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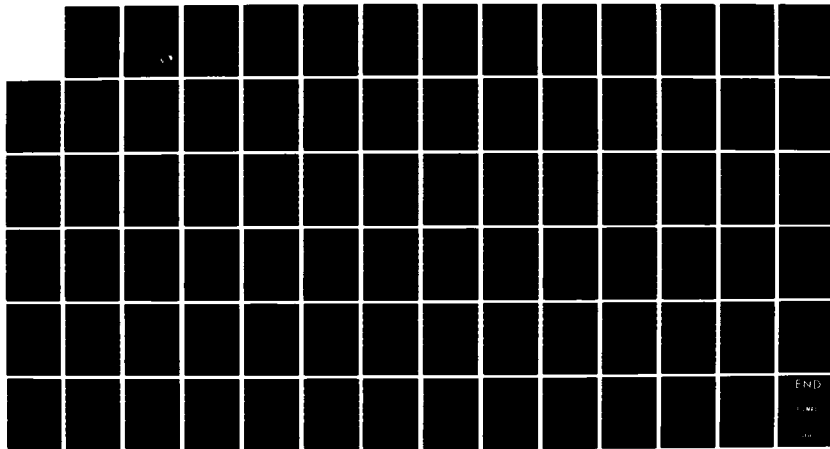
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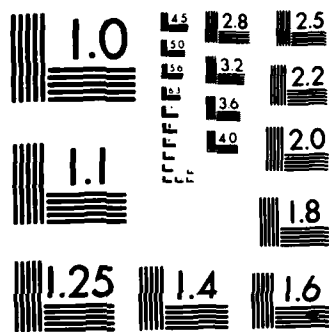
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FINAL REPORT

LOUIS BERKOFSKY

THE BEHAVIOR OF THE ATMOSPHERE IN THE DESERT PLANETARY BOUNDARY LAYER

AFOSR-84-0036

THE JACOB BLAUSTEIN INSTITUTE FOR DESERT RESEARCH

BEN-GURION UNIVERSITY OF THE NEGEV

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surface layer, the potential temperature at the ground, the height of the inversion layer, the dust concentration at the top of the surface layer, the moisture at the top of the surface layer, and the soil moisture at the ground. The radiation flux is also calculated as a function of time.

The equations were programmed for solution on a 300 x 600 km grid, with 10 km grid spacing, on a grid staggered in both time and space. The lateral boundary conditions were of the radiation type.

Initially, the one-dimensional version was tested (no horizontal advection). All fields showed reasonable evolution for a twenty-four hour prediction. Data (dust concentration, inversion height) are now being gathered for verification.

The two-dimensional version was first run with a time step of two minutes and boundary conditions held fixed in time. Although the interior fields, starting from artificial initial data, developed reasonably, the calculations blew up after 4 hours, probably due to the restrictive boundary conditions. When the radiation boundary conditions were used, the model ran for 6 hours, did not blow up, but developed unrealistically near the boundaries. Efforts are continuing to improve the model by introducing appropriate smoothing. Upon checkout, real data including topography, for Israel will be introduced as initial conditions.

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THE BEHAVIOR OF THE ATMOSPHERE IN THE DESERT PLANETARY BOUNDARY LAYER

Louis Berkofsky
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14 October 1984

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PREFACE

The research described in this report was conducted by personnel of the Jacob Blaustein Institute for Desert Research, Ben-Gurion University of the Negev, Sede Boqer, Israel from 15 October 1983 to 14 October 1984 under Grant No. AFOSR-0036 to the Ben-Gurion University of the Negev, Research and Development Authority, P.O. Box 1025, Beersheva, Israel.

Participating personnel concerned with the tasks described in this report include Prof. Louis Berkofsky, Principal Investigator, Dr. Avraham Zangvil, Research Associate, Ms. Andrea Molod, Meteorologist-Programmer, Ms. Perla Druian, Meteorologist-Programmer, and Mr. Tapani Koskela, Meteorologist-Programmer.

Observational data used in this study were obtained from the Institute's meteorological (4 m) tower, and from the radiation center, collected on a data logger and analyzed in the laboratory. Dust data were obtained from the Institute's Size Selective Inlet High Volume Sampler.

The Director of the Institute during the conduct of this study was Prof. Joseph Gale.

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INTRODUCTION

There exist a large number of planetary boundary layer models each designed for specific purposes, (Deardorff, 1974; Mahrt and Lenschow, 1976; Stull, 1976; Heidt, 1977; Yamada, 1979; Tennekes and Driedonks, 1981; Chen and Cotton, 1983). Many of these consider the top of the boundary layer a material surface. Some consider the top of the boundary layer to be coincident with the inversion, and consider entrainment across its interface. Some are multi-level, some are bulk, single-level models. The various models are of one, two and three dimensions. The greater the number of dimensions, the greater the computational complexity.

It is possible to reduce the computational complexity, and still not eliminate the three-dimensionality completely by using a variation of the "momentum integral" method (Schlichting, 1968). By means of this approach, the vertical structure of several of the variables is specified and incorporated into the vertically integrated equations. In this way, the model becomes two-dimensional in the horizontal, and vertical variations are incorporated into various coefficients. The method was introduced into meteorology by Charney and Eliassen (1979), who derived the highly successful "equivalent barotropic model". The method has also been used in studying nocturnal drainage flow (Manins and Sawford, 1979).

In this study, one of the guiding principles was that computers of limited power would be available to us. Therefore we decided at the outset to attempt to model the atmospheric circulation in the desert planetary boundary layer by means of a vertically-integrated, parameterized model.

THE MODEL AND MODEL EQUATIONS

We consider a model of the planetary boundary layer (depth approximately 1km). This layer is itself divided into a surface layer (20m), a transition layer, which at certain times and places becomes very well mixed (and is frequently called the "mixed layer") and an inversion layer. (See Figure 1). We shall not assume that the transition layer is always well mixed.

Very often, the top of the planetary boundary layer is capped by an inversion. This is particularly true in many desert and semi - desert regions. In Israel for example, there are 222 days per year, on the average, of mid-day inversions just about 100 km north of the beginning of the Negev desert. (Shaia and Jaffe 1976) As we go farther south, closer to the center of the Hadley cell, the frequency of occurrence of inversions is probably even greater. When the capping inversion exists, and when convection occurs below the inversion, the inversion changes height due to upward and corresponding downward fluxes through it by turbulence. The inversion height changes affect the dust concentration. These processes have to be modelled. Further, the processes which we wish to model are on such a scale that fairly high resolution is needed on the order of 10-20 km in the horizontal, over a region approximately 300x600 km. If then the vertical resolution above the surface layer is to be very fine - say 100m - the computation time for solution of only the boundary layer mesoscale equations may become prohibitive. Thus, in spite of the fact that the optimum mesoscale model must be three-dimensional, we expect to gain valuable insights with a vertically parameterized two-dimensional nonsteady model.

We shall concern ourselves with a form of the primitive equations derived by ensemble averaging over a horizontal area $\Delta x \Delta y$ which is large enough to contain the sub-grid scale phenomena, but small enough to be a fraction of the mesoscale system. We define

$$\left. \begin{aligned} (\overline{\alpha}) &= \frac{1}{\Delta x \Delta y} \iint \alpha' dx dy \\ \alpha &= \overline{\alpha} + \alpha' \end{aligned} \right\} \quad (1)$$

where α is any scalar variable.

With the above definitions, the appropriate equations are, approximately

$$\frac{\partial u}{\partial t} + \frac{\partial}{\partial x}(u^2) + \frac{\partial}{\partial y}(uv) + \frac{\partial}{\partial z}(uw) - f(v - v_g) = -\frac{\partial}{\partial z}(\overline{u'w'}) \quad (2)$$

$$\frac{\partial v}{\partial t} + \frac{\partial}{\partial x}(uv) + \frac{\partial}{\partial y}(v^2) + \frac{\partial}{\partial z}(vw) + f(u - u_g) = -\frac{\partial}{\partial z}(\overline{v'w'}) \quad (3)$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad (4)$$

$$\frac{\partial \theta}{\partial t} + \frac{\partial}{\partial x}(u\theta) + \frac{\partial}{\partial y}(v\theta) + \frac{\partial}{\partial z}(w\theta) = -\frac{1}{\rho c_p} \frac{\partial F}{\partial z} - \frac{\partial}{\partial z}(\overline{w'\theta'}) \quad (5)$$

$$\frac{\partial q}{\partial t} + \frac{\partial}{\partial x}(uq) + \frac{\partial}{\partial y}(vq) + \frac{\partial}{\partial z}(wq) = -\frac{\partial}{\partial z}(\overline{w'q'}) \quad (6)$$

$$\frac{\partial c}{\partial t} + \frac{\partial}{\partial x}(uc) + \frac{\partial}{\partial y}(vc) + \frac{\partial}{\partial z}[(w + \Omega)c] = -\frac{\partial}{\partial z}(\overline{w'c'}) \quad (7)$$

In the above set of equations, the unbarred variables $u, v, w, u_g, v_g, \theta, F, p, q, c$, are all mean values according to Equation (1). We have used the Boussinesq assumption, and the variables are defined as follows:

- u, v, w = components of the wind vector
- u', v', w' = turbulent components of the wind vector
- u_g, v_g = geostrophic wind components
- f = Coriolis parameter
- θ = potential temperature
- p = air density
- F = net radiation flux
- q = specific humidity
- c = dust concentration
- θ', q', c' = turbulent fluctuations of θ, q, c
- x, y, z, t = space variables and time

$$\begin{aligned}
c_p &= \text{specific heat of air at constant pressure} \\
\Omega(r) &= \text{fall velocity of particle of radius } r
\end{aligned}$$

Equations (2) and (3) are the horizontal equations of motion, Equation (4) is the continuity equation, Equation (5) is the thermodynamic energy equation, Equation (6) is the moisture equation, Equation (7) is the dust concentration equation.

The lower boundary condition is

$$w = w_T = \mathbf{V} \cdot \nabla z_T \text{ at } z = z_T = \text{terrain height} \quad (8)$$

Here $\mathbf{V} = u\mathbf{i} + v\mathbf{j}$ = horizontal wind vector, $\mathbf{i}$ and $\mathbf{j}$ are unit vectors in the E and N directions respectively and ∇ is the gradient operator in 2 - dimensions,

$$\nabla = \mathbf{i} \frac{\partial}{\partial x} + \mathbf{j} \frac{\partial}{\partial y}.$$

In the present investigation, we assume that any condensed moisture stays in the air. Thus we do not treat clouds or precipitation explicitly in this model (but implicit predictions are possible).

In order to expedite deriving appropriate expressions for predicting inversion height, we first derive inversion "interface" conditions. The results are essentially the upper boundary conditions. Let $h(x,y,t)$ be the inversion height. Let δ be a small layer of constant thickness above the inversion level. In Mahrt and Lenschow (1976) this is called the turbulent inversion layer, which is sufficiently thin so that terms of $O(\delta)$ may be

neglected in the integrated equations.

Define

$$(\tilde{\alpha}) = \frac{1}{\delta} \int_{\alpha}^{\alpha+\delta} (\alpha) dz \quad (9)$$

Let

$$\begin{aligned} \Delta \alpha &= \alpha_{\alpha+\delta} - \alpha_{\alpha} \\ &= \text{jump in } \alpha \text{ across inversion} \end{aligned} \quad (10)$$

By Leibniz's rule,

$$\left. \int_{\alpha}^{\alpha+\delta} \frac{\partial \alpha}{\partial x_i} dz = \int \frac{\partial}{\partial x_i} \tilde{\alpha} - \Delta \alpha \frac{\partial h}{\partial x_i} \right\} \quad (11)$$

where $x_i = (x, y, t)$

We apply the operator Equation (9) to Equations (2), (3), (5), (6), (7), allow to approach zero, and obtain.

$$\left(\frac{\partial h}{\partial t} - w_{\alpha} \right) \Delta u + \Delta(u^2) \frac{\partial h}{\partial x} + \Delta(uv) \frac{\partial h}{\partial y} = - \overline{(u' w')}_{\alpha} \quad (12)$$

$$\left(\frac{\partial h}{\partial t} - w_{\alpha} \right) \Delta v + \Delta(uv) \frac{\partial h}{\partial x} + \Delta(v^2) \frac{\partial h}{\partial y} = - \overline{(v' w')}_{\alpha} \quad (13)$$

$$\left(\frac{\partial h}{\partial t} - w_h\right) \Delta \theta + \Delta(u\theta) \frac{\partial h}{\partial x} + \Delta(v\theta) \frac{\partial h}{\partial y} = -\overline{(w'\theta')}_h \quad (14)$$

$$\left(\frac{\partial h}{\partial t} - w_h\right) \Delta q + \Delta(uq) \frac{\partial h}{\partial x} + \Delta(vq) \frac{\partial h}{\partial y} = -\overline{(w'q')}_h \quad (15)$$

$$\left[\frac{\partial h}{\partial t} - (w_h + \Omega)\right] \Delta C + \Delta(uc) \frac{\partial h}{\partial x} + \Delta(vc) \frac{\partial h}{\partial y} = -\overline{(w'c')}_h \quad (16)$$

In the above derivations, we have assumed that

$$\int_h^{h+\delta} \frac{1}{\rho C_p} \frac{\partial F}{\partial z} dz \approx \frac{1}{\delta \rho C_p} (F_{h+\delta} - F_h) = 0$$

and

$$(\Omega + w)_{h+\delta} = (\Omega + w)_h$$

Each of the above equations can be viewed as equations for the vertical eddy fluxes, or as prediction equations for h if these eddy fluxes are known. The quantity $\left(\frac{\partial h}{\partial t} - w_h\right)$, which represents the motion of the air relative to that of the inversion, is called the "entrainment velocity", w_e . w_h is the larger scale vertical velocity at the interface. The terms involving $\partial h / \partial x$ and $\partial h / \partial y$ are usually omitted in derivations of these interface

conditions, since most inversion height models assume horizontal homogeneity.

Our approach will be to integrate the system of Equations (2)-(7) inclusive, with respect to z from $z = k = \text{constant} = \text{height of surface layer}$, to $z = h = \text{inversion height}$, then to introduce modelling assumptions for all the variables, i., e., to specify their variations with height. If we do this, it becomes possible to express all of the jump quantities in Equations (12)-(16) inclusive in terms of their values at specific levels.

Parameterizations

Winds

Surface Layer

We assume that the surface layer is neutral, so that we may use a constant flux profile

$$V(x, y, z, t) = \frac{V_*}{k_1} \ln \left(\frac{z+z_0}{z_0} \right), \quad 0 \leq z < k \quad (17)$$

where $k_1 = \text{von Karman constant} = 0.4$, $V_* = \text{friction velocity}$,

$z_0 = \text{roughness parameter}$. Here $V_* = (u_*^2 + v_*^2)^{1/2}$,

where u_* and v_* are defined below.

Transition Layer:

We assume

$$u(x, y, z, t) = A(z) \hat{u}(x, y, t) \quad (18)$$

$$v(x, y, z, t) = B(z) \hat{v}(x, y, t)$$

where

$$(\hat{q}) = \frac{1}{(h-k)} \int_k^h q \, dz \quad (19)$$

At the level $z = k$, the two expressions (17), (18) must match

$$u(k) = \frac{u_*}{k_1} \ln \left(\frac{k+z_0}{z_0} \right) = A(k) \hat{u}$$

$$v(k) = \frac{v_*}{k_1} \ln \left(\frac{k+z_0}{z_0} \right) = B(k) \hat{v}$$

Therefore

$$\left. \begin{aligned} u_* &= \frac{k_1 A(k) \hat{u}}{\ln \left(\frac{k+z_0}{z_0} \right)} \\ v_* &= \frac{k_1 B(k) \hat{v}}{\ln \left(\frac{k+z_0}{z_0} \right)} \end{aligned} \right\} \quad (20)$$

Potential Temperature

Surface Layer

Assuming that the turbulent flux of heat is also constant with height in the surface layer, we find

$$\theta(x, y, z, t) = \theta_{GR} + (\theta_k - \theta_{GR}) \frac{\ln\left(\frac{z}{z_0}\right)}{\ln\left(\frac{h}{z_0}\right)} \quad (21)$$

We derive a modelling approximation for potential temperature in regions where a nighttime inversion exists, and where surface heating during the day leads to convection and turbulent mixing. In Figure 1, an inversion exists in the early morning. The potential temperature at $z = k$ is $\theta_{kI} = \theta(x, y, k, 0)$. The potential temperature increases linearly with height according to

$$\theta(x, y, z, t) = \theta_{kI} + \gamma(0)(z-k) \quad (22)$$

up to $z=h$, and linearly from there up to $z = h+\delta$, with a lapse rate $\gamma_{\delta}(0)$ within the inversion layer. Here $\gamma(0)$ is also the lapse rate above the inversion layer.

Thus

$$\theta(x, y, h+\delta, t) = \theta_{h+\delta} = \theta_{kI} + \gamma(0)(z-k) + \gamma_{inv}(0)\delta \quad (23)$$

It is assumed that heating destabilizes the lapse rates, so that, at some later time

$$\theta(x, y, z, t) = \theta_k + \gamma(t)(z-k) \quad (24)$$

$$\theta(x, y, h, t) = \theta_h = \theta_k + \gamma(t)(h-k)$$

$$\theta(x, y, h+\delta, t) = \theta_{h+\delta} = \theta_k + \gamma(t)(h-k) + \gamma_{inv}(t)\delta \quad (25)$$

It is assumed that Equations (23) and (25) will yield the same result for $\theta_{h+\delta}$. In that case,

$$\Delta \theta = (\theta_{kI} - \theta_k) + [\gamma(0) - \gamma(t)](h-k) + \gamma_{inv}(0)\delta \quad (26)$$

From Equation (26), we see that

$$\frac{\partial}{\partial t}(\Delta \theta) = - \frac{\partial \theta_k}{\partial t} + [\gamma(0) - \gamma(t)] \frac{\partial h}{\partial t} - (h-k) \frac{\partial \gamma}{\partial t}$$

and, since

$$\frac{\partial \theta_{h+\delta}}{\partial t} = \frac{\partial \theta_h}{\partial t} + \gamma(t) \frac{\partial h}{\partial t} + (h-k) \frac{\partial \gamma}{\partial t}$$

from first of Equations (25), we have

$$\frac{\partial}{\partial t}(\Delta \theta) = - \frac{\partial \theta_h}{\partial t} + \gamma(0) \frac{\partial h}{\partial t} \quad (27)$$

This is similar to the result obtained by Tennekes and Driedonks (1981) for a well-mixed, horizontally homogeneous layer, i.e., "the magnitude of the temperature jump θ increases in two ways: it increases as the height of the mixed layer increases, and decreases if the boundary layer warms up". Here we have not assumed well-mixedness ($\theta_h \neq \theta_m$) or horizontal homogeneity, so that Equation (27) is more general than was realized.

In the case of flow over water, the lapse rate $\Upsilon(t)$ is replaced by the appropriate expression for a marine environment, say $\Upsilon_1(t)$.

Moisture

We follow the same formulation as for potential temperature,

$$q(x, y, z, t) = q_k(x, y, t) + \zeta(t)(z-k) \quad (28)$$

$$q(x, y, z, 0) = q_{kI} + \zeta(0)(z-k) \quad (29)$$

$$\Delta q = (q_{kI} - q_k) + [\zeta(0) - \zeta(t)](h-k) + \zeta_{inv}(0)\delta \quad (30)$$

In the case of flow over water, the lapse rate of moisture $\xi(t)$ is replaced by its appropriate value over water, say $\xi_1(t)$.

Dust

We assume that the dust concentration is given by

$$C(x,y,z,t) = D(z) C_k(x,y,t) \quad (31)$$

So that

$$\Delta C = [D(h+\delta) - D(h)] C_k(x,y,t) \quad (32)$$

If we make the further assumption that there is no dust at the top of the inversion layer, i.e., at $z = h + \delta$, then $D(h+\delta) = 0$, (See Carlson and Prospero, 1972, concerning top of Saharan dust layer), and

$$\Delta C = - D(h) C_k(x,y,t) \quad (33)$$

Surface Parameterizations

For the momentum, we use

$$\left. \begin{aligned} \overline{(u'w')}_{\mathbf{k}} &= -C_d [A(\mathbf{k})] |\mathbf{V}| \hat{\mathbf{u}} \\ \overline{(v'w')}_{\mathbf{k}} &= -C_d [B(\mathbf{k})] |\mathbf{V}| \hat{\mathbf{v}} \end{aligned} \right\} \quad (34)$$

where C_d is the turbulent transfer coefficient for momentum,

$$C_d = 5 \times 10^{-4} V^{1/2} \quad (V \text{ in } \text{ms}^{-1}) \quad (\text{Berkofsky, 1982})$$

For the convective heating,

$$\overline{(w'\theta')}_{\mathbf{K}} = C_{HO} A(\mathbf{K}) \hat{\mathbf{u}} (\theta_{GR} - \theta_{\mathbf{k}}) \quad (35)$$

where θ_{GR} is the potential temperature at the ground, C_{HO} is the

For the moisture,

$$\overline{(w'q')}_{\mathbf{k}} = C_{HO} A(\mathbf{k}) \hat{\mathbf{u}} [q_{\text{sat}}(\theta_{GR}) - q_{\mathbf{k}}] \frac{W_{GR}}{W_{\mathbf{x}}} \quad (36)$$

where $q_{\text{sat}}(\theta_{\text{gr}})$ means saturation mixing ratio at temperature

$\theta_{\text{GR}}, w_{\text{GR}}$ = ground soil moisture, w_k = potential saturation

value of w .

For the dust,

$$\overline{(w'c')}_{\text{k}} = C_{\text{d}} A(k) \hat{u} (C_{\text{GR}} - C_{\text{k}}) \quad (37)$$

where C_{GR} is the dust concentration in a thin layer near the ground.

Ground Albedo

$$\alpha_{\text{gr}} = a + b \frac{w_{\text{GR}}}{w_k}, b < 0 \quad (38)$$

a, b constants

In the above, $w_{\text{GR}}, \theta_{\text{GR}}, C_{\text{GR}}$ must be predicted.

Radiation

The formulation of short and longwave energy exchange in the air and at the ground is based on Gates et al (1971). The system is applied at three levels:

ground, top of surface layer, and top of transition layer: Thus the temperatures at these levels ($z = 0$, $z = k$, $z = h$) are needed, as is the temperature at 2m. All of these are obtainable within the framework of the model by converting potential temperatures as given to temperatures using $T = \theta \left(\frac{p}{p_0} \right)^k$

Longwave radiation balance (positive if upwards) at each of the three levels is defined by R_h , R_k and R_{GR} as follows:

$$\left. \begin{aligned} R_h &= 0.736 \left[\sigma T_g^4 \tau(u_{\infty}^* - u_k^*) + \sigma (T_a^4 - T_k^4) \frac{1 + \tau(u_k^*)}{2} \right] + 0.8 C_4 \tau(u_k^*) \\ R_k &= 0.736 \left[\sigma T_g^4 \tau(u_{\infty}^* - u_k^*) + \sigma (T_a^4 - T_k^4) \frac{1 + \tau(u_k^*)}{2} \right] + 0.8 C_4 \tau(u_k^*) \\ R_{GR} &= \sigma T_a^4 \left[0.6 \sqrt{\tau(u_{\infty}^*)} - 0.1 \right] + C_4 \end{aligned} \right\} \quad (39)$$

where

$$\left. \begin{aligned} \tau(u_i^*) &= \frac{1}{1 + 1.75 (u_i^*)^{0.416}} \\ C_4 &= \sigma (T_{GR}^4 - T_a^4) \\ T_a &= \text{temperature at 2m.} \\ \sigma &= \text{Stefan-Boltzmann constant} \end{aligned} \right\} \quad (40)$$

u_i^* is the effective water vapor content between ground level and i , and is obtained from

$$u_i^* = \int_0^{z_i} \rho \left(\frac{p}{p_{GR}} \right) q dz = \frac{1}{g} \int_{p_i}^{p_{GR}} \left(\frac{p}{p_{GR}} \right) q dp \quad (41)$$

where p_{gr} pressure at the ground p_i = pressure at level i .

$$q = q_{GR} \left(\frac{p_i}{p_{GR}} \right)^\lambda, \quad (42)$$

where q_{gr} is the mixing ratio at the ground and λ = constant = 2.92 (Smith, 1966).

For levels k, h, ∞ , we obtain

$$\left. \begin{aligned} u_k^* &= \frac{q_{GR}}{g p_{GR}^{\lambda+1}} \frac{p_{GR}^{\lambda+2} - p_k^{\lambda+2}}{\lambda+2} \\ u_h^* &= \frac{q_{GR}}{g p_{GR}^{\lambda+1}} \frac{p_{GR}^{\lambda+2} - p_h^{\lambda+2}}{\lambda+2} \\ u_\infty^* &= \frac{q_{GR}}{g p_{GR}^{\lambda+1}} \frac{p_{GR}^{\lambda+2} - p_\infty^{\lambda+2}}{\lambda+2}, \quad p_\infty = 120 \text{ mb} \end{aligned} \right\} \quad (43)$$

Note: if we assume $u_k^* = 0, \tau(u_k^*) = 1, \tau(u^* - u_k^*) = \tau(u_\infty^*)$.

Also, if we assume $T_k^4 \gg (T_a^4 - T_k^4)$, we obtain

a simple form for R_k . We have not made use of these.

The effect of CO_2 absorption is taken into account by the coefficients 0.736 and the term $0.6 \sqrt{\tau(u_\infty^*)} - 0.1$. The former value actually applies at 600 mb in the Mintz - Arakawa model, but we use this for h and k , which are

very much lower than 600 mb. The effect of the error is not known.

Shortwave radiation (positive if downwards) is given by

$$\begin{aligned}
 S_R &= S_R^a = S_0^a \left\{ 1 - 0.271 \left[(u_{\infty}^* - u_R^*) \sec Z \right]^{0.303} \right\} \\
 S_R &= S_R^a = S_0^a \left\{ 1 - 0.271 \left[(u_{\infty}^* - u_R^*) \sec Z \right]^{0.303} \right\} \\
 S_{GR} &= S_{GR}^a + S_{GR}^s \\
 S_{GR}^a &= (1 - \alpha_{GR}) S_0^a \left[1 - 0.271 (u_{\infty}^* \sec Z)^{0.303} \right] \\
 S_{GR}^s &= \frac{S_0^s (1 - \alpha_{GR})(1 - \alpha_0)}{(1 - \alpha_0 \alpha_{GR})}
 \end{aligned} \tag{44}$$

where S_0^a = part of the solar radiation subject to absorption =

$$S_0 \times 0.651 \cos Z$$

S_0^s = part of the solar radiation subject to scattering =

$$S_0 \times 0.349 \cos Z$$

α_{gr} = ground albedo,

$$\alpha_0 = \min \left\{ 1, 0.085 - 0.247 \log_{10} \left[\frac{p_{GR}}{p_{\infty}} \cos Z \right] \right\}$$

= sky albedo,

(45)

Z = zenith angle of the sun

S_0 = solar constant

The radiation balance = outgoing - incoming, i.e. negative radiation balance at the ground means input of radiative heat to the surface.

Closures

At this point, we define several closure formulas, and will indicate later where and why they are used.

$$\left. \begin{aligned} (\overline{w' \theta'})_R &= -A, (\overline{w' \theta'})_R \\ (\overline{w' c'})_R &= A^*(h) \left(\frac{\partial c}{\partial z} \right)_R \\ A^*(z) &= \begin{cases} V_* h z, & z \leq h \\ \text{constant}, & h < z \leq h \end{cases} \end{aligned} \right\} \quad (46)$$

We are now in a position to derive the final form of the equations. The procedure is to apply the averaging Equation (19) to Equations (2)-(7) inclusive and use the interface conditions Equations (12)-(16) inclusive to eliminate the fluxes at inversion height, thus obtaining the transition layer equations. If we do this in all of the equations, we are left without a prediction equation for $\frac{\partial h}{\partial t}$. However if we use the first of Equations (44), which states that the turbulent flux of heat at the interface is a fraction of, and opposite in sign, to that at the top of the surface layer, in the first law of thermodynamics, this latter equation is then closed. We may then use this same (well-known, see Carson, 1973) closure in the interface Equation (14), together with the various modelling assumptions, to derive a prediction equation for $\frac{\partial h}{\partial t}$.

The ground temperature and soil moisture equations are adapted from Deardorff (1978).

The final form of the equations, in which we have used Leibniz's rule in the form

$$\int_k^l \frac{\partial q}{\partial x_i} dz = (l-k) \frac{\partial \hat{q}}{\partial x_i} + (\hat{q} - q_k) \frac{\partial l}{\partial x_i}, \quad x_i = (x, y, t) \quad (47)$$

is

First Equation of Motion

$$\begin{aligned} & \frac{\partial \hat{u}}{\partial t} + \hat{A}^2 \frac{\partial \hat{u}^2}{\partial x} + \hat{A} \hat{B} \frac{\partial}{\partial y} (\hat{u} \hat{v}) - f(\hat{v} - \hat{v}_g) + \frac{[A(l+\delta)w_k - A(l)w_k]}{(l-k)} \hat{u} \\ & + \frac{\hat{u}}{(l-k)} \left\{ [A(l) - A(l+\delta)] \frac{\partial l}{\partial t} + [\hat{A}^2(l) + A^2(l) - \hat{A}^2 - A^2(l+\delta)] \hat{u} \frac{\partial l}{\partial x} \right. \\ & \left. + [A(l)B(l) + A(l)B(l) - \hat{A}\hat{B} - A(l+\delta)B(l+\delta)] \hat{v} \frac{\partial l}{\partial y} \right\} \\ & = - \frac{c_d A(l) |\hat{v}| \hat{u}}{(l-k)} \end{aligned} \quad (48)$$

Second Equation of Motion

$$\begin{aligned} & \frac{\partial \hat{v}}{\partial t} + \hat{A} \hat{B} \frac{\partial}{\partial x} (\hat{u} \hat{v}) + \hat{B}^2 \frac{\partial}{\partial y} (\hat{v}^2) + f(\hat{u} - \hat{u}_g) + \frac{[B(l+\delta)w_k - B(l)w_k]}{(l-k)} \hat{v} \\ & + \frac{\hat{v}}{(l-k)} \left\{ [B(l) - B(l+\delta)] \frac{\partial l}{\partial t} + [A(l)B(l) + A(l)B(l) - \hat{A}\hat{B} - A(l+\delta)B(l+\delta)] \hat{u} \frac{\partial l}{\partial x} \right. \\ & \left. + [\hat{B}^2(l) + B^2(l) - \hat{B}^2 - B^2(l+\delta)] \hat{v} \frac{\partial l}{\partial y} \right\} \\ & = - \frac{c_d B(l) |\hat{v}| \hat{v}}{(l-k)} \end{aligned} \quad (49)$$

First Law of Thermodynamics

$$\begin{aligned} & \frac{\partial \theta_k}{\partial t} + \frac{\partial}{\partial x} (\hat{u} \theta_k) + \frac{\partial}{\partial y} (\hat{v} \theta_k) + \frac{(l-k)}{2} \frac{\partial r}{\partial t} \\ & + \frac{\hat{u}}{(l-k)} \left\{ [1 - A(l)] \theta_k + r [\widehat{A(z-k)} - A(l)(l-k)] \right\} \frac{\partial l}{\partial x} + r \left\{ \frac{\partial}{\partial x} [\hat{u} \widehat{A(z-k)}] \right. \\ & + \frac{\hat{v}}{(l-k)} \left\{ [1 - B(l)] \theta_k + r [\widehat{B(z-k)} - B(l)(l-k)] \right\} \frac{\partial l}{\partial y} \left. + \frac{\partial}{\partial y} [\hat{v} \widehat{B(z-k)}] \right\} \\ & + \frac{\theta_k (w_k - w_k)}{(l-k)} + w_k r = \frac{F_k - F_k}{\hat{p} c_p (l-k)} + \frac{(1+A_1) C_{H_0} V_k (\theta_{GR} - \theta_k)}{(l-k)} \end{aligned} \quad (50)$$

Inversion Height Equation

$$\frac{\partial h}{\partial t} = w_R - \left\{ (\theta_{RI} - \theta_R) + [r(0) - r](h - h) + r_{inv}(0)\delta \right\}^{-1} \times$$

$$\left\{ \hat{u} \frac{\partial h}{\partial x} \left(A(z+\delta) \theta_{RI} - A(z) \theta_R + A(z+\delta) r_{inv}(0)\delta + (h-h) [A(z+\delta) r(0) - A(z) r] \right) \right.$$

$$\left. + \hat{v} \frac{\partial h}{\partial y} \left(B(z+\delta) \theta_{RI} - B(z) \theta_R + B(z+\delta) r_{inv}(0)\delta + (h-h) [B(z+\delta) r(0) - B(z) r] \right) \right\}$$

$$- A_1 C_{H_2O} V_R (\theta_{GR} - \theta_R)$$
(51)

Dust Concentration Equation

$$\frac{\partial C_R}{\partial t} + \frac{\hat{A}D}{\hat{D}} \frac{\partial}{\partial x} (C_R \hat{u}) + \frac{\hat{B}D}{\hat{D}} \frac{\partial}{\partial y} (C_R \hat{v})$$

$$+ \frac{C_R}{\hat{D}(h-h)} \left[\hat{D} \frac{\partial h}{\partial t} + \hat{A}D \hat{u} \frac{\partial h}{\partial x} + \hat{B}D \hat{v} \frac{\partial h}{\partial y} - (w_R + \Omega) \right] = \frac{C_d V_* (C_{GR} - C_R)}{\hat{D}(h-h)}$$
(52)

Moisture Equation

$$\frac{\partial q_R}{\partial t} + \frac{\partial}{\partial x} (q_R \hat{u}) + \frac{\partial}{\partial y} (q_R \hat{v}) + \frac{[q_{RI} + z(0)(h-h) + r_{inv}(0)\delta] w_R - q_R w_R}{(h-h)}$$

$$+ \left\{ \frac{(h-h)[z-z(0)] + r_{inv}(0)\delta - (q_{RI} - q_R)}{(h-h)} \right\} \frac{\partial h}{\partial t} + \frac{z}{(h-h)} \left[\hat{A}(z-h) - A(z+\delta)(h-h+\delta) \right] \hat{u} \frac{\partial h}{\partial x}$$

$$+ \frac{z}{(h-h)} \left[\hat{B}(z-h) - B(z+\delta)(h-h+\delta) \right] \hat{v} \frac{\partial h}{\partial y} + \frac{(h-h)}{2} \frac{\partial z}{\partial t}$$

$$+ z \left\{ \frac{\partial}{\partial x} [\hat{A}(z-h) \hat{u}] + \frac{\partial}{\partial y} [\hat{B}(z-h) \hat{v}] \right\} = \frac{C_{H_2O} V_R [q_{sat}(\theta_{GR}) - q_R] \frac{w_{GR}}{w_R}}{(h-h)}$$
(53)

Ground Temperature Equation

$$\frac{\partial \theta_{GR}}{\partial t} = - \frac{2\pi \frac{1}{2}}{\beta C_s d_1} H_A - \frac{2\pi}{\tau_1} (\theta_{GR} - \theta_s)$$
(54)

$$H_A = \rho_R C_p C_{H_2O} A(h) \hat{u} (\theta_{GR} - \theta_R) - R_{NETGR}$$

Here R_{NETGR} = net radiation balance at the ground

Soil Moisture Equation

$$\frac{\partial W_{GR}}{\partial t} = - \frac{c_1 (E_g - P)}{\rho_w} - \frac{c_2 (W_{GR} - W_2)}{\rho_w \tau_1} \quad (55)$$

c_1 and c_2 are constants

ρ_w = density of liquid water

W_2 bulk moisture (analogous to O_2)

P = precipitation rate (prescribed)

ρ_s = soil density

c_s = soil specific heat

$d_1 = (k_s \tau_1)^{1/2}$

k_s = soil thermal diffusivity

τ_1 = period of 1 day

θ_2 = deep soil potential temperature

In Equations (50) and (53) above, there appear the lapse rates of potential temperature and mixing ratio, $\Upsilon(t)$, and $\mathcal{Z}(t)$, and their derivatives $\frac{\partial \Upsilon}{\partial t}$ and $\frac{\partial \mathcal{Z}}{\partial t}$. In this type of model, it is not possible to derive an equation for prediction of these quantities. Thus we have specified $\Upsilon(t)$ and $\mathcal{Z}(t)$. See Fig. 2 for the form of $\Upsilon(t)$.

In addition to the prediction scheme, Equations (48)-(55) inclusive, there exist three diagnostic equations, two for the geostrophic wind components, and the equation of continuity for the vertical velocity.

Geostrophic Wind Equations

$$\left. \begin{aligned} \hat{u}_g &\approx -\frac{R}{f} \frac{\partial}{\partial y} [\theta_k + r(h-k)] \\ \hat{v}_g &\approx \frac{R}{f} \frac{\partial}{\partial x} [\theta_k + r(h-k)] \end{aligned} \right\} \quad (56)$$

Continuity Equation

$$w_k = w_k - (h-k) \left(\frac{\partial \hat{u}}{\partial x} + \frac{\partial \hat{v}}{\partial y} \right) - \left\{ [1-A(k)] \hat{u} \frac{\partial h}{\partial x} + [1-B(k)] \hat{v} \frac{\partial h}{\partial y} \right\} \quad (57)$$

The expression for w_k is derived in the following way:

Substituting Eq. (20) into Eq. (17), we have

$$\left. \begin{aligned} u &= \frac{A(k)}{\ln\left(\frac{k+z_0}{z_0}\right)} \ln\left(\frac{z+z_0}{z_0}\right) \hat{u} \\ v &= \frac{B(k)}{\ln\left(\frac{k+z_0}{z_0}\right)} \ln\left(\frac{z+z_0}{z_0}\right) \hat{v} \end{aligned} \right\} \quad (58)$$

Then, integrating the continuity equation

$$\begin{aligned} w_k &= w_T - \int_{z_T}^k \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) dz \\ &= w_T - \left[A(k) \frac{\partial \hat{u}}{\partial x} + B(k) \frac{\partial \hat{v}}{\partial y} \right] \left[\ln\left(\frac{k+z_0}{z_0}\right) \right]^{-1} \int_{z_T}^k \ln\left(\frac{z+z_0}{z_0}\right) dz \end{aligned} \quad (59)$$

i.e.,

$$\left. \begin{aligned} w_R &= w_T - I \left[\ln \left(\frac{h+z_0}{z_0} \right) \right]^{-1} \left[A(h) \frac{\partial \hat{u}}{\partial x} + B(h) \frac{\partial \hat{v}}{\partial y} \right] \\ I &= (h+z_0) \ln \left(\frac{h+z_0}{z_0} \right) - h \end{aligned} \right\} \quad (60)$$

w_T is given by Eq. 8, and in that equation is evaluated from

$$V_{z_T} = \frac{V_*}{k_1} \ln \left(\frac{z_T + z_0}{z_0} \right) \quad (61)$$

Given initial values of $\hat{u}, \hat{v}, \theta_k, h, c_k, q_k, \theta_{GR}, w_{GR}$, the system can be solved. If we are concerned with a limited area, lateral boundary conditions are important. These will be discussed later. The upper and lower boundary conditions have already been prescribed.

If we assume no change of magnitude or direction of horizontal wind with height within the transition layer only, then $A(z) = B(z) = 1$. This situation frequently exists when the transition layer is well mixed. The equations then become:

First Equation of Motion

$$\begin{aligned} & \frac{\partial \hat{u}}{\partial t} + \frac{\partial}{\partial x} (\hat{u}^2) + \frac{\partial}{\partial y} (\hat{u} \hat{v}) - f (\hat{v} - \hat{v}_g) + \frac{[A(h) w_R - w_R]}{(h-k)} \hat{u} \\ & + \frac{\hat{u}}{(h-k)} \left\{ [1-A(h)] \frac{\partial \hat{u}}{\partial t} + [1-A(h)] \hat{u} \frac{\partial \hat{u}}{\partial x} + [1-A(h) B(h)] \hat{v} \frac{\partial \hat{u}}{\partial y} \right\} \\ & = - \frac{c_d |\hat{v}| \hat{v}}{(h-k)} \end{aligned} \quad (62)$$

Second Equation of Motion

$$\begin{aligned} \frac{\partial \hat{v}}{\partial t} + \frac{\partial}{\partial x} (\hat{u} \hat{v}) + \frac{\partial}{\partial y} (\hat{v}^2) + f(\hat{u} - \hat{u}_g) + \frac{[B(z+\delta) w_R - w_R]}{(z-k)} \hat{v} \\ + \frac{\hat{v}}{(z-k)} \left\{ [1-B(z+\delta)] \frac{\partial z}{\partial t} + [1-A(z+\delta)B(z+\delta)] \hat{u} \frac{\partial z}{\partial x} + [1-B^2(z+\delta)] \hat{v} \frac{\partial z}{\partial y} \right\} = -\frac{c_d |\hat{v}| \hat{v}}{(z-k)} \end{aligned} \quad (63)$$

First Law of Thermodynamics

$$\begin{aligned} \frac{\partial \theta_R}{\partial t} + \frac{\partial}{\partial x} (\hat{u} \theta_R) + \frac{\partial}{\partial y} (\hat{v} \theta_R) + \frac{(z-k)}{2} \frac{\partial r}{\partial t} + \frac{\theta_R (w_R - w_k)}{(z-k)} \\ + \frac{r}{2} (w_R + w_k) = \frac{(F_R - F_k)}{\hat{p} c_p (z-k)} + \frac{(1+A_1) c_{H_0} |\hat{v}| (\theta_{GR} - \theta_R)}{(z-k)} \end{aligned} \quad (64)$$

Inversion Height Equation

$$\begin{aligned} \frac{\partial z}{\partial t} = w_R - \left[(\theta_{RI} - \theta_R) + (r_I - r)(z-k) + r_{inv}(0)\delta \right] \times \\ \left\{ \hat{u} \frac{\partial z}{\partial x} \left(A(z+\delta) \theta_{RI} - \theta_R + A(z+\delta) r_{inv}(0)\delta + (z-k) [A(z+\delta) r_I - r] \right) \right. \\ \left. + \hat{v} \frac{\partial z}{\partial y} \left(B(z+\delta) \theta_{RI} - \theta_R + B(z+\delta) r_{inv}(0)\delta + (z-k) [B(z+\delta) r_I - r] \right) - A_1 c_{H_0} |\hat{v}| (\theta_{GR} - \theta_R) \right\} \end{aligned} \quad (65)$$

Dust Concentration Equation

$$\begin{aligned} \frac{\partial c_R}{\partial t} + \frac{\partial}{\partial x} (c_R \hat{u}) + \frac{\partial}{\partial y} (c_R \hat{v}) + \frac{c_R}{(z-k)} \left[\frac{\partial z}{\partial t} + \hat{u} \frac{\partial z}{\partial x} + \hat{v} \frac{\partial z}{\partial y} - \frac{(w_R + w_k)}{\hat{D}} \right] \\ = \frac{c_d |\hat{v}| (c_{GR} - c_R)}{\hat{D} (z-k)} \end{aligned} \quad (66)$$

Moisture Equation

$$\begin{aligned}
 & \frac{\partial q_k}{\partial t} + \frac{\partial}{\partial x} (q_k \hat{u}) + \frac{\partial}{\partial y} (q_k \hat{v}) + \left[\frac{q_{kT} + \gamma(0)(h-k) + \gamma_{\text{sur}}(0)\delta}{(h-k)} \right] - \frac{q_k w_k}{(h-k)} \\
 & + \left\{ \frac{[(h-k)[\gamma-\gamma(0)] + \gamma_{\text{sur}}(0)\delta - (q_{kT} - q_k)}{(h-k)} \right\} \frac{\partial h}{\partial t} + \frac{\gamma}{(h-k)} \left[\frac{(h-k)}{2} - A(h+\delta)(h-k+\delta) \right] \hat{u} \frac{\partial h}{\partial x} \\
 & + \frac{\gamma}{(h-k)} \left[\frac{(h-k)}{2} - B(h+\delta)(h-k+\delta) \right] \hat{v} \frac{\partial h}{\partial y} + \gamma \left\{ \frac{\partial}{\partial x} \left[\frac{(h-k)}{2} \hat{u} \right] + \frac{\partial}{\partial y} \left[\frac{(h-k)}{2} \hat{v} \right] \right\} \\
 & = C_{H_0} |\hat{V}| [q_{\text{sat}}(\theta_{\text{cr}}) - q_k] \frac{w_{kr}}{w_{ra}} (h-k)^{-1}
 \end{aligned} \tag{67}$$

The Ground Temperature Equation (54), Soil Moisture Equation (55), and Geostrophic Wind Equations (56) are unchanged.

The expressions for u and v in the surface layer become

$$\left. \begin{aligned}
 u &= \frac{\ln \left(\frac{z+z_0}{z_0} \right)}{\ln \left(\frac{h+z_0}{z_0} \right)} \hat{u} \\
 v &= \frac{\ln \left(\frac{z+z_0}{z_0} \right)}{\ln \left(\frac{h+z_0}{z_0} \right)} \hat{v}
 \end{aligned} \right\} \tag{68}$$

Equations of Continuity

$$\left. \begin{aligned}
 w_k &= w_k - (h-k) \left(\frac{\partial \hat{u}}{\partial x} + \frac{\partial \hat{v}}{\partial y} \right) \\
 w_k &= w_T - I \left[\ln \left(\frac{h+z_0}{z_0} \right) \right]^{-1} \left(\frac{\partial \hat{u}}{\partial x} + \frac{\partial \hat{v}}{\partial y} \right)
 \end{aligned} \right\} \tag{69}$$

From Eq. (69), we deduce

$$\left. \begin{aligned}
 w_k &= w_T + \frac{J w_k}{(h-k+J)} \\
 J &= \left[\ln \left(\frac{h+z_0}{z_0} \right) \right]^{-1} I
 \end{aligned} \right\} \tag{70}$$

This expression is useful in a model in which w_h is prescribed, as in the one - dimensional model to be described below. For a range of values of h ($300\text{m} \leq h \leq 2000\text{m}$), $k = 20\text{m}$, $Z_0 = 0.7\text{cm}$, and with $w_T = 0$, we find

$$-.06 w_h \leq w_k \leq -.01 w_h$$

Thus, in this model w_k is very small, and is essentially zero, unless $w_T = 0$.

Finally, we write the equations for a model in which horizontal gradients are absent.

First Equation of Motion

$$\frac{\partial \hat{u}}{\partial t} - f(\hat{v} - \hat{v}_g) + [1 - A(h+k)] \frac{\hat{u}}{(h-k)} \left(\frac{\partial h}{\partial t} - w_k \right) = - \frac{c_d |\hat{v}| \hat{u}}{(h-k)} \quad (71)$$

Second Equation of Motion

$$\frac{\partial \hat{v}}{\partial t} + f(\hat{u} - \hat{u}_g) + [1 - B(h+k)] \frac{\hat{v}}{(h-k)} \left(\frac{\partial h}{\partial t} - w_k \right) = - \frac{c_d |\hat{v}| \hat{v}}{(h-k)} \quad (72)$$

First Law of Thermodynamics

$$\frac{\partial \theta_k}{\partial t} + \frac{(h-k)}{2} \frac{\partial r}{\partial t} + \frac{r}{2} (w_R + w_k) = \frac{(F_R - F_k)}{\hat{\rho}_p (h-k)} + \frac{(1+A_1) c_{H_2O} |\hat{V}| (\theta_{GR} - \theta_k)}{(h-k)} \quad (73)$$

Inversion Height Equation

$$\frac{\partial h}{\partial t} = w_R - \frac{A_1 c_{H_2O} |\hat{V}| (\theta_{GR} - \theta_k)}{\left\{ (\theta_{RI} - \theta_k) + [r(0) - r](h-k) + r_{inv}(0) \delta \right\}} \quad (74)$$

Dust Concentration Equation

$$\frac{\partial c_R}{\partial t} + \frac{c_R}{(h-k)} \left[\frac{\partial h}{\partial t} - \left(\frac{w_R + r}{\hat{\delta}} \right) \right] = \frac{c_d |\hat{V}| (c_{GR} - c_R)}{\hat{\delta} (h-k)} \quad (75)$$

Moisture Equation

$$\begin{aligned} & \frac{\partial q_R}{\partial t} + \left[\frac{q_{RI} + z(0)(h-k) + z_{inv}(0) \delta}{(h-k)} \right] w_R \\ & + \left\{ \frac{(h-k) [z - z(0)] + z_{inv}(0) \delta - (q_{RI} - q_R)}{(h-k)} \right\} \frac{\partial h}{\partial t} \\ & = \frac{c_{H_2O} |\hat{V}| [q_{sat}(\theta_{GR}) - q_R]}{(h-k)} \frac{w_{GR}}{w_R} \end{aligned} \quad (76)$$

The Ground Temperature Equation (54) and Soil Moisture Equation (55) are unchanged. The geostrophic wind Equations (56) cannot be applied, so $\hat{u}_g, \hat{v}_g$ must be specified. Similarly, the Equations of Continuity (69) cannot be applied, so that, if an estimate of the effect of w_h is desired, w_h must be specified. Then, w_k can be deduced from Eq. (70).

THE FINITE - DIFFERENCE SCHEME

We have used a domain 300km x 60km, with $\Delta x = 10$ km. Fig. 3 shows the Eliassen grid (Mesinger and Arakawa, 1976), which is a space - time grid staggered in both space and time, convenient for the leapfrog scheme associated with centered space differencing.

Two and four point averages of variable quantities were taken as needed to provide values at the grid point under consideration.

Thus averages are defined either as

$$|\bar{q}|_{i,j} = \frac{1}{2} (q_{i+\frac{1}{2},j} + q_{i-\frac{1}{2},j}) \quad (77)$$

or

$$|\bar{q}|_{i,j} = \frac{1}{4} (q_{i+1,j} + q_{i-1,j} + q_{i,j+1} + q_{i,j-1}) \quad (78)$$

Centered differences were taken over one or two grid intervals as dictated

by locations of variables on the grid. For example, when predicting u_{ij}^{n+1} , a term like $(\partial h / \partial x)^n$ is approximated using a one-grid interval centered difference

$$(\delta_x h)_{i,j}^n = \frac{1}{\Delta x} (h_{i+\frac{1}{2},j}^n - h_{i-\frac{1}{2},j}^n) \quad (79)$$

When predicting $\theta_{i,j}^{n+1}$, a term like $(\partial h / \partial x)^n$ is approximated using a two-grid interval centered difference

$$(\delta_x h)_{i,j}^n = \frac{1}{2\Delta x} (h_{i+1,j}^n - h_{i-1,j}^n) \quad (80)$$

When a two or four point average was necessary for squared terms, the averaging operator was performed first, then the average was squared.

When a choice was necessary between one or two grid - interval differences for nonlinear terms, such as (u^2) , the one grid interval difference was used. All products, such as u^2 , were formed after appropriate averaging to provide values at the same point.

The leap-frog time differencing scheme is

$$\left. \begin{aligned} q_{i,j}^{n+1} &= q_{i,j}^{n-1} + 2\Delta t F_{i,j}^n \\ q_{i,j}^{n+1/2} &= q_{i,j}^0 + \Delta t F_{i,j}^0 \end{aligned} \right\} \quad (81)$$

LATERAL BOUNDARY CONDITIONS

We use the radiation condition proposed by Orlanski (1976). This makes use of the Sommerfeld radiation condition.

$$\frac{\partial \phi}{\partial t} + C \frac{\partial \phi}{\partial x} = 0 \quad (82)$$

where C is constant.

The finite - difference leap-frog representation of this equation is

$$\frac{\phi^n(JM) - \phi^{n-2}(JM)}{2\Delta t} = -\frac{C}{\Delta x} \left[\frac{\phi^n(JM) + \phi^{n-2}(JM)}{2} - \phi^{n-1}(JM-1) \right] \quad (83)$$

Here JM refers to the boundary point.

The essence of Orlanski's (1976) technique is: instead of fixing a constant value of the phase velocity, we numerically calculate a propagation velocity from the neighboring grid points, using the same Equation (83) for each variable to calculate C. Thus we find

$$C_\phi = - \frac{\left[\phi^n(JM-1) - \phi^{n-2}(JM-1) \right]}{\left[\frac{\phi^n(JM-1) + \phi^{n-2}(JM-1)}{2} \right] - \phi^{n-1}(JM-2)} \frac{\Delta x}{2\Delta t} \quad (84)$$

To determine the boundary grid point, C_ϕ from Equation (84) is substituted for C in Equation (83), in which the time index is increased by 1. We find

$$\phi^{n+1}(JM) = \left[\frac{1 - \left(\frac{\Delta t}{\Delta x}\right) C_\phi}{1 + \left(\frac{\Delta t}{\Delta x}\right) C_\phi} \right] \phi^{n-1}(JM) + \frac{2 \left(\frac{\Delta t}{\Delta x}\right) C_\phi}{\left[1 + \left(\frac{\Delta t}{\Delta x}\right) C_\phi \right]} \phi^n(JM-1) \quad (85)$$

In this formulation, we require $0 < C_\phi \leq \Delta x / \Delta t$.

For the limiting outflow condition, $C_\phi = \Delta x / \Delta t$,

$$\phi^{n+1}(JM) = \phi^n(JM-1) \quad (86)$$

$$\text{If } C_\phi = 0, \quad \phi^{n+1}(JM) = \phi^{n-1}(JM) \quad (87)$$

No information has come from the interior solution when $C_\phi = 0$, so we must regard this as inflow information, to be prescribed from a previous time step.

Finally, we have:

Calculate C_ϕ from Equation (84).

$$\left. \begin{array}{l} \text{If } C_\phi > \Delta x / \Delta t \text{ (limiting outflow), set } C_\phi = \Delta x / \Delta t \\ \text{If } 0 < C_\phi < \Delta x / \Delta t \text{ (outflow), use } C_\phi \text{ as is} \\ \text{If } C_\phi < 0 \text{ (inflow), set } C_\phi = 0 \end{array} \right\} \quad (88)$$

Use C_ϕ from Equation (88) to calculate ϕ^{n+1} (JM) from Equation (85).

In our initial tests, we shall use only the condition corresponding to $C_\phi = 0$, i.e., Equation (87), on all boundaries, since this is an easy condition to apply for testing the model equations themselves.

In discussing the above, we have tacitly assumed that we are dealing with the right and bottom boundaries respectively. To derive the appropriate equations for the left and top boundaries*, we must have

$$\frac{\phi^n(JM) - \phi^{n-2}(JM)}{2\Delta t} = -\frac{c}{\Delta x} \left\{ \phi^{n-1}(JM+1) - \left[\frac{\phi^n(JM) + \phi^{n-2}(JM)}{2} \right] \right\} \quad (89)$$

where, due to the method of indexing, JM+1 now refers to the first grid point in from the left and top boundaries. Applying Equation (89) to neighboring grid points,

*_____

when applied to the top and bottom boundaries, Δx is replaced by Δy in the set of equations.

$$C_{\phi} = - \frac{[\phi^n(JM+1) - \phi^{n-2}(JM+1)]}{\phi^{n-1}(JM+2) - \left[\frac{\phi^n(JM+1) + \phi^{n-2}(JM+1)}{2} \right]} \frac{\Delta x}{2\Delta t} \quad (90)$$

We now substitute Equation (90) into Equation (89), using C_{ϕ} for C , and increase the time index by 1.

We obtain

$$\phi^{n+1}(JM) = \left[\frac{1 + \left(\frac{\Delta t}{\Delta x}\right) C_{\phi}}{1 - \left(\frac{\Delta t}{\Delta x}\right) C_{\phi}} \right] \phi^{n-1}(JM) - \frac{2 \left(\frac{\Delta t}{\Delta x}\right) C_{\phi}}{\left[1 - \left(\frac{\Delta t}{\Delta x}\right) C_{\phi} \right]} \phi^n(JM+1) \quad (91)$$

In this formulation, we require $-\Delta x/\Delta t < C_{\phi} \leq 0$.

For the limiting outflow condition, $C_{\phi} = -\Delta x/\Delta t$,

$$\phi^{n+1}(JM) = \phi^n(JM+1) \quad (92)$$

as before.

If $C_{\phi} = 0$,

$$\phi^{n+1}(JM) = \phi^{n-1}(JM) \quad (93)$$

This is again regarded as inflow information.

Finally, we have:

Calculate C_ϕ from Equation (90).

If $C_\phi < -\Delta x/\Delta t$, (limiting outflow), set $C_\phi = -\Delta x/\Delta t$

If $-\Delta x/\Delta t < C_\phi \leq 0$, (outflow), use C_ϕ as is. (94)

If $C_\phi > 0$ (inflow), set $C_\phi = 0$

Use C_ϕ from Equation (94) to calculate ϕ^{n+1} (JM) from Equation (91).

In the above Equations (84) and (90), it is conceivable that C_ϕ may become infinite or indeterminate.

Case 1 - C_ϕ infinite

Equation (85) may be written

$$\phi^{n+1}(JM) = \left[\frac{\frac{1}{C_\phi} - \left(\frac{\Delta t}{\Delta x}\right)}{\frac{1}{C_\phi} + \left(\frac{\Delta t}{\Delta x}\right)} \right] \phi^{n-1}(JM) + \left[\frac{2\left(\frac{\Delta t}{\Delta x}\right)}{\frac{1}{C_\phi} + \left(\frac{\Delta t}{\Delta x}\right)} \right] \phi^n(JM-1) \quad (95)$$

$$\lim_{C_\phi \rightarrow \pm\infty} \phi^{n+1}(JM) = 2\phi^n(JM-1) - \phi^{n-1}(JM) \quad (96)$$

Similarly, Equation (91) becomes

$$\lim_{C_\phi \rightarrow \pm\infty} \phi^{n+1}(JM) = 2\phi^n(JM+1) - \phi^{n-1}(JM) \quad (97)$$

Case 2 - C_ϕ indeterminate

This situation arises when, in addition to the fact that the denominator of Equation (84) is zero, the numerator is also. then

$$\phi^n (JM-1) = \phi^{n-2} (JM-1) \quad (98)$$

If applied to the boundary point (JM), this is essentially the statement Equation (87) corresponding to $C_\phi = 0$. Thus, in case the numerator of Equation (84) or Equation (90) is zero, we use the condition corresponding to $C_\phi = 0$, i.e., Equation (87) or Equation (93).

EXPERIMENTS

One - Dimensional

Our initial experiments are all concerned with a dry atmosphere. We first ran the one - dimensional model, given by Equations (71)-(75) inclusive plus Equation (54), with the following conditions:

$$A(h+\frac{1}{2}) = B(h+\frac{1}{2}) = 1 \text{ (no wind-shear across inversion)}$$

$$\hat{u}_g = \hat{v}_g = 0 \text{ (no geostrophic wind)}$$

$$a.) w_h = 0; w_k = 0$$

$$b.) w_h = - (h-k) \left(\frac{\partial \hat{u}}{\partial x} + \frac{\partial \hat{v}}{\partial y} \right) = - (h-k) B \text{ (} B = \text{constant)}; w_k = 0$$

$$\begin{aligned}
B = & -5 \times 10^{-5} s^{-1} (0900-1500) \\
& -5 \times 10^{-5} s^{-1} + 5 \times 10^{-5} s^{-1} (1500-2100) \\
& 5 \times 10^{-5} s^{-1} (2100-0300) \\
& 5 \times 10^{-5} s^{-1} - 5 \times 10^{-5} s^{-1} (0300-0900)
\end{aligned}$$

- c.) $\hat{u} = \hat{v} = 100 \text{ cm s}^{-1}$
- d.) $\theta_k = 303 \text{ }^\circ\text{K}, \theta_{GR} = 303.2 \text{ }^\circ\text{K}$
- e.) $C_{ho} = 4 \times 10^{-2}$
- f.) $h_o = 300 \text{ m}$
- g.) $C_k = 100 \mu\text{gm}^{-3}$
- h.) $C_{GR} = 100 \mu\text{gm}^{-3} = \text{constant};$
- i.) $C_{GR} = 10,000 \mu\text{gm}^{-3} = \text{constant}$

The results of the experiment with $w_h = 0$ are shown in Figures 4, 5, and 6.

Figure 4 shows the evolution of the fields of $\hat{u}$ and $\hat{v}$ (the caps are omitted from the figure). These fields evolve smoothly. The absolute value of the wind reaches a maximum at about 1300 LST and a minimum at about 0100 LST. Fig. 5 shows the evolution of the ground temperature θ_{GR} and the temperature at the top of the surface layer θ_k . θ_{GR} reaches its maximum value at about 1400, while θ_k reaches its maximum at about 1600 local time. Both of these are reasonable. The ground temperature reaches its minimum at about 0600, while the air temperature reaches its minimum at about 0800, which is somewhat late. The maximum and minimum of θ_{GR} both exceed the corresponding values for, θ_k which is realistic. The range of both values is somewhat less than should be expected on a summer day with light winds.

Figure 6 shows the evolution of the inversion height (H in the figure) and dust concentration C_k for the two cases,

$$C_{GR} = 100 \mu\text{gm}^{-3}, C_{GR} = 10,000 \mu\text{gm}^{-3}.$$

The former of these corresponds to an average air value for Saharan dust. It turned out, after 6 months of observation at Sde Boqer, that the average value is closer to $60 \mu\text{gm}^{-3}$. However, the use of 100 will not alter these results in any substantial way. The value $10,000 \mu\text{gm}^{-3}$ corresponds to that within a strong dust storm. The first thing that can be seen from this figure is that the inversion height rises steadily throughout the day. This may be indicative of the fact that a convective boundary layer model should apply only during daylight hours - or it may indicate that subsidence at inversion level is required to bring the inversion down at night.

The curve $C_{GR} = 100 \mu\text{gm}^{-3}$ shows the trend of C_k (dust concentration at 20 meters). This quantity decreases steadily with time. This is not surprising, since, according to Equation (75), the tendency of C_k is inversely proportional to the inversion height. It also indicates that the turbulent transport of dust was too weak to overcome the thinning out of C_k as the inversion rose. With $C_{GR} = 10,000 \mu\text{gm}^{-3}$, there is continuous intense turbulent transport, so that the dust concentration at $z = k$ is kept high throughout the period.

It should be recalled that both θ_k and h are dependent upon the assumed form of $\Gamma(t)$ (Figure 2). Thus, it is possible to "tune" the model by experimenting with other curves of $\Gamma(t)$.

Figures 7, 8, 9 shows the results for the same quantities when w_h , the vertical velocity at inversion height, is not zero. In actual fact, this quantity should be obtained by solving the continuity equation, which is not available in a model without horizontal transport. Thus we assume values of the horizontal divergence B (given in the list of data), which vary with time throughout the day. Again, this quantity is "tunable", but we wish to

highlight the effect of subsidence on inversion height.

Figure 7 shows the evolution of $\hat{u}$ and $\hat{v}$ when $w_h \neq 0$. The results are indistinguishable from those of Figure 4. This is simply because the w_h terms vanish from Equations (71) and (72) under the conditions we have assumed.

Figure 8 shows the evolution of θ_{GR} and θ_k . There are some small differences between these results and those with $w_h = 0$, but the evolution is more or less the same in both cases.

The major differences in the case $w_h \neq 0$ can be seen in Figure 9, when compared with Figure 6. Figure 9 shows the evolution of inversion height, h , and of dust concentration, C_k . The inversion height now reaches a maximum of about 1400 m at about 1800 LST, and then falls due to subsidence. It reaches a minimum of about 600 m at about 0500, and then starts up again. Even though the value itself at the minimum may not be realistic, this experiment very strongly highlights the effect of the vertical velocity at inversion height level on the inversion height itself.

The same type of result is true for C_k . For $C_{GR} = 100 \mu\text{gm}^{-3}$, there is little change in C_k , except that it does not decrease as much as it did in the case $w_h = 0$. This is so because the subsidence during the latter part of the period tends to increase the concentration at lower levels.

This effect is even more marked in the case of $C_{GR} = 10,000 \mu\text{gm}^{-3}$. There is intense turbulent transport upward during the entire period. During the second half of the day, the upward transport to level $z=k$ is intensified by subsidence to that level, so that C_k continues to increase.

It should be realized that the assumption of $C_{GR} = \text{constant}$ for 24 hours is rather weak, in the sense that wind erosion, which causes variations in C_{GR} , occurs in bursts. We shall discuss this point later.

The legends at the top of all the figures contain the heading "NON -

PARAMETERIZED DUST EQ." We have distinguished these results from results with "PARAMETERIZED DUST EQ", to be shown below, for the following reasons.

We have used the interface Equations (12)-(16) inclusive, to eliminate the turbulent fluxes, at $z=h$ except for Equation (14). It is also possible to parameterize the other fluxes, for example $\overline{(w'c')}_h$ in Equation (16). If we use the flux - gradient relation

$$-\overline{w'c'} = A^*(z) \frac{\partial C}{\partial z} \quad (99)$$

$$\text{then } -\overline{(w'c')}_h = A^*(h) D'(h) c_k \quad (100)$$

where $A^*(z)$, the coefficient of eddy diffusion, is given by Equation (46).

In that case, Equation (16) becomes

$$\frac{\partial h}{\partial t} = (w_R + \Omega) - \frac{A^* D'(h)}{D(h)} \quad (101)$$

and the dust concentration equation becomes

$$\begin{aligned} \frac{\partial C_R}{\partial t} + \frac{[\hat{D} - D(h)]}{\hat{D}(h-h)} C_R \frac{\partial h}{\partial t} + \frac{[D(h) - \hat{D}] w_R + (\hat{D} - 1) w_R + [D(h) - 1] \Omega}{\hat{D}(h-h)} \\ = \frac{C_d |\hat{V}| (C_{GR} - C_R) + A^* D'(h) C_R}{\hat{D}(h-h)} \end{aligned} \quad (102)$$

instead of Equation (75). We now see that the model in this form contains two

inversion height equations, Equation (74) due to convection of heat and Equation (102) due to turbulent diffusion of dust. We carried out experiments with the same initial data, but in which the inversion height was calculated as an average of the results from Equation (74) and (102). The results are shown in Figures 10-15 inclusive. The major differences between these results and the non-parameterized results are in the inversion height and dust calculations, seen in Figures 12 and 15. These should be compared with Figures 6 and 9 respectively. For the $w_h = 0$ case, the results show similar trends, but the non-parameterized inversion height went much higher, and the curve is less smooth. This is undoubtedly due to the averaging involved in obtaining the parameterized height. The variation of C_k is quite similar in both cases, although when $C_{GR} = 10,000 \mu\text{gm}^{-3}$, C_k does not drop down, in the parameterized case as it did in the non-parameterized case. When $w_h \neq 0$ the curves look quite similar, except that the maxima and minima of inversion height occur about an hour later in the parameterized case than in the non-parameterized case.

The conclusion to be drawn from these comparisons is that the non-parameterized system, which is theoretically more correct, should be used.

Two - Dimensional Experiments

We used the system of Equations (62) - (66) inclusive, Equations (68), (69), (70). We have not assumed $A(h+\delta)$, $B(h+\delta) = 0$, i.e., we have allowed wind shear through the inversion.

a). Constant Boundary Conditions

We consider a region 300km x 600km, with a grid spacing $\Delta x = \Delta y = 10\text{km}$. In this experiment, we used the lateral boundary condition corresponding to $C_\phi = 0$, i.e.,

$$\phi^{n+1}(JH) = \phi^{n-1}(JH) \quad (87)$$

Thus we expect that this fixed boundary condition will eventually lead to instability due to reflection at the boundaries.

As this experiment was essentially a check of the program, we used very simple initial conditions.

$$\hat{u} = 100 \text{ cm s}^{-1} \text{ everywhere}$$

$$\hat{v} = 0$$

$$h = 650 \text{ m}$$

$$\theta_k = 303^\circ\text{K}$$

$$\theta_{GR} = 303.02^\circ\text{K}$$

$Y(t)$ as in Figure 2.

$$C_k = 100 \mu\text{gm}^{-3}$$

$$C_{GR} = 100 \mu\text{gm}^{-3}$$

$$A(h+\delta) = B(h+\delta) = 1.01 - \text{corresponding to } 1\text{ms}^{-1} (10\text{m})^{-1}$$

$$\hat{u}_g \text{ was taken as } 1 \text{ ms}^{-1}$$

$$\hat{v}_g = 0$$

We expect changes in the variables due to changes in the radiation fluxes.

We used a time step of $\Delta t = 1$ minute. When the program ran smoothly for 33 time steps, we tried $\Delta t = 2$ minutes, with identical results. We then ran for a longer period, but the calculations blew up at time step 122 = 4.07 hours, primarily due to boundary instability. The evolution of the interior fields seemed reasonable.

b.) Radiation Boundary Conditions

Starting from the same initial fields, we applied the radiation conditions Equations (82) - (98) inclusive. The experiments have been run so far for 6 hours, with one minute time steps. The evolution of the interior fields seemed reasonable. Strong gradients did not develop in all the interiors as they did in the constant boundary condition case.

c.) Comparison of Results of the Two Experiments

In the figures to be discussed below, we have displayed the printouts for the various fields, only for rows 1,2,3,4,5,58,59,60,61. The remaining fields are smooth transitions. Due to the printing limitations, each row of the grid is represented by almost two full rows on the printout, so that columns 1 through 17 go from left to right, while columns 18 through 31, just beneath them, go from right to left. We have since modified the print routine to give a clear rectangular array, and future results will be printed in the manner.

Figure 16 shows the ψ -field at 180 minutes, with constant boundary conditions. Fig. 17 shows the ψ -field with radiation boundary conditions. Although the numbers on the bottom boundary of the latter are larger than in the constant B.C. case, the fields everywhere else are quite uniform and

smooth. Figures 18 and 19 show the $\hat{v}$ -fields in the constant and radiation cases. Again, the interior fields in the radiation case are much smoother, and less subject to gradients created by boundary reflection. The inversion heights are shown in Figures 20 (constant) and 21 (radiation). There is no question of the superiority of the radiation condition for this field, even though the left and upper boundaries are not sufficiently smooth. Figures 22 and 23 show the θ_k fields in the constant and radiation cases. Except for the bottom row, the radiation condition gives a smoother field. Figures 24 and 25 show θ_{GR} in the constant and radiation cases. Again, the radiation case is clearly superior. Figures 26 and 27 show the C_k (dust) fields in the constant and radiation cases. In this field, the interior for the constant case already shows large, unrealistic values, while these values for the radiation case are very smooth. Finally, Figures 28 and 29 show the w_h values and radiation cases. These values should all be zero, as both $\hat{u}$ and $\hat{v}$ should be developing uniformly. While all are very small, the fields in the constant case are already beginning to develop, while they are almost all zero in the radiation case.

These results clearly illustrate the efficacy and superiority of the radiation boundary condition over the constant boundary condition. Yet the boundaries still require additional treatment. We plan to experiment with suitable filters (Shapiro, 1975) to control spurious high frequency oscillations on the boundaries themselves. There are also suggestions (Miller and Thorpe, 1981) for improved versions of the radiation boundary condition.

As noted earlier, the radiation boundary condition experiments have been continued for 6 hours, with one minute time steps. All of the fields developed reasonably, with little encroachment from the boundaries, except

the inversion height field. While the calculations still did not blow up at 6 hours, spurious oscillations were developing in this field. It is clear that some kind of smoothing is required. This will be attempted in future experiments.

CONCLUSIONS

The one - and two - dimensional versions of the desert planetary boundary layer model appear to be checked out, in the sense that they give reasonable meteorological results.

The one - dimensional version runs well for 24-hours, and can certainly be run for longer periods. It is now possible to use this model for a number of sensitivity experiments, such as prescription of dust concentration at the ground as a function of time, variable vertical velocity at inversion height, variable surface albedo.

The two - dimensional version runs well for up to 6 hours before fluctuations in the inversion height field set in. Thus, more numerical investigation is needed in order to carry the experiments further. As already stated above, the investigations will take the form of smoothing and filtering operators, and possible improved forms of the radiation boundary conditions.

We have already prepared a set of base data of all fields for Israel, and will carry out experiments with these data, over irregular terrain, following adoption of more suitable numerical techniques.

RECOMMENDATIONS

There are a number of steps which can be taken which may lead to improvement of the present model. Although the model appears to be checked out, in the sense that it does not blow up by 6 hours, and gives reasonable evolution of the fields during that time it is desirable to focus on a model which may be useful operationally.

There are still several steps which may be taken to improve the radiation boundary conditions. Among them are the application of a suitable filter (Shapiro, 1975), which was successfully applied to this type of problem by Eliassen and Thorsteinsson (1984). Another is the possibility of applying an improved version of the radiation boundary condition according to the method suggested by Miller and Thorpe (1981).

There are also several ways of improving the physics in the dry model. We could try a possibly more realistic version of the stability $V(t)$. We could also try to improve the assumption that the dust concentration near the ground, C_{GR} , is constant. To do so requires a method for predicting erosion of soil by wind. A first step in this direction has been taken by Berkofsky (1984) who developed an equation describing the processes of detachment, transport and deposition which make up wind erosion.

When all of the above has been incorporated we can then include moisture and a thermally active surface layer. Real data (already compiled for Israel for this model) can then be used as input, together with topography, for operational testing.

Finally, it is possible to combine this model with that of the free atmosphere for a simplified version of a tropical operational model. Such a model has been suggested by Berkofsky (1983).

DUST CONCENTRATION DATA

In Table 1 we present dust concentration data for Sede Boquer, compiled since June 1984. For a variety of technical reasons, the data are not continuous. These dust concentration data were obtained with an ultra-high volume sampler (Sierra Instruments) with cascade impactor, with a constant flow meter operating at 40 cubic feet per minute. These categories are:

C_1 : 7.2 - ∞ μ

C_2 : 3.0 - 7.2 μ

C_3 : 1.5 - 3.0 μ

C_4 : 0.95 - 1.5 μ

C_5 : 0.49 - 0.95 μ

C_6 : < 0.49 μ

The averages in μgm^{-3} , are:

Total	C_1	C_2	C_3	C_4	C_5	C_6
59.81	11.24	15.23	12.13	10.26	5.98	18.71

The minimum value was $10.47 \mu\text{gm}^{-3}$ on 11/11/84. The maximum value was $133.20 \mu\text{gm}^{-3}$ on 1/8/84. The wind direction is given as a sort of twenty - four hour average. It is seen that westerly winds dominate.

These data will have to be analyzed with respect to the prevailing synoptic situation.

Table 1. - Dust Concentration Data at Sede Boquer.

DATE	TOT. S ($\mu\text{gr}/\text{m}^3$)	C1 ($\mu\text{gr}/\text{m}^3$)	C2 ($\mu\text{gr}/\text{m}^3$)	C3 ($\mu\text{gr}/\text{m}^3$)	C4 ($\mu\text{gr}/\text{m}^3$)	C5 ($\mu\text{gr}/\text{m}^3$)	C6 ($\mu\text{gr}/\text{m}^3$)	V (m/sec)	U (dir)
17-06-84	54.98	11.03	12.25	2.93	2.93	5.79	20.05	4.5	N/N
20-06-84	66.08	18.85	24.24	3.19	1.25	4.70	13.84	4.4	N/W
28-06-84	63.88	15.75	18.91	5.49	7.93	10.92	11.54	4.5	N/NH/SH
01-07-84	43.25	5.69	8.21	3.10	2.64	4.94	18.67	4.0	NH/W
02-07-84	72.95	10.00	14.67	5.79	5.59	7.10	29.80	4.3	N/NH/NH/W/E
04-07-84	79.26	17.69	6.35	2.79	5.18	11.77	35.68	4.0	N/NH/W/SE/E
08-07-84	55.33	13.20	14.20	4.53	3.74	6.74	12.93	4.2	NH/W
09-07-84	68.73	18.02	20.88	5.97	4.65	7.34	11.87	4.7	N/NH/W
10-07-84	57.54	15.83	16.25	4.30	3.64	6.33	11.17	4.6	NH
11-07-84	58.34	11.79	14.59	3.57	3.27	5.83	19.29	4.7	NH/SH
12-07-84	43.57	6.45	8.70	3.04	2.25	3.83	19.29	4.4	NH/W/SH
15-07-84	51.36	6.63	7.33	2.44	3.84	5.41	25.71	4.1	NH/SH
16-07-84	57.46	9.65	11.05	2.93	3.91	5.56	24.36	4.1	NH/W
17-07-84	57.30	7.25	10.01	4.26	4.55	4.50	26.73	4.3	N/NH/W/SH/S
18-07-84	60.68	6.70	8.85	2.45	3.09	3.14	36.45	4.5	N/NH/SH
19-07-84	73.17	9.04	14.46	7.01	5.48	7.63	29.55	5.1	NH
22-07-84	80.90	14.38	19.71	5.57	6.16	10.83	24.06	4.7	NH/W
24-07-84	83.64	15.16	24.51	7.64	7.83	10.80	17.69	4.4	NH/W
25-07-84	86.66	17.34	23.04	7.14	6.72	10.08	20.34	4.8	NH/W
26-07-84	77.15	12.78	15.14	5.87	8.18	12.35	22.83	3.9	N/NH/W
29-07-84	70.02	14.50	15.11	5.84	4.98	10.32	19.29	4.5	NH/W
30-07-84	79.59	19.03	21.67	4.64	5.70	9.04	19.50	4.8	NH/W
31-07-84	60.54	13.08	3.60	4.61	15.23	8.85	15.17	4.9	N/NH
01-08-84	133.20	31.83	35.17	9.04	7.07	9.63	10.47	6.6	N
09-08-84	51.67	6.47	13.13	4.44	4.19	7.60	16.52	4.6	N/NH/W
14-08-84	50.46	7.52	16.89	5.46	2.88	4.20	13.51	5.4	N/NH/SH
19-08-84	35.55	7.01	13.36	4.07	2.31	5.16	3.65	4.7	NH/W
21-08-84	42.61	7.15	11.93	3.71	2.97	6.00	10.85	4.2	NH/W
22-08-84	43.84	5.45	12.32	3.95	3.40	7.01	11.71	4.3	NH/W
26-08-84	36.29	3.97	5.85	2.47	2.15	2.93	18.92	3.0	N/NH/VAR
29-08-84	57.54	10.46	12.50	4.15	5.16	8.15	17.12	4.6	NH/W
30-08-84	46.31	3.86	7.11	5.94	6.42	1.24	21.74	4.5	N/W
02-09-84	61.06	12.76	18.21	4.42	3.38	5.93	16.35	4.2	NH/W
03/4-09-84	90.30	14.01	20.59	23.72	4.00	6.44	21.54	4.1	NH/SH
05/6-09-84	73.72	13.53	18.28	3.61	3.07	4.75	30.48	3.8	NH/W
09-09-84	60.31	9.59	9.85	4.03	4.83	7.41	24.60	3.9	NH
17-09-84	74.47	14.42	18.45	5.62	5.82	0.99	29.17	4.2	N/NH
19-09-84	102.96	17.96	23.65	6.89	6.31	7.46	10.69	4.5	NH/W
30-09-84	47.76	11.45	13.14	4.08	2.19	3.54	13.35	4.3	NH/W
01-10-84	57.67	15.68	20.52	5.63	2.74	4.21	8.89	4.6	N/NH
07-10-84	57.16	6.31	19.40	6.83	3.96	3.67	16.99	4.5	NH/SH
08-10-84	50.13	8.62	13.21	4.64	4.08	4.13	15.45	4.7	NH
28-10-84	42.80	9.02	12.84	3.31	2.34	3.71	11.58	3.8	N/NH/W
30-10-84	111.34	18.50	47.93	15.43	7.66	5.07	16.75	4.6	NH/W
31-10-84	42.00	6.21	18.18	6.89	2.71	2.65	5.36	4.0	NH
04-11-84	52.30	8.32	14.83	4.35	4.08	4.85	15.87	4.6	NH/SH
05-11-84	23.57	4.82	7.01	2.08	0.93	2.43	6.30	3.6	NH/W
06-11-84	49.81	9.07	13.58	2.96	2.65	6.98	14.57	3.9	NH/W/SH
11-11-84	10.47	2.26	2.42	1.00	1.16	2.00	1.63	3.2	NH/W
12-11-84	26.08	5.95	7.21	2.34	1.80	3.31	5.47	3.5	N/NH

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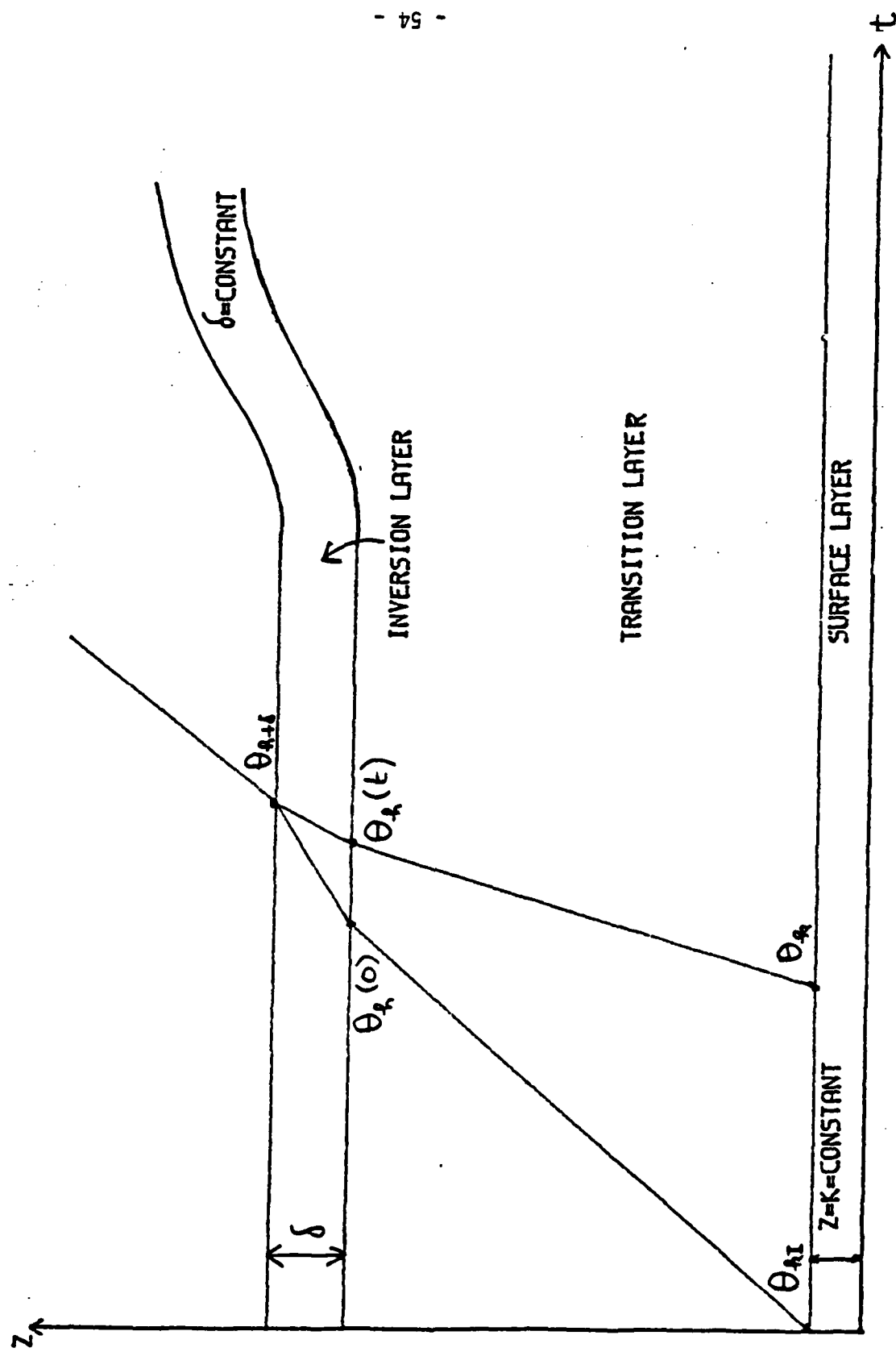


Fig. 1 - Schematic of Planetary Boundary Layer.

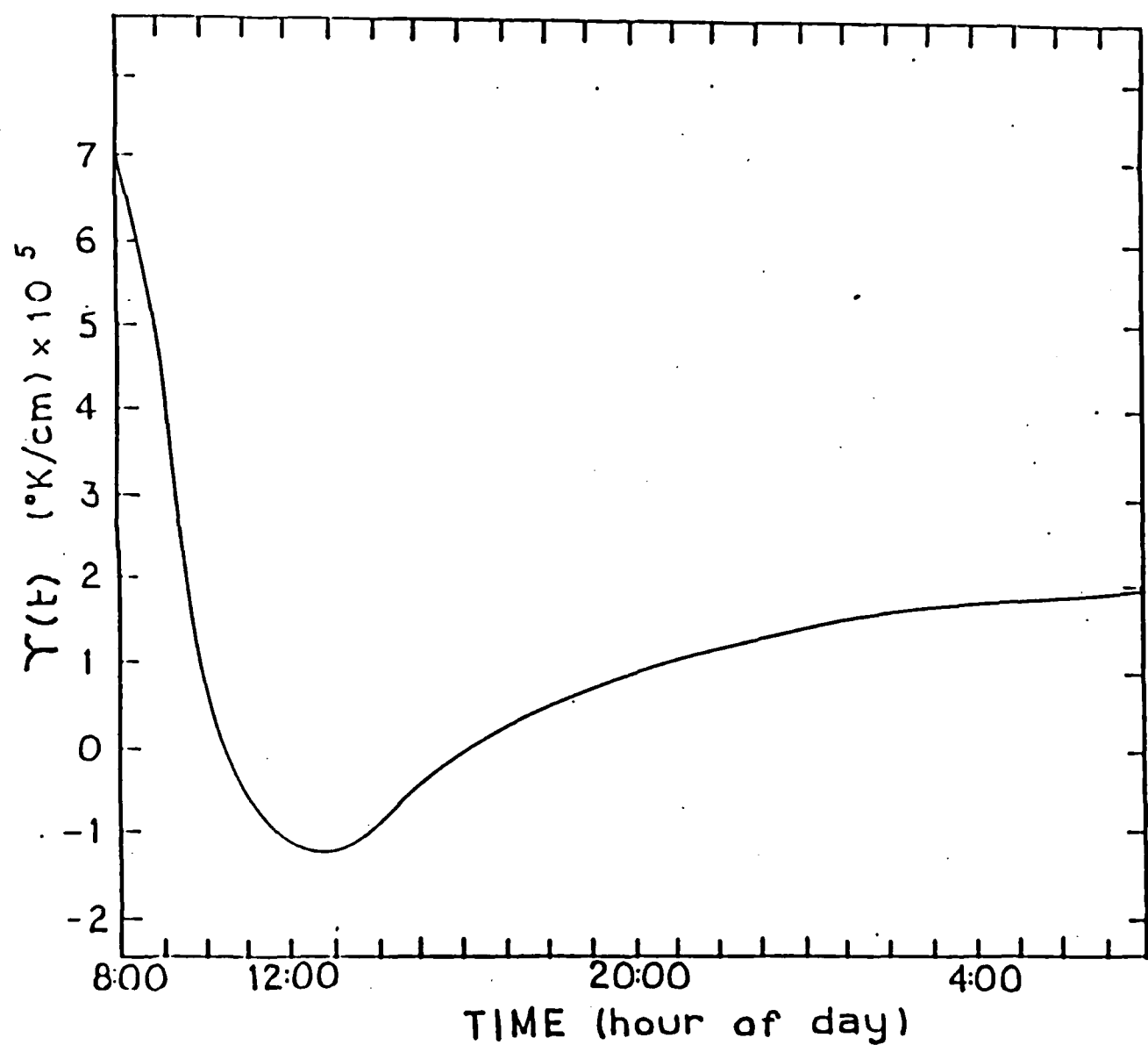


Fig. 2. - The Lapse-Rate $\gamma(t)$.

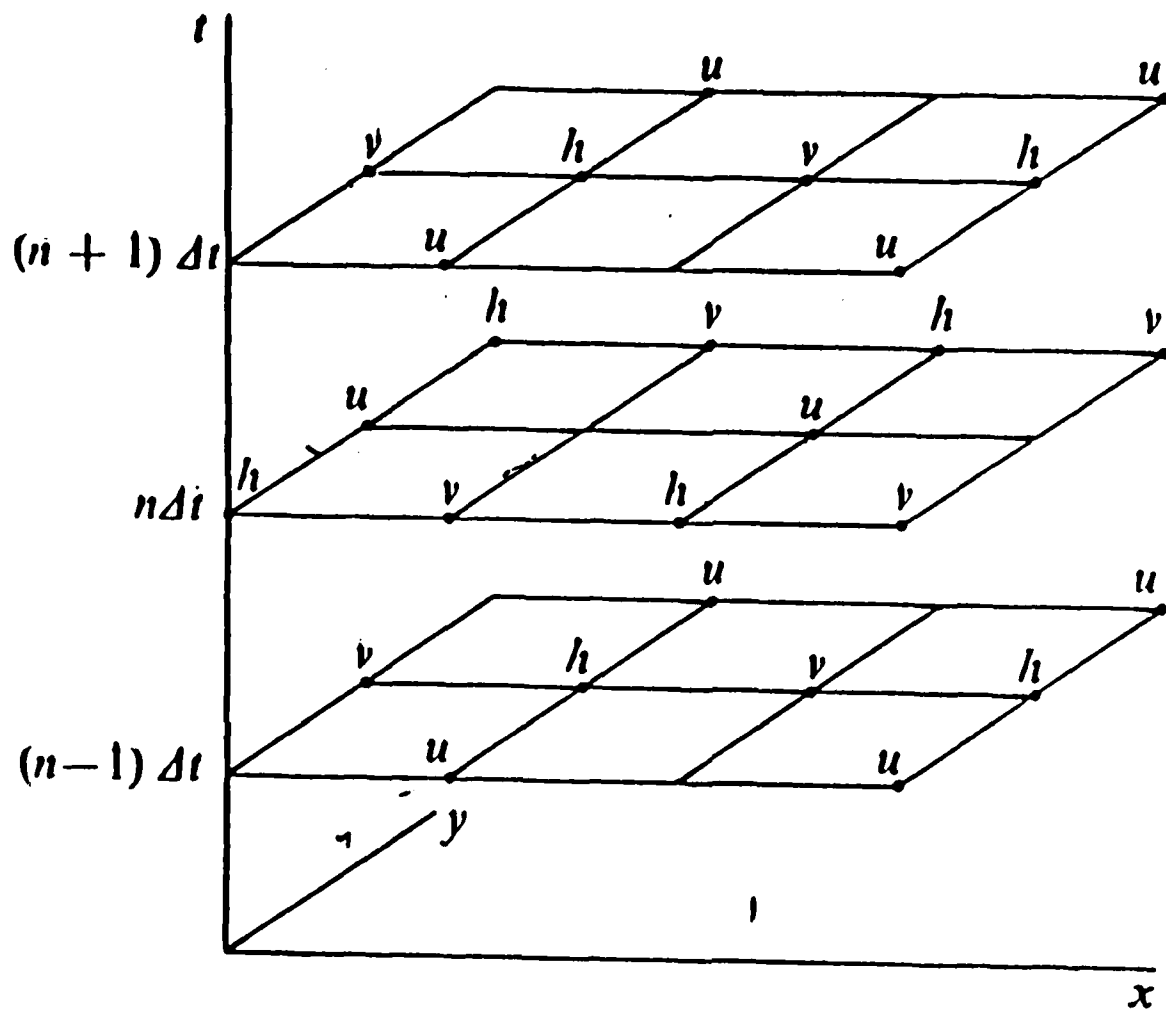


Fig. 3. - Space-time Grid Staggered Both in Space and Time, Convenient for the Leapfrog Scheme Associated with Centered Space Differencing (after Eliassen, 1956).

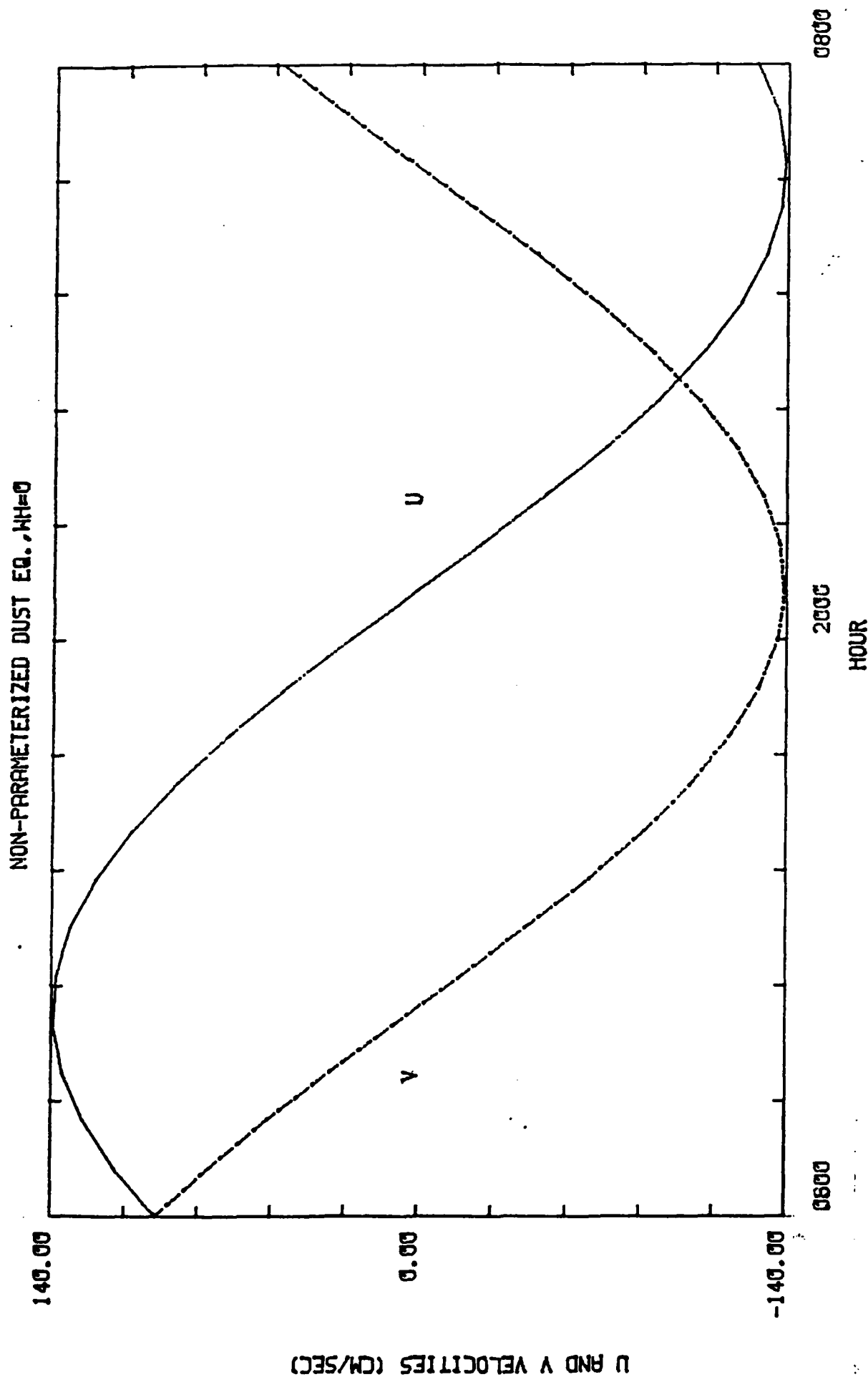


Fig. 4. - Evolution of $\hat{u}$ and $\hat{v}$ from One-Dimensional Non-Parameterized Dust Model, $w_h = 0$.

NON-PARAMETERIZED DUST EQ., $W_H=0$

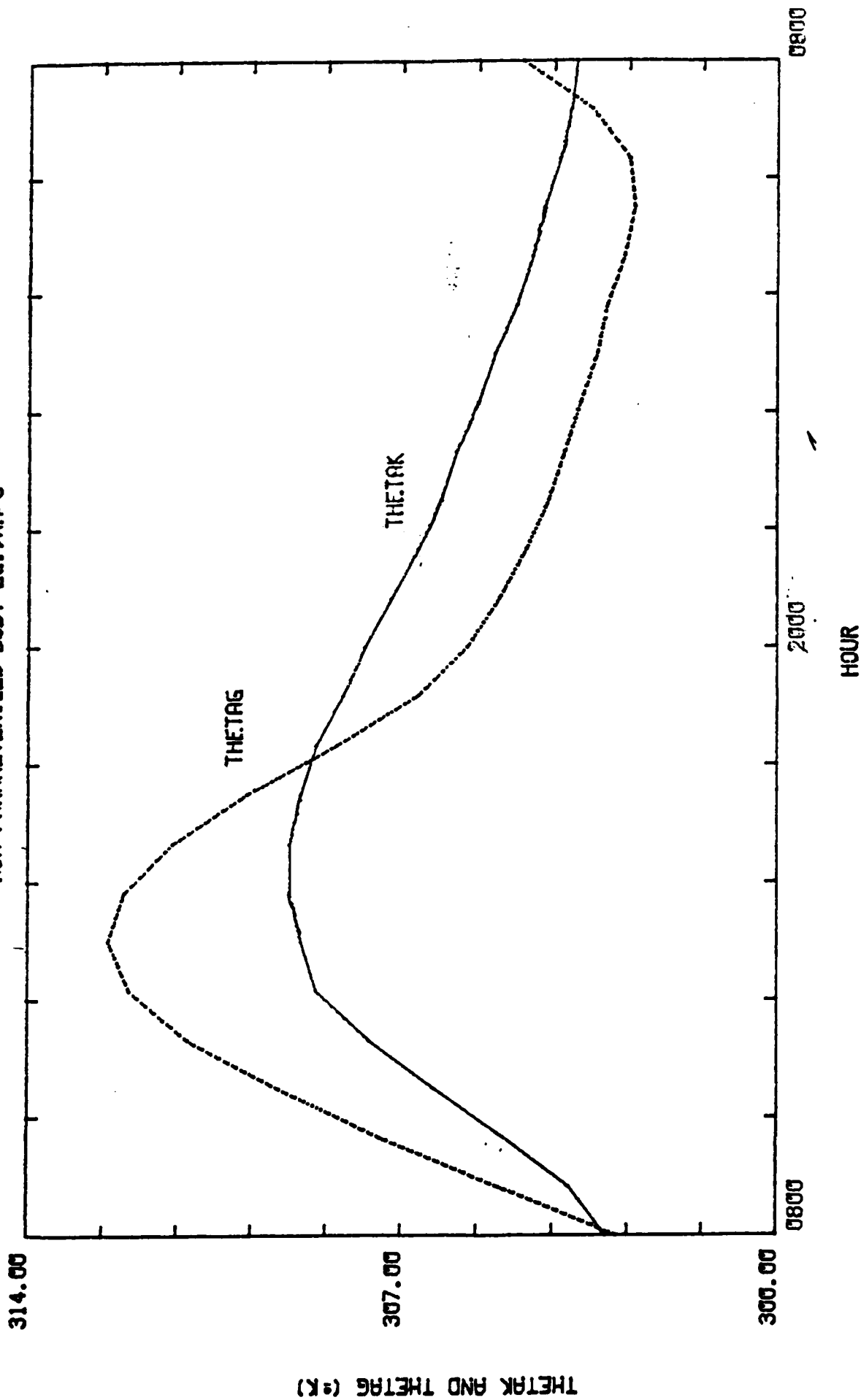


Fig. 5. - Same as Fig. 4 for θ_{Gr} and θ_k .

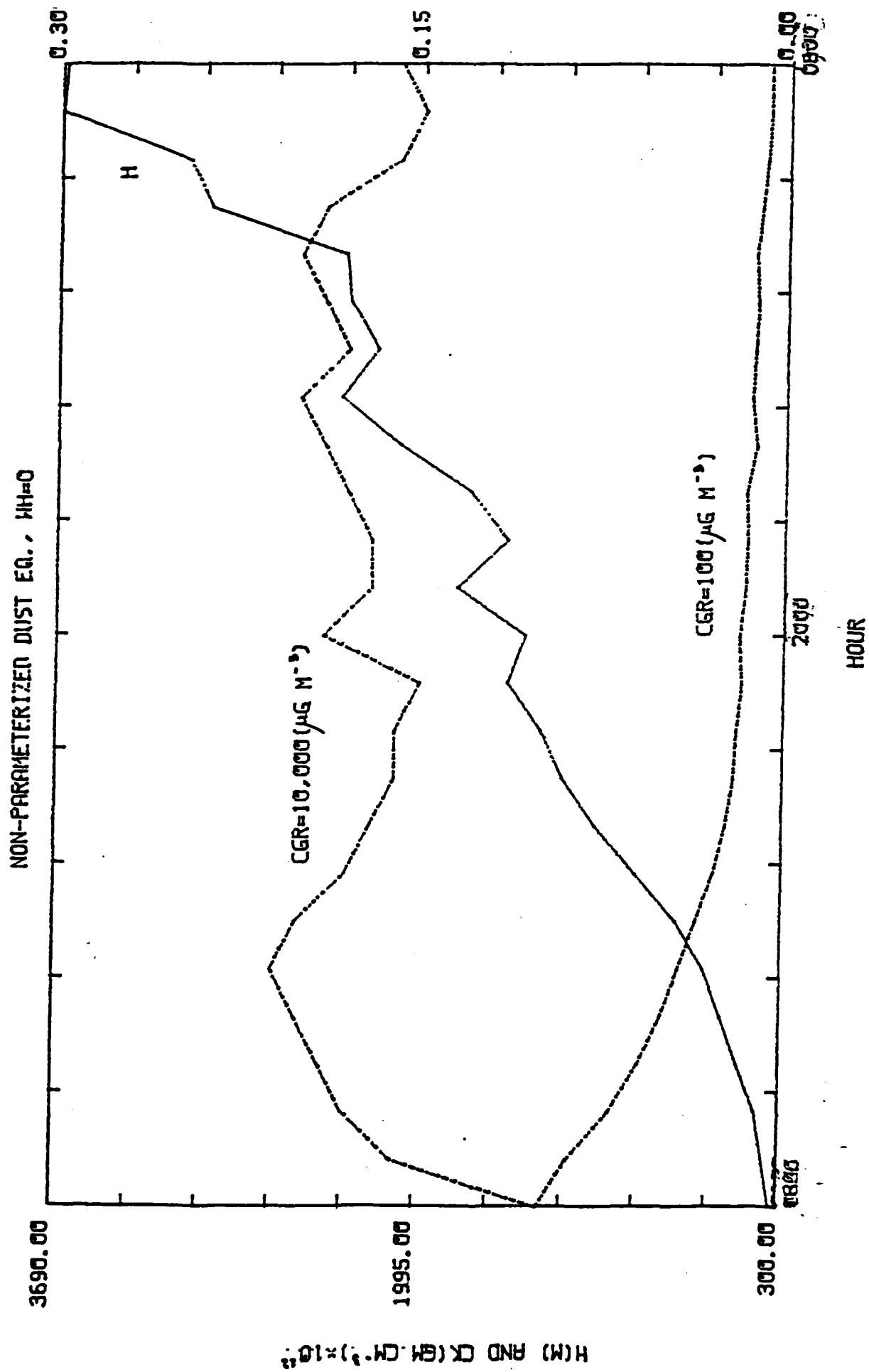


Fig. 6. - Same as Fig. 4 for h , C_k (for $C_{gr} = 100 \mu g m^{-3}$, $10,000 \mu g m^{-3}$).

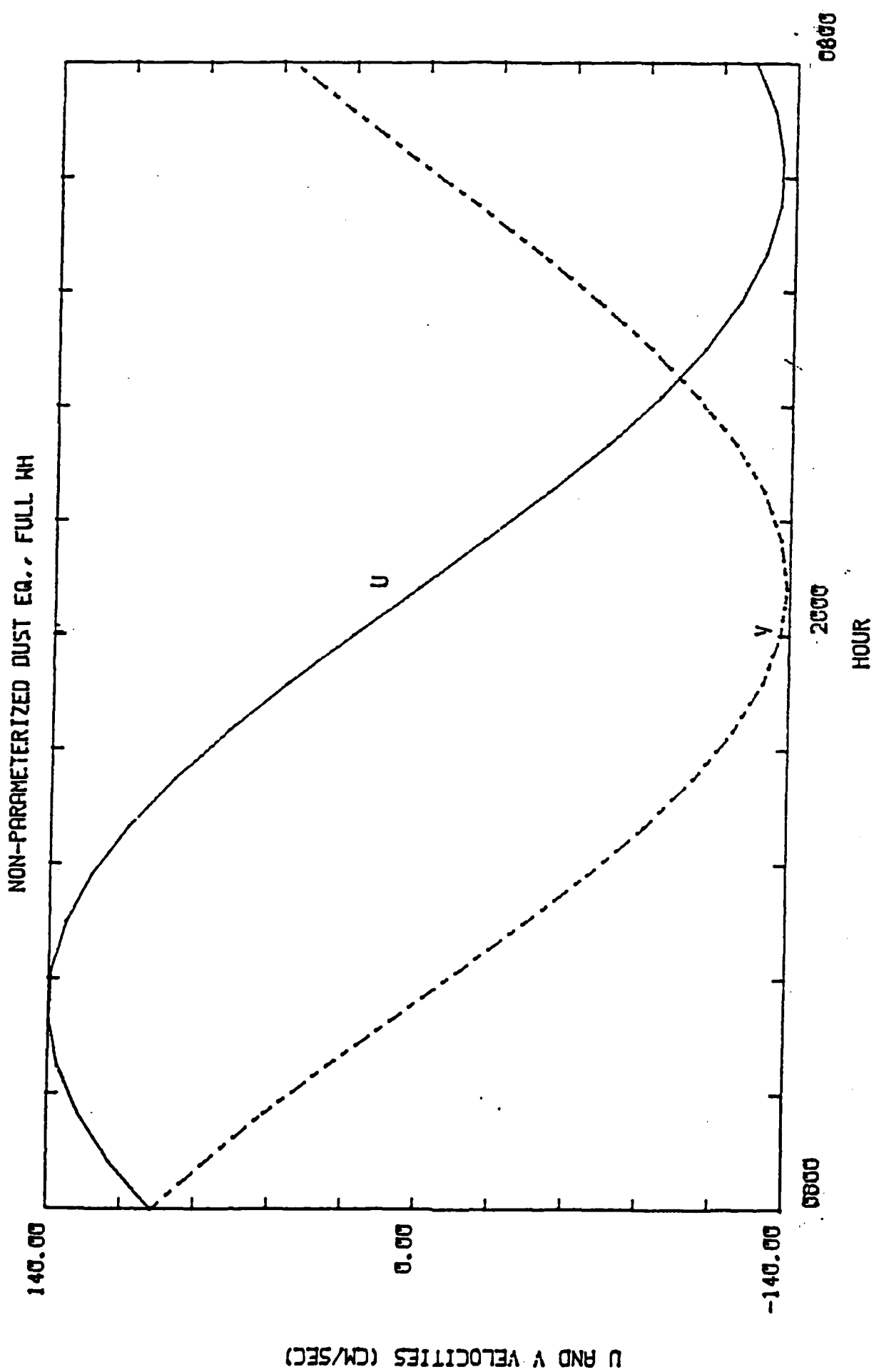


Fig. 7. - Same as Fig. 4 for $\hat{u}$, $\hat{v}$, $w_h \neq 0$.

NON-PARAMETERIZED DUST, FULL MH

314.00

THETAK AND THETAG (°K)

307.00

300.00

THETAG

THETAK

0800

2000
HOUR

0800

Fig. 8. - Same as Fig. 7 for θ_{GR} and θ_k .

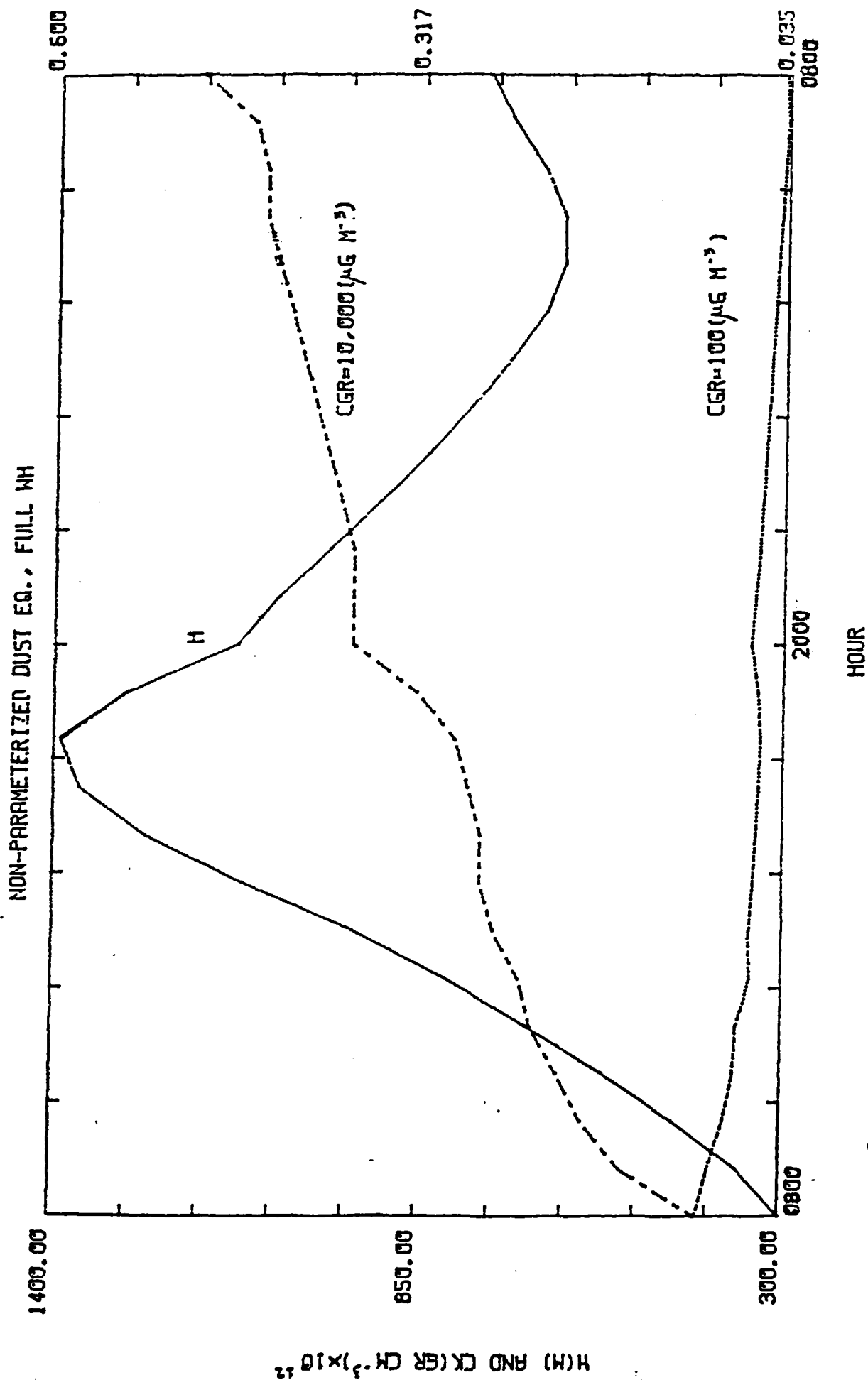


Fig. 9. - Same as Fig. 7 for h , C_k (for $C_{gr} = 100 \mu\text{gm}^{-3}$, $10,000 \mu\text{gm}^{-3}$).

PARAMETERIZED DUST EQ., $W_h = 0$

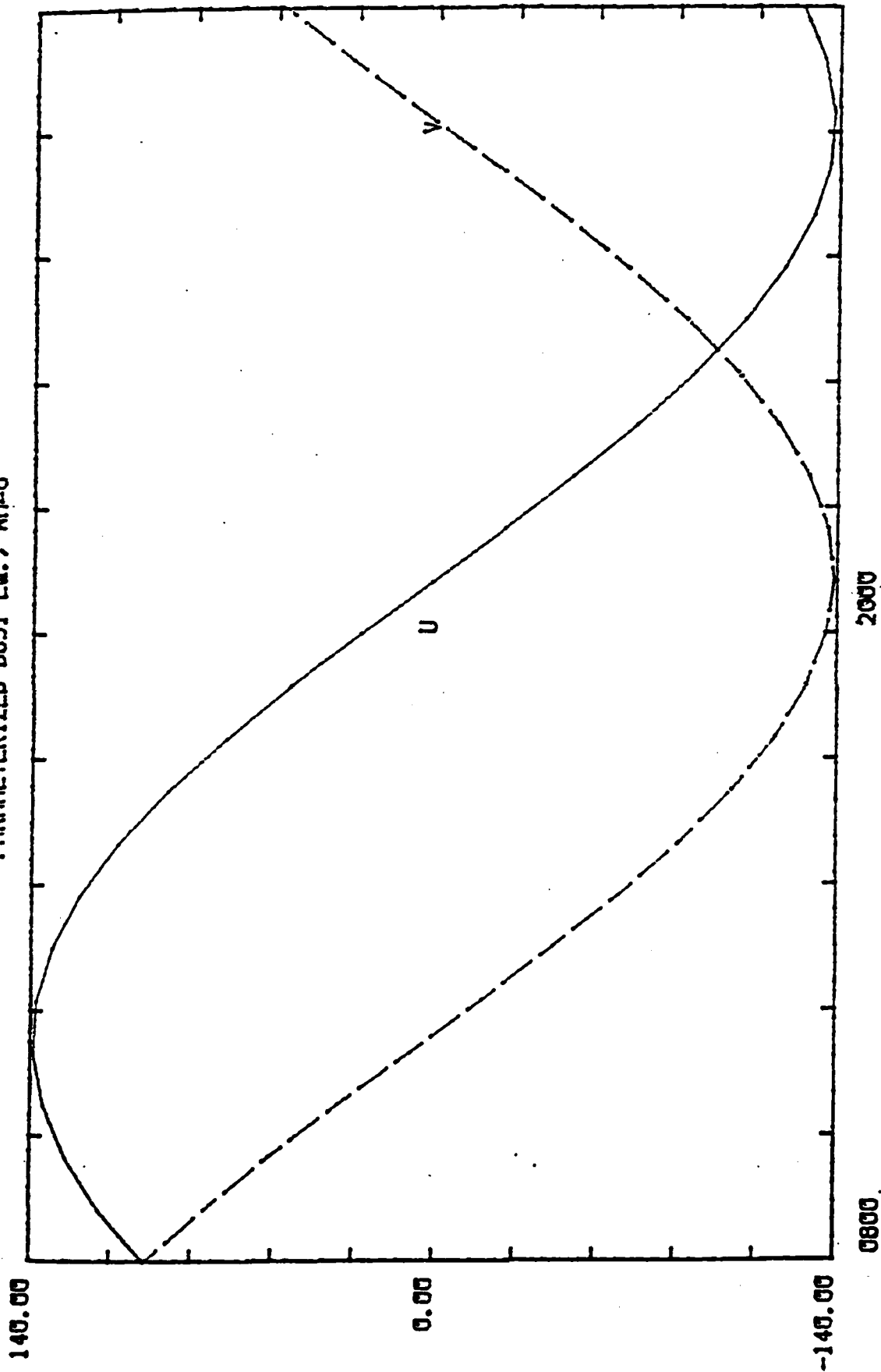


Fig. 10. - Evolution of $\hat{u}$ and $\hat{v}$ from One-Dimensional Parameterized Dust Model, $w_h = 0$.

PARAMETERIZED DUST EQ., $WH=0$

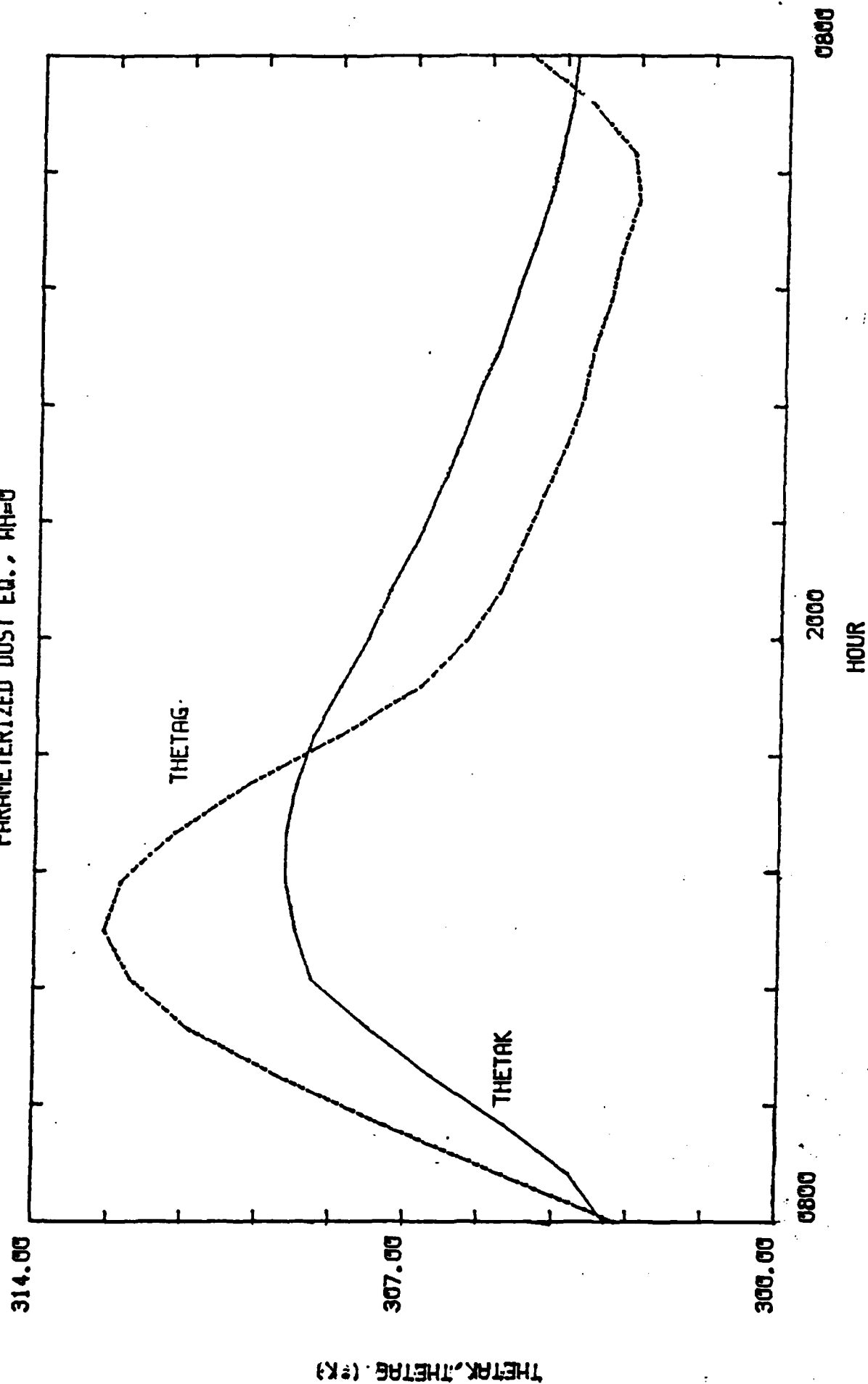


Fig. 11. - Same as Fig. 10 for θ_{GR} and θ_k .

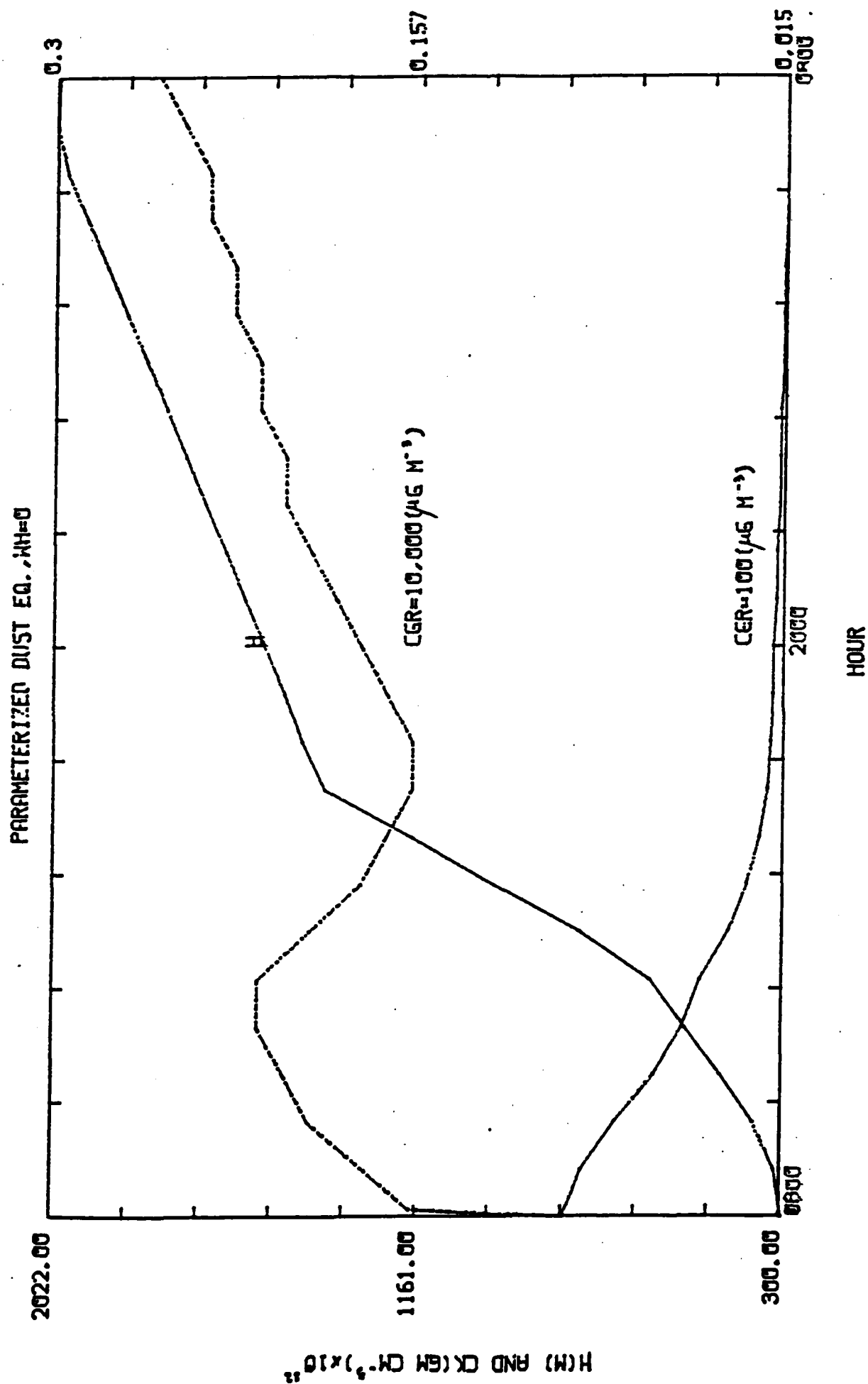


Fig. 12. - Same as Fig. 10 for h , C_k ($C_{GR} = 100 \mu\text{gm}^{-3}$; $10,000 \mu\text{gm}^{-3}$).

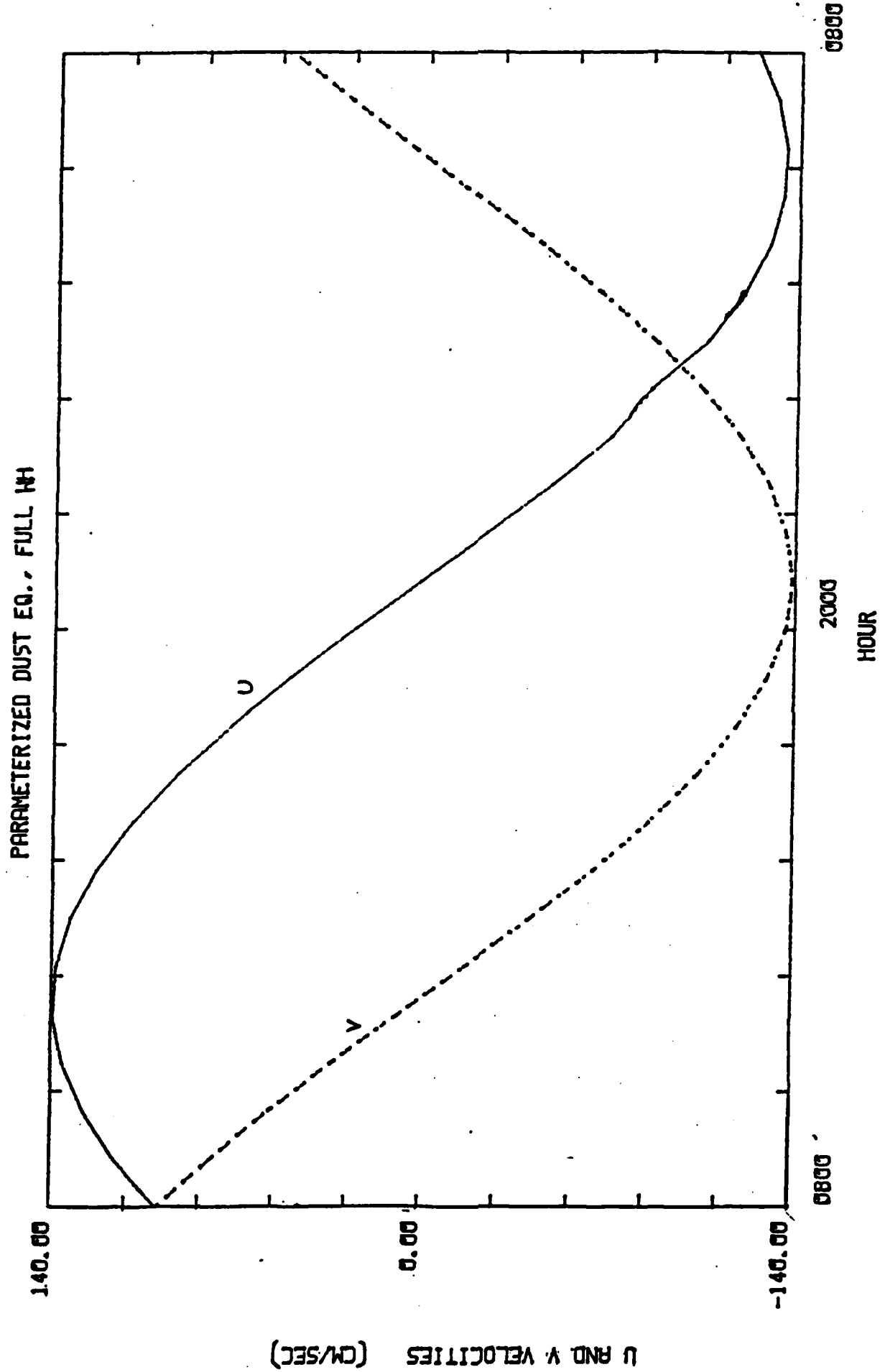


Fig. 13. - Same as Fig. 10 for $\hat{u}$, $\hat{v}$, $w_h \neq 0$.

PARAMETERIZED DUST EQ., FULL MH

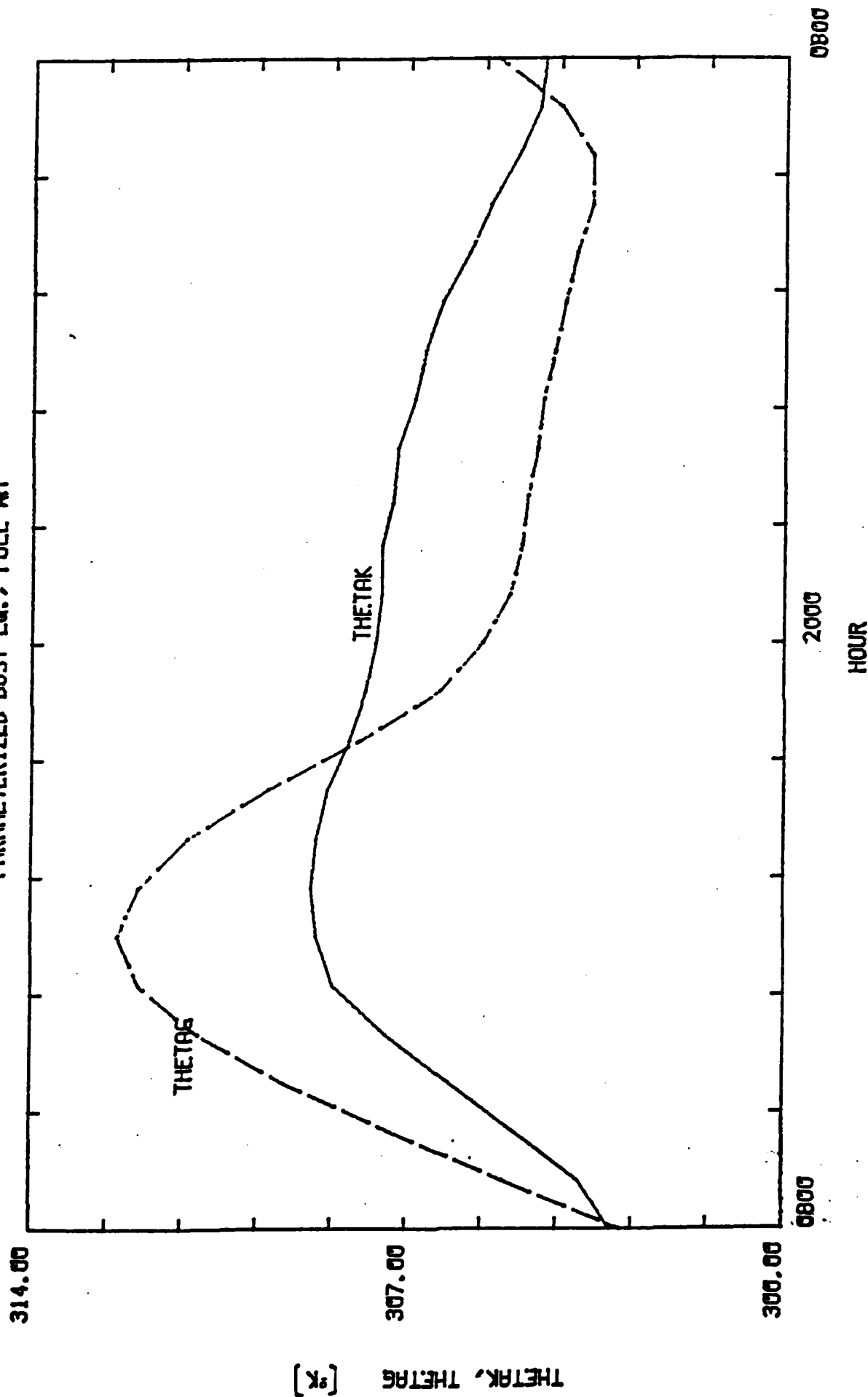


Fig. 14. - Same as Fig. 13 for θ_{GR} and θ_K .

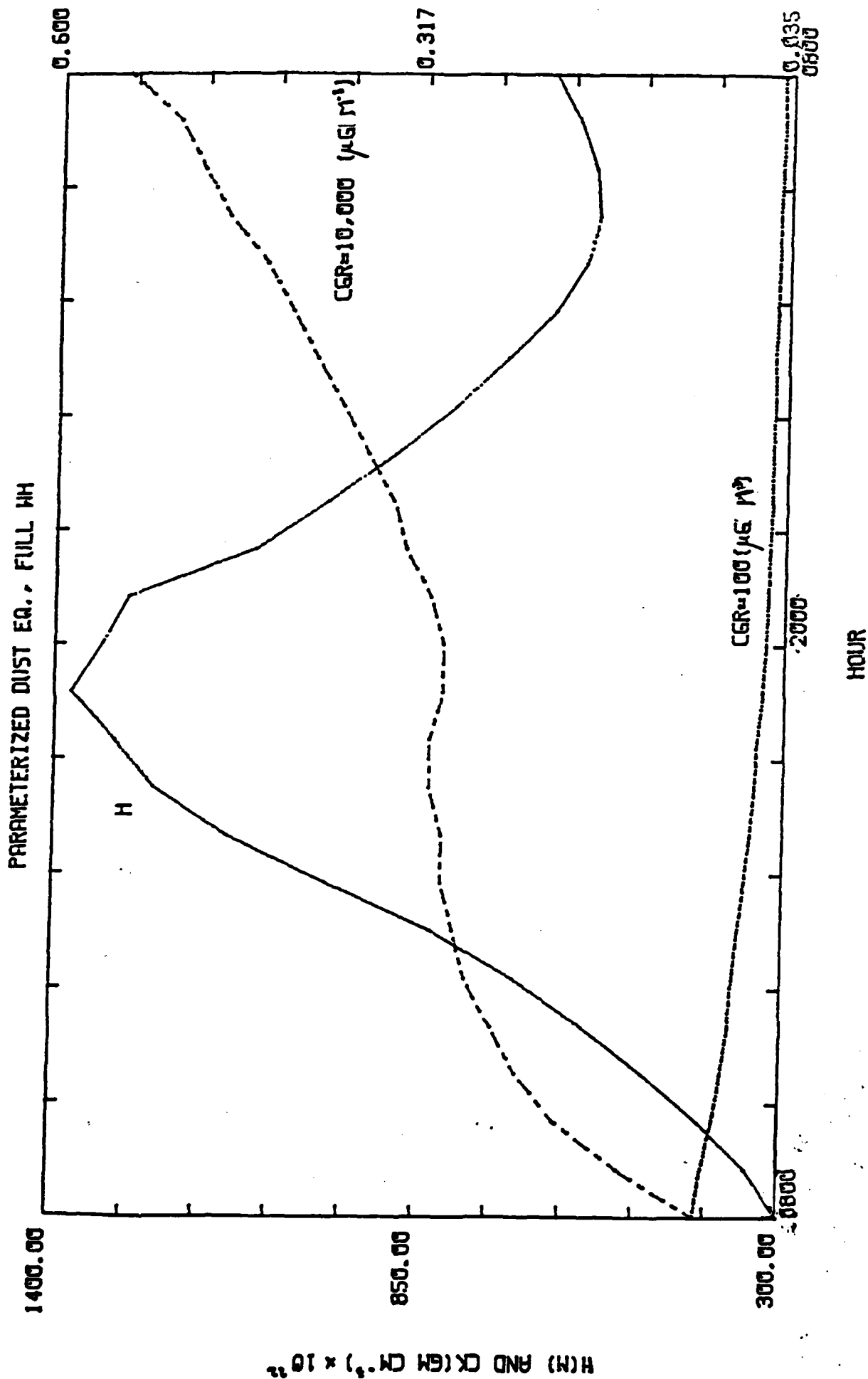


Fig. 15. - Same as Fig. 13 for h , C_k ($C_{GR} = 100 \mu\text{gm}^{-3}$, $10,000 \mu\text{gm}^{-3}$).

VELOCITY	FIELD	IN	CM/SEC	STEP	1-2	3-4	5-6	7-8	9-10	11-12	13-14	15-16	17-18	19-20	21-22	23-24	25-26	27-28	29-30	31-32	33-34	35-36	37-38	39-40	41-42	43-44	45-46	47-48	49-50	51-52	53-54	55-56	57-58	59-60	61-62	63-64	65-66	67-68	69-70	71-72	73-74	75-76	77-78	79-80	81-82	83-84	85-86	87-88	89-90	91-92	93-94	95-96	97-98	99-100	101-102	103-104	105-106	107-108	109-110	111-112	113-114	115-116	117-118	119-120	121-122	123-124	125-126	127-128	129-130	131-132	133-134	135-136	137-138	139-140	141-142	143-144	145-146	147-148	149-150	151-152	153-154	155-156	157-158	159-160	161-162	163-164	165-166	167-168	169-170	171-172	173-174	175-176	177-178	179-180	181-182	183-184	185-186	187-188	189-190	191-192	193-194	195-196	197-198	199-200	201-202	203-204	205-206	207-208	209-210	211-212	213-214	215-216	217-218	219-220	221-222	223-224	225-226	227-228	229-230	231-232	233-234	235-236	237-238	239-240	241-242	243-244	245-246	247-248	249-250	251-252	253-254	255-256	257-258	259-260	261-262	263-264	265-266	267-268	269-270	271-272	273-274	275-276	277-278	279-280	281-282	283-284	285-286	287-288	289-290	291-292	293-294	295-296	297-298	299-300	301-302	303-304	305-306	307-308	309-310	311-312	313-314	315-316	317-318	319-320	321-322	323-324	325-326	327-328	329-330	331-332	333-334	335-336	337-338	339-340	341-342	343-344	345-346	347-348	349-350	351-352	353-354	355-356	357-358	359-360	361-362	363-364	365-366	367-368	369-370	371-372	373-374	375-376	377-378	379-380	381-382	383-384	385-386	387-388	389-390	391-392	393-394	395-396	397-398	399-400	401-402	403-404	405-406	407-408	409-410	411-412	413-414	415-416	417-418	419-420	421-422	423-424	425-426	427-428	429-430	431-432	433-434	435-436	437-438	439-440	441-442	443-444	445-446	447-448	449-450	451-452	453-454	455-456	457-458	459-460	461-462	463-464	465-466	467-468	469-470	471-472	473-474	475-476	477-478	479-480	481-482	483-484	485-486	487-488	489-490	491-492	493-494	495-496	497-498	499-500	501-502	503-504	505-506	507-508	509-510	511-512	513-514	515-516	517-518	519-520	521-522	523-524	525-526	527-528	529-530	531-532	533-534	535-536	537-538	539-540	541-542	543-544	545-546	547-548	549-550	551-552	553-554	555-556	557-558	559-560	561-562	563-564	565-566	567-568	569-570	571-572	573-574	575-576	577-578	579-580	581-582	583-584	585-586	587-588	589-590	591-592	593-594	595-596	597-598	599-600	601-602	603-604	605-606	607-608	609-610	611-612	613-614	615-616	617-618	619-620	621-622	623-624	625-626	627-628	629-630	631-632	633-634	635-636	637-638	639-640	641-642	643-644	645-646	647-648	649-650	651-652	653-654	655-656	657-658	659-660	661-662	663-664	665-666	667-668	669-670	671-672	673-674	675-676	677-678	679-680	681-682	683-684	685-686	687-688	689-690	691-692	693-694	695-696	697-698	699-700	701-702	703-704	705-706	707-708	709-710	711-712	713-714	715-716	717-718	719-720	721-722	723-724	725-726	727-728	729-730	731-732	733-734	735-736	737-738	739-740	741-742	743-744	745-746	747-748	749-750	751-752	753-754	755-756	757-758	759-760	761-762	763-764	765-766	767-768	769-770	771-772	773-774	775-776	777-778	779-780	781-782	783-784	785-786	787-788	789-790	791-792	793-794	795-796	797-798	799-800	801-802	803-804	805-806	807-808	809-810	811-812	813-814	815-816	817-818	819-820	821-822	823-824	825-826	827-828	829-830	831-832	833-834	835-836	837-838	839-840	841-842	843-844	845-846	847-848	849-850	851-852	853-854	855-856	857-858	859-860	861-862	863-864	865-866	867-868	869-870	871-872	873-874	875-876	877-878	879-880	881-882	883-884	885-886	887-888	889-890	891-892	893-894	895-896	897-898	899-900	901-902	903-904	905-906	907-908	909-910	911-912	913-914	915-916	917-918	919-920	921-922	923-924	925-926	927-928	929-930	931-932	933-934	935-936	937-938	939-940	941-942	943-944	945-946	947-948	949-950	951-952	953-954	955-956	957-958	959-960	961-962	963-964	965-966	967-968	969-970	971-972	973-974	975-976	977-978	979-980	981-982	983-984	985-986	987-988	989-990	991-992	993-994	995-996	997-998	999-1000	1001-1002	1003-1004	1005-1006	1007-1008	1009-1010	1011-1012	1013-1014	1015-1016	1017-1018	1019-1020	1021-1022	1023-1024	1025-1026	1027-1028	1029-1030	1031-1032	1033-1034	1035-1036	1037-1038	1039-1040	1041-1042	1043-1044	1045-1046	1047-1048	1049-1050	1051-1052	1053-1054	1055-1056	1057-1058	1059-1060	1061-1062	1063-1064	1065-1066	1067-1068	1069-1070	1071-1072	1073-1074	1075-1076	1077-1078	1079-1080	1081-1082	1083-1084	1085-1086	1087-1088	1089-1090	1091-1092	1093-1094	1095-1096	1097-1098	1099-1100	1101-1102	1103-1104	1105-1106	1107-1108	1109-1110	1111-1112	1113-1114	1115-1116	1117-1118	1119-1120	1121-1122	1123-1124	1125-1126	1127-1128	1129-1130	1131-1132	1133-1134	1135-1136	1137-1138	1139-1140	1141-1142	1143-1144	1145-1146	1147-1148	1149-1150	1151-1152	1153-1154	1155-1156	1157-1158	1159-1160	1161-1162	1163-1164	1165-1166	1167-1168	1169-1170	1171-1172	1173-1174	1175-1176	1177-1178	1179-1180	1181-1182	1183-1184	1185-1186	1187-1188	1189-1190	1191-1192	1193-1194	1195-1196	1197-1198	1199-1200	1201-1202	1203-1204	1205-1206	1207-1208	1209-1210	1211-1212	1213-1214	1215-1216	1217-1218	1219-1220	1221-1222	1223-1224	1225-1226	1227-1228	1229-1230	1231-1232	1233-1234	1235-1236	1237-1238	1239-1240	1241-1242	1243-1244	1245-1246	1247-1248	1249-1250	1251-1252	1253-1254	1255-1256	1257-1258	1259-1260	1261-1262	1263-1264	1265-1266	1267-1268	1269-1270	1271-1272	1273-1274	1275-1276	1277-1278	1279-1280	1281-1282	1283-1284	1285-1286	1287-1288	1289-1290	1291-1292	1293-1294	1295-1296	1297-1298	1299-1300	1301-1302	1303-1304	1305-1306	1307-1308	1309-1310	1311-1312	1313-1314	1315-1316	1317-1318	1319-1320	1321-1322	1323-1324	1325-1326	1327-1328	1329-1330	1331-1332	1333-1334	1335-1336	1337-1338	1339-1340	1341-1342	1343-1344	1345-1346	1347-1348	1349-1350	1351-1352	1353-1354	1355-1356	1357-1358	1359-1360	1361-1362	1363-1364	1365-1366	1367-1368	1369-1370	1371-1372	1373-1374	1375-1376	1377-1378	1379-1380	1381-1382	1383-1384	1385-1386	1387-1388	1389-1390	1391-1392	1393-1394	1395-1396	1397-1398	1399-1400	1401-1402	1403-1404	1405-1406	1407-1408	1409-1410	1411-1412	1413-1414	1415-1416	1417-1418	1419-1420	1421-1422	1423-1424	1425-1426	1427-1428	1429-1430	1431-1432	1433-1434	1435-1436	1437-1438	1439-1440	1441-1442	1443-1444	1445-1446	1447-1448	1449-1450	1451-1452	1453-1454	1455-1456	1457-1458	1459-1460	1461-1462	1463-1464	1465-1466	1467-1468	1469-1470	1471-1472	1473-1474	1475-1476	1477-1478	1479-1480	1481-1482	1483-1484	1485-1486	1487-1488	1489-1490	1491-1492	1493-1494	1495-1496	1497-1498	1499-1500	1501-1502	1503-1504	1505-1506	1507-1508	1509-1510	1511-1512	1513-1514	1515-1516	1517-1518	1519-1520	1521-1522	1523-1524	1525-1526	1527-1528	1529-1530	1531-1532	1533-1534	1535-1536	1537-1538	1539-1540	1541-1542	1543-1544	1545-1546	1547-1548	1549-1550	1551-1552	1553-1554	1555-1556	1557-1558	1559-1560	1561-1562	1563-1564	1565-1566	1567-1568	1569-1570	1571-1572	1573-1574	1575-1576	1577-1578	1579-1580	1581-1582	1583-1584	1585-1586	1587-1588	1589-1590	1591-1592	1593-1594	1595-1596	1597-1598	1599-1600	1601-1602	1603-1604	1605-1606	1607-1608	1609-1610	1611-1612	1613-1614	1615-1616	1617-1618	1619-1620	1621-1622	1623-1624	1625-1626	1627-1628	1629-1630	1631-1632	1633-1634	1635-1636	1637-1638	1639-1640	1641-1642	1643-1644	1645-1646	1647-1648	1649-1650	1651-1652	1653-1654	1655-1656	1657-1658	1659-1660	1661-1662	1663-1664	1665-1666	1667-1668	1669-1670	1671-1672	1673-1674	1675-1676	1677-1678	1679-1680	1681-1682	1683-1684	1685-1686	1687-1688	1689-1690	1691-1692	1693-1694	1695-1696	1697-1698	1699-1700	1701-1702	1703-1704	1705-1706	1707-1708	1709-1710	1711-1712	1713-1714	1715-1716	1717-1718	1719-1720	1721-1722	1723-1724	1725-1726	1727-1728	1729-1730	1731-1732	1733-1734	1735-1736	1737-1738	1739-1740	1741-1742	1743-1744	1745-1746	1747-1748	1749-1750	1751-1752	1753-1754	1755-1756	1757-1758	1759-1760	1761-1762	1763-1764	1765-1766	1767-1768	1769-1770	1771-1772	1773-1774	1775-1776	1777-1778	1779-1780	1781-1782	1783-1784	1785-1786	1787-1788	1789-1790	1791-1792	1793-1794	1795-1796	1797-1798	1799-1800	1801-1802	1803-1804	1805-1806	1807-1808	1809-1810	1811-1812	1813-1814	1815-1816	1817-1818	1819-1820	1821-1822	1823-1824	1825-1826	1827-1828	1829-1830	1831-1832	1833-1834	1835-1836	1837-1838	1839-1840	1841-1842	1843-1844	1845-1846	1847-1848	1849-1850	1851-1852	1853-1854	1855-1856	1857-1858	1859-1860	1861-1862	1863-1864	1865-1866	1867-1868	1869-1870	1871-1872	1873-1874	1875-1876	1877-1878	1879-1880	1881-1882	1883-1884	1885-1886	1887-1888	1889-1890	1891-1892	1893-1894	1895-1896	1897-1898	1899-1900	1901-1902	1903-1904	1905-1906	1907-1908	1909-1910	1911-1912	1913-1914	1915-1916	1917-1918
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V VELOCITY -FIELD IN *1 CM/SEC STEP 130																	
I:	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17
	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17
01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
02	0	-40	-41	-41	-41	-41	-41	-41	-41	-41	-41	-41	-41	-41	-41	-41	-41
03	0	-75	-75	-75	-75	-75	-75	-75	-75	-75	-75	-75	-75	-75	-75	-75	-75
04	0	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77
05	0	-75	-75	-75	-75	-75	-75	-75	-75	-75	-75	-75	-75	-75	-75	-75	-75
06	0	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77
07	0	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77
08	0	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77
09	0	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77
10	0	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77
11	0	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77
12	0	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77
13	0	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77
14	0	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77
15	0	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77
16	0	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77
17	0	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77

Fig. 18. - $\hat{v}$ field at 180 minutes, constant B.C.

V VELOCITY -FIELD IN *1 CM/SEC STEP 180																	
I:	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17
01	-17	-32	-37	-41	-41	-41	-41	-41	-41	-41	-41	-41	-41	-41	-41	-41	-41
02	-75	-75	-75	-75	-75	-75	-75	-75	-75	-75	-75	-75	-75	-75	-75	-75	-75
03	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79
04	-79	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77	-77
05	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79
06	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79
07	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79
08	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79
09	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79
10	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79
11	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79
12	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79
13	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79
14	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79
15	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79
16	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79
17	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79	-79

Fig. 19. - $\hat{v}$ field at 180 minutes, radiation B.C.

INVERSION HEIGHT - FEET				IN METERS													
I:	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17
J:	31	30	29	28	27	26	25	24	23	22	21	20	19	18			
01	650	650	650	650	650	650	650	650	650	650	650	650	650	650	650	650	650
02	650	702	610	650	650	650	650	650	650	650	650	650	650	650	650	650	650
03	650	704	710	650	650	650	650	650	650	650	650	650	650	650	650	650	650
04	650	698	714	710	650	650	650	650	650	650	650	650	650	650	650	650	650
05	650	650	717	710	650	650	650	650	650	650	650	650	650	650	650	650	650
06	650	701	717	710	650	650	650	650	650	650	650	650	650	650	650	650	650
07	650	704	721	710	650	650	650	650	650	650	650	650	650	650	650	650	650
08	650	670	687	701	650	650	650	650	650	650	650	650	650	650	650	650	650
09	650	650	650	650	650	650	650	650	650	650	650	650	650	650	650	650	650

Fig. 20. - Inversion height at 180 minutes, constant B.C.

INVERSION HEIGHT - FEET		IN METERS																
I:	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	
J:	31	30	29	28	27	26	25	24	23	22	21	20	19	18				
01	711	737	657	650	650	747	631	644	714	640	733	739	739	653	753	660	660	
02	714	713	710	710	710	710	710	710	710	710	710	710	710	710	710	710	710	
03	653	717	713	710	710	710	710	710	710	710	710	710	710	710	710	710	710	
04	704	717	718	710	710	710	710	710	710	710	710	710	710	710	710	710	710	
05	705	717	710	710	710	710	710	710	710	710	710	710	710	710	710	710	710	
06	677	710	710	710	710	710	710	710	710	710	710	710	710	710	710	710	710	
07	519	713	713	710	710	710	710	710	710	710	710	710	710	710	710	710	710	
08	755	717	719	710	710	710	710	710	710	710	710	710	710	710	710	710	710	
09	715	710	710	710	710	710	710	710	710	710	710	710	710	710	710	710	710	

Fig. 21. - Inversion height at 180 minutes, radiation B.C.

TABLE AT K - 1000			
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Fig. 22. - θ_k at 180 minutes, constant B.C.

[illegible]

Fig. 23. - θ_k at 180 minutes, radiation B.C. .

IN-1A AT	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17
01	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303
02	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303
03	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303
04	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303
05	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303
06	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303
07	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303
08	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303
09	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303
10	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303
11	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303
12	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303
13	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303
14	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303
15	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303
16	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303
17	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303	303

Fig. 24. - θ_{CR} at 180 minutes, constant B.C.

IN-1A AT	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17
01	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311
02	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311
03	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311
04	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311
05	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311
06	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311
07	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311
08	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311
09	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311
10	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311
11	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311
12	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311
13	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311
14	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311
15	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311
16	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311
17	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311	311

Fig. 25. - θ_{CR} at 180 minutes, radiation B.C.

DUST CONC	-FIELD IN *10 US/M3				STEP 180												
01	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17
01	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
02	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
03	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
04	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
05	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
06	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
07	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
08	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
09	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10

Fig. 26. - C_k at 180 minutes, constant B.C.

DUST CONC	-FIELD IN *10 US/M3				STEP 180												
01	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17
01	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
02	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
03	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
04	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
05	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
06	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
07	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
08	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
09	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10

Fig. 27. - C_k at 180 minutes, radiation B.C.

W AT H	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17
I:	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17
01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
03	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
04	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
05	97139	97797	שדות על	פנטון בע"מ	0	0	0	0	0	0	0	0	0	0	0	0	0
53	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
54	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
55	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
56	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Fig. 28. - W_h at 180 minutes, constant B.C.

W AT H	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17
I:	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17
01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
04	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
05	97139	97797	שדות על	פנטון בע"מ	0	0	0	0	0	0	0	0	0	0	0	0	0
58	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
59	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
60	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
61	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Fig. 29. - W_h at 180 minutes, radiation B.C.

END

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