Atmospheric Environment 84 (2014) 230–243

Contents lists available at ScienceDirect

Atmospheric Environment

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

Review

A review of toxicity models for realistic atmospheric applications

Ajith Gunatilaka*, Alex Skvortsov, Ralph Gailis

Land Division, Defence Science and Technology Organisation, 506 Lorimer Street, Fishermans Bend, VIC 3207, Australia

HIGHLIGHTS

- We describe a number of toxicity models found in the literature.
- We compare models using realistic simulated concentration time series data.
- Results show the importance of including biological recovery in the models.
- The use of advanced models is hampered by the lack of validated model parameters.

ARTICLE INFO

Article history:
Received 3 March 2013
Received in revised form
18 November 2013
Accepted 22 November 2013

Keywords:
Toxicity models
Exposure
Concentration fluctuations
Toxic load
Health effects

ABSTRACT

There are many applications that need to study human health effects caused by exposure to toxic chemicals. Risk analysis for industrial sites, study of population health impacts of atmospheric pollutants, and operations research for assessing the potential impacts of chemical releases in military contexts are some examples. Because of safety risks and the high cost of field trials involving hazardous chemical releases, computer simulations are widely used for such studies. Modelling of atmospheric transport and dispersion of chemicals released into the atmosphere to determine the toxic chemical concentrations to which individuals will be exposed is one main component of these simulations, and there are well established atmospheric dispersion models for this purpose. Estimating the human health effects caused by the exposure to these predicted toxic chemical concentrations is the other main component. A number of different toxicity models for assessing the health effects of toxic chemical exposure are found in the literature. Because these different models have been developed based on different assumptions about the plume characteristics, chemical properties, and physiological response, there is a need to review and compare these models to understand their applicability. This paper reviews several toxicity models described in the literature. The paper also presents results of applying different toxicity models to simulated concentration time series data. These results show that the use of ensemble mean concentrations, which are what atmospheric dispersion models typically provide, to estimate human health effects of exposure to hazardous chemical releases may underestimate their impact when toxic exponent, n, of the chemical is greater than one; the opposite phenomenon appears to hold when $n < 1$. The results also show that some toxicity models that disregard biological recovery processes may predict greater toxicity than the explicitly parameterised models. Despite the wide variety of models of varying degrees of complexity that is available, we find that it is challenging or impossible to pick the 'best' model because of the lack of validation data. While it may be extremely challenging to create this validation data, there may be opportunities for more indirect validation or more simplistic checks of realism. Additional investigations of this nature in the future may at least help rank or put further constraints on the applicability of each of these models.

1. Introduction

Accidental or deliberate releases of toxic chemicals into the atmosphere can cause significant health effects on exposed individuals. The study of these toxic effects is important in many applications, including risk analysis of industrial sites, assessment of atmospheric pollutants on population health, and operations

* Corresponding author. Tel.: +61 3 9626 8586; fax: +61 3 9626 7830.
E-mail address: ajith.gunatilaka@dsto.defence.gov.au (A. Gunatilaka).

1352-2310/$ – see front matter
http://dx.doi.org/10.1016/j.atmosenv.2013.11.051

research conducted to assess the vulnerability of military missions to chemical attacks and to support major purchase decisions in chemical defence. Because of safety risks and the high cost of field trials involving releases of hazardous chemical agents, computer simulations are widely used for these studies. Such studies require the ability to estimate likely human casualties resulting from different levels of exposure.

Computer simulation tools used for these studies first need to model the chemical concentrations resulting from the release of a toxic chemical into the atmosphere. Then, they need to estimate the likely human health effects experienced by individuals that are exposed to these concentrations. Atmospheric transport and dispersion models (e.g., SCIPUFF) for predicting ensemble average concentration resulting from a chemical release are well established (Sykes et al., 2004); some models for simulating fluctuating concentrations are also available (Du et al., 1999; Hilderman and Wilson, 1999; Gunatilaka et al., 2011, 2012). Once the concentration is known, toxicity models are used to estimate human health effects (e.g., death, injury) caused by exposure to the concentration. While various toxicity models for estimating human health effects due to toxic chemical exposure are found in the literature, they are based on different underlying assumptions and so there is a need to understand which models are applicable under specific scenarios of interest. This paper reviews several toxicity models described in the literature and discusses some of their strengths and limitations. Some of these models have previously been discussed in an excellent review presented by Sommerville et al. (2006), and we have drawn heavily from it when discussing these models in the present paper. In this paper, we review some additional toxicity models and also present results of applying a number of toxicity models to simulated concentration time series. While there are many phenomenologically-based toxicity models that do not have any parametric description of biological processes such as inhalation uptake, recovery, or saturation and physiologically-based toxicity models that explicitly account for these, none of these models have been validated using exposure to fluctuating concentrations of hazardous materials. Therefore, there is no experimental evidence available at present to choose the 'best' model.

2. Toxic effects

Individual members of a population respond differently to a given chemical exposure; for example, while exposure to a particular level of a toxic chemical may cause severe harm or even death to the weakest members of the population, the same exposure level may cause only minor health effects or no effect at all in the strongest members. Therefore, toxic effects of chemicals are usually quantified by the dosage from exposure (product of concentration and exposure time) required to produce a specific toxicological effect such as death or incapacitation in a given fraction of the population; for example, the dosage that is lethal to 50% of an exposed, unprotected population, denoted by LCt_{50}, and the dosage that will cause incapacitation in 50% of an exposed, unprotected population, denoted by ICt_{50}, are used to characterise chemical toxicity. It is also common to characterise the toxicity by specifying the concentration that is required to produce a specific effect in a given fraction of an exposed population within a particular exposure duration; for example, LC_{10}, LC_{50}, and LC_{90} are the concentrations that are lethal to 10%, 50%, and 90%, respectively, of an exposed population at a specific exposure duration (Fig. 1).

3. Probit analysis

Toxic dosages and toxic concentrations are usually estimated by analysing experimental data from animal exposure studies and

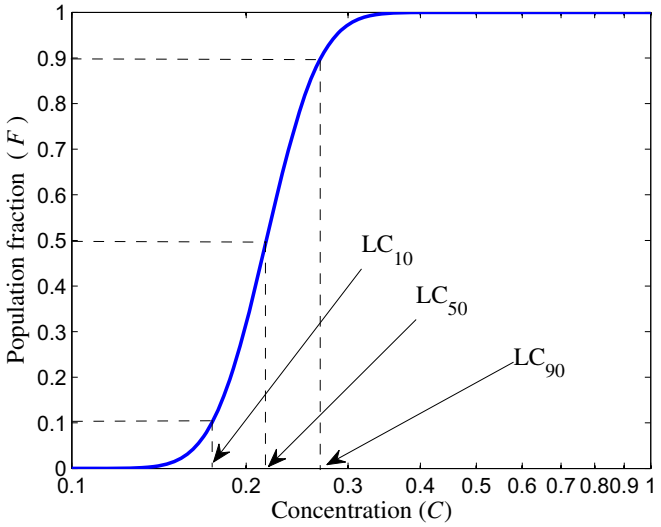

Fig. 1. The fraction of a population showing lethal response to various concentrations of a hypothetical chemical at a given exposure duration.

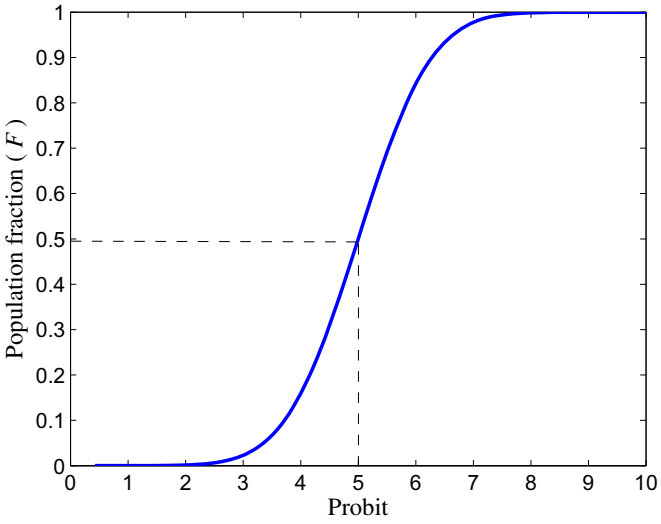

Fig. 2. The plot of response fraction of a population versus the probit. Dashed lines show that a probit value of five corresponds to a response fraction of 0.5 (the median response).

then extrapolating these results to human populations. The probit method, introduced by Bliss (1934a,b) and popularised by Finney (1971), is commonly used to linearise the cumulative normal distribution of population response to toxic dosage.

Let z be the dosage of toxic agent that a population is exposed to and let $x = \log z$. The fraction F of the population that responds with some effect when exposed to the toxic agent can be expressed as:

$$F = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{X} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2} \right) dx, \tag{1}$$

where μ is the mean and σ is the variance of the normal distribution of the logarithm of tolerances of members in the population. Furthermore, $\mu = \log(ECt_{50})$, where ECt_{50} is the median effective dosage, i.e., the dosage that will produce a response in half the population. By substituting $u = (x-\mu)/\sigma$, Equation (1) can be put in the standard form as: