MODELING FOR ENVIRONMENTAL RADIATION DOSE RECONSTRUCTION

Bruce Napier
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 Topics

➤ NCRP Report No. 163
➤ Atmospheric dispersion modeling
➤ Reconstruction of dose from releases of iodines and noble gases from plutonium production facilities (Hanford and Mayak)
➤ Uncertainty analyses
Definition of exposure scenarios/exposed groups
Identification of exposure pathways
Development and implementation of dose reconstruction methods
Evaluation of uncertainties
Presentation/interpretation of results
* Data and information
* QA/QC
Airborne Releases: Basic Questions for Modeling

➤ WHERE is the release going?
   -- Wind direction

➤ WHEN will the release arrive at a location?
   -- Wind speed

➤ WHAT is the release concentration?
   -- Atmospheric diffusion
The Lower Atmosphere
Instantaneous Plumes and Stability Classes
Measuring Atmospheric Stability

- Should be continuously measurable
- Often divided into finite classes, A-G
- Often inferred, e.g. from solar insolation, cloud cover, or temperature differences
- Methods of determination do not always agree
Modeling Dispersion in the Atmosphere: the Advection - Diffusion Equation

$$\frac{\partial \chi}{\partial t} = K_x \frac{\partial^2 \chi}{\partial x^2} + K_y \frac{\partial^2 \chi}{\partial y^2} + K_z \frac{\partial^2 \chi}{\partial z^2} - u \frac{\partial \chi}{\partial x} \pm S$$

$\chi$ = air concentration (activity m$^{-3}$)  
$t$ = time (s)  
$K_x, K_y, K_z$ = eddy diffusion coefficients in the x, y, and z directions, respectively  
$S$ = sources and sinks  
u = average wind speed (m s$^{-1}$)
Solving the Advection-Dispersion Equation

► Analytical (Closed Solutions)
  ■ Exact solution
  ■ Easy to program, fast to run, limited to simple cases

► Numerical
  ■ More general & flexible, complex geometries, temporal variations, treat more processes explicitly, often need extensive data and resources

► Gaussian Plume Model
  ■ Most commonly used atmospheric dispersion model
  ■ It is consistent with the random nature of turbulence
  ■ It is a solution to the Fickian (gradient transport) diffusion equation for constant K (diffusivity) and u (wind speed)
Gaussian Plume Model: Ground-level, Center

\[
\frac{\chi(x)}{Q} = \frac{1}{u \pi \sigma_y(x) \sigma_z(x)} \exp \left[ - \frac{1}{2} \left( \frac{H}{\sigma_z(x)} \right)^2 \right]
\]

Limitations of the Gaussian model
- Low wind speeds
- Complex terrain
- Spatial and temporal changes in wind velocity
- Deposition and transformation within the plume during travel
- Diffusion coefficients ("sigmas") are empirical
Uncertainty in Gaussian Plume Model

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Range, Predicted over Observed air concentration (P/O)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highly instrumented site; ground-level, centerline; within 10 km of a continuous point source</td>
<td>0.65 to 1.35</td>
</tr>
<tr>
<td>Specific time and location, flat terrain, steady meteorology, within 10 km of release point</td>
<td>0.1 to 10</td>
</tr>
<tr>
<td>Annual average, specific location, flat terrain, within 10 km of release point</td>
<td>0.5 to 2</td>
</tr>
<tr>
<td>Annual average, specific location, flat terrain, 10 m to 150 km downwind</td>
<td>0.25 to 4</td>
</tr>
<tr>
<td>Complex terrain or meteorology, episodic releases</td>
<td>0.01 to 100</td>
</tr>
<tr>
<td>Episodic, surface-level releases, wind speeds less than 2 m s(^{-1})</td>
<td>1 to 100</td>
</tr>
</tbody>
</table>

(C.W. Miller, Ch.3 in C.J. Maletskos, Ed. 1995)
Other Possible Solutions

► Puff Trajectory Models
- Series of discrete puffs used to approximate a continuous plume
- Wind direction, wind speed, mixing depth, and stability updated regularly
- Allows temporal variations in source characteristics
- Allows spatial and temporal variations in meteorological conditions
- Diffusion within each circular puff generally assumed to be Gaussian in nature

► Particle-in-Cell Models
- Source emissions approximated by a large number of particles
- Each particle is followed over a fixed coordinate system
- Concentration in each grid square is found by adding the contribution from each particle
- Requires specification of a wind field
- Specified wind velocity is three-dimensional, and may vary from cell to cell
- Terrain effects may be incorporated
More Complex Models Require More Resources

- Data input requirements are larger and more complex
- Larger computer capacity required
- Generally longer computer running times
- Model predictions more difficult to verify
An Example: The Hanford Environmental Dose Reconstruction (HEDR) Project

- Over 750,000 curies of I-131 were emitted from Hanford 1944-1950
- The RATCHET puff model was developed to use *hourly* meteorological data, *daily* emission rates, and provide daily depositions over 75,000 square mile domain
- This was used to ‘drive’ an environmental model with 1102 locations. The environmental model required ~monthly information on crops, milk distribution, etc.
Another Example: The Russian Mayak Production Association

- Over 1,000,000 curies of I-131 and over 4,600,000,000 curies of noble gases (primarily short-lived Ar-41, Xe-138, Kr-87) were released from Mayak between 1948 and the 1970s

- The models developed for the Hanford analyses are being adapted for use by the Russians

- Input data are not ‘as good’ – meteorological data every 3 hours, source terms intentionally averaged over longer periods for national security reasons

- At both Hanford and Mayak, uncertainty analyses are primary considerations in dose modeling
Validation of the Puff Model RATCHET

- At Hanford, good results with 8 different datasets used including both I-131 and noble gases (PNWD-2221 HEDR; 1994) (Kr-85 shown)

- At Mayak, TLD of bricks from building in city of Ozersk at about 10 km distance compared to predictions within uncertainties of measurement
All doses should be estimated with uncertainties

- There are different kinds of uncertainty
- Dose parameters for each individual are not perfectly known:
  - Individual variability in residence history, life habits, and human metabolism (aleatory; Type A)
  - Lack of knowledge about other parameters, such as radionuclide releases, transport, or residence histories (epistemic; Type B)
**Shared versus Unshared Uncertainties**

- Uncertainties may be the same for groups of people: The radionuclide composition of the releases (for the whole cohort), or dose rates inside of specific homes (for families)
  - These are *shared* (within groups or the cohort)

- Uncertainties may be unique: Individual habits (time spent out of the area) or metabolism (uptake and retention of radionuclides)
  - These are *unshared*

- *Shared* uncertainties induce correlations
Classical versus Berkson Uncertainties

- Classical uncertainties typically involve lack of precision in measurements - *Measurements*
  - The estimate differs from the true value by an error that is stochastically independent of the true value
  - Classical uncertainties decrease the slope of the dose-response (bias towards the null hypothesis)

- Berkson uncertainties typically involve use of assigned values (a regional average dose rate for all members of a region), or modeling results (ICRP dose conversion factors) - *Grouping*
  - The true value varies from the estimate by an error that is random and is independent of the estimate
  - Berkson uncertainties may not affect the slope of the dose-response (if unbiased), although they may increase the standard errors of the estimate
Modular (Two-Dimensional) Uncertainty Analyses

- A method of dealing with correlations, shared parameters, and disaggregating aleatory and epistemic uncertainties
- Empirical joint distributions of shared parameters are generated
  - Monte Carlo realizations of parameters are preserved for repeated use
The TRDS-MC Computer System: A 2-dimensional Monte Carlo analysis

[Diagram with flowchart showing data flow and processes]
Summary Comments

▶ This has been an incomplete discussion!
▶ NCRP Report No. 163 provides more detail in many areas than I have had time to address
▶ Atmospheric (and surface water!) dispersion modeling can be reasonably accurate – if detailed information about local meteorology and release rates are available. However, accounting for the joint uncertainties in these can be complex and time consuming (i.e., expensive)
  ▶ Puff models running on hourly input data are probably appropriate for your application.
▶ Uncertainty analyses are probably required. Recent developments in radiation epidemiology emphasize the need to identify Classical (measurement) and Berkson (grouping) components of uncertainty; there are ways to separate them available.