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# Reconstruction and prediction of radionuclide transport in the Mediterranean sea chain

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**Abstract**

A model forced with meteorological and run-off data and anthropogenic radioactivity input, was developed to simulate the transport of radionuclides in the chain system of the Mediterranean seas. It incorporates submodels of the Black Sea, Azov Sea, Marmara Sea, Western and Eastern Mediterranean. One-and-a-half-dimensional multi-layer lagrangian models were used to describe horizontally averaged fields of temperature, salinity and tracer concentration in the seas proper. Simple models of hydraulically controlled straits were applied to the Bosphorus, Dardanelles, Sicily and Gibraltar. An empirical relation was used for the shallow Kerch Strait. The model was forced with time series of wind, temperature and freshwater influx. It was used to reconstruct and predict, for the time period 1960–2010, the $^{137}$Cs contamination resulting from atmospheric testing of nuclear weapons and the Chernobyl accident. The model predictions for water, salinity and $^{137}$Cs budget are in reasonable agreement with the available data. The peculiarities of Black Sea exchange processes were analysed and compared with other Mediterranean seas. © 1999 Elsevier Science Ltd. All rights reserved.

*Keywords:* Lagrangian model; Radionuclides; Salinity; Tracer concentration

## 1. Introduction

The Mediterranean seas can be compared with an ocean basin consisting of a set of seas connected by relatively narrow and shallow straits. The exchange through the straits and the fresh water budget control the hydrological regimes of the main sub-basins: the Azov Sea, the Black Sea, the Marmara Sea, and the Eastern and Western Mediterranean. Strong mixing in the Mediterranean Sea proper, driven by buoyancy loss due to evaporation and winter cooling, results in a ventilation of deep

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water, whereas the surplus of fresh water in the Black Sea prevents deep convection and maintains a thick anoxic layer. The sub-basins differ in size and water renewal time. The Mediterranean Sea, and especially the Black and Azov seas with a shallow life-supporting layer, are strongly affected by natural climate changes and by man-made impact. Therefore study of the variability of thermohaline fields, circulation and mass transport in the Mediterranean sub-basins on the scale of decades requires an understanding of the whole variability of the system.

Isotope techniques are important tools for physical oceanography (Buesseler et al., 1990) and in the environmental protection studies (Fabry et al., 1993). The reconstruction of the $^{137}$Cs redistribution in the Mediterranean seas resulting from atmospheric bomb testing in the 60s and from the Chernobyl accident is of particular interest in modelling of mixing in the seas and water exchange through the straits. At present, 3-D models have been used successfully to simulate radionuclide tracer transport in semi-enclosed seas (e.g. Roether et al., 1995; Margvelashvily et al., 1998). However, in some instances (e.g. a complicated sea chain, long-term evolution, probabilistic prediction) these models are too elaborate. The simple one-and-a-half-dimensional models (Killworth & Smith, 1984; Stigebrandt, 1985, 1987; Maderich & Efroimson 1986; Efroimson & Maderich, 1987; Maderich, 1998) are irreplaceable tools for such studies. In these simple models, the conservation of mass, heat and salt is considered only in the vertical direction ('one dimension'). The 'half-dimension' represents the strait in- and out-flows which act as forcing terms for vertical circulation.

In this paper, the modified layered model of Efroimson and Maderich (1987) is applied to the system Azov Sea–Black Sea–Marmara Sea–East Mediterranean–West Mediterranean in order to reconstruct the fate of $^{137}$Cs deposited on the sea surface by fallout from bomb testing and the Chernobyl accident. The model is presented in the next section. The results of a simulation of the long-term $^{137}$Cs evolution are then presented. The model equations are given in the Appendix.

## 2. The model

The model of the Mediterranean sea system consists of submodels of the deep parts of the Western and Eastern Mediterranean, the Black and Marmara seas, a submodel of the shallow Azov sea, submodels of the Gibraltar, Sicily, Dardanelles and Bosphorus straits and a submodel of the Kerch strait.

The modified 'lagrangian layer' model (Efroimson and Maderich, 1987) was used as a submodel for the deep parts of the Eastern and Western Mediterranean, and the Black and Marmara seas. The vertical hydrological structure of the water body was approximated by a set of homogeneous layers. It was supposed that horizontally averaged temperature $T$, salinity $S$ and radionuclide concentration $C$ in solution are constant in the layers. The number of layers and their thickness and position vary in time. The surface area of the layers is a function of depth. The layers can move in the vertical direction according to the mass balance ('lagrangian layer'). The system of layers includes a surface mixed layer (SML), that is under direct atmospheric influence, and internal and bottom layers. The model is forced using time series of wind, air temperature and freshwater influx. Based on experimental data (Vakulovskii et al., 1980; UNEP/IAEA, 1992) the exchange processes between $^{137}$Cs in solution, in suspended and bottom sediments were neglected.

For the shallow Azov sea, a one-layer model was used. The sea-averaged temperature $T$, salinity $S$, suspended sediment concentration $S_s$, the radionuclide concentration in solute $C$, in the suspended sediments $C_s$ and in the bottom deposit $C_b$ were predicted. The processes of adsorption–desorption and sedimentation–resuspension were parameterized. A simple model of two-layer exchange processes (Maderich & Efroimson, 1986, 1990) was applied to the Bosphorus, Dardanelles, Sicily and Gibraltar. The water exchange through the Kerch strait was parametrized following the empirical relations of Simonov and Altman (1991) which related the exchange through the strait with the river run-off in the Azov Sea. The equations of the multilayer model and the strait exchange relations are given in the Appendix.

## 3. Model forcing

### 3.1. Meteorological series and run-off

The computations discussed in this paper were carried out for the period 1960–2010. Volumes and horizontal surface areas of the layers in the Mediterranean, Black and Marmara seas were calculated using the data of Goncharov et al. (1976). The climatological monthly mean values of surface air temperature $T_a$ and the friction velocity $u_*$ were adopted from Simonov and Altman (1991) for the Black and Azov seas and from Ovchinnikov et al. (1976) for the Mediterranean Sea. The climatological monthly mean net freshwater flux to the seas, that is the sum of river run-off, precipitation and evaporation, was adopted from Remizova (1984), Simonov and Altman (1991), Ünlüata et al. (1990), Ovchinnikov et al. (1976) for the Azov, Black, Marmara and Mediterranean seas, respectively. For 1960–1994, the data on the net freshwater flux to the Black sea, kindly provided by Dr. O. Voitsekhovitch, were used. Climatological mean annual values of the net freshwater flux are given in Table 1. The sea strait parameters and calculated discharges through the straits are given in Table 2. The signs ± correspond to the influx and outflux for Azov, Black and Marmara seas and the Eastern and Western Mediterranean, respectively.

Table 1
Parameters of the Mediterranean Sea sub-basins

| Sea basin | Surface area (km$^2$) | Volume (km$^3$) | Fresh water influx (m$^3$ s$^{-1}$) |
|---|---|---|---|
| Azov Sea | $3.7 \times 10^4$ | $2.6 \times 10^2$ | 570 |
| Black Sea | $4.2 \times 10^5$ | $4.2 \times 10^5$ | 5970 |
| Marmara Sea | $1.1 \times 10^4$ | $4.2 \times 10^3$ | − 130 |
| Eastern Mediterranean | $1.64 \times 10^6$ | $2.41 \times 10^6$ | − 46 200 |
| Western Mediterranean | $8.54 \times 10^5$ | $1.64 \times 10^6$ | − 15 400 |

Table 2
Parameters of the Mediterranean Sea straits

| Strait | Length (km) | Width (km) | Depth (m) | Volume fluxes ($m^3 s^{-1}$) | |
|---|---|---|---|---|---|
| | | | | Upper layer | Bottom layer |
| Kerch | 40 | 4 | 5 | $-1.00 \times 10^3$ | $0.43 \times 10^3$ |
| Bosphorus | 31 | 0.8 | 40 | $-1.20 \times 10^4$ | $0.55 \times 10^4$ |
| Dardanelles | 60 | 4 | 70 | $-1.54 \times 10^4$ | $0.91 \times 10^4$ |
| Sicily | 20 | 30 | 300 | $1.04 \times 10^6$ | $-1.00 \times 10^6$ |
| Gibraltar | 50 | 15 | 300 | $1.03 \times 10^6$ | $-0.97 \times 10^6$ |

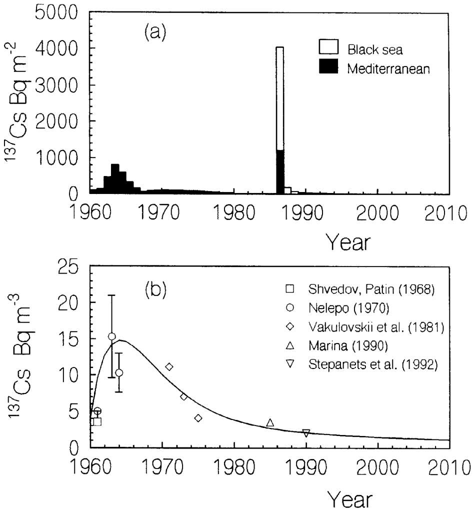

Fig. 1. Reconstructed deposition of $^{137}$Cs in the Mediterranean and Black Seas (a) and the concentration of $^{137}$Cs in the surface layer of the North-Eastern Atlantic (b).

### *3.2. Atmospheric nuclear weapons testing fallout*

The reconstruction of the $^{137}$Cs fallout on the Black and Mediterranean seas is shown in Fig. 1a. Data from Batrakov et al. (1994) for the deposition of $^{90}$Sr over the Black sea area in 1960–1973 were used to calculate the $^{137}$Cs bomb fallout over the Black Sea and Mediterranean Sea assuming that the ratio $^{137}$Cs/$^{90}$Sr = 2, chosen according to Batrakov et al. (1994). For $^{137}$Cs fallout in 1980–1985, a deposition rate of 13 $Bq\,m^{-2}\,a^{-1}$ in Monaco was adopted (UNEP/IAEA, 1992). The fallout in 1974–1980 was linearly interpolated. The reconstructed total density of the $^{137}$Cs deposition in 1960–1985 in the Black and Mediterranean seas is 3.7 $kBq\,m^{-2}$. It conforms with the value of $3.3 \pm 0.6$ $kBq\,m^{-2}$ obtained for the Mediterranean Sea by

Holm et al. (1988). For an assumed ratio $^{137}$Cs/$^{90}$Sr = 1.5, the reconstructed value reduces to 2.8 kBq m$^{-2}$.

### 3.3. Chernobyl fallout

Kanivets et al. (1997) presented calculations of the Chernobyl $^{137}$Cs fallout in the Black Sea in 1987–1994 based on observations at five meteorological stations in Crimea. These data were used in the present simulation. A small constant value, of 10 Bq m$^{-2}$ a$^{-1}$, was accepted for 1995–2010. Kanivets et al. (1997) argue that the data for the Crimean stations in 1986 (4987 Bq m$^{-2}$) are not representative of the whole Black Sea area. Therefore, a value of 4050 Bq m$^{-2}$ was adopted, as proposed by Vakulovskii et al. (1991). This estimation of the total amount of Chernobyl $^{137}$Cs in the Black Sea is based on a survey in October 1986. It was assumed in our simulations that the whole fallout in 1986 was instantaneous (1 May) because 90% of the fallout took place in May. The density of deposition in the Azov sea was the same as in the Black sea. The Chernobyl $^{137}$Cs fallout in the Mediterranean Sea in 1986 was accepted to be 1247 Bq m$^{-2}$, using estimates by UNEP/IAEA (1992) which suggested that the Chernobyl deposition is around 25–40% of the already existing inventory. It was assumed that it was also instantaneous (1 May). After 1986, the annual fallout was set at 10 Bq m$^{-2}$. The density of deposition was the same in the West and East Mediterranean and the Marmara Sea. To simulate the exchange of $^{137}$Cs with the Atlantic ocean through Gibraltar, the measured $^{137}$Cs concentrations in the surface layer of the adjacent area of the North-Eastern Atlantic were approximated by an empirical curve (Fig. 1b).

## 4. Results

### 4.1. Vertical distributions of temperature, salinity and $^{137}$Cs

The calculated vertical profiles of temperature and salinity in the Black sea and Eastern Mediterranean are given in Fig. 2. They show the main features of hydrography, caused by differences in the fresh water budget. The thickness of the surface mixed layer in the Black Sea varies between 12 m and 90 m in the summer and winter, respectively. In the Eastern Mediterranean, it ranges from 15 m in summer to the sea bottom through winter convection. The cold intermediate layer in the Black Sea is clearly visible. Deep winter convection in the Eastern Mediterranean results in a quasi-homogeneous distribution of salinity with depth. The simulated exchanges through the straits (Table 2) are consistent with most observations. It should be noted, however, that considerable discrepancies exist in estimates of the net fresh water flux $Q_f$ and these can have a large influence on the exchange through the straits. For the Mediterranean Sea, Ovchinnikov et al. (1976), Bethoux (1979) and Bryden and Kinder (1991) estimated $Q_f$ as 61 600; 76 000 and 44 000–52 000 m$^3$ s$^{-1}$, respectively. Simonov and Altman (1991) found that in the Black Sea $Q_f = 5900$ m$^3$ s$^{-1}$ whereas Ünlüata et al. (1990) estimated $Q_f = 9500$ m$^3$ s$^{-1}$.

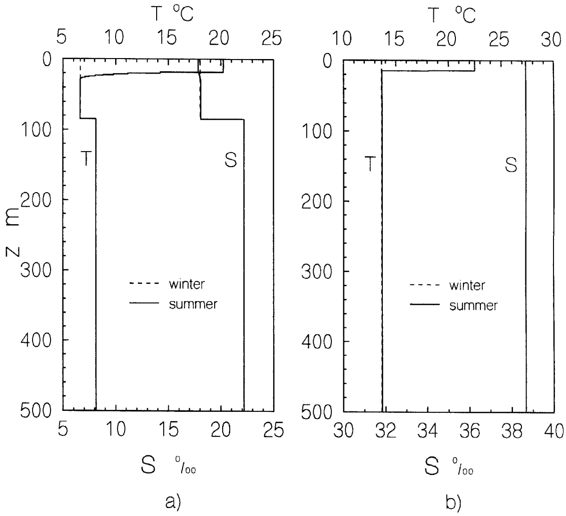

Fig. 2. Computed winter and summer profiles of the temperature and salinity in the Black Sea (a) and the Eastern Mediterranean (b).

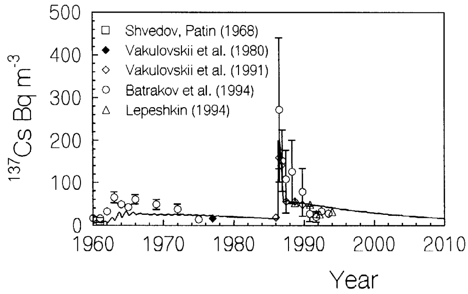

Fig. 3. Comparison of simulated with observed variations of $^{137}$Cs concentration in the surface mixed layer of the Black Sea. Data of Lepeshkin (1994) were adopted from Kanivets et al. (1997).

In Fig. 3, the results of the simulation of $^{137}$Cs concentrations in the surface mixed layer of the Black sea are compared with measured data. It can be seen that the model computes the tracer evolution quite realistically after both continuous and instantaneous inputs. Batrakov et al. (1994) calculated concentration of $^{137}$Cs from $^{90}$Sr data for 1960–1972 using a ratio $^{137}$Cs/$^{90}$Sr = 2. However, unlike $^{137}$Cs, the important source of $^{90}$Sr in this sea was run-off from the drainage basin. According to Batrakov et al. (1994), the ratio of river influx to atmospheric deposition of $^{90}$Sr in 1960–1973 was 1/3. Buesseler and Livingston (1996) estimate that the pre-Chernobyl $^{137}$Cs/$^{90}$Sr ratio was close to 1, whereas in the open ocean the $^{137}$Cs/$^{90}$Sr ratio is 1.45 (Bowen et al., 1974). This can explain the difference to simulated values for the 1960s.

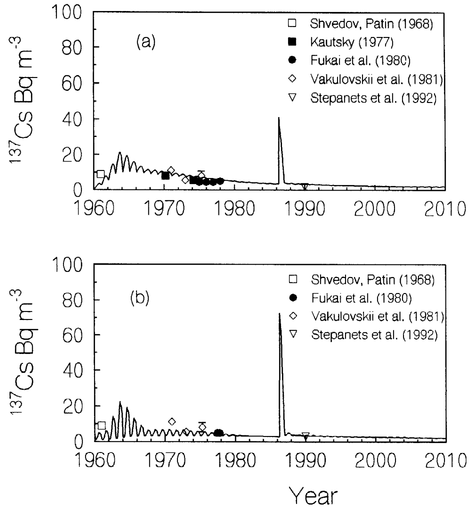

Fig. 4. Comparison of simulated with observed variations of $^{137}$Cs concentration in the surface layer of the Western (a) and Eastern (b) Mediterranean.

The calculated $^{137}$Cs activity in the Azov Sea water column in 1985 was 22 Bq m$^{-3}$. It increased up to 280 Bq m$^{-3}$ in May 1986 and fell to 38 Bq m$^{-3}$ in 1987. That is in good agreement with the range 20–40 Bq m$^{-3}$ observed by Nikitin et al. (1993) in 1987. The model predicts the decay of activity down to its pre-Chernobyl level in 2010. The results for the West and East Mediterranean are presented in Fig. 4. These calculations also fit to observations. Noticeable seasonal effects, caused by deep winter convection, were most pronounced in the Eastern Mediterranean, where winter convection reaches the bottom. As a result, the Chernobyl signal disappears in the surface waters of the Mediterranean sea proper.

The computed and basin-averaged measured profiles of $^{137}$Cs in the Black Sea in 1977 and at the end of 1986 are shown in Fig. 5. The model predicted quite well the surface and deep-sea concentrations. However, the model results for 1977 are in rather poor agreement with the observed profile of $^{137}$Cs in the intermediate layer between 100 and 500 m. This can be explained by local mixing of the Mediterranean water with the contaminated cold intermediate water (Buesseler et al., 1990; Ozsoy et al., 1993). Later the mixture of Mediterranean water and cold intermediate water gradually fills the intermediate layer.

### 4.2. *Inventory of radionuclide in the sub-basins and fluxes through the straits*

The calculated total amount of $^{137}$Cs in the seas as a function of time is shown in Fig. 6. It can be compared with some calculations based on observations. According to Vakulovskii et al. (1980), the total amount of $^{137}$Cs in the Black sea in 1977 was 1.37 ± 0.30 PBq in the water column and 0.18 PBq in bottom deposits. The computed

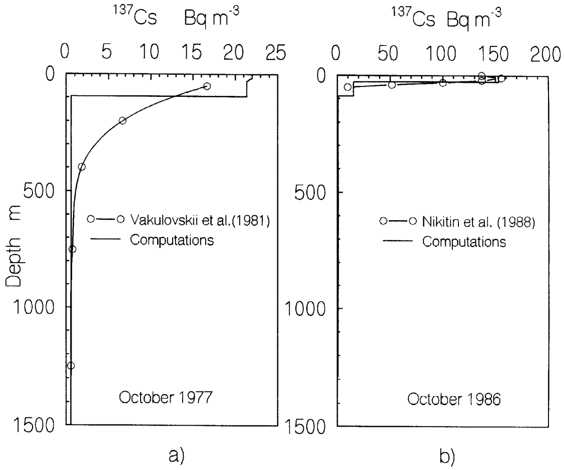

Fig. 5. Computed vs. observed profiles of $^{137}$Cs activity in the Black Sea in 1977 (a) and 1986 (b).

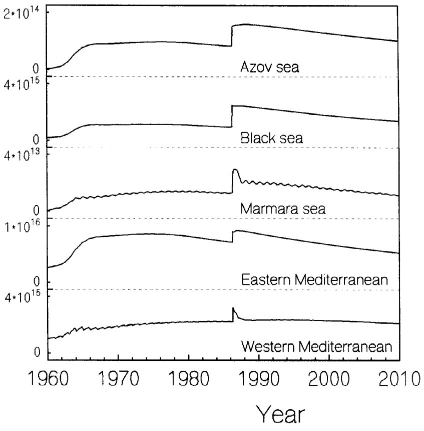

Fig. 6. Simulated $^{137}$Cs inventory (Bq) in the Mediterranean sea chain in 1960–2010.

amount was 1.15 PBq in the water column. By 1985, the computed amount fell to 0.98 PBq, which was comparable with a decay-corrected value of 1.05 PBq (Vakulovskii et al., 1980). Vakulovskii et al. (1988) estimated the increase of $^{137}$Cs in the Black sea in 1986 to be 1.66 PBq, whereas the predicted value was 1.55 PBq. However, Stepanets et al. (1992) estimated the total amount of $^{137}$Cs in the 0–50 m layer of the Black sea by the end of 1996 to be 4.07 ± 1.48 PBq, much higher than the estimate by Vakulovskii et al. (1977, 1988) of the total amount in the water column (2.67 PBq) and our computed value (2.53 PBq). This discrepancy can be explained by the strong patchiness of the contamination in 1986 resulting in the estimate's uncertainty. The

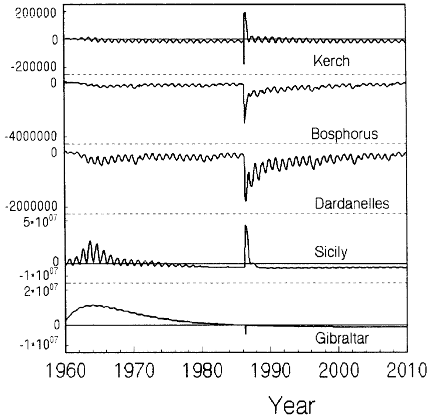

Fig. 7. Simulated fluxes of $^{137}$Cs through the Mediterranean straits (Bq $s^{-1}$).

model predicted that most of the total $^{137}$Cs inventory in the Azov Sea is deposited in the bottom sediments. Less than 10% of the activity remains in the water column. The calculated inventory in 1985 was 82 TBq which was comparable to the measurement-derived value of 70 TBq (Nikitin et al., 1993). The predicted amount of $^{137}$Cs in the water column and in bottom deposits in 1987 was 10 and 159 TBq, respectively. Nikitin et al. (1993) estimated these values to be 92 and 200 TBq, respectively. Exchange through the straits results in different temporal evolutions of the total amount of $^{137}$Cs in the Western and Eastern Mediterranean. The radionuclide brought into the Western Mediterranean through the Gibraltar strait and by atmospheric fallout was transported to the Sicily strait by the upper layer current. Thereafter, it entered the Eastern Mediterranean, mixed down by winter convection and returned to the Western Mediterranean by a bottom undercurrent through the Sicily strait. Therefore, the amount of $^{137}$Cs in the Western Mediterranean has remained almost constant since 1980 in contrast to the Eastern Mediterranean. This is why the Chernobyl signal disappeared quickly in the Western Mediterranean. The calculated inventory in 1985 for the whole Mediterranean Sea was 9.54 PBq which was comparable to the UNEP/IAEA (1992) estimate of 11 ± 1 PBq (10.2, 0.5, 0.3 PBq in the water column, bottom sediments and biomass, respectively).

The calculated fluxes of $^{137}$Cs through the Mediterranean straits are shown in Fig. 7. The tracer transport through the Kerch strait from 1960–1994 was 8.7 TBq (6% of fallout in the Azov Sea) and through the Bosphorus strait was 0.4 PBq (7% of fallout in the Black Sea). The exchanges through the Sicily and Gibraltar straits were more important for the radionuclide budget. The transport through Gibraltar in 1960–1985 was 4.7 PBq (40% of fallout in the Mediterranean Sea). The computed value differs from the estimated 1.2 PBq of UNEP/IAEA (1992) which was calculated with a supposed constant value of 5 Bq $m^{-3}$ for the Atlantic surface water activity.

## 5. Conclusions

In this paper, we have demonstrated the usefulness of simple one-and-a-half-dimensional modelling in simulating the transport of radionuclides in the system of the Mediterranean seas, forced with meteorological and run-off data and anthropogenic radioactivity input. It incorporates submodels of the Black Sea, the Azov Sea, Marmara Sea and the Western and Eastern Mediterranean. Simple models of the hydraulically controlled straits were applied to the Bosphorus, Dardanelles, Sicily and Gibraltar. An empirical relation was used for the shallow Kerch strait. The model was forced with time series of wind, temperature and freshwater influx.

This model was used to reconstruct and predict for the time period 1960–2010 the $^{137}$Cs contamination resulting from atmospheric testing of nuclear weapons and the Chernobyl accident. The comparisons of model prediction and observations are in reasonable accord and are probably as good as can be expected given the fallout data available. Mixing in the Mediterranean Sea proper, driven by buoyancy loss due to evaporation and winter cooling, results in ventilation of deep water, whereas the surplus of fresh water in the Black Sea prevents deep convection and maintains a stable stratification. Therefore the tracer ($^{137}$Cs) distributions essentially differ in the sub-basins. Exchanges through the straits also result in different temporal evolutions of the $^{137}$Cs signal and inventory in the sub-basins.

## Acknowledgement

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## Appendix A. Model equations

Presented here is the Black Sea submodel as an example of a multilayer Lagrangian model. The structure of the Marmara and Mediterranean submodels is identical to that described below. The Black Sea model includes the mass balance equation

$$Q_1^B + Q_2^B + Q_f^B + Q_f^A = 0 \tag{A.1}$$

where $Q_f^B$ is the flux of the fresh water (sum of the river run-off, precipitation and evaporation) in the upper Black Sea layer; $Q_f^A$ is the flux of the fresh water in the Azov Sea; $Q_1^B$ and $Q_2^B$ are discharges of the upper and bottom Bosphorus currents, respectively.

The evolution of the vertical hydrological structure is described by the system of equations for the heat, salt and radionuclide tracer concentration $C$ in the surface mixed layer (SML) of the Black Sea

$$V_u \frac{\mathrm{d}T_u}{\mathrm{d}t} = \sigma_u (T_n - T_u)(w_e + w_*) - q_T \sigma_u - (T_A - T_u) Q_1^B \tag{A.2}$$

$$V_u \frac{\mathrm{d}S_u}{\mathrm{d}t} = \sigma_u(S_n - S_u)(w_e + w_*) - (S_A - S_u)Q_1^B \tag{A.3}$$

$$V_u \frac{\mathrm{d}C_u}{\mathrm{d}t} = \sigma_u(C_n - C_u)(w_e + w_*) - q_c\sigma_u$$

$$- (C_A - C_u)Q_1^B - \lambda V_u C_u \tag{A.4}$$

the equation of the evolution of SML thickness

$$\sigma_u \frac{\mathrm{d}h_u}{\mathrm{d}t} = \sigma_u w_e - Q_2^B \tag{A.5}$$

and the equations for heat, salt and tracer in the internal layers

$$V_i \frac{\mathrm{d}T_i}{\mathrm{d}t} = \sigma_{i+1}(T_{i+1} - T_i)w_* - \sigma_i(T_i - T_{i-1})w_* \tag{A.6}$$

$$V_i \frac{\mathrm{d}S_i}{\mathrm{d}t} = \sigma_{i+1}(S_{i+1} - S_i)w_* - \sigma_i(S_i - S_{i-1})w_* \tag{A.7}$$

$$V_i \frac{\mathrm{d}C_i}{\mathrm{d}t} = \sigma_{i+1}(C_{i+1} - C_i)w_* - \sigma_i(C_i - C_{i-1})w_* - \lambda V_i C_i \tag{A.8}$$

with $i = 2, \ldots, n$.

The evolution of the displacement of internal layers is given by

$$\sigma_i \frac{\mathrm{d}h_i}{\mathrm{d}t} = Q_2^B. \tag{A.9}$$

The equations for the heat, salt and tracer concentration in the bottom layer are

$$V_1 \frac{\mathrm{d}T_1}{\mathrm{d}t} = \sigma_2(T_2 - T_1)w_* - (T_1 - T_S)Q_2^B, \tag{A.10}$$

$$V_1 \frac{\mathrm{d}S_1}{\mathrm{d}t} = \sigma_2(S_2 - S_1)w_* - (S_1 - S_S)Q_2^B, \tag{A.11}$$

$$V_1 \frac{\mathrm{d}C_1}{\mathrm{d}t} = \sigma_2(C_2 - C_1)w_*(C_1^i - C_S)Q_2^B - \lambda V_1 C_1. \tag{A.12}$$

Here $T_u$, $S_u$, $C_u$, $V_u$, $\sigma_u$, $h_u$ are the temperature, salinity, tracer concentration, volume, area and thickness of SML, respectively; $T_i$, $S_i$, $C_i$, $V_i$, $\sigma_i$, $h_i$ are the equivalent values of $i$th layer, respectively (for the bottom layer $i = 1$); $T_S$, $S_S$, $C_S$ are the temperature, salinity and concentration of the tracer in the Marmara waters that flow via the Bosphorus; $q_T$ is the heat flux; $Q_1^K$ is the inflow from the Azov sea, $T_\mathrm{A}$, $S_\mathrm{A}$, $C_\mathrm{A}$ are temperature, salinity and tracer concentration in the Azov sea, respectively; $\lambda$ is the decay constant of the radionuclide tracer; $q_c$ is the flux of the tracer in the upper layer; $w_e$ is the entrainment velocity in the lower boundary of SML; $w_*$ is the rate of internal mixing.

The linear equation of the state of sea water is

$$\rho = \rho_0(1 - \alpha_T(T - 17.5^\circ\text{C}) + \beta_T(S - 35‰)) \tag{A.13}$$

here $\alpha_T$ is the thermal expansion coefficient; $\beta_T$ is the salinity coefficient.

Two different regimes for the evolution of the vertical structure were distinguished:

(1) 'Entrainment regime', when the thickness of the surface mixed layer increases due to turbulent entrainment of the lower layer as a result of wind and convective mixing;
(2) 'Detrainment regime', when the turbulence in the surface mixed layer diminishes and a new surface mixed layer is formed with smaller thickness.

For $w_e$, the entrainment model of Resnyansky (1976) was used

$$w_e = \frac{2c_1 u_* \phi_1 - h_u q_b \phi_2}{b_u h_u} \tag{A.14}$$

where

$$\phi_1 = \begin{cases} \left(1 - \dfrac{h_u}{\Lambda_R}\right), & h_u \leqslant \Lambda_R \\ 0, & h_u > \Lambda_R \end{cases}$$

$$\phi_2 = \begin{cases} 1, & q_b \geqslant 0 \\ c_c, & q_b < 0, \end{cases}$$

Here $u_*$ is the friction velocity; $\Lambda_R = u_*/(c_2 f)$ is the limit of the wind mixing depth; $b = g(\rho_u - \rho_0)/\rho_0$ is the buoyancy; $q_b$ is the flux of buoyancy on the sea surface; $q_b = (\alpha_T q_T - \beta_T q_S)$; $q_S$ is the salt flux; $f$ is the Coriolis parameter; $c_1$, $c_2$, $c_c$ are empirical coefficients. For the detrainment regime, i.e. when value $w_\text{e} < 0$, it is assumed that a new SML arises with a thickness

$$h_u = \frac{u_*^3}{c_2 f u_*^2 + q_b/(2c_1)}. \tag{A.15}$$

In this case, the temperature, salinity and tracer concentration of the new layer are determined by Eqs. (A.6)–(A.8). Here $h_u$ is given by (A.15) with $w_e = 0$. The number of the internal layers increases by one, because the remnants of the upper layer form a new internal layer. The heat flux on the sea surface was parametrized as $q_\text{T} = a(T_u - T_a)$, where $T_a$ is the surface air temperature, $a = 5.10^{-6}\,\text{m}\,\text{s}^{-1}$ is an empirical parameter (Haney, 1970).

A simple parametrization of the exchange processes in the straits with two layer water exchange was proposed by Maderich and Efroimson (1986, 1990). It was supported by the laboratory experiments of Maderich et al. (1997). The discharges of upper and bottom currents are

$$Q_1 = -\frac{1}{4} G_s Q_m \left(1 + \frac{Q_f}{G_s Q_m}\right)^2$$
$$Q_2 = \frac{1}{4} G_s Q_m \left(1 - \frac{Q_f}{G_s Q_m}\right)^2, \tag{A.16}$$

where $Q_m = (b_s D \sigma_s)^{1/2}$, $b_s$ is the buoyancy in the strait, $D$ is the average depth of strait, $\sigma_s$ is the cross section area of the strait, $G_s$ is an empirical parameter of strait. The formulae for the Bosphorus, Dardanelles, Sicily strait and Gibraltar are the same, taking into account differences in the water balance.

The model consists of a set of empirical parameters ($c_1$, $c_2$, $c_c$, $w_*$, $G_s$). The calibration and sensitivity study for these parameters was carried out in the Black Sea case by Nikolenko and Efroimson (1989). They found that the best fit with the observed vertical profiles of temperature and salinity was for the parameter values: $c_1 = 10, c_2 = 2.6, c_c = 0.5, w_* = 5.1 \times 10^{-8}$ m s$^{-1}$. The model was most sensitive to $c_2$, $c_c$ and $w_*$ variations. The values of parameter $G$ were chosen to be 0.3; 0.09; 0.4; 0.5 for the Bosphorus, Dardanelles, Sicily strait and Gibraltar, respectively. With these parameter values the model reproduces the observed vertical structures of temperature and salinity and the water exchange between the Mediterranean sub-basins (see Table 2 and Fig. 2).

The system of ordinary differential equations (A.2)–(A.12) was solved numerically using a second order Eulerian method. In each time-step, the conditions of the appearance and disappearance of layers were controlled. The optimal number of layers that describe the vertical structure of the seasonal thermocline and halocline was 50 with minimal thickness 0.5 m.

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