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A Study on the Atmospheric Dispersion over Complex Terrain

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Abstract

Although the Gaussian plume model is very useful and effective, higher predictive ability on the complex terrain is also required. Many numerical model were developed, but the numerical schemes were sometimes still discussed. With this study it is aimed to develop the 3-D numerical model based on the most suitable numerical method.

Our limited comparative study on numerical methods suggested that the most suitable one may be the Taylor-Galerkin scheme for the discretazation for the advection equation. And, also a filter is attractive for such a Galerkin-type numerical method that has inherent numerical negative diffusion. Therefore, we developed a 3-D numerical model by using the operator splitting method based on the locally one-dimensional Taylor-Galerkin with Forester filter method. The wind field on the complex terrain is estimated by the high-resolution meteorological model by using the Four Dimensional Data Assimilation (FDDA) technique.

This model was applied to the air quality simulation for Tochigi area. This area is north edge of Kanto plain, and foothill of Ashio mountainous area. The size of objective area is about 10 km square. In this area, the intensive meteorological observations and air tracer experiment were conducted, in which ten pibal stations were deployed. The calculated surface tracer concentrations were compared with the observed data, and good consistency were obtained.

1.　INTRODUCTION

Air quality simulation models (AQSM's) belong to the most important tools when making a decision on air pollution prevention program. As for the complex terrain, the US.EPA's CTDMPLUS and many other models were developed: for example, VALLEY, COMPLEX I and RTDM, and so on(US.EPA,1993). Although these Gaussian plume models are very useful and effective, higher predictive ability on the steeper complex terrain is also required. Many numerical models were developed for simulating the global, regional and urban scale air pollution. However, the numerical methods for these models were sometimes still discussed(Chock,1991; Syrakov and Galperin, 1998). With this study it is aimed to develop the 3-D numerical model based on the most suitable numerical method for a three-dimensional air quality simulation model applicable to a site over complex terrain.

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2. MODEL DESCRIPTION

2.1 Numerical Model

Recent progress in numerical method has been very rapid, and the number of methods developed are not countable. The Galerkin finite element method using a chapeau function is an attractive scheme for the discretization of a space derivative. However, the combination with a first-order time differencing makes the scheme unstable, because of computational pseudo-negative diffusion. The Petrov-Galerkin and the Taylor-Galerkin methods can mitigate these situations. An extensive evaluation study for the numerical methods was carried out by Chock (1991), and it was concluded that the Taylor-Galerkin method is one of the most appropriate choices for solving the advection equation. The one-dimensional advection equation descretized by the Taylor-Galerkin method is shown in eq.(1), in case that the wind speed is uniform for the whole computational domain.

$$(1-\mu^2)C_{i-1}^{n+1} + (4+2\mu^2)C_i^{n+1} + (1-\mu^2)C_{i+1}^{n+1} = (1+3\mu+2\mu^2)C_{i-1}^{n} + 4(1-\mu^2)C_i^{n} + (1-3\mu+2\mu^2)C_{i+1}^{n} \qquad (1)$$

where, μ is the Courant number ; $\mu = u\,\Delta t / \Delta x$.

The Galerkin-type numerical methods are useful for solving the advection equation. However, these methods produce a great deal of computational noise in highly steep gradient area of the values (concentrations). In order to smooth the computational values, Forester (1977) proposed an iteration smoothing process, and Chock (1991) called it the Forester filter. This filter is identical to the diffusion calculation to compensate computational-generated ripples. In this study this filtering method was combined with the Taylor-Galerkin method. The filtering procedure in each calculation step is expressed by eq.(2)

$$.\,C_i^{k+1} = C_i^k + \frac{\nu}{2}\left\{(C_{i+1}-C_i)(\phi_{i+1}+\phi_i) - (C_i-C_{i-1})(\phi_i+\phi_{i-1})\right\}^k \qquad (2)$$

where ø is a function , and its value is one or zero depending on the existence of the numerical ripples. The coefficient v plays a similar role to the diffusion coefficient. The superscript k means the number of iterations.

Comparative study on numerical methods including the Taylor-Galerkin-Forester method was presented by Okamoto et al.(1998). The three dimensional diffusion and advection equation on the terrain adjusted coordinate system is solved by the operator splitting method based on the locally one-dimensional Taylor-Galerkin descretization. The concentration at time level n+1 can be calculated by

$$C^{n+1} = A_x \; A_y \; A_z \; A_z \; A_y \; A_x \; C^{n-1}, \qquad (3)$$

where, Ax and Ay are horizontal advection and diffusion operators, and Az is the vertical advection and diffusion, source and sink operator.

The vertical diffusion coefficient for tracers was estimated by using the method proposed by Shir and Shieh(1974), and the horizontal coefficient was estimated by the incremental difference of σ–y of Pasquill-Gifford diagram. The lid height was estimated by an empirical function based on the accumulated solar insulation.

2.2 Meteorological Preprocessor

The three-dimensional numerical diffusion model requires the mean wind vectors and turbulence or diffusion coefficients for all grid points within the computational domain. In order to fulfill these requirements, the computational fluid dynamic models were usually applied. Our limited comparative study showed that the predictive performances for several CFD models and variational MASCON models were not so much different (Okamoto, et al., 1996), and the MASCON model was most convenient to use. However, the MASCON model can not express the circulating flow within deep valleys.

Although four-dimensional data assimilation may be one of the most useful tools for preparing meteorological variables for all grid points, there were not so much applications for small areas in which the grid space was less than one kilometer. Only a few reference concerning FDDA applied to these areas could be found (Fast and O'Steen, 1994). By using the simple governing equations and precise meteorological data, the appropriate results were obtained for the short-range dispersion calculation (Okamoto, et al., 1998a).

In this FDDA model, the nonhydrostatic momentum equation and the continuity equation on the terrain-adjusted grid system were employed. The diffusion coefficients for the momentum were expressed by the simplest form; horizontal term was modeled by the grid space and wind velocity gradients; vertical term was expressed by the function of estimated friction velocity. The governing equation was solved by the Semi-Implicit Method for Pressure-Linked Equation (SIMPLE). The tendency term were added to the governing equation in order to mitigate the difference between the observed and calculated values as shown;

$$\delta \phi / \delta t = F(\phi, x, y, z, t) + G_{\phi} w_T w_{xyz} (\phi_{obs} - \phi) \qquad (4)$$

where, F is a governing equation for variable ø , Gø is a nudging coefficient, and w 's are weighting coefficients; w_T is a temporal weighting function, and w_{xyz} is a spatial weighting function. If the observation point were located within that grid mesh, $w_{xyz} = 1$; otherwise, $w_{xyz} = 0$. The value of the nudging coefficient was tentatively assumed to be 0.005.

3. RESULTS

In order to evaluate the proposed numerical model, an air quality simulation was carried out for Tochigi area. This area is north edge of Kanto plain, and foothill of Ashio mountainous area. The size of objective area is about 10 km square. In this area, intensive meteorological observations and air tracer experiment were conducted, in which ten pibal stations were deployed. The surface tracer concentrations were measured by about forty sampling points. The tracer was released from about five meter in height, and sampling duration was 60 minutes. These experiments were conducted in December 1980 and April 1981. The air sampling network and pilot balloon sounding points for spring experiment is shown in Fig.1

The FDDA result for the neutral case (run 4) is shown in Fig.2. In this case, relatively large difference in wind direction were observed; south wind was observed in the plane, but wind direction in mountainous area was mainly northeast. This tendency was expressed by our simulation. The circulating flow in the valley was also reproduced by this FDDA model as shown in Fig.3.

The calculated surface tracer concentrations were shown in Fig.4. The statistical evaluation scores are shown in Table 1. This result is more satisfactory compared with that by using the wind field derived by MASCON model.

4. CONCLUSION

A practical air quality simulation model has been developed based on the Taylor-Galerkin discretization with Forester filter for the advection equation. This model was applied to air quality simulation using the Tochigi area dispersion experimental data. When the computing time is taken into consideration, the predictive performance of this model is considered to be fairly good. However, a more extensive validation study and a model refinement will be necessary for dispersion conditions in a very stable drainage flow.

Acknowledgements

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Table 1　Statistical scores for Tochigi experimental data

Wind model	Constant a*	Slope b*	Corr.coef.	Ave. error
MASCON	98.2	0.516	0.58	398.
FDDA	85.9	1.439	0.57	404

Regression line y = a + bx

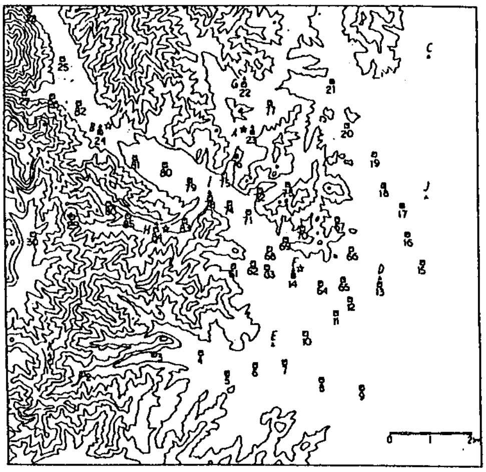
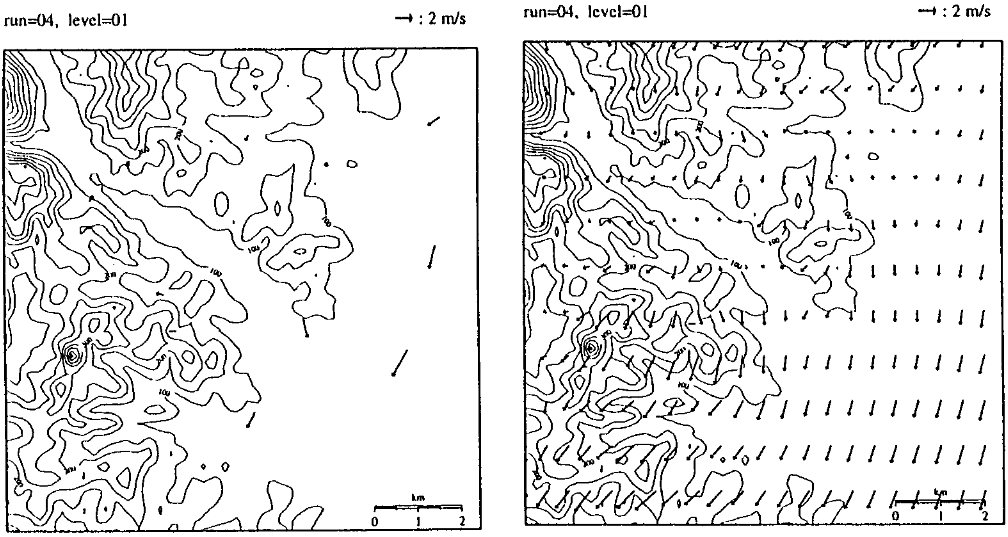


Fig1.　Map of experimental site;　triangle: pibal station,　rectangular: air sampling point,　contour line is 50m interval in height.



(a) observed wind　　(b) calculated wind

Fig.2　Comparison between the observed surface wind and calculated wind by FDDA.

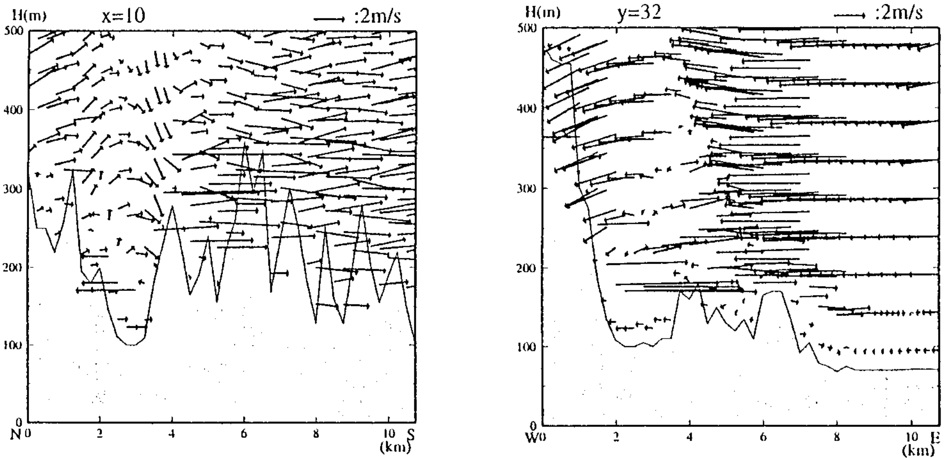
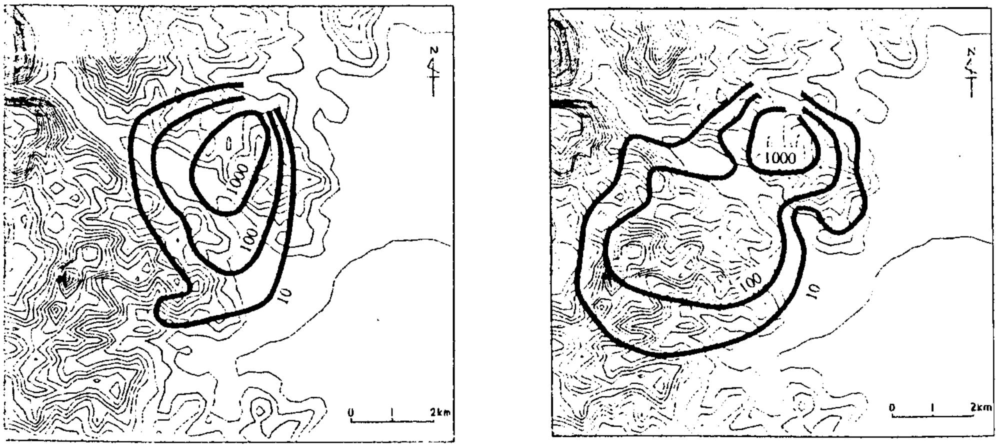
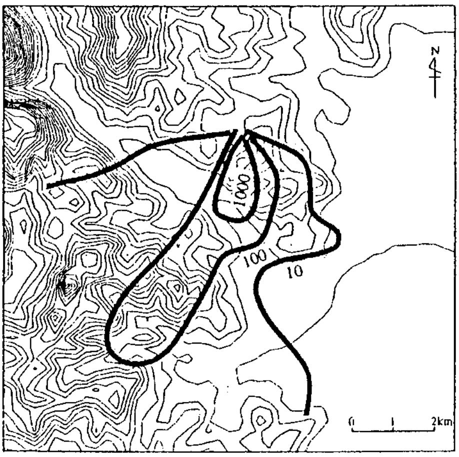


Fig.3 The vertical cross-section of the calculated wind field by FDDA



(a) MASCON-generated wind was used

(b) FDDA-generated wind was used.



(c) observed concentration pattern

Fig.4 Comparison of the surface tracer concentration; (a)MASCON-generated wind was used. (b)FDDA-generated wind was used. (c)oberved concentration pattern (unit: ppt).

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