MODELLING THE DISTRIBUTION OF ^{90}Sr AND ^{137}Cs IN THE MEDITERRANEAN SEA (MTPII - MATER)

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Abstract

Within the frame of the MTPII-MATER project (MAST), the distribution of ^{90}Sr and ^{137}Cs in the Mediterranean Sea was modelled, as these radionuclides are useful tracers of water circulation. The Mediterranean Sea was divided into 81 boxes, corresponding to 21 regions, taking into account water mass circulation, bathymetry and data availability. Transfer rates were obtained from the MOM model run under MEDMEX conditions. The model was run with realistic inputs, which included weapons global fallout, Chernobyl ^{137}Cs, nuclear industry and river runoff. It was observed that existing data are scarce, especially in the eastern Mediterranean. In general, model predictions agreed well with observations, showing maximum concentrations in surface waters and maxima due to global fallout (^{137}Cs and ^{90}Sr) and to the Chernobyl accident (^{137}Cs only).

1. INTRODUCTION

1.1. The MTPII-MATER Project

Established by the European Commission in 1993, the MAST III Programme Mediterranean Targeted Project (MTP) represents a major effort in the understanding of the Mediterranean Sea today (both Western and Eastern basins). During the MTP I phase (1993-1996) 180 main scientists from 70 research centres in 14 European countries worked in 14 independent projects. During the MTP II phase, the MTP II - MATER Project integrates the efforts of 220 main scientists from 80 research centres in 11 European countries and 2 African countries.

The overall objective of the MTP II MATER is to study and to quantify the triggering and controlling mechanisms of mass and energy transfer between the different compartments (land-sea, sea-atmosphere, water-sediment, living-non living, pelagos-benthos), in contrasting trophic environments (from eutrophic to oligotrophic) of the Mediterranean Sea and to investigate the ecosystem response to such a transfer. The program is designed to assess the processes at various time and space scales, from the entire basin down to the local scale, and from daily processes up to inter annual variations.

The MATER project is an integrated and multiscale approach structured in seven research Tasks or scientific themes: Seasonal and interannual variability of the general circulation, Water mass formation processes and thermohaline circulation, Subbasin scale circulation and mesoscale dynamics, Processes controlling particle dynamics, Biotic and abiotic processes controlling biogeochemical cycles and fluxes, Benthic response to downward fluxes and Ecosystem studies. And five Work Packages or implementation areas: Basin scale process studies, Multidisciplinary studies in the western Mediterranean subbasin, Multidisciplinary studies in the Adriatic / Ionian subbasin, Multidisciplinary studies in the eastern Mediterranean and Ecological models and process studies.

1.2. Modelling

Within this large project, numerous pollutants are studied, mainly as tracers of oceanographic processes. Various marine processes, covering different time scales, can be studied using radiotracers, depending on the phenomena involved and the observational techniques used. Some natural radionuclides, such as ^{210}Pb and ^{7}Be, are continuously entering the marine environment in association with particles. On the other hand, some artificial radionuclides, such as ^{90}Sr, ^{137}Cs and ^{239,240}Pu entered the marine environment mainly during the sixties following nuclear tests in the Northern Hemisphere [1]. Both contributions, mostly of atmospheric origin, can today be traced in the marine environment using suitable techniques.

^{90}Sr and ^{137}Cs are, essentially, soluble elements in seawater [2] and have a radioactive half-life close to 30 years. Thus, they are useful radiotracers to study water mass transport in the oceans [3-5]. In this sense, the Mediterranean Sea has often been described as a small scale oceanographic laboratory [6] and offers a unique opportunity to test the suitability of using ^{137}Cs as a long-term radiotracer of water mass transport on a large scale.

The aim of this work was to develop a numerical model to contribute to the understanding of the main features of global circulation in the Mediterranean Sea, and to explain past and present levels of ^{137}Cs and ^{90}Sr. To do this, a 81 box model was developed and run with realistic input functions. Results were compared with ^{90}Sr and ^{137}Cs concentrations in Mediterranean Sea waters during the period 1954-1994 reported in the scientific literature.

2. METHOD

2.1. Model

The Mediterranean Sea was divided into 21 regions (Figure 1) and its water column was split into four layers, taking into consideration the different water types present in each region. The North Adriatic Sea was considered as one single box. Each box was carefully defined taking into account bathymetry, main water fluxes, input sources and data availability (used for model validation purposes).

The transfer rate between boxes was obtained from the MOM model run under MEDMEX conditions. The transfer of radiotracers between boxes was described by the advection-diffusion equation [7]. The numerical resolution of the differential equation was carried out with a FORTRAN program using the Runge-Kutta 4th order system. A full simulation needed a computation time of less than 1 minute with a personal computer provided with a 200 MHz Pentium processor.

2.2. Source term

The ^{90}Sr and ^{137}Cs sources considered in the model were global fallout from nuclear weapons, the Chernobyl accident, low-level liquid wastes from the nuclear industry and river runoff. As no long-term atmospheric ^{137}Cs sequences exist in Europe, its deposition was estimated from ^{90}Sr measurements, as its ratio has been shown to be almost constant in global fallout [1, 8].

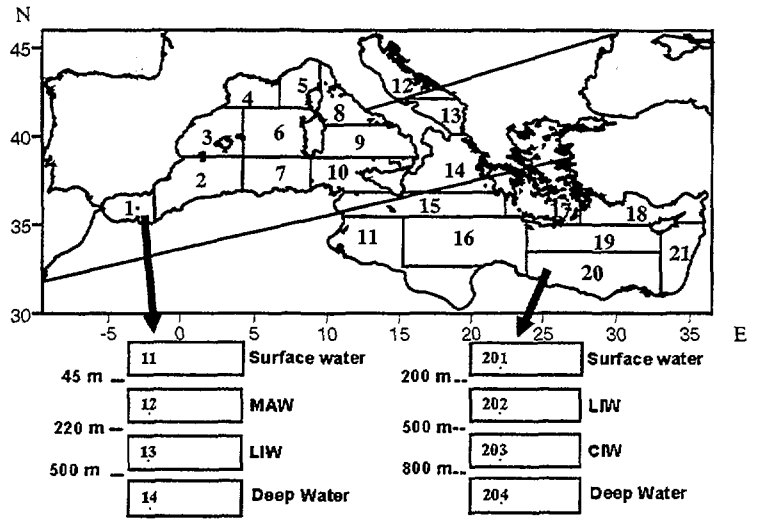

FIG 1. Map of the Mediterranean Sea showing the considered regions. Each region is vertically divided into several boxes, depending on the water depth and water characteristics

In 1986 the Chernobyl accident was responsible for a major input of, amongst other radionuclides, ^{137}Cs to Mediterranean surface waters. In this case, the deposition pattern was patchy, depending on the trajectories of the contaminated air plumes and rainfall during their passage [9]. Therefore, ^{137}Cs deposition was estimated from local studies found in the literature [10-14]. The input of Black Sea waters was described by Egorov and co-workers [15]. The ^{137}Cs input due to the nuclear industry has been reviewed during the Marina-Med project [16]. Finally, the ^{137}Cs input from river runoff was described by Fukai and co-workers [17].

2.3. Observations

The model was designed to predict ^{137}Cs annual mean concentrations in each box. In order to validate the model, these results were compared with observed mean values calculated from data available in each box, if any. The sources of information and data treatment are described in detail elsewhere [18]. Briefly, existing data in each box were explored for outliers, which were discarded in calculations. Then, the resulting distribution was tested for normality using the Kolmogorov-Smirnov non-parametric test, the results of which were always found to be positive. Finally, the mean and standard error of the mean was calculated for each box.

3. RESULTS AND DISCUSSION

3.1. Temporal evolution in surface waters

Surface water concentrations ranged from 0-87 $Bq \cdot m^{-3}$ and 0-19 $Bq \cdot m^{-3}$, for ^{137}Cs and ^{90}Sr, respectively. In most boxes the most prominent feature was the existence of one ^{90}Sr and two ^{137}Cs concentration maxima, corresponding to the maximum air concentrations of both radionuclides due to nuclear weapons fallout (1963) and of ^{137}Cs due to the Chernobyl accident (1986). Maximum concentrations were observed in surface waters in all regions, generally decreasing as mean water depth increased. The predicted ^{137}Cs maximum concentration in the 60s ranged, across the Mediterranean Sea, from 7.54 $Bq \cdot m^{-3}$ in the Libyan Sea, to 16.7 $Bq \cdot m^{-3}$ in the Adriatic Sea. The predicted ^{90}Sr maximum concentrations ranged, from 4.16 $Bq \cdot m^{-3}$ in the Libyan Sea, to 8.62 $Bq \cdot m^{-3}$ in the Adriatic Sea.

Largest concentration gradients were observed during, and shortly after, the global fallout maxima. After the global fallout maximum was reached, levels decreased, first rapidly and later on more slowly, reaching pre-Chernobyl concentrations. ^{90}Sr concentrations decreased slowly until present. The maximum ^{137}Cs concentrations due to the Chernobyl accident, which ranged from 3.02-87.4 $Bq \cdot m^{-3}$, showed largely different peak values because the deposition pattern was highly irregular. The maximum concentrations, 87.4 $Bq \cdot m^{-3}$ and 28.1 $Bq \cdot m^{-3}$, were predicted to occur in the Adriatic Sea, where higher deposition was observed in the nearby terrestrial areas [14].Levels rapidly reached pre-Chernobyl values. The evolution of ^{137}Cs and ^{90}Sr inventories in the Mediterranean Sea are shown in Figure 2.

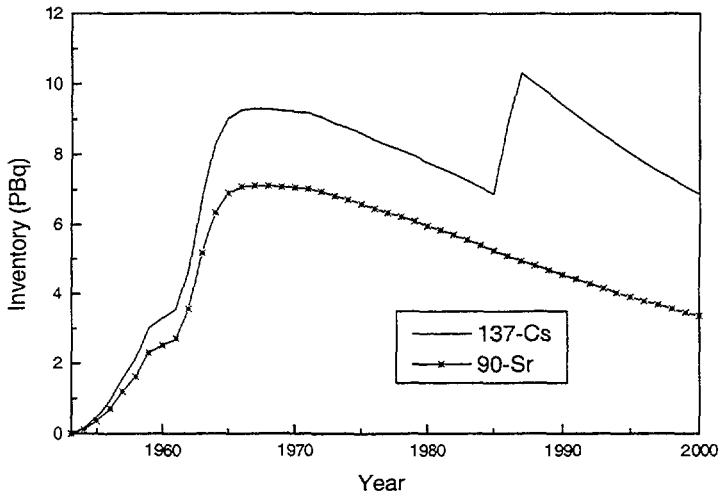

FIG 2. Modelled time evolution of ^{90}Sr and ^{137}Cs inventory in the Mediterranean Sea.

3.2. Temporal evolution in the water column

Because of the atmospheric origin of the contamination, maximum concentrations were observed in surface waters in all regions, generally decreasing as mean water depth increased. Largest concentration gradients were observed during, and shortly after, the global fallout maxima. Because ^{90}Sr and ^{137}Cs entered underlying waters essentially by mixing with surface waters, fallout maxima were usually delayed in deeper waters. This delay was longer as mean water depth increased. For example, in the Central-Occidental basin, global fallout maxima occurred during 1963 in surface waters, during 1965 in the second layer (Mixed Atlantic Waters), and during 1966-67 in the third layer (Levantine Intermediate Waters).

Before the Chernobyl accident, concentrations in the second layer progressively approached those in surface waters and were, in all cases, almost identical just before the accident. Predicted concentrations in the third layer showed a maximum much later than surface waters. The relative importance of this maximum was variable, and it was almost undetectable in some regions such as the Thyrrenian Sea, the Levantine Basin and the Libyan Sea, where an almost stable concentration was reached. In the fourth layer (Very Deep Mediterranean Waters), levels were in general very low and were steadily increasing until the present.

After the Chernobyl accident, new vertical concentration gradients appeared only for ^{137}Cs. Although the accident also affected the second layer waters, pre-Chernobyl conditions were rapidly attained and concentrations in the first two water layers were again equal by the end of the modelled period in most regions. An increase in third layer waters concentrations was also predicted for most regions, while a very low impact was predicted for very deep waters.

3.3. Model validation

The model was validated by comparison with annual mean concentrations of ^{137}Cs in Mediterranean Sea waters [17]. An important conclusion of this work was that, not unexpectedly, the number of available data points for model validation was limited. In general, existing data are dispersed over the whole basin and, except in the Adriatic Sea, no long-term series exist. This is an important limitation for the validation of any model using radiotracer data.

An example of mean annual ^{137}Cs concentrations measured in surface waters is presented, together with model predictions, in Figure 3. An 80 % of the measured data are in the range of values predicted by the model. The type of model presented here is especially well suited to describe systems in which temporal and spatial gradients are not large. In the contrary case, a higher resolution model is needed.

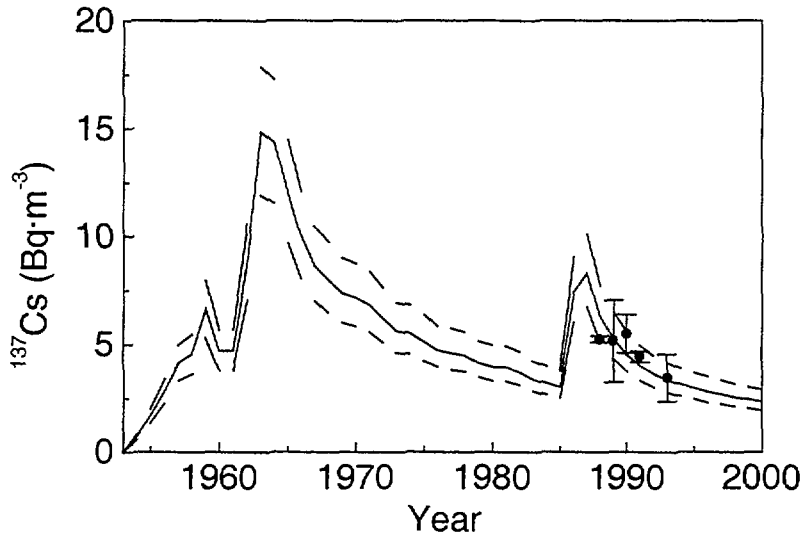

FIG 3. Mean annual ^{137}Cs concentrations observed in Mediterranean Sea surface waters (Catalan Sea) and model predictions. Dotted lines show a 20 % uncertainty estimation of the model.

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