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V. N. Egorov, Dr. Sc., Head of RChBD**, G. G. Polikarpov,** Acad. NAS U, Chief Sc.**,**
N. A. Stokozov, Dr., Senior Sc.**, N. Yu. Mirzoyeva,** Sc.

The A. O. Kovalevsky's Institute of Biology of the southern Seas,
National Academy of Sciences of Ukraine, Sevastopol, Ukraine

ESTIMATION OF ^{90}Sr AND ^{137}Cs TRANSFER FROM THE BLACK SEA TO THE MEDITERRANEAN BASIN AFTER THE CHERNOBYL NPP ACCIDENT

The ^{90}Sr and ^{137}Cs inputs from the Black Sea to the Mediterranean Basin through the Bosporus Strait after the Chernobyl NPP accident were estimated. It is obtained that the ^{90}Sr and ^{137}Cs fluxes from the Black Sea to the Sea of Marmara are decreased with an effective exponential half-lives (T_{05}) 9.5 years and 6.4 years, respectively. The estimations have shown that 110 TBq ^{90}Sr and 250 TBq ^{137}Cs in 1986–2000 was delivered from the Black Sea to the Mediterranean Basin after the Chernobyl NPP accident. The radioactive pollution of the Mediterranean Basin will continue for 5 half-lives, i.e. 47 years for ^{90}Sr and 32 years for ^{137}Cs. The total ^{90}Sr and ^{137}Cs inputs from the Black Sea into the Mediterranean Basin have been assessed as 168 TBq and 311 TBq, respectively.

Key words: Chernobyl NPP accident, ^{90}Sr and ^{137}Cs fluxes, prediction, the Bosporus Currents, Black Sea, Mediterranean Basin

After the Chernobyl NPP accident, about 1.3 – 8.1 PBq of ^{90}Sr and 37 – 100 PBq of ^{137}Cs were released to the environment. In May 1986 the atmospheric fallouts after the Chernobyl NPP accident were the main source of the ^{137}Cs input into the Black Sea. The atmospheric fallouts of ^{90}Sr and ^{137}Cs over the Black Sea were 100 – 300 TBq and 1700 – 2400 TBq, respectively. The ^{90}Sr input to the Black Sea was caused by atmospheric fallout and run off from the Dnieper River (57.8 TBq) and the Danube River (32.8 TBq) during the following years [1, 5, 7, 10].

The investigations are devoted to the assessment of the discharge fluxes of ^{90}Sr and ^{137}Cs from the Black Sea into the Mediterranean via the Bosporus Strait after the Chernobyl NPP accident. The results are the determinations of the long-lived radionuclides (^{90}Sr and ^{137}Cs) contents in the water of 0 – 50 m and the assessments of the water fluxes from the Black Sea into the Sea of Marmora via the Bosporus Strait.

Materials and methods. Published data [1, 10] as well as the results of investigations at IBSS were utilized for assessment of radioactive pollution of the Black Sea. The collection of the IBSS data [3, 4 ,5, 6, 8] were carried out between 1986 – 2000 on the oceanographic vessels with support from the National programs of Ukraine, EU programs EROS–2000 and EROS–21, IAEA projects NR 7400 RB and RER/2/003, and in collaboration with WHOI and EPA (USA).

Intercomparison of ^{90}Sr and ^{137}Cs radioactivity measurements in water were fulfilled jointly with WHOI, RISO National Laboratory (Denmark), and with the support of IAEA with responsible laboratories of Bulgaria, Georgia, Romania, Russia and Turkey. Current intensity via the Bosporus Strait was assessed using the water balance of the Black Sea, data from the Ukrainian Research Hydrometeorological Institute [12] and the help of mathematical models using the water, salt and radioisotope balance of the Black Sea with annual averaged parameters [2].

Results and discussion. The modern estimations [2] of water exchange between the Black Sea and the Mediterranean Basin via the Bosporus Strait are based on the results of the Upper and Lower Bosporus Currents investigations. The Upper Bosporus Current passes low-salinity waters (18 $^0/_{00}$) from the Black Sea to the Sea of Marmara, and the Lower Bosporus Current passes high-salinity waters (35 $^0/_{00}$) to the Black Sea. These high-salinity waters are distributed in deep-water layers of the Black Sea water area. Therefore the waters of Upper Bosporus Current have the same radioactivity as the Black Sea waters 0 – 50 m layer have.

The investigations have shown that the Upper and Lower Bosporus Current discharges are ruled by the seasonal changes of the Black Sea water balance. The 1875 – 1985 [11] investigations revealed that the sea level of the Black Sea is at maximum in May and minimum in October. Long-term investigations have discovered there is an annual increase of the Black Sea level in the order 1.2 – 2.0 mm per year, which is in agreement with the general tendency of the World Ocean.

The components of the Black Sea water balance are shown in Fig.1 (the data were obtained by Ukrainian Hydrometeorology Service from 1923) [12].

During the investigation period, an increase of evaporation has been observed as a result of the climatic changes. The annual water flux from the Sea of Azov to the Black Sea has decreased due to increasing of runoff from the Don and Kuban Rivers. At the same time, river runoff, outflow of the Black Sea water to the Sea of Azov, as well as the total water balance of the Black Sea has not changed. The water balance changes have been compensated by the increase of the Upper Bosporus Current and by the decrease of the Lower Bosporus Current. The relationship between the Upper and Lower Bosporus Currents discharges and total annual Black Sea runoff are shown in Fig. 2 (the data were obtained by Ukrainian Hydrometeorological Service) [12].

Fig. 2 shows that the dependence between the Bosporus Currents and total annual rivers discharges can be described by liner functions. It allows us to estimate the annual Upper Bosporus Current discharge with the help of annual river discharge data.

The observations have shown, that during the first year after the Chernobyl NPP accident the ^{90}Sr and ^{137}Cs distribution in the Black Sea surface water was extremely non homogeneous due to the non-uniformity of atmospheric fallouts [1, 8, 10]. Further, more uniform radionuclide distribution was observed as a result of the physical water mixing processes. The ^{90}Sr and ^{137}Cs distributions in the mixed surface layer of the Black Sea between 1998 – 2000 are shown in Fig. 3.

Vertical ^{90}Sr and ^{137}Cs distributions in the centre of the Black Sea Western cyclonic gyre (Fig. 4, 5) have shown that up to 1987 a quasi-uniform distribution of these radionuclides in 0 – 50 m layer was observed. In the subsequent period, the gradients of concentrations of ^{90}Sr and ^{137}Cs within the 0 – 50 m layer were insignificant. The average values annual radionuclides concentrations data within the 0 – 50 m water layer were used to calculate ^{90}Sr and ^{137}Cs concentrations in water of the Upper Bosporus Current.

The results of the calculations of radionuclide fluxes transferred out from the Black Sea via the Bosporus Strait are shown in Table 1. The changes in the flux of radionuclides migrated out of the Black Sea are illustrated by Fig. 6.

This figure shows the presented data in a logarithmic scale for ordinates axis, the points can be approximated by the direct line.

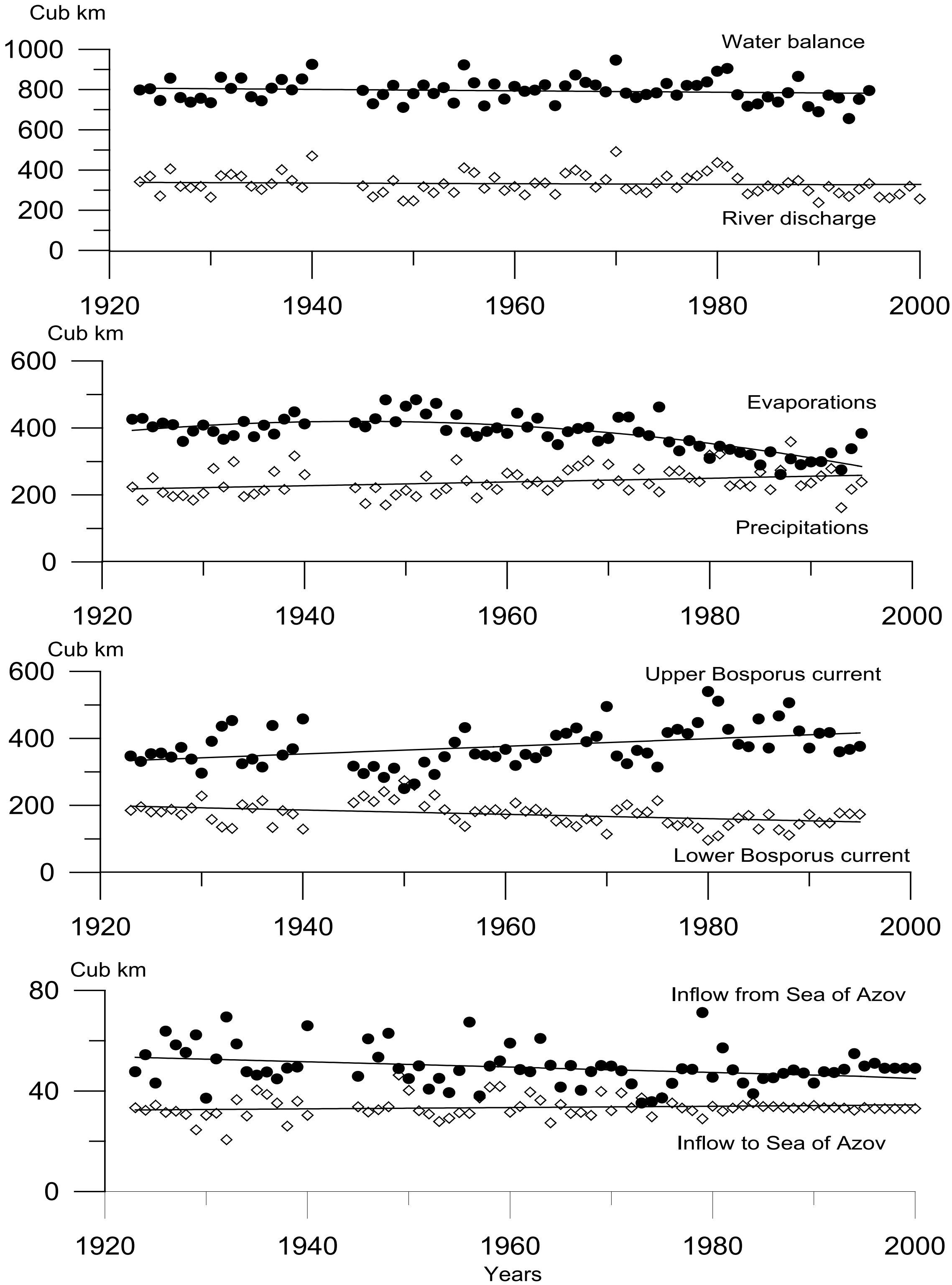

Fig. 1. The components of the Black Sea water balance
Рис. 1. Компоненты водного баланса Черного моря

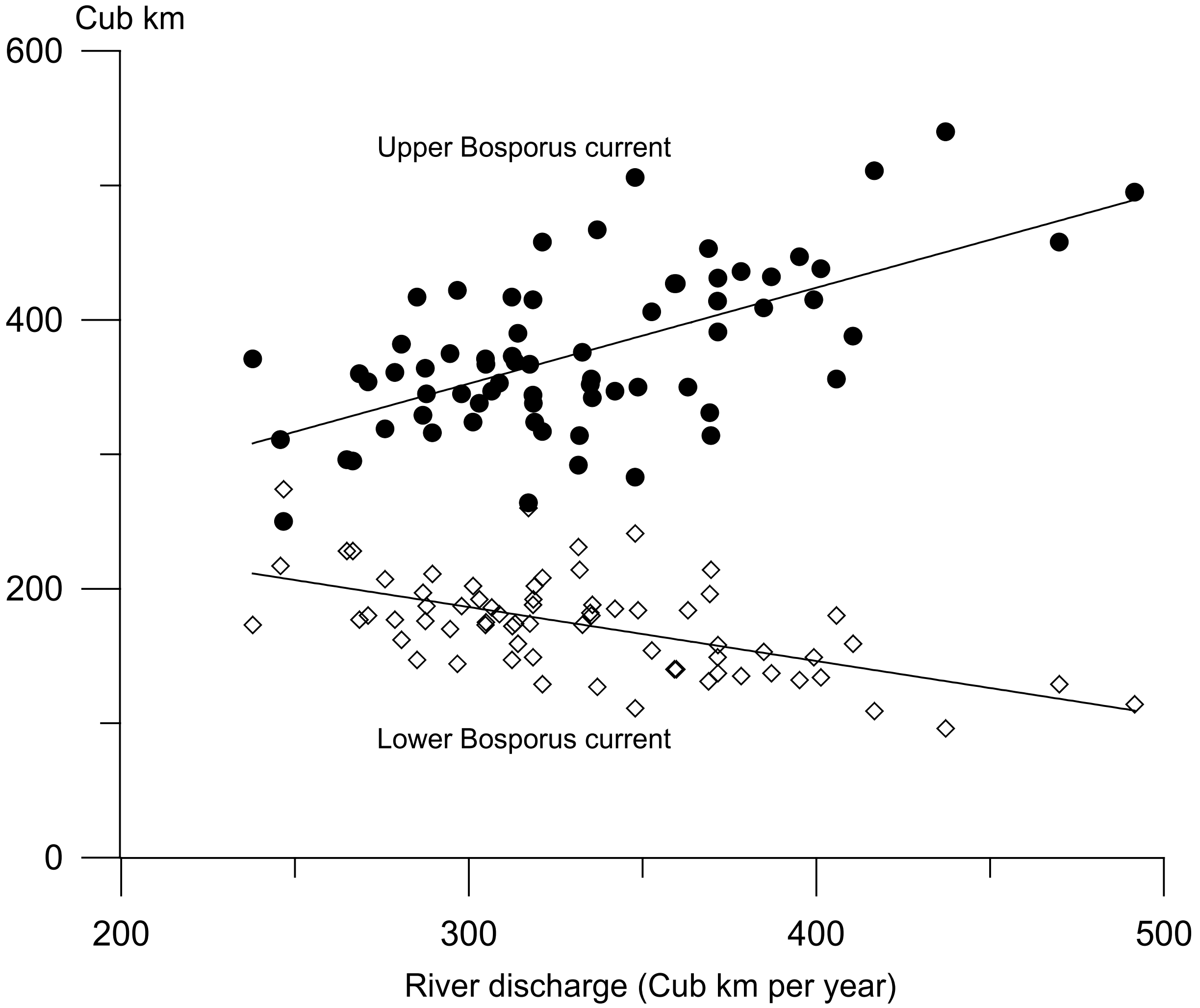

Fig. 2. Relationship between the Upper and Lower Bosporus Currents discharges according to the total annual the Black Sea runoff

Рис. 2. Соотношение между интенсивностью Верхнего и Нижнего Босфорского течений в зависимости от суммарного ежегодного стока рек в Черное море

For ^{90}Sr data a factor of determination (r^2) was estimated as 0.836 and for ^{137}Cs 0.874. From this it follows that regularities of radionuclides transfer fluxes change can be described by the exponential function with a sufficient degree of adequacy. This function can be used to predict estimates.

It is obvious, that integration of these functions will allow estimates of total fluxes of radionuclides from the Black Sea to the seas of the Mediterranean Basin for the time intervals within the limits of integration. According to our data, the total fluxes for ^{90}Sr (Q_1) and ^{137}Cs (Q_2) are estimated as:

$$Q_1 = 12.52 \int_a^b \exp(-0.0723\, t)\, dt, \quad (1)$$

$$Q_2 = 34.60 \int_a^b \exp(-0.1075\, t)\, dt, \quad (2)$$

where, t – time (years).

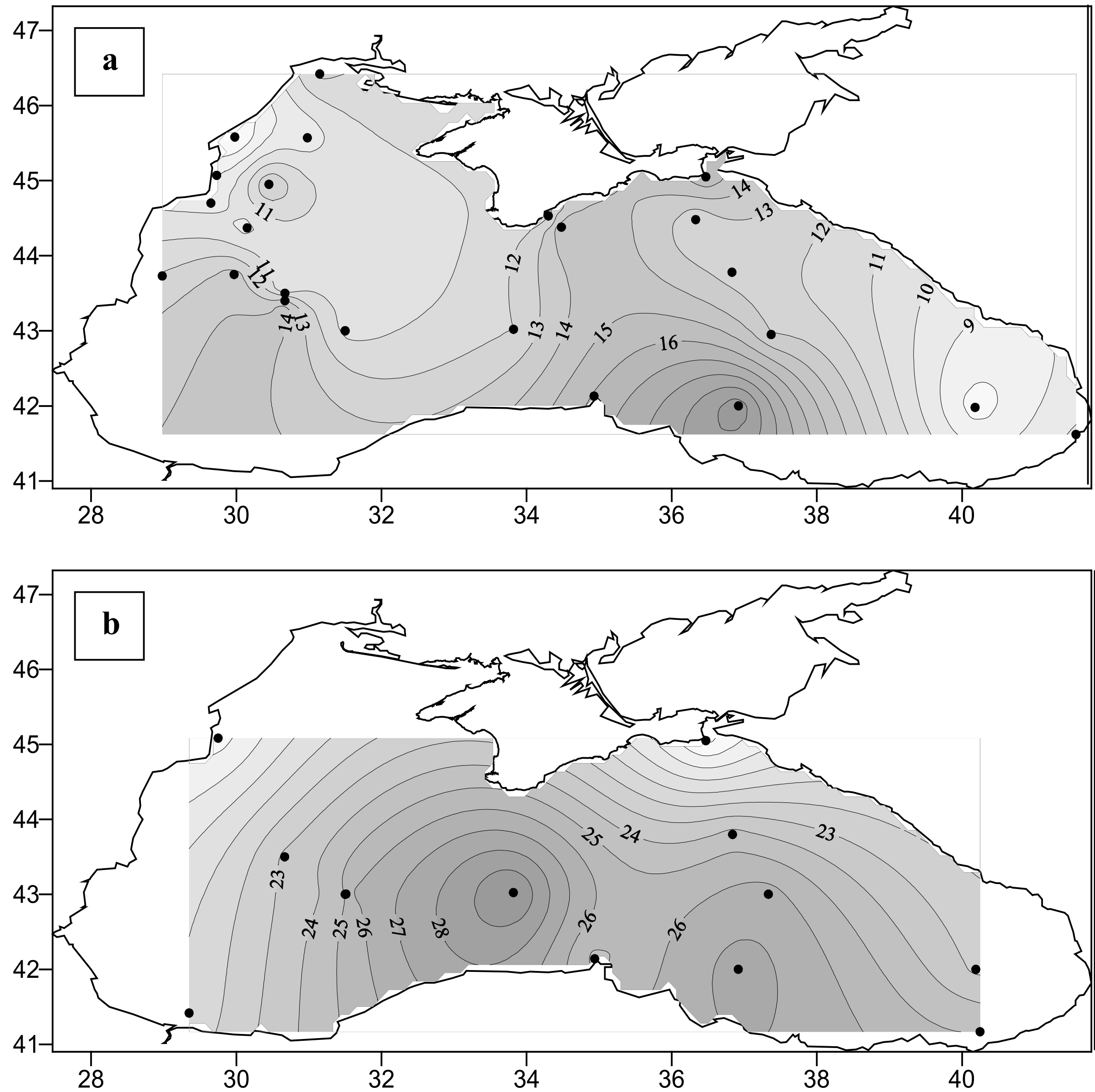

Fig. 3. ^{90}Sr (a) and ^{137}Cs (b) (Bq m^{-3}) distributions in the surface mixed layer of the Black Sea between 1998 – 2000

Рис. 3. Распределение ^{90}Sr (а) и ^{137}Cs (б) (в Бк $м^{-3}$) в поверхностном слое Черного моря в период 1998 – 2000 гг.

Conclusions: By integrating equations (1) and (2) for the period 1986 - 2004, the ^{90}Sr outflow via the Bosporus Strait can be estimated as 126.0 TBq, and for ^{137}Cs – 275.4 TBq during this 18 year period. Calculations have shown, that the half-lives for the ^{90}Sr flow ($T_{05,1}$ = 0.693/0.0723) equals to 9.5 years, and for ^{137}Cs ($T_{05,2}$ = 0.693/0.1075) – 6.4 years. It is widely accepted, that complete time of the ecosystems reaction on radioactive contaminations can be estimated as 5 half-lives.

Thus, as a qualitative prediction of assessments, it is possible to conclude that radioactive pollution of the Mediterranean Basin by ^{90}Sr will proceed for approximately 47 years, and for ^{137}Cs – 32 years.

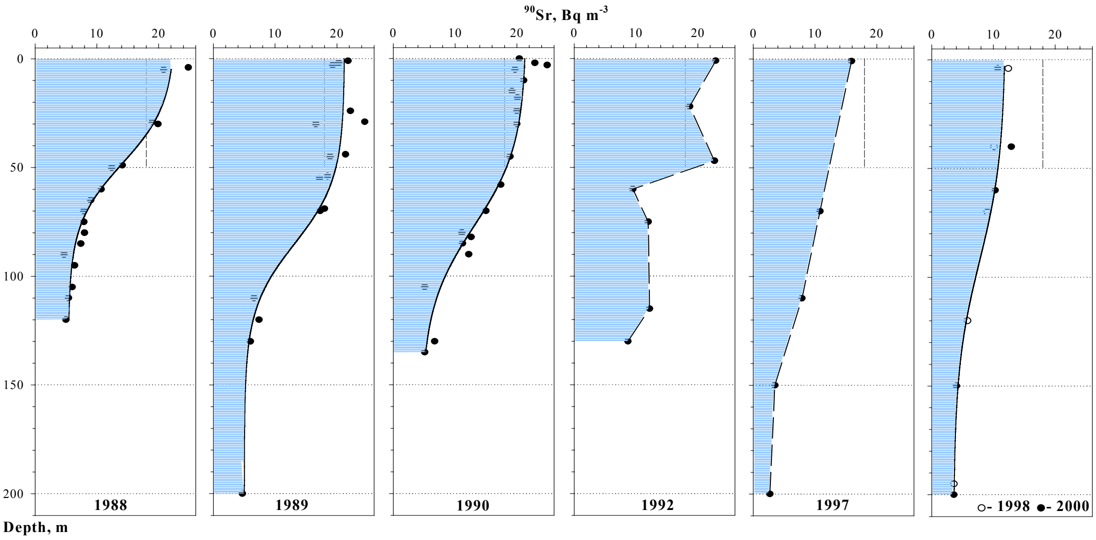

Fig. 4. Vertical distributions of the ^{90}Sr in the Western Black Sea Central Basin between 1988 – 2000 (circles and medium dashed line), the approximations (solid lines) and level of ^{90}Sr concentration in the 0 – 50 m layer before the Chernobyl NPP accident (short dashed lines)

Рис. 4. Вертикальное распределение ^{90}Sr в Западном и Центральном районах Черного моря за период 1988 – 2000 гг. (круги и средней длины пунктирная линия), их аппроксимация (сплошная линия) и уровень концентрации ^{90}Sr в 0 – 50 м слое до аварии на Чернобыльской АЭС (короткая пунктирная линия)

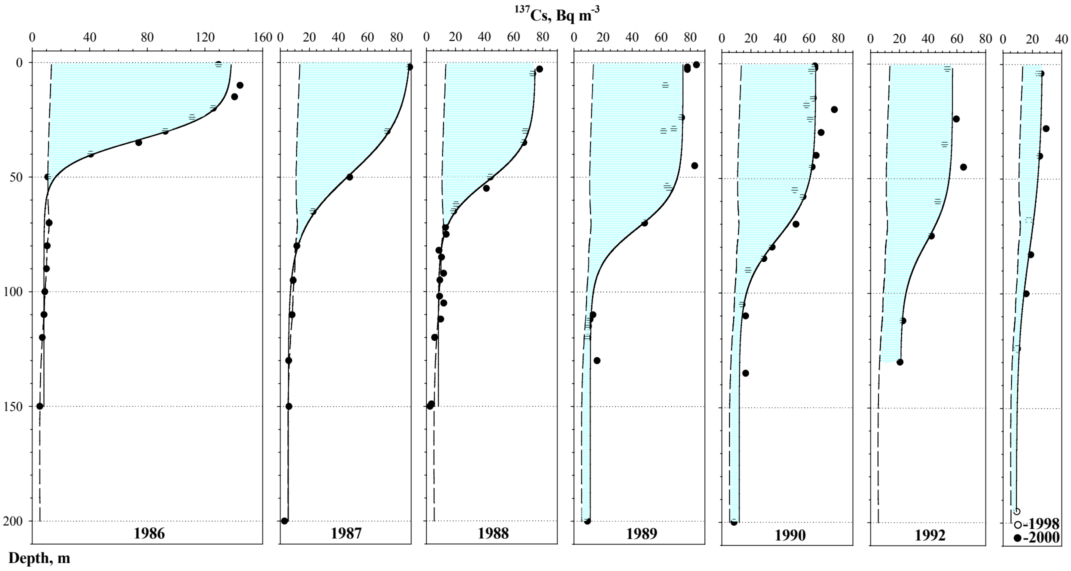

Fig. 5. Vertical distributions of the ^{137}Cs in the Western Black Sea Central Basin in 1986 – 2000 (circles), the approximations (solid lines) and level of ^{137}Cs concentration in the 0 – 200 m layer before Chernobyl NPP accident (dashed lines)

Рис. 5. Вертикальное распределение ^{137}Cs в Западном и Центральном районах Черного моря за период 1988 – 2000 гг. (круги), их аппроксимация (сплошная линия) и уровень концентрации ^{137}Cs в 0 – 50 м слое до аварии на Чернобыльской АЭС (пунктирная линия)

Table 1. Assessments of the ^{90}Sr and ^{137}Cs fluxes from the Black Sea via the Bosporus Strait to the Mediterranean Basin after the Chernobyl NPP accident

Табл. 1. Оценки потоков поступления ^{90}Sr и ^{137}Cs из Черного моря через пролив Босфор в Средиземноморский бассейн после аварии на Чернобыльской АЭС

Years	Upper Bosporus Strait flux - water outflow from the Black Sea to the Sea of Marmara ($km^3 \cdot year^{-1}$)	^{90}Sr		^{137}Cs	
		Average conc. in water layer 0-50 m +/- 1σ ($Bq\ m^{-3}$)	Flux from the Black Sea via Bosporus Strait ($TBq\ y^{-1}$)	Average conc. in water layer 0-50 m +/- 1σ ($Bq\ m^{-3}$)	Flux from the Black Sea via Bosporus Strait ($TBq\ y^{-1}$)
1986	371	53.0+/-13.8	13.1	134.1+/-51.5	33.2
1987	476	24.5+/-4.4	11.7	77.3+/-13.1	36.8
1988	506	19.5+/-1.4	9.9	62.7+/-11.8	31.7
1989	422	22.8+/-3.8	9.6	60.5+/-5.8	25.5
1990	371	21.4+/-3.1	7.9	57.8+/-5.3	21.4
1991	415	21.5	8.9	52.0+/-7.7	21.6
1992	417	21.5	9.0	48.1+/-2.9	20.1
1993	360	22.0	7.9	37.1	13.4
1994	367	27.3+/-1.9	10.0	27.7	10.2
1995	376	15.0+/-1.3	5.6	29.6	11.1
1998	412	12.4+/-1.6	5.1	24.5+/-2.6	10.1
2000	389	10.7+/-1.6	4.2	25.9+/-2.6	10.1

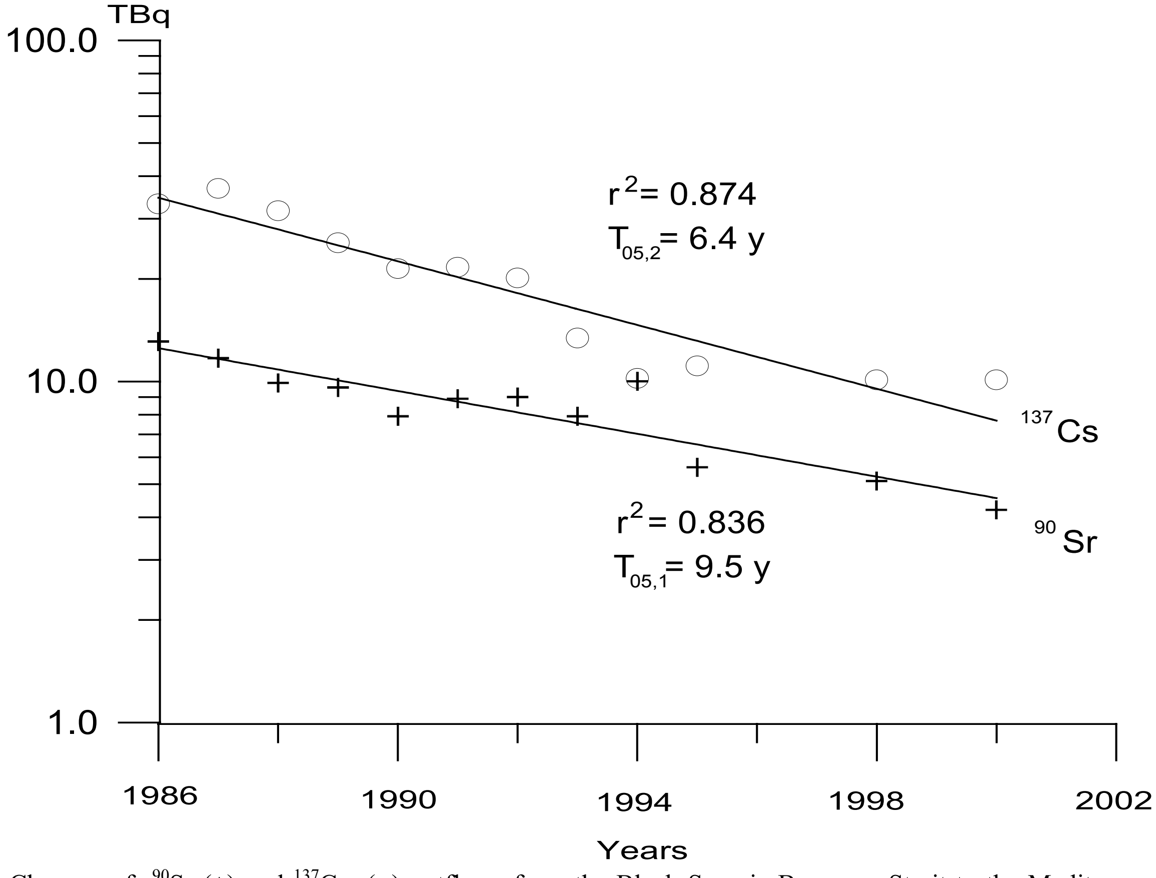

Fig. 6. Changes of ^{90}Sr (+) and ^{137}Cs (○) outflows from the Black Sea via Bosporus Strait to the Mediterranean Basin

Рис. 6. Изменение выноса ^{90}Sr (+) и ^{137}Cs (○) из Черного моря через пролив Босфор в Средиземноморский бассейн

By inputting 47 years into equation (1) and 32 years into equation (2) we concluded that the total outflow of ^{90}Sr into the seas of the Mediterranean Basin will reach 168 TBq, which is 56–168 % of the short-term atmospheric fallout of this radioisotope on the Black Sea surface after the Chernobyl NPP accident. The Total flux of ^{137}Cs release into the Mediterranean Basin will reach 311 TBq, which is 13 – 18 % of its atmospheric fallout on the Black Sea surface after the 1986 Chernobyl NPP accident.

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Оцінка та прогноз переносу ^{90}Sr і ^{137}Cs з Чорного моря у Середземноморський басейн після аварії на ЧАЕС. В. М. Єгоров, Г. Г. Полікарпов, М. О. Стокозов, Н. Ю. Мирзоєва. Оцінено потік надходження ^{90}Sr та ^{137}Cs з Чорного моря у Середземноморський басейн через протоку Босфор після аварії на Чорнобильській АЕС. Отримано, що потік ^{90}Sr з Чорного у Мармурове море зменшується експоненційно з періодом напівзменшення ($T_{0.5}$) 9.5 року, а ^{137}Cs – 6.4 року. Розрахунки показали, що після аварії на ЧАЕС за період 1986 – 2000 рр. з Чорного моря у Середземноморський басейн надійшло 110 ТБк ^{90}Sr та 250 ТБк ^{137}Cs. Радіоактивне забруднення Середземноморського басейну ^{90}Sr буде продовжуватися протягом 5 $T_{0.5}$, тобто 47 років, а ^{137}Cs – 32 роки. Сумарне надходження ^{90}Sr з Чорного моря у Середземноморський басейн складе 168 ТБк, а ^{137}Cs – 311 ТБк.

Ключові слова: аварія на Чорнобильської АЕС, потоки ^{90}Sr та ^{137}Cs, прогноз, Босфорський плин, Чорне море, Середземноморський басейн

Оценка и прогноз переноса ^{90}Sr и ^{137}Cs из Черного моря в Средиземноморский бассейн после аварии на ЧАЭС. В. Н. Егоров, Г. Г. Поликарпов, Н. А. Стокозов, Н. Ю. Мирзоева. Оценен поток поступления ^{90}Sr и ^{137}Cs из Черного моря в Средиземноморский бассейн через пролив Босфор после аварии на Чернобыльской АЭС. Получено, что поток ^{90}Sr из Черного в Мраморное море снижается экспоненциально с периодом полууменьшения ($T_{0.5}$) 9.5 лет, а ^{137}Cs – 6.4 года. Расчеты показали, что после аварии на ЧАЭС за период 1986 – 2000 гг. из Черного моря в Средиземноморский бассейн поступило 110 ТБк ^{90}Sr и 250 ТБк ^{137}Cs. Радиоактивное загрязнение Средиземноморского бассейна ^{90}Sr будет продолжаться в течение 5 T_{05}, т. е. 47 лет, а ^{137}Cs – 32 года. Суммарное поступление ^{90}Sr из Черного моря в Средиземноморский бассейн составит 168 ТБк, а ^{137}Cs – 311 ТБк.

Ключевые слова: авария на Чернобыльской АЭС, потоки ^{90}Sr и ^{137}Cs, прогноз, Босфорское течение, Черное море, Средиземноморский бассейн