Simulation of long time averaged concentration under actual meteorological conditions

Tomohiro Hara, Ryohji Ohba, Kazuki Okabayashi and Jiro Yoneda
Nagasaki R&D Center, Mitsubishi Heavy Industries, Ltd., Fukahori machi 5-717-1, Nagasaki, Japan
Ryohji_ohba@mhi.co.jp

Haruyasu Nagai and Takashi Hayashi*

Nuclear Science and Engineering Directorate,
Japan Atomic Energy Agency
Shirakata 2-4, Toukaimura, Ibaragiken, Japan
*:Former Affiliation

Abstract - We simulated a meandering effect of wind direction fluctuation on horizontal gas diffusion over Mt. Tsukuba near Tokyo, using a rotating turntable in the wind tunnel experiment. Experimental results of wind velocity and gas concentration were validated with field data observed by Japan Atomic Energy Research Institute (JAERI), 1989 and 1990. This technique can be applied to environmental assessment based on the air quality standard usually defined by 1 hour or 30 min. averaged concentration.

Recently, mesoscale meteorological models become able to simulate local scale phenomena in the mesh size up to about 10m, by improving turbulence closure model. We simulated actual unsteady phenomena of airflow and gas diffusion over Mt. Tsukuba, and compared the calculated results with field data. Both data agreed well under neutral, stable and unstable atmospheric stabilities.

Key words –Meandering, atomospheric stability, wind tunnel, meteorological model, diffusion.

1 Introduction

Variation of gas concentration in the field depends on unsteady meteorological conditions of wind velocity, wind direction and atmospheric stability. However, conventional wind tunnel experiments and Computational Fluid Dynamic (CFD) models cannot simulate these unsteady phenomena, because they assume steady state meteorological conditions.

Environmental assessments need a long time averaged concentration for 30 min., 1 hour or 1 year in actual site. Some empirical formula for a meandering factor have been used for these needs. However, the meandering factor depends on a terrain and a stability condition at each site.

We simulated a meandering effect of wind direction fluctuation on horizontal gas diffusion over Mt. Tsukuba near Tokyo, by our original technique using a rotating turntable. In the wind tunnel experiment, and by the mesoscale meterological model (RAMS/HYPACT).

2 Field experiments

Field experiments were carried out at Mount Tsukuba region (Fig. 1) in Japan.

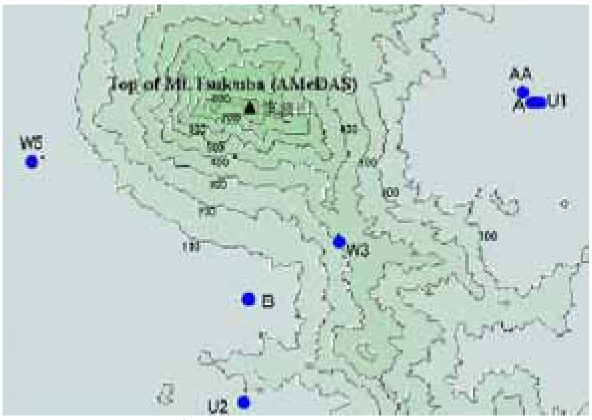


Fig.1 Map of Mt. Tsukuba region. Locations of measuring stations are denoted by closed circles.

The observed data refer to two atmospheric diffusion experiments carried out in 1989 from 13 to 20 November, and in 1990 from 10 to 18 November, in the Tsukuba area as part of the "Experiment to Demonstrate the Propriety of Atmospheric Dispersion Evaluation Method for Safety Analysis" (Hayashi et al., 1999a, 1999b), conducted by Japan Atomic Energy Research Institute in cooperation with the Japan Weather Association. In Fig. 1, the campaign domain with the locations of the measurement points are shown also.

The available meteorological observations for the station at the top of Mt. Tsukuba (named TOP) were collected from the AMeDAS (Automated Meteorological Data Acquisition System of the Japan Meteorology Agency) dataset. The AMeDAS system measures wind speed, wind direction, temperature, and precipitation automatically, recording 10-minute-averaged data every hour.

At the AA station, a Doppler sodar was used, providing wind speed and direction measures, and standard deviations of velocity fluctuation, every hour as 10-minute-averaged data. Turbulence data were available for the 1990 campaign, from the Doppler sodar at the AA station and from sonic anemometers at the U1 and U2 stations.

Fig. 2 shows diagrams of the occurrence frequency for wind direction for AA at 100 m height AGL and for W5 at 5.5 m AGL.

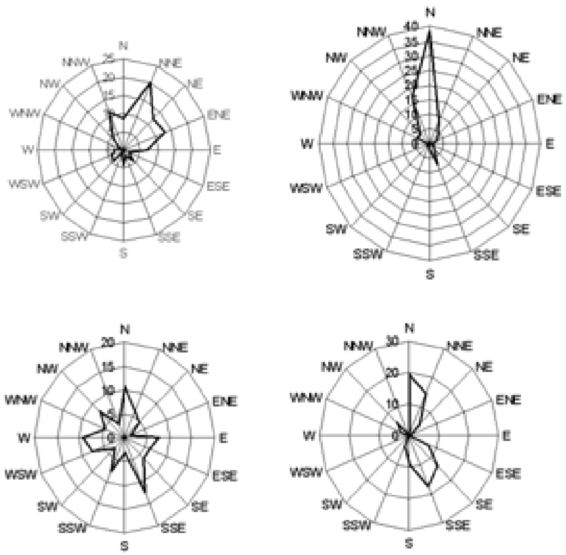


Fig 2. Occurrence frequency (%) of observed wind directions at 100m AGL on AA (left) and 5.5m AGL on W5 (right), for the periods 11/13 - 11/19 1989 (top) and 11/11 - 11/16 1990 (bottom)

Tracer gas of SF6 was released at A and B point from pressured vessel lifted by a balloon at 100m height for 90 minutes, several times under neutral, stable and unstable conditions. Gas concentration was sampled by sampling bags at 63points during the last 30 minutes in 180 minutes of gas release time.

3 Wind tunnel experiments

Ide et al. of MHI (1994) developed a new method to simulate a long time averaged concentration by rotating a circular terrain model on a turn-table shown in Fig. 3 and 4, and named it "Overlapping method". Their rotating speed is in inverse proportional to the occurrence probability of wind direction, and ground level concentration is measured at more than 400 sampling points, simultaneoursly and continuously.

We conducted a validation experiment of the Overlapping method under the corresponding meteorological condition to the field experiment at Mt. Tsukuba under 3 kinds of wind fluctuation variannce;

σ_{θ} =4.5, 9.0 and 12.0 deg. (Hayashi et al. 2001) .Correlation of these results in Table 1 indicate that wind fluctuation variance of 9.0 deg seems to be good.

Table 1 Correlation coefficient of concentration data

Wind fluctuation	Correaltion	Regression
4.5 deg	0.82	0.59
9.0 deg	0.90	0.89
12.0 deg	0.89	0.98

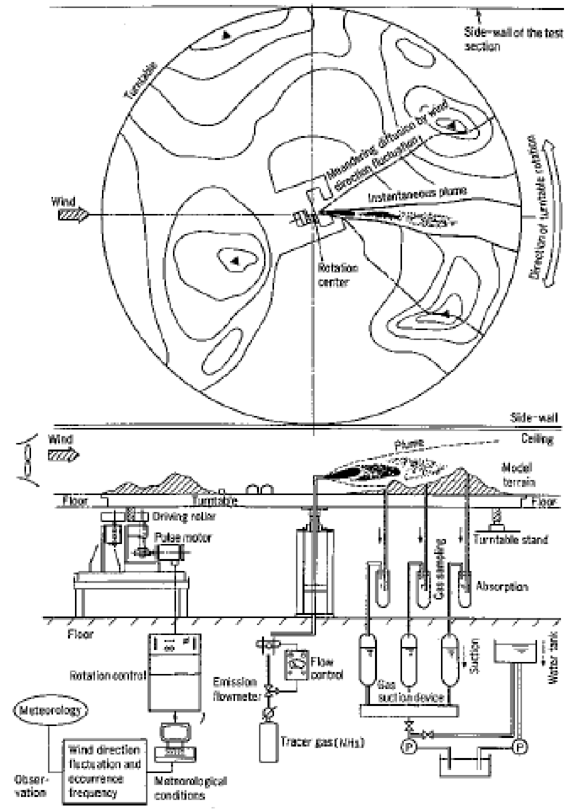


Fig. 4 Schematic illustration of overlappking eqipment in wind tunnel (top-view above and side-view below)

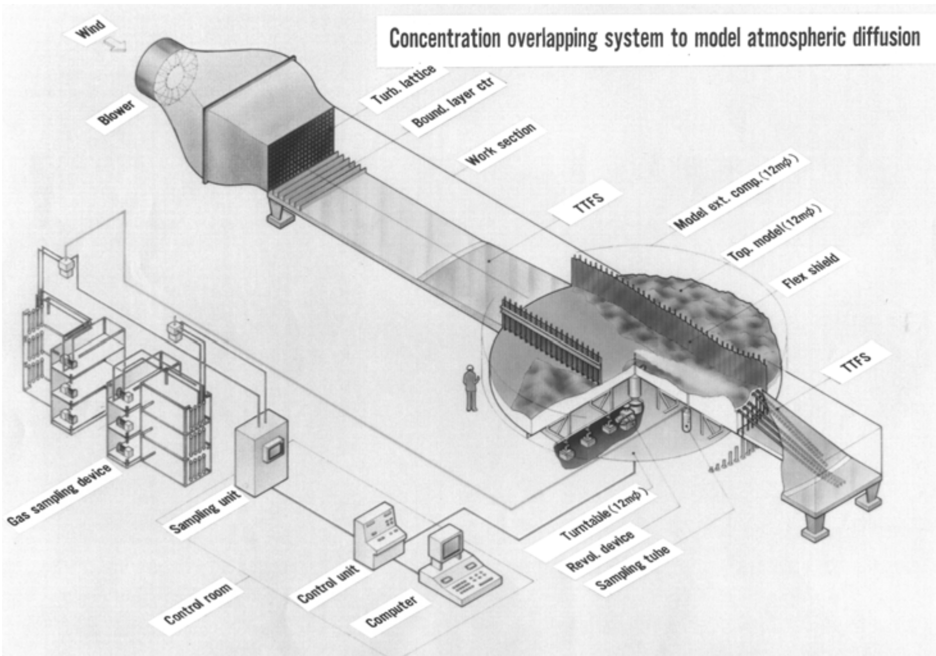
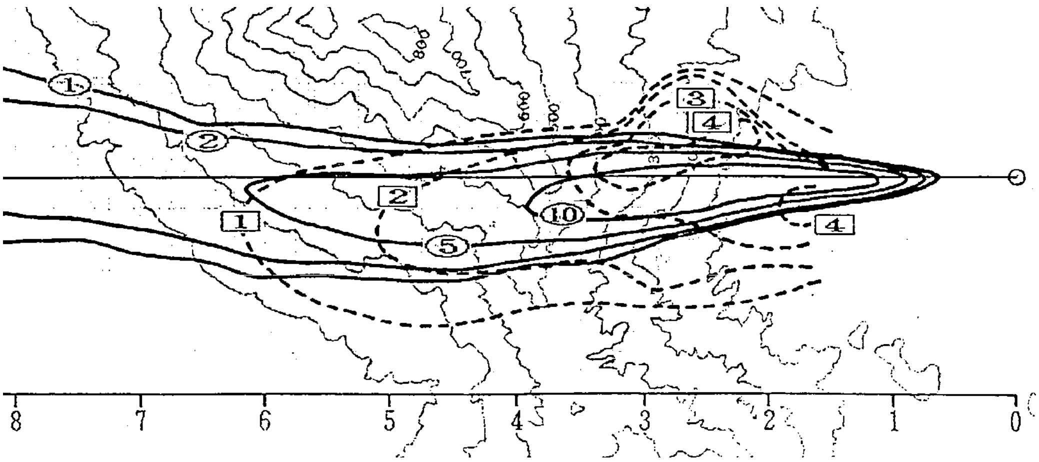


Fig. 3 Overlapping system to simulate a meandering effect on gas diffusion in wind tunnel

a) Conventional method (constant wind direction: σ_θ=0.0)



b) Overlapping method (turn table method; σ_θ=9.0)

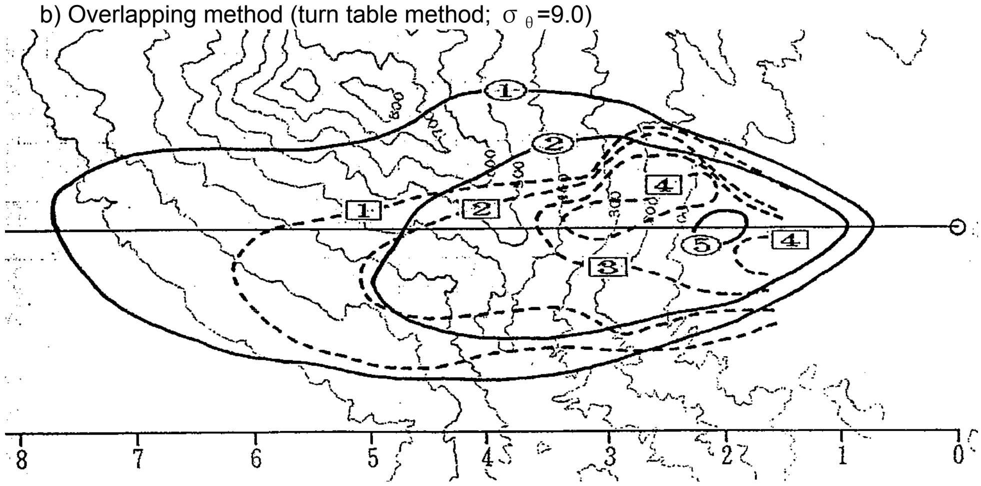


Fig. 5 Ground level concentration distribution around Mt. Tsukuba without and with Overlapping method, where broken curves represent field data (RUN 89-3) and solid ones wind tunnel

The results of conventional wind tunnel experiment and the Overlapping one were compared with field data, as shown in Fig. 5. The Overlapping method simulates a wide lateral spread caused by meandering effect for 30 minutes.

Axial ground-level concentrations were compared with field data in Fig.6. It was found from Fig. 6 that the conventional method overestimated the concentration due to the underestimation of lateral plume spread, while the Overlapping method reproduced well the field data. Standard deviation of lateral wind fluctuation was 2 degree and 9 degree in the wind tunnel with and without overlapping method, respectively. It was confirmed from Fig. 6 and 7 that axial concentration is in inverce propotion to lateral wind spread σ_y.

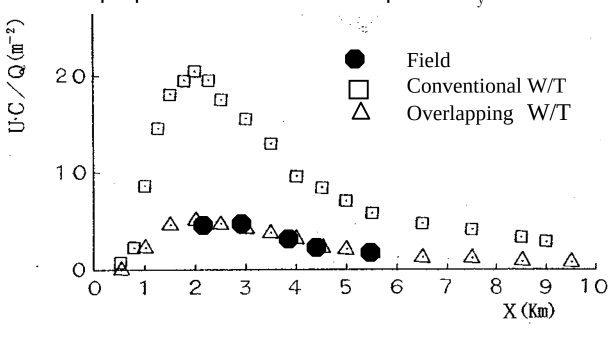


Fig. 6 Axial ground-level concentrations

Because P-G curves of A to F in Fig. 7 were obtained from field observed data for few minutes sampling time, they are lower than the σ_y value of σ_θ =9.0 in correspondance with 30 minutes sampling time.

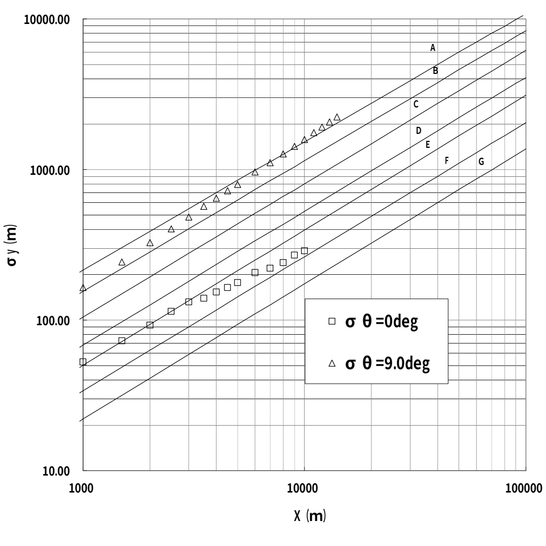
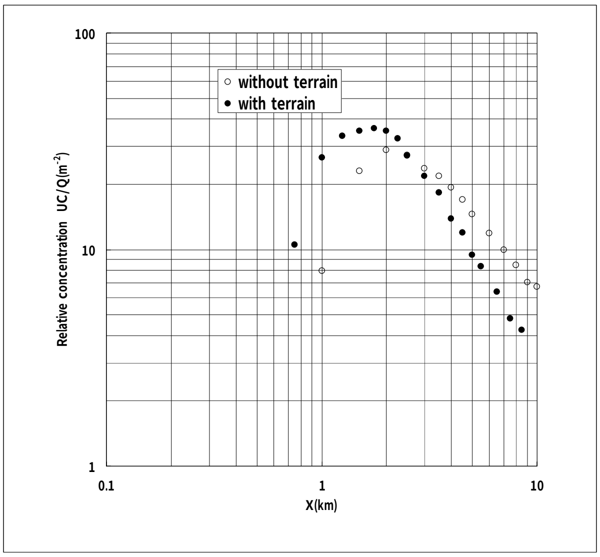


Fig. 7 Lateral plume spreads of wind tunnel

Next, we examined terrain effect on axial ground level concentration and lateral plume spread,as shown in Figs. 8 and 9. There are some differences of terrain effect between two conditions of wind direction fluctuation for axial concnetration and lateral plume spread.

without wind direction fluctuation



with wind direction fluctuation

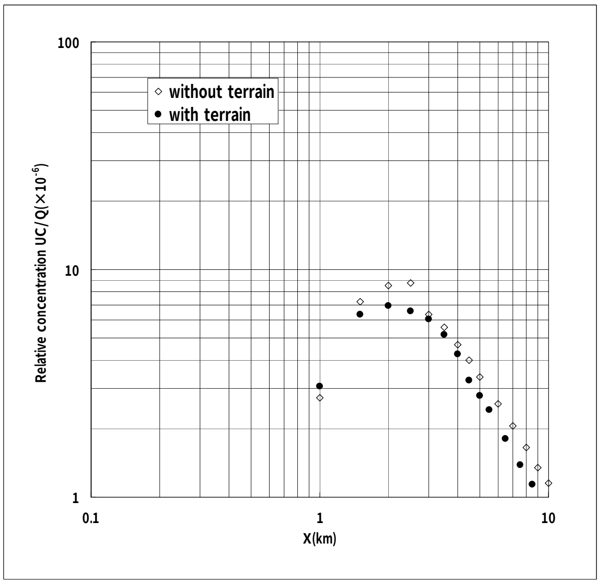


Fig. 8 Axil ground level concentration with and without terrain model

It was found from Fig. 8 and 9 that the terrain effect on concentration depends on a meandering effect; without meandering effect by conventional method, there is significant change of concentration by terrain effect, while with meandering effect by Overlapping method, there is no significant chenge.

Next, we compared the terrain effect on lateral plume spread without and with meandering effect, in Fig,. 10. It was also found that the terrain effect on lateral plume spread depends on the meandering factor, as well as concentration. Sometime, concentration of wind tunnel for short sampling time have been transformed into one for long sampling time by multipling the meandering factor (α), in the same way as P-G formula for environmental assessment.

$$PG(1hr) = \alpha \times PG(3\min)$$

$$\alpha = \left(\frac{3}{60}\right)^{\frac{1}{2}\sim\frac{1}{5}}$$

However,.it may underestimate the axial concnetration over complicated terrain to use the same value of meadering factor (α) as PG formula , because PG formula was obtained from experimental data over flat terrain.

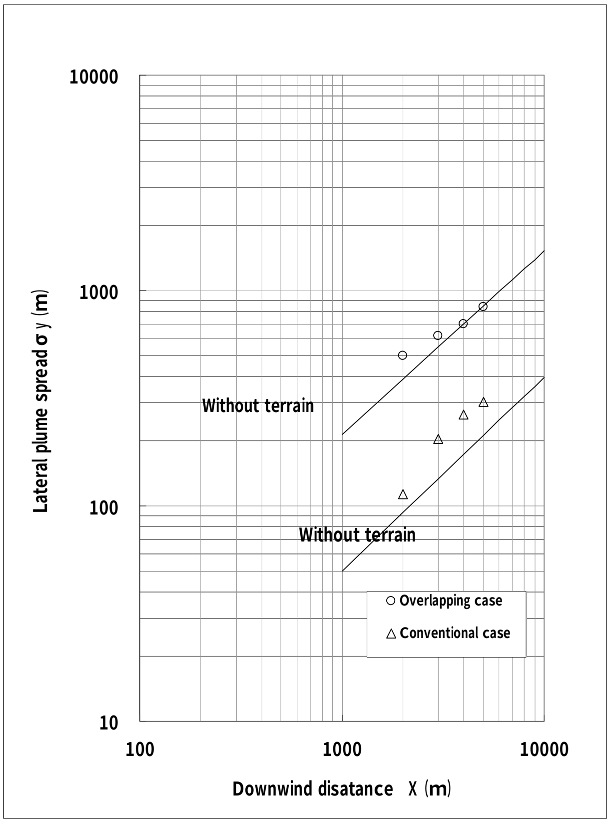


Fig. 9 Lateral plume spread with and without terrain model

4 Meteorological model simulation

RAMS version 5.05 was adopted to simulate meteorological fields around Mt. Tsukuba, located in the North of the Kanto region of Japan. To provide high spatial resolution in the area including Mt. Tsukuba in RAMS simulations, four nested grids were used, with resolution of 16 km, 4 km, 1 km and 250 m and domains of approximately 975 x 750, 245 x 245, 40 x 50 and 20 x 25 km, respectively, as shown in Fig. 10. A stretched vertical grid was used, starting from a first layer about 50 m deep and with a stretch ratio of 1.2, with a maximum Δz of 1000m, up to about 15 km. Klemp-Wilhelmson lateral boundary conditions were chosen for the velocity component perpendicular to the boundaries and a zero-gradient inflow and outflow for the other variables. Landuse, vegetation and topographical data from RAMS libraries were used for the coarser grids 1 and 2, while on grids 3 and 4 a 50 m resolution topography dataset by the Geographical Survey Institute of Japan was input. ECMWF reanalysis data with horizontal resolution of 0.5 degree were used as initial input and for the nudging procedure, applied at the lateral boundaries of the coarse domain during the run.

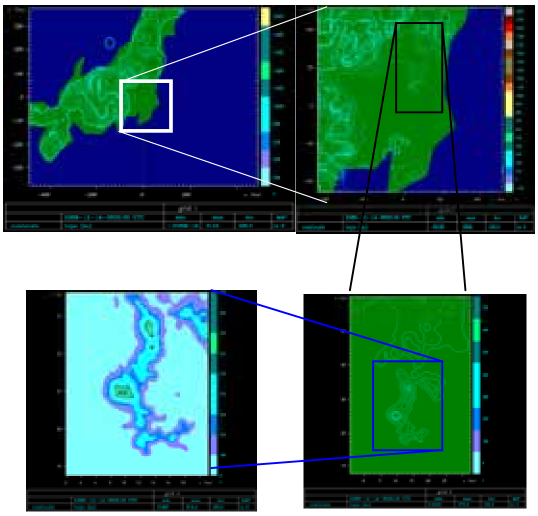


Fig. 10 Multi grid configulations of calculation domain

HYPACT is a dispersion model aimed at simulating the motion of atmospheric tracers, driven by the atmospheric flow which, in this case, is simulated by RAMS. The advantage of using HYPACT lays in its hybrid Lagrangian-Eulerian approach. The tracer is represented by Lagrangian particles near the source region, where concentration gradients are large and the atmospheric dispersion is not yet dictating the broadening of the plume. At appropriate large distances downwind, where the plume is well mixed and broadly spread, an Eulerian treatment is adopted to estimate the concentrations. Here, the gas dispersion was simulated with the version 1.2 of HYPACT with Lagrangian mode. At each time step, corresponding to 30 seconds, 20 particles were emitted from about a height of 100m, at AA or BB station according to which experiment was simulated. Concentration was computed by counting the number of the particles within each grid cell at each output time.

Fig.11 and Fig.12 show time series of wind direction and wind speed at the top of Mt. Tsukuba, W3, and W5, respectively. It is found that the simulated results are in good agreement with the observed ones.

Fig.13 shows time series of turbulent kinetic energy at AA, U1, and U2. The simulated results were improved by using a new closure model implemented by Castelli(2006), and reproduced the observed ones very well.

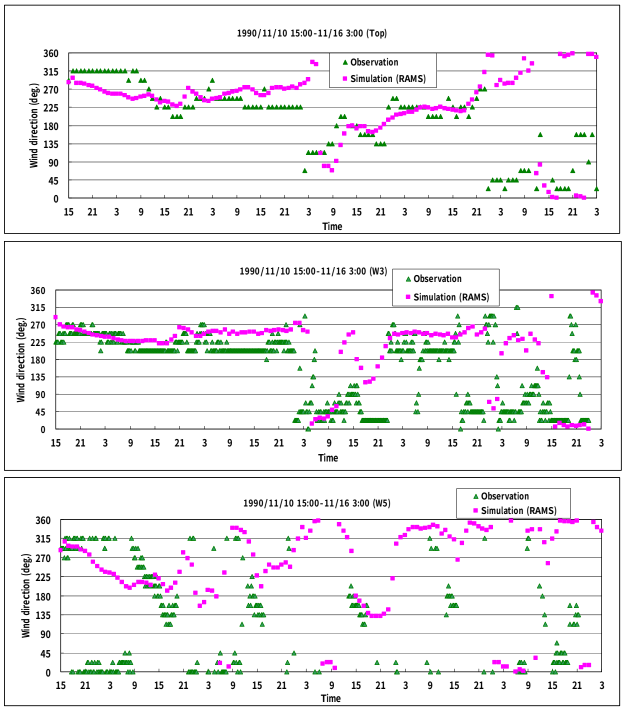


Fig.11 Time series of wind direction at Top of Mt.Tsukuba(top), W3(middle), and W5(bottom).

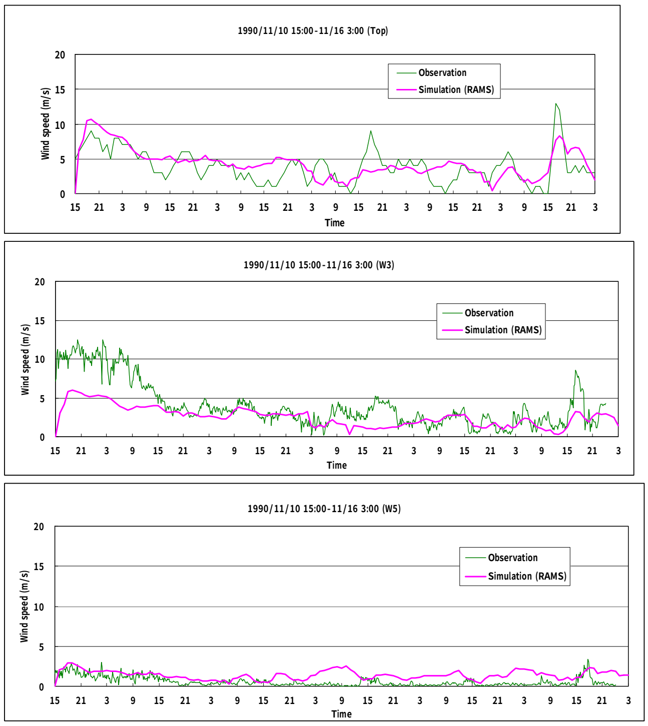


Fig.12 Time series of wind speed at Top of Mt.Tsukuba(top), W3(middle), and W5(bottom).

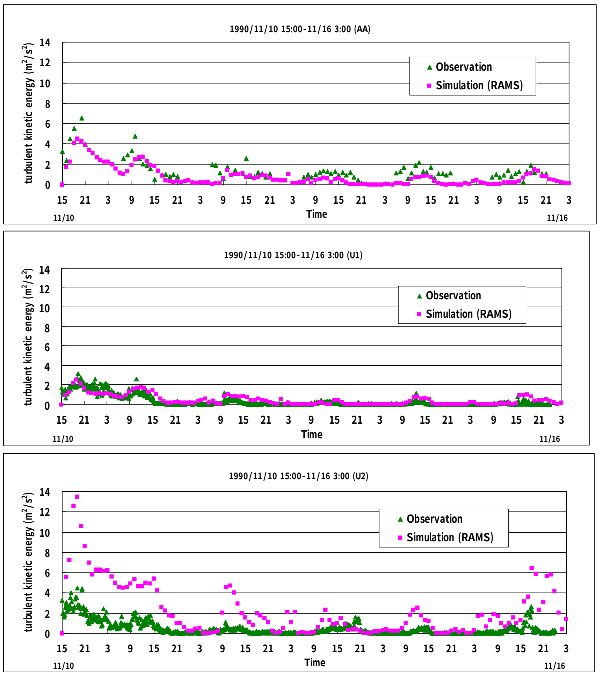


Fig.13 Time series of turbulent kinetic energy at AA(top), U1(middle), and U2(bottom).

Gas concentrations simulated by HYPACT code are compared with field data by contour maps, as shown in Fig. 14 and Fig. 15. The release height of the tracer gas was about 100m AGL and the release period was 90 minutes. The release occurred at the same location and for an equal period for both years, 1989 and 1990. Simulated results of gas concentration were also averaged during the last 30 minutes of release period, in the same way as the field observations.

The simulated results of axial ground level concentration are compared with the observed data, as shown in Fig. 16 and Fig. 17. The available data for the measured concentrations are sparse, so that they do not strictly indicate the axial ground level concentration. Only their distance from the source identifies the available observations, no coordinates are specified and their horizontal topographical location is provided only graphically. To avoid a non-precise selection of the data along the real plume axis, we decided to plot all the measured data. The predicted data are instead defined on a regular grid, and it is possible to identify the central axis of the simulated plume.

To provide a comparison with the performance of the methodology usually adopted in environmental assessment, the results obtained from a plume model are also shown in the same figures.

In the following, a discussion of the results for the cases Run 89-2 and Run 90-5 is proposed.

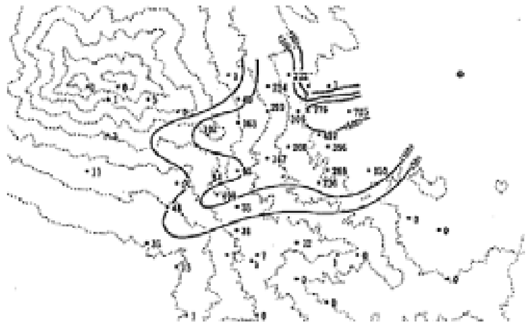
Run 89-2, covering the period from 10:00 to 11:30 of 15th November in 1989, is characterized by nearly neutral conditions, described by Pasquill stability class C-D; the mean wind speed ranges between 2 and 4 ms-1 at the foothill of Mt. Tsukuba and the wind direction is almost steady from NE.

Simulated results of axial ground level concentration show that the maximum of concentration is found at a distance of about 330 m from the emission point. On the other hand, the first observed data are available only at a distance of 1800 m.The simulated results give in general a good agreement with measured data.

The results of the plume model show a different behaviour than RAMS-HYPACT modelling system. The maximum is found at about 1500 m from the emission point and after the maximum, the values keep being always higher than RAMS-HYPACT simulated results and than observed data. This may be due to not considering the meandering effect affecting the wind direction during a sampling time of 30 minutes. Since the sampling time of the Plume model using Pasquill chart of plume spreads is a few minutes, the meandering effect is not taken into account and the axial ground level concentrations are overestimated.

Run 90-5, covering the period from 19:30 to 21:00 of 12th November in 1990, is characterized by a stable stratification of Pasquill class F, the mean wind velocity is nearly calm and it takes values less than 2 ms-1 at the foothill of Mt. Tsukuba. Wind direction is not steady and shows a consistent fluctuation.

a) Field observation



b) Simulation

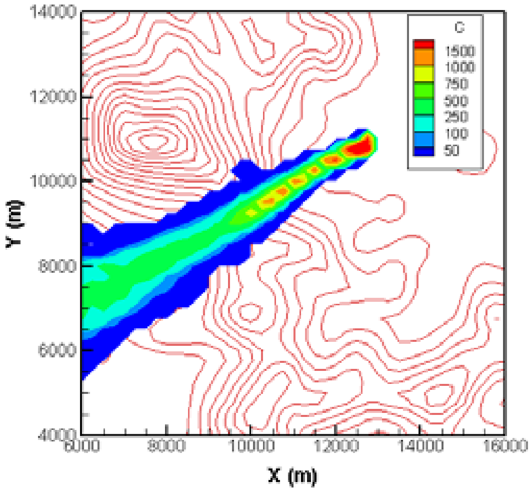
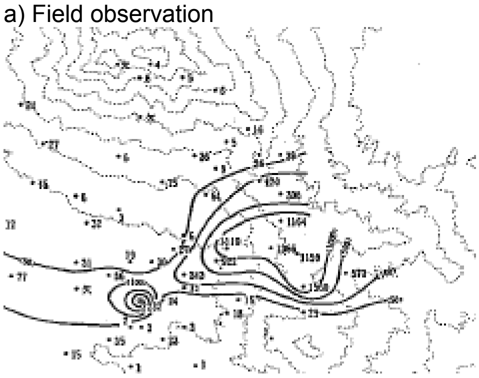


Fig.14 Contours of concentration on the ground (CASE: Run89-2)

a) Field observation



b) Simulation

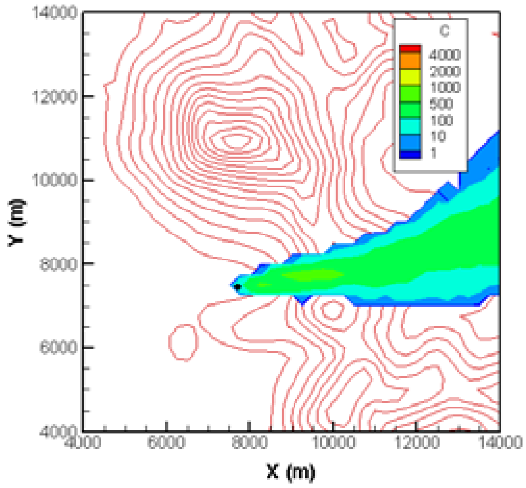


Fig.15 Contours of concentration on the ground (CASE: Run90-5)

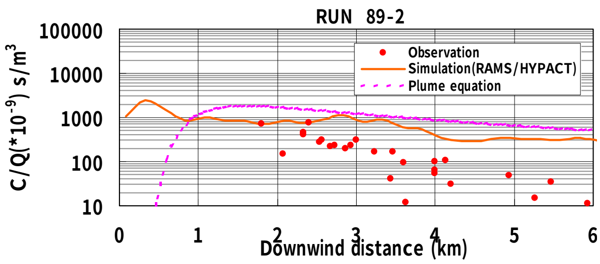


Fig.16 Relative axial ground level concentration (CASE: Run89-2: Neutral stability)

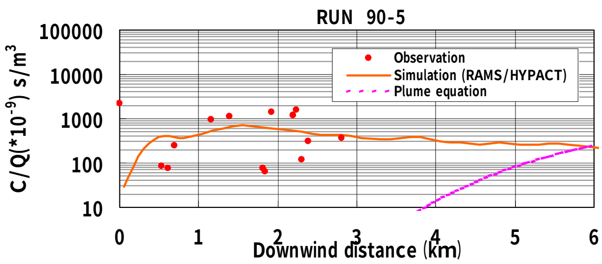
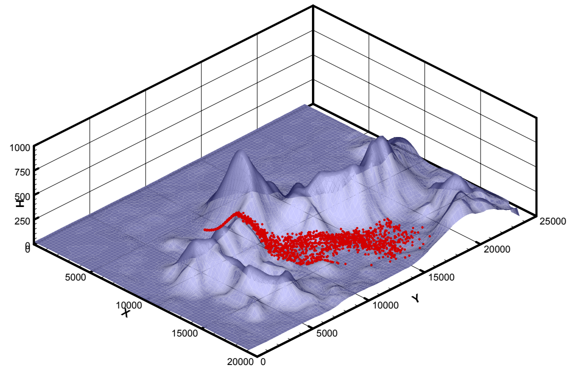


Fig.17 Relative axial ground level concentration (CASE: Run90-5: Stable stability)

It is found in Fig.17 that the simulated axial ground level concentrations correspond with the observed data. The concentration field calculated by the plume model is shifted farther from the source, at about 4000 m and it is heavily inconsistent with the observed data. This may indicate a limit of plume model under low wind velocity and unsteady wind direction.

Next, we compared 3D view of particle dispersion around Mt. Tsukuba for two kinds of turbulent models, as shown in Fig. 18. Mellor-Yamada(MY) turbulence model(Level 2.5) is the most popular turbulence model in meteorological model, like the k-epsilon turbulence model in Computaitonal Fluid Dynamic(CFD) model. MY model usually assumes a 2D boundary layer approximation and neglects a horizontal diffusion terms.

a) Mellor-Yamada turbulent model(Level2.5)



b) Castelli 3D turbulent model

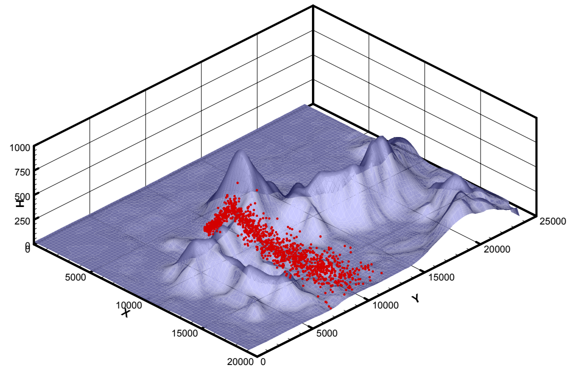


Fig. 18 3D view of particle dispersion around Mt. Tsukuba calculated by RAMS/HYPACT codes (CASE: Run90-5)

We developed a new 3D turbulence model with Castelli(2006) for total kinetic energy(E), as follows.

a) Mellor-Yamada 2D turbulence model (Level2.5)

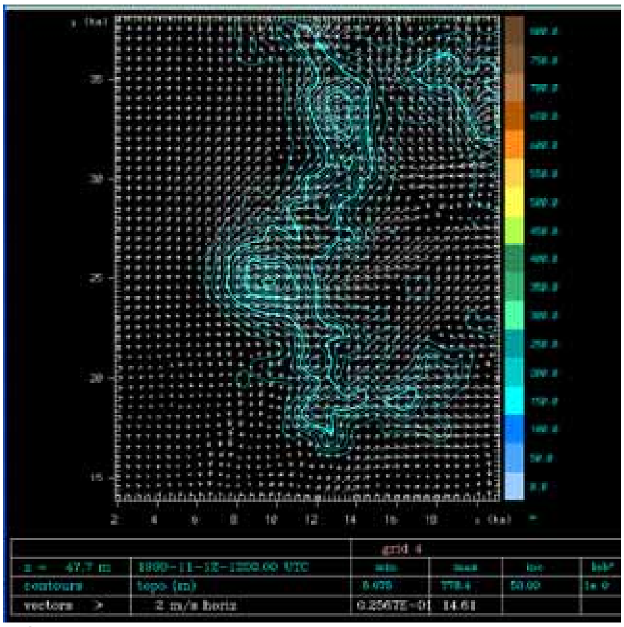
$$\frac{dE}{dt} = \frac{\partial}{\partial z} K_E \frac{\partial E}{\partial z} + P - \varepsilon$$

b) Castelli 3D turbulence model

$$\frac{dE}{dt} = \frac{\partial}{\partial x_j} K_E \frac{\partial E}{\partial x_j} + P - \varepsilon$$

The upper result of MY model shows relatively narrower diffusivity than Castelli model, as shown in Fig. 18. This seems to be due to a difference of horizontal and vertical diffusion by each model. And the plume axis of MY model flows behind Mt. Tsukuba, while Catelli model flows straightly. This difference is due to the horizontal wind patterns shown in Fig.19; there exists low wind region around Mt. Tsukuba in Fig. 19a) of MY model, which means strong stable layer appears over the surface of the ground. This may be due to the difference of vertical diffusivity by both models

a) MY model



b)Castelli model

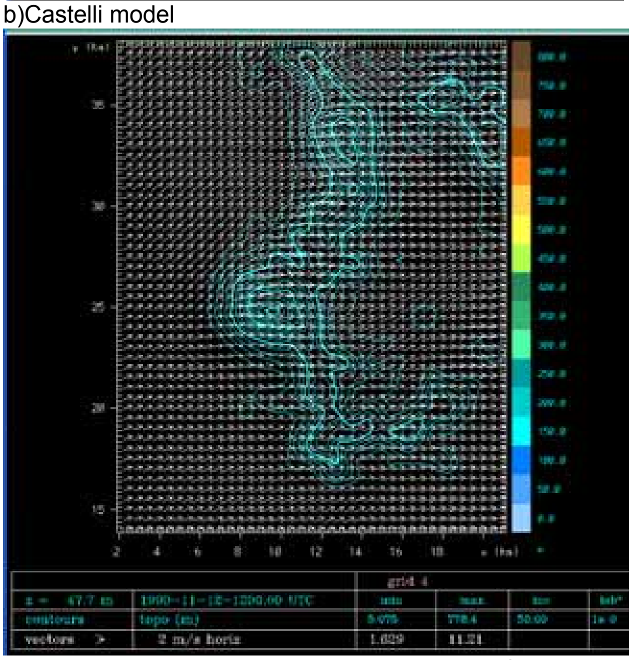


Fig. 19 Horizontal wind vectors over ground surface

5 Conclusions

It was found from this study that

(1) Overlapping method can simulate the meandering effect on gas diffusion around complicated terrain.

(2) RAMS and HYPACT codes can simulate well the actual diffusion experiment in Mt. Tsukuba with a new 3D turbulent model.

We are now developing a new assessment system to estimate the pollutant concentration for one year with RAMS and HYPACT codes, in stead of conventional assessment scheme using the plume model, as shown in Fig. 20.

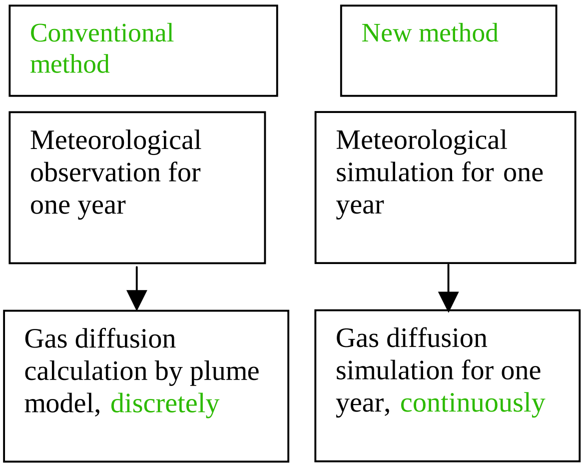


Fig. 20 Flowchart of a conventional and a new environmental assessments

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