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Simulation of ^{137}Cs transport and deposition after the Chernobyl Nuclear Power Plant accident and radiological doses over the Anatolian Peninsula

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HIGHLIGHTS

- Chernobyl Nuclear Power Plant accident simulation with WRF-HYSPLIT models.
- Analysis of air concentrations and deposition of ^{137}Cs over Anatolian peninsula.
- Estimation of radiological impact of ^{137}Cs on Turkish population.

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ABSTRACT

The Chernobyl Nuclear Power Plant (CNPP) accident occurred on April 26 of 1986, it is still an episode of interest, due to the large amount of radionuclides dispersed in the atmosphere. Caesium-137 (^{137}Cs) is one of the main radionuclides emitted during the Chernobyl accident, with a half-life of 30 years, which can be accumulated in humans and animals, and for this reason the impacts on population are still monitored today. One of the main parameters in order to estimate the exposure of population to ^{137}Cs is the concentration in the air, during the days after the accident, and the deposition at surface. The transport and deposition of ^{137}Cs over Europe occurred after the CNPP accident has been simulated using the WRF-HYSPLIT modeling system. Four different vertical and temporal emission rate profiles have been simulated, as well as two different dry deposition velocities. The model simulations could reproduce fairly well the observations of ^{137}Cs concentrations and deposition, which were used to generate the 'Atlas of Caesium deposition on Europe after the Chernobyl accident' and published in 1998. An additional focus was given on ^{137}Cs deposition and air concentrations over Turkey, which was one of the main affected countries, but not included in the results of the Atlas. We estimated a total deposition of 2–3.5 PBq over Turkey, with 2 main regions affected, East Turkey and Central Black Sea coast until Central Anatolia, with values between 10 kBq m^{-2} and 100 kBq m^{-2}. Mean radiological effective doses from simulated air concentrations and deposition has been estimated for Turkey reaching 0.15 mSv/year in the North Eastern part of Turkey, even if the contribution from ingestion of contaminated food and water is not considered, the estimated levels are largely below the 1 mSv limit indicated by the International Commission on Radiological Protection.

1. Introduction

Chernobyl Nuclear Power Plant (CNPP) located in northern Ukraine is well known for one of the worst nuclear accident, it occurred at 01:23 AM (Moscow Time) on Saturday, 26th of April 1986, when two explosions destroyed the core of Unit 4 and the roof of the reactor building (OECD/NEA, 2002). The accident happened while performing an experiment, but there is a general agreement that the main causes were deficiencies in the design of the reactor and operator errors (De Cort et al., 1998). The explosions during the accident caused the release of a wide spectrum of radionuclides into the atmosphere. It was estimated that about 8 tonnes of radioactive particulate material were released between the 26th of April and the 5th of May (Sandalls et al., 1993). Although further releases probably occurred after 6th of May, these are not thought to have been significant (OECD/NEA, 2002). Most of the particulate materials released to the atmosphere was deposited within 20 km from the reactor, but due to the long duration of the release and the meteorological conditions, about one-third of the released material was transported and deposited even at distances of thousands of kilometers, on most of the European continent (Powers et al., 1987; Steinhauser et al., 2014). After an accident like in Chernobyl, with the release of a mixture of short and long-lived radionuclides to the atmosphere, stochastic health effects are expected over a wide area, while deterministic health effects are probable in the region close to the accident (INES/IAEA, 2008).

People, animals and environment were exposed to ionizing radiation due to the released radioactive gases and particles. The exposure to radioactive material dispersed in the environment is generally

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separated into external and internal exposure. External exposure is determined by the radionuclides suspended in the atmosphere and deposited on the ground, the effective dose due to radionuclides suspended in the atmosphere is commonly called cloud gamma dose. The internal exposure is the one determined by inhalation from air and ingestion from food and water contaminated by radioactive material. Caesium-137 is a man-made radionuclide produced through nuclear fission. Caesium-137 has a long life time, 30.1 year half-life, on the other hand it is known to migrate through soil and, depending on the mineral composition and the presence of organisms such as fungi, exhibits an effective half-life that can be significantly shorter than the physical half-life (Zhdanova et al., 2005; Pröhl et al., 2006; Steinhauser et al., 2013). Nevertheless ^{137}Cs is the main source of the internal and external exposure of the population for decades after the Chernobyl accident (Kinley and Diesner-Kuepfer, 2008). In the case of inhalation or ingestion, ^{137}Cs is distributed to the whole body and mainly accumulating in the muscles.

The Chernobyl accident in 1986 deposited ^{137}Cs, along with other radioactive debris, over large parts of Europe. In 1998 the European Commission published the "Atlas of caesium deposition on Europe after the Chernobyl accident" (De Cort et al., 1998; http://rem.jrc.ec.europa.eu/, for brevity referred as Atlas throughout the text). The Atlas was based on radiological data provided by participating scientific institutes and competent authorities of more than thirty European countries and have been integrated in an information platform by the European Commission Joint Research Centre (JRC-Ispra, EC), Roshydromet (Moscow, Russia), the Institute of Global Climate and Ecology (Moscow, Russia), the Committee for Hydrometeorology (Minsk, Belarus) and Minchernobyl (Kiev, Ukraine). De Cort et al. (1998) estimated a total deposited ^{137}Cs activity of 64 PBq (64×10^{15} Bq) over Europe, ranging between 2 kBq m^{-2} and more than 1480 kBq m^{-2}. The values smaller than 2 kBq m^{-2} were attributed to residual levels (in May 1986) of ^{137}Cs deposition from the atmospheric testing of nuclear weapons.

More recent studies estimated the deposition of ^{137}Cs over the entire continent using more sophisticated atmospheric models. Brandt et al. (2002) used a combination of Lagrangian and Eulerian model, DREAM (the Danish Rimpuff and Eulerian Accidental release Model), to simulate the distribution and deposition of ^{137}Cs, ^{134}Cs and ^{131}I after the CNPP accident using different parameterizations for dry and wet deposition. Their simulations compared to measurements were within a factor of two or three in the worst cases, Suh et al. (2009) used the Lagrangian model LADAS (Long-range Accident Dose Assessment System) to test the impact of different parameters, such as mixing height and diffusion coefficient, on ^{137}Cs deposition after the CNPP accident. The coupled model LMDzORINCA was used to simulate the CNPP accident using two different vertical resolutions and source emission distribution (Evangeliou et al., 2013). All these model simulations represented fairly well the radioactive contamination in most of the European regions and similar to the Atlas.

After the CNPP accident emitted radioactive cloud caused the deposition of radioactive material over the Anatolian peninsula, especially North Western and the Eastern Black Sea regions (Cetiner and Ozmen, 1995). Although all Turkey was affected by the radioactive cloud for several, only one measurement of ^{137}Cs deposition was performed and provided to the Atlas study, and for this reason only a small fraction of the Turkish territory is covered by the Atlas. Kindap et al. (2008) tested the MM5T (Chen and Dudhia, 2001) tracer model to reproduce the dispersion of radioactive material after the CNPP accident, using a constant emission rate during the period from 26th of April and the 5th of May. Kindap et al. (2008) noted that a larger part of the Anatolian peninsula was affected by the CNPP accident, despite a widely accepted belief in Turkish population that only the northern Black sea coasts were reached by the radioactive cloud.

In this study we investigate the impacts of the CNPP accident and quantify the transport and deposition of ^{137}Cs over Europe. A simulation of the transport and deposition of ^{137}Cs after the Chernobyl accident was performed using the WRF meteorological model and the HYSPLIT dispersion model. The simulated episode started from the first day of accident, the 26th of April and continued until the 10th of May, 1986. Due to the large uncertainty related to the temporal and vertical distribution of the emitted radioactive material, we tested four different source distributions, average constant emission at constant altitude and three different times and vertical profiles as used in recent studies (Brandt et al., 2002; Suh et al., 2009; Evangeliou et al., 2013). For each experiment we also tested two different values of dry deposition velocity for ^{137}Cs, which affect the transport efficiency of the radionuclide. Our results were compared with the JRC-REM deposition and air concentrations dataset, which was used to create the Atlas of caesium deposition on Europe. We also focused on deposition and air concentrations of ^{137}Cs occurred over the Anatolian peninsula, which was not included in the Atlas and only partially discussed in Kindap et al. (2008). A final section is dedicated to the estimate of the total ^{137}Cs effective doses to which Turkish population was exposed.

2. Materials and methods

2.1. WRF

The Weather Research Forecast model (WRF version 3.3 http://www.wrf-model.org, Skamarock and Klemp, 2008) was used to reproduce the meteorological conditions that occurred during the Chernobyl accident. WRF is a well-known regional meteorological model, used in several studies also in the area of interest of this study (i.e. Eastern Europe, Im et al., 2010, 2011) We performed a meteorological simulation of the period 20/4/1986–21/5/1986 for a domain covering all Europe (160×130 grid cells, Fig. 1) with a horizontal resolution of 36×36 km and 31 vertical layers, from surface to 10 hPa. In order to reproduce the specific meteorological conditions occurred during the Chernobyl episode, we used the National Centers for Environmental Protection (NCEP) Operational Global Analysis data ($1° \times 1°$ horizontal and 6 h temporal resolutions) as boundary conditions and to nudge the WRF simulations. The main WRF physical options chosen to simulate this episode were: the Kessler microphysics scheme (Kessler, 1969); RRTM (rapid radiative transfer model) long-wave radiation scheme (Mlawer et al., 1997); Dudhia short-wave radiation scheme (Dudhia, 1989); NOAH land surface model (Chen and Dudhia, 2001); Yonsei University Planetary Boundary Layer scheme (Hong and Lim, 2006); and Kain–Fritsch cumulus parameterization scheme (Kain, 2004).

2.2. HYSPLIT

The HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory, http://ready.arl.noaa.gov/HYSPLIT.php, version 4) model from NOAA-ARL's (National Oceanic and Atmospheric Administration Air Resources Laboratory) is a complete system for computing simple air parcel trajectories to complex dispersion and deposition simulations using either puff or particle approaches (Draxler et al., 2009). Some of the applications include tracking and forecasting the release of radioactive material, volcanic ash, wildfire smoke, and pollutants from various stationary and mobile emission sources. We used HYSPLIT to calculate the ^{137}Cs total deposition (wet and dry) and surface air concentrations occurred over Europe and Turkey after the Chernobyl nuclear reactor accident. The radioactive decay of ^{137}Cs is taken into account in HYSPLIT model to estimate the amount of deposited radioactive materials (Draxler and Hess, 1997, Draxler et al., 2009). The decay constant for radioactive processes (λ_{rad}) is defined by the half-life T1/2,

$$\lambda_{rad} = \ln 2/T1/2 \quad (1)$$

and the radioactive mass of a pollutant ($mt + \Delta t$) after a time interval Δt, either in the air or deposited at the soil, becomes,

$$mt + \Delta t = mt \ \exp(-\lambda_{rad}\,\Delta t) \quad (2)$$