Journal of Environmental Radioactivity 165 (2016) 206–218

Contents lists available at ScienceDirect

Journal of Environmental Radioactivity

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

Derivation and validation of a novel Semi Empirical Deposition Estimation Model (SEDEM)

Matias Koivurova [a], [*], Ari-Pekka Leppänen [b], [1]

[a] *University of Eastern Finland, Department of Physics and Mathematics, P.O. Box 111, FI-80101, Joensuu, Finland*
[b] *Radiation and Nuclear Safety Authority – STUK, Environmental Surveillance and Measurement, Lähteentie 2, FIN-96400, Rovaniemi, Finland*

ARTICLE INFO

Article history:
Received 18 April 2016
Received in revised form
29 September 2016
Accepted 12 October 2016

Keywords:
SEDEM
Deposition model
Fallout
Aerosol
Sedimentation
^{134}Cs
^{137}Cs
^{131}I

ABSTRACT

Predictive models are necessary in order to minimize potential damages in the event of a nuclear or radiological release. For this reason, a novel model for the calculation of both wet and dry deposition from airborne radioactivity is proposed. Full derivation of the model and the estimation of uncertainty are presented, and the validity of the model is evaluated by calculating deposition based on several measured airborne activities in different countries. The results are compared with the corresponding measured deposition activities and the predictive power of the model is found to be good, i.e. calculated depositions being within the limits of measurement uncertainty. Additionally, limitations of the model and possible sources of error in the calculations are discussed.

1. Introduction

The first detonation of a nuclear weapon was on July 16, 1945 in New Mexico, USA. The detonation was carried out by the United States Army and it was codenamed Trinity (Szasz, 1984). At the time, scientists were preoccupied on trying to understand the effects of the blast and the functioning of the bomb itself, and no one had expected that the aftermath could be so problematic. Because of this, the consequences caused by anthropogenic radionuclides in the environment were neglected. Serious study on the effects of radioactive fallout didn't start until 1949, after J.H. Webb proposed that a radioactive contaminant encountered in paper was actually from the Trinity blast (Webb, 1949). This was the first proof that a radioactive particle may travel over long distances, which raised concern over the possible health effects of radioactive deposition. Since then, numerous studies have been published on all of the known transport mechanisms of radioactive particles in the atmosphere and the environment. Today it is known that anthropogenic radionuclides can produce very high activity concentrations over a relatively large area, and that aerosols formed through different mechanisms can travel over very long distances.

Nuclear weapons tests, such as the aforementioned Trinity in 1945 and the considerably larger Tsar Bomba in 1961, as well as nuclear accidents, like the ones in Chernobyl in 1986 and Fukushima in 2011, have demonstrated that there is a need for predictive models in the event of a radioactive release, in order to minimize the potential damages. It is estimated that the Chernobyl accident alone has already caused adverse health effects for thousands of people (Peplow, 2006), although studies on the effects of radiation are subject to much controversy. Nonetheless, it has recently been found that high amounts of radiation is not the only cause for concern, since even low amounts of radiation may increase blood pressure (Sasaki et al., 2002), cause a degenerative brain disease (Kempf et al., 2013), or increase risk of cancer (Cardis et al., 1995). There are several difficulties when studying the effects of radiation in humans, since the radiation doses, intake mechanisms, living habits and general health of the subjects varies, and it is very difficult to determine what is caused by radiation and what by other sources. Despite the inconclusiveness of many studies on the subject, the general view has been that exposure to radioactive

---

[*] Corresponding author.
E-mail address: matias.koivurova@uef.fi (M. Koivurova).
[1] Current address: Preparatory Commission for Comprehensive Nuclear Test-Ban Treaty Organisation (CTBTO), Wagramerstrasse 5, 1400 Wien, Austria.

http://dx.doi.org/10.1016/j.jenvrad.2016.10.008
0265-931X/

elements is harmful to human health and hence exposure need to be minimized.

Several studies have been done to gain insight into all of the involved processes in a nuclear discharge: release of radioactive matter (Stohl et al., 2012; Kirchner et al., 2012; Schöppner et al., 2012), transport phenomena (Baklanov and Sørensen, 2001; Stohl et al., 2012; Lujanienė et al., 2012; Tsumune et al., 2012; Nakano and Povinec, 2012), deposition (Baklanov and Sørensen, 2001; Stohl et al., 2012; Hirose, 2012; Pálsson et al., 2006; 2012), transfer to foodstuffs (Koivurova et al., 2015; Leppänen et al., 2011; Dahlgaard, 1994) and the effects on humans (Leppänen et al., 2011; Dahlgaard, 1994). Out of these, transfer to foodstuffs and the effects on people have been studied the most. The transfer of radioactive particles in nature is, in principle, quite simple. First, radioactive aerosols sediment to the ground – either by gravitational settling or by precipitation scavenging – from where they are taken up by plants. Then, the plants are eaten by animals, transferring and concentrating the radioactive matter to them. For example, in the Nordic countries, one of the most important food chains which transfers radioactive matter very efficiently to humans is the lichen-reindeer-human chain (Koivurova et al., 2015; Leppänen et al., 2011; Hanson, 1967; Macdonald et al., 2007; Åhman and Åhman, 1994; Rissanen and Rahola, 1989). These kinds of chains have been studied extensively, but what has been somewhat neglected in earlier studies are the mechanisms of deposition.

For estimating deposition, there does exist some models which have a sufficiently good predictive power, but most of them don't have much to do with actual physical phenomena, and are largely centered on precipitation. This is because of the fact that atmospheric processes are usually very complicated and precipitation is the most effective way of aerosol scavenging. Therefore, the earlier approaches have been to either make a crude approximation or to produce a mathematical fitting in order to estimate the deposition densities. In this study it is shown that most of the complex atmospheric processes may be accounted for with some justifiable simplifications, while keeping the accuracy and predictive power of the model at a high level.

The results presented here were published in an MSc thesis, *Derivation and validation of a physical deposition model* (Koivurova, 2015) and some of the text of this study is taken from the thesis.

2. Theory

2.1. Overview of earlier model types

Traditionally, deposition has been estimated with models which use the well-known relationship between precipitation and deposition density, or with mathematical fittings between airborne activity concentration and deposition density. For precipitation dependent models, the usual approach has been to simply describe deposition density as the product of airborne activity concentration and amount of precipitation during a given time period. A sum of these products over the studied time gives the total deposition density (Pálsson et al., 2006), as in

$$D_x = \sum_i C_{Ri} \cdot P_{Xi} \tag{1}$$

where P_{Xi} is the amount of precipitation at a site X during time period i, in meters, and C_{Ri} is the decay corrected airborne activity concentration at the reference site R during the same time period i, in Bq/m^3. From this equation, the total decay corrected estimate of the deposition density D_x is obtained, which is in units of Bq/m^2. This is a type of rough approximation used to simplify complicated atmospheric events. It doesn't have much to do with atmospheric processes, but it may still be called a physical model since it links two observable quantities together in a simple manner. Surprisingly enough, it does give some kind of estimation for deposition density, but it completely neglects the effect of dry deposition.

Another deposition model type is one which attempts to describe all of the processes involved in deposition by accounting for them mathematically. The basic structure of such a model is that it has several variables in a single linear or exponential function with different weights for each variable. Usually the weights have been obtained by fitting the studied function to experimental data. Such a model may be of the form suggested by Pálsson et al. (2012).

$$d(t, \Delta t, x) = f_1(t) \cdot f_2(r(t, \Delta t, x)) \cdot f_3(x) \tag{2}$$

where $d(t,\Delta t,x)$ is the deposition density, $f_1(t)$ accounts for the time dependency of the model, $f_2(r(t,\Delta t,x))$ is a function of precipitation rate and $f_3(x)$ is purely a function of geographical effect. The model above doesn't have its own function for dry deposition, but it is accounted for by adding a 1–6 mm bias on precipitation. This type of model still uses physical quantities and even attempts to account for all atmospheric effects. But because it is basically a function fitted to experimental data, it is actually more of a mathematical model than a physical one. Nonetheless, such a model has proved to be an improvement over earlier deposition estimations.

In atmospheric science the term aerosol traditionally refers to suspended particles that contain a large proportion of condensed matter other than water, and aerosol physics studies how atmospheric aerosols form and what role they play in the Earth's climate (Pöschl, 2005). Physicists in this field attempt to integrate laboratory and outdoor measurements with theories and models in order to understand and predict the impact of human-caused and natural changes on climate. In this domain, there exists many physically accurate models and theories, which may be used together to estimate deposition. The problem with these theories is that they easily become very complicated and it makes using them a lot more difficult than the types of models described above. Because of the unnecessary complication, these physically accurate model types won't be covered here.

2.2. Derivation

Derivation of a rigorous atmospheric deposition model would be unnecessarily difficult to do, and even models which use rough approximations have proved to be sufficiently accurate in many situations. The model derived in this chapter falls somewhere in between a rigorous one and a crude approximation. This is in order to take advantage of the good sides of both extremes, to make a semi-empirical model which is accurate but still sufficiently simple to use. The model which is considered here takes into account both dry and wet deposition, and as such the two parts will be derived separately.

2.2.1. Dry deposition

Dry deposition has mostly been neglected in earlier studies where radionuclides have been noted to come from far away sources. In this situation, the contribution of dry deposition to the total deposition density is usually low, on the order of 10–20%. In a long term study the deposition of Be-7 and Cs-137 collected in Helsinki during 1993–2006 showed that, on average, in the case of Be-7 89% of the total deposition was composed of wet deposition whereas in the case of Cs-137 the wet deposition fraction was found to be 69% (Outola and Saxén, 2012). This is because long range transport takes several days – for example it took 8 days for the fallout from Fukushima to reach Finland (Leppänen et al., 2013) –