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DEVELOPMENT OF A THREE-DIMENSIONAL LOCAL SCALE ATMOSPHERIC MODEL WITH TURBULENCE CLOSURE MODEL

May 1989

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Development of a Three-Dimensional Local Scale Atmospheric Model with Turbulence Closure Model

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(Received April 27, 1989)

Through the study to improve SPEEDI's capability, a three-dimensional numerical atmospheric model PHYSIC (Prognostic HYdorStatic model Including turbulence Closure model) was developed to apply it to the transport and diffusion evaluation over complex terrains.

The detailed description of the atmospheric model was given. This model consists of five prognostic equations; the momentum equations of horizontal components with the so-called Boussinesq and hydrostatic assumptions, the conservation equations of heat, turbulence kinetic energy and turbulence length scale. The coordinate system used is the terrain following z_* coordinate system which allows the existence of complex terrain. The minute formulae of the turbulence closure calculation, the surface layer process, the ground surface heat budget, and the atmospheric and solar radiation were also presented.

The time integration method used in this model is the Alternating Direction Implicit (A.D.I.) mothod with a vertically and horizontally staggered grid system. The memory storage needed to execute this model with 31 × 31 × 16 grid points, five layers in soil and double precision variables is about 5.3 MBytes. The CPU time is about 2.2×10^{-5} s per one step per one grid point with a vector processor FACOM VP-100.

Keywords: Atmospheric Model, Three-dimensional, Hydrodynamic, Numerical, Local Scale, Mesoscale, Complex Terrain, Transport, Diffusion, Turbulence Closure

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乱流クロージャーモデルを用いた3次元局地スケール気象モデルの開発

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SPEEDIの高精度化研究の中で，複雑地形上での移流・拡散評価を目的とした3次元数値気象モデル（PHYSIC）を開発した。本レポートは，モデルを詳細に記述したものである。

モデルの基本部分は5つの予報方程式から成る。即ち，ブジネスク近似及び静水圧近似を用いた水平風成分の運動方程式及び熱，乱流エネルギー，乱流長さスケールの保存方程式である。座標系は地形準拠 z_* 座標系を用いており，複雑地形の考慮が可能である。

この他に，乱流量計算，接地層過程，地表面熱収支及び大気放射・日射に関する詳細な計算式を記述した。

本モデルでの時間積分は，交互方向陰解法（A. D. I. 法）を用いて行なわれ，差分化は水平・鉛直両方向のスタッガードグリッドを用いている。本モデルを実行するのに必要なメモリー容量は，大気について31×31×16のグリッド，地中に5層を取り，倍精度変数を用いた場合、約5.3MBである。ベクトルプロセッサーFACOM　VP－100を用いた計算では1グリッドポイント及び1ステップ当り 2.2×10^{-5} 秒のCPU時間が必要である。

東海研究所：〒319-11　茨城県那珂郡東海村白方字白根2－4

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symbols

A: albedo of ground surface

C_p: heat capacity of air

f: Coriolis parameter

G_0: conductive hear flux at ground surface

g: gravitational acceleration

H: substantial top of model

$\overline{H}$: top of model in z_* coordinates system

H_0: sensible heat flux at ground surface

I: direct solar radiation

K_H: vertical eddy diffusivity of heat

K_M: vertical eddy diffusivity of momentum

K_x, K_y, K_{xy}: horizontal eddy diffusivities

k: von Kármán constant

L: Monin–Obukhov stability length scale

l: turbulence length scale

lE_0: latent heat flux at ground surface

l_0: upper limit of turbulence length scale (level 2.0)

P: air pressure

P_0: air pressure at reference height

q^2: twice of turbulence kinetic energy

q' : specific humidity

q_{sfc}: specific humidity at ground surface

q_*: friction specific humidity

q_0: saturation specific humidity

r: relative wetness of ground surface

S: solar radiation at a slope

$S\downarrow$: global solar radiation at a horizontal ground surface

T_{sfc}: ground surface temperature

u, v: horizontal wind components

u_g, v_g: geostrophic wind components

w: vertical wind velocity

w_*: vertical wind velocity in z_*-coordinates system

w_∞: effective precipitable water depth

z_g: ground elevation from model bottom

z_0, z_T, z_q: roughness length of wind velocity, potential temperature and specific heat, respectively

β: thermal expansion coefficient ($=\Theta_0^{-1}$)

Γ_a: adiabatic lapse rate

Γ_T: potential temperature gradient at model top

γ: solar zenith angle

γ_s: effective solar zenith angle at slope

$\delta t, \delta x, \delta y, \delta z_*$: time increment and grid intervals

ε: emissivity of ground surface

ζ: non-dimensional stability parameter ($=z/L$)

η: ($=\overline{H}/(H-z_g)$)

Θ_0: potential temperature of reference state

θ: potential temperature deviation from reference state

κ: ($=R/C_p=0.286$

Π: potential pressure (Exner function)

σ_θ: radiative cooling/heating rate

φ_M, φ_H: shear functions of wind speed and potential temperature, respectively

1. Introduction

It is a common complexity in evaluating the atmospheric transport and diffusion that an atmospheric situation changes both temporally and spatially. Most of the nuclear power plants in Japan are located in complex terrains near seacoast giving rise to additional complexities such as the fumigation phenomena caused by the thermal internal boundary layer. In evaluation of the atmospheric transport and diffusion under such conditions by using a diagnostic model (e.g. SPEEDI[1]), the accuracy of the calculation results highly depends on the observation density of both space and time. It has been shown by Chino and Ishikawa[2] that such a diagnostic model successfully evaluates the atmospheric transport and diffusion even over a complex terrain when the general flow is dominant and the atmospheric stability is neutral or unstable. On the other hand, it has been also shown by them that the reliability of calculation results decreases, even using rather dense wind observation network, when the general wind is weak and the representability of observation is low because the locality of atmospheric phenomena is very strong. Therefore, in order to construct a high performance dispersion and dose calculation model system, it is considered that an atmospheric model must be able to prognosticate occurrence of various atmospheric phenomena and their three dimensional structure without dense meteorological observation data.

In recent years, with the progression of computer ability, local scale, mesoscale and synoptic scale atmospheric models which are made up of basic equations of physical processes in the atmosphere are utilized not only to analyze atmospheric phenomena but also to apply them to the atmospheric transport and diffusion evaluation[3] . These numerical models have two main characteristics; they are prognostic and can simulate various phenomena such as land-sea breeze. This means that such the model does not basically need any observed data once the model calculation starts with an initial condition. It had been shown by many studies (e.g. Yamada[4]) that such models successfully simulate various atmospheric phenomena such as drainage flow and sea breeze. In addition to above characteristics, these models are used in combination with turbulence calculation models, to provide indispensable information about atmospheric diffusion. Therefore, it is considered that these models meet the requirements to evaluate atmospheric transport and diffusion in the local scale and mesoscale atmosphere. In the present report, detailed description of the atmospheric model developed through the study of SPEEDI's capability improvement is given.

2. Outline of model PHYSIC

The main frame of the present model PHYSIC (Prognostic HYdroStatic model Including Closure model) consists of five basic equations for horizontal wind speed components (u and v), potential temperature deviation (θ), turbulence kinetic energy (q^2) and turbulence length scale (multiplied by turbulence kinetic energy as $q^2 l$). The conservation equation for water vapor is not included in PHYSIC at the moment. The Boussinesq approximation is used, in which the air density is assumed to be constant except for the gravitational force terms in the horizontal momentum equations. The hydrostatic equation is employed in this model instead of the vertical momentum equation. This equation means that the vertical pressure gradient force and the gravitational force balance each other. The Boussinesq approximation and hydrostatic equation are commonly used in models of the local scale and mesoscale atmosphere. These are thought to be valid except for atmospheric phenomena whose vertical scale is comparable to horizontal scale. These equations are written in the terrain following z_* coordinate system.

A second-order turbulence closure model developed by Yamada[5] is used to close turbulence quantities in the momentum equations and the heat energy conservation equation. This turbulence closure model prognostically calculate the turbulence kinetic energy and the turbulence length scale. It is possible to calculate the eddy diffusivities as well as other turbulence quantities, e.g. $\overline{w'^2}, \overline{u'^2}, \overline{v'^2}$ etc., directly from those prognostically calculated quantities.

3. Basic equations

Symbols used in this section is listed in Appendix. A terrain following z_* coordinate system (x, y, z_*) is used. Its relation to the cartesian coordinate system (x, y, z) is

$$z_* = \overline{H}(z - z_g)(H - z_g)^{-1} \tag{1}$$

and the horizontal coordinates are the same in the both systems. A schematic illustration of the z_* coordinate system is depicted in Fig. 1. The transformed vertical coordinate z_* is zero at the ground surface and $\overline{H}$ at the model top. The height of model top H is constant with time and space.

The horizontal momentum equations in the z_* coordinate system are given by

$$\frac{Du}{Dt} = f(v - v_g) + \beta g \hat{\theta}\left(1 - \frac{z_*}{\overline{H}}\right)\frac{\partial z_g}{\partial x} + \eta^2 \frac{\partial}{\partial z_*}\left(K_M \frac{\partial u}{\partial z_*}\right) + \frac{\partial}{\partial x}\left(K_x \frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{xy} \frac{\partial u}{\partial y}\right), \tag{2}$$

$$\frac{Dv}{Dt} = -f(u - u_g) + \beta g \hat{\theta}\left(1 - \frac{z_*}{\overline{H}}\right)\frac{\partial z_g}{\partial y} + \eta^2 \frac{\partial}{\partial z_*}\left(K_M \frac{\partial v}{\partial z_*}\right) + \frac{\partial}{\partial x}\left(K_{xy} \frac{\partial v}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial v}{\partial y}\right), \tag{3}$$

where the operator D/Dt is defined as follows,

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y} + w_*\frac{\partial}{\partial z_*}. \tag{4}$$

The pressure gradient terms, $fu_g = -\beta\,\partial\Pi/\partial y$ and $fv_g = \beta\,\partial\Pi/\partial x$ are calculated from the potential temperature field by using the hydrostatic equation, i.e.,

$$\frac{\partial \Pi}{\partial z_*} = -g\{\eta(\Theta_0 + \theta)\}^{-1}, \tag{5}$$

where Π is the potential pressure referred to as Exner function and defined as follows,

$$\Pi = C_p\left(\frac{P}{P_0}\right)^{\kappa}. \tag{6}$$

After integrating Eq. (5) and algebraically rearranging, the following expressions of the pressure gradient terms is obtained,

$$u_g = -(f\beta)^{-1}\frac{\partial \pi_T}{\partial y} - \beta g(f\overline{H})^{-1}\left\{ \frac{\partial z_g}{\partial y} - (H-z_g)\frac{\partial}{\partial y} \right\}\int_{z_*}^{\overline{H}} \hat{\theta}\, dz_*' , \tag{7}$$

$$v_g = (f\beta)^{-1}\frac{\partial \pi_T}{\partial x} + \beta g(f\overline{H})^{-1}\left\{ \frac{\partial z_g}{\partial x} - (H-z_g)\frac{\partial}{\partial x} \right\}\int_{z_*}^{\overline{H}} \hat{\theta}\, dz_*' , \tag{8}$$

where π_T is the potential pressure at the model top ($z_*=\overline{H}$) and $\hat{\theta}$ is the potential temperature deviation from horizontal mean. The derivation of these expressions are given in detail by Yamada[4] . The continuity equation in z_* coordinate system is expressed as follows,

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w_*}{\partial z_*} - (H-z_g)^{-1}\left(u\frac{\partial z_g}{\partial x} + v\frac{\partial z_g}{\partial y} \right) = 0. \tag{9}$$

The vertical wind velocity w_* in z_* coordinates system is calculated by integrating above equation as follows,

$$w_* = \int_0^{z_*}\left\{ -\frac{\partial u}{\partial x} - \frac{\partial v}{\partial y} + (H-z_g)^{-1}\left(u\frac{\partial z_g}{\partial x} + v\frac{\partial z_g}{\partial y} \right) \right\} dz_*' , \tag{10}$$

where w_* is zero at ground surface ($z_*=0$). The vertical velocity w of the cartesian coordinate system is expressed using w_*, i.e.,

$$w = (\overline{H})^{-1}\left\{ (H-z_g)w_* + (\overline{H}-z_*)\left(u\frac{\partial z_g}{\partial x} + v\frac{\partial z_g}{\partial y} \right) \right\}. \tag{11}$$

The heat energy equation is

$$\frac{D\theta}{Dt} = \eta^2\frac{\partial}{\partial z_*}\left(K_H\frac{\partial \theta}{\partial z_*} \right) + \frac{\partial}{\partial x}\left(K_x\frac{\partial \theta}{\partial x} \right) + \frac{\partial}{\partial y}\left(K_y\frac{\partial \theta}{\partial y} \right) - \sigma_\theta , \tag{12}$$

where σ_θ is radiative cooling rate that is expressed by the Newtonian cooling using the temperature difference between air and ground surface.

The turbulence kinetic energy equation and the turbulence length scale equation are as below,

$$\frac{Dq^2}{Dt} = \eta^2\frac{\partial}{\partial z_*}\left(K_q\frac{\partial q^2}{\partial z_*} \right) + \frac{\partial}{\partial x}\left(K_x\frac{\partial q^2}{\partial x} \right) + \frac{\partial}{\partial y}\left(K_y\frac{\partial q^2}{\partial y} \right) + P_q + D_q , \tag{13}$$

$$\frac{Dq^2 l}{Dt} = \eta^2\frac{\partial}{\partial z_*}\left(K_q\frac{\partial q^2 l}{\partial z_*} \right) + \frac{\partial}{\partial x}\left(K_x\frac{\partial q^2 l}{\partial x} \right) + \frac{\partial}{\partial y}\left(K_y\frac{\partial q^2 l}{\partial y} \right) + P_l + D_l . \tag{14}$$

The production terms P_q and P_l and the dissipation terms D_q and D_l are expressed as follows,

$$P_q=2\eta^2 K_M\left\{\left(\frac{\partial u}{\partial z}\right)^2+\left(\frac{\partial v}{\partial z}\right)^2\right\}-2\eta K_H\beta g\frac{\partial\Theta}{\partial z}, \tag{15}$$

$$P_l=\eta^2 l E_1 K_M\left\{\left(\frac{\partial u}{\partial z}\right)^2+\left(\frac{\partial v}{\partial z}\right)^2\right\}-\eta l E_1 K_H\beta g\frac{\partial\Theta}{\partial z}, \tag{16}$$

$$D_q=-\frac{2q^3}{\Lambda_1}, \tag{17}$$

$$D_q=-\frac{q^3 l}{\Lambda_1}\left\{1+E_2\left(\frac{\eta l}{k z}\right)^2\right\} . \tag{18}$$

The soil temperature T_s is calculated by solving a heat conduction equation, i.e.,

$$\frac{\partial T_s}{\partial t}=\frac{\partial}{\partial z_s}\left(k_s\frac{\partial T_s}{\partial z_s}\right), \tag{19}$$

where k_s is the thermal conductivity of soil and the suffix s denotes variables of soil layer. The ground surface temperature which is the boundary condition of Eqs. (12) and (19) is calculated by a heat budget equation, i.e.,

$$\varepsilon(L\downarrow-\sigma T_{sfc}^4)+(1-A)S=H_0+lE_0+G_0, \tag{20}$$

where ε and A are the emissivity and albedo of ground surface, respectively, and $L\downarrow$ the downward long-wave radiation, S the solar radiation. The terms H_0, lE_0 and G_0 are the sensible heat flux, the latent heat flux and the conductive heat flux at ground surface, respectively.

4. Minute formulae

4.1 Turbulence closure model

The present model comprises two second-order turbulence closure models; the turbulence closure models level 2.5[5] and level 2.0[6]. The former model (level 2.5) calculates the turbulence kinetic energy and the turbulence length scale prognostically by using Eqs. (13) through (18). The turbulent diffusivities in Eqs. (2), (3) and (12) through (14) are given by following formulae,

$$K_M=\frac{l_1 q^3 [q^2(1-3c_1)+G_2\{(\Lambda_2-3l_2)-3c_1(4l_1+\Lambda_2)\}]}{q^4+G_1 l_1 q^2+3l_1 G_2\{q^2(7+\Lambda_2/l_1)+G_1(\Lambda_2-3l_2)+3G_2(4l_1+\Lambda_2)\}}, \tag{21}$$

$$K_H=\frac{l_2 q^3-l_2 G_1 K_M}{q^2+G_2(4l_1+\Lambda_2)}, \tag{22}$$

where

$$G_1=6l_1\eta^2\left\{\left(\frac{\partial u}{\partial z_*}\right)^2+\left(\frac{\partial v}{\partial z_*}\right)^2\right\},$$

$$G_2=3l_2\beta g\eta\frac{\partial \Theta}{\partial z_*},$$

and

$$K_q=s_q q l \ , \ s_q=0.2, \tag{23}$$

$$K_x=2c\delta x\delta y\left|\frac{\partial u}{\partial x}\right|, \tag{24}$$

$$K_y=2c\delta x\delta y\left|\frac{\partial v}{\partial y}\right|, \tag{25}$$

$$K_{xy}=c\delta x\delta y\left(\left|\frac{\partial u}{\partial y}\right|+\left|\frac{\partial v}{\partial x}\right|\right), \tag{26}$$

$c=0.01.$

$$(l_1, l_2, \Lambda_1, \Lambda_2)=(A_1, A_2, B_1, B_2)l, \tag{27}$$

$$(A_1, A_2, B_1, B_2, C_1, E_1, E_2)=(0.92, 0.74, 16.6, 10.1, 0.08, 1.8, 1.33). \tag{28}$$

In PHYSIC, the turbulence quantities are calculated mainly by the level 2.5 closure model.

The level 2.0 closure model is employed to initialize the turbulence quantities from the mean quantity distributions of the horizontal wind velocities and the potential temperature. The turbulence kinetic energy is given by assuming local balance of its production and dissipation, i.e.,

$$\frac{q^3}{\Lambda_1}=\eta^2 K_M\{(\frac{\partial u}{\partial z_*})^2+(\frac{\partial v}{\partial z_*})^2\}(1-R_f), \qquad (29)$$

where R_f is the flux Richardson number and its relation to the gradient Richardson number R_i is given by

$$R_f = (\beta g K_H \frac{\partial \Theta}{\partial z_*})[\eta K_M\{(\frac{\partial u}{\partial z_*})^2+(\frac{\partial v}{\partial z_*})^2\}]^{-1}$$

$$= \frac{K_H}{K_M}R_i, \qquad (30)$$

The turbulent diffusivities are given by the following formulae,

$$K_M = lq\tilde{S}_M, \qquad (31)$$

$$K_H = lq\tilde{S}_H, \qquad (32)$$

where

$$\tilde{S}_M = 3A_1(\gamma_1-\gamma_2\Gamma)\{\gamma_1-C_1-(6A_1+3A_2)\Gamma/B_1\}(\gamma_1-\gamma_2\Gamma+3A_1\Gamma/B_1)^{-1}, \qquad (33)$$

$$\tilde{S}_H = 3A_2(\gamma_1-\gamma_2\Gamma), \qquad (34)$$

$$\gamma_1 = 1/3-2A_1/B_1, \qquad (35)$$

$$\gamma_2 = (B_2+6A_1)/B_1, \qquad (36)$$

$$\Gamma = R_f/(1-R_f). \qquad (37)$$

Substituting Eqs. (31) through (37) and constants (Eqs. 27 and 28), Eq. (30) becomes

$$R_f=0.659\{R_i+0.178-(R_i^2-0.322R_i+0.0316)^{1/2}\}. \qquad (38)$$

The length scale l is given by the Blackader's formulation,

$$l=kz_*(\eta+kz_*/l_0)^{-1}, \qquad (39)$$

where

$$l_0=\alpha\int_0^\infty z_* q dz_* \left(\eta\int_0^\infty q dz_*\right)^{-1}. \tag{40}$$

After rearranging the above equations, l_0 is calculated from the following integration equation,

$$\int_0^\infty \frac{kz_*\eta^2(l_0-\alpha\eta z_*)}{l_0+kz_*/\eta}\left[\tilde{S}_M\left\{\left(\frac{\partial u}{\partial z_*}\right)^2+\left(\frac{\partial v}{\partial z_*}\right)^2\right\}-\frac{\beta g}{\eta}\tilde{S}_H\frac{\partial\Theta}{\partial z_*}\right]^{1/2}dz_*=0. \tag{41}$$

After Mellor and Yamada[6], the constant α is chosen as α=0.01.

4.2 Surface layer formulae and heat budget equation

The lowest grid level of the model is set in the surface layer. The bottom boundary conditions of Eqs. (2), (3) and (12) are given by the surface layer formulae based on the Monin–Obukhov similarity theory. In the surface layer, the vertical profiles of wind velocities, potential temperature and specific humidity are given by[*]

$$u = \frac{u_*}{k}\left\{\ln\frac{z}{z_0}+\psi_M(\zeta)\right\}, \tag{42}$$

$$v = \frac{v_*}{k}\left\{\ln\frac{z}{z_0}+\psi_M(\zeta)\right\}, \tag{43}$$

$$\Theta-\Theta_{s/c} = \frac{\theta_*}{k}\left\{\ln\frac{z}{z_T}+\psi_H(\zeta)\right\}, \tag{44}$$

$$q'-q_{s/c} = \frac{q_*}{k}\left\{\ln\frac{z}{z_q}+\psi_q(\zeta)\right\}, \quad (44)$$

and the following relations are assumed

$$z_q = z_T, \tag{46}$$

$$\psi_q = \psi_H. \tag{47}$$

The roughness parameter z_0 is determined by a method proposed by Kondo and

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*) In the surface layer formulae presented in above section(4.2), a vertical coordinate z measured from ground surface is used in order to keep consistency with conventional expressions. The coordinate transformation would be done by using Eq. (1) and taking it into account that z in above equations is equivalent to $z-z_g$ in Eq. (1).

Yamazawa[7], in which z_0 is expressed in terms of the land surface utilization.

The relation between the surface potential temperature Θ_{sfc} and the surface temperature T_{sfc} is $\Theta_{sfc}=T_{sfc}+\Gamma_a z_g$ where Γ_a is the adiabatic lapse rate. The functions ψ_M and ψ_H are defined as

$$\psi_M(\zeta)=\int_{\zeta_0}^{\zeta}\frac{\varphi_M(\zeta')-1}{\zeta'}d\zeta' , \tag{48}$$

$$\psi_H(\zeta)=\int_{\zeta_T}^{\zeta}\frac{\varphi_H(\zeta')-1}{\zeta'}d\zeta' , \tag{49}$$

where $\zeta=z/L, \zeta_0=z_0/L, \zeta_T=z_T/L$ and the shear functions:

$$\varphi_M(\zeta)=\begin{cases}(1-16.4\zeta)^{-1/4} & \zeta<0\\ 1+8\zeta(1+\zeta)^{-1} & \zeta\geq 0,\end{cases} \tag{50}$$

$$\varphi_H(\zeta)=\begin{cases}(1-16.4\zeta)^{-1/2} & \zeta<0\\ 1+8\zeta(1+\zeta)^{-1} & \zeta\geq 0,\end{cases} \tag{51}$$

are used. According to Yamada[5], the bottom boundary conditions of Eqs. (13) and (14) are given as follows,

$$q^2 = B^{2/3}u_*^2\{\varphi_M(\zeta)-\zeta\}^{2/3}, \tag{52}$$

$$q^2 l = kzq^2. \tag{53}$$

The sensible and latent heat flux terms in the heat budget equation (20) are expressed as

$$H_0 = -C_p\rho_a(u_*^2+v_*^2)^{1/2}\theta_* , \tag{54}$$

$$lE_0 = -l\rho_a(u_*^2+v_*^2)^{1/2}q_*^{*)}. \tag{55}$$

In this model, the specific humidity q' **) in the surface layer is not solved and treated as constant. The specific humidity at the ground surface is calculated by

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*) The symbol l in this equation stands for the vaporization heat of unit weight water.

**) Both the turbulence kinetic energy (q^2) and the specific humidity (q) are conventionally expressed by the same symbol. In this report, the symbol q is used for the turbulence kinetic energy and the specific humidity is expressed by q' except that it is used with suffix.

$$q_s = r q_0(T_{s/c}), \tag{56}$$

where q_0 is the saturation specific humidity at temperature $T_{s/c}$. The relative wetness r is in the range of 0 to 1.

4.3 Radiation formulae

According to Kondo and Miura[8], the global solar radiation $S\downarrow$ and the direct solar radiation I at a horizontal surface are expressed as

$$S\downarrow = I_0 \cos\gamma (C_{s1} + 0.7\times 10^{-f_{s1}\sec\gamma})(1-i_{s1})(1+j_{s1}), \tag{57}$$

$$I = I_0 \cos\gamma (C_{s2} + 0.75\times 10^{-f_{s2}\sec\gamma})(1-i_{s2}), \tag{58}$$

respectively, where I_0 is the solar constant, γ the solar zenith angle and

$$f_{s1} = 0.056+0.16\beta_a^{1/2}, \tag{59}$$

$$i_{s1} = 0.014(\sec\gamma+7.0+2.0x_r)x_r, \tag{60}$$

$$j_{s1} = (0.066+0.34\beta_a^{1/2})(A-0.15), \tag{61}$$

$$c_{s1} = \begin{cases} 0.21-0.2\beta_a & \beta_a \leqq 0.3 \\ 0.15 & \beta_a > 0.3, \end{cases} \tag{62}$$

$$f_{s2} = 0.075+0.65\beta_a^{1/2}, \tag{63}$$

$$i_{s2} = 0.020(\sec\gamma+5.5+1.5x_r)x_r, \tag{64}$$

$$c_{s2} = \begin{cases} 0.15-0.2\beta_a & \beta_a \leqq 0.3 \\ 0.09 & \beta_a > 0.3, \end{cases} \tag{65}$$

$$x_r = \log w_\infty. \tag{66}$$

The unit of effective precipitable water w_∞ is centimeter. The solar radiation S at a slope is

$$S = \begin{cases} 0 & \gamma < 0, \\ S\downarrow - I\{\max(\cos\gamma, 0) - \max(\cos\gamma_s, 0)\} & \gamma \geqq 0. \end{cases} \tag{67}$$

This equation means that the scattered solar radiation does not depend on the slope angle, while the direct solar radiation depends on both the solar zenith angle and the slope angle. The solar zenith angle is given as

$$\cos\gamma = \sin\varphi \sin\delta + \cos\varphi \cos\delta \cos h, \tag{68}$$

where φ is the latitude, δ the solar latitude and h the solar time angle. The effective solar zenith angle γ_s at a slope is calculated by the spherical trigonometry as

$$\cos\gamma_s = \cos\gamma_g \cos\gamma + \sin\gamma_g \left\{ \frac{\cos\psi_g}{\cos\psi} (\sin\delta - \sin\varphi\cos\gamma) + \sin\psi_g \cos\delta \sin h \right\} \tag{69}$$

where

$$\cos\gamma_g = \left\{ \left(\frac{\partial z_g}{\partial x}\right)^2 + \left(\frac{\partial z_g}{\partial y}\right)^2 + 1 \right\}^{1/2}, \tag{70}$$

$$\cos\psi_g = -\frac{\partial z_g}{\partial y} \left\{ \left(\frac{\partial z_g}{\partial x}\right)^2 + \left(\frac{\partial z_g}{\partial y}\right)^2 \right\}^{-1/2}, \tag{71}$$

$$\sin\psi_g = \frac{\partial z_g}{\partial x} \left\{ \left(\frac{\partial z_g}{\partial x}\right)^2 + \left(\frac{\partial z_g}{\partial y}\right)^2 \right\}^{-1/2}. \tag{72}$$

Although these formulae of solar radiation seem time consuming, all terms except for the solar time angle h are constant with time and they do not need much computational time.

The long-wave radiation $L\downarrow$ is given by Kondo[9] as

$$L\downarrow = \sigma T_a^4 (0.73 + 0.2x_r + 0.06x_r^2), \tag{73}$$

where T_a is the average temperature of the lower atmosphere. In these radiation calculations, the effective precipitable water w_∞, the air turbidity β_a and the albedo A must be specified adequately according to object cases.

5. Grid system

The grid system used in this model is schematically depicted in Fig. 1. The vertical spacing of grid is not uniform having a dense spacing in the lower part near the ground surface so as to improve resolution in the lower atmosphere where the vertical change of physical quantities is large. An example of vertical grid height which is used in a simulation of a sea breeze at Tokai site[10] is given in Table 1. The horizontal spacings of grids in x and y directions are uniform and denoted by δx and δy, respectively.

In order to discretize the equations presented in chapters 3 and 4, a staggered grid system both in the horizontal and vertical directions (Fig. 2) is used to increase the accuracy of finite difference scheme. In this staggered grid system, horizontal wind velocity and the other quantities are defined at alternating horizontal grid points and the mean quantities and the turbulence quantities are defined at alternative vertical grid points. By using this staggered grid system, the vertical eddy diffusivities (K_M and K_H) are defined at intermediate vertical grid points of mean quantities to simplify the finite difference form of the diffusion terms.

6. Numerical procedure

Time integration is performed by using the Alternating Direction Implicit (A.D.I.) method. This method has been applied to an atmospheric numerical model by Yamada[5]. By expressing a variable of nth step as $\varphi^{(n)}$ and ones of two intermediate time steps between nth and n+1th steps as φ^{*} and φ^{**}, respectively, the time integration is done alternately in the three directions, i.e.,

$$\text{(i)}\quad \frac{\varphi^{*}-\varphi^{(n)}}{\delta t} = \frac{1}{2}\Delta_{z}(\varphi^{*}+\varphi^{(n)}) + \Delta_{x}\varphi^{(n)} + \Delta_{y}\varphi^{(n)} + A\varphi^{*} + F, \tag{74}$$

$$\text{(ii)}\quad \frac{\varphi^{**}-\varphi^{*}}{\delta t} = \frac{1}{2}\Delta_{x}(\varphi^{**}-\varphi^{(n)}), \tag{75}$$

$$\text{(iii)}\quad \frac{\varphi^{(n+1)}-\varphi^{**}}{\delta t} = \frac{1}{2}\Delta_{y}(\varphi^{(n+1)}-\varphi^{(n)}), \tag{76}$$

where

$$\Delta_{x} = \frac{\partial}{\partial x}K\frac{\partial}{\partial x} - u\frac{\partial}{\partial x}, \tag{77}$$

$$\Delta_{z_*} = \eta^{2}\frac{\partial}{\partial z_*}K\frac{\partial}{\partial z_*} - w_*\frac{\partial}{\partial z_*}. \tag{78}$$

The terms $A\varphi^{*}$ and F respectively denote a dissipation term such as D_q in Eq. (13) and a external force term such as the pressure force terms in the momentum equations.

The finite difference form of $\Delta_{z_*}\varphi$ is expressed as follows,

$$(\Delta_{z_*}\varphi)_k = \frac{\eta^{2}}{\delta z_{*k}}\left\{\frac{K_{k+1/2}}{\delta z_{*k+1/2}}(\varphi_{k+1}-\varphi_k) - \frac{K_{k-1/2}}{\delta z_{*k-1/2}}(\varphi_k-\varphi_{k-1})\right\} - \mathrm{ADV}, \tag{79}$$

where ADV is an advection term and given by the first-order upwind difference scheme, i.e.,

$$\mathrm{ADV} = \begin{cases} \dfrac{w_{*k-1/2}}{\delta z_{*k-1/2}}(\varphi_k-\varphi_{k-1}) & w_{*k} \geqq 0 \\[2ex] \dfrac{w_{*k+1/2}}{\delta z_{*k+1/2}}(\varphi_{k+1}-\varphi_k) & w_{*k} < 0. \end{cases} \tag{80}$$

The finite difference forms of $\Delta_x\varphi$ and $\Delta_y\varphi$ are expressed in the similar form to Eqs. (79) and (80) except for $\eta=1$ and the grid interval that is uniform in the horizontal directions. The external force term in Eq. (74) is calculated from nth step values except for the pressure gradient terms in the horizontal momentum equations. The pressure gradient terms are calculated from n+1th value of potential temperature that is calculated first in the time integration calculation section.

The general flow of model calculation is shown in Fig. 3. In the diagnostic calculation section, K_M, K_H, w_* and other quantities necessary to calculate values of n+1th step are evaluated. In the next section, the time integration section I, the soil temperature and the potential temperature of n+1th step are calculated, then the pressure gradient terms in the horizontal momentum equations are evaluated in the following subsection. Finally, u, v, q^2 and q^2l are calculated in the last section.

Boundary conditions are decided according to object cases. The typical boundary conditions are as follows. The lateral boundary condition is given by the radiation condition, i.e.,

$$\frac{\partial\varphi}{\partial t}+c\frac{\partial\varphi}{\partial n} = 0 , \tag{81}$$

where $\partial\varphi/\partial n$ is a differentiation of φ in the direction normal to the lateral boundary and c is the phase velocity calculated from the values at inner grid points. The top boundary conditions are as follows,

$$\frac{\partial u}{\partial z_*} = \frac{\partial v}{\partial z_*} = 0, \tag{82}$$

$$\frac{\partial\theta}{\partial z_*} = \Gamma_T, \tag{83}$$

$$q^2 = q^2l = 0, \tag{84}$$

where Γ_T is the potential temperature gradient at the top of model and its typical value is 3.5°C/km. The bottom boundary conditions are set to satisfy Eqs. (20), (42) through (44), (52) and (53).

The memory storage needed to execute this model with 31 × 31 × 16 grid points, five layers in soil and double precision variables is about 5.3 MBytes. The CPU time is about 2.2×10^{-5} s per one step and one grid point with a vector processor FACOM VP-100, and that is about forty s for a one hour integration using the above grid system with a time increment of thirty s.

7. Conclusions

A three-dimensional numerical atmospheric model PHYSIC was developed to apply it to the transport and diffusion evaluation over complex terrains. This model consists of five prognostic equations; the momentum equations of horizontal components with the so-called Boussinesq and hydrostatic assumptions, the conservation equations of heat, turbulence kinetic energy and turbulence length scale. The coordinate system used is the terrain following z_* coordinate system which allows the existence of complex terrain.

In the minute formulae of the turbulence closure calculation, the second-order turbulence closure model by Yamada was employed. In addition to this, the minute formulae of the surface layer process, ground surface heat budget and the atmospheric and solar radiation were given.

The *time integration method* used in this model is the Alternating Direction Implicit (A.D.I.) method with a vertically and horizontally staggered grid system. The memory storage needed to execute this model with 31 × 31 × 16 grid points, five layers in soil and double precision variables is about 5.3 MBytes. The CPU time is about 2.2×10^{-5} s per one step per one grid point with a vector processor FACOM VP-100.

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Table 1 Grid height in air layer and grid depth in soil layer.

No.	mean variables height (m)	turbulence variables height (m)	soil temperature depth (m)
1	5.0	11.6	0.01
2	25.0	47.7	0.03
3	84.3	130.8	0.09
4	186.0	247.8	0.18
5	314.4	384.7	0.36
6	457.7	533.0	
7	609.0	688.3	
8	767.8	848.2	
9	929.5	1011.5	
10	1094.1	1177.2	
11	1260.8	1344.8	
12	1429.2	1513.9	
13	1598.0	1684.1	
14	1769.6	1855.3	
15	1941.2	2027.3	
16	2113.6	2200.0	

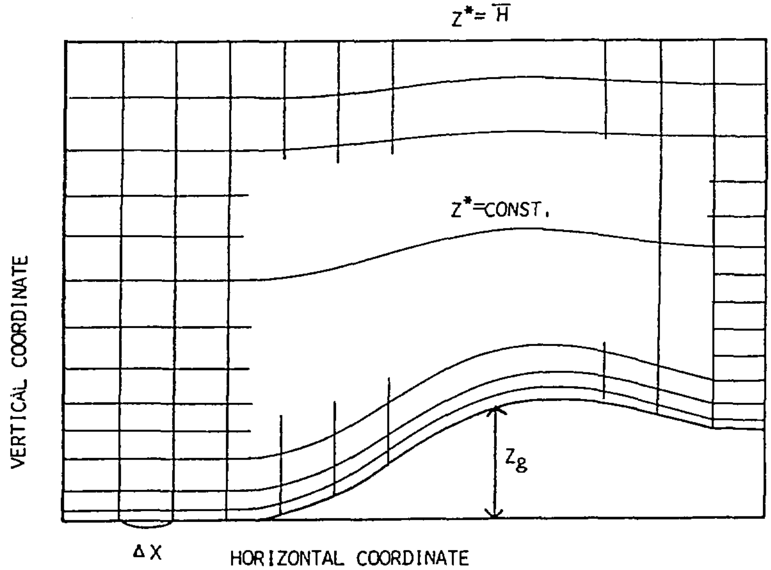

Fig.1 Schematic illustration of the grid system with the z_* coordinates system in a vertical cross section.

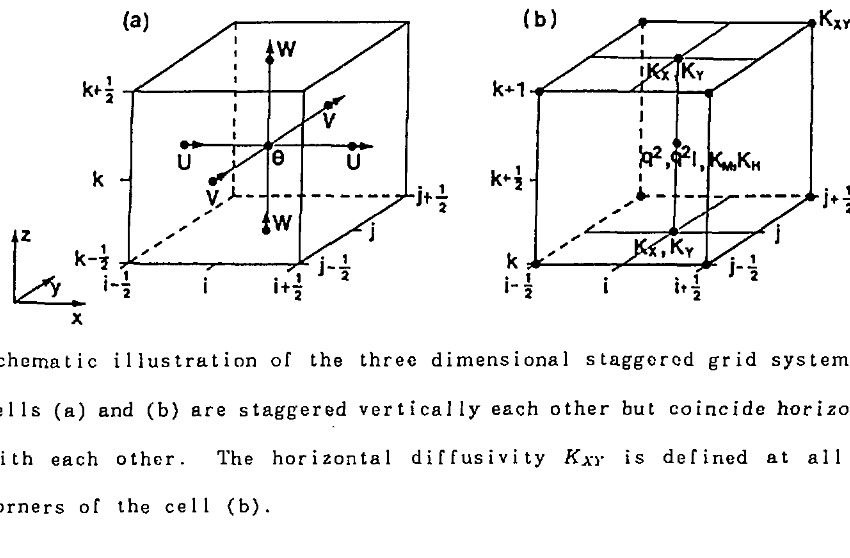

Fig.2 Schematic illustration of the three dimensional staggered grid system. The cells (a) and (b) are staggered vertically each other but coincide horizontally with each other. The horizontal diffusivity K_{XY} is defined at all eight corners of the cell (b).

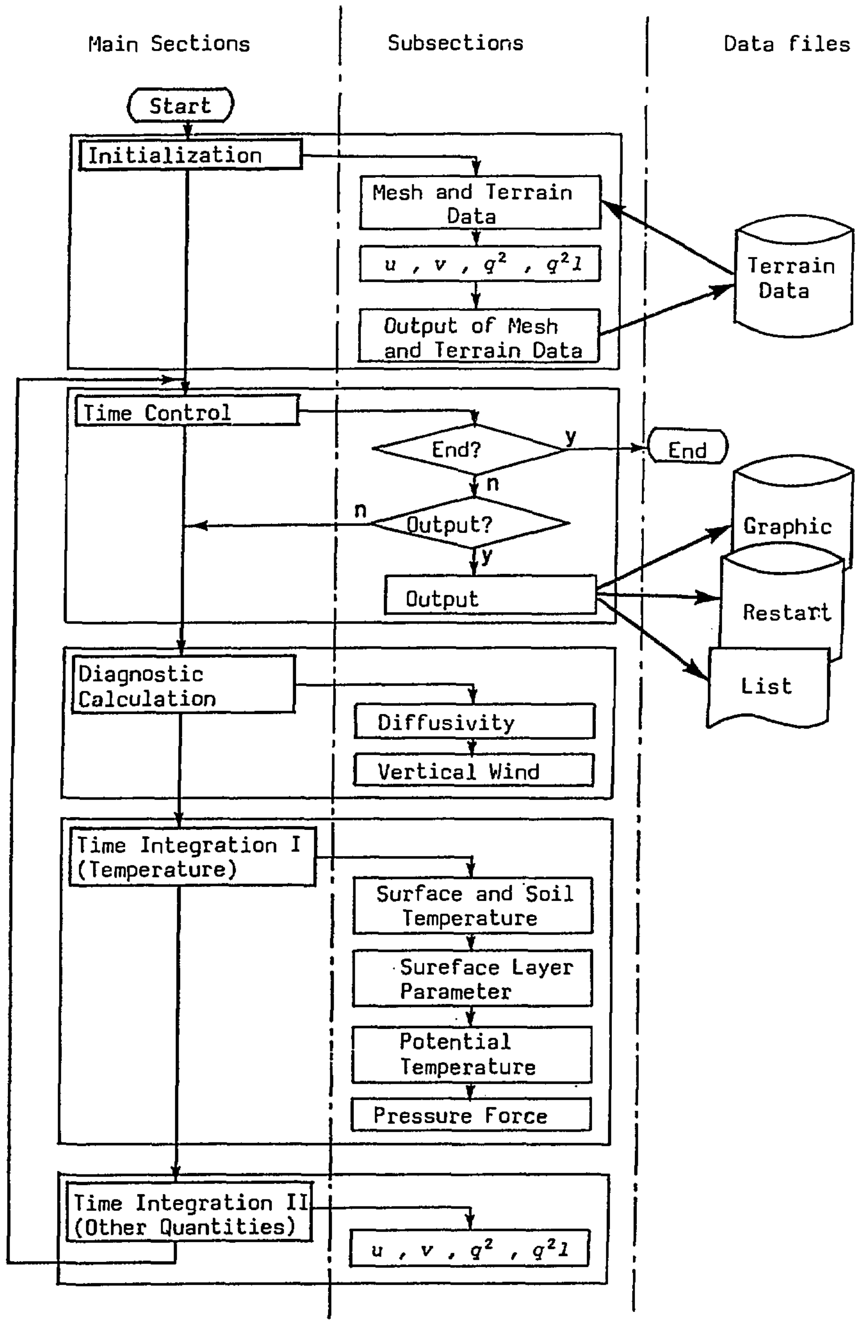

Fig.3 General flow of initialization and main calculation of PHYSIC.