Characterizing the Detectability of Emission Signals from a North Korean Nuclear Detonation

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1. Introduction

The Comprehensive Test Ban Treaty Organization (CTBTO) is charged with the detection of clandestine nuclear detonations worldwide (Auer and Prior, 2014). The International Monitoring System (IMS) is to accomplish this through 1) the detection of sonic and seismic waves emitted from an explosion and 2) the monitoring of radionuclides expected to be released (Wotawa et al., 2003; Auer and Prior, 2014), xenon in particular (Medalia, 2010; Kokaji and Shinohara, 2014). This noble gas (created in nuclear explosions and as a decay product of iodine, another fission product (Medalia, 2010)) is very difficult to contain (Hafemeister, 2007; Wotawa et al., 2010) and is detectable at low levels (Medalia, 2010). The monitored xenon isotopes of interest are ^{135}Xe (half-life = 9.14 hours), $^{133\text{m}}\text{Xe}$ (half-life = 2.19 days), ^{133}Xe (half-life = 5.24 days), and $^{131\text{m}}\text{Xe}$ (half-life = 11.93 days) (Wotawa et al., 2010), and can be measured at long distances for up to two weeks after a release (Medalia, 2010). As an example, early suggestions that the Democratic People's Republic of Korea (DPRK) had completely contained radioxenon from its test of February 2013 (Dahl, 2013) were refuted with the April identification of a corresponding xenon signal by the IMS stations at Ussuriysk, Russia and Takasaki, Japan (Ringbom et al., 2014). Similarly, the 2006 DPRK test emitted radionuclides that were observed as far away as Canada (Saey et al., 2007; Kokaji and Shinohara, 2014).

It is desired that any signal detected at a sensor be ascribed to a known source, or else flagged as being from an unknown source. To accomplish this, the Provisional Technical Secretariat (PTS) of the CTBTO currently runs the FLEXPART diffusion model (Stohl et al., 2005), forced with ECMWF $1^0 \times 1^0$ meteorological data (Wotawa et al., 2010) as part of its Atmospheric Transport Modeling system. This is used to calculate the 'source receptor sensitivity' (SRS) – a matrix that relates the 'signal' at any sensor location to all potential source points (Wotawa et al., 2003). Given a signal at a sensor, the SRS can be used to produce a 'Field of Regard' (FOR) – the area that influences that sensor and could be the source region (Wotawa et al., 2003). Detections of a single source at several sensors will yield multiple FORs, and the area over which they intersect will represent a suspected source region, as was done for the 2013 test

(Ringbom et al., 2014). These results demonstrate that atmospheric transport models coupled with meteorological models are powerful tools for recreating the motion of a plume from its point of emission (Kim et al., 2008; Eslinger et al., 2014; Arnold et al. 2015; Saito et al., 2015).

The ability to detect any signal of interest and ‘backtrack’ it to a unique source depends on the proximity of that source to other sources, as transport modeling will associate the composite signal from a set of mixed plumes from different sources with a large FOR that encompasses the overall source area of all the plumes, not just that of the clandestine signal. This could result in the emissions from a nuclear test remaining indistinguishable from known sources. Radioxenon is released from nuclear power plants and medical isotope facilities (Kalinowski and Tuma, 2009; Matthews et al., 2010) as well as from a nuclear detonation, so the task of uncovering a DPRK radioactive source is complicated by the existence of nuclear facilities in South Korea, China, and Japan (Wotawa et al., 2010). In particular, ^{133}Xe is emitted from weapons tests, reactor operations, and medical isotope facilities (Kokaji and Shinohara, 2014). While isotope ratios for nuclear detonations are different from other sources (Matthews et al., 2010), the reliable detection of multiple isotopes from an underground nuclear test is not always possible (Bowyer et al., 2013; Eslinger et al., 2014).

Mesoscale modeling has been applied to identify the source regions of observed signals for specific releases (e.g., the 2006 and 2013 DPRK tests) (Kim et al., 2008; Ringbom et al., 2014), and the simulation of a series of hypothetical releases has been used by Eslinger et al. (2015) to derive general properties of radioactive plume dispersion. Our goal here is to quantify our ability to discriminate a clandestine DPRK signal from known signals (the ‘detectability’), and we do so by simulating a series of hypothetical releases (similar to the methodology of Eslinger (2015)). Plume simulations were done with a mesoscale meteorological model coupled to a transport model. By simulating emissions from locations surrounding the Sea of Japan for several periods, the degree to which the DPRK signal stands out from the known signals emitted in the same region was quantified with two defined metrics: the signal strength and the area overlap ratio of the plumes, and compared to that of the other sources in the region. A partially distinct plume is required if we hope to narrow the potential source region based on an FOR

analysis alone, and we demonstrate that the DPRK source will often extend over a large area without being strongly mixed with plumes from other sources in the region.

2. Material and Methods

2.1 Modeling

The meteorological conditions were generated using the Regional Atmospheric Modeling System (RAMS) (Pielke et al., 1992). RAMS has been applied extensively to produce meteorological simulations on a range of scales (e.g., Cotton et al., 2003), and is ideal for this research. A domain over the Sea of Japan was selected, encompassing Japan and the Korean peninsula (Fig. 1). The model used two grids – a larger, outer grid at 30 km grid spacing, and an inner grid at 10 km spacing (Fig. 1a). The inner grid (depicted in Fig. 1b) comprises 251×251 grid points and was centered at 39°N , 133.5°E . The vertical spacing started at 30 m for the lowest level, and increased 15% for each successive level. The model was run with the Harrington radiation scheme (Harrington, 1997), and the LEAF-2 land surface scheme (Walko et al., 2000). The Mellor-Yamada planetary boundary layer scheme (Mellor and Yamada, 1982) was used to calculate vertical turbulent (sub-grid scale) diffusion, with a Smagorinsky (1963) horizontal deformation scheme used for the horizontal diffusion. The model also used a 30 second (roughly 800 m) topographic field (Fig. 1b), which can resolve many of the interactions between orography and airflow. Boundary conditions were supplied using the Global Forecast System (GFS, Environmental Modeling Center 2003) output, with 0.5° horizontal resolution and at 3-hr intervals.

The interaction of a DPRK plume with plumes from other sources can be sensitive to seasonal shifts in wind patterns (Achim et al., 2013). Therefore, RAMS was run for four periods: Autumn (October 21st through October 31st, 2012), Summer (July 22nd through July 28th, 2012), Winter (Feb 10th through Feb 19th, 2013) and Spring (April 4th through April 15th, 2013). Data were saved every 10 minutes, allowing the dispersion simulations to resolve features with short time scales. The RAMS meteorological output was used as input to the Hybrid Single-Particle Lagrangian Integrated Trajectory dispersion model (HYSPLIT, Draxler and Hess, 1998).

HYSPPLIT has been used in numerous applications (e.g., Becker et al., 2007; Butler et al., 2005; Yerramilli et al., 2012; Stunder et al., 2007) related to simulating the large-scale dispersion of effluent. This Lagrangian model simulates the release of a large number of ‘particles’, recalculating the position of each one at each time step according to both an advective wind field (resolved in the RAMS model) and a dispersive term derived from the RAMS-simulated turbulent kinetic energy (which RAMS does not explicitly resolve). The particles begin at the release point as a concentrated cloud, which then spread out and are transported downwind as the simulation progresses. Data from the first two days of each coupled simulation (e.g., April 4th and 5th) were eliminated as spin-up.

The RAMS/HYSPPLIT coupled models were run for the four periods with releases at eight known source locations: nuclear power plants at Ohi (release rate 9.13×10^3 GBq/yr), Wolsong (9.13×10^3 GBq/yr), Hanbit (1.37×10^4 GBq/yr), Hanul (1.37×10^4 GBq/yr), Kori (9.13×10^3 GBq/yr), Tianwan (4.56×10^3 GBq/yr), Qinshan (1.14×10^4 GBq/yr) (all from Kalinowski and Tuma, 2009), and a medical isotope production (MIP) facility (7.3×10^2 GB/yr) (Yonezawa, 2012; Achim, 2013) (Fig. 1b). Ohi and MIP are in Japan, Tianwan and Qinshan are in China, and the others are in South Korea. The two Chinese sources are actually located slightly beyond the western edge of Grid 2, but were shifted eastward (200 km for Tianwan, 60 km for Qinshan) for the simulation to allow them to serve as emission sources. Although Ohi is currently not operational (Matsuyama, 2013), it was active during the four selected periods (BBC, 2012). In addition, a hypothetical ninth source was located in Punggye, DPRK (indicated by the red star in Fig. 1), the site of previous underground nuclear tests. Note also the locations of fixed CTBTO surface samplers at Takasaki, Japan and at Ussuriysk, Russia, to be discussed later. An underground nuclear detonation will produce its signature nuclides within a short time, but their release into the free atmosphere can be more gradual - the signal observed in April from the February 2013 detonation was ascribed to a release from a only few days earlier (Ringbom et al., 2014), indicating that the test site was either still ‘leaking’ xenon weeks after the detonation, or that surface conditions were altered near the test site to allow for emissions out of the ground. A 10-kt nuclear detonation (a magnitude roughly achieved by recent DPRK tests (Forsythe, 2016))

will produce radionuclides ~8 orders of magnitude greater than the daily output of a nuclear plant (Matthews et al., 2010; Bowyer et al., 2013). An underground test, however, will likely experience a reduced rate of release (possibly by 7 orders of magnitude¹), with the result often being a signal only modestly stronger than the regional background (e.g., Ringbom et al., 2014; Eslinger et al., 2015). Our goal is to demonstrate the degree to which the various plumes interact or remain distinct, a primary concern when atmospheric models are used to backtrack detected plumes to their respective sources. To isolate this effect from the effects of varying source terms, we assume that all sources are continuously emitting xenon at a rate of 1.37×10^4 GBq/yr, equivalent to the release rate at the Hanul plant (Kalinowski and Tuma, 2009), and that it is not subject to atmospheric depletion. We will not apply a factor for radioactive decay in the initial simulations, but will do so for subsequent runs as described below. In the simulations conducted here, the plumes started as a point source and tended to reach their maximum size after roughly 3 to 4 days, after which the plume often exited the modeling domain. Therefore, each plume can be considered to be the result of a continuous 3 to 4 day release.

The simulations calculated the instantaneous concentrations at all points within the domain. In reality, however, sampler data represent gas collected over a 12 to 24 hour period at specific locations (Kokaji and Shinohara, 2014; Wotawa et al., 2010), so a value observed at a sensor will actually represent a time-averaged value. This can cause two separate plumes that arrive at the same location at different times to appear as one, making it harder to discriminate between them. To account for this, the simulated concentration data were subjected to a 12-hour averaging. Sensors also have a minimum concentration below which they cannot observe a signal, and the prescribed minimum concentration limit for CTBT sensors is 1.0 mBq/m^3 (Bowyer et al., 2013). In practice, however, the actual threshold is much lower for most stations, with an estimated sensitivity as low as 0.1 mBq/m^3 (Wotawa et al., 2010; Bowyer et al., 2013), and a newer unit now in testing will achieve about 0.05 mBq/m^3 (Hayes et al., 2015). We

¹ <https://elliott.gwu.edu/sites/elliott.gwu.edu/files/downloads/events/2.2%20Bowyer.pdf>

therefore assumed the 0.1 mBq/m³ threshold by setting all simulated concentrations below this threshold to zero.

2.2 Detectability

With the dispersion simulation, the concentrations at each point from all sources can be calculated, and the mixing of plumes from different sources can be determined. Two measures of signal detectability were applied. One measure of how strongly a signal stands out in a time series at a single point is the ‘signal strength’ (*SS*) relative to the background, defined as:

$$SS = \begin{cases} \frac{C_u - C_k}{C_k} & (1a) \\ \frac{C_u - C_k}{C_k} & (1b) \\ \frac{C_u - C_k}{C_k} & (1c) \end{cases}$$

The symbols C_u and C_k represent the concentrations of the ‘unknown’ and ‘known’ (i.e., produced by known sources) plumes at a point in the domain, respectively. The value of C_k represents the maximum value of C_k in the time series, and Eq. 1c is implemented to prevent very small signals from contributing to the *SS* metric. The *SS* at any sensor ranges from 0.0 (the unknown plume does not stand out amidst the known multiple overlapping plumes or is weak relative to the rest of the time series) to 1.0 (only the plume from the unknown source is over the sensor at that time).

The degree to which two airborne plumes are mixed (and difficult to discriminate) can also be quantified by their area overlap ratio. The concept was applied on a global scale by Pawson and Nielsen (2010, hereafter referred to as PN10), who showed how strongly plumes from multiple CO₂ sources intersect as a function of time and source separation, and explained the implications for the use of inverse modeling to relate observed CO₂ concentrations to observed fluxes. It can also be applied on a regional scale, and is similar to the ‘figure of merit in space’ used by Straume (2001) to quantify the spatial overlap of a simulated plume with observations.

The approach is to first define two plumes (m and n), each from a different source, of areas A_m and A_n . Assume that plume m is from an unknown source, while plume n is from a

known source, and the two plumes have an overlap area $A_{m,n}$, defined as the area within which 1) both the known and unknown sources exist, and 2) the value of SS is less than 0.9. The SS criterion will allow any location in which the unknown plume concentration is over 10 times that of the known plume to be considered as containing only the unknown plume. Our ability to detect plume m without being confounded by the existence of plume n is reduced by the fraction of plume m that is ‘contaminated’ by plume n . PN10 quantified this fraction as

$$R_{m,n} = \frac{A_{m,n}}{A_m} \quad (2)$$

$R_{m,n} = 1$ implies a complete overlap of signals, whereas when $R_{m,n} = 0$ there is perfect detectability (i.e., no overlap). Ideally, values of $R_{m,n}$ will be low for the DPRK source, indicating that the clandestine plume is not well mixed with the known sources, making it theoretically easier to rule out the latter as the source of any observed peak in concentration.

The SS and $R_{m,n}$ can be calculated for various known and unknown source combinations - each of the actual known sources can in turn be assigned as the ‘unknown’ source, with all of the remaining sources serving as the ‘known’ sources, allowing for an estimate of the separation of the unknown and known plumes. Figure 1b shows that some sources are more distant from the sampler locations than others, and the variation in detectability for Wolsong, Ohi, and DPRK (each as the ‘unknown’ source) was determined.

3. Results and Discussion

The Korean nuclear plant at Wolsong is located in close proximity to several other sources on the Korean peninsula (Fig. 1b), and it is therefore expected to be difficult to discern that source from the others. (The intermittent DPRK source is not used for this simulation or the simulation with Ohi as the unknown source.) Maps for the February and October simulations show how this ‘unknown’ plume was mostly hidden within the combined plumes from the other sources (the red area, in which the unknown plume exists but the SS value is below 0.9), failing to stand out above the known sources (Fig. 2, left), and values of $R_{m,n}$ are high for this source, usually greater than 0.9 for all seasons (Fig. 3).

The Japanese power station at Ohi (Fig. 2, middle) is more remote from the other sources, and its signal is expected to remain distinct from the others. Periods of good detectability ($SS > 0.9$) - Feb. 14th at 1200 UTC (Fig. 3a) and Oct. 25th at 1200 UTC (Fig. 3d) - alternated with periods when the plumes are well mixed (Feb. 16th at 0000 UTC (Fig. 3a)). The values of $R_{m,n}$ were lower than for Wolsong as the unknown source is now more distant from the known sources, though detectability was greater for February and October (Fig. 2, Fig. 3), with more mixing in April and July (Figs. 3b,c).

For the DPRK release, we assumed the combined plumes from the eight actual known sources represent the ‘known’ plume, while the DPRK plume is now added as a ninth ‘unknown’ plume. For February and October, periods of weaker mixing (e.g., Feb. 14th at 0000 UTC and Oct. 25th at 0000 UTC) (Fig. 2, right; Fig. 3a, d) alternated with periods when the plume was well mixed (Feb. 19th at 0000 UTC (Fig. 3a) and Oct. 29th at 0000 UTC (Fig. 3d)), similar to the release from Ohi. Overall detectability was greatest for April, with stronger plume mixing in July.

The above results are mostly a function of wind direction. The DPRK source lies further north than the others, so westerly or northwesterly winds will tend to allow for a large plume to extend from that source without interacting with other known sources. The winds for the latter half of the April simulation are mostly from the west, allowing for periods of low $R_{m,n}$ (Fig. 3b). The February and October simulations were also characterized by periods of northwest and westerly winds, allowing for periods in which approximately 1/3rd of the DPRK plume was distinct from the known sources (Fig. 3a, d). The July simulation, however, was dominated by southwesterly winds, which allowed the South Korean and Chinese sources to mix with the DPRK plume and reduce its detectability (only about 10% of the plume is unmixed) (Fig. 3c).

A dispersion model can aid in verifying the existence of a suspected source by identifying the existing sensor locations most likely to detect a signal from that source (the ‘catch the plume scenario’ as outlined by Ross (2010)), or in identifying promising locations for the deployment of a mobile sensor (as was done after the January and September 2016 DPRK nuclear tests (Lamothe, 2016; Lendon, 2016)). Concentration values from the four simulations can be

‘sampled’ at the two CTBT sites in Fig. 1b, and used to identify periods when the DPRK signal is more clear. Figure 2 (right) indicates that ‘pure’ effluent from DPRK passed over central Japan around October 25th and southeastern Russia on Feb. 14th, with the plume from DPRK over other parts of the domain thoroughly mixed with plumes from the other sources. The simulated time series of sampler concentration at the CTBT sensor location at Ussuriysk (the yellow circle in Fig. 1b) shows a clear DPRK signal for each of the 4 simulations (Fig. 4), existing as a pure signal. The concentrations at Takasaki (not shown) also indicate distinct signals for the April and October simulations. Also note that Ussuriysk detected a strong signal in July (Fig. 4c), despite the fact that strong plume mixing occurred during this simulated period (Fig. 3c) – although the plume was mostly mixed, winds were such as to allow the small unmixed portion to pass over the Ussuriysk sensor.

Given that ^{133}Xe (half-life of 5.24 days) is released from a weapons test, a nuclear reactor, and a medical isotope facility (Kokaji and Shinohara, 2014), we reran the February analysis accounting for radioactive decay. This implied a weaker weapons test signal among the other possible sources. Due to the relatively short transport time, the *SS* patterns in Fig. 2a and the values of *R* seen in Fig. 3a are little altered when the 5.24-day decay was imposed (not shown), and the time series in Fig. 4a are only reduced by 10-20%, with the signal from the DPRK test still clear in the data.

4. Conclusions

Simulations of hypothetical releases in the area surrounding the Sea of Japan with a high-resolution mesoscale transport model, combined with two metrics, indicated that, despite the existence of other sources in the region, the plume emitted from Punggye, DPRK remains distinct for much of the time during three of the four periods, each representing a different season, considered here. This supports the established use of transport modeling and the application of the FOR to reveal nuclear detonations within DPRK, and indicates that a DPRK signal need not be significantly higher than the confounding nearby sources to be detected. Even with substantial

mixing, a well-placed sensor will often be within the area of the ‘clean’ signal (e.g., the July simulation).

Application of this technique following an actual suspected weapon test requires a more thorough knowledge of source variability and strength in time. The application shown here assumed all sources were continuously emitting radioactivity into the atmosphere at the same release rate for all sources. Facilities that emit radionuclides often operate intermittently (Wotawa et al., 2010), and variability in source strength will necessarily alter the conclusions reached in the examples shown here. For the foreseeable future, the detection of airborne nuclides from a DPRK nuclear test will be confounded by the presence of other facilities near the Sea of Japan with a similar signature. High resolution mesoscale modeling will therefore remain a crucial component of the global monitoring system.

Acknowledgments

The authors gratefully acknowledge the NOAA Air Resources Laboratory (ARL) for the provision of the HYSPLIT transport and dispersion model and/or READY website (<http://www.ready.noaa.gov>) used in this publication.

Funding for this study was provided by the U.S. Department of Energy and the Laboratory Directed Research and Development Program at the Savannah River National Laboratory. SRNL is operated by Savannah River Nuclear Solutions for the U.S. Department of Energy under contract number DE-AC09-08SR22470.

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Fig1

Fig2

Fig3

Fig4