numbers are comparable with the heat losses during the development of deep convection elsewhere in the Mediterranean ($-17\,\mathrm{MJ\,m^{-2}\,day^{-1}}$).

Taking into account the special conditions for development of deep convection in the Levantine Sea, it would be interesting to estimate roughly the intensity of this process in comparison with other energetic areas of the Mediterranean where the highly saline intermediate layer hinders the convective mixing to the great depths [*Ovchinnikov et al.*, 1985; *Voorhis and Webb*, 1970]. According to our preliminary estimates [*Ovchinnikov et al.*, 1990], the sinking rate in the convective "break-through" could be as high as 2.8 cm/s. However a more correct approach to the evaluation of the original data, together with the calculations using various techniques, have shown the rate here to be as low as 0.08–0.10 cm/s. Hence, despite significant differences in the water structures and convection-favorable conditions, the order of magnitude of vertical velocities in all energetic areas of the Mediterranean is approximately the same.

The focused studies by R/V *Yakov Gakkel'* in 1987–1990 in the Rhodos cyclonic gyre (RCG), where there were many prerequisites for the development of deep convection, yielded highly interesting results, which are very important for the hydrographic regime of the Eastern Mediterranean, namely:

1. For the first time in the Levantine Sea, deep convective mixing, which was associated with the RCG center, was found and explored. The free convection here developed from the sea surface down to the 1000-m depth, while the penetrative convection is traced to 1500–2000 m. These findings helped to solve finally the problem of participation of the Levantine Sea surface waters in the formation of the deep waters of this basin.

2. The lowered salinity of the surface waters and the lack of highly saline intermediate layer in the RCG center result in the development of deep convection here differing completely from analogous processes in the north of the western basin and the Adriatic Sea. In the RCG, the vigorous upwelling of cold deep water (not the high salinity intermediate layer) contributes to the intensification of the convective process induced by surface water cooling due to its interaction with the atmosphere. The positive contribution of the low temperature of this water mass to the densification of the mixed waters overrides the negative contribution of its low salinity. The severe cooling of the less saline surface water in the RCG center and the intense upwelling of cold deep waters in this gyre, well developed in winter, likely are interrelated in an optimum way that helps to support the deep convection for a comparatively long time.

3. However, despite its peculiarities, the deep convection development in the RCG could be conveniently divided into three phases, as suggested by the MEDOC Group [1970]:

a) "The preconditioning phase" of winter convection, which develops due to the influence of the polar air outbreaks, and reaches the 150–200-m depth to form the Levantine Intermediate Water (LIW).

b) "The violent mixing phase," which is the main link in the process of deep convective mixing, develops due to the interaction of the convection from above and the active upwelling of cold deep waters from below, when the RCG is getting significantly stronger. This results in the appearance of a convective "break-through" in the pycnocline dome to 1000 m, which is maintained by the dynamic upwelling of deep waters for 7–10 days or more.

c) "The sinking and spreading phase" of convectively mixed waters is being characterized initially by the penetrative convection to the 1500–2000-m depth. Later, spreading vertically and laterally, these waters begin to come into active contact with the deep water mass of advective origin and participate in the formation of the Levantine-type deep waters. This process of further sinking and spreading of mixed waters lasts a month or even more after the completion of the violent mixing phase.

4. The intense, prolonged (up to 10 days) mixing in the RCG center penetrates through the pycnocline's dome to the great depths and destroys the geostrophic balance in this gyre. As a result, the general cyclonic circulation here (chiefly under the main pycnocline) breaks down into several counter-rotating mesoscale eddies:

a) The anticyclonic eddies, which, as a rule, are associated with the extensive convective depression in the middle of the RCG, could be combined into a unified anticyclonic circulation of thermohaline origin. This movement, which encompasses the part of the cyclonic gyre under the pycnocline, reduces its stability and, with the termination of the strong wintertime winds, could result in a sharp weakening and even the complete destruction of the RCG.

b) The cyclonic eddies form above separate peaks of the deformed pycnocline's dome, reminiscent of a volcanic caldera, when the convection is actively developed. This relationship explains the circular arrangement of the eddies around the crater-like "break-through" in the middle of the gyre. On the outer sides of the cyclonic eddies, there are weak remnants of a circular cyclonic current which meanders intensively.

c) In the outer meanders of the ring current, active anticyclonic eddies form and surround the weakened RCG. The most conspicuous is the very active anticyclonic eddy Kufonisi, south of the Strait of Kassos, and the active anticyclonic gyre south of the RCG, named Mersa-Matruch by Egyptian oceanographers.

Such a complex, but well organized dynamic system of the Rhodos gyre emerges from the data collected by three expeditions that found deep convection here in the winters of 1987, 1989, and 1990.

5. In those cases, when the convective depression becomes a deep valley oriented SW-NE, the RCG is divided into two nearly independent parts by the convergent zone, which replaces the initial divergence zone where the convective processes began. The northwestern part of the RCG, located near Karpathos and Rhodos, develops much more strongly; it is likely that this part serves as a base for the RCG recovery when the deep wintertime convection ceases.

6. The wintertime convection in the middle of the RCG results in the sinking to great depths of about $170,000\,\mathrm{km}^3$ of mixed water with a large admixture of oxygenated surface waters. This water refills and ventilates the main body of the deep waters of the Adriatic origin, significantly modified while travelling to the Levantine Sea. At the same time, the sinking water contributes to the self-purification of the deep water mass from pollutants.

References

Anati, D. A., A Dome of cold water in the Levantine Basin, *Deep-Sea Research, 31,* No. 10, 1251–1257, 1984.

El-Gindy, A. A. H., and S. H. S. El-Din, Water masses and circulation patterns in the deep layer of the eastern Mediterranean, *Oceanologica Acta, 9*, No. 3, 239–248, 1986.

Georgopoulos, D., et al., On the formation of dense water over the shelf areas of the northern Aegean Sea, *XXXI Congress ICSEM*, Athens, October 1988.

Gertman, I. F., I. M. Ovchinnikov, and Yu. I. Popov, Deep water formation in the Aegean Sea, *Rapp. Comm. Int. Mer Medit. (S.I.E.S.M.), 32,* No. 1, 164, 1990a.

Gertman, I. F., I. M. Ovchinnikov, and Yu. I. Popov, Deep convection in the Levantine Sea, *Rapp. Comm. Int. Mer Medit. (S.I.E.S.M.), 32*, No. 1, 172, 1990b.

Gertman, I. F., Yu. I. Popov, and V. G. Trigub, Deep convection in the Levantine Sea, March 1987, 20 pp., *Archived at VINITI*, Moscow, No. 6581–B87, 1987.

Gertman, I. F., and Yu. I. Popov, Analysis and genesis of the Aegean Sea water masses by data of the detailed wintertime survey of 1988, 23 pp., *Archived at VINITI*, Moscow, No. 1201–B89, 1989.

Ivanov, Yu. A., *Krupno Mashtabnaya i Sinopoticheskaya Izmenchivost' Ploey v Okeane* (Large-scale and Synoptic Variability of Oceanic Fields), 168 pp., Nauka, Moscow, 1981.

MEDOC Group, Observation of formation of deep water in the Mediterranean Sea, 1969, *Nature, 227*, 1037–1040, 1970.

Moskalenko, L. V., and I. M. Ovchinnikov, Geostrophic circulation of the Mediterranean Sea, *Oceanology, 31,* No. 6, 907–915, 1991.

Nielsen, I. N., Hydrography of the Mediterranean and adjacent waters, *Rep. Danisch. Oceanogr. Exped. Medit. 1908–1910, 1*, 77–191, 1912.

Ovchinnikov, I. M., Circulation in the surface and intermediate layers of the Mediterranean Sea, *Oceanology, 6,* No. 1, 62–75, 1966.

Ovchinnikov, I. M., et al., *Gidrologiya Sredizemnogo Morya* (Hydrology of the Mediterranean Sea), 375 pp., Gidrometeoizdat, Leningrad, 1976.

Ovchinnikov, I. M., On the renewal of main water masses of the Mediterranean Sea, *Oceanology, 23,* No. 6, 960–962, 1983.

Ovchinnikov, I. M., Formation of intermediate waters in the Mediterranean Sea, *Oceanology, 24,* No. 2, 217–225, 1984.

Ovchinnikov, I. M., and E. A. Plakhin, Formation of intermediate waters of the Mediterranean Sea in the Rhodos cyclonic gyre, *Oceanology, 24,* No. 3, 417–420, 1984.

Ovchinnikov, I. M., V. I. Zats, V. G. Krivosheya, and A. I. Udodov, Formation of the deep Eastern Mediterranean waters in the Adriatic Sea, *Oceanology, 25,* No. 6, 911–917, 1985.

Ovchinnikov, I. M., Yu. I. Popov, and I. F. Gertman, A study of the deep water formation in the eastern Mediterranean Sea, *Oceanology, 30,* No. 6, 1039–1041, 1990.

Ozsoy, E., A. Hecht, and U. Unluata, Circulation and hydrography of the Levantine Sea, Results of POEM coordinated experiments 1985–1986, *Prog. Oceanog., 22*, 125–170, 1989.

Voorhis, A. D., and D. C. Webb, Large vertical currents observed in a winter sinking region of the Northwestern Mediterranean, *Cah. Oceanogr., 22,* No. 6, 571–580, 1970.

Zore-Armanda, M., Formation of Eastern Mediterranean deep water in the Adriatic, *Colloq. Intern. CNRS No. 215, Form. Eaux Prof.*, October 1972, 127–133, 1974.

(Received December 7, 1992.)