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Potential Threats from a Likely Nuclear Power Plant Accident: a Climatological Trajectory Analysis and Tracer Study

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Abstract The legacy of Chernobyl is not the only nuclear accident likely to confront Turkish territory, which is not far from other insecure power plants, especially the Metsamor. The main purpose of this study was to examine the possible impacts to Turkish territory of a hypothetical accident at the Metsamor Nuclear Plant. The research was performed based on two different methodologies: First, a 10-day trajectory analysis was carried out a set of long-term (30 years) meteorological data; second, a tracer study was performed using the MM5T online model for the selected episode. Trajectory and tracer studies showed that an accident at the Metsamor Nuclear Power Plant would influence all of Turkey. Furthermore, vulnerable regions in Turkey after the Chernobyl disaster were demonstrated as a new and first attempt in this study.

Keywords Nuclear accidents · Trajectory analysis · MM5 Tracer Model

This paper is dedicated to the loving memory of our outstanding colleague, Dr. Umit Anteplioglu, who passed away during the course of this research. We will miss him forever.

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1 Introduction

The hazardous effects of a nuclear power plant accident were unimaginable until the Chernobyl accident occurred in 1986, when a large quantity of radionuclide was released and eventually contaminated a wide geographical area (Tschiersch and Georgi 1987; IAEA 1991). The total mass of radioactive particulate material released during 26 April–5 May, 1986 was about 8,000 kg (Sandalls et al. 1993). Most of the released radioactive materials were in particulate form (Khitrov et al. 1994), whereas noble gases and most of the iodine were in gaseous form (Pöllanen et al. 1999). Pöllanen et al. (1997) showed that after the Chernobyl accident, several European countries were affected by large and highly radioactive particles. In the Chernobyl accident, most of the particulate materials were deposited within 20 km of the plant, but about one-third was transported even thousands of kilometers (Powers et al. 1987; Charles et al. 1997). Even today, scientists in many countries remain interested in the consequences of the accident in contaminated areas, primarily related to the health risks to the present and future generations (e.g. Veen and Meijer 1989; Facchinelli et al. 2002; Varinlioglu and Kose 2005). Contrary to most European countries, the accident has unfortunately not been the center of concern in Turkey. Even though the Turkish territory was thought to be at a safe distance (more than a thousand kilometers) from the site of the accident, it was affected by large depositions and high concentrations of radioactive pollutants released to the atmosphere during the accident (e.g. Pöllanen et al. 1997; Langner et al. 1998), and this has recently become a current issue in the country due to the increasing number of cancer cases in Northern Turkey, the area most affected by the accident.

A similar hazard could be faced in the near future as insecure nuclear power plants with a high risk of accidents remain in the region, and this time it could pose a more dangerous threat for Turkey. The Metsamor Nuclear Power Plant in (MNPP) Eastern Armenia is the closest (16 km) Russian-designed nuclear power plant to Turkey (Fig. 1). In addition to its old technology and unsatisfactory safety measures, the power plant is in a location exposed to severe seismic waves, yielding a high possibility of accidents (Cisternas et al. 1989; Balassanian et al. 1999; Okay and Tuysuz 1999). In the past, this risk to the Metsamor Power was recognized and it was closed down following the 1988 earthquake in Armenia. However, notwithstanding the objections of some neighboring countries, the Armenian government decided to reopen the plant, which now meets 40% of the national electricity demand, in 1993 due to energy shortages in the country. This re-launch of its operations has once again raised concerns about the likely accident risk of the plant.

A similar concern exists for the Kola Nuclear Power Plant (KNPP) in northern Russia. For this reason, the Norwegian Radiation Protection Authority and the Institute for Energy Technology performed a joint project investigating the consequences of poten-

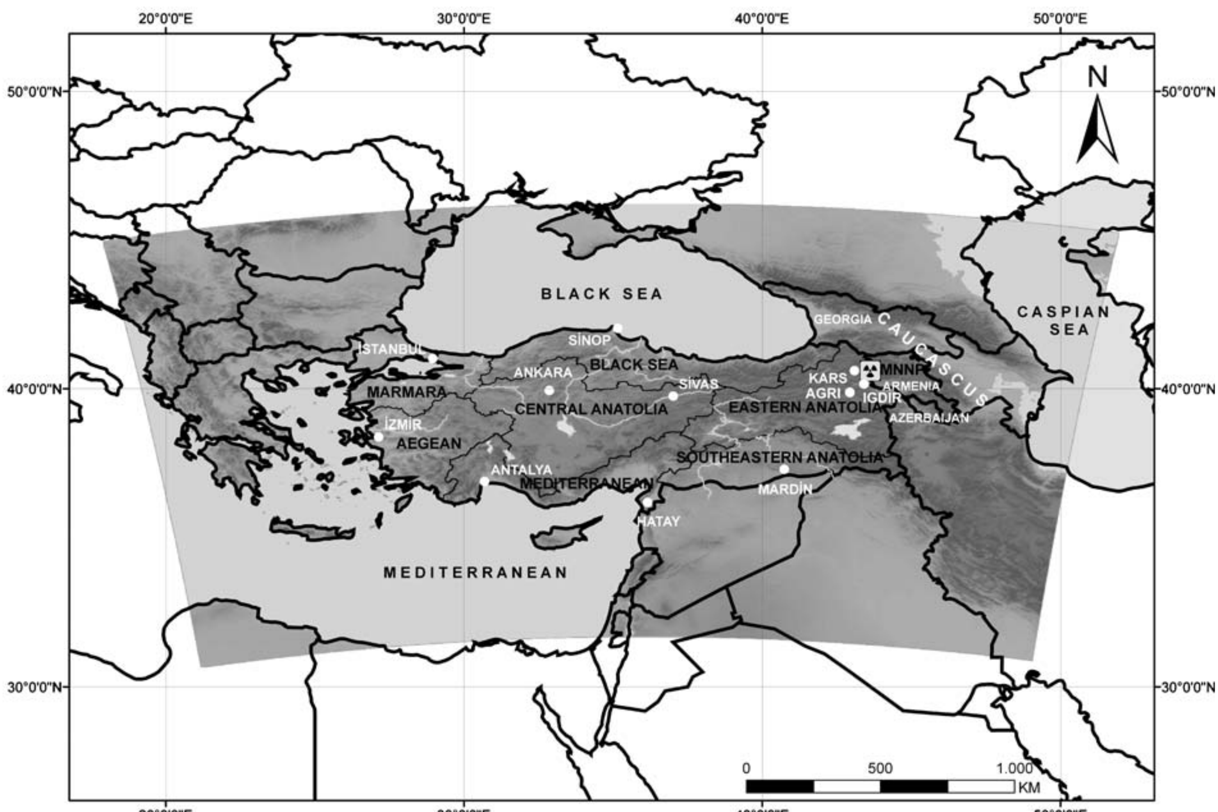

Fig. 1 The location of Metsamor Nuclear Power Plant (MNPP) and regions of Turkey with selected cities

tial accidents at the KNPP (Bartnicki and Saltbones 1997; Saltbones et al. 1997). Climatological trajectory analyses and episode studies were also done for KNPP by Saltbones et al. (2000). In this study, the authors answered the following question: “What is the probability for a radioactive cloud, emitted during an accident, to ‘hit’ a certain location?” Similar methodology had been used earlier by other authors (Nordlund et al. 1988; OECD 1977). The trajectories were computed according to a method described by Pettersen (1956).

It is a well-known fact that once radioactive particles and gases are released to the atmosphere, long-range atmospheric transport processes can cause widespread distribution of these radioactive matters, although they originate from a single point as in the case of the Chernobyl accident (e.g. Mason and Macdonald 1987; Renato et al. 1994). The Chernobyl experience clearly showed that a possible accident in the Metsamor Power Plant would affect Turkish territory by large depositions and high concentrations of radioactive pollutants released to the atmosphere. For this reason, the main goal of this study was to assess the possible impacts on Turkey of a hypothetical nuclear accident at the MNPP. The research was performed based on two different methodologies: First, a trajectory analysis was carried out for long-term (30 years) meteorological data used for a 10-day trajectory analysis. Secondly, a tracer study was performed using a tracer model (MM5T) recently developed and used (Chen et al. 2008 and Kindap 2008) for the selected episode. Furthermore, a numerical experiment was performed for the Chernobyl disaster in order to evaluate the model performance. This study is the first to display the influence zone of the Chernobyl accident over Turkey.

2 Study Area

The Caucasus, also called Caucasia, lies in Eurasia between the eastern shore of the Black Sea and the western shore of the Caspian Sea and includes the countries Armenia, Azerbaijan and Georgia (Fig. 1). The terrain elevation is quite high over the area and Mount Elbrus in western Ciscaucasia in Russia is considered to be the highest point in Europe (~5,600 m). Meteorological conditions over the area are determined by the air circulation over the Eurasian continent. The formation of climate over the zone is influenced by cold air masses (Scandinavian anticyclones; Siberian anticyclones and Azores maximum), hot air masses (subtropical anticyclone and southern cyclones), Central Asian anticyclones, and local weather conditions (http://en.wikipedia.org/wiki/Climate_of_Azerbaijan). Cold Arctic air masses come over the area during the winter season. In the winter, air masses also come down over the Caspian Sea from the mountainous regions of Iran. Both of these high-pressure convergent air masses drive cyclones over the zone. Moreover, cyclones generated over the Black and the Mediterranean Seas impact the region’s weather.

3 Climatological Trajectory Approach

3.1 Trajectory Method

Trajectory analyses are generally performed to describe air pollution transport patterns. In this study, however, this approach was used to identify the vulnerable regions on Turkish territory following a hypothetical accident in the MNPP. To get a comprehensive evaluation, a period of 30-year (1961–1990) NCEP/NCAR (National Centers for Environmental Predictions/National Centers for Atmospheric Research) reanalysis data (NNRP-NCEP NCAR Reanalysis Project −2.5°, 6-hourly) was used for the climatological trajectory evaluation. The distribution of trajectories was shown at $\sigma = 0.995$ level. This corresponds to a near-surface level. The trajectories were computed according to a method described by Pettersen (1956) as a forward trajectory approach in an 81-km grid resolution. An air parcel was released once every 6h and a total of 42,368 air parcels (trajectories) were released during these 30 years (1961–1990). The method is similar to that of the FLEXTRA (Stohl et al. 1998) trajectory model. In addition, the accuracy of our results was tested and proved against the NOAA ARL HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) model.

In this study, in the case of an accident during these 30 years, the probability of the arrival of the trajectories (T) to a given grid cell (ij) is equal to the number of trajectories crossing this grid cell (N_{ij})

divided by the total number of air trajectories released (N_{tot}):

$$T_{ij} = N_{ij}/N_{tot} \quad (1)$$

The computed probability is dependent on the size of the grid squares and the length of the trajectories. In general, the probability of the arrival increases with the length of the trajectories, but for trajectories longer than 8 days it does not change much (Saltbones et al. 2000). In this study, therefore, 10-day trajectories were researched.

The map displaying the probability of being hit by the emitted material is shown in Fig. 2. The distribution of probabilities is quite smooth and isotropic to some extent. However, the distribution of moderate probabilities extended slightly in the southeast direction and lost its circular shape over the related area. It is a well known fact that the Persian Gulf low pressure system is generally seen during the summer months. It starts in the middle of June, stabilizing by the end of the month, remaining dominant during July and August and disappears very quickly in mid-September (Bitan and Sa'Aroni 1992). Similarly, seasonal distribution of the trajectories indicated that a dominant distribution in the southeast direction was formed specifically in summer months (not shown). As a result, this system probably causes this kind of motion in summer time in this area. Because of the long averaging period, this seasonal duration could be partly eliminated. As seen in the figure, similar to the Chernobyl tragedy, most of the European Continent would be affected after an accident at the Metsamor NPP.

In addition, the average travel time was computed by calculating the number of points along the trajectories (every 6 h) from the Metsamor NPP to any grid cell and was shown on the map (Fig. 3). For each trajectory, the counting started from the source point and was continued until the first point in the grid square (ij) was reached. The number of points was multiplied by the time step for the trajectories to calculate the average travel time. Due to the course time resolution of the NCEP/NCAR Global Reanalysis NNRP data, the results might not give the absolute values for the travel time in this study. Nevertheless, they correspond to average values in a larger set of data covering the long period and they gave an idea about how long the average time was for a radioactive plume emitted during an accident at the MNPP to hit the selected locations. It can be seen in the figure that radioactive plumes could already reach any point of Turkish territory at the end of 5 days. For the selected receptors, detailed information about the likelihood of the arrival and average travel time is listed in Table 1.

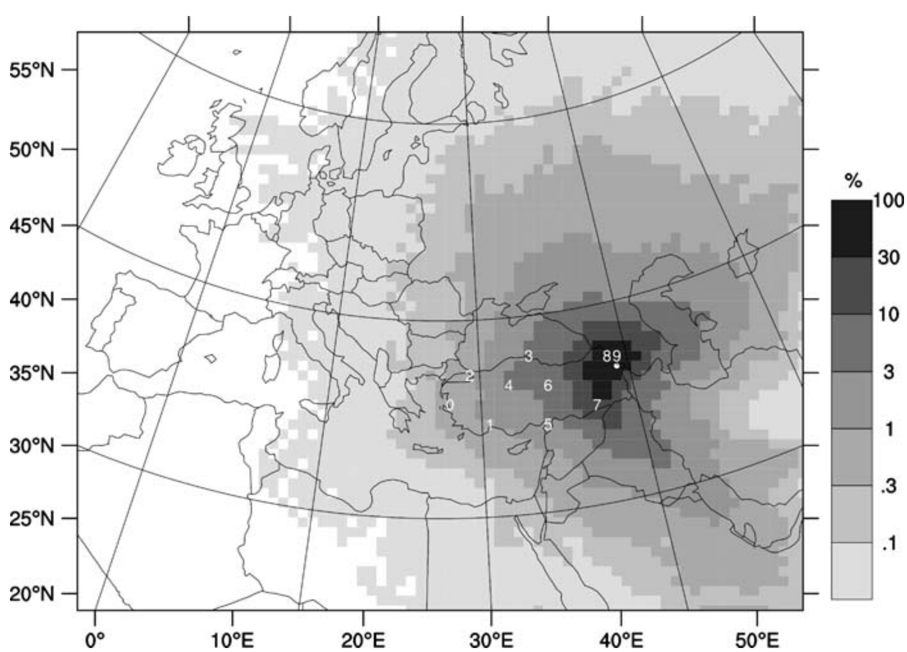

Fig. 2 Map for the probability of arrival of radioactivity based on the method (Eq. 1) and calculated for the trajectories of air parcels for 10days released from MNPP for a period of 30years. The *dot* shows the location of the Metsamor NPP. Each *number* indicates a selected city in Turkey as receptors (*0* Izmir, *1* Antalya, *2* Istanbul, *3* Sinop, *4* Ankara, *5* Antakya, *6* Sivas, *7* Mardin, *8* Kars, *9* Sources close to the MNPP)

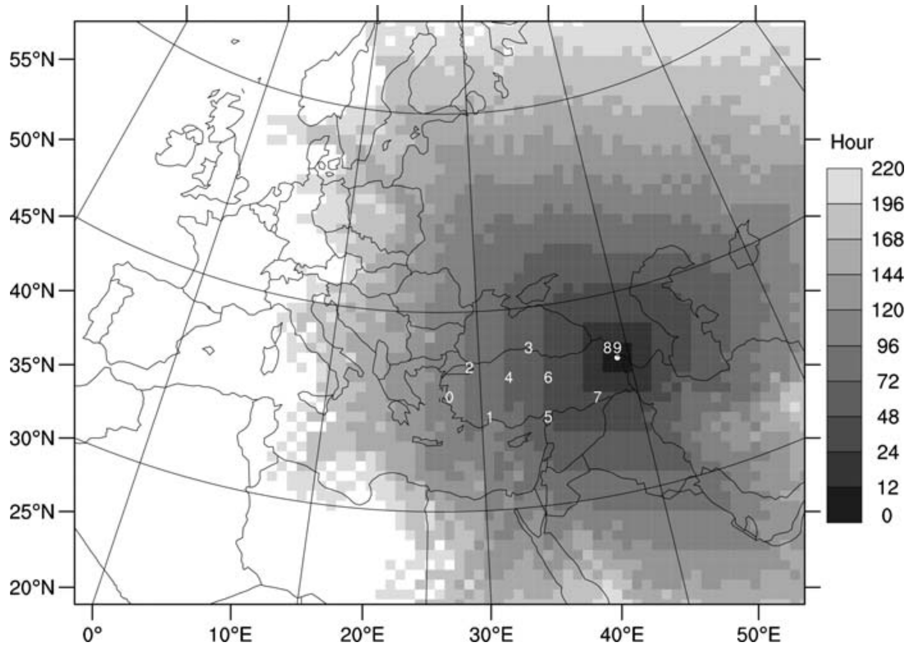

Fig. 3 Map of average travel time from the MNNP to any given grid square based on 30-year meteorological data. The *dot* shows the location of the Metsamor NPP. Each *number* indicates a selected city in Turkey as receptors (*0* Izmir, *1* Antalya, *2* Istanbul, *3* Sinop, *4* Ankara, *5* Antakya, *6* Sivas, *7* Mardin, *8* Kars, *9* Sources close to the MNPP)

Focusing on Turkish territory in Fig. 2, the probability of arrival is highest for the Eastern sections of Turkey, as expected. This probability reached more than 60% near the source and in adjacent towns (such as Kars, Agri, and Igdir). Specifically, while a probability of 61.08% was observed over the city of Kars (8), it reached 66.09% near the Metsamor NPP (Near Source—9) (Table 1). Furthermore, this area might be affected within a very short time period, approximately 12 h (Fig. 3). On the other hand, the probability of arrival decreases to 27.7% over Mardin (7) in the Southeast Anatolia Region; 5.57% and 3.36% over Sivas (6) and the capital Ankara (4) in the Central Anatolia Region; 2.14% and 0.87% over Antakya (5) and Antalya (1) in the Mediterranean Region; 3.69% over Sinop (3) in the Black Sea Region; 0.76% over Istanbul (2) in the Marmara Region and 0.43% over Izmir (0) in he Aegean Region (Table 1). Average travel time to these cities ranges between 12 and 120 h according to Fig. 3.

4 Tracer Modeling Approach

4.1 Tracer Model

Chen et al. (2008) developed an on-line tracer model (MM5T) based on the fifth-generation Penn State/

Table 1 Number of arriving, probability of arrival, and average travel time from the Metsamor NPP to selected receptors

Selected receptors city number and name	Number of arrival trajectories for each receptor	Probability of arrival for each receptor (%)	Average travel time for each receptor (h)
0-Izmir	181	0.43	96–120
1-Antalya	367	0.87	72–96
2-Istanbul	324	0.76	72–96
3-Sinop	1564	3.69	48–72
4-Ankara	1422	3.36	48–72
5-Antakya	906	2.14	24–48
6-Sivas	2361	5.57	24–48
7-Mardin	11736	27.7	24–48
8-Kars	25879	61.08	0–12
9-Near Source	28002	66.09	0–12

NCAR Mesoscale model (MM5; Grell et al. 1995), which was used in this study. MM5T includes the original MM5 model and a continuity tracer equation. The advection, boundary layer mixing, sub-grid cumulus convective mixing, and sedimentation of tracers were taken into account in the tracer calculation. The only source term is the emission from the surface and the only sink term is the dry deposition to the surface due to sedimentation. Chemical reactions and wet depositions were excluded. The use of an on-line approach can avoid temporal interpolation errors. The detail of the MM5T is provided in Chen et al. (2008).

The model configuration included a single domain with a horizontal resolution of 81-km. There were 68 × 58 grid points in the east–west and south–north directions, respectively. Twenty-nine stretched full-sigma levels were used in the vertical. The chosen model physics options were: the rapid radiative transfer model (RRTM) radiation scheme (Mlawer et al. 1997), Kain–Fritsch cumulus parameterization (Kain 2004); medium range forecast (MRF) boundary layer parameterization (Hong and Pan 1996), and the simple ice microphysics scheme (Dudhia 1989). NCEP/NCAR (The National Centers for Environmental Prediction/The National Center for Atmospheric Research) reanalysis data with a resolution of 2.5° × 2.5° were used for initial and boundary conditions for MM5T simulations.

4.2 The Application of the MM5T to the Chernobyl Accident

The tracer model was applied to the Chernobyl Nuclear Plant accident in order to evaluate the MM5T model performance. During the Chernobyl disaster, 6,000–8,000 kg radioactive particulate matter was released to the atmosphere (Sandalls et al. 1993). In this study, emission data was arranged according to this amount and it was released with a constant rate of 35 kg/h continuously during the entire simulation period from April 26 to May 5, 1986.

Radioactive particulate materials released during 26 April–5 May, 1986 were found in many European countries after the accident. A study which was performed by United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) in 1988 showed the spread of radioactive plumes over Europe after the Chernobyl nuclear accident as indicated in Fig. 4. Due to the prevailing meteorological conditions in the period following the accident, a radioactive plume distribution was initially observed over Northern European countries (Plume A: number 1 and 2 in Fig. 4). The MM5T simulation produced similar results (Fig. 5). Specifically, a high pressure system over Western Siberia creating strong south-easterly winds caused the transport of radioactive clouds to the North of Europe, especially Sweden and Finland on April 26 and 27 (Fig. 5a). Then, high radioactive observations were witnessed in Central Europe 5days after the accident (Plume B: number 3, 4, and 5 in Fig. 4). Meanwhile, the high pressure system over western Siberia moved westward and another high pressure system was formed on April 30 over the North of Europe, changing the wind directions to the south (Fig. 5b). One day later (May 1), the high pressure system continued moving westward and was located over the Scandinavian countries. As a result of this formation, the radioactive plume was carried to the central European countries (Fig. 5c).

Finally, due to the changing meteorological conditions, radioactive clouds were seen over the Balkan countries in Eastern Europe on May 3, 1986 (Plume C: number 6 and 8 in Fig. 4). On the other hand, the

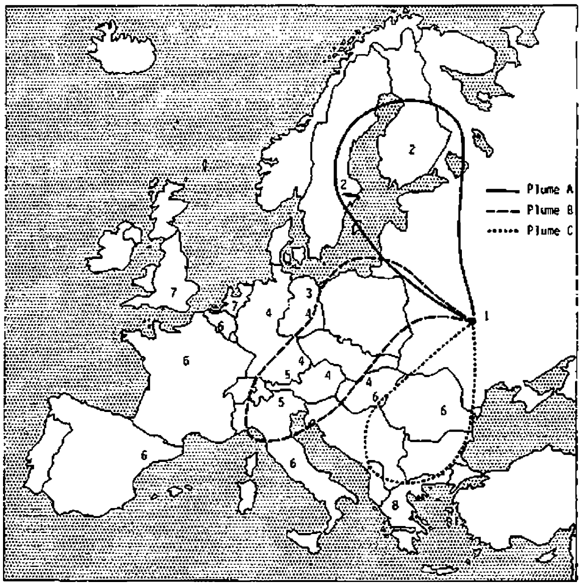

Fig. 4 Spreading of radioactive plumes over Europe after the Chernobyl nuclear accident. *Numbers 1–8* represent plume arrival times at respective areas: *1* April 26; *2* April 27; *3* April 28; *4* April 29; *5* April 30; *6* May 1; *7* May 2 and *8* May 3 (The figure was adapted from the UNSCEAR report for 1988)

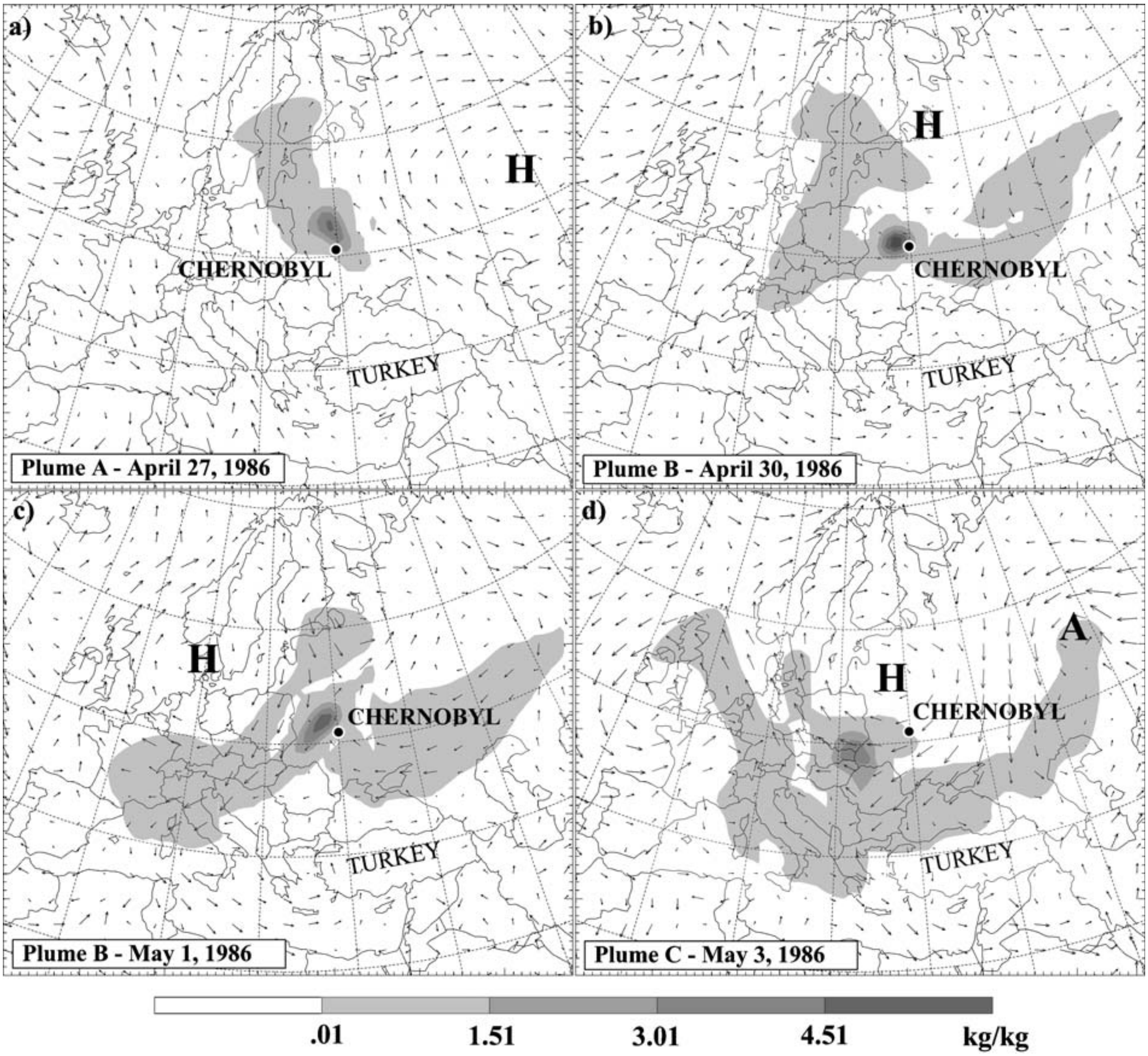

Fig. 5 Simulated tracers and wind vectors near surface at (**a**) 48-h simulation (**b**) 120-h simulation (**c**) 144-h simulation and (**d**) 192-h simulation. *H* and *L* indicate the locations of high and low pressure formation respectively. The *dots* show the location of the Metsamor Nuclear Power Plant (MNPP)

Chernobyl impact was detected in Western European countries including England (Plume C: number 7 in Fig. 4). The combination of a high pressure system located over Northern Europe and a low pressure system positioned over Western Siberia caused a transport of radioactive clouds to the Balkan countries, including Turkey, in the late hours of May 3 (Fig. 5d).

On the other hand, a study performed by Borzilov and Klepikova (1993) showed the spread of radioactive plumes over Europe after the Chernobyl nuclear accident. In addition to findings of the previous study, they also calculated the eastward distribution of the radioactive plumes. According to the results of the study, the MM5T simulation could also produce similar outcomes.

4.3 The Application of the MM5T to a Hypothesized Metsamor Accident

In this study, a hypothetical episode of the Metsamor NPP accident was simulated. It was assumed that the power plant accident occurred at the Metsamor instead of the Chernobyl on April 26, 1986. A numerical simulation with the same model configuration, numerical setup, and time period as the Chernobyl simulation was performed.

During the simulation period, meteorological conditions (especially wind direction) over the Metsamor and its vicinity changed continuously and radioactive plumes were transported to different regions of Turkey by strong winds. With an accident occurring in the Metsamor NPP on April 26, 1986 radioactive plumes would already have affected a substantial part of Eastern Turkey at the end of the first day (Fig. 6a). During the first day, the prevailing easterly winds provided plume transport into the Turkish territory. Generally, the Eastern Anatolian Region, where around six million people live, was subject to fatal concentrations of radioactive matter at the end of the first simulation day. In addition, the figure indicates that the Eastern Black Sea Region was also subjected to a high concentration of radioactive matter. A vertical distribution of the radioactive plume after 6h of simulation on a

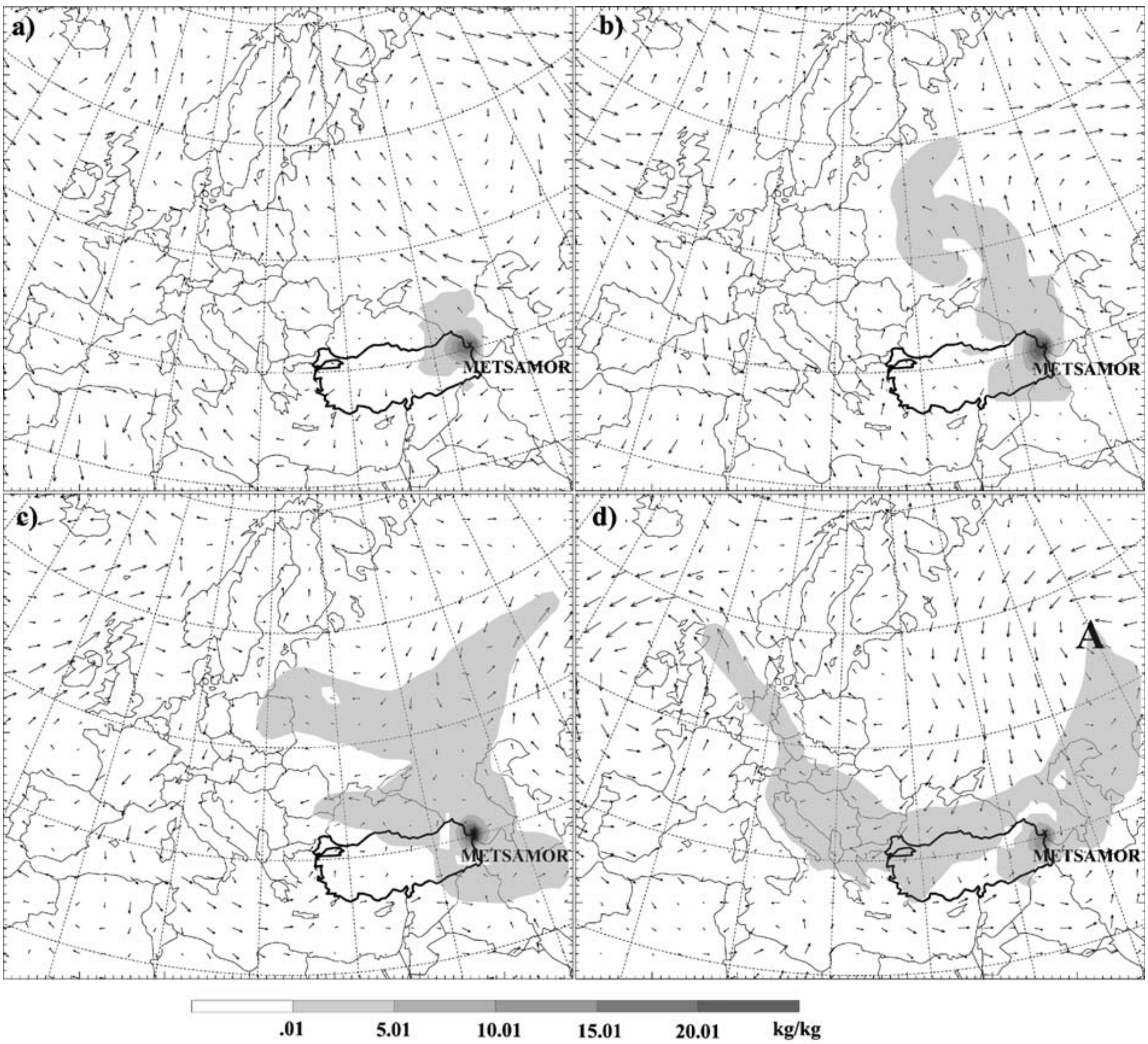

Fig. 6 Simulated tracers and wind vectors near surface at (**a**) 24-h simulation (**b**) 72-h simulation (**c**) 120-h simulation and (**d**) 216-h simulation. The crosses (*x*) show the location of the Metsamor Nuclear Power Plant (MNPP)

transect between Metsamor and the city of Kars, which is one of the closest residential areas in Turkey to the MNPP, is shown in Fig. 7a. It can be clearly seen in the figure that Metsamor, which is 130 km from Kars, poses a serious threat for the inhabitants of the city. There is no doubt that after a possible accident at Metsamor NPP, cities in its vicinity such as Igdir, Kars, Agri etc. (Figs. 1 and 6), would be exposed to extremely high levels of radioactive matter.

After 3days (72-h simulation), radioactive plumes continued being diffused to the inland of Turkey (Fig. 6b). Most of them were dispersed to the North with strong southeasterly winds, while a high concentration of radioactive matter had already reached the Southeast Anatolian Region of Turkey (Fig. 6b). The cross-section of the radioactive clouds between the power plant and the border city of Mardin proved this dispersion (Fig. 7b).

At the end of 5 days (i.e., 120-h simulation), radioactive plumes moved to the North of Europe first and then were transferred to the South by strong northerly winds influencing the central and eastern shorelines of the Black Sea (Fig. 6c). A cross-section of the distribution of tracers between the city of Sinop, the northernmost point of Turkey, and the Metsamor NPP can be seen in Fig. 7c. In addition to

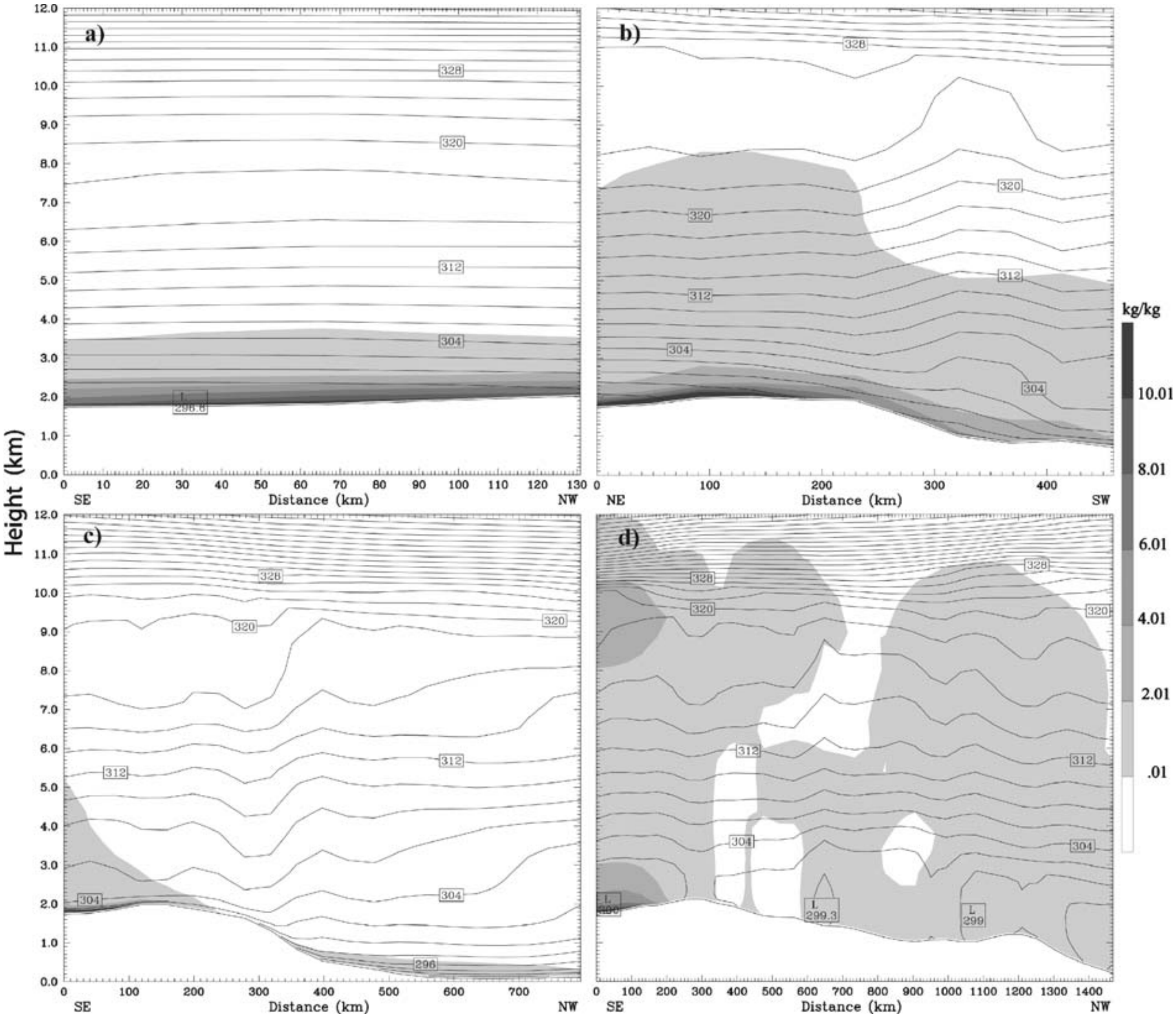

Fig. 7 Cross-sections of the tracers between the power plant and city of Kars (**a**), Mardin (**b**), Sinop (**c**), Izmir (**d**) after 6- 72- 120 and 216-h simulations respectively

the horizontal dispersion, this figure also demonstrates the transport of nuclear clouds vertically over the north side of Turkey (Fig. 7c). The radioactive plume was trapped in a lower vertical depth (less than 1 km) over the city (Fig 7c). On the other hand, Fig. 6c indicated that the most intense amounts of radioactive matter were observed on the Eastern side of the Metsamor NPP and in its nearby environment.

Finally, after 9 days (i.e., a 216-h simulation), northeasterly winds over Western Russia caused the transport of radioactive plumes to the West and North of Turkey (Fig. 6d). Although the intensive deposition of the radioactive matters was limited over Eastern Turkey, most Turkish territory was contaminated by this time. A cross section of the plume distribution between Izmir, one of the westernmost points of Turkey by the Aegean Sea, and the Metsamor NPP illustrated clearly that radioactive clouds dominated over Turkey (Fig. 7d). Hence, it can be clearly seen in the figure that at even more than a distance of 1,400 km from the power plant it would not be possible to avoid the influence of potential accidents at the Metsamor Nuclear Power Station.

5 Summary and Conclusions

Despite the terrible consequences associated with the Chernobyl accident in 1986, Turkish authorities have not yet paid sufficient attention to the different aspects of safety at nuclear installations in the former Soviet Union. The vulnerable Metsamor Nuclear Power Plant in neighboring Armenia has not gained enough attention in any official reports, and an emergency response system has not been constituted at this point.

This study focused on the potential threat from radiation released by a likely accident at the Metsamor Nuclear Power Plant and the subsequent atmospheric transport of radioactive materials. Trajectory analysis and tracer simulations were used to evaluate the problem. This nuclear power plant in Eastern Armenia is the closest (16 km) Russian-designed nuclear power plant to Turkey. In addition to old technologies and unsatisfactory safety measures, the Spitak Earthquake (1988), which was also called Leninakan Earthquake, showed that the location of the power plant is exposed to severe seismic waves, giving a high possibility of accidents.

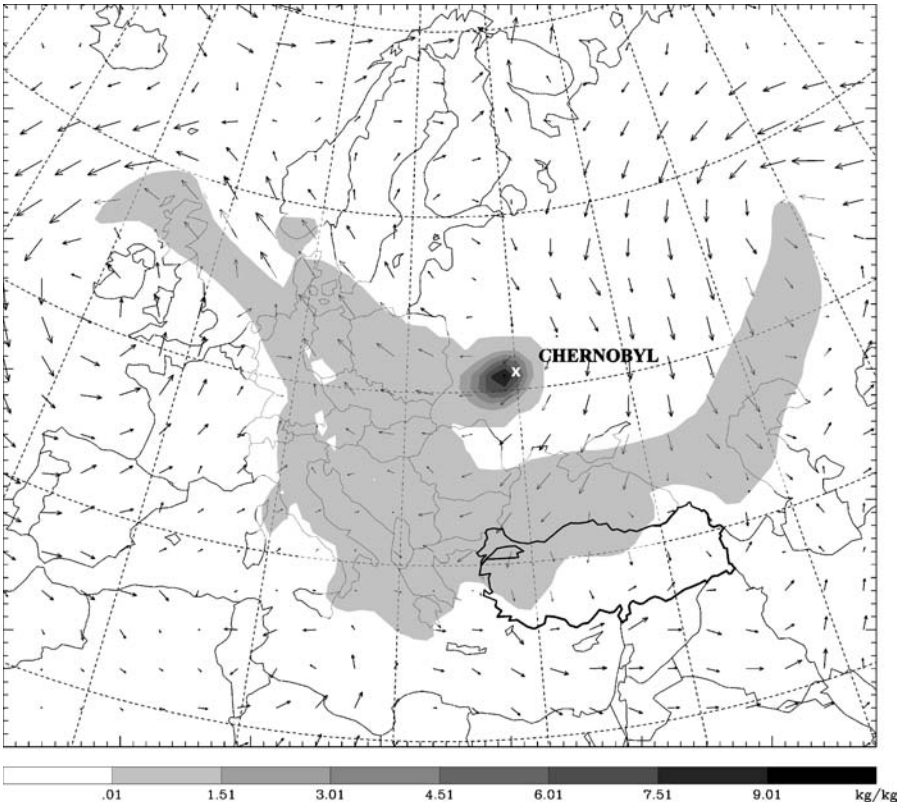

Fig. 8 Simulated tracers and wind vectors at 925 mb layer after a 210-h simulation (4 May 1986 18:00 UTC). The cross shows the location of the Metsamor Nuclear Power Plant (MNPP)

In the first part of the study, a trajectory analysis was performed using 30-year historical analysis data (1960–1991). Forward trajectories with radiative matters released from the MNPP were calculated and demonstrated (Fig. 2). A smooth and isotropic distribution of probability was seen. Summertime Siberian and Mediterranean anticyclones were potentially the cause of the southeastern elongation of this rather isotropic distribution. Results indicate that although Turkish territory is influenced in its entirety, the Eastern part of Turkey is highly threatened by the hypothesized MNPP accident. In addition, the probability of arrival and approximate travel time for each selected receptor was shown in Table 1. This table also shows that cities in proximity to the MNPP in the Eastern Anatolian Region (e.g Igdir, Kars, Agri) might be exposed to high levels of radioactive matter (at a probability of more than 61.08%) in a short time period (less than 12 h). Radionuclide transport to central Turkey (e.g. Ankara, the capital) could occur in two and a half days with 3.36% of the trajectories, but the border city of Mardin in the South-East Anatolia Region would already be influenced at the end the first day in 27% of the trajectories. The city of Izmir, in the far West of the country, is also influenced in about 5 days with a 0.43% probability after a hypothesized accident (Table 1).

The MM5 Tracer model was used for the second part of the source-receptor study. The tracer simulation was first performed for the Chernobyl Nuclear Plant accident in order to evaluate the model performance. When compared with previous studies (e.g. UNSCEAR 1988; Pöllänen 1997; Brandt et al. 2002; UN Chernobyl Forum 2005), the model gave a similar distribution of radioactive plumes during the Chernobyl accident. Besides a satisfactory model performance, this simulation is the first study to show the Chernobyl effects over Turkey. It was believed that the northern parts of Turkey were mostly affected by the Chernobyl accident. This study, however, showed that other parts of Turkish territory, such as the Marmara Region, the Aegean Region, and even the Central Anatolian Region were influenced as well (Fig. 8).

On the assumption that an accident had occurred at the Metsamor NPP instead of the Chernobyl on April 26, 1986, radioactive plumes were simulated to perform episode studies. During the simulation time, continuously changing meteorological conditions provided a comprehensive evaluation for the area of interest. At the end of the first day, radioactive plumes already dominated a substantial part of Eastern Turkey and they presented an isotropic distribution similar to that of the trajectory study (Fig. 6a). On the other hand, when the simulation was completed, it was clearly observed that the entire Turkish territory had been affected by the radioactive matter (Fig. 6). The tracer episode study demonstrated that if there had been an accident at the MNPP plant on April 26, 1986 instead of the Chernobyl, Turkish territory would have faced an extremely serious problem, in particular for eastern Turkey, which would not be able to recover for many years.

In a nut shell, the Metsamor project with its trajectory and tracer simulations has produced a risk map in terms of both location and time to the Turkish people in the event of such a probable accident. The above-mentioned MM5T on-line tracer model provides some advantages that avoid temporal interpolation errors. The accuracy of the model and the direness of its predictions should galvanize the Turkish authorities to take the necessary precautions. All in all, it could be used as an “emergency tool” to enhance public alertness against nuclear accidents.

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