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Atmospheric plume progression as a function of time and distance from the release point for radioactive isotopes

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ABSTRACT

The radionuclide network of the International Monitoring System comprises up to 80 stations around the world that have aerosol and xenon monitoring systems designed to detect releases of radioactive materials to the atmosphere from nuclear explosions. A rule of thumb description of plume concentration and duration versus time and distance from the release point is useful when designing and deploying new sample collection systems. This paper uses plume development from atmospheric transport modeling to provide a power-law rule describing atmospheric dilution factors as a function of distance from the release point. Consider the plume center-line concentration seen by a ground-level sampler as a function of time based on a short-duration ground-level release of a nondepositing radioactive tracer. The concentration C (Bq m^{-3}) near the ground varies with distance from the source with the relationship $C = R \times A_{D,C} \times e^{-\lambda(-1.552+0.0405\times D)} \times 5.37 \times 10^{-8} \times D^{-2.35}$ where R is the release magnitude (Bq), D is the separation distance (km) from the ground level release to the measurement location, λ is the decay constant (h^{-1}) for the radionuclide of interest and $A_{D,C}$ is an attenuation factor that depends on the length of the sample collection period. This relationship is based on the median concentration for 10 release locations with different geographic characteristics and 365 days of releases at each location, and it has an R^2 of 0.99 for 32 distances from 100 to 3000 km. In addition, 90 percent of the modeled plumes fall within approximately one order of magnitude of this curve for all distances.

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1. Introduction and background

The radionuclide network of the International Monitoring System (IMS) comprises up to 80 stations around the world that have aerosol and xenon monitoring systems designed to detect releases of radioactive materials to the atmosphere from nuclear explosions (CTBT, 1996; CTBTO, 2013). Only two of the 80 stations with atmospheric monitoring equipment are closer than 750 km apart, and about 60 percent of the monitoring stations are 1500 km or more apart. The station on Easter Island is more than 3500 km from any other station. Initially only 40 of the 80 stations will contain xenon sampling equipment. The distances between the stations intended to have xenon sampling capabilities range from 1000 to 4300 km, and 15 of the 40 stations are at least 2500 km from the next nearest radioxenon station.

In the absence of a scientific basis for optimizing the duration of atmospheric sampling, historically scientists used sampling integration times from 24 h to 14 d for radionuclides (Thomas et al., 1977). This approach was adequate in the past because the sources of the signals were far away from sampling locations and the releases were large. Thus, the resulting plumes were usually smeared out over several days by the time they had traveled as far as 10,000 km. The earthquake and resulting tsunami on March 11, 2011 damaged the Fukushima Dai-ichi nuclear reactors in Japan and they released approximately as much ^{133}Xe (Eslinger et al., 2014a) as a 1-megaton atmospheric nuclear explosion. As a consequence, that release was easily detected at long distances from the release point.

No atmospheric nuclear explosions have occurred since 1980 and the emphasis has shifted towards detecting releases from much smaller nuclear explosions that are conducted below ground. Large explosions have strong seismic or acoustic indicators of the explosion location. However, seismic signals from small tests may be so low they are on the threshold of reliable detection. In addition, the releases of radioactive materials to the atmosphere can be quite small. The recent nuclear tests announced by North Korea

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(Ringbom et al., 2014, 2009) illustrate the nature of the detection problem. Seismic signals have provided good estimates of the location of the tests in North Korea, but there is no guarantee that similar coverage will occur for low yield explosions potentially located elsewhere. Thus, measurements of radioactive materials in the atmosphere are also used to help determine the release location. Although a discussion of the techniques used to estimate a release location from atmospheric measurements is beyond the scope of this paper, in general the accuracy of location estimates improve with the number of detections and the number of locations with detections (Rao, 2007).

Releases of radioactivity to the atmosphere from small underground nuclear explosions can be within the range of routine releases from nuclear power plants or medical isotope production facilities (Bowyer et al., 2013; Eslinger et al., 2014b; Saey, 2009). Detections of atmospheric radionuclides at that level of release often are possible only at distances of a few hundred to a few thousand km from the source point, even with very sensitive sampling equipment. There is also the need to distinguish atmospheric releases from a nuclear explosion from atmospheric releases typically associated with operations of civilian nuclear facilities. Detection of only one anthropogenic radioactive isotope in the air is not proof that a nuclear explosion occurred. Detections of at least two different isotopes are needed to potentially distinguish between source mechanisms. The four xenon isotopes ^{131m}Xe, ^{133}Xe, ^{133m}Xe, and ^{135}Xe can be used for this source categorization purpose with high decision accuracy (Kalinowski et al., 2010), but some of those isotopes have short half-lives.

Site-specific analysis of contaminant transport in the atmosphere is very useful when examining the effect of a release at a known location. However, one cannot assume that a country attempting to conduct an illicit nuclear explosion will publish the test location. Thus, a general analysis can inform the planning behind deployment of systems to detect radioactive releases, no matter where the release occurs on the planet. The general analysis in this paper uses a large number of atmospheric transport model runs to develop summary rules on the movement of radioactive materials in the atmosphere. These summary rules provided a scientific basis for selecting equipment sensitivity, sample durations, and the number of sampling locations that explicitly address the typical movement of contaminant plumes through the atmosphere.

2. Approach and models

2.1. Release points and plume tracking

It has been known for many years that the horizontal and vertical dispersion coefficients for Gaussian plume models of atmospheric transport can be approximated by power laws (Bultynck and Malet, 1972). Gaussian plume models are most often used in situations where the samplers are located at relatively short distances from the release point, and Lagrangian type models (Draxler and Hess, 1998; Stohl et al., 1998) are often used for longer distances. The general analysis approach in this paper uses multiple runs of a Lagrangian atmospheric transport model to propagate plumes based on hypothetical contaminant releases through the atmosphere. The resulting contaminant concentrations are then categorized as a function of time and distance from the release point. Not unexpectedly, power-law models can be used to approximate the dilution of the plume in the atmosphere even at large distances.

The results presented here are developed for short-duration ground-level releases of a nondepositing tracer. In this context, a short-duration release has a constant release rate one hour in length. In addition, it is assumed that any sampler is located near the ground surface. Several isotopes of xenon are produced by nuclear fission and their relative abundance can be used to distinguish releases from a nuclear explosion from releases produced by other nuclear processes (Kalinowski et al., 2010). Xenon is a noble gas, and rainout and deposition processes do not significantly alter its concentrations in the air. Other isotopes produced in nuclear explosions, such as isotopes of cesium and iodine, are subject to rainout and deposition processes.

The first step in describing modeled plume behavior at each of several distances from the release point is to locate the maximum concentration anywhere on a circle a specified distance from the release point. The maximum concentration is used to select a location on the circle of the specified distance and then the time history of the plume concentration at that location is used in the analysis. Thus, the results presented here are based on the optimal sampler location at a given distance, and the optimal sampling location can be different for every release. Offset distances were calculated using a spherical earth approximation in the Vincenty formula (Vincenty, 1975).

Depending on the local weather conditions, plumes released at different times will move in different directions. Local weather conditions, in turn, are affected by global atmospheric patterns. The global atmospheric patterns depend, in part, on the latitude of the release point and the proximity of the release point to continents. In an effort to span the range of global patterns with a reasonable amount of computational effort, 10 release locations were selected. The release locations are described in Table 1. The model runs used a separate release every day in 2011 for all 10 locations; thus, there are 3650 modeled plumes.

2.2. Atmospheric transport model

Atmospheric transport was modeled using the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model (parallel version released in Feb. 2013) that is maintained by the U.S. National Oceanographic and Atmospheric Administration (Draxler and Hess, 1998; Draxler et al., 2013). The transport runs were performed on a 176 compute-node Linux cluster. Modeled dilution factors at sampling locations were averaged over the bottom 100 m of the atmospheric column. The top of the atmospheric model domain was set to 10,000 m above ground level. Wet and dry deposition mechanisms were deactivated for the runs and no radioactive decay was calculated unless otherwise stated. The particle-tracking mode of the code was used and dilution factor data were output on a 1-h time step for a 0.25° grid in latitude and longitude for 240 h (10 d) after the start of the release. Dilution factors at points on the circles of interest were obtained using linear interpolation on the output grid. Archived meteorological data for 2011 on a 0.5° global grid (GHDA, 2012) were used.

Table 1
Release locations and associated geographic characteristics.

Location	Geographic characteristics
Cayenne, French Guiana	Low latitude, continent shore
Kampala, Uganda	Equatorial, mid-continent
South Tarawa, Kiribati	Equatorial, small island
Lucerne, Switzerland	Mid latitude, mid-continent, mountainous
Miami, United States	Mid latitude, continent shore
Reykjavik, Iceland	High latitude, large island
Seattle, United States	Mid latitude, continent shore
Tokyo, Japan	Mid latitude, island, continental influence
Townsville, Australia	Low latitude, continent shore
Wichita, KS, United States	Mid latitude, mid-continent, plains

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