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A SIMPLIFIED MODEL OF THE TURBULENT MICROBURST

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A SIMPLIFIED MODEL OF THE TURBULENT MICROBURST

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ABSTRACT

This report develops a simple model to describe the low altitude shear associated with a microburst (or small downburst) in the atmosphere. Such microbursts are thought to be the cause of convective radial flows near the ground which represent potentially hazardous conditions to aircraft during take-off and during approach and landing. Closed form solutions are presented for the equations of mass, momentum and thermal energy to give the spreading rate of the microburst and the velocity and temperature decay due to turbulence. An analysis of the impact of the microburst and its radial spreading over the ground is given and illustrative examples are provided. The solution for the downward and outward wind velocities are given in terms of simple dimensionless algebraic parameters which can be computed readily in realtime during a piloted simulation of an aircraft flying through a microburst.

ACKNOWLEDGEMENTS

This work was supported by NASA Ames Research Center under NASA Cooperative Agreement NCC 2-270. Mr. Richard S. Bray of NASA was particularly helpful in providing background information on the subject studied in the Report.

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a, b, c	constants of Gaussian profiles
x	vertical distance (downward) from source of downburst
y	radial distance
z, h	vertical distance from ground
h_o	altitude of origin of microburst
u, -w	vertical velocity (downward)
u_1	downward vertical velocity at altitude h_1 on axis of microburst
v_1	radial velocity of reference distance y_1 from center, at $h = o$
v	radial velocity
g	gravitational acceleration, 32 ft/sec
$\varepsilon_u, \varepsilon_\theta, \varepsilon_w$	diffusivity coefficients
m, n, p	velocity exponents
T	temperature
D_u	microburst diameter for velocity
D_θ	microburst diameter for temperature
D_1	$D_u(x_1)$
θ	temperature ratio $\frac{T_\infty - T}{T_\infty}$
E	$\frac{u_1^2}{\theta_1 g x_1}$, dimensionless energy ratio
Q	$\frac{\theta_1 g D_1}{u_1^2} \cdot \frac{D_1}{h_1} \cdot \frac{3b}{8 \log 2}$
ξ	y/x
ζ	h/y, z/y
$f(\xi)$	vertical velocity profile
$h(\xi)$	temperature profile
$k(\xi)$	radial velocity profile

LIST OF FIGURES

I. Introduction

This paper presents a simple model to describe the low altitude shear associated with a microburst (or small downburst) of lower temperature air in the atmosphere. Such microbursts are thought to be the cause of convective radial flows near the ground which represent potentially hazardous conditions to aircraft during takeoff and during approach and landing.

A typical microburst has been described[1] as having high downward velocities, perhaps up to a maximum of 60-70 ft/sec, over a region of 1,000 to 10,000 feet diameter, and lasting many minutes in duration. The microburst impinges on the ground and spreads radially, causing local horizontal wind velocities comparable to those in the downward flow, and is accompanied by intense shear profiles near the ground. An aircraft flying through such a phenomena would experience initially a headwind, and subsequently a tailwind as it passed through the microburst.

During the past several years a number of attempts have been made to describe the velocity and temperature fields associated with downburst phenomena. The most simple of these[2] is a correlation of observed velocity profiles which provides a semiempirical, easily calculated, algebraic expression that is suitable for use in flight simulation. A physically more realistic model[3], also suitable for use in flight simulation, takes account of some of the fluid dynamics of the flow by representing the microburst by a distribution of singularities (sources, vortices and doublets) but does not take into account the temperature field and its associated buoyancy effects, nor the effect of turbulent diffusion. More elaborate models[4,5,6] take into account those effects but require substantial computational time to provide numerical results and are generally not suitable for real-time simulation.

The work presented here is an attempt to develop a model which is suitable for use with real time flight simulators, permitting adjustment of parametric constraints to fit observed measurements while retaining the essential physical aspects of buoyancy and turbulent diffusion.

2. Analysis

The approach used in the present analysis assumes that the microburst is a steady axially symmetric downward flow issuing from a point (ie, a virtual origin) in the atmosphere at distance h_o above the ground. It is acted upon by turbulent diffusion and by buoyancy associated with a temperature difference $(T_\infty - T_o)$ between the center of the downflow and the ambient atmosphere. In the close vicinity of the ground the flow is turned in a radial direction and forms a ground jet. No account is taken of the effects of ground roughness in the present analysis (ie, a smooth ground is assumed). Figures 1-3 show the general schematic for the flow and the geometry of the downflow and subsequent radial outflow near the ground.

2.1 The Downflow

The differential equations for conservation of mass, momentum and thermal energy in the presence of gravity are written for an incompressible fluid, as

$$\frac{\partial}{\partial x}(uy) + \frac{\partial}{\partial y}(vy) = 0 \tag{1}$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} - \theta g = \frac{1}{y}\frac{\partial}{\partial y}\left(\varepsilon_u y\frac{\partial u}{\partial y}\right) \tag{2}$$

and

$$\frac{u\partial\theta}{\partial x} + v\frac{\partial\theta}{\partial y} = \frac{1}{y}\frac{\partial}{\partial y}\left(\varepsilon_\theta y\frac{\partial\theta}{\partial y}\right) \tag{3}$$

where ε_u and ε_θ are eddy diffusivities associated with the velocity and thermal fields.

In the foregoing equations temperature and density changes are assumed to be small so that

$$1 - \frac{\rho_\infty}{\rho} = 1 - \frac{T}{T_\infty} = \theta \text{ (small)} \tag{4}$$

The integral forms of equations (2) may be found by integration radially across the flow, ie,

$$\int_0^\infty \left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} - g\theta \right) y dy = \left[\varepsilon_u y \frac{\partial u}{\partial y} \right]_0^\infty = 0 \tag{5}$$

since the right hand side vanishes at both limits.

The second term in equation (5) may be written, using equation (1), as

$$\int_0^\infty v\frac{\partial u}{\partial y} y dy = \int_0^\infty u\frac{\partial}{\partial x}(yu) dy$$

so that equation (5) becomes

$$\frac{d}{dx}\int_0^\infty u^2 y dy - \int_0^\infty g\theta y dy = 0 \tag{6}$$

Equation (6) is the integral form of the downward momentum equation and describes the rate of increase of downward momentum that results from the (negative) buoyancy of the colder air within the downflow.

Similarly, the integral form of equation (3) may be found as

$$\int_0^\infty \left(u\frac{\partial \theta}{\partial x} + v\frac{\partial \theta}{\partial y} \right) y\partial y = \left[\varepsilon_\theta y \frac{\partial \theta}{\partial y} \right]_0^\infty = 0 \tag{7}$$

or, using equation (1),

$$\int_0^\infty v\frac{\partial \theta}{\partial y} y dy = \int_0^\infty \theta\frac{\partial}{\partial x}(uy) dy$$

equation (7) becomes:

$$\int_o^\infty u\theta y dy = \text{constant} \tag{8}$$

Equation (8) is the integral form of the equation of thermal convection in the absence of thermal sources.

It is assumed that the downburst originates in a localized region of the atmosphere which can be approximated as a virtual point source so that all quantities depend on a similarity variable. More specifically solutions are considered of the form

$$u = u_1 \left(\frac{x}{x_1}\right)^n f(\varsigma), \qquad \theta = \theta_1 \left(\frac{x}{x_1}\right)^n h(\varsigma) \tag{9}$$

where $\varsigma = y/x$, and u_1 and θ_1 are reference values of u and θ at the point $x = x_1$ measured downward along the axis from a virtual origin $x = o$ located at an altitude h_o.

Substitution of these expressions into equations (6) and (8) gives

$$u_1^2 \left[\int_o^\infty f^2(\varsigma)\varsigma d\varsigma\right] \frac{d}{dx}\left(\frac{x}{x_1}\right)^{2m+2} - C\ g\left[\int_o^\infty h(\varsigma)\varsigma d\varsigma\right]\left(\frac{x}{x_1}\right)^{n+2} = 0 \tag{10}$$

and

$$u_1\theta_1 \left[\int_o^\infty f(\varsigma)h(\varsigma)\varsigma d\varsigma\right]\left(\frac{x}{x_1}\right)^{m+n+2} = \text{constant} \tag{11}$$

Equations (10) and (11) yield for the exponents m and n

$$2m + 1 = n + 2$$

and

$$m + n + 2 = 0$$

giving

$$m = \frac{1}{3}$$

and

$$n = -\frac{5}{3} \tag{12}$$

Substitution of these values into equation (10) gives a relation between u, θ, and x_1 ie

$$E = \frac{u_1^2}{\theta g x_1} = \frac{3}{4} \frac{\int_o^\infty h(\varsigma)\varsigma d\varsigma}{\int_o^\infty f^2(\varsigma)\varsigma d\varsigma} \tag{13}$$

It is well known that for turbulent jet flows the profiles $f(\varsigma)$ and $h(\varsigma)$ are Gaussian in character, ie they can be approximated by

$$\left. \begin{aligned} f(\varsigma) &= e^{-a\varsigma^2} \\ h(\varsigma) &= e^{-b\varsigma^2} \end{aligned} \right\} \tag{14}$$

where a and b are constants.

Substitution of these profiles into equation (13) gives a relation between a and b, ie

$$a = \frac{3}{2E} b \tag{15}$$

(The constant b is known from experimental results to be of the order of 100) Equation (15) indicates that the velocity profile is influenced by the thermal conditions through the parameter E.

The constants a and b also established the relationship between the half width of the microburst (where the velocity is equal to half the value at the center of the jet.)

Thus, setting

$$e^{-a\zeta^2} = \frac{1}{2}$$

gives

$$\zeta = \left(\frac{\log 2}{a}\right)^{\frac{1}{2}}$$

and the diameter of the microburst (within which the velocity exceeds one half of the value at the center) is

$$D_u(x) = 2\zeta \quad x = \left(\frac{4\log 2}{a}\right)^{\frac{1}{2}} x$$

or

$$D_u(x) = \left(\frac{8\log 2}{3}\frac{E}{b}\right)^{\frac{1}{2}} x \tag{16a}$$

Similarly, the thermal diameter of the microburst is

$$D_\theta(x) = \left(\frac{4\log 2}{b}\right)^{\frac{1}{2}} x \tag{16b}$$

To summarize, the solution for the downflow in the microburst can be written in terms of reference values u_1 and θ_1 occurring at a location x_1

The velocity and temperature distributions are given by

$$\frac{u}{u_1} = \left(\frac{x}{x_1}\right)^{-\frac{1}{3}} \exp\left[-\frac{3b}{2E}\left(\frac{y}{x}\right)^2\right] \tag{17a}$$

and

$$\frac{\theta}{\theta_1} = \left(\frac{x}{x_1}\right)^{-\frac{5}{3}} \exp\left[-b\left(\frac{y}{x}\right)^2\right] \tag{17b}$$

where

$$E = \frac{u_1^2}{gx_1}\frac{T_\infty}{T_\infty - T_1} \tag{18}$$

These equations are readily calculated in real-time to give the downward velocity profile and the temperature profile at an altitude $h = h_o - x$ when u_1, θ_1 and $h_1 = h_o - x$ are known or assumed.

2.2 The Outflow

For the radial outflow along the ground the equations for conservation of mass and momentum are written

$$\frac{\partial}{\partial z}(wy) + \frac{\partial}{\partial y}(vy) = 0 \tag{19}$$

$$w\frac{\partial v}{\partial z} + v\frac{\partial v}{\partial z} = \frac{\partial}{\partial y}\left(\epsilon_w y\frac{\partial v}{\partial z}\right) \tag{20}$$

where w is the velocity normal to the ground in the z direction and v is again the radial velocity in the y-direction; ϵ_w is an eddy diffusivity for this flow (thus z and x are related by $z = h_o - x$, and $w = -u$).

For the radial flow along the ground the effect of buoyancy if neglected and the thermal energy equation is not used.

The integral form of equation (20) is found by integrating in the z direction.

$$\int_o^\infty \left(w\frac{\partial v}{\partial z} + v\frac{\partial v}{\partial y}\right) dz = \left[\epsilon_w y\frac{\partial v}{\partial z}\right]_o^\infty = 0$$

or, through the use of equation (19)

$$\frac{d}{dy}\left[\int_o^\infty v^2 y dz\right] = 0$$

ie

$$\int_o^{\infty} v^2 y dz = \text{constant} \tag{21}$$

At large distances from the origin a self - similar solution applies of the form

$$v = v_1 (y/y)^p \, k(\xi) \tag{22}$$

where $\xi = z/y$

Substitution into equation (21) gives

$$\left(\frac{y}{y_1}\right)^{2p+2} \left[\int_o^{\infty} k^2(\xi) d\xi \right] = \text{constant}$$

Thus $p = -1$ and

$$v = v_1 \left(\frac{y}{y_1}\right)^{-1} k(\xi)$$

Since, in this analysis, a smooth ground plane is assumed the flow corresponds to that of radial free jet which conserves radial momentum. Again it is assumed that the velocity profile $k(\xi)$ has the form

$$k(\xi) = \exp\left(-c\xi^2\right)$$

where c is experimentally determined and is of the order 100. The half width of this radial jet is

$$\bar{\xi} = \left(\frac{\log 2}{c}\right)^{\frac{1}{2}}$$

and the velocity profile at large radial distances is

$$v = v_1 \left(\frac{y}{y_1}\right)^{-1} \exp\left[-c(z/y)^2\right] \tag{23}$$

where y_1 and v_1 are reference values to be determined.

2.3 The Stagnation Region

In the stagnation region the velocity in the downward flow impinges on the ground and is turned radially outward. This outward flow reaches a peak velocity and then subsequently decays due to turbulent diffusion. The properties of the downward and of the radial outflow are related through conservation of mass and momentum in the stagnation region. For simplicity, it is assumed that the radial outflow along the ground ($z = o$, or $x = h_o$) has the form:

$$\left.\begin{aligned} v &= v_1 \frac{y}{y_1} \qquad \text{for} \quad y < y_1 \\ v &= v_1 \left(\frac{y}{y_1}\right)^{-1} \qquad \text{for} \quad y > y \end{aligned}\right\} \tag{24}$$

and that the pressure difference $p - p_\infty$ has the form

$$p - p_\infty = \frac{1}{2}\rho_\infty(v_1^2 - v^2) \qquad \text{for} \quad y < y_1$$
$$p - p_\infty = 0 \qquad \text{for} \quad y > y_1$$

Equating the momentum change of the downflow with the overpressure on the ground then gives a relation between v_1 and y_1 as follows

$$\left[\int_o^\infty u^2 y\,dy\right]_{z=c} = \int_o^{y_1} \frac{1}{2}(v_1^2 - v^2)y\,dy \tag{25}$$

and substitution for u from equation (17a) and v from (24) gives

$$u_1^2 h_o^2 \left(\frac{h_o - h_1}{h_o}\right)^{\frac{2}{3}} \int_o^\infty e^{-2a\varsigma^2} \varsigma d\varsigma = \frac{1}{8} v_1^2 y_1^2$$

ie

$$\frac{u_1}{v_1} = \frac{y_1}{h_o}\left(\frac{a}{2}\right)^{\frac{1}{2}}\left(1 - \frac{h_1}{h_o}\right)^{-\frac{1}{3}} \tag{26}$$

Similarly equating the mass of the downflow at $x = h_o$ with that of the radial flow at $y = y_1$ gives

$$\left[\int_o^\infty u\ y\ dy\right]_{z=o} = \left[\int_o^\infty vydz\right]_{y=y_1} \tag{27}$$

and substitution for u from equation (17a), and v from (23) gives

$$u_1 h_o^2 \left(1 - \frac{h_1}{h_o}\right)^{\frac{1}{3}} \int_o^\infty e^{-a\varsigma^2} \varsigma d\varsigma = v_1 y_1^2 \int_o^\infty e^{-C\xi^2} d\xi$$

ie

$$\frac{u_1}{v_1} = \left(\frac{y_1}{h_o}\right)^2 a \left(\frac{\pi}{c}\right)^{\frac{1}{2}}\left(1 - \frac{h_1}{h_o}\right)^{-\frac{1}{3}} \tag{28}$$

Equations (26) and (28) than give

$$\frac{y_1}{h_o} = \left(\frac{c}{2\pi a}\right)^{\frac{1}{2}}, \qquad \frac{v_1}{u_1} = \left(\frac{4\pi}{c}\right)^{\frac{1}{4}}\left(1 - \frac{h_1}{h_o}\right)^{\frac{1}{3}} \tag{29}$$

Finally, it is convenient to express these quantities in terms of references quantitie at the height h_1, and to eliminate the virtual origin h_o. This may be done by using the relation

$$\frac{D_1}{x_1} = \left(\frac{8\log 2}{3b}\cdot E\right)^{\frac{1}{2}} \qquad \text{from (16a.)}$$

and

$$\frac{h_o}{h_1} = 1 + \frac{x_1}{h_1}$$

Thus

$$E = \frac{u_1^2}{\theta_1 g x_1} = \frac{u_1^2}{\theta_1 g D_1}\frac{D_1}{x} = \frac{u_1^2}{\theta_1 g D_1}\left(\frac{8\log 2}{3b}E\right)^{\frac{1}{2}}$$

ie

$$E^{\frac{1}{2}} = \frac{u_1^2}{\theta_1 g D_1}\left(\frac{8\log 2}{3b}\right)^{\frac{1}{2}} \tag{30}$$

and

$$\left.\begin{aligned} \frac{h_o}{h_1} &= 1 + \frac{D_1}{h_1}\frac{x_1}{D_1} \\ &= 1 + \frac{\theta_1 g D_1}{u_1^2}\frac{D_1}{h_1}\cdot\frac{3b}{8\log 2} \\ &= 1 + Q \end{aligned}\right\} \tag{31}$$

The expressions in equation (29) can now be written:

$$\frac{y_1}{D_1} = \frac{y_1}{h_o}\frac{h_o}{h_1}\frac{h_1}{D_1} = \left(\frac{c}{2\pi a}\right)^{\frac{1}{2}}(1+Q)\frac{h_1}{D_1}$$

and using $\left(\frac{1}{a}\right)^{\frac{1}{2}} = \left(\frac{2E}{3b}\right)^{\frac{1}{2}}$, this becomes

$$\frac{y_1}{D_1} = \left(\frac{c}{8\pi \log 2}\right)^{\frac{1}{2}} \cdot \frac{1+Q}{Q} \tag{32}$$

Also, from (29)

$$\frac{v_1}{u_1} = \left(\frac{4\pi}{c}\right)^{\frac{1}{2}} \left(\frac{Q}{1+Q}\right)^{\frac{1}{2}} \tag{33}$$

where

$$Q = \frac{3b}{8 \log 2} \cdot \frac{D_1}{h_1} \cdot \frac{\theta_1 g D_1}{u_1^2}$$

In the foregoing expressions b and c are known constants and θ_1, D_1, u_1 and h_1 are parameters which describe the microburst at the height h_1.

3. Discussion and Illustrative Example

(a) At Altitude

At an altitude h_1 at a large distance from the ground, the velocity along the axis of the microburst is u_1 and the velocity profile, ie its variation with y, is given by equation (17a):

$$\begin{aligned} u &= u_1 \exp \frac{-3b}{2E} \left(\frac{y}{x_1}\right)^2 \\ &= u_1 \exp \left[-4 \log 2 \left(\frac{y}{D_1}\right)^2\right] \end{aligned} \tag{34}$$

At any altitude h, the velocity is given by

$$\frac{u}{u_1} = \left(\frac{x_1}{x}\right)^{\frac{1}{2}} \exp \left[-4 \log 2 \left(\frac{y}{D_1}\right)^2 \left(\frac{x_1}{x}\right)^2\right]$$

where

$$\frac{x_1}{x} = \frac{h_o/h_1 - 1}{h_o/h_1 - h/h_1} = \frac{Q}{Q + 1 - h/h_1}$$

Thus

$$\frac{u}{u_1} = \left(\frac{Q}{Q+1-h/h_1}\right)^{\frac{1}{2}} \exp\left[-4\log 2\left(\frac{Q}{Q+1-h/h_1}\right)^2\left(\frac{y}{D_1}\right)^2\right] \tag{35}$$

For example, with $b = 100, \theta_1 = 10^{-2}, D_1 = 10^3$ ft, $g = 32$ ft/sec^2, $u_1 = 50$ ft/sec, $h_1 = 10,000$ ft then $Q = 7$. For $h = 5,000$ ft substitution into (35) gives

$$\frac{u}{u_1} = .84 \exp\left[.94\left(\frac{y}{D_1}\right)^2\right]$$

The velocity at the center of the microburst decays rather slowly (ie a reduction of about 16% at $h = 5,000$ ft. from its value at 10,000 ft) and a spreading of the profile radially.

An aircraft flying through this velocity profile would experience a downdraft and a consequent reduction of lift since the effective angle of attack would be reduced by $\Delta\alpha \approx \frac{u_1}{V_{\text{aircraft}}}$. For a microburst of small dimensions (ie approaching the span of the aircraft) the aircraft would experience a rolling moment proportional to $\frac{u_1}{V_{\text{aircraft}}} \times \frac{\text{span}}{D_1}$ where D_1 is the diameter of the downburst, in addition to a reduction in lift. Rolling would be in the direction toward the center of the downburst.

(b) Near the ground

At a distance h above the ground the radial velocity is given by

$$\frac{v}{u_1} = \frac{4\pi}{c}(2\log 2)^{\frac{1}{2}}\left(\frac{Q}{1+Q}\right)^{4/3} \cdot \frac{y}{D_1}\exp\left[-c\,\frac{(h/D_1)^2}{(y/D_1)^2}\right] \tag{36a}$$

for

$$\frac{y}{d_1} \leq \left(\frac{c}{8\pi \log 2}\right)^{\frac{1}{2}} \frac{1+Q}{Q}$$

and

$$\frac{v}{u_1} = (2\log 2)^{-\frac{1}{2}} \left(\frac{Q}{1+Q}\right)^{-\frac{1}{2}} \left(\frac{y}{D_1}\right)^{-1} \exp\left[-c\frac{(h/D_1)^2}{(y/D_1)^2}\right]$$

for

$$\frac{y}{D_1} \geq \left(\frac{c}{8\pi \log 2}\right)^{\frac{1}{2}} \frac{1+Q}{Q} \tag{36b}$$

For example for an aircraft on a path passing through the center of the microburst using the same numerical values as in the previous example but with h = 1,000 ft., and c = 50 equations (36a and b) give

$$\frac{v}{u_1} = .09\frac{y}{D_1} \exp\left[-50/\left(\frac{y}{D_1}\right)^2\right]$$

for

$$\frac{y}{D_1} \leq 4.11$$

and

$$\frac{v}{u_1} = 1.53\left(\frac{y}{D_1}\right)^{-1} \exp\left[-50/\left(\frac{y}{D_1}\right)^2\right]$$

for

$$\frac{y}{D_1} > 4.11$$

This velocity profile, shows a rapid decay with altitude above the ground (compared with the limiting case $h = o$). Thus, in this example, the largest effect of the radial outflow is felt at altitudes very close to the ground (ie much less than 1,000 ft). An aircraft descending toward a landing would experience an increase in headwind if moving toward the center of the microburst followed by a decreasing headwind close to the center and, after crossing the center, an increasing tailwind and an eventual decrease in tailwind.

4. Concluding Remarks

The microburst model described in this paper provides very simple closed form expressions for the velocity in the microburst at altitude and in the vicinity of the ground. Two constants of the velocity profiles associated with turbulent diffusion may be chosen to fit experimental data if these are available, or used to change the magnitude of velocity gradients in the microburst at altitude and near the ground.

The model, however, does not account for the presence of thermal sources which may add energy to the microburst and therefore it may underestimate the magnitude of the velocity within the microburst as it approaches the ground. For the purpose of generating velocity profiles for flight simulation this deficiency in the model can be offset by increasing the effective initial velocity on the axis of the microburst. However, an improved model, taking into account thermal sources, is desirable in order to provide a more realistic representation of the physical phenomena.

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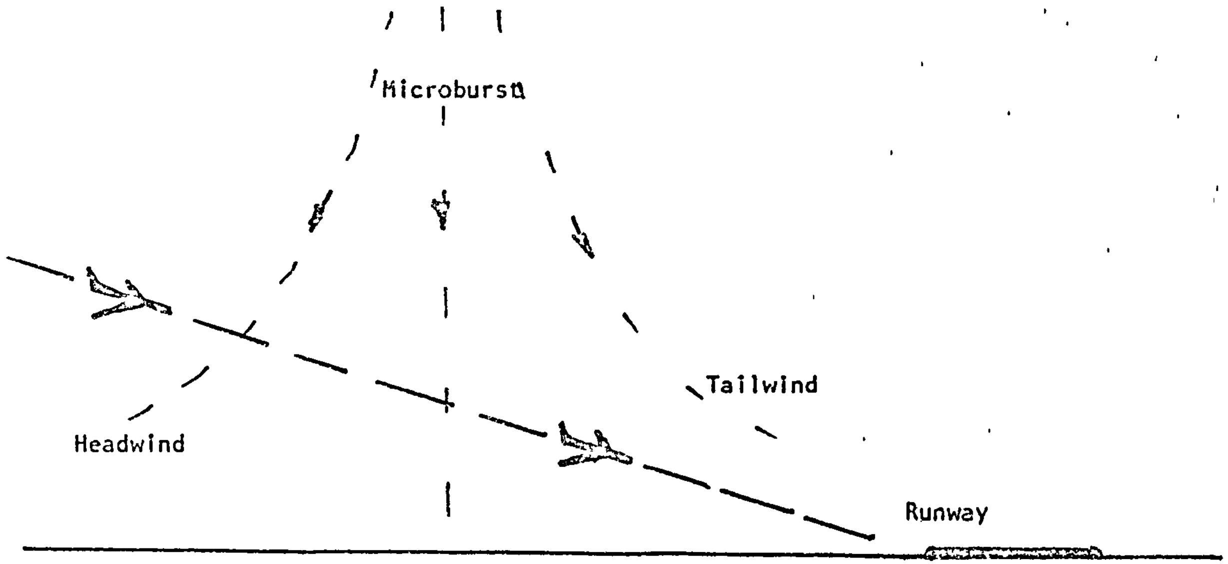

Fig. 1 Schematic diagram of microburst

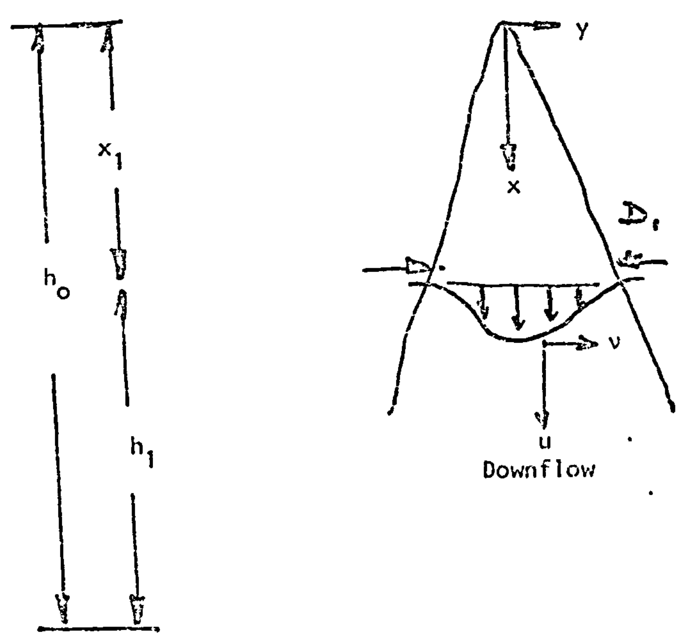

Fig. 2 Microburst flowfield at altitude

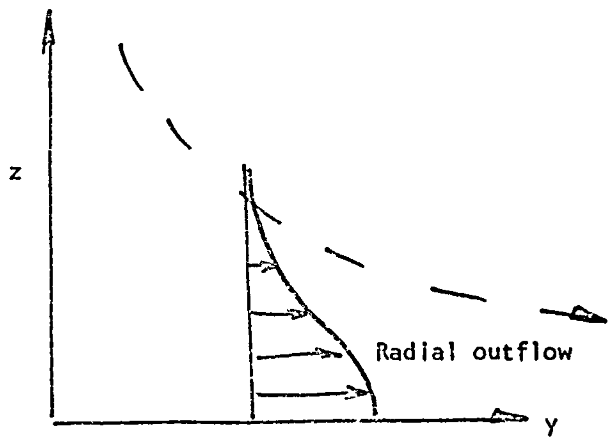

Fig. 3   Microburst outflow near ground

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