Commentary

Roles and Limitations of Atmospheric Dispersion Calculations

–Is It Possible to Make Atmospheric Dispersion Simulations that are Useful and Informative in a Nuclear Accident?–

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There has been some confusion with respect to atmospheric dispersion calculations for radioactive materials released from nuclear facilities at the Fukushima Daiichi Nuclear Power Plant during and after the accident. The assessments of atmospheric dispersion in the nuclear field tend to focus excessively on the assessment methodology, such as "to use the dispersion models in this way," while neglecting actually happening phenomena in the natural world. An overall revision is probably required to address what kind of methodology should be adopted for the assessments of atmospheric dispersion in the nuclear field.

I. Introduction

Most of the onshore environmental impact produced by the accident at the Fukushima Daiichi Nuclear Power Plant (such accident being hereinafter referred to as the "Fukushima Accident") was associated with the atmospheric dispersion of radioactive materials. Since the Accident, the calculation of atmospheric dispersion has been discussed in a variety of settings. There has undeniably been some confusion with respect to the adequacy of the results from the estimations made using SPEEDI at that time and the way that they were handled. Similarly, the method used to estimate dispersion in relation to the revision of the Nuclear Emergency Preparedness Guide has proven controversial, as has the interpretation of the results. Meanwhile, the calculation of atmospheric dispersion associated with the Fukushima Accident is applied in post-hoc analysis, such as, inverse estimation of the release rate from monitoring data and analysis of the migration of airborne radioactive materials during the accident.

This commentary first provides an overview of atmospheric dispersion phenomena and then outlines the roles played by, or expected from, the atmospheric dispersion calculations as well as their inherent limitations. The author believes that both the providers of calculation functions, who develop and operate models, and the recipients, who use the resultant information, need to understand these roles and limitations accurately in accordance with their respective levels of responsibilities. This approach offers the most direct way of making the

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most of obtained information while avoiding the unnecessary confusion that can result from an excessive focus on details concerning the phenomena of atmospheric dispersion and their calculations. Although this commentary is not exhaustive, it is expected to serve as an entry point for substantive discussions among persons who make use of the data produced from atmospheric dispersion calculations.

II. Overview of the Realistic Picture of Atmospheric Dispersion Phenomena and Its Calculation

1. What Determines Atmospheric Dispersion?

Any materials released into the atmosphere is subjected to the following: (1) advection in a wind field; (2) dispersion by atmospheric turbulence; (3) removal by deposition or other such phenomena; and (4) disappearance or generation through physical or chemical changes. The concentration in an affected area is determined mostly by these factors. Advection and dispersion are determined by the atmospheric conditions alone, except for in the case of large particles of the target materials that have notable gravitational sedimentation. On a side note, some have explained in reference to the impact of the Fukushima Accident that, without the involvement of rainfall, the (dry) deposition of radioactive materials and the like depends on gravitational sedimentation, but this is misleading. In fact, gravitational sedimentation has only a marginal environmental impact. In dry deposition, the dominant factors are downward turbulent transport in the atmosphere and transport (i.e., the inertial collision and Brownian dispersion of particulate matter and the molecular dispersion of gaseous matter) in the air near the surface of objects on the ground (e.g., soil, vegetation, and buildings).

To return to the topic of discussion, **Figure 1** provides a schematic illustration of the space and time scales involved in atmospheric dispersion and the related meteorological phenomena. The factors that influence advection and dispersion vary depending on the targeted time

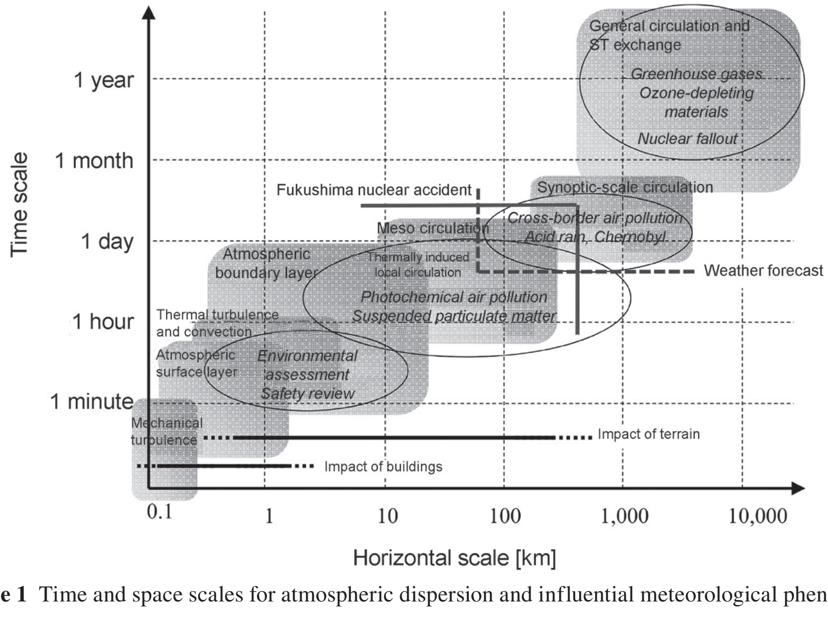

Figure 1 Time and space scales for atmospheric dispersion and influential meteorological phenomena

and space scales. An extensive movement across several hundred kilometers or more is determined by synoptic-scale circulation phenomena, such as lows, highs, and fronts. The relatively limited impact of small geographical features and short-term changes on this scale makes it relatively easy to calculate atmospheric dispersion and assess the extensive distribution of concentration. Examples of this include the Europe-wide impact of the Chernobyl Accident, the transport of materials that cause acid rain, and the extensive transport of suspended particulate matter (SPM).

On a scale of around 100 km or less (i.e., a mesoscale), advection and dispersion are influenced significantly by factors that matter relatively less if a more extensive scale is used. For instance, the airflow, which is mainly determined by the local terrain, shapes the courses of advection and dispersion. The terrain also has an impact through thermal effects (e.g., the mesoscale thermally induced circulation of land and sea breezes as well as mountain-valley winds), which in turn influence the turbulence structure in the atmospheric boundary layer. The thermal impact may change considerably in the course of a few hours. In an even smaller horizontal range of a few kilometers, some terrains can be assumed to be homogenous (flat). An assessment of dispersion can, excluding the impact that buildings have on the dispersion process, be easily performed using adequate on-site wind measurements.

The impact of the Fukushima Accident varies greatly according to the degree of impact in question. Full-scale decontamination is required within the range of a few dozen kilometers. The air dose rate is believed to have substantially exceeded the natural fluctuation within the range of a few hundred kilometers due to the accident. For this type of scale, the general direction of advection is determined by the winds generated from the synoptic-scale circulation associated with lows, highs, fronts, and the like. The meteorological phenomena in this space scale are familiar to us due to their coverage in weather forecasts. The general winds produced in the synoptic scale are observed almost directly as local winds out at sea or on plane fields. However, the spatial distribution of winds is altered considerably by mountains and other topographical features. Even with the same terrain, the degree of change may differ significantly depending on the temperature stratification in the atmosphere. The more stable the stratification is, the more pronounced the air currents are along routes that bypass mountains or pass through valleys and saddlebacks. Such mesoscale local wind fields are formed by the difference in land and sea temperatures and the heating and cooling of mountain slopes during the day and at night. Phenomena of this scale were influential within the range that experienced a significant impact from the accident.

2. How to Calculate?

Any numerical calculation of atmospheric dispersion phenomena first requires the calculation of the wind speed distribution and the turbulence distribution involved in advection and dispersion as well as the calculation of the precipitation distribution (with these three types of distributions being referred to collectively as a “meteorological field”) for the deposition calculation. The calculated meteorological field is applied to calculate the airborne concentration of the target materials and the amount of its deposition on the ground surface (**Figure 2**). Various methods can be applied based on the target space scale and the purpose of the assessment. The most standard method can be described as follows.

The standard method applies the results obtained from an objective analysis or numerical forecast based on data gained from routine observations performed by meteorological organizations (e.g., JMA, ECMWF, and NOAA) in meteorological fields of the global or synoptic scale (i.e., covering a few thousand kilometers). For instance, updated data from the JMA can

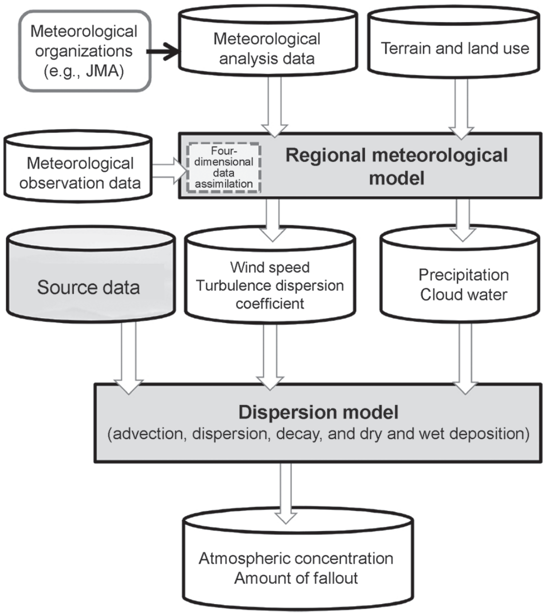

Figure 2 Typical process for the calculation of atmospheric dispersion

be obtained online a few times a day to perform instant calculations as long as a line has been properly installed. The calculated wind corresponds to the general wind mentioned earlier. This wind is applied as the initial and boundary conditions to calculate the meteorological field in detail by using each atmospheric dynamic model (regional meteorological model) for a specific area of interest (e.g., East Japan or in the environs of Fukushima Prefecture). The results are applied to calculate the advection, dispersion, and deposition of the target materials.

In the past few decades, the marked advancement in regional meteorological models has made it possible to calculate meteorological fields that take into account local terrain and thermal impact on land and at sea. Precipitation is highly reproducible given appropriate initial and boundary conditions. In addition, some community models are used by large number of researchers involved in the field of atmospheric science (e.g., MM5, WRF, and RAMS). The forecast performance of these models is verified and improved in various respects. Most models adopt four-dimensional data assimilation to reflect any observation data related to winds and the like in the calculation of atmospheric dynamics, thereby making it possible to enhance the accuracy of the calculation as long as observation data is available. Nonetheless, the assimilation is widely applied only in the calculation of meteorological fields. No standard assimilation methods have been established for calculating dispersion. WSPEEDI-II and most other atmospheric dispersion models for analyzing the impact of the Fukushima Accident adopt the abovementioned standard method. SPEEDI also employs its own regional meteorological model.

These atmospheric dispersion models are being developed and employed even in Japan by numerous research institutes and universities. Private companies (e.g., weather service providers and environmental consultancies) are also capable of performing the necessary calculations. Proper calculations that have been performed using the standard method do not produce any significant differences between the wind fields calculated using different models in a synoptic scale or a larger mesoscale (i.e., meso-α or meso-β scale across 20 km or more).

However, differences may be produced in small-scale wind fields, the vertical structures of turbulence fields, and precipitation patterns due to differences in settings such as the adopted cloud physics processes, the turbulence models, the grid settings, and the boundary conditions of the ground surface and the sea surface. In addition, the methods used to handle wet disposition (e.g., the modeling approach, accuracy, and parameter values) vary significantly in the dispersion calculation, and they are recognized to produce significant differences between models in the calculated distributions of the deposited amount and the atmospheric concentration. Currently, the Science Council of Japan is spearheading an intercomparison of the major models that have been adopted to assess the impact of the Fukushima Accident.

In relation to the standard method mentioned earlier, the calculation of atmospheric dispersion over more extensive areas requires less detailed consideration of the terrain, as is the case in regional meteorological models. These calculations depend largely on data obtained from meteorological organizations. Naturally, the prediction accuracy depends on the data that is obtained from these organizations. Conversely, detailed calculations of meteorological fields and atmospheric dispersion over smaller areas (e.g., a few kilometers) grow increasingly difficult due to the more pronounced influence of smaller terrains and terrestrial objects (e.g., buildings). Nonetheless, provided we assume a flat terrain as well as homogeneous and steady state meteorological field, a simplified calculation (plume model) may be applied for atmospheric dispersion by assuming the Gaussian distribution as the analytical solution of the dispersion equation. One example of this type of model is MACCS2, which is commonly used in Level 3 PSA and has been employed by the Nuclear Regulation Authority in its dispersion assessments. The scope of application for the plume model is limited because the assumption is not realistic in most cases. In each case of dispersion, the concentration must be calculated after confirming that the assumption of a steady state and homogeneous meteorological field has been satisfied.

III. Selection of the Appropriate Method for Each Assessment

The previous section explained the basics and methods for calculating atmospheric dispersion in general terms. The appropriate method must be selected according to the intended purpose and assessment target, while also bearing in mind its limitations. It is particularly important to identify the requirements in light of the purpose of the intended assessment, such as to obtain average and steady state values is enough or not, to obtain dynamic fluctuations in specific cases is needed or not, or to consider the terrain, weather, and other local characteristics is needed or not. Different approaches must be taken in the assessment of dispersion associated with an accident. In doing this, it is important to clarify the relevant goals, such as ex-ante predictions for responding to emergencies or detailed ex-post assessments.

1. Environmental Assessments and Safety Reviews

The plume model is employed extensively in the calculation of atmospheric dispersion for the concentration and dose assessments in environmental assessments and reactor safety reviews. In most of these cases, the plume model is employed to assess the average concentration over a relatively small distance of a few kilometers over a short time period (e.g., one hour). The results obtained from multiple calculations of dispersion are then superimposed to assess the annual average concentration. This practice is reasonable because a flat terrain and a constant meteorological field over a period of one hour can be expected to a certain degree.

However, an hourly calculation of the concentration becomes less rational in the event of changing wind directions and atmospheric stability (hence, turbulence field) or if the impact of the terrain cannot be ignored. Even if the terrain is flat, the assumption of a homogeneous spatial wind field and turbulence field does not reflect reality. Each calculated value should be applied with great care. The plume model is applied to calculate the average figure over a long period not only because of the practicality of the simplified method, but also because random parts of the errors from the assessment of each case of dispersion associated with the simplified model are expected to cancel each other out by the superimposition of the calculation results. This effect has been confirmed in the long-term field dispersion experiment conducted by the author and his colleagues in Tokai-mura.

2. Prediction of the Accident Impact

An assessment of the impact of an accident in almost real time or its predicting for the next few hours or a few dozen hours targets one event at a certain point in time to follow factors such as the space distribution of the atmospheric concentration, the deposition amount (surface concentration), and the dose rate as well as changes in these factors over time. As highlighted by the accident in question, an assessment of the dispersion across 10 km or more is susceptible to the impact caused by unsteady meteorological field and the local terrain. The application of a plume model would appear to be unreasonable because of the oversimplification of its dispersion process.

The application of the simple model may be possible provided the terrain is flat and that there is a small temporal change in the meteorological field (mainly winds) associated with thermally induced circulation and synoptic-scale circulation (Figure 1). The plume model could be reasonably applied to nuclear facilities in the US or European countries, which tend to be located on terrain that is flatter than that in Japan. However, it is unclear whether this type of model can be easily applied to nuclear facilities in Japan, which are mostly located on complex coastal terrains. Few Japanese nuclear facilities are located on flat terrains.

The results for atmospheric dispersion calculations performed based on the standard method are affected by uncertainty concerning the release rate and other source data as well as the calculations per se. The verification of the model has been done using data from dispersion experiments conducted with artificial tracers and data from actual accidents. For instance, the verification of WSPEEDI-II using data from the Chernobyl Accident demonstrated that the calculated deposition amount was within the range of one fifth to five times that of the actual measurements in about 65% of the target spots 1). In general, the calculated overall distribution patterns of the atmospheric dispersion are highly reproducible. However, the atmospheric concentration and the deposition amount at each spot often differ from the actual measurements by several factors. In other words, even if the direction and manner of advection and dispersion can be roughly reproduced by the calculation, even tiny differences in the plume position and arrival time translate into a large difference in the concentration at the target spot at each point in time because of the significant gradient in the concentration at the edge of the plume. Consequently, in order to predict the impact of an accident, it is better to track the overall distribution pattern and its changes over time, rather than follow the specific values at each target spot.

The source data is essential for predicting the concentration, dose rate, and other absolute values. However, the experience gained from the Fukushima Accident demonstrates that it is difficult to predict the release rate in advance. Nonetheless, provided real-time data is available from stack monitors or surrounding monitoring equipment and allowing for a certain degree of uncertainty, it might be possible to assess the current distributions of the dose rate and concentration based on the proportional relation between the obtained measurements and the calculated values. Nowcasting might also be possible with the concentration and dose rate in the area where the plume is expected to arrive in one or two hours.

3. State of Dispersion Predictions Performed in Response to the Fukushima Accident

A commentary provided in this journal describes the findings from a review of the results obtained from many calculations performed using SPEEDI in the immediate aftermath of the Fukushima Accident 2). The author reached a similar conclusion after his own analysis based on the general approach to performing dispersion assessments for an accident as discussed in the previous section. Part of his findings will be presented in the report issued by the AESJ Investigation Committee on the Accident at the Fukushima Daiichi Nuclear Power Plant. In summary, the author shared the following findings.

(1) The overall dispersion processes could be reproduced in many cases, although the direction of advection could not be reproduced in some cases.

(2) In many cases, the complex dispersion associated with time varying wind directions could be predicted. Inaccuracies were limited to one or two compass points in the wind directions or two or three hours when the wind directions changed.

(3) The integrated values of the deposition amount and dose rate over a period of 24 hours (regarding the impact of the events that took place mainly in the afternoon on both March 12 and 15) had already been obtained before dawn or in the morning of the same day. The predicted results were closely aligned with the actual state of contamination.

(4) Except for the ex-post calculations announced by the Nuclear Safety Commission on March 23 and other dates, all of the calculations were carried out using a hypothetical release amount or the unit amount. Therefore, the absolute values of the concentration and dose rate had not been obtained by any calculations.

By piecing together these facts, it was possible to produce very reliable predictions using the atmospheric dispersion calculation with uncertainties in the plume arrival time of a few hours and in the plume directions of 45 degrees. However, it was difficult to predict the dispersion with errors of up to one hour and one compass point. About half a day before both March 12 and 15, the impact could already be predicted accurately to be able to say something like, “From late afternoon through to this evening, the impact today is expected to be experienced in the northwest (including west-northwest and north-northwest).” Combined with the real-time dose rate data obtained along the site boundary, these predictions could be very useful information.

Uncertainties concerning predictions generally include those contained in the meteorological data obtained from the meteorological agency. For instance, when a low-pressure system passes through the target area, a prediction may err considerably depending on the pathway and relative position of the plume. Nonetheless, predictions can be extremely useful in predicting one or two days in the future, as long as such limitations are taken into account. In fact, calculations performed using WSPEEDI-II could be used to make some predictions two or three days in advance that are closely aligned with the state of dispersion as we understand it today. Examples include the slight impact observed on land from March 16 to 19 that was mainly due to the plume advancing over the sea, the clockwise landward advancement of the plume on March 20 that affected the area from north Miyagi to south Iwate with the wet deposition of materials released on the same afternoon, and the plume that stalled over the Kanto region (advancing toward Tokyo) from March 21 to 22 to cause deposition by precipitation. Due to space limitations, instead of the relevant figures being included here, these forecast results have been published on the websites of the NRA and other relevant organizations as of the writing of this commentary.

4. Ex-Post Analysis of Accident Impact

In the early phase of the accident, almost no measurements were conducted to determine the atmospheric concentration. Retrospective calculations of the atmospheric concentration must be performed to assess the internal dose from inhalation. To predict one event with a high accuracy, such an ex-post analysis has the same requirements as the aforementioned predicting of the accident impact. The difference lies in the possibility of performing calculations by incorporating the observed meteorological data. As explained earlier, regional meteorological models enable four-dimensional data assimilation. In general, such an assimilation can be performed over the entire timeframe to enhance the accuracy of the calculation.

Unfortunately, many of observational meteorological data are missing from the Fukushima Accident. Especially during the initial phase, measurements could not be performed around the site due to the earthquake and the subsequent tsunami. As such, the assimilation of observation data has not had much effect. Before the calculation results are used, it is important to keep in mind that, to a certain degree, they have similar limitations to those for the aforementioned predicting of the accident impact. The direct application of the calculation results is not necessarily sensible even with high temporal and spatial resolutions for the atmospheric dispersion. These results should be used with the appropriate temporal and spatial resolutions while keeping in mind the possibility of temporal errors in the precipitation and changes in the concentration being caused by changes in the wind direction as well as possible errors in the location of the plume by a few mesh points.

5. Estimation of Source Data

It is extremely difficult to keep track of the species, amount, release locations, and physiochemical conditions of radioactive materials released into the environment both during and after a nuclear accident. In such circumstances, the vital information that is required includes the concentration and dose rate measured in the environment. Many attempts have been made for not only the Fukushima Accident 3) but also other preceding events 4) to extract information related to release sources by employing atmospheric dispersion calculations. Details can be found in the reference materials, but the basic approach for this method involves searching for the release rate needed to reproduce the concentration and dose rate measured in the environment by performing atmospheric dispersion calculations.

The author and his colleagues have conducted studies concerning incidents such as the Fukushima Accident, the Chernobyl Accident, the criticality accident at Tokai-mura and the release of Cs-137 from Algeciras. These studies have led them to the following findings. It is difficult to estimate the release rate precisely from environmental data. In most cases, however, rough estimates can be produced that may differ by about three times. The uncertainty of such estimates is mainly due to the uncertainty of the atmospheric dispersion calculation and the inadequacy of the temporal and spatial representativeness of the measurement values. Many kinds of measurements are conducted, including the atmospheric concentration in gaseous and particulate forms, the ground surface concentration (per area and per environmental sample weight), and the dose rate (the contribution of plume and ground surface deposition). Their temporal and spatial densities are inhomogeneous and sparse. For these reasons, it is difficult to develop a tool with a predetermined procedure and method. The release rate must be estimated in an ad-hoc manner. With respect to the method, special attention must be paid in relation to the adoption of Bayesian statistics or other mathematical methods in the development of relevant technologies. They may prove effective in certain circumstances, but the essence of making estimates could be misunderstood if it is simply regarded as a matter of mathematical or numerical solutions.

6. Ex-Ante Atmospheric Dispersion Calculations with Postulated Accidents

In recent years, systematic calculations of the atmospheric dispersion of materials released in postulated accidents have been conducted mainly by local governments to provide a reference for emergency preparedness. This new practice is driven by the perceived needs of local governments to understand the nature, extent, and severity of the impact of postulated accidents according to the respective local characteristics so that they can fulfill their responsibility to protect residents on the ground in the event of an accident. These calculations, exemplified by those conducted by the prefectural governments of Shiga and Gifu, are sensible responses to the Fukushima Accident.

The author led the committee for Gifu Prefecture in conducting a calculation aimed at identifying (1) local or seasonal factors that may influence the nuclear impact in the prefecture; and (2) the geographical extent of the areas that are expected to be affected significantly and the severity of the impact. This calculation also adopted the basic approach explained in sections III-2 to III-4. To achieve the first goal, detailed calculations were performed using atmospheric dispersion over a period of one year by reproducing the local terrain and past weather conditions. Dispersion characteristics associated with the local terrain that was identified in the calculation were used to deploy monitoring posts. The computation requirements are not slight, but they can be achievable relatively easily given the capability of computers today.

Meanwhile, the meteorological guidelines issued by the former Nuclear Safety Commission state that a dose assessment must be performed after any accident by using the plume model and the statistical value (97 percentiles from the least impact). This stipulation has remained unchanged for over 30 years without revision. When the author first came across these guidelines more than twenty-five years ago, he questioned the soundness and validity of this approach. An environmental assessment certainly takes a similar approach in that it takes note of the statistical characteristics of any changes in the concentration of permanently present environmental materials. It is unclear whether this approach can be applied to any release of radioactive materials caused by a specific accident. This question remains unresolved.

IV. Conclusions

This commentary provided an overview of atmospheric dispersion and the various assessment methods. It went on to explain the current practices employed in nuclear-related assessments and their possible future. The quantitative understanding of atmospheric dispersion remains insufficient, particularly with respect to wet deposition. However, models that are available to us today still hold useful potential. Unfortunately, this fact remained unrecognized among nuclear societies before and after the Fukushima Accident. Arguably, a “dinosaur-like” method that is mixed up with principles and was defined more than a quarter of a century ago is still blindly followed, even though it is probably irrelevant to the actual phenomena to be assessed. The author believes that an overhaul is much needed to address how atmospheric dispersion is calculated in the nuclear field in order to understand and assess the phenomena that are actually encountered based on scientific principles and practices.

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