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A tentative model of *Andhi*

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सार – छरबा (1974) तथा गोफ (1976) के तूफान डाउनड्राफ्ट मॉडल पर आधारित आंधी के परीक्षणात्मक मॉडल (उतर–पश्चिम भारत की संवहनी आंधी) का सुझाव दिया गया है। यह मॉडल विशेष प्रकार–1 की आंधी की दृश्यता के विचरण का गुणात्मक रूप से व्याख्या कर सकने में सक्षम है (चारों प्रकार की आंधी की दृश्यता विचरण की व्याख्या जोसेफ एवं अन्य 1980 में की गई है)। प्रकार–2 (रात्री समय) की आंधी दृष्यता के धीमे सुधार तथा अपेक्षाकृत लम्बी अवधि भी औचित्यपूर्ण एवं व्याख्यात्मक है। यदि यह माना जाये कि आंधी का शीर्ष रात्रि में आगे को धीमी गति से चलता है जब कि वायुमंडलीय घनत्व अधिक होता है। ये अनुमान 'गुरुत्व धारा' शीर्ष के प्रस्थापन के अध्ययन के सैद्धांतिक पक्ष की भी पुष्टि करते हैं।

ABSTRACT. Based on the thunderstorm downdraft model developed by Charba (1974) and Goff (1976), a tentative model of *Andhi* (the convective duststorm of northwest India) has been suggested. This model is able to explain qualitatively the visibility variations in a typical type-1 *Andhi* (The details of visibility variations in the four types of *Andhi* have been given by Joseph *et al.* 1980). The slower visibility improvement and the consequent longer duration of type-2 (night time) *Andhi* also gets a logical explanation, if one assumes that the *Andhi* 'head' moves forward more slowly at night, when the ambient air-density is higher. This assumption has theoretical support from studies on the propagation of 'gravity current' heads.

1. Introduction

The convective type of duststorm occurring over northwest India during the pre-monsoon season April to June is called *Andhi*. Joseph *et al.* (1980) made a study of 40 cases of *Andhi* that occurred at Delhi airport during the period 1972 to 1977, using available meteorological records. From the nature of variations of horizontal visibility and wind speed near the ground level associated with these duststorms, it was found that 4 types of *Andhi* occur. From radar photographs of the cumulonimbus cloud or squall line associated with *Andhi* it was found that the distance between the *cb* cloud or squall line (as seen in the radar) and the associated *Andhi* dust-wall on the ground is as large as 30 km.

Study of the downdraft from severe thunderstorms is considered very important in view of the role of such downdrafts in causing aircraft accidents. "The large wind-shears that are characteristic of the gust-front occurs mainly in the lowest 1-2 km of the atmosphere and, therefore, are a particular hazard to aircraft flying at low levels. In fact, low level wind shear in and around thunderstorms has recently been labelled as the primary probable cause in several major airline crashes" (Mitchell and Hovermale 1977).

2. Charba-Goff model of thunderstorm downdraft

Charba (1974) studied the low level wind and thermal structure of one intense Oklahama gust-front using data upto a height of 444 m above ground from an instrumented tower and also data from a surface meso-network, both operated by the National Severe Storms Laboratory (NSSL) of USA. Goff (1976) also using the NSSL tower, studied time-height sections of the wind and thermal patterns of 20 different gust-front cases. Because of the dynamic similarity between the gust-front and experimental gravity currents (Simpson 1969), laboratory gravity current studies have enabled deduction of the gust-front structure above the tower observations, especially in regard to the frontal boundary shape and internal circulation in the cold outflow (Charba 1974 and Goff 1976). Information on these were also deduced from the observed profiles of the dust-walls of duststorms (Lawson 1971 and Idso *et al.* 1972).

Essential details of a model of thunderstorm downdraft as obtained from the studies of Charba (1974) and Goff (1976) are given in Fig 1. Some of the terminology used in describing important features of the downdraft (thunderstorm outflow) are the following:

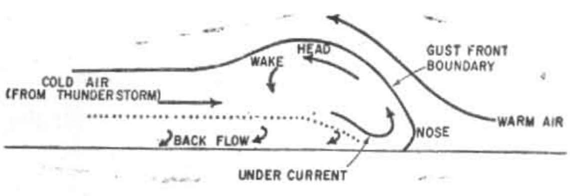

Fig. 1. Model of cold air downdraft of squall-line thunderstorm, adapted from studies of Charba (1974) and Goff (1976) using NSSL tower data. This may be called the Charba-Goff model. Important features of the downdraft flow over the ground are marked in the figure and explained in the text. The wind vectors marked are with reference to the gust-front, *i.e.*, with reference to an X-Z frame fixed to the gust-front

The 'nose' is the protruding leading edge of the cold air outflow extending towards the warm ambient air. The cold air 'back-flow' is the drag induced surface layer flow away from the gust-front (Flows pictured in this model and given in Fig. 1 are relative ot the movement of the gust-front, *i.e.*, with reference to an X-Z frame fixed to the gust-front). The term 'gust-front' is defined as the boundary separating the cold air outflow from the displaced warm air. The dotted line indicates the top of layer of 'back-flow'. Around this dotted line, therefore, large vertical wind shears can be expected; another vertical wind shear zone is near the top of the cold air outflow.

The vertical bulge near the front of the cold downdraft is called the 'head'. Charba (1974) in his case study deduced the profile of the cold outflow by extrapolating the observed (upto 444 m) temperature profile, upwards to three times the tower height and then applying the hydrostatic equation using the observed surface pressure rise. He thus got the height of the top of the head as 1700 m. The upper surface of the cold air downdraft, up-stream of the 'head', is relatively shallow; here the cold air depth in Charba's case-study was estimated as 1350 m. The corresponding heights obtained by Goff (1976) are very much less.

The most prominent characteristic of the flow pattern inside the outflow airmass observed by both, is the strong forward current at low levels beneath the 'head'. This high speed current centred only a small distance above the ground and beneath the head is called an 'undercurrent'.

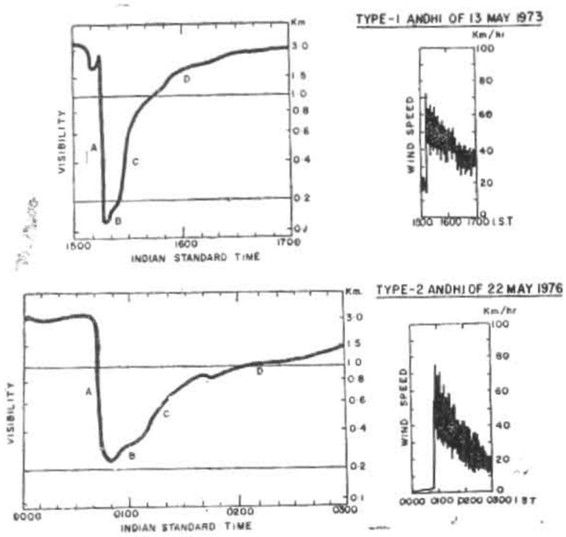

Fig. 2. An example, each of a type-1 (day time) and type-2 (night time) *Andhi* showing the phases A, B, C, and D (taken from Joseph *et al.* 1980). In type-2 *Andhi* each of the 4 phases takes longer time compared to type-1 (*i.e.*, the variation of visibility is slower), although the surface wind speed variations are similar

Inside the 'head' in Fig. 1, an anti-clockwise vertical eddy may be seen. Charba (1974) finds in the down-motion side of this circulation, high wind gustiness and large fluctuations in temperature. He found that this turbulent air is slowly transported downward and it may partly be entrained into the undercurrent. Charba (1974) further remarks that the flow pattern (as in Fig. 1) at low levels, beneath the head and in the nose, is consistent with both measurements of dust content and visual motion of dust-cloud lobes at the leading edge of *Haboobs* as may be seen from the studies by Lawson (1971) and Idso *et al.* (1972).

3. Application of Charba-Goff model to explain visibility variation in *Andhi*

Fig. 2 gives an example each of the visibility variations in a type-1 and a type-2 *Andhi* taken from Joseph *et al.* (1980). The visibility given is the horizontal visibility at a height of 2.8 metres above ground. The strong 'undercurrent' (which is recorded by the surface wind recorder as the squall in Fig. 2, *i.e.*, the sudden increase in wind speed) raises the loose dust in the hot dry Delhi pre-monsoon conditions and the strong upward current inside the head takes this dust upwards and backwards.

In an *Andhi* or *Haboob*, a thick dustwall sloping backwards travels long distances. In intense *Andhi* cases at Delhi airport it is observed that visibility is reduced to less than 100 metres. The following mechanism is suggested for the generation of such high dust-density dustwalls. The dust kicked up from the ground by the 'undercurrent' is carried upwards and backwards in the

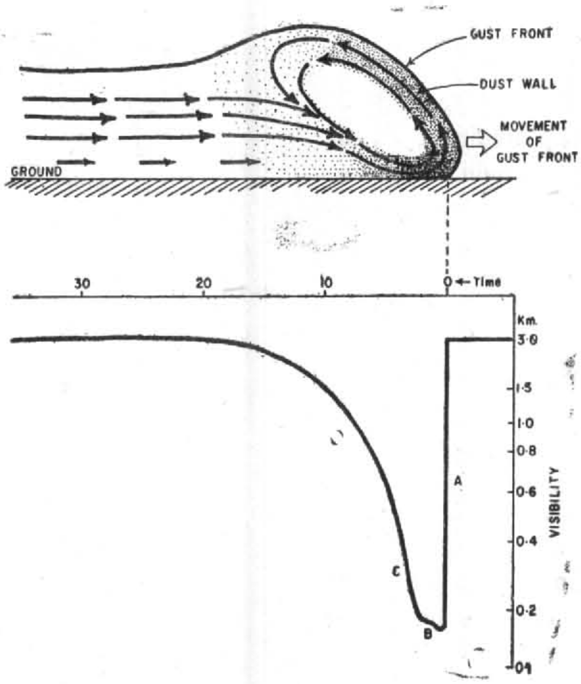

Fig. 3. A proposed model for *Andhi* to explain the visibility variation is shown in the upper part of the figure. The wind motion vectors marked are with reference to the ground. The corresponding surface visibility variations at a station, which depends on the instantaneous dust-density over it, are shown in the lower part. As the gust-front moves forward, the visibility variation as shown is recorded. The unit of time is inversely proportional to the speed of movement of the gust-front

cold air in the 'head' and brought down by the 'down-current' behind the head back into the 'undercurrent'. Thus this vertically rolloing motion in the 'head' or the 'vertical eddy' can progressively increase the dust content in the dust-wall and after some travel over land, the dust-wall may carry large quantities of dust. This is a possible mechanism that can explain the large quantities of dust carried by the fully developed *Andhi* dustwall. That the dust intensity in the *Andhi* is built up this way, will have to be tested. At Delhi airport there is at present a skopograph (transmissometer) installed at one end of the main runway. Another skopograph is being installed at the other end. When the twin skopograph system becomes operational (the distance between them is about 3 km) we may be able to test whether the visibility in the *Andhi* generally decreases as the duststorm moves from one instrument to the other. Better verification becomes possible with a meso-network of observatories around Delhi airport, a suggestion for which has been given by Joseph and Madan (1978).

The largest accummulation of dust should be at the gust-front where the undercurrent slows down and turns upward. This explains the sharp fall of visibility (Phase A). The other phases with reference to the dust laden vertical eddy within the 'head' may be as pictured in Fig. 3 (Here the flow is pictured with reference to the ground). As different parts of the vertical eddy move across a station, phases A, B, C and D occur at the station. If the vertical eddy moves forward faster, then the visibility variations are also faster and correspondingly the duration of the dust-storm at a station is shorter and *vice-versa*.

4. Why type-2 *Andhi* has longer duration than type-1

The visibility variations in *Andhi* are slower at night (type-2 case) compared to day (type-1 case), so that type-2 duststorms last longer than type-1 (Joseph *et al.* 1980). A possible explanation for this is that the *Andhi* dustwall or the gust-front moves more slowly at night. Then as per section 3, each of the phases A, B, C and D will last for a longer period. There is theoretical support for such a hypothesis as may be seen from the following.

The problem of steadily propagating 'gravity currents' has been theoretically studied by Von Karman (1940), who applying Bernoulli's equation obtained an expression for the displacement speed V of the gravity current as :

$$V = k \sqrt{gd \left(\frac{\rho_2 - \rho_1}{\rho_1} \right)}$$

where ρ_2 and d are the density and the mean depth of the gravity current, ρ_1 is the density of the ambient medium and g is the acceleration due to gravity (*see* also Benjamin 1968). The theoretical value of k as derived is $\sqrt{2}$ (*i.e.*, 1.414). Keulegan (1958) and Middleton (1966) using laboratory models, empirically obtained the value of k as applicable to the atmospheric case as 1.09.

Using Karman's formula, the speed of movement of the *Andhi* dust-wall has been computed (as done for the squall-line thunderstorm case by Charba 1974), for a type-1 and type-2 *Andhi* (evening and mid-night cases), using typical values of densities for the cold downdraft air and the ambient air at Delhi in the month of May. These temperatures (T) and densities (ρ) at levels separated by 10 mb between 970 mb (ground level) and 850 mb, obtained from typical radiosonde ascents of May 1973 are given in Table 1.

The virtual temperature (T') is about 1°K more than the air temperature (T), as dew points are usually in the range 6° to 10°C at levels up to 850 mb in the *Andhi* atmosphere. Density ρ in kg/m³ is calculated using the formula :

$$\rho = 0.34838 \ (p/T')$$

where p is the atmospheric pressure in mb and T' is the virtual temperature in degrees Kelvin. The 1200 GMT rediosonde ascent of the date of the type-1 *Andhi* (13 May 1973) shown in Fig. 1 was made about one hour after the *Andhi*, so that it may be taken as representative of the cold downdraft air that has spread around. The mid-night values are taken as the mean of the 1200 GMT ascent of 12 May 1973 and 0000 GMT ascent of 13 May 1973 during which period there was no *Andhi*. The ambient temperature data

TABLE 1

Temperature and density of thunderstorm downdraft and ambient air

Level (mb)	Cloud downdraft		Ambient air (Eveing)		Ambient air (Mid-night)	
	Temp. (°K)	Density (kg/m³)	Temp. (°K)	Density (kg/m³)	Temp. (°K)	Density (kg/m³)
850	297.0	0.9937	302.0	0.9773	299.0	0.9871
860	297.8	1.0027	303.0	0.9855	299.8	0.9960
870	298.6	1.0116	303.9	0.9941	300.6	1.0049
880	299.4	1.0205	304.9	1.0022	301.5	1.0135
890	300.2	1.0294	305.9	1.0103	302.5	1.0216
900	301.0	1.0382	306.8	1.0187	303.5	1.0297
910	301.6	1.0477	307.8	1.0266	304.2	1.0387
920	302.2	1.0571	308.9	1.0342	305.0	1.0474
930	302.8	1.0665	309.9	1.0421	305.8	1.0560
940	303.3	1.0762	310.9	1.0499	306.7	1.0643
950	304.0	1.0851	312.0	1.0574	307.4	1.0731
960	304.5	1.0947	313.0	1.0685	307.7	1.0834
970	305.2	1.1036	314.1	1.0724	308.0	1.0936
970-900 layer mean		1.0711		1.0462		1.0608
970-850 layer mean		1.0482		1.0261		1.0392

TABLE 2

Speed movement of the *Andhi* during evening and mid-night

Ht. of downdraft and ambient air layers	Speed (m/s) of movement of *Andhi*			
	Evening		Mid-night	
	k=1.414	k=1.09	k=1.414	k=1.09
970-900 mb (approx. 700 m)	18.1	13.9	11.5	8.9
970-850 mb (approx. 1200 m)	22.5	17.3	14.3	11.0

for evening are from the 1200 GMT ascent of 12 May 1973. The speed of movement of the *Andhi* or the gust-front (V) is calculated using the two values of k (*i.e.*, 1.414 and 1.09) and for two possible thickness above ground (a) and (b) of downdraft air (mean density is average of the densities at 10 mb intervals) as given below :

(a) 970-900 mb (thickness taken as approximately 700 m)

and

(b) 970-850 mb (thickness taken as approximately 1200 m).

(The ground level pressure at Delhi was about 970 mb in these cases). The velues of V thus calculated are given in Table 2. The speed of movement of the *Andhi* or gust-front is considerably slower at mid-night.

The mid-night temperature is taken as the arithmetic mean of 1200 GMT and the following 0000 GMT values. In reality it will be closer to the 0000 GMT value, as the initial fall in temperature during evening and early night is faster. Moreover the type-II *Andhi* shown in Fig. 2 has occurred a little more than an hour after mid-night and 12 GMT temperatures of 21 May 1976 are lower than that of 12 May 1973. These factors will give a still smaller value for V for the case of type-2 *Andhi* in Fig. 2. Thus it may be seen that the visibility variations shown in Fig. 2 are reasonably well explained.

5. Wind shear zones of *Andhi*

The cold airflow from severe thunderstorms consists of several zones hazardous for modern aircraft. One of the major hazards is wind shear. Gust-front is a zone of large horizontal wind shear between the under-current manifested as the sudden increase in surface wind speed (squall) and the usually light speed of the ambient wind flow. From the Charba-Goff model of the downdraft, it may be seen that there are two zones of marked vertical wind shear, (a) the dotted line in Fig. 1 which is the thin layer between the back-flow region and the fast flowing cold downdraft air from the thunderstorm and (b) the top of the fast flowing cold downdraft air above which is the ambient air. Of (a) and (b), the most dangerous zone for aircraft landing operations, is the shear zone (a), as it will be a decreasing head-wind shear and it is closer to the ground. It is necessary to measure the heights of these vertical wind shear zones for a number of *Andhi* cases. As the dust practically clears at a station after the vertical eddy in the *Andhi* 'head' has moved off, we may use slow rise balloons along with optical theodolite to monitor the shear zones as done by Ragette (1973). According to Joseph *et al.* (1980), the distance between the thunderstorm cloud and the *Andhi* dustwall is about 30 km in a typical *Andhi*. Taking the speed of movement of the thunderstorm as about a kilometre a minute, the wind shear zones may persist over a station for about half an hour during which period we may be able to make a few pilot balloon soundings to study the vertical wind shear zones. Such studies are important for drawing up procedures for aircraft landing and take-off operations with an *Andhi* around an airfield.

6. Consclusion

A tentative model of *Andhi* has been suggested in this paper, based on the study of Charba (1974) and Goff (1976) on American squall-line thunderstorm out-fiows using the tall NSSL instrumented tower. This model has been able to explain qualitatively the four phases of the type-1 duststorm. It has also been able to explain the slow improvement in visibility and the consequent longer duration of the night-time *Andhi* (type-2).

As the spreading cold air of the thunderstorm downdraft which creates the *Andhi* is a major aviation hazard, particularly on account of the wind-shear zones associated with it, meso-scale numerical and laboratory studies of the problem should be undertaken on high priority. A meso-scale model for numerical study of 'gust-front' has been developed by Mitchell and Hovermale (1977).

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