Modeling the Atmospheric Radionuclide Air Concentrations and Deposition from the Fukushima Daiichi NPP Accident

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Overview

The calculation of the transport and dispersion from the source was done using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT – Draxler and Hess, 1998) model. In HYSPLIT, the computation is composed of four components: particle transport by the mean wind, a turbulent transport component, scavenging and decay, and finally the computation of the air concentration. A large number of pollutant particles (by convention called "particles" but are computational "point" entities that may be particles or gases), are released at the source location each time step and passively follow the wind. The mean particle trajectory is the integration of the particle's position vector in space and time. The turbulent component of the motion defines the dispersion of the pollutant cloud and is computed by adding a random component to the mean advection velocity in each of the three-dimensional wind component directions. The vertical and horizontal turbulence is computed from the local stability estimated from the wind and temperature profiles. Air concentrations or dispersion factors in this case, are computed by summing each particle's mass as it passes over a concentration grid cell and dividing the result by the cell's volume. A detailed description of the computational aspects of the model can be found in Draxler and Hess (1997) and its configuration is reviewed in the User's Guide (Draxler, 1999).

One critical aspect for quantitative predictions of air concentration is the wet and dry scavenging that occurs along the transport pathway. The computational details are given below. Four generic species were tracked as surrogates for the radionuclides: a gas with no wet or dry scavenging, a gas with a relatively large dry deposition velocity (0.01 m/s) and wet removal (Henry's constant = 0.08) to represent gaseous I-131, a particle with a small deposition velocity (0.001 m/s), and a particle with a large deposition velocity (0.01 m/s). There can be considerable variability in scavenging coefficients and the wet scavenging coefficients used in these calculations are lower than the original model default values (Draxler and Hess, 1997; Hicks, 1986) but these lower values are consistent with the results from more recent deposition studies (Cohen et al., 2002) using the HYSPLIT scavenging parameterizations.

Simulation Configuration

The HYSPLIT simulation is divided into multiple 3-hr release segments. Each segment is an independent calculation using a unit source (1 per hour) emission rate represented by 100,000 particles per hour which were followed for 72 hours and then terminated. Each calculation provides the dispersion factors from the release point for that emission period to all downwind grid locations, defining how much of the emissions are transferred to each location for every output time period. The concentration grid of 601 (West to East) and 401 (South to North) grid cells defined on a regular latitude-longitude grid at 0.05 degrees resolution (about 5 km) centered at 38N and 140E. The output is calculated as 3-hour averages for air concentrations and 3-hour deposition totals. Calculations were started every 3 hours from 11 March 0000 UTC through 31 March 2100 UTC, resulting in 168 independent calculations.

The transport, dispersion, and deposition calculation used the global meteorology from NOAA's Global Data Assimilation System (GDAS) at 0.5 degree horizontal resolution, on the native hybrid vertical coordinate system, and at a temporal resolution of every 3 hours. The second simulation used the high resolution meteorological analyses from the Japan Meteorological Agency also at 3 hour resolution but with a horizontal resolution of 5 km. A second set of calculations was also conducted with each meteorological data where the model derived precipitation field was replaced by JMA radar/rain gauge analyzed precipitation as described by Nagata (2011). The temporal resolution is 30 min and the spatial resolution is 45 seconds in longitude and 30 seconds in latitude covering a domain from 20N to 40N and 118E to 150E.

HYSPLIT Configuration Summary

Center	Meteorology	ATM	Release	Output
NOAA	GDAS 0.50d 56 levels 3 hourly	HYSPLIT dt=6min	1 unit/h 1 m -100 m 300K p/3h	601x401 grid 0.05d x 100m 3-hr averaged
NOAA	JMA 5 km 50 levels 3 hourly	HYSPLIT dt=6min	1 unit/h 1 m -100 m 300K p/3h	601x401 grid 0.05d x 100m 3-hr averaged

Vertical Velocity Calculations

The calculations using the global meteorological model data used the vertical velocities provided with the data. However the JMA vertical velocities were first remapped to a terrain following coordinate system consistent with the HYSPLIT computational framework. The vertical velocity correction,

$$\sigma \, (u \, \partial\eta/\partial x + v \, \partial\eta/\partial y),$$

was applied at all levels based upon the slope of the terrain surface (η) and decreasing with height (σ).

Computation of Scavenging and Deposition

In HYSPLIT, wet scavenging is parameterized through removal constants β (s^{-1}), where the deposition D over time step Δt for each particle of mass M is

$$D = M \{1\text{-}\exp[-\Delta t \, (\beta_{dry}+\beta_{gas}+\beta_{inc}+\beta_{bel})\,]\, \}. \quad (1)$$

The particle mass is reduced by D each time step. The time constant for within-cloud removal for particulate pollutants is

$$\beta_{inc} = S\ P\ \Delta Z_p^{-1}, \quad (2)$$

where S is the ratio of the pollutant's concentration in water to its concentration in air ($4x10^4$), ΔZ_p is the depth of the pollutant layer, and the precipitation rate P is the value predicted by meteorological model used in the calculation. Below-cloud removal is defined directly as a rate constant ($\beta_{bel} = 5x10^{-6}$), independent of the precipitation rate. The wet deposition of gases depends upon their solubility and for inert non-reactive gases it is a function of the Henry's Law constant (H - Molar atm^{-1}), the ratio of the pollutant's equilibrium concentration in water to that in air. Therefore, the gaseous wet removal time constant is

$$\beta_{gas} = H\ R\ T\ P\ \Delta Z_p^{-1}, \quad (3)$$

where R is the universal gas constant (0.082 atm M^{-1} K^{-1}), T is temperature, and the wet removal of gases is applied at all levels from the ground to the top of the cloud-layer. The dry deposition calculation is limited to particles within the surface layer (ΔZ_p is usually about 75 m), and the time constant is

$$\beta_{dry} = V_d\ \Delta Z_p^{-1}. \quad (4)$$

Although radioactive decay, by itself, does not result in deposition, airborne and deposited radioactive pollutants do decay, and hence the airborne particle mass and deposition amounts are adjusted for radioactive decay each time step also using the time constant approach

$$\beta_{rad} = \ln 2 / T_{½}, \quad (5)$$

where the decay constant for radioactive processes is defined by the half-life ($T_{½}$).

References

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