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Modeling the fallout from stabilized nuclear clouds using the HYSPLIT atmospheric dispersion model

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ABSTRACT

The Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model, developed by the National Oceanic and Atmospheric Administration's Air Resources Laboratory, has been configured to simulate the dispersion and deposition of nuclear materials from a surface-based nuclear detonation using publicly available information on nuclear explosions. Much of the information was obtained from "The Effects of Nuclear Weapons" by Glasstone and Dolan (1977). The model was evaluated against the measurements of nuclear fallout from six nuclear tests conducted between 1951 and 1957 at the Nevada Test Site using the global NCEP/NCAR Reanalysis Project (NNRP) and the Weather Research and Forecasting (WRF) meteorological data as input. The model was able to reproduce the general direction and deposition patterns using the coarse NNRP data with Figure of Merit in Space (FMS – the percent overlap between predicted and measured deposition patterns) scores in excess of 50% for four of six simulations for the smallest dose rate contour, with FMS scores declining for higher dose rate contours. When WRF meteorological data were used the FMS scores were 5–20% higher in five of the six simulations, especially at the higher dose rate contours. The one WRF simulation where the scores declined slightly (10–30%) was also the best scoring simulation when using the NNRP data. When compared with measurements of dose rate and time of arrival from the Town Data Base (Thompson et al., 1994), similar results were found with the WRF simulations providing better results for four of six simulations. The overall result was that the different plume simulations using WRF data had more consistent performance than the plume simulations using NNRP data fields.

1. Introduction

The National Oceanic and Atmospheric Administration's (NOAA) Air Resources Laboratory (ARL) has its origins in providing meteorological support to other Federal agencies during the Cold War's nuclear arms race. In 1948, a predecessor of ARL, the U.S. Weather Bureau created a Special Projects Section (SPS), in Washington, D.C., to bridge the gap between the meteorological expertise of the Weather Bureau and the research needs of other agencies related to nuclear weapons testing and development. As the arms race accelerated, a need arose to determine where clandestine nuclear tests were conducted using measurements of nuclear fallout around the world. The SPS was involved in determining the location of the first Soviet nuclear test (Machta, 1992) conducted in 1949 using backward trajectory analysis from interceptions of radioactive debris measured by Air Weather Service B-29 weather reconnaissance aircraft. As this collaboration progressed, it became clear that the development of more complex atmospheric transport models was needed to predict the long-range transport and deposition of nuclear materials from the many tests being conducted around the world, and over the next several decades ARL maintained a continued interest in the transport, dispersion, and deposition of nuclear materials (Draxler, 1982; Ferber and Heffter, 1961, 1976; Heffter, 1969, 1980; Hoecker and Machta, 1990; Machta and List, 1956; Machta et al., 1962; Machta and Heffter, 1986; Telegadas et al., 1978, 1979; Telegadas and List, 1964; List et al., 1961).

With an increase in the concern for future terrorist incidents since the September 11, 2001, attack on the World Trade Center in New York City and the Pentagon in Washington, D.C., and the possibility that terrorists could acquire nuclear materials and develop an Improvised Nuclear Device (IND), ARL expanded its capabilities for responding to exercises and incidents involving the detonation of a nuclear device and made them available to the

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civilian forecasters of the U.S. National Weather Service in support of their local clients.

A number of models have been used to simulate the explosion and fallout from a nuclear weapon with varying degrees of complexity. For example, the HotSpot Gaussian plume model (Homann and Aluzzi, 2013) developed by the U.S. Department of Energy is designed to provide a quick response to field personnel on the radiation effects from the atmospheric release of radioactive materials and is designed for short-range (less than 10 km), and short-term (less than a few hours) predictions. A special purpose program is included in HotSpot to model the effects of a surface-burst nuclear weapon; however the model assumes a constant wind direction and speed and does not take into account the effects of terrain on the wind flow.

A much more sophisticated model is the Hazard Prediction & Assessment Capability (HPAC) model developed by the Defense Threat Reduction Agency (DTRA, 2001; Chang et al., 2005). HPAC, which is a composed of a hazard source definition module, a transport module, and an effects module, uses the Second-order Closure Integrated PUFF (SCIPUFF) dispersion model to quickly predict the hazards from nuclear, biological, chemical, and radiological weapons and facilities. The second-order turbulence closure theory employed by SCIPUIFF provides a unique advantage over other models in that it can also produce a probabilistic estimate of the uncertainty in the concentration results due to atmospheric dispersion. HPAC can input real-time observed wind speed and direction at a single location or use 3-dimensional gridded wind and temperature fields to calculate the pollutant transport. HPAC uses the Nuclear Weapon (NWPN) module to calculate the initial stabilized nuclear cloud prior to modeling the dispersion and deposition by SCIPUFF.

Recently, the Norwegian Meteorological Institute (Bartnicki and Saltbones, 2008) modified the Severe Nuclear Accident Program (SNAP) model to not only predict the dispersion of radioactive debris following a nuclear accident, but also from a nuclear explosion. The model assumes two types of stabilized cloud shapes; a cylinder and a mushroom shape. Particle sizes range from 2 to 200 μm in ten discrete size ranges and an activity distribution that assumes 10% of the activity is in each category. They found that the results were not sensitive to different initial nuclear cloud shapes, however there were considerable differences in the plumes for various nuclear yields due to transport at different levels in the atmosphere.

Finally, one of the most advanced nuclear fallout models is the Defense Land Fallout Interpretive Code (DELFIC, Norment, 1979a, 1979b), which was originally developed in 1968 by the Defense Atomic Support Agency and has been subsequently revised by the military, government laboratories, and private organizations. DELFIC includes a dynamic, one-dimensional cloud rise module that explicitly calculates the growth of the nuclear cloud based on the yield of the weapon, the soil type, the height of burst, the atmospheric profile, the particle size distribution, etc. DELFIC is intended for use in the research of local nuclear fallout prediction and to be the standard against which simpler models are compared. DELFIC computes the downwind spread of nuclear material based on the assumed particle fall velocities and turbulence in the downwind direction from the calculated cloud rise module.

One of the atmospheric dispersion models developed by ARL in the late 1970's, and the primary model in use by NOAA today, is the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) (Draxler, 1999; Draxler and Hess, 1997, 1998) model. This model originally used surface weather observations and upper-air soundings as its source of meteorology until gridded meteorological model forecast data became routinely available from the U.S. National Weather Service in the late 1980's. Today, HYSPLIT serves as the operational dispersion model for the National Weather Service providing routine forecasts of smoke from wild fires (Rolph et al., 2009; Stein et al., 2009), windblown dust (Draxler et al., 2010), volcanic ash (Stunder et al., 2007), and atmospheric dispersion products for chemical and nuclear accidents (Draxler and Rolph, 2012).

The focus of the research presented here will be to model the dispersion, deposition, and decay of nuclear debris that followed the detonation of six relatively small (<50 kT) nuclear devices in the 1950's in Nevada using the HYSPLIT model and to calculate the radioactive dose rates from the local fallout using a new module developed for calculating doses in HYSPLIT. The resulting dose rate patterns will then be compared to the measured dose rate patterns from each of the six Nevada nuclear tests. The goal is to parameterize the HYSPLIT model using information currently available in the literature about the nuclear source term so that it can be run quickly to give a realistic estimate of the magnitude and pattern of deposition from small nuclear devices. Therefore, HYSPLIT will not be used to model the initial nuclear cloud growth, but will assume that the nuclear cloud has stabilized before proceeding with the transport and deposition calculations. In addition, the model will be run with global- and local-scale gridded meteorological data to determine if increasing the horizontal and vertical resolution of the meteorological data will result in improved predictions of nuclear fallout.

2. Dispersion model experimental design

2.1. HYSPLIT model

The Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model is a Lagrangian particle and puff model that is used by air quality researchers and forecasters to model the transport of pollutants using 3-dimensional gridded meteorological fields. In a recent publication (Moroz et al., 2010), the model was used to reconstruct the ^{137}Cs deposition from nuclear tests in the Marshall Islands, the Nevada Test Site, and the Semipalatinsk Test Site of the former Soviet Union. HYSPLIT was configured with a log-normal particle distribution and each particle size bin was assigned a fraction of the total ^{137}Cs activity. The resulting ^{137}Cs modeled deposition patterns were then compared to the observed patterns from each nuclear test. The study suggested that given adequate spatial and temporal meteorological data, HYSPLIT can be used to determine where and when nuclear material was deposited with relatively good degree of accuracy. They also found that when no measurements are available, HYSPLIT can be used to determine if fallout might have occurred at a given location and also some indication of the magnitude of the deposition.

In this application, we expand on the work of Moroz et al. (2010) and configure the model with several particle size and activity distributions obtained from various published sources, and compute dose rate contours for several nuclear tests at the Nevada Test Site in Nevada, USA.

2.2. Stabilized nuclear cloud

To model the nuclear fallout quickly it is necessary to establish the characteristics of the nuclear cloud just after stabilization instead of calculating the complex evolution of the cloud beginning at the time of detonation. Stabilization occurs after the temperature of the nuclear cloud is equalized with the ambient temperature in the surrounding air. At this point entrainment of outside air ceases and the vertical growth of the cloud stops. Nuclear particles have been formed directly by the fission reaction, the condensation of vaporized material lofted from the surface, and the vaporized