Journal of Marine Systems xxx (2013) xxx–xxx

Contents lists available at SciVerse ScienceDirect

Journal of Marine Systems

journal homepage: www.elsevier.com/locate/jmarsys

Evolution and fluxes of ^{137}Cs in the Black Sea/Turkish Straits System/North Aegean Sea

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ARTICLE INFO

Article history:
Received 22 December 2011
Received in revised form 10 January 2013
Accepted 30 January 2013
Available online xxxx

Keywords:
Black Sea
Turkish Straits System
^{137}Cs
Fluxes
Vertical profiles and inventory

ABSTRACT

The vertical profiles of ^{137}Cs were determined in the North Aegean, Marmara and Black Seas, to assess inventories and fluxes of the radionuclide in these basins. The inventory of ^{137}Cs in the Western Black Sea integrated from the surface down to 400 m water depth is 3.4 ± 0.1 kBq m^{-2}, which is surprisingly close to the amount determined in 1988, decay corrected to 2007 (2.9 ± 0.1 kBq m^{-2}). On the other hand, based on the comparison of profiles roughly 20 years apart, it is estimated that about 1 kBq m^{-2} has been transferred from above the halocline to depths below the halocline, emphasizing the effective redistribution of tracers within the same period.

We estimate that about 12 TBq y^{-1} of ^{137}Cs presently leaves the Black Sea with the upper layer flow through the Bosphorus and only 2 TBq y^{-1} is returned with the lower layer inflow of Mediterranean water from the Marmara Sea. Accounting for river fluxes, estimated on the order of 2 TBq y^{-1} few years after the Chernobyl accident, and possibly decreased by now, we can thus estimate a net rate of loss of about 8–10 TBq y^{-1}.

Investigating the effective redistribution in the upper water column, the supply by the inflowing Mediterranean water alone does not explain the increase of ^{137}Cs concentration and inventory at intermediate depths in the Western Black Sea. The most important mechanism transferring ^{137}Cs and dissolved contaminants from the surface water to the sub-pycnocline layer appears to be the turbulent entrainment of a larger quantity of Black Sea water into the inflowing plume of Mediterranean water through mixing processes on the southwestern shelf and continental slope following its exit from the Bosphorus. This process produces an extra export of some10 TBq y^{-1} of ^{137}Cs from the surface to the sub-pycnocline depths of the Black Sea, a quantity comparable in magnitude to the total export out from the basin. It is the entrainment flux resulting from the mixing, and the further advection and penetration of this water into the Black Sea deeper layer (200–600 m) that seems to maintain the inventory with little change over time. Through these two processes the Black Sea surface layer (0–50 m) loses every year about 4% of its total inventory of ^{137}Cs.

1. Introduction

In recent years, increasing anthropogenic pressures produced significant changes in the ecosystems of the Black Sea and Turkish Straits. Great concern comes from a series of anthropogenic inputs (nutrients, heavy metals, radionuclides) from the atmosphere, the coastal areas and through river discharges (IOC, 2000; Polat and Tuğrul, 1995). Among these, there are some anthropogenic radionuclides and, in particular, those released by the Chernobyl accident on April 26, 1986. The fallout deriving from the accident was deposited in a very short time, but was very intense. ^{137}Cs (half-life 30.17 y) was one of the most abundant radionuclides released by the accident: it is estimated that about 1700–2400 TBq of ^{137}Cs were deposited onto the Black Sea in the first days of May 1986 (Egorov et al., 1999). Moreover, the Black Sea received a delayed input of about 26 TBq of Chernobyl ^{137}Cs through the rivers Danube and Dniepr in the period 1986–1994 (Egorov et al., 1999). This input is significantly greater than that produced by global fallout from atmospheric nuclear weapon testing in the early sixties: in fact, in the period of maximum global fallout deposition (1960–63), the average deposition of ^{137}Cs onto the Black Sea was about 294 TBq (IAEA, 2004).

^{137}Cs is a conservative radionuclide, mainly present in the open sea in the soluble form Cs^{+}. Its distribution is then strictly related to water mass circulation and transformation (Bowen et al., 1980). Also in the low-salinity Black Sea surface water, only a small fraction (<0.2%) of the total Cesium was found to be associated with suspended sediments

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0924-7963/$ – see front matter © 2013 Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.jmarsys.2013.01.006

(Buesseler et al., 1991), thus supporting its use as a conservative tracer in this study.

^{137}Cs distribution in the Black Sea was extensively studied after the Chernobyl accident through programs promoted and coordinated by the US Environmental Protection Agency, the European Commission and the International Atomic Energy Agency, that allowed an evaluation of the distribution and inventory in the whole basin and the identification of the main mechanisms controlling them (Buesseler et al., 1991; IAEA, 2004). However, till now no data have been published on ^{137}Cs concentrations and fluxes in the Turkish Straits System (TSS).

The Black Sea would have been the largest totally land-locked marine basin in the world, if it did not possess the limited exchange with the external ocean through the Bosphorus Strait. Freshwater input from large rivers (Danube, Dniepr, Dniestr and Don) and precipitation largely exceed loss by evaporation. It has limited exchange with the Mediterranean Sea through the TSS, consisting of the shallow Bosphorus (length 35 km, min. width 0.7 km, average depth ~65 m) and Dardanelles Straits (length 75 km, min. width 1.3 km, average depth ~55 m) and the Sea of Marmara. The density-driven two-layer exchange flow through the Straits carries at the surface the excess of Black Sea Water to the Mediterranean and at depth the saline Mediterranean water first to the Marmara Sea and then to the Black Sea. This hydrological balance, along with the restricted exchange through the Turkish Straits, supports a stable environment in the Black Sea, with two main components: colder, fresher, surface waters overlying warmer, more saline deep waters, anoxic below the permanent pycnocline (Özsoy and Ünlüata, 1997). The mean residence time for the Black Sea waters increases from 5 ± 4 yr at about the depth of the halocline, to 625 ± 430 yr at 500 m depth (Lee et al., 2002) and to the estimated values of 850 ± 300 yr (Top et al., 1990) well up to about 2000 yr (Östlund and Dyrssen, 1986) in the deeper Black Sea (Özsoy and Beşiktepe, 1995; Özsoy and Ünlüata, 1997).

Turbulent convection in the Black Sea efficiently ventilates the surface waters, leading to the formation of Cold Intermediate Water (CIW) overlying the pycnocline. The halocline and the pycnocline coincide typically at depths of ~100 m, which further coincides with the lower boundary of the CIW. The oxycline and the chemocline also occur in the same depth interval as the halocline, because similar mechanisms determine the vertical exchange of these scalar properties (Gaines et al., 2006; Murray et al., 1989, 1991; Özsoy and Ünlüata, 1997).

The cascading of Mediterranean waters in the South Western Black Sea effectively contributes to cross pycnocline mixing at intermediate depths and becomes further enhanced by double diffusive convection near the continental slope (Buesseler et al., 1991; Murray et al., 1991; Özsoy and Beşiktepe, 1995; Özsoy et al., 1993, 2002).

The surface circulation is characterized by a basin-scale, coherent, cyclonic boundary current, the Rim Current, enclosing a series of medium–small eddies along the coast and quasi-permanent larger features such as the Batumi anticyclonic gyre in the southeastern corner of the Black Sea (Özsoy and Ünlüata, 1997).

In the TSS, the surface waters reflect Black Sea characteristics, modified by mixing and entrainment between the layers at the Straits and along the basin, while the deeper waters are relatively uniform and show the influence of seasonal intrusions of Mediterranean waters into the basin (Beşiktepe et al., 1993, 1994). As in the Black Sea, the two-layer flow at the Straits produces a permanent and stable pycnocline at a depth of about 25 m. In the Marmara Sea, the mean upper layer circulation is anticyclonic, mainly driven by the southward flowing Bosphorus jet in the enclosed domain. Mediterranean water, more saline and well oxygenated, entering from the Dardanelles, supplies the sub-halocline layer. The intrusion of new Mediterranean water into the Marmara Sea is the sole mechanism of ventilation of deep layers, only partly compensating the oxygen consumed by the degradation of organic matter sinking from the high productivity surface layer. The circulation in the sub-halocline is characterized by a slow drift from West to East following the bathymetry. The average residence time of the surface water is on the order of few months, while it is estimated to be about 7 years for the deep waters (Beşiktepe et al., 1993, 1994).

In this paper we present the first vertical profiles of ^{137}Cs in the water column of the North Aegean and the Marmara Sea along with one station in the Western Black Sea, already visited in 1986 and 1988, and discuss the role of the exchanges at the TSS in the total budget of the radionuclide in the Western Black Sea.

2. Sampling and analysis

Samples were collected in 2007 in two of the three northern deep basins of the Marmara Sea and in the interior of the South Western Black Sea during an oceanographic cruise of the Turkish R/V “Bilim”. The North Aegean Sea samples were collected in 2001 by the Italian R/V “Urania” (Fig. 1, Table 1).

CTD casts were performed to define the hydrological structure at the sampling sites. For the ^{137}Cs analyses, water samples 20 L in volume were collected by a Rosette sampler. In the surface layer two samples were collected in the Marmara Sea and one in the Black Sea. In the sub-halocline layer samples were collected at regular intervals. The water samples were acidified with 50 mL of concentrated HCl and transferred in plastic containers to the on-land laboratory, where cesium was pre-concentrated by the classical AMP (Ammonium MolibdoPhosphate) method (IAEA, 1970). Briefly, a known amount of ^{134}Cs (about 1.5 Bq) is added to the samples as yield determinant and the pH is adjusted to 1.5. Six grams of AMP are then added to the solution, air-stirred for at least 3 h to allow cesium coprecipitation with AMP. The supernatant is then discarded and the AMP precipitate is collected in plastic beakers and dried in the oven at 50 °C, until all residual water is removed. Once dry, AMP is transferred in calibrated geometry for gamma spectrometry. The chemical recovery for this set of samples was 95 ± 2%.

Gamma spectrometry was performed using an ORTEC High Purity Germanium, low background well detector (2.28 keV resolution at 1332 keV), with absolute efficiency of 15% for ^{137}Cs. Samples were counted for 60,000–300,000 s, depending on their specific activity. The minimum detectable activity ranged between 0.2 and 0.4 Bq m^{-3}, depending on counting time. Detector calibration was performed with an Amersham QCYK primary standard solution, containing 10 gamma-emitting radionuclides, covering the energy range from 59 keV (^{241}Am) to 1836 keV (^{88}Y). Accuracy of the results is regularly checked by the analysis of standard reference materials (IAEA 300 and 315, NBS 4350b).

3. Results

The ^{137}Cs concentrations in the water column of the Black and Marmara Sea and North Aegean Sea are reported in Table 1. In the Marmara and Black Sea the vertical profiles of this radionuclide show a decreasing trend from surface to bottom, while in the Aegean Sea relatively high values are found in the surface modified Black Sea Water and in the deep water filling the Skyros basin, with a relative minimum at intermediate depths marking the Levantine origin water.

3.1. Black Sea

At St. M30M45, the upper 10 m layer is characterized by constant, low salinity (18.07‰) values and low temperature (Fig. 2), indicating the beginning of the formation of the seasonal thermocline. This water mass overlies the Cold Intermediate Layer, centered at about 50 m depth, just above the pycnocline, with core temperature and salinity of 7.4 °C and 18.3‰, respectively. Below this layer both salinity

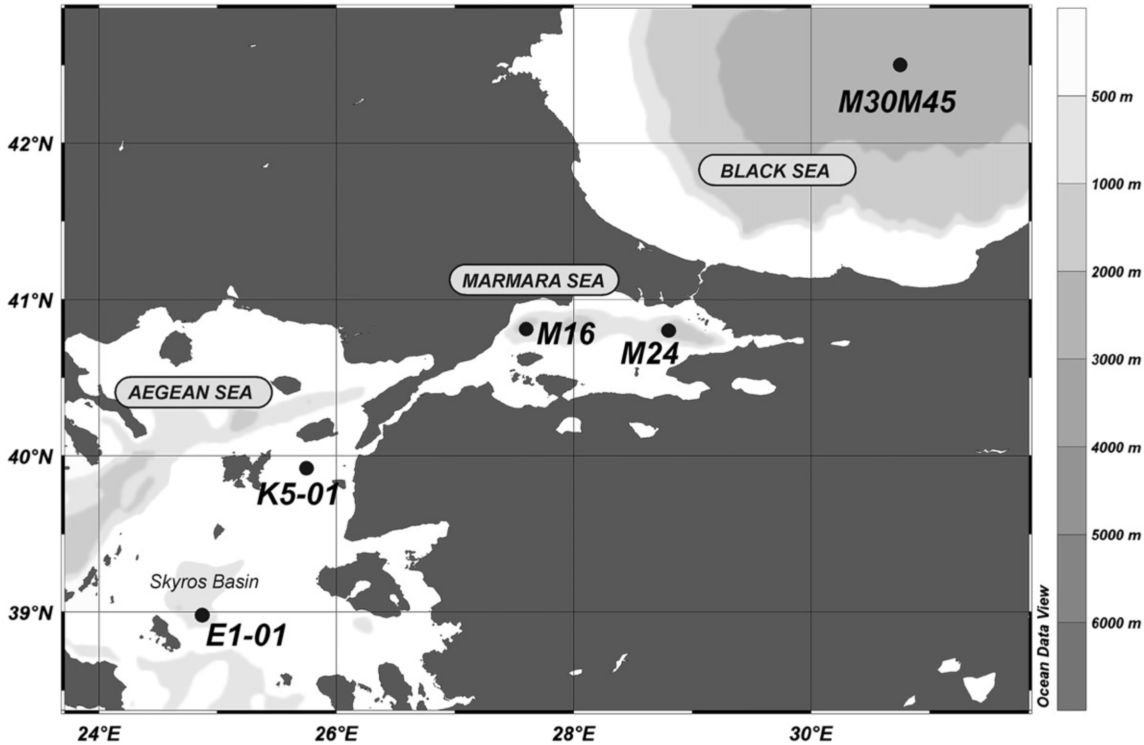

Fig. 1. Sampling sites.

Table 1
^{137}Cs concentration in the water column of the Marmara Sea (M16, M24), Black Sea (M30M45) and North Aegean Sea (E101, K5).

Station/date	Coordinates/water depth (m)	Sampling depth (m)	Sal (‰)	T Pot. (°C)	^{137}Cs (Bq m^{-3}) 2001	Uncertainty (Bq m^{-3}) 2001	^{137}Cs (Bq m^{-3}) 2007	Uncertainty (Bq m^{-3}) 2007
M16	40° 49′ N 27° 36′ E	10	23.71	13.75			14.0	0.6
May 5, 2007	Depth: 1135	40	38.41	15.15			4.8	0.6
		160	38.66	14.64			4.2	0.6
		550	38.65	14.33			4.0	0.2
		1120	38.65	14.26			3.9	0.2
M24	40° 48′ N 28° 48′ E	0	21.53	13.18			15.0	0.9
May 4, 2007	Depth: 1200	40	38.45	15.09			3.5	0.1
		160	38.65	14.68			3.6	0.2
		400	38.65	14.35			4.4	0.3
		700	38.65	14.32			3.9	0.4
		900	38.65	14.31			4.0	0.3
		1150	–	–			3.6	0.4
M30M45	42° 30′ N 30°45′ E	10	18.07	12.98			20.0	1.1
May 10, 2007	Depth: 1770	50	18.37	7.41			19.5	0.5
		150	21.27	8.57			7.9	1.2
		250	21.70	8.76			4.5	0.3
		500	20.06	8.34			0.9	0.1
		1000	22.28	8.36			0.6	0.1
		1500	22.32	8.88			0.6	0.1
		1750	22.33	8.90			0.7	0.2
K5-01	39° 55′ N 25°45′ E	5	35.86	18.36	6.2	0.5	5.4 (*)	0.4
June 16, 2001	Depth: 83	23	38.89	17.43	3.8	0.2	3.3 (*)	0.2
		78	38.92	15.09	3.6	0.3	3.2 (*)	0.3
E1-01	38° 59′ N 24° 52′ E	3.5	38.99	21.03	3.9	0.2	3.4 (*)	0.2
June 16, 2001	Depth: 1037	25	39.02	19.75	3.0	0.1	2.6 (*)	0.1
		200	38.93	14.88	3.4	0.2	2.9 (*)	0.1
		500	39.07	13.49	4.3	0.2	3.7 (*)	0.2
		900	39.16	13.23	4.8	0.2	4.1 (*)	0.2

(*) Concentrations decay corrected to 2007.

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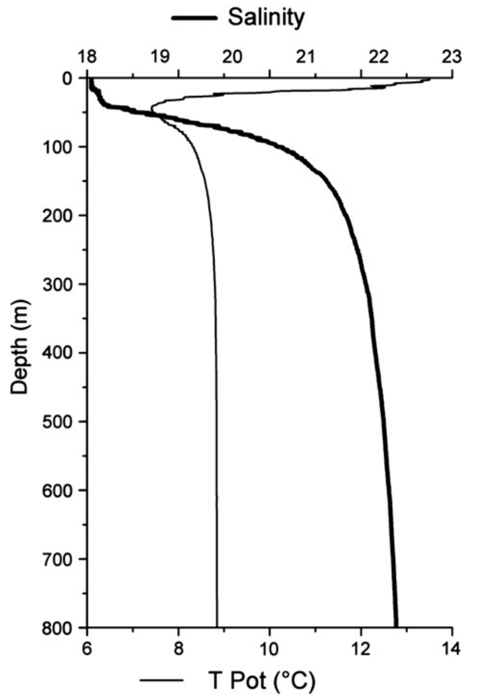

Fig. 2. Vertical profiles of salinity and potential temperature at station M30M45, Black Sea, 2007.

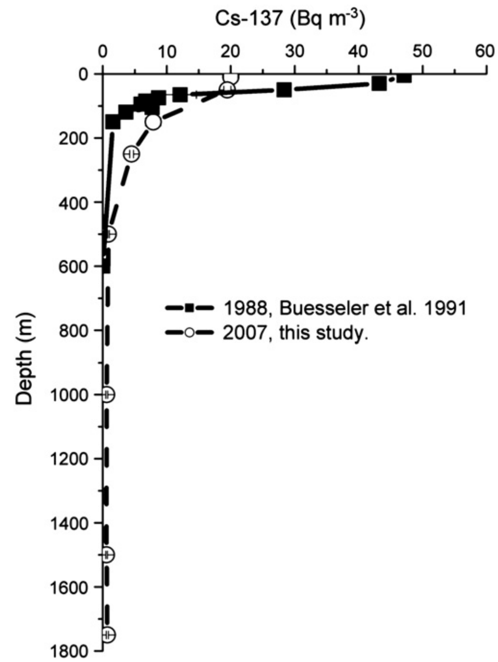

Fig. 3. Time trend of the vertical profile of ^{137}Cs in the Western Black Sea. Open circles: Station M30M45, this work, 2007. Solid squares: 1988 (Buesseler et al., 1991), decay corrected to 2007.

and potential temperature progressively increase, reaching maximum values of 22.3‰ and 8.9 °C at maximum depth of the profile.

Two samples for ^{137}Cs analysis were collected in surface water (mixed layer, 10 m, and core of CIW, 50 m). Below the halocline, three samples were retrieved in the layer 150–500 m, where the intrusions of shelf-modified water are important, and three samples in the deep, stagnant waters (1000, 1500 and 1750 m). The upper 50 m layer of water shows uniform ^{137}Cs concentration (about 20 Bq m^{-3}), decreasing through the halocline to 7.9 ± 1.2 Bq m^{-3} at 150 m and to 4.5 ± 0.3 Bq m^{-3} at 250 m depth. Below the 500 m depth layer the concentration reaches a mean value of 0.64 ± 0.07 Bq m^{-3} until the bottom (Fig. 3).

The vertical profile of ^{137}Cs was also determined in 1988 by Buesseler et al. (1991) at a station (St. 9: 42° 09.62′N, 31° 18.0′E), about 50 km apart from our station M30M45. Both stations are located at water depths > 1500 m, outside the continental slope and the main path of the Rim current. Both profiles, decay corrected to 2007, are plotted in Fig. 3: in 2007 the concentrations in the surface layer are significantly lower (less than a half) than expected by radioactive decay only, but have been significantly increased at depth, below the halocline.

3.2. North Aegean Sea

Two stations were sampled in 2001 in the N-Aegean Sea (Fig. 1). This area is strongly influenced by the input of low salinity–high ^{137}Cs concentration water from the Black Sea. Previous studies showed that in general, ^{137}Cs concentration in the surface modified Black Sea Water (BSW) decreases with increasing salinity (range: 3 to 15 Bq m^{-3} of ^{137}Cs, salinity range: 39–31‰), due to mixing with low Cs/high salinity Aegean waters (Papucci et al., 2003). Station K5-01 is close to the Dardanelles Strait, with a water depth of 85 m. The surface 10 m layer is occupied by modified BSW, with salinity around 36‰, overlying a layer of saltier water (38.94–38.97‰) of Levantine origin, that also characterizes the depth interval 0–350 m at Station E1-01, in the Northern Skyros Basin, where the surface BSW layer is absent (Fig. 4). More saline and colder water fills the deepest, isolated part of the Skyros basin. At K5-01 ^{137}Cs concentration in BSW is 6.2 ± 0.5 Bq m^{-3}. The subsurface water at Station K5-01 and the surface water at Station E1-01 show an average concentration of 3.6 ± 0.3 Bq m^{-3}, while the "isolated" waters filling the deep basin (below 800 m) contain about 5 Bq m^{-3} of the radionuclide.

3.3. Marmara Sea

Stations M16 and M24 are located in the northern part of the Marmara Sea in the westernmost and easternmost of the three main topographic depressions characterizing the area. At both stations the surface 25 m layer was occupied by Modified BSW, overlying water of Mediterranean origin. Station M24, in the Eastern Marmara Sea is under the direct influence of the Bosphorus inflow and is characterized by lower surface salinity (21.53‰) than at Station M16 (23.68‰). A Cold Intermediate Layer, formed by local cooling in the Marmara Sea, is present at both stations, but more pronounced at M16. No significant differences are found below the halocline (20–40 m) with salinity progressively increasing from 38.55‰ to 38.65‰ and potential temperature decreasing from 15.17 °C to 14.28 °C. ^{137}Cs concentrations reflect the characteristics of the two main water masses, but not the fine structure shown by the hydrological parameters. The vertical profiles (Fig. 5) show higher values in the surface Black Sea Water (15.0 ± 0.9 and 14.0 ± 0.6 Bq m^{-3} in the eastern and western basins, respectively) and almost constant concentrations in the sub-halocline waters, with mean values of 3.8 ± 0.3 Bq m^{-3} in the eastern basin and 4.2 ± 0.4 Bq m^{-3} in the western basin. The only significant difference (95% confidence level) between the two basins is at 40 m depth, where ^{137}Cs concentration in the western basin (4.8 ± 0.6 Bq m^{-3}) is higher than the one in the eastern basin (3.5 ± 0.1 Bq m^{-3}).

4. Discussion

Due to the intense direct Chernobyl fallout and to the delayed input from rivers, the Black Sea became a source of radionuclides

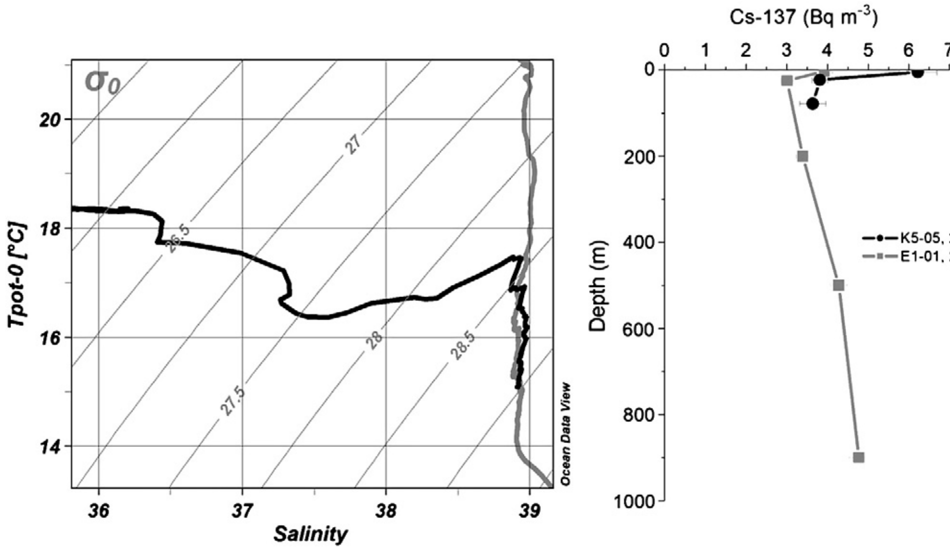

Fig. 4. N. Aegean Sea (2001): Theta/S diagrams and vertical profiles of ^{137}Cs (Gray: St. K5; Black: St. E101).

like Cs isotopes, ^{90}Sr, and the shorter-lived ^{144}Ce, ^{106}Ru (Livingston et al., 1988) for the Marmara and Mediterranean Sea. Some of these, like the long lived ^{137}Cs, are still easily detectable in the Black Sea and traceable along their pathway in the North Aegean Sea. After the accident, the radioactivity levels in surface seawater increased of 1–2 orders of magnitude (Livingston and Povinec, 2000). Concentrations were of no radiological concern, however, the determination of the spatial distribution of the long lived radionuclides like ^{137}Cs, for which the input function is known and information on the time trend in surface water is available, can greatly help in elucidating the exchanges of dissolved contaminants between the basins and the role of the TSS in the contaminants budget of the Black Sea.

In Fig. 3 we show how the vertical profile of ^{137}Cs has changed since 1988 in the South Western Black Sea. ^{137}Cs concentration below the halocline is significantly increased, while the levels in surface water are less than a half of what would be expected from physical decay only. From a quantitative point of view, the inventories in the last 20 years did not decrease: 2.9 ± 0.1 kBq m^{-2} in 1988, decay corrected to 2007 (layer 0–400 m) and 3.4 ± 0.1 kBq m^{-2} (same depth interval) in 2007. The increase at depths below the halocline, in this deep-sea area, compensates the loss at the surface. Vertical diffusion is strongly limited by the very high density gradient between surface and deep water and cannot account for such a large transfer of ^{137}Cs. We discuss below the relative importance of the processes responsible for this vertical re-distribution with time.

Based on mean annual volume fluxes in the TSS estimated by Beşiktepe et al. (1994) (Fig. 6a) and on our ^{137}Cs measurements in the North Aegean, Marmara and Black Seas (Fig. 6b), we have calculated ^{137}Cs fluxes (TBq y^{-1}) in the system (Fig. 6b), using the equations reported below.

In the TSS:

$$\text{Aegean to Dardanelles} = F_1 * C_1$$

$$\text{Dardanelles to Marmara} = (F_1 – F_2) * C_1 + F_3 * C_4$$

$$\text{Marmara to Bosphorus} = F_5 * C_2$$

$$\text{Bosphorus to Black Sea} = (F_5 – F_6) * C_2 + F_7 * C_3$$

$$\text{Black Sea to Bosphorus} = F_9 * C_3$$

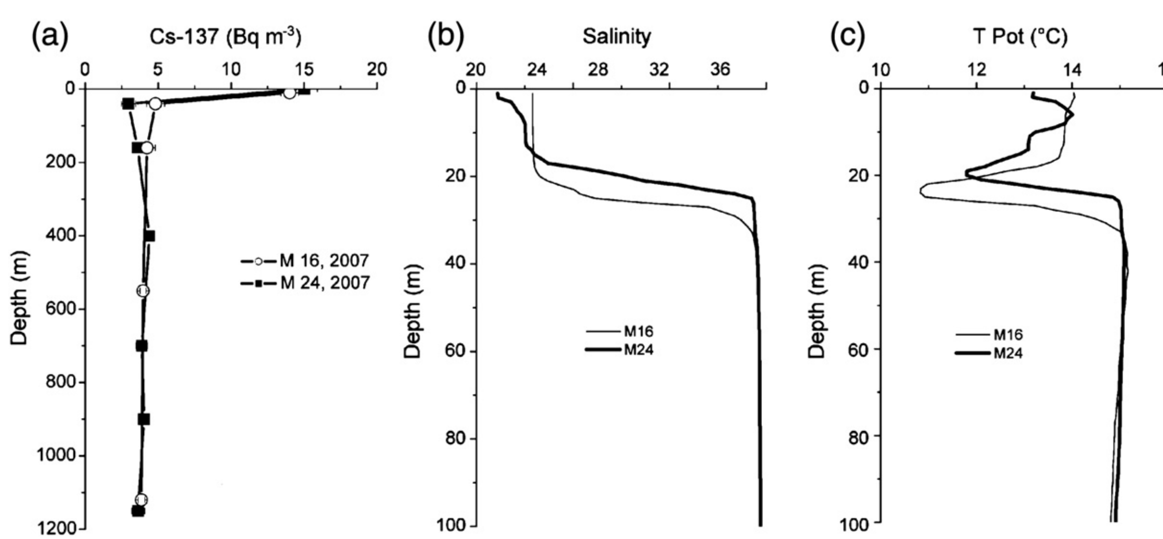

Fig. 5. Stations M16 and M24 in the Marmara Sea (2007): vertical profiles of ^{137}Cs in the whole water column (a); salinity (b) and potential temperature (c) in the upper 100 m.

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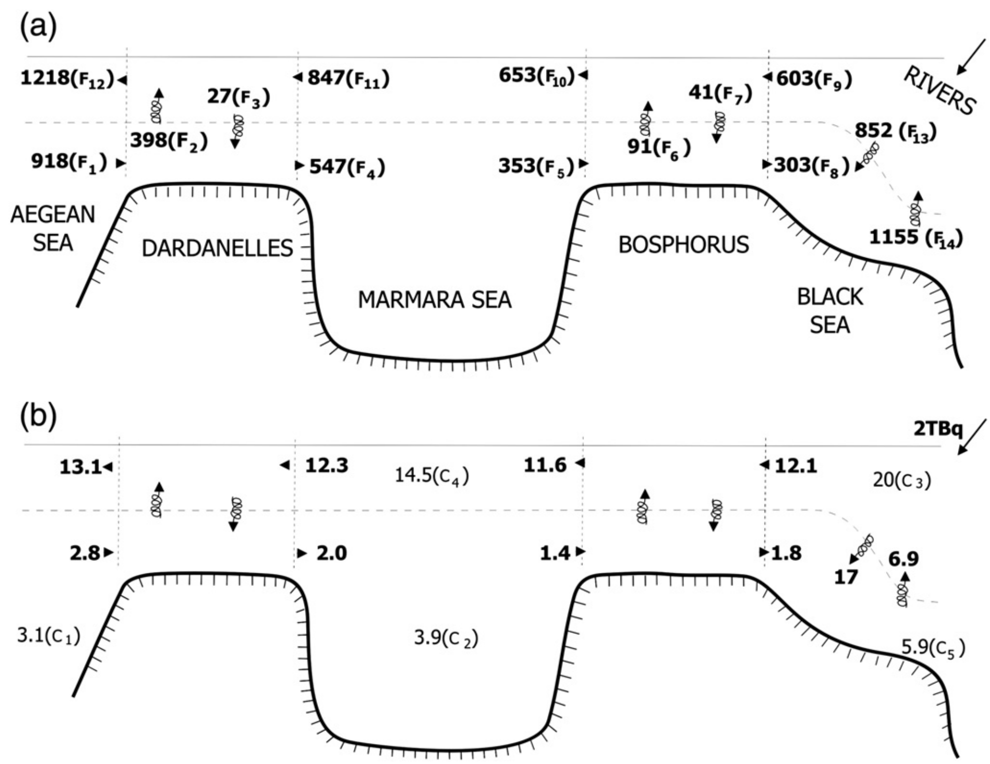

Fig. 6. (a) Volume fluxes ($km^3\ y^{-1}$) across the Turkish Strait System according to Beşiktepe et al. (1994) and (b) concentrations (C_{1-5}, Bq m^{-3}) and fluxes (TBq y^{-1}) of ^{137}Cs in the TSS in 2007.

Bosphorus to Marmara $= (F_9 - F_7) * C_3 + F_6 * C_2$

Marmara to Dardanelles $= F_{11} * C_4$

Dardanelles to Aegean $= (F_{11} - F_3) * C_4 + F_2 * C_1$

^{137}Cs concentration in Mediterranean Water entering the Black Sea, $C_5 = ((F_5 - F_6) * C_2 + F_7 * C_3)/F_8$.

On the Black Sea shelf:

Mediterranean water to surface water $= C_5 * F_{14}$

Surface water to Mediterranean water $= C_3 * F_{13}$.

where F_n are the volume fluxes in m^3y^{-1}(Beşiktepe et al., 1994) between the different compartments, and C_{1-4} are ^{137}Cs mean concentrations in the subsurface Aegean Sea (C_1), sub-halocline Marmara Sea (C_2), surface Black Sea (C_3) and surface Marmara Sea (C_4). The volume fluxes used in the computation have been obtained from a box model of the TSS using surface and river flux estimates and salt budgets obtained from long term observations of salinity at control sections (Beşiktepe et al., 1993, 1994; Ünlüata et al., 1990). Although these estimates were later updated to account for seasonal changes of up to 40% of the mean (Beşiktepe, 2003), we use only the long-term average fluxes which we believe to be more compatible with the time scales of tracers.

The Mediterranean Water entering the Dardanelles is North Aegean water of Levantine Origin, characterized by relatively high salinity (38.94–38.97‰). We have calculated ^{137}Cs level in this water mass ($C_1 = 3.1$ Bq m^{-3}) as the mean of the concentrations in the depth layer 23–78 m of station K5-01 and in the depth layer 3–200 m of station E1-01, decay corrected to 2007. Taking into account mixing at the strait, the flux of ^{137}Cs entering the Marmara Sea is 2.0 TBq y^{-1}. Dividing this ^{137}Cs flux by the water flux F_4 we estimate an average ^{137}Cs concentration of 3.6 Bq m^{-3} in this inflowing water mass, only slightly higher than that in the N-Aegean and in very good agreement with our data in the subhalocline layer of the Marmara Sea ($C_2 = 3.9$ Bq m^{-3}, mean of the concentrations measured in the depth layer 40 m to bottom at stations M16 and M24). The flow towards the Aegean Sea is 6 times higher, 13.1 TBq y^{-1}, with an estimated average concentration at the exit of the strait of 10.8 Bq m^{-3}. The deep Marmara Sea water flowing towards the Black Sea is further enriched in ^{137}Cs through mixing at the Bosphorus strait. The flux to Black Sea is 1.8 TBq y^{-1} (average concentration $C_5 = 5.9$ Bq m^{-3}). Assuming that ^{137}Cs concentration of the surface waters entering the Bosphorus (C_3) is the same as that at our deep-sea station M30M45 (20 Bq m^{-3}), ^{137}Cs flux from the Black Sea to the Bosphorus is 12.1 TBq y^{-1}, becoming 11.6 TBq y^{-1} at the entrance of the Sea of Marmara, after mixing at the Strait.

We did not find any recent data on ^{137}Cs input flux from rivers, but Egorov et al. (1999) estimated for 1995 a flux of 2 TBq, which we can assume as an upper limit also for 2007. Considering this contribution, a net amount of about 10 TBq of ^{137}Cs left the Black Sea surface layer in 2007 and less than 2 TBq flew back with the modified Mediterranean water through Bosphorus. At present, ^{137}Cs transported into the Black Sea with the modified Mediterranean Water mass is only some 20% of the amount leaving the Black sea in the surface layer, i.e. the Black Sea is progressively cleaning-up.

Also in the past the flux of ^{137}Cs leaving the Black Sea has always been higher than the influx from the Marmara Sea: the concentration of the radionuclide in the Black Sea surface layer has been, for most of the time, higher than in the Mediterranean water entering the TSS (Egorov et al., 1999) and the water outward flux is double than the influx.

Despite this, the inventory of ^{137}Cs in the deep South Western Black Sea remained substantially unchanged from 1988 till today. From 1988 to 2007 at station M30M45, the inventory decreased of about 1000 Bq m^{-2} (excluding radioactive decay) in the depth interval

0–50 m and increased of an even greater amount, about 1200 Bq m^{-2}, between 100 and 400 m (excluding radioactive decay). The increase in this depth layer is not justified by the return inflow from the Marmara Sea alone. The present results confirm the importance of shelf and slope mixing processes, identified to be the main agents responsible for interior mixing in the Black Sea confined to the upper 500 m (Özsoy and Ünlüata, 1997). Several authors (Buesseler et al., 1991; Latif et al., 1991; Özsoy et al., 1993, 2001, 2002) have already evidenced the importance of the mixing processes taking place on the southwestern shelf of the Black Sea between the modified Mediterranean water mass injected through the Bosphorus and the resident water. In fact, after passing a sill outside Bosphorus and flowing through a channel, the denser Mediterranean water evolves over the wide continental shelf by entraining ambient water several times greater than its original volume. Along the steep continental slope, the entrainment is increased by an order of magnitude. The plume that has evolved over the continental shelf finally cascades down the continental slope after flowing over a distance of 50 km from the Bosphorus exit (Latif et al., 1991; Özsoy et al., 1993, 2001). Measurements of hydrological parameters and of radioactive tracers (Buesseler and Livingston, 1997; Östlund, 1974; Özsoy and Beşiktepe, 1995; Özsoy et al., 2002; Rank et al., 1999; Top, 1999) as well as model results (Stanev et al., 1999; Staneva et al., 1999) indicate that the influence of the mixing initiated by the modified Mediterranean Water is limited to the upper 500 m depth.

To define the magnitude of this vertical transport, we have used the volume flux indicated by Beşiktepe et al. (1994), and reported in Fig. 6. The transport from surface Black Sea water to the Mediterranean water is then given by $F_{13} * C_3 = 17.0$ TBq y^{-1}, while the flux from Mediterranean Water to Surface Water is $F_{14} * C_5 = 6.9$ TBq y^{-1}. In 2007 the net flux of ^{137}Cs from surface to the sub-halocline waters is then about 10 TBq y^{-1}. The amount of ^{137}Cs transferred from the surface and coastal water masses and subsequently advected to the central part of the Black Sea through this process equals the amount leaving the surface Black Sea through Bosphorus.

5. Conclusions

A complete set of measurements of the vertical distribution of ^{137}Cs in the system North Aegean, Marmara and Western Black Sea allowed to produce the first estimate of the fluxes of this radionuclide through the Turkish Straits System and to define the role of the Mediterranean influx on the Black Sea budget. The Black Sea surface layer is continuously cleaning-up from ^{137}Cs through two main mechanisms:

- 12 TBq y^{-1} of ^{137}Cs, about 2% of the total inventory in the 0–50 m depth layer, are presently exported to the Marmara Sea through Bosphorus;
- in the southwestern Black Sea shelf area a similar amount, about 10 TBq y^{-1} of ^{137}Cs, is transferred, through mixing and entrainment, from surface/coastal waters to the Mediterranean water flow coming from the Marmara Sea and injected at intermediate depths in the interior of the Black Sea basin.

As a result, the "cleaning rate" from ^{137}Cs of the Black Sea surface oxygenated water, important for health and economic activities, is relatively fast. The same applies to all dissolved pollutants injected to the Black Sea surface waters.

Acknowledgments

This study has been partly funded by the EU 6th Framework project SESAME (EC contract no. GOCE-036949). We would like to thank Süleyman Tuğrul for providing local laboratory facilities; the crew and scientific team on board the R/V Bilim for careful seawater sampling; the IMS-METU personnel in Erdemli for their assistance during the analytical treatment.

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Please cite this article as: Delfanti, R., et al., Evolution and fluxes of ^{137}Cs in the Black Sea/Turkish Straits System/North Aegean Sea, J. Mar. Syst. (2013), http://dx.doi.org/10.1016/j.jmarsys.2013.01.006