Fair Weather Convection and Light Aircraft, Helicopter, and Glider Accidents

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A study of Australian Bureau of Air Safety Investigation accident reports for the period 1983–1985 indicates that fair weather convective wind gusts may be a factor in up to 10% of all accidents of light aircraft and helicopters. (Moist convective gusts and wind shear may contribute to a further 10% of all accidents.) Data from the same period indicate that dry convective gusts may be a factor in up to 24% of glider accidents. (Wind shear may contribute to a further 6% of glider accidents.) The role of dry convective gusts is examined by modeling downdrafts and horizontal and vertical wind-speed variances, using known statistical relationships for the atmospheric boundary layer. For typical convective conditions, the model shows that 1 out of 25 downdraft occurrences could produce a variation in lift of about ±30% for landing light aircraft and could cause loss of directional control for helicopters. The information presently available at airports does not adequately warn pilots of this hazard. The small time and length scales of downdraft and outflow phenomena mean that a safe management program for takeoff and landing must be based directly on measurements.

Nomenclature

g	= acceleration due to gravity
h	= height of the convective boundary layer
k	= the von Kármán constant, $\cong 0.41$
r	= radius
$u*$	= friction velocity, $\equiv (\tau_0/\rho)^{1/2}$
w, w_B, w_D, w_U	= vertical velocity
$w*$	= convective velocity, $\equiv u*(-h/kL)^{1/3}$
z	= height
B	= depth of outflow region
C_P	= specific heat at constant pressure for air
E_0	= surface evaporative flux
H_0	= surface heat flux
L	= the Obukhov length, $\equiv -u_*^3/[(kg/\theta)(H_0/\rho C_p)(1+0.61C_pT/\lambda\beta)]$
R	= radius of downdraft
T	= air temperature
U	= horizontal wind speed
$\lvert V\rvert$	= modulus of the horizontal outflow perturbation wind
α	= dimensionless radius
β	= Bowen ratio, $\equiv H_0/\lambda E_0$
$\Delta_U, \Delta_D, \Delta_B$	= fractional area of updrafts, downdrafts, and downdrafts at height B, respectively
θ	= potential temperature
λ	= latent heat of vaporization
ρ	= air density
$\sigma_{u,v}, \sigma_{\lvert V\rvert}, \sigma_D$	= standard deviations of horizontal wind components, horizontal wind perturbation, and downdrafts, respectively
τ_0	= surface stress

Subscripts

B	= quantity at height B
U	= updraft
D	= downdraft

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Introduction

A LARGE proportion of Australian accidents involving light aircraft, helicopters, and gliders, where the accidents are not traceable to mechanical problems, occur under fair weather conditions, with sunny skies and light breezes. Why should there be so many accidents in conditions apparently ideal for flying?

In an attempt to answer this question, we have studied the accident reports of light aircraft, helicopters, and gliders published by the Bureau of Air Safety Investigation of the Australian Department of Aviation for the period 1983–1985. These reports indicate that variation in lift or control difficulties due to fluctuating winds could be an important factor in initiating many of these accidents, even under what appear to be ideal flying conditions. Loss of lift encountered at a critical time during landing or takeoff could have resulted, for example, in landing hard, landing short of the runway, and hitting the boundary fence. Pilots with relatively little flight experience are particularly at risk. Other groups at risk are agricultural pilots with very heavily laden aircraft and helicopter pilots who are hovering or moving slowly, close to the ground. This problem of loss of lift or directional stability can occur without warning and can affect even experienced pilots.

In this paper, we present the results of the study of these accident reports. We also estimate the magnitude of the variances of horizontal and vertical wind speeds and of the downdraft speeds due to dry convection. A model of the structure of the downdraft and outflow region is then developed that enables us to calculate the variation of lift (wind) and the probability of encounter. Finally, we conclude by pointing out the need for a detection and warning system based directly on measurements from surface anemometers.

Survey of Accidents, 1983–1985

We have reviewed the accounts of light aircraft, helicopter, and glider accidents for the years 1983–1985 given in the *Air Safety Digest* and in other information provided to us by the Bureau of Air Safety Investigation. Our methodology for treating the data, however, differs from that of the Bureau of Air Safety Investigation.

We first eliminated cases in which there were mechanical problems. Other cases were eliminated when their description specifically indicated circumstances that ruled out weather conditions. However, if, in our opinion, weather conditions could not be ruled out, even if the published description did not mention them, we considered them as possibilities requiring further investigation. These cases were divided into dry convection cases (no rain processes at the time and wind speeds ≤ 10 knots), moist convection cases (rain processes or frontal situations), and wind shear (wind speeds > 10 knots). For each case in which weather could have been a factor, available surface observations (wind, temperature, pressure, cloudiness, position of any cold front in relation to the accident, present weather, amount of recent rainfall) and upper air observations (wind and temperature) were examined near the accident site and in the surrounding area. Table 1 summarizes the preliminary findings. These results are preliminary in the sense that even when the wind speed was less than 10 knots, wind shear associated with convective rolls rather than fair weather convection may have been predominant. This point is discussed further in the section on accidents in convective conditions. A number of cases in the preliminary dry convection category were studied in greater detail and are discussed later.

Estimates of Wind Speed Variances

The intensity of dry convection is characterized by the convective velocity scale $w*$ proposed by Deardorff[1] and defined as

$$w^3* = h(g/\theta)(H_0/\rho C_p)(1 + 0.61C_pT/\lambda\beta) \tag{1}$$

whereas the pattern of the dominant convection elements is regulated by the ratio of $w*$ to the surface friction velocity $u*$. The pattern of convection may also be classified through the ratio of lengths h/L, where L, the Obukhov length, is defined so that

$$(w*/u*)^3 = -h/kL \tag{2}$$

The important role that each of the parameters $w*$, h, and $-h/L$ plays in convection dynamics will become apparent as we develop the theory.

Figures 1 and 2 show vertical profiles of the measured horizontal and vertical wind-speed variances in the atmospheric boundary layer.[2] Also shown are the average results for two laboratory simulations[3] and the results of a third-order closure numerical model of the convective atmospheric boundary layer.[4] The horizontal variances $\sigma^2_{u,v}$ appear to be nearly independent of height and can be written as

$$\sigma^2_{u,v} = 0.36w^3* \tag{3}$$

This expression is also shown in Fig. 1.

The vertical variance σ^2_w must decrease both near the ground and near the top of the boundary layer. An empirical expression for the vertical variance as a function of height is

$$\sigma^2_w = (1.3 - z/h)^2(z/h)^{2/3}w^2_* \tag{4}$$

This expression is plotted in Fig. 2 along with the laboratory and modeling results.

Figures 1 and 2 show the large amount of scatter of the atmospheric measurements. This scatter indicates the difficulty of obtaining good measurements of turbulent quantities above the atmospheric surface layer (higher than $\cong 20$ m) and the variability of the atmosphere. The results from the laboratory, numerical modeling, and empirical fit agree well with each other for the vertical variance and with the measurements. The results of the laboratory and numerical modeling studies for the horizontal variances, on the other hand, are smaller than the variances from the empirical fit and the measured values. This is thought to be due to the absence of energy at the larger length scales in the laboratory and in the numerical studies.

Model of Downdraft and Outflow Region

Vertical Perturbations

For aviation applications, it is useful to decompose the vertical motions into statistically separate distributions of downdrafts and updrafts, as suggested by Lenschow[5] and incorporated into models of plume dispersion by Best et al.[6]

Lamb[7] has provided experimental estimates of profiles of mean downdraft speeds $\bar{w}_D$ and of the fractional area Δ_D occupied by downdrafts. This information and the relationships for the total area and the conservation of mass

$$\Delta_D + \Delta_U = 1 \tag{5}$$

$$-\Delta_D\bar{w}_D + \Delta_U\bar{w}_U = 0 \tag{6}$$

allow the associated profiles of the mean updrafts $\bar{w}_U$ and fractional area Δ_U to be estimated.

The variances of updrafts and downdrafts about their means must be written in such a way that the total variance is in agreement with Eq. (4). Based on Lamb's data, this agreement is obtained with the following empirical formulations:

$$\bar{w}_D = \sigma_D = 0.9(1 - z/h)(z/h)^{1/3}w* \quad z/h \leq 0.5$$
$$= 0.45(1 - z/h)^{1/3}w*, \quad 0.5 \leq z/h \leq 1.0 \tag{7}$$

$$\bar{w}_U = \sigma_U = 0.9(1 - 0.4z/h)(z/h)^{1/3}w* \quad z/h \leq 0.5$$
$$= 0.72(1 - z/h)^{1/3}w*, \quad 0.5 \leq z/h \leq 1.0 \tag{8}$$

$$\Delta_D = \bar{w}_U/(\bar{w}_U + \bar{w}_D) = 1 - \Delta_U \tag{9}$$

Our interest here is with low-altitude operations of light aircraft, helicopters, and gliders, i.e., $z/h \leq 0.2$. Hence, we shall be concerned only with the first part of Eqs. (7) and (8).

The usefulness of the relations of Eqs. (7–9), if we assume Gaussian probability distributions for the updrafts and downdrafts, can be tested with Doppler acoustic radar observations of actual updraft-downdraft distributions during daytime convection. Quintarelli et al.[8] have acquired such data at Stanwell, Queensland, Australia, using an acoustic radar turbulence measuring system developed by Dr. Ian

Table 1 Summary of the number of light aircraft, helicopter, and glider accidents for 1983–1985 in which weather may have been a factor

	Light aircraft and helicopters				Gliders			
Year	Dry convection	Moist convection	Wind shear	All causes	Dry convection	Moist convection	Wind shear	All causes
1983	35	5	16	265	5	—	2	21
1984	16	4	19	220	4	—	—	19
1985	18	6	19	211	3	—	1	9
Average frequency of occurrence, %	10	2	8	100	24	0	6	100

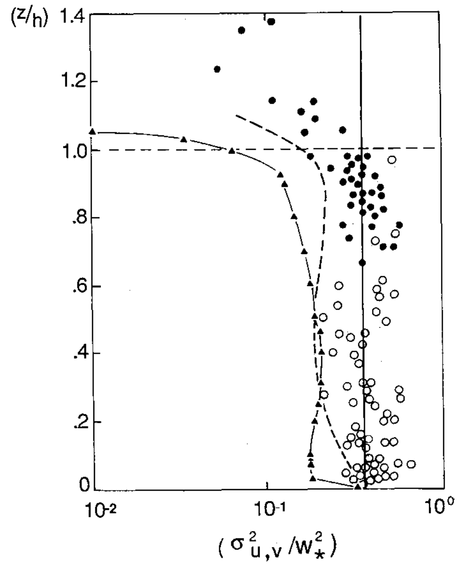

Fig. 1 The horizontal velocity variance normalized by the convection velocity $w*$. The open circles represent the Minnesota data, and the closed circles the Ashchurch data.[2] The dashed line is the average profile for the laboratory experiments S1 and S2 of Willis and Deardorff[3]; the line with triangles is the profile for the numerical experiments of André et al.[4]; the solid line is the empirical result used in this study.

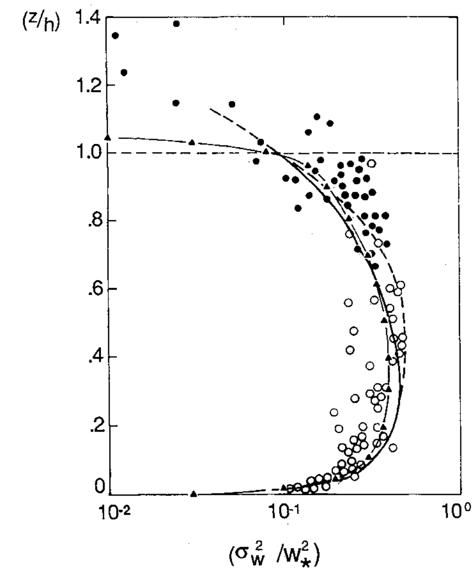

Fig. 2 The same circumstances apply as in Fig. 1, except for the vertical velocity variance.

Bourne at the Physics RAAF Department of the University of Melbourne. This system has a beam 10 deg wide and measures frequency shifts of echoes backscattered from a pulse volume 140 m deep.

Histograms of daytime vertical velocities for the period February 21-26, 1983, are shown in Figs. 3-5 for heights of 140, 240, and 340 m, respectively. This daytime period was characterized by $h \cong 2000$ m and $w* \cong 2$ m/s (Ref. 23). These conditions are common in Australia.

The mean vertical velocity is nonzero for these histograms. This result has been interpreted by Spillane[9] as being compatible with Gaussian distributions of updrafts and downdrafts

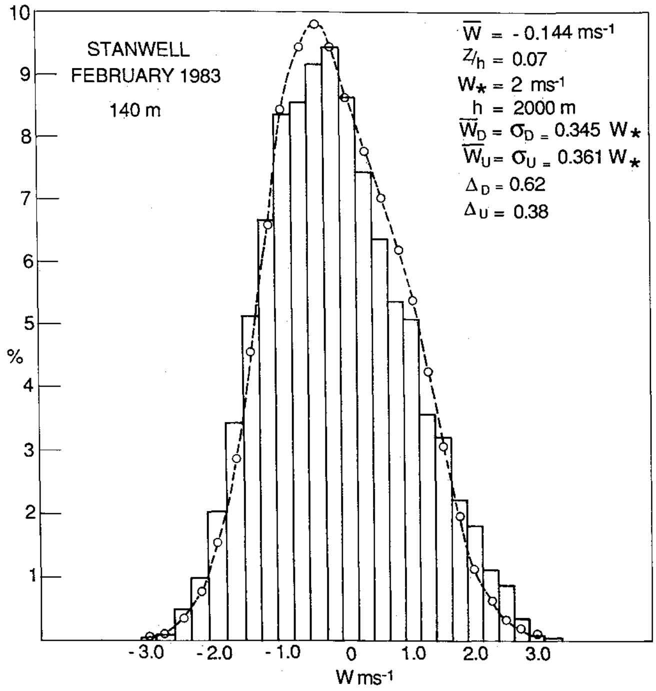

Fig. 3 Vertical velocity histograms partitioned in 0.25 m/s bins for convective daytime conditions at Stanwell, Queensland, Australia, for 140-m height. The dashed curve represents the predicted value based on separate Gaussian distributions for updrafts and downdrafts. The parameters of the model are shown here.

[with the "universal" parameters given by Eqs. (7-9)], being advected across the site, but with a sampling bias toward downdraft occurrence. This bias is probably due to terrain features, upwind, within a drift time of $4t*(=4h/w*)$ that is the approximate lifetime of the convection pattern.[10]

On this basis, the distributions of expected (predicted) vertical drafts have been calculated as the sum of separate Gaussian distributions for updrafts and downdrafts. These results are also shown in Figs. 3-5. The agreement between predicted and observed values is excellent, particularly in the tails of the downdraft distribution. The significance to aviation is seen in the occurrence of downdrafts greater than 2 m/s($\cong$394 ft/min) at a height of 140 m ($\cong$459 ft) for 2% of the time, or 1 landing in 50.

Horizontal Perturbations

The outflow or spreading of strong downdrafts at the ground causes patterns of horizontal wind perturbations (gusts) that are also important to aircraft operating at low altitudes.

To predict the characteristic behavior of these outflows, we construct a model that ensures agreement between Eqs. (3) and (7). A downdraft of radius R, spreading uniformly in a boundary layer of depth B, will cause a symmetrical vector wind perturbation V with a radial profile given by (see Fig. 6)

$$
\begin{aligned}
|V| &= w_B r/2B & 0 \le r \le R \\
&= w_B R^2/2Br & R \le r \le \alpha r
\end{aligned}
\qquad (10)
$$

where w_B is the downdraft speed at height B and α is a constant. The value of α is known from FM-CW radar observations[11] to be about 2-2.5. THe variance contributed to wind fluctuations by such a pattern is obtained by taking an average of $|V|^2$ over the area of outflow. For conservation of the outflow geometry, i.e., preservation of R/B for all possible values of w_B, we obtain an expression for the variance of the

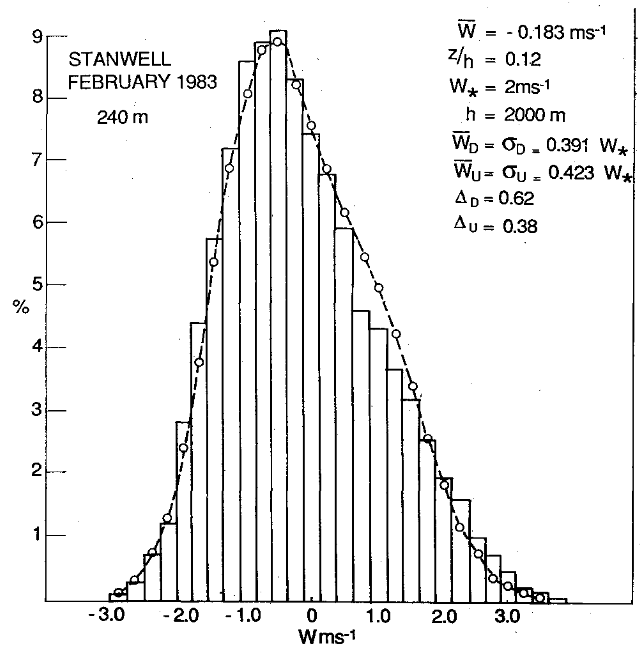

Fig. 4 The same circumstances apply as in Fig. 2, except for 240-m height.

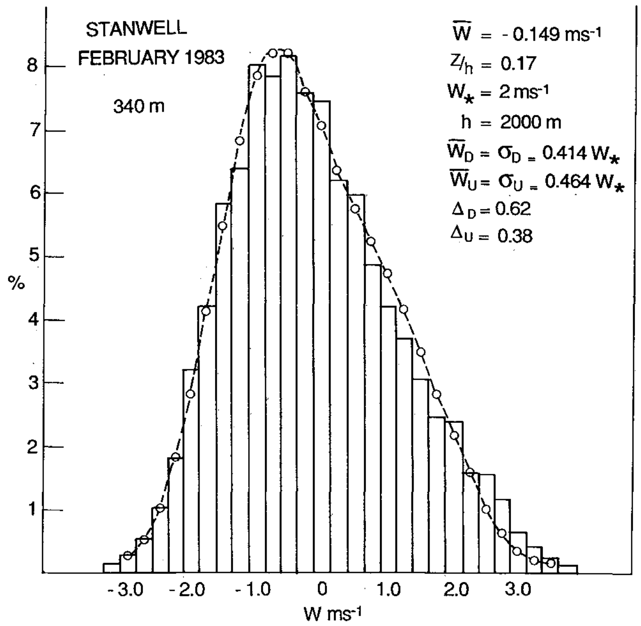

Fig. 5 The same circumstances apply as in Fig. 2, except for 340-m height.

vector perturbation,

$$\sigma^2_{|V|} = (\sigma_u^2+\sigma_v^2)_D = 2(\sigma^2_{u,v})_D$$

$$= 2\langle w_B^2\rangle (R/2B)^2(0.25+\ln\alpha)/\alpha^2 \tag{11}$$

where the subscript D indicates the outflow from a downdraft and $\langle\ \rangle$ denotes an ensemble average. $\langle w_B^2\rangle = \bar{w}_B^2+\sigma_B^2 = 2\bar{w}_B^2$ from Eq. (7).

If we substitute for $\langle w_B^2\rangle$, it follows from Eq. (11) that the contribution to variance in the wind components due to downdraft spreading is

$$(\sigma^2_{u,v})_D \cong 2\bar{w}_B^2(R/2B)^2(0.25+\ln\alpha)/\alpha^2 \tag{12}$$

By eliminating $\bar{w}_B$ in Eqs. (7) and (12), we can write the horizontal velocity standard deviations for the downdraft outflow as

$$(\sigma_{u,v})_D = 0.45(1-B/h)(B/h)^{1/3}(R/B)w*$$

$$(0.5+2\ln\alpha)^{1/2}/\alpha \tag{13}$$

We can simplify this relation further by noting that acoustic radar observations[12] indicate that $2R\cong h$; thus, Eq. (13) becomes

$$(\sigma_{u,v})_D = 0.225(1-B/h)(B/h)^{-2/3}w*$$

$$(0.5+2\ln\alpha)^{1/2}/\alpha \tag{14}$$

The standard deviations given in Eq. (14) can be compared to the horizontal standard deviations from all causes found from Eq. (3)

$$\sigma_{u,v} = 0.6w* \tag{15}$$

We can now make a statement about the outflow geometry, using Eqs. (14) and (15), by defining the lower bound on B/h to occur when $(\sigma_{u,v})_D = \sigma_{u,v}$. If $\alpha = 2$, then $B/h \geq 0.11$; if

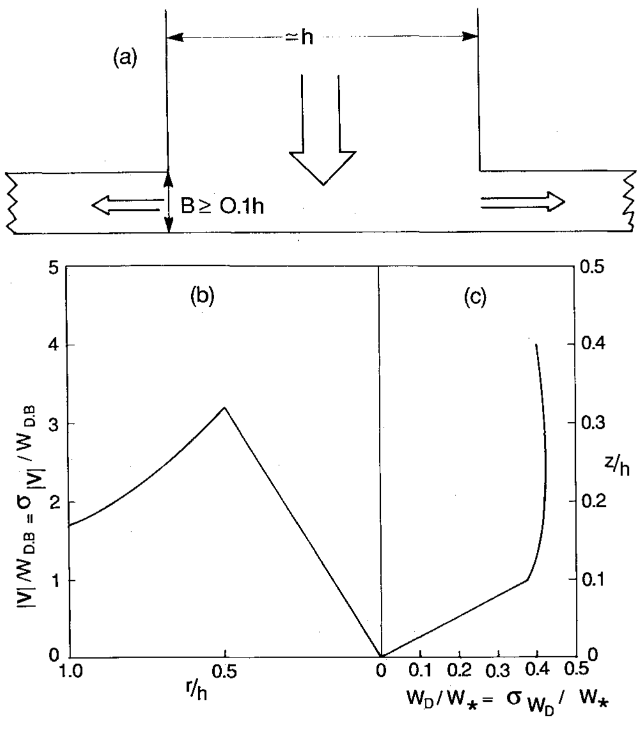

Fig. 6 a) Vertical cross section of the model, showing axisymmetrical downdraft and outflow, b) radial profile of (axisymmetrical) perturbation in horizontal wind speed due to the spreading of the characteristic downsdraft of diameter h in the outlfow layer of depth $B \geq 0.10\ h$, and c) vertical profile of characteristic downdraft speed over diameter h.

$\alpha = 2.5$, then $B/h \geq 0.094$. Because of the inherent uncertainty in α and in the approximation $2R\cong h$, we recommend

$$B/h \cong B/2R \geq 0.1 \tag{16}$$

This value of $B \cong 0.1\ h$ also agrees with the height of the convective "wall" of the updraft region.[13,14]

For a symmetrical wind perturbation, we can estimate the maximum horizontal shear from Eqs. (10) and (16). This gives

$$|\Delta V| = w_B (R/B) \leq 5 w_B \quad (17)$$

The average shear in the horizontal wind is representative of the layer B and extends to the ground, but the actual wind perturbation experienced must depend on the downdraft symmetry, the phase of the downdraft life cycle, and the aircraft track with respect to the downdraft core. These additional aspects influence the probability of encounter of a particular sequence of wind and sink variation during the approach to landing.

Summary of the Model

In general, we may expect the following characteristics to be useful in predicting sink and wind gusts due to fair weather convection:

1) The characteristic diameter of downdraft ≅ depth of convection layer h, i.e., $2R \cong h$.

2) The characteristic depth of the surface spreading layer B is given by $B \cong 0.10\ h$.

3) The mean and standard deviations of downdrafts at height B are given by $\bar{w}_{D,B} = \sigma_{D,B} = 0.38\ w*$ from Eq. (7). These downdrafts may usefully be regarded as having a Gaussian distribution of velocities.

4) The mean and standard deviations of the modulus of the maximum vector perturbation in the horizontal wind [from Eq. (10) and its assumption of symmetry and items 1–3] are given by

$$\langle |V|_{\max} \rangle = \sigma_{|V|_{\max}} = 2.50 \bar{w}_B = 0.94 w*$$

5) The maximum shear across a downdraft perturbation is $|\Delta V| = 2|V|_{\max}$ and occurs in a flight path of $2R \cong h$.

6) The downdraft velocity (sink) decreases linearly below height B.

As $-h/L$ falls from 100 ($w*/u* \cong 6.3$) to 50 ($w*/u* \cong 5.0$), the pattern of convection changes from random plumes to one containing hexagonal cellular groups with major axes elongated downwind.[13-15] By $-h/L \cong 25$ ($w*/u* \cong 4.0$), the pattern is dominated by longitudinal rolls with axes at a small angle to the wind and of average spacing $3h$.[16-19]

Application of the Model to Aviation

Fair weather convection under an inversion at 1500 m and with $w* \cong 2$ m/s is a common occurrence in the dry season of Australian climate. It is instructive to consider the extreme conditions faced by a (typical) light aircraft during 1 landing in 50. This corresponds to 1 out of 25 downdraft occurrences, since downdrafts occupy only about half the area. From characteristic 2 in the preceding section, $B = 150$ m (≅492 ft), and from 3 we determine that the 1-in-25 downdraft is of strength $(\bar{w} + 1.75\ \sigma_D)_B = 2.09$ m/s. The associated maximum vector perturbation in wind is 5.2 m/s (10.4 knots) (found by multiplying the relation 4 by 2.75), and the maximum horizontal shear is 10.4 m/s (20.8 knots) over a 1500-m flight path.

Consider a light aircraft approaching at 70 knots and encountering this downdraft at a height of 75 m (≅246 ft) and 1500 m from touchdown. An initial headwind increase of 10.4 knots [+32% in lift above the 70 knots indicated air speed (IAS)] would be followed by entry into the downdraft core, of descent averaging 1.05 m/s (≅206 ft/min), but decreasing with reduced ground clearance, and decreasing headwind being replaced by a tailwind component of 10.4 knots (−28% in lift below 70 knots IAS but −59% below that at maximum headwind).

The pilot must correct for lift variations of, say, ±30% and downdraft sink up to 206 ft/min, while maintaining the planned descent rate of 350 ft/min, and IAS of 70 knots during the final 43 s of approach.

The preceding is based on a traverse of a symmetrical downdraft core, but to safely negotiate a headwind or crosswind gust (fluctuation) of 10.4 knots at "flare" requires a high level of skill.

This brings us to the impact of directional variation in wind on helicopters operating at low translational speed near the ground. In apparently ideal fair weather as previously described, a light background wind of 3 m/s (6 knots) superimposed on an axisymmetrical 1 in 25 downdraft perturbation could force directional swings of 60 deg about the mean wind direction with gusts of 6.0 m/s (12 knots). For a hovering single rotor, antitorque tail rotor configuration helicopter, such fluctuations could contribute to the loss of directional control through the "tail rotor vortex ring state" or "main rotor disk vortex interference."[20]

Accidents in Convective Situations

The role of convective perturbations as factors in accidents to landing aircraft depends on the three parameters $w*$, h, and $-h/L$. Together, they determine the intensity and dimensions of convective-induced perturbations and also the probability distribution of the perturbations, at least for $-h/L > 50$, say. The detectability and significance to aircraft of these perturbuations also depend, in part, on the background average wind speed $\bar{U}$.

In the survey of accidents reported, a wind speed of 5.0 m/s(10 knots) was used to discriminate between accidents possibly caused by dry convection and by wind shear. This preliminary division is based on the influence of wind speed on L, the Obukhov length and, thus, on the stability parameter $-h/L$ and the pattern of convection.

The use of a 5m/s wind-speed criterion to discriminate between fair weather convection gusts and wind-shear cases can only serve as a guide. A more detailed examination of the data is shown in Table 2. Use of the criterion $-h/L > 50$ indicates that the Biloela and Wallacia cases must be classified as possible wind-shear situations owing to the presence of convective rolls. The remainder of the cases fall into the fair weather convection category, in which the possible influence of random convection-induced gusts in initiating the accident cannot be excluded.

The procedure used to evaluate L and thus h/L for the accidents in Table 2 is detailed in Hess and Spillane.[21] The locations for the accident sites are shown in Fig. 7.

The Need for a Detection and Warning System for General Aviation

The characterization of the structure and intensity of convective perturbations has proved useful in identifying and discussing aspects of importance to the operation of light aircraft and helicopters. This understanding, no matter how precise, cannot in itself provide a practical advisory service due to the inherently stochastic nature of significant (hazardous) events and to the small time and length scales involved.

We have already pointed out (as at Stanwell) that local terrain may induce a bias toward updrafts or downdrafts at a particular site and such a bias will vary with wind direction. The existence of bias is directly open to measurement and, ideally, this type of measurement program should be part of any survey to select a site (inland) for general aviation operations.

The immediate research need is to 1) confirm that appropriate scaling can provide universal descriptions of the variations in intensity and dimensions of downdrafts, and 2) test the validity of the concepts that describe the geometry, pattern, and life cycle of downdraft spreading at the ground.

This research appears to us to be prerequisite to engineering solutions giving automatic warnings of hazard. The design of

Table 2 Parameters of convection and characteristics of the downdraft and outflow model

Location	$\bar{U}$, m/s	h,m	$-h/L$	B,m	w_*, w_* m/s	$\langle \lvert V \rvert_{max} \rangle = \sigma_{\lvert V \rvert_{max}}$ m/s	$\lvert V \rvert_{max}$ 2.0% of time, m/s
Canberra	2.0	2000	80	200	2.01	1.89	5.20
Redcliffe	2.0	1600	137	160	2.09	1.96	5.40
Renmark	2.5	2400	142	240	2.50	2.35	6.46
Bourke[a]	2.5	2000	67	200	1.56	1.47	4.04
Witchellina[a]	2.5	3000	254	300	2.04	1.92	5.27
Hebel	2.0	1400	80	140	1.06	1.00	2.75
Wiluna	2.0	1100	182	110	1.59	1.49	4.10
Biloela	5.0	2000	25	200	1.89	1.78	4.89
Griffith	2.5	2000	296	200	2.30	2.16	5.94
Boggabri	2.5	1800	130	180	1.91	1.79	4.92
Wallacia	2.5	1200	21	120	1.45	1.36	3.75
Hoxton Park	2.0	1300	57	130	1.82	1.71	4.69
Cape Keer Weer	2.5	2000	641	200	1.77	1.66	4.57

[a]The procedure used probably underestimates w_* and overestimates L at the time of these accidents.

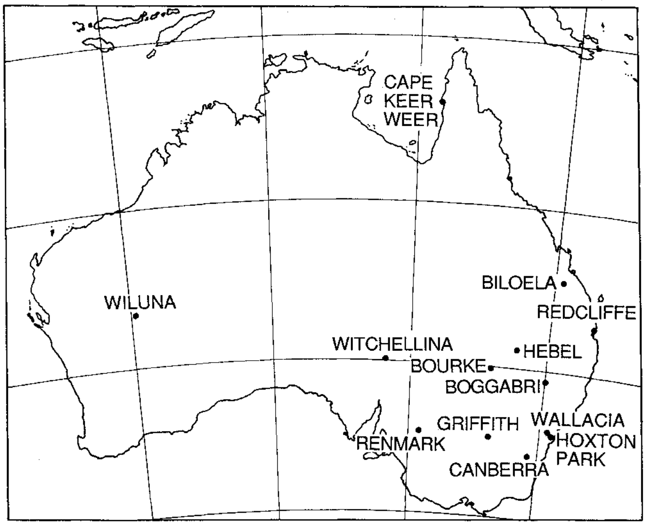

Fig. 7 The sites of the accidents given in Table 2.

an appropriate measurement system needs to be based on a sound understanding of the phenomena to be measured.

A recent editorial in *Aviation Safety Digest*[22] expressed the view that, "Although annual accident rates have been gradually reducing in Australia for some time, it seems the rate of improvement has slowed or even plateaued. At the same time the proportion of accidents where pilot factors are assigned continues to be unacceptably high. It is now believed both here and overseas that civil aviation generally may have reached the limit of accident prevention through regulation and the way forward is through improved safety education."

It is our view that a direct measurement system for the detection and warning of convective gusts and wind-shear hazard, which would include microbursts, offers a potential for reducing the number of light aircraft and helicopter accidents. The results of our study show that fair weather convection and wind-shear effects together may be contributing factors in up to 20% of the total number of accidents.

Conclusions

This study of the possible role of fair weather convection in initiating accidents of light aircraft, helicopters, and gliders indicates that these convective wind gusts may be more important than previously thought. The model of downdrafts and the outflow region developed here suggests that for one landing in 50, or one out of 25 downdraft occurrences, aircraft will experience a variation in lift of ±30% during landing. Pilots with relatively little flight experience, agricultural pilots with heavily laden aircraft, and helicopter pilots flying at low translational speed close to the ground are particularly at risk.

A detection and warning system based directly on measurements could reduce the number of accidents. Before implementing such a system, however, there is an immediate need for more research to confirm our understanding of the dynamic processes controlling the geometry and life cycle of updrafts and downdrafts.

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