Journal of Hydroscience and Hydraulic Engineering
Vol. 10, No. 1, May, 1992, 49-54

# AIR-SOIL CONNECTION ON THE URBAN CLIMATE
## ----- NUMERICAL EXPERIMENT OF EVAPORATION, CONVECTIVE CLOUDS AND RAINFALL -----

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## SYNOPSIS

A three dimensional numerical model has been developed for investigating the initiation and development of convective clouds considering the effect of air-soil interactions. This model consists of three subsystems of atmosphere, surface layer and soil. For the expression of subgrid turbulence process, 'Large Eddy Simulation(LES)' model is adopted with the time-dependent turbulence energy equation. The temporal change of the spatial temperature distribution in soil is determined to satisfy both energy and moisture balances at the soil-air interface. Microphysical processes of the cloud formation and the rain generation are described by the Kessler's parameterization. The results show that the initiation of convection is effected strongly by the soil moisture distribution at the ground surface, and the soil-air interactions intensify the development of convective clouds.

## INTRODUCTION

Increase in the precipitation and aggravation of convective storm activity in urban area has been shown by many climatological studies. The severe convective storms over urban area are considered to be caused mainly by the thermal instability of air near the ground surface. However, there are only a few researches about the relationship between the near ground condition and the development of convective cloud. Yonetani (7) suggested that the upward motion of air mass induced by Heat-Island can be a trigger to initiate the cumulus. Balaji and Clark (1) demonstrated that convection at early stages near ground produced by solar heating can have a significant influence on the later course of the dynamical evolution. It is possible that Heat-Island phenomenon make much effect to the convective cloud.

We aim at the investigation of the soil-air coupling by our numerical model, and show that the effect of soil-air interactions, such as water supply from the ground soil and changes in ground surface temperature, on the initiation and development of convective clouds.

## BASIC EQUATIONS

Our numerical model has such features ;

1) Both energy and water budget are satisfied at the ground and water surface.
2) Large Eddy Simulation ( LES ) method is adopted for the subgrid turbulence parameterization.
3) Momentum, heat and vapor fields are solved simultaneously.
4) Kessler's model is adopted for the microphysical parameterization for the process of formation of cloud and rain.

Atmosphere system

## (1) Equation for Air System

### Momentum

$$\frac{Du}{Dt} = -C_p\theta_M\frac{\partial\pi}{\partial x}+\Omega v+D_{u1} \qquad (1a)$$

$$\frac{Dv}{Dt} = -C_p\theta_M\frac{\partial\pi}{\partial y}-\Omega u+D_{u2} \qquad (1b)$$

$$\frac{Dw}{Dt} = -C_p\theta_M\frac{\partial\pi}{\partial z}+g\left[\frac{\theta}{\overline{\theta}}+0.61(q_v-\overline{q_v})-q_c-q_r\right]+D_{u3} \qquad (1c)$$

$$C_p\left[\frac{\partial}{\partial x^2}+\frac{\partial}{\partial y^2}+\frac{\partial}{\partial z^2}\right](\theta_M\pi) = \frac{\partial Q_i}{\partial x_i}-\frac{\partial}{\partial t}\left(\frac{\partial u_i}{\partial x_i}\right) \qquad (2)$$

$$K_m = C_m L E^{1/2} \quad (3a) \qquad L = (\Delta x\Delta y\Delta z)^{1/3} \quad (3b)$$

$$K_h = 3K_m$$

$$D_{ui} = \frac{\partial R_{ij}}{\partial x_j} \qquad R_{ij} = K_m\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)-\frac{2}{3}\delta_{ij}E$$

$$Q_i = -u_j\frac{\partial u_i}{\partial x_j}+D_{ui}+\delta_{i3}g\left[\frac{\theta}{\overline{\theta}}+0.61(q_v-\overline{q_v})-q_c-q_r\right]$$

### Turbulence Energy

$$\frac{DE}{Dt} = \overline{gw\left[\frac{\theta}{\overline{\theta}}+0.61(q_v-\overline{q_v})-q_c-q_r\right]}-R_{ij}\frac{\partial u_i}{\partial x_j}+\frac{\partial}{\partial x_j}\left[K_m\frac{\partial E}{\partial x_j}\right]-\frac{C_e}{L}E^{3/2} \qquad (4)$$

### Temperature & moisture

$$\frac{D\theta}{Dt} = \frac{\partial}{\partial x_i}\left[K_h\frac{\partial\theta}{\partial x_i}\right]-\lambda\left(\frac{Dq_{vs}}{Dt}+E_r\right) \qquad (5)$$

$$\frac{Dq_v}{Dt} = \frac{\partial}{\partial x_i}\left[K_h\frac{\partial q_v}{\partial x_i}\right]+E_r+\frac{Dq_{vs}}{Dt} \qquad (6)$$

$$\frac{Dq_c}{Dt} = \frac{\partial}{\partial x_i}\left[K_h\frac{\partial q_c}{\partial x_i}\right]-A_r-C_r-\frac{Dq_{vs}}{Dt} \qquad (7)$$

$$\frac{Dq_r}{Dt} = \frac{\partial}{\partial x_i}\left[K_h\frac{\partial q_r}{\partial x_i}\right]-E_r+A_r+C_r-\frac{1}{\rho}\frac{\partial}{\partial z}\left(\overline{\rho}V_r q_r\right) \qquad (8)$$

## (2) Equations for Soil System

$$\rho_l\frac{\partial M}{\partial t} = -\frac{\partial}{\partial z}\left[-D_M\left(\frac{\partial M}{\partial z}\right)-D_{Ts}\left(\frac{\partial Ts}{\partial z}\right)+K\right] \qquad (9)$$

$$\frac{\partial Ts}{\partial t} = -\left(\frac{1}{C}\right)\frac{\partial}{\partial z}\left[-\lambda\left(\frac{\partial Ts}{\partial z}\right)-LD_{vap}\left(\frac{\partial M}{\partial z}\right)\right] \qquad (10)$$

$$D_M = D_{M,liq}+D_{M,vap}$$
$$D_T = D_{T,liq}+D_{T,vap} \qquad (11a)$$

$$D_{M,liq} = K\left(\frac{\partial\psi}{\partial M}\right), \quad D_{T,liq} = K\left(\frac{\partial\psi}{\partial T}\right) \qquad (11b)$$

$$D_{M,vap} = D_{atm}f(M)\rho_0 gh\left(\frac{\partial\psi}{\partial M}\right)/RT \qquad (11c)$$

$$D_{T,vap} = D_{atm}f(M)h\left(\frac{d\rho_0}{dT}\right) \qquad (11d)$$

## (3) Equation for Energy Budget

$$S = R + H + LE + R_{long} + R_{short} \qquad (12)$$

$$R_{short} = (1-a)R_0\sin\left(\frac{\pi t}{T_p}\right) \qquad (12a)$$

$$R_{long} = \varepsilon\sigma T_{s0}^4\left(\alpha_1+\alpha_2\sqrt{e_0}-1\right) \qquad (12b)$$

$$H = -\rho C_p\theta^* U^* \qquad LE = -\rho L q_v^* U^* \qquad (12c)$$

$$S = \lambda\left(\frac{\partial Ts}{dz}\right)_{z=0} = \lambda\frac{(Ts_0-Ts_1)}{dz_1} \qquad (12d)$$

$$U^* = \kappa\frac{U}{\varphi_m(\zeta)} \qquad \theta^* = \kappa\frac{(\theta_1-\theta_0)}{\varphi_h(\zeta)} \qquad (13a)$$

$$q_v^* = \kappa\frac{(q_{v1}-q_{v0})}{\varphi_h(\zeta)} \qquad \zeta = \frac{\kappa g\theta^* z}{\theta u^{*2}} \qquad (13b)$$

$$\phi_m(\zeta) = \begin{cases}(1-16\zeta)^{-1/4} & (\zeta<0)\\ 1+7\zeta & (\zeta>0)\end{cases}$$
$$\phi_h(\zeta) = \begin{cases}(1-16\zeta)^{-1/2} & (\zeta<0)\\ 1+7\zeta & (\zeta>0)\end{cases} \qquad (13c)$$

| | |
|---|---|
| $a$ | Albedo |
| $C$ | Heat capacity |
| $C_m, C_e$ | LES constants |
| $C_p$ | Specific Heat at constant pressure |
| $E$ | Turbulence Energy |
| $e$ | Water vapor pressure |
| $e_0$ | e at the surface |
| $f$ | Porosity and tortuosity factor |
| $g$ | Acceleration due to gravity |
| $H$ | Sensible heat flux |
| $h$ | Relative humidity at the soil surface |
| $K_m$ | Eddy viscosity of momentum |
| $K_h$ | Eddy viscosity of heat |
| $K$ | Hydraulic Conductivity |
| $L$ | Latent heat of evaporation |
| $M$ | Water content in soil |
| $l$ | Mixing length |
| $LE$ | Latent heat flux |
| $P$ | Pressure |
| $P_0$ | P of the reference state |
| $q_v$ | Mixing ratio of vapor |
| $q_c$ | Mixing ratio of cloud drops |
| $q_r$ | Mixing ratio of rainwater |
| $q_v^*$ | The scale of mixing ratio of vapor |
| $R_{long}$ | Long wave radiation |
| $R_{short}$ | Short wave radiation |
| $S$ | Ground heat flux |
| $T$ | Air temperature |
| $T_s$ | Soil temperature |
| $u, v, w$ | Velocity component |
| $V_r$ | Terminal velocity of rain drops |
| $U^*$ | Frictional velocity |
| $z$ | Height |
| $\alpha_1, \alpha_2$ | Empirical constant |
| $\varepsilon$ | Overall infrared emissivity |
| $\zeta$ | Nondimensional height |
| $\theta$ | Potential temperature |
| $\theta_M$ | Virtual Potential temperature |
| $\theta^*$ | Potential temperature scale |
| $\kappa$ | Karman constant |
| $\lambda$ | Thermal conductivity of soil |
| $\pi$ | Eksner function |
| $\rho$ | Mass density of air |
| $\rho_0$ | $\rho$ of reference state |
| $\rho_l$ | Mass density of liquid |
| $\sigma$ | Stefan Boltzmann constant |
| $\Omega$ | Coriolis parameter |

*Velocity*

The air-flow is described by the momentum conversation law of Navier-Stokes equations ( Eqs.(1 a,b,c) ). Pressure field ( Eq.(2)) is expressed by the Poisson type differential equation which is derived from the equations of momentum ( Eqs.(1,a,b,c) ) and mass continuity. The last term in the right hand side of Eq.(2) represents the correction term for the mass conservation introduced in the MAC method of numerical computation of fluid flow ( Harlow and Welch (3) ). The overbar symbols represent the value of a equilibrium state.

*Subgrid turbulence parameterization*

For the subgrid turbulence process, 'Large Eddy Simulation(LES)' model is adopted with the time-dependent turbulence energy equation( Eqs.(3),(4)). LES is based on the assumption that the scale of grid is included within the inertial subrange of turbulence motion. We have applied this method from the following points; 1) Compared with other turbulence models, the formulation is one of the simplest ( in this model , there are only two unknown parameters). So we can exclude the uncertainty in determining the unknown parameters. 2) The assumption is supported by some observations of in-cloud variances of velocity from Doppler radar ( Klemp and Wilhelmson (5) ), and unknown parameters contained in this model have already been estimated. 3) The scales of grid ( 0.5-1 km) and time ( 10 sec ) used in this model are included within the region in which the power spectrum of turbulence is proportional to $k^{-5/3}$. This fact supports the hypothesis of the local isotropy of turbulence ( the inertial subrange ).

*Air temperature and water vapor*

The similar equations are obtained for the description of the temperature, water vapor, cloud drops and rainwater ( Eqs.(5)(6)(7)(8) ) fields. The terms $A_r$ , $C_r$ and $E_r$ in Eqs.(5),(6),(7) and (8) represent the rates of autoconversion , collection and evaporation of rain , respectively, which are determined using the Kessler's parameterization. Vr is the terminal velocity of the rainwater. Radiation is assumed to be constant irrespective of rainwater and cloud drops.

Soil system

Heat transfer and water movement are solved simultaneously by Eqs.(9)and(10) ( Philips & de Vries (6) ), where fluxes of both moisture and temperature are expressed by gradient type formulas. The relative humidity at the ground surface is determined through the thermodynamical equilibrium between the liquid and vapor phase. The hydrological characteristics of soil are expressed by the van Genuchten formula. The effects of rainwater to the ground surface are not considered here.

Planetary boundary layer

The vertical profile of horizontal velocity, temperature, and water vapor are expressed by the Monin-Obukhov similarity law ( Eqs.(13a,b,c)). Heat and moisture ( vapor ) fluxes at the bottom boundary of the atmosphere and at the upper boundary of the soil must be continuously connected at the ground surface. To achieve this requirement, the energy budget equation at the ground surface (Eq.(12)) is solved implicitly for determining the surface temperature until both the heat and water budgets are satisfied at the same time ( Camillo (2)).

## NUMERICAL SIMULATION OF THE CONVECTIVE CLOUDS CONSIDERING THE EFFECT OF SOIL-AIR INTERACTIONS

Method of computation

*Finite difference method*

The fundamental equations are solved simultaneously by the finite difference method. Center difference method has been applied, except for the convection terms in the air-flow equations which are discretized by the fourth order upwind difference ( Kawamura Scheme, (4) ) to perform computation with high accuracy and to fulfil the stability condition. The temporal differences are approximated by the first order implicit scheme of Euler type.

*Computational domain*

Computational domain simulates three-dimensionally the air flow region (width 24 km, length 24 km and height 12 km ), and the soil ( width 24 km, length 24 km and depth 0.5 m ). The meshes of 26 x 26 x 18 covers the air flow region , and the meshes 26 x 26 x 9 the soil layer. The Heat-Island effect is given by the difference in water content between urban and rural area ;i.e. the initial moisture distribution at the ground surface in the center of the domain is drier than its surroundings ( Fig.1 ). The basic state of the atmosphere is convectively unstable ( Fig.2 ). Other environmental parameters are shown in Table.1. Under the above condition, constant radiation is given at t=0. The time-dependent process of the initiation and development of convective clouds due to thermal instability are simulated.

*Boundary condition*

At the lateral and top boundaries , the second derivatives of variables are assumed to be zero. The bottom of the soil is assumed to be impervious and to be held at constant temperature.

Table.1 Environmental parameters.

| | |
|---|---|
| $R_{short}$ | 800 (w/m$^2$) |
| a | 0.12 |
| $C_e$ $C_m$ | 0.2 |
| $\lambda_{SOIL}$ | 0.034 (J/cm, s, k) |
| Ks | 0.5 |

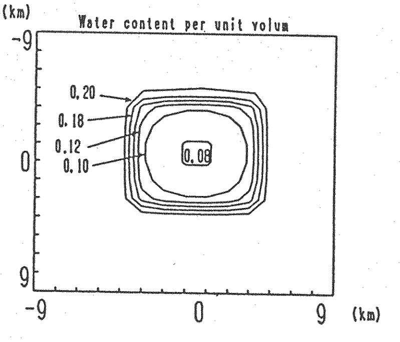



Fig.1 Initial distribution of water content at the ground surface

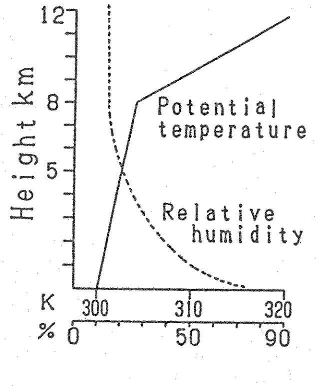
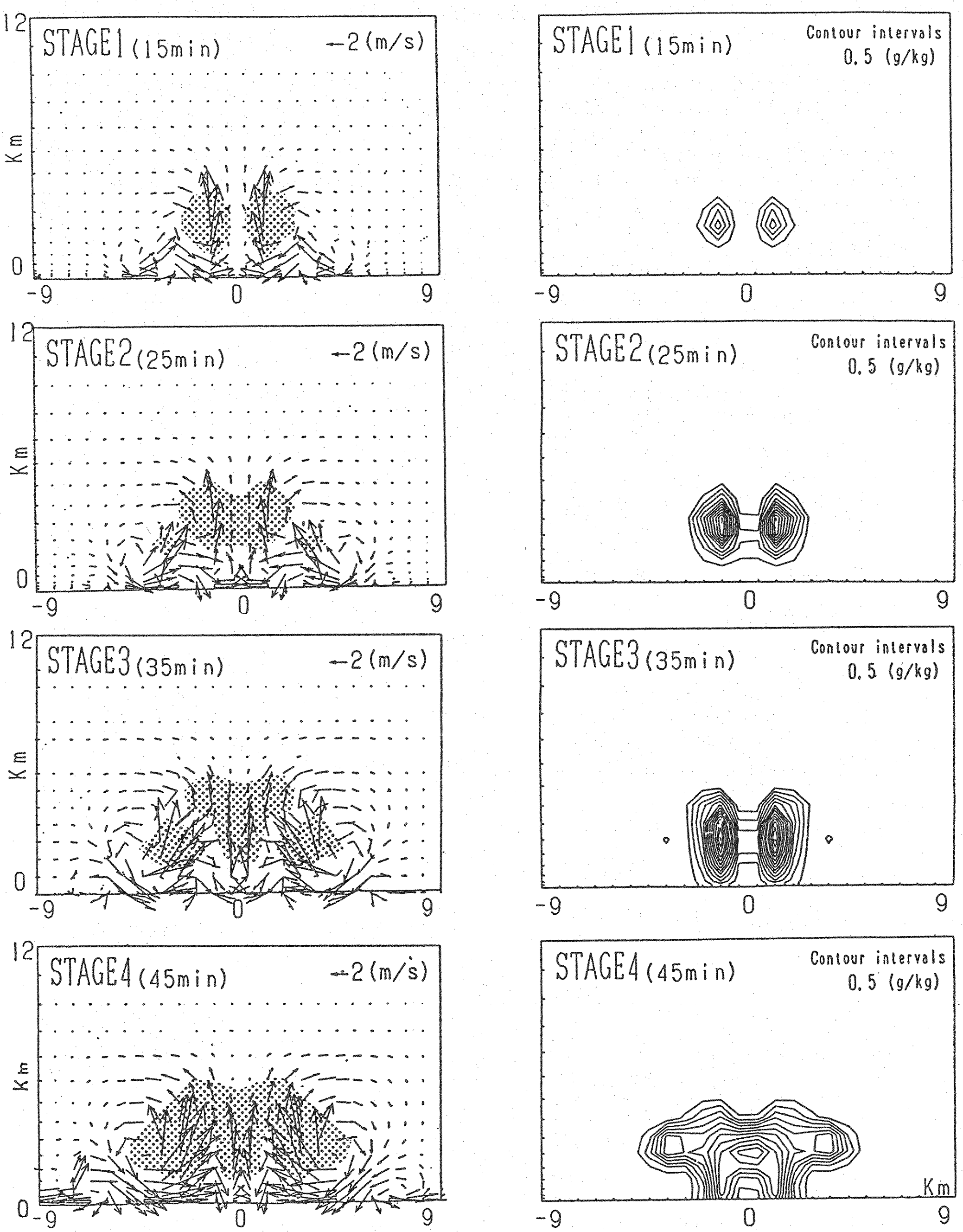



Fig.2 Initial distribution of temperature and humidity.

## RESULTS AND DISCUSSION

At the early stage, the surface temperature increases faster in the center region than in the surroundings, because the surface temperature is influenced directly by the evaporation rate corresponding to the water content through the




(a) Velocity and mixing ratio of cloud drops

(b) mixing ratio of rainwater

Fig.3 (a) The XZ cross section of velocity and cloud drops
( hatched area represents cloud drops )
(b) The XZ cross section of rainwater fields

energy budget. Therefore, the small convections occur firstly at the center because of temperature perturbation at the ground ( t=15min ), and they develop ( t=25 min ).

Figs.3 (a)and (b) show the XZ cross section of velocity, cloud drops and rainwater fields at mature stages. Evaporation of rainwater at the lower part of the convective cloud and the insufficient water supply from the ground surface weaken the updraft of the air mass around the center region ( t=35min ). The higher water content of the ground surface at the surroundings keeps the surface temperature lower than that of the center at the early stage, but once the updraft is occurred, the convection develops more rapidly than at the center because of its sufficient water vapor supply. As a result, new convections of the surroundings merge with the old convection at the center( t=45min ). Figs.4 and 5 show the perturbation of temperature and horizontal velocity, respectively. The front of convection , which has the strong velocity, corresponds to the high temperature gradient of the ground surface. The convections activate the heat and vapor transfer at the ground surface and generate the local horizontal gradient of the surface temperature. On the other hand, the temperature gradient makes the convections stronger in turn.

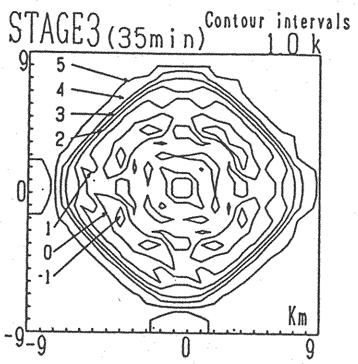



Fig.4 Perturbation of surface temperature ( Z=0 m, T= 35 min ).

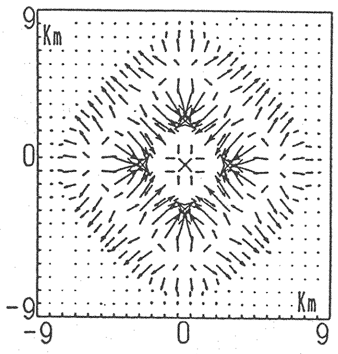



Fig.5 Wind velocity near the ground ( Z=50 m, T= 35 min ).

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(Received October 2, 1991;revised January 24, 1992)