Journal of NUCLEAR SCIENCE and TECHNOLOGY, Supplement 4, p. 491–494 (March 2004)

Simulations of Transboundary Atmospheric Transport of Radioactivity Released from Nuclear Risk Sites at the Far East

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A long-range transport of radioactive pollutants in the atmosphere has received considerable attention in recent years, corresponding with many models to address these issues. In this paper a trajectory model *TraModel* and a Lagrangian particle dispersion model *ParModel* were introduced and applied successfully to simulate transboundary atmospheric transport of radioactivity released from the Tian Wan Nuclear Power Plant (NPP) in China and Vladivostok nuclear risk site (NRS) in the Russian Far East for some specific weather condition.
KEY WORDS: Transboundary transport, Trajectory, Lagrangian Particle Dispersion, Nuclear Risk Site

I. Introduction

In recent years the focus has been on the analysis of possible danger to environment and population in the neighboring countries due to normal operations and potential accidental situations at the nuclear risk sites (NRSs) including the nuclear power plants (NPPs), nuclear submarines, manufactories of nuclear material, storage facilities, etc. The together attention-getting questions people are trying to answer are: What is the probability of radionuclide atmospheric transport to adjacent countries in a case of an accident at the NRSs? In addition the accidents at Chornobyl and Three-Mile Island have demonstrated the need to prepare for airborne dispersion of radioactive material.

There are many NRSs in the Far East related to Russia, China, Japan and North and South Koreas. Several years ago, "The Radiation Safety of the Biosphere" (RAD) Project was started to focus on the independent evaluation of the currently existing radioactive pollution problems and specifically those of the Russian Federation, and in particular, its emphasis is on the potential trans-boundary aspects (Mahura, 2001; Parker et al., 2003). In 2003, Chinese scientists, who were supported by International Institute for Applied System Analysis (IIASA) and National Natural Science Foundation of China (NSFC), will add to this study by providing specific data on Chinese territory, participating in the modeling of atmospheric transport, and applying Chinese codes for parallel calculation of atmospheric transport at the Far East (IIASA, 2003).

In this paper, a trajectory model *TraModel* and a Lagrangian particle dispersion model *ParModel* were introduced and applied to simulate transboundary atmospheric transport of radioactivity released from the Tian Wan Nuclear Power Plant (NPP) in China and Vladivostok nuclear risk site (NRS) in the Russian Far East.

II. Methodology

1. Trajectory model - *TraModel*

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Trajectory models describe the paths of air parcels. When assuming that we have a specific infinitesimally small air parcel, the coordinates of the parcel, i.e. trajectory, are defined by the following equation:

$$x_i(t+\Delta t) = x_i(t) + \frac{\Delta t}{2}\cdot \left\{v[x_i(t),t] + v[x_i(t+\Delta t), t+\Delta t]\right\}, \quad (1)$$

where $x_i(t) = [x(t), y(t), z(t)]$ is the coordinates of the parcel at time t;

$$v[x_i(t),t] = \left\{[\bar{u}(x_i(t),t], [\bar{v}(x_i(t),t], [\bar{w}(x_i(t),t]\right\}$$

is the wind speed of the parcel at position of $x_i(t)$.

In principle, trajectories can be calculated directly from wind observations by interpolating between the measurement locations. In practice, however, trajectory calculations are mostly based on the gridded output of numerical models. On the synoptic scale, the most accurate wind data come from *numerical weather prediction* (NWP) centers. They use the most sophisticated methods currently available to provide with accurate analysis fields for their model forecasts. Hence a time series of these analyses should be used whenever possible. An additional bonus of this data source is that the data are easily accessible to many researchers. From most NWP models, data are available either on levels used internally by the model or on pressure levels that are interpolated from the model levels for synoptic purposes. For trajectory calculations, data on model levels are clearly better suited since interpolation errors are much smaller.

2. Lagrangian particle dispersion model - *ParModel*

Lagrangian particle dispersion models calculate trajectories of a large number of individual so-called particles to describe the transport and diffusion of airborne pollutants in the atmosphere. They are different from trajectory models which are impossible to describe transport phenomena in atmospheric turbulent flow by calculating individual trajectories. The movement of a marked particle is a sum of displacement due to the mean wind and a random displacement due to the diffusion processes:

$$x_i(t+\Delta t) = x_i(t) + v_i(x_i(t),t)\Delta t + v_i'(x_i(t),t)\Delta t .$$

$$i=1,\ 2,\ 3 \qquad (2)$$

where x_i is the coordinate component of particle (x, y, z); v_i the component of mean velocity $(\overline{u},\ \overline{v},\ \overline{w})$; v_i' the component of velocity fluctuation $(u',\ v',w')$; Δt the time step. The mean wind fields are obtained as mentioned in section 3.2. The velocity fluctuations are obtained for each time step from a Markov chain simulation after:

$$u'(t+\Delta t) = u'(t)R + (1-R^2)^{1/2}\sigma_u \xi ,$$
$$v'(t+\Delta t) = v'(t)R + (1-R^2)^{1/2}\sigma_v \xi , \qquad (3)$$
$$w'(t+\Delta t) = w'(t)R + (1-R^2)^{1/2}\sigma_w \xi + (1-R)\tau \frac{\partial \sigma_w^2}{\partial z}$$

where ξ is a normally distributed random numbers with mean zero and unit variance. $\sigma_u = (\overline{u'^2})^{1/2}$, $\sigma_v = (\overline{v'^2})^{1/2}$ and $\sigma_w = (\overline{w'^2})^{1/2}$ are the variances of the turbulent velocity fluctuations. $R(\Delta t) = \exp(-\Delta t/\tau)$ is the Lagrangian autocorrelation function. τ is the Lagrangian time scale.

The solution of above particle dispersion equations requires the knowledge of σ_{vi} and τ_{Li} at any time and at any position of a particle trajectory. For their determination, Hanna (1982) proposed a parameterization scheme that is based on the boundary layer parameters h, L, w_*, z_0 and u_*, i.e. PBL height, Monin-Obukhov length, convective velocity scale, roughness length and friction velocity, respectively. A modification method from Ryall and Maryon (1997) is adopted for σ_w for convective conditions since Hanna's scheme does not always yield smooth profiles of σ_w throughout the whole PBL to lend to an unmixing of well-mixed particles. The above parameters can be determined by the profile method, reported by Berkowicz and Prahm (1982), which uses wind and temperature data provided at the first model level and at the 10 m and 2 m. The following equations are solved through an iterative procedure:

$$u_* = \frac{\kappa \Delta u}{\ln \frac{z_i}{10} - \Psi_m(\frac{z_i}{L}) + \Psi_m(\frac{10}{L})}, \qquad (4)$$

$$\Theta_* = \frac{\kappa \Delta \Theta}{R\left[\ln \frac{z_i}{2} - \Psi_h(\frac{z_i}{L}) + \Psi_h(\frac{2}{L})\right]}, \qquad (5)$$

$$L = \frac{\overline{T} u_*^2}{g \kappa \Theta_*}, \qquad (6)$$

where κ is the Karman constant; z_i the height of the first model level; Δu the difference between wind speed at the first model level and at 10 m; $\Delta\Theta$ the difference between potential temperature at the first model level and at 2 m; Ψ_m and Ψ_h the stability correction functions for momentum and heat; g the acceleration of gravity; Θ_* the temperature scale and $\overline{T}$ the average surface layer temperature.

The concentration at each grid cell C_k (Bq/m^3) is calculated by summing up the contribution of each particle to the cell with

$$C_k = \frac{Q}{N}\sum_{i=1}^{N} N_{ik} \cdot \Delta t / V_k , \qquad (7)$$

where Q is the radioactivity (Bq) of the release; N the total number of particles; N_{ik} the total number of time step of particle i at the cell k; V_k the volume of cell k. The radioactive decay of nuclides is taken into account during the concentration calculation.

The dry and wet deposition is calculated using the source depletion concept by assuming the deposition velocity (m/s) and washout coefficient (s^{-1}), respectively. The deposition velocity depends on the type of nuclides and the condition of the surface. The washout coefficients for elemental iodine and other particulates are functions of the rainfall intensity (mm/h).

III. Applications and Analysis

1. Modeling region and NRSs

The influence on the environment and population will vary with temporal and spatial conditions. We simulated transboundary atmospheric transport of radioactivity released from two sites, i.e. Tian Wan Nuclear Power Plant (NPP) in China and Vladivostok nuclear risk site (NRS) in the Russian Far East (as shown in **Figure 1**).

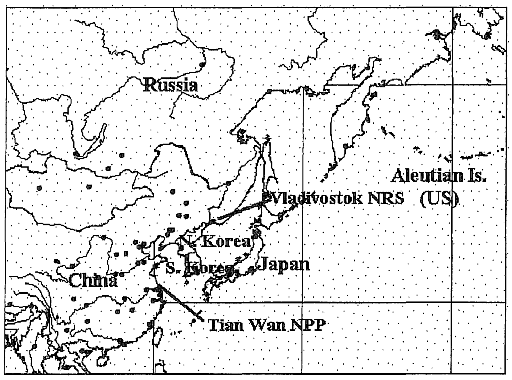

Fig. 1 Geographical modeling region and position of NRSs.

Vladivostok is the location of the Russian Pacific Fleet headquarters and is located at 132.4°E vs. 42.9°N. In 2001, the focus of IIASA's research plan was on the analysis of possible danger to the environment and population in the neighboring countries due to normal operations and potential accidental situations at the nuclear submarines and storage facilities (Mahura, 2001). Tian Wan NPP is located at Hou Yun Tai Mountain on the eastern coast of China and located at 119.5°E vs. 34.7°N.

Considerring the general atmospheric circulation patterns in East Asian Regions and the position of the two sites, the modeling region was located between 90°E-170°W and 15-70°N which covers China, North and South Koreas, Japan, Russia and Aleutian Chain Islands (US) (as shown in **Figure 1**).

2. NCEP global tropospheric analysis dataset

In this study the gridded dataset we used is from the Dataset DS083.2 - NCEP Global Tropospheric Analyses, which is one of the major gridded analyses available at the National Center for Atmospheric Research (NCAR, Boulder, Colorado). The DS083.2 dataset is on 1° × 1° grids covering the entire globe every six hours. Analysis has been done on a daily basis at 00, 06, 12 and 18 UTC terms (Universal Coordinated Time).

3. Trajectory modeling

There are usually several different trajectory types depending on their treatment of the vertical wind component and coordinate system. The commonly used types of trajectory are: 1) three-dimensional (3D) trajectories which use all three wind components and represent more realistic movement of air parcels; 2) isobaric trajectories which follow the surfaces of the constant pressure; 3) isentropic trajectories which assume air parcels are moving along the surfaces of the constant potential temperature. In addition, trajectories also are distinguished by simulating air parcels following either forward (forward trajectories) or backward (back trajectories) in time.

Here the forward 3D and isentropic trajectories from the two sites were simulated during from April 29 to May 1, 2003 with the time interval of 3 h and the length of an individual trajectory of 192 h. **Figure 2** and **3** show the 3D and isentropic trajectories for Tian Wan NPP and Vladivostok NRS, respectively.

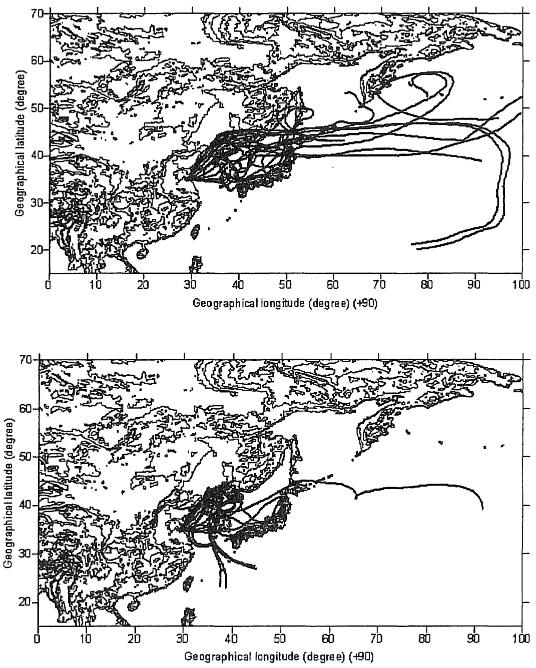

Fig. 2 3D (upper) and isentropic (lower) trajectories for Tian Wan NPP.

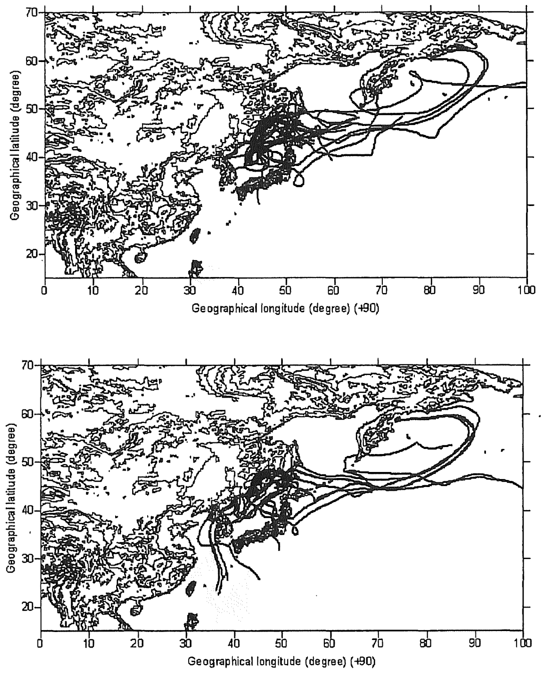

Fig. 3 3D (upper) and isentropic (lower) trajectories for Vladivostok NRS.

The calculated results of 3D and isentropic trajectory were different in case of Tian Wan NPP and similar in case of Vladiostock NRS. As Draxler (1996) demonstrated, isentropic and three-dimensional trajectories resemble each other closely during most of the time (90%), but can differ substantially when they enter baroclinic regions of the troposphere. So it indicates that if accurate fields of w are available, three-dimensional trajectories are more accurate than all the others.

In addition, the impact region of release is different in the case of Tian Wan NPP and Vladivostok NRS as for the 3D trajectories. For the release from the Tian Wan NPP, the main impact regions include South Koreas, Japan, the northeastern regions of Russian Far East and Aleutian Chain Islands. For the release from the Vladivostok NRS, the regions include the north regions of Japan, a majority of east Siberia regions of Russian and Aleutian Chain Islands.

4. Lagrangian particle dispersion modeling

Nuclide concentrations every 3 hours after a hypothetical release from the two sites were computed for the following input condition: beginning time of the release – at 18:00UTC, 2003-4-29; duration of the release – 1 hour; height of the release – 100 m; whole quantity of the released ^{131}I nuclide – 1×10^{10} Bq. Dry deposition is calculated by assuming deposition velocity of 0.0025 m/s for ^{131}I. Wet deposition cannot be calculated because of lack of precipitation data. **Figure 4** shows the deposition concentrations after 192 hours of the release for Tian Wan NPP and Vladivostok NRS.

The impact region is similar to the results obtained by trajectory calculations. The calculations showed differences in ground level air concentrations and deposition concentrations for the release from the two sites due to the differences of wind field caused by the different release positions. It also shows that the maximum concentrations of the release from Vladivostok NRS are higher than those from Tian Wan NPP.

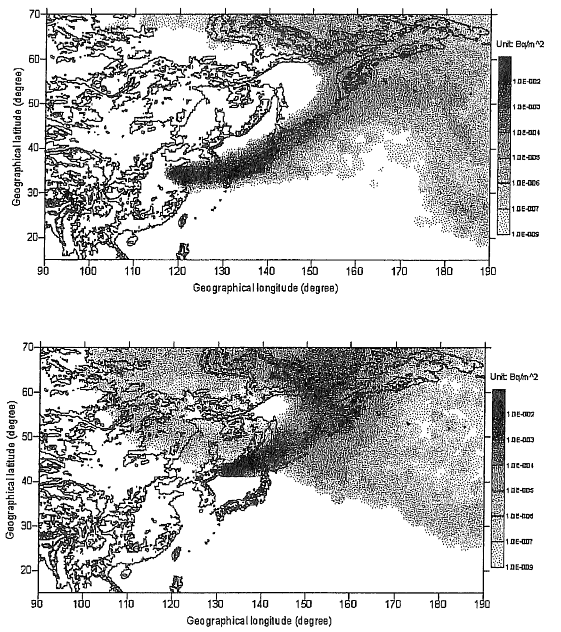

Fig. 4 Dry deposition concentrations of ^{131}I after 192 hours of the release for Tian Wan NPP (upper) and Vladivostok NRS (lower).

Although State of Alaska (US) is not included into the modeling region, it can be seen that the air and deposition concentrations in the region are less 4 – 5 orders of magnitude than those in South Koreas, Japan and regions of Russian Far East. In addition, northeastern China can be contaminated and some regions are contaminated again several days after the release of Vladivostok NRS.

Other numerical tests show that a few changes of the release height and duration, such as the variations of height of 10 – 500 m and duration of 10 min – 6 hours, the air and deposition concentrations are not significantly changed.

IV. Concluding Remarks

The trajectory model *TraModel* and Lagrangian particle dispersion model *ParModel* were successfully applied to simulate transboundary atmospheric transport of radioactivity released from the Tian Wan NPP in China and Vladivostok NRS in the Russian Far East. The introduction mentioned above is just the pilot study and we need to do much work in future. The entire assessment of a model is difficult especially on large scale. For example, as for the trajectory model, it requires the determination of a "true" reference trajectory. Although many different tracers have been used, none of them is ideally suited, either because it is not conserved well enough, because its determination is difficult, or because it is not normally available (Stohl, 1998).

The principle of Lagrangian particle dispersion model is fascinating. Calculations of dispersion using it have directly relations with turbulence characteristics of atmosphere without assumption of uniform and stationary flow and have no artificial numerical diffusion like Eulerian models. Here we just give some results for a specific weather condition. We believe that the research tools introduced in this paper will be applied to carry out analysis of the probabilistic patterns of atmospheric transport from the NRSs at the Far East and to evaluate consequences of an accident in the further studies.

Acknowledgments

Authors are grateful to the Department of International Cooperation of National Natural Science Foundation of China and IIASA. And we are grateful to Academician Pan Ziqiang, Professor Liu Senlin, Professor Liu Xinhe and Professor Frank L. Parker and Professor Vladimir Novikov of IIASA for their support on this research.

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