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DUST DEVIL METEOROLOGY

Jack R. Cooley

CENTRAL REGION
Kansas City, Mo.

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1. INTRODUCTION

Much of the literature on dust devils has used observations resulting as a matter of chance rather than from deliberate and careful planning, and the instruments used were not sufficiently sensitive and responsive to adequately measure the various parameters. Several intensive studies have been made but until recently these have been confined largely to qualitative rather than quantitative measurements. Thanks to the intensive and thorough efforts of Sinclair, quantitative measurements are now also available. Even so, the available literature is scattered through a number of publications. It is the intent here to summarize this material so it may be studied more easily, thoroughly, and systematically. A sincere effort has been made to keep the text simple so it can be read with ease. A sincere effort has also been made to survey as much of the existing literature as possible, filtering out the older parts that have been disproven, and yet retaining old ideas yet unproven or subject to question. This effort has led to a survey of the Meteorological and Geoastrophysical Abstracts Volumes 1 (1950) through 17, #7 (July 1966); The Reader's Guide to Periodical Literature 1952 through 1966; Dissertation Abstracts (by Xerox, Ann Arbor, Mich.) 1954 through June 1966; a thorough search of the card catalogues at both the University of Michigan and Rutgers as well as all of the likely reference books, meteorological, aeronautical and related texts on the shelves of these libraries.

The relation of the dust devil to larger scale circulations appears obvious and is discussed. It would appear that a thorough knowledge of the dust devil could lead to further knowledge of larger-scale circulations of the atmosphere. The purposes of this treatise will be well fulfilled if it is helpful in giving interested persons a better understanding of not only the dust devil but other larger and more destructive circulations as well.

1.1 Some Early Accounts of Dust Devils

Archaeological reports indicate dust devils being portrayed on the capitals of the Corinthian pillars of St. Sophia in Thessalonika, Greece which date back to the fifth century B. C. On these pillars acanthus leaves are shown being picked up by a whirlwind (23). Observers as far back as Aristotle, Pliny and Fulke made comments about the mystery of the "Whyrlewynde". Following Aristotle's teachings and text "Meteorologica", Pliny (28) had described the process of a freakish wind known as the whirlwind. Fulke (28) suggested, "a whyrlewynde some tyme is caused by meanes of twoo contrary wyndes that meete together." The whirlwind was commonly regarded with terror because of its ability to lift objects of considerable weight. In some cases the "exhalation" believed to form the whirlwind was supposed to become sufficiently hot to catch fire, and this flaming catastrophe, which often appeared as a pillar of flame, was called "prester" (28). It would seem that this was lightning in connection with thunderstorms. By the same token, however, it is not unlikely that thunderstorms, lightning and ordinary whirlwinds could have occurred more or less simultaneously with cold frontal passages.

Possibly the most epic whirlwind in history was the one that reportedly occurred (38) during Mohammed's first battle in 624 A.D. Awakening from a spiritual trance at a critical turn of the fighting, Mohammed impulsively picked up a handful of dirt and flung it toward his enemies with a holy curse. He mounted his horse and charged like a madman into the midst of the fray, followed by a very small dust devil that had curiously sprung to life from his cast handful of earth. As the wrathful prophet dashed forward it is said that the whirling spiral of dust behind him grew rapidly in size and speed until it drew abreast of Mohammed and swept with full fury into the masses of enemy swordsmen. In a few minutes the enemy was so blinded and confused by the unexpected storm that most of them turned and fled thus assuring the first Moslem victory.

1.2 Definition

For the purpose of this treatise a dust devil will be defined as a small but vigorous atmospheric circulation, created when highly unstable, superheated, dry air near the ground breaks through the boundary layer and shoots upward. We will also impose the restriction that the air has been superheated by solar radiation. Dust devils of this type have an average lifetime of a few minutes and are frequently rendered visible by debris from the ground whirled aloft by the updraft of rising superheated air. Dust devils are usually several yards in diameter and several hundred feet in height.

1.3 The Atmospheric Circulation Family

The dust devil is one of the smaller members of a whole family of circulations occurring naturally in the free atmosphere. The various members of this family are usually distinguished by orders of magnitude in their respective diameters. The "big daddy" of the family is the extratropical cyclone and its counterpart, the anticyclone, commonly referred to as "Lows" and "Highs" on the weather map. They generally have diameters of a thousand miles or more. Next in size is the tropical cyclone commonly called a hurricane or typhoon, characterized by an average diameter of a few hundred miles. Tornadoes, and their maritime counterparts, the waterspout, have average diameters of a fraction of a mile, while the diameters of dust devils and their maritime counterparts, small waterspouts, have average diameters of several yards.

As defined above, dust devils are distinctly different from other members of this family in that other members, in general, either create, dissipate, or are spawned by clouds. In the systems where cloudiness, and especially where precipitation is produced, a significant part of the energy sustaining the system is derived from the release of the latent heat of condensation.

Dust devils, on the other hand, seldom if ever produce condensation and consequently their primary energy source is the highly unstable superheated air in the boundary layer. Dust devils appear to be only indirectly related to cloudiness to the extent that cloudiness will reduce solar radiation which in turn will reduce the probability of the boundary layer becoming sufficiently superheated to produce the instability necessary for formation of dust devils.

1.4 Other Similar Small-Scale Circulations

There are several types of small-scale rotational winds which, although closely related to the dust devil, will only be mentioned briefly now, and then excluded from further discussion because they derive much or all of their energy from sources not included in the dust devil definition. These related small-scale circulations include: A. small waterspouts; B. whirlies; C. fire whirlwinds; and D. whirlwinds associated with cold fronts.

1.41 Small Waterspouts

Small waterspouts (or fair-weather waterspouts) are here considered to be the maritime equivalent of dust devils, and in general have similar sizes and shapes, but derive their energy primarily from conditionally unstable air (whereas the dust devil derives its energy primarily from absolute instability). That is, the small waterspout's source of energy is primarily due to high surface humidity rather than high surface temperature (7). Since the surface air over water does not usually become appreciably superheated except in connection with cold frontal passages (30).

1.42 Whirlies

Sir Douglas Mawson (37) reported a wind phenomena in Adelie Land, Antarctica that he called "Whirlies". He described them as violent, snow-carrying whirlwinds, sized from a few to over a hundred yards in diameter, and occurring on the slopes of Adelie Land in otherwise calm air. Mawson noted that these occurred about the time of the equinoxes during the years he was in Adelie Land (1911-1914). "The whirlies tracked about in an irregular manner and the high velocity of the wind in the rotating column was verified when one moved a 350 pound lid fifty yards, then later picked it up again and returned it to the originating vicinity by another "whirly". Over the sea they may lift brash 200 to 400 feet into the air, and form columns of water drops 4,000 feet high."

Humphreys (30) hypothesized that the whirlies were the by-product of low-level jet streams but more recent evidence by Shaw (44) indicates that the wind in the area of Mawson is usually katabatic. The lapse rate from Mawson to a point 2,000 feet up the slope averaged over nearly a year was super-adiabatic lapse rates even at night! It would, therefore, appear that Mawson's whirlies could be caused by thermal instability, possibly aided by dynamic wind factors.

Valtat et. al. (56) appear to have investigated this or some similar phenomena at the Dumont-d'Urville base in Adelie Land in 1957 and 1958 in considerable detail. They give a detailed description of two typical cases including synoptic evolution, upper-air evolution, and rapid variations in pressure, temperature and relative humidity. Biter and Stinson (3) have also made a significant contribution in this area.

1.43 Fire Whirlwinds

Graham (25) studied whirlwinds resulting from forest fires in the Pacific Northwest. He concluded that the most favorable condition for fire whirlwind occurrence is over a hot fire near the top of a steep slope with strong winds over the ridge top. Byram et. al. (11) have studied erratic fire behavior in the southwest. Glaser (24) and Hissong (29) have studied whirlwinds in connection with a huge bonfire and an oil tank fire respectively.

1.44 Whirlwinds Associated With Cold Fronts

Ockenden (40) recognized the existence of small rotary systems in advance of a true cold front in Iraq and discussed the problem of forecasting such whirls. Whirlwinds are also frequently observed in North Africa in connection with the violent turbulence incited by sharp cold fronts (21). Rows of whirlwinds have developed along the leading edge of steep cold fronts in Texas (59). Fortner, et. al. (19) report the occurrence of dust devils on the Kanto Plains of Japan which also appear to be associated with cold frontal passage. They point out that there were no indications of lapse rates exceeding the dry adiabatic, but this is evidently based on macrometeorological measurements rather than micrometeorological information.

Grant (26) observed whirlwinds in the vicinity of Goose Bay Labrador during the middle of a June day. These may have been associated with a cold front a few miles to the northwest. The surface temperature was around 60°F with a partial cloud cover of stratocumulus. The upper-air observation indicated a super-adiabatic lapse rate from the surface to 4,600 feet.

Sinclair (45) indicates that considerable whirlwind activity occurs in desert regions during the late winter or early spring. This occurs in connection with cold frontal passages when cold air flows over relatively warm ground. Only slight warming of the air behind the cold front is necessary to produce a super-adiabatic layer which in turn produces dust devils.

It is evident that whirlwind activity (including dust devils) depends primarily upon an unstable atmospheric temperature profile. That is, the magnitude of the surface temperature is only of secondary importance.

1.5 Damage Caused By Dust Devils

Dust devils are smaller and generally less violent than tornadoes but have on occasion been reported to change into tornadoes (7). Although this is certainly an exception, they should by no means be considered non-destructive in their normal state.

There is a record of a well-formed dust devil that struck the locomotive of a moving train in western Kansas with such force that the engineer could feel the cab shake, but no material damage was done (17). On the other hand, dust devils can do considerable damage to grain fields particularly near harvest time (57). There appears in the literature no record of dust devils causing structural damage to buildings (10) or causing loss of life but they have been known to break windows and hurl loose boards through the air (23).

Dust devils are also significant agents in the spread of debris and pollen. Their updraft may often be strong enough to carry objects as large as cornstalks or packing cases hundreds of feet aloft (35). In Linclonshire (England?) in 1897, what appears to have been a dust devil thinly covered an area of 5,000 acres with plants from sand dunes twenty-five miles or more away (4). Seeds, leaves, and dust thus travel far in this manner. The dust devil can raise debris and pollen many thousands of feet into the atmosphere and eject it into the free atmosphere resulting in a downwind fallout pattern that could cover a quite large area.

Frequently, the dust devil is more mischievous and annoying than damaging. Here are a few examples of such reports: The dust devil was of sufficient strength to raise an army type sleeping cot several yards into the air (20). In the Sahara Desert they have been strong enough to blow a man out of a tent (17). (It would also appear likely that one of this strength could do some damage to the tent.) Three people were caught up in a dust devil in Lubeck, Germany. Two men were in it for some time. Their clothes were flapping about vigorously and they had to hold on to their hats tightly. They had great difficulty in keeping their feet (22).

1.51 Dust Devils Vs. Aircraft Safety

"Aviation Weather" (53) indicates that dust devils produce strong lift for soaring but can be very violent. It is recommended that they not be entered below 500 feet above the ground and further point out that it is safer to avoid them entirely. Sinclair, however, has utilized an instrumented sailplane to measure the temperature and vertical velocity of dust devils (46).

Garbell (21) points out the fact that flight through a dust devil at high speed may produce accelerations in excess of the airplane design load factors. Since the high accelerations experienced during such flight can continue for only a fraction of a second, it is generally insufficient for the work of deformation exerted on the aircraft structure to rupture the primary structural parts of the airplane. Consequently, physical damage may not be noted despite the fact that the design loads of the aircraft were instantaneously exceeded.

Dust devils are certainly not to be treated lightly by pilots, especially pilots of light aircraft flying at low speeds. A Texas pilot nearly lost his life and airplane when he flew through a nearly invisible dust devil over a vegetated area where little or no surface debris was available to form a visible column (2).

Pilots intending to land on a superheated runway, especially in desert areas, should carefully scan the airport and an area 2-3 miles upwind for dust swirls or grass spirals to preclude the possibility of penetrating a dust devil at low altitude and near stall speeds. They should also be alert to the possibility of formation of a dust devil during the landing or takeoff maneuver and take evasive action if one forms along or crosses the intended flight path.

2. FORMATION

2.1 Optimum Locations (Macro and Micro)

Dust devils have been reported in many areas ranging from the tropics to as far northward as Canada (32), Scotland (43), and Iceland (latitude approximately 65°N) (22). The dust devils observed in Iceland occurred over vegetationless plains of black lava sand during the middle of the day and extended as high as 3,000 feet.

Ives (32) noted furthermore that dust devils are rarely seen in areas of deciduous forest, well watered grassland, salt marshes, or over lakes. He further noted that they are seldom seen over areas with pronounced topographical relief such as badlands, dissected plateaus, or mountains. On the other hand, Geiger (22) has noted that a favorite point of origin for dust devils is at haycocks, roadside slopes, piles of stone or at the edge of a plateau. At first glance these observations of Ives and Geiger may appear contradictory, but Geiger appears to imply a relatively level terrain with projections above the surface (or at the edge of the level surface in the case of the plateau). It would also appear that these projections were subject to superheating, but the point is that these objects offer a break in the lower boundary layer and act as an origin where the superheated air near the ground may begin to rise and finally escape in the form of a dust devil. By the same token in areas of pronounced topographical relief, such as badlands, the surface area to be heated would be significantly greater than a flat surface, much of this terrain would be orientated at a slope unfavorable for maximum interception of solar radiation, and if superheating did occur there could be enough projections of sufficient height to allow thermal relief through the boundary layer in a more common and less violent convection process.

A ship's officer in the Middle East (33), while navigating a river through a desert area, noted a large number of dust devils one day. He further noted that they would stop within about 300 feet of the river bank and gradually die down without coming any closer, the reason apparently being that the river offered sufficient advection of cool air to minimize significant superheating for some distance on either side of it.

In summation, if it were possible to make a world study of dust devil frequency, one would undoubtedly find a maximum of occurrence in the barren, arid regions of the tropics and sub-tropics with activity diminishing to near zero in similar areas of the polar regions. Likewise, activity at a particular latitude would range from a maximum over barren, arid regions to a minimum over well watered, well vegetated regions and regions with pronounced topographical relief, or with slopes having low solar incidence angles.

2.2 Optimum Time of Occurrence

As indicated above, high incident solar angles are more conducive to surface superheating and dust devil formation than are low incident solar angles. Consequently, one would expect a maximum of activity in the summer months and a minimum in the winter months. This is well verified by Flower's observations as extracted from Geiger (22) and presented graphically in Figure 1.

Sinclair (46) and Flower (18) working independently, with large samples, in different decades, and in the western and eastern hemispheres respectively have both indicated that the maximum of dust devil activity does not occur at the time of maximum temperature (as read in an instrument shelter some six feet above the ground) as one might first suspect but instead occurs around 1330 LST. This is more nearly the time of maximum solar radiation, or the time of the maximum ground level temperature and, therefore, it is also the time of the maximum temperature gradient in the lowest layers of the atmosphere. Flower's data as presented by Geiger (22) indicates the diurnal frequency distribution shown in Figure 2.

Figure 1. Probability of sighting a dust devil during a particular month. (From Flower's observations in the Eastern Mediterranean area 1927-1932).

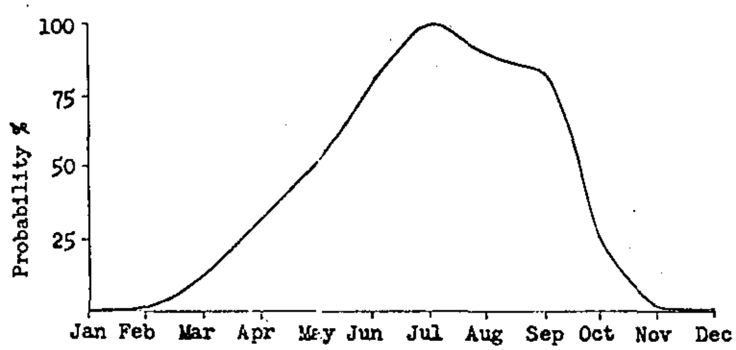
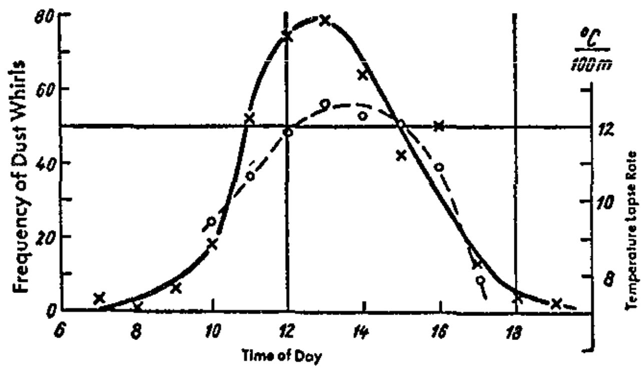


Figure 2. Frequency of dust whirls (continuous line) and temperature gradient from 4 to 50 feet (broken line). (After W. D. Flower)



2.3 Conditions Favoring Dust Devil Formation

A number of investigators have given conditions they found conducive to dust devil formation. Several of these factors have already been implied but they may all be summarized as follows: 1. Intense surface heating creating very steep lapse rates in the lowest few hundred feet of the atmosphere; 2. Cyclonic curvature in the upper-air flow; 3. Abundant surface material (dust, sand, etc.); and 4. Level terrain. There are, of course, a number of factors that are implied in these criterion, so each of these four prerequisite conditions will now be examined.

2.31 Factors Favoring Steep Lapse Rates Near The Ground

Steep lapse rates near the ground are favored by: A. large incident solar radiation angles; B. minimum cloudiness; C. low humidity; D. dry barren soil; and E. surface winds below a critical value.

A. Large Incident Solar Radiation Angles

Large incident solar radiation angles indicate that lapse rates (and dust devil activity) will generally tend to be greater in summer than winter and greater during the midday hours than at other times of day as discussed and verified by observations presented in sections 2.1 and 2.2.

B. Minimum Cloudiness

Clear skies likewise are conducive to more intense and uniform surface heating; however, this is certainly not to imply that dust devil occurrence is limited to those times when skies are clear. Sinclair (46) conducted an extensive dust devil census in small portions of Arizona and found that an increase of cloud cover from zero to two or three-tenths would decrease dust devil activity by approximately 50%.

C. Low Humidity

Low relative humidities are also conducive to steeper lapse rates in the surface layers due to the fact that water vapor is a strong absorber in the wavelengths of terrestrial radiation, but nearly transparent in the solar radiation wavelengths. Therefore, when atmospheric humidity (water vapor) is very low the terrestrial radiation is passed to outer space with a minimum warming of the atmosphere. With high humidity, the atmospheric water vapor absorbs much of the outgoing terrestrial radiation, in turn warming the atmosphere and thus reducing the temperature gradient between the surface and the lower layers of the atmosphere. Of course, high humidity favors cloudiness that would reduce activity.

D. Dry Barren Soil

If one were to consider the albedo (reflectivity) of various surfaces, Table 1, he might conclude that wet sand, forest, or sea surfaces would be the most likely places for extremely high lapse rates because these surfaces absorb much more of the solar radiation than does dry sand or desert surfaces. Such a conclusion would, of course, be incorrect.

Table 1

Surface	Solar albedo
Fresh snow	80-85%
Cloud surface	60-90
Old snow	40-70
Desert	24-28
Dry sand	17
Wet sand	9
Forests	5-18
Sea Surface	8-10

The reason lies in the fact that the thermal diffusivity of dry sand (0.0013 cm^2 Sec^{-1}) is much less than for wet soil (0.01 cm^2 Sec^{-1}) (42), the thermal diffusivity being the rate of heat penetration into the soil. Therefore, from a consideration of albedo, wet soil will absorb about 10% more solar radiation than dry sand, but the wet soil will conduct this heat away from the soil-air interface and into the lower soil layers 10 times faster than the dry soil. Thus, the resultant surface temperature (and atmospheric lapse rate) will be less with the wet, sandy surface.

In forests, the active surface (the primary receiver of solar radiation and primary radiator of terrestrial radiation) is at the crown level and there is greater opportunity for convection to disperse any significant excesses of heat that build up at that level. There are two reasons for this: 1. the active surface is not a solid surface like the ground; and 2. the thermal diffusivity of the air is from 20 to 10^7 times greater than for wet soil (Petterssen estimates the thermal diffusivity of still air to be 0.2 cm^2 Sec^{-1} and to range up as high as 10^5 cm^2 Sec^{-1} for stirred air (42).

In the same sense, barren soil will enhance excessive lapse rates. If vegetation is present, the active radiational surface is moved upward from the ground, the active surface becomes a non-solid surface, the ground becomes partially shaded and once again there is more opportunity for convection and breaks in the boundary layer created by the vegetation, etc. Also, some of the solar radiation is used in evapotranspiration and thus not available to heat the air.

E. Surface Winds Below A Critical Value

For the insolation type of dust devils we have limited ourselves to, it is recognized that the surface winds must be below some critical value. Although this value hasn't been well defined, it would appear that the threshold value would be in the neighborhood of 5 mph measured at the standard height of 30 feet. Typical wind speeds associated with the greatest dust devil activity are 1 to 10 mph (45). Brooks (7) further indicates that the wind field should be slightly irregular but gives no explanation or quantitative values; however, it would seem that an irregular wind field would enhance eddy motion and in turn enhance vertical motion.

The necessity for restricted wind movement is due to the fact that the air layer adjacent to the ground then has a laminar structure that may often reach a depth of five feet and may exceed this depth by a considerable amount upon occasion (22). For wind speeds in excess of the threshold, the air movement becomes turbulent, the thermal diffusivity increases tremendously as indicated above, and heat is conducted away from the surface quickly enough that there is no longer significant superheating in the layer of air near the ground.

2.32 Potential Lapse Rates Near The Ground

Meteorologists have long recognized that atmospheric processes on a macroscale may be assumed to be adiabatic and atmospheric flow to be turbulent. In recent years however, they have been forcefully confronted with the fact that micrometeorological processes are not adiabatic (they are diabatic) and flow is frequently laminar. The adiabatic assumption is not valid in the boundary layer because with slight increases in height (and nearly negligible pressure changes) there may frequently be very pronounced changes in temperature. With this in mind, let us briefly review the classical adiabatic concepts of atmospheric instability.

The dry adiabatic lapse rate was defined as the critical lapse rate between stability and instability for a parcel of dry air. At this critical lapse rate a parcel of dry air displaced either upward or downward will continue in the direction of displacement; but, it must be noted that this instability will not be realized until, or unless, the parcel is displaced, i.e., given a push by some external force such as an eddy of wind. The dry adiabatic lapse rate was derived from the hydrostatic equation in elementary meteorology and found to have a numerical value of about 1°C/100m.

In the free atmosphere, superadiabatic lapse rates not only occur rarely but when they do occur they surpass the adiabatic rate by only a few tenths of a degree. In the layer of air near the ground, however, superadiabatic lapse rates are probably the rule rather than the exception during clear days without snow cover.

The autoconvective lapse rate is defined as the lapse rate of temperature in an atmosphere in which the density is constant with height, and is equal to g/R where g is the acceleration of gravity and R is the gas constant. Numerically, this lapse rate becomes 3.4°C/100m. This is based upon the hydrostatic equation which assumes among other things that frictional terms are negligible compared with those involving the vertical pressure force and the force of gravity. These assumptions are not valid in the boundary layer; in fact, measurements have shown that during sunny days atmospheric density frequently increases with height at a phenomenal rate in the lower few feet of the atmosphere. Kendrew (34) indicates that, in parts of the tropics, the lapse rate is superadiabatic from the surface up to about 500 feet on most afternoons in the dry season, and Sutton (54) gives measurements made near a closely cropped lawn on a hot day in summer where it was verified that temperature gradients may be as much as 30 times the autoconvective lapse rate.

When the autoconvective lapse rate is exceeded and density increases with height, inferior mirages and terrestrial scintillation may be noted. The frequency and distribution of such lapse rates can be reasoned from the frequency of observing "puddles of water" over superheated highways, "lakes" on the desert, and "heat waves" rising from the horizon, roadways, etc. However, superautoconvective lapse rates occur much more frequently than one would suspect from this reasoning.

It is the presence of viscosity and radiative heat transfer that usually prevents the occurrence of rapid overturning when the autoconvective lapse rate is exceeded. Consequently, if a layer of heated air near the surface is undisturbed, the lapse rate may exceed the autoconvective without convection taking place automatically.

Williams (60) has investigated this in some detail and indicates that fluid having an increase in density with height can remain in equilibrium so long as the density distribution does not exceed certain limits. From the equations given, and for realistic conditions averaged over a depth of 10 meters, the critical lapse rate became 21°C/100m, or 21 times the dry adiabatic lapse rate. For very shallow layers near the ground, say in the depth of 1 meter, the critical value could become about 21°C/m, or 2100 times the dry adiabatic rate and 600 times the autoconvective lapse rate.

Ives (32) has observed lapse rates of up to 32.8°C/m in the lowest foot of the atmosphere under optimum conditions, while Ohman and Pratt (41) have measured temperature lapse rates over the desert southwest in excess of 70°C/m in the lowest 2 inches of the atmosphere, during winter!

Geiger (22) relates an experiment where lapse rates were measured above an electrically heated plate. A temperature difference of 10°C was measured between the surface of the plate and a height of 1/10 mm, which is a lapse rate of 10^5 °C/m. It appears there a need for further investigations into both the actual and theoretical lapse rates possible within the lowest meter of the atmosphere.

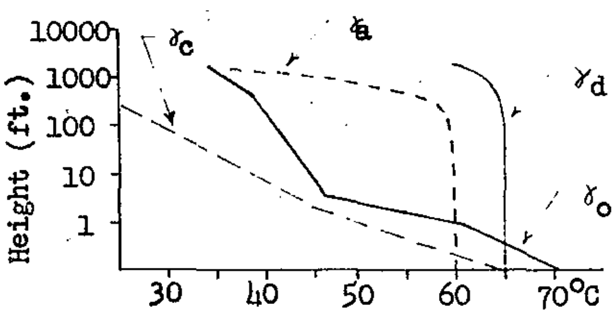
The above facts, of course, lead one to wonder how such excessive lapse rates can maintain themselves in a manner which seems to disobey the laws of the environment. The answer is that the dynamics of free convection is complicated by the fact that any motion initiated by density differences is at once modified by the action of viscosity and conduction. Thus, what at first appears to be a relatively simple problem of a shallow layer of fluid heated from below, expands to a situation where vertical motion does not occur immediately, since the diffusing action of conduction and viscosity tends to smooth out differences of temperature and velocity (54).

Humphreys (30) points out that it is virtually impossible for an extensive layer of warm, light air at the surface of the earth to all rise at the same time. It must rise locally and in streams if at all. Similarly, the upper air must settle locally if at all. That this actually takes place is evident from the observation of terrestrial scintillation or shimmer.

Ives (32) indicates that there may be an upper limit to the amount of thermal relief which can be brought about by strictly thermal convection. He has estimated that lateral migration of hot air to cooler regions may account for 50% of the surface thermal relief (an extreme example would be the peripheral anabatic desert basin winds), while vertical convection accounts for 20% of the thermal relief and dust devils and similar small vortices must, therefore, account for the remaining 30%.

All of this, of course, leads one to wonder what magnitude of lapse rates are necessary for the formation of dust devils. Ives (32) measured temperatures at 0, 1, 5, 500, and 2,000 feet above ground level during a "Great Basin High" when there were frequent occurrences of dust devils. This information has been consolidated in Figure 3 to give

Figure 3.
Observed lapse rate (γ_o)
Dry adiabatic rate (γ_d)
Autoconvective rate (γ_a)
Critical lapse rate (γ_c)



a better concept of the necessary magnitudes of the lapse rate at the various levels with respect to the various theoretical lapse rates derived from fluid dynamics. (The critical lapse rate given in Williams (60) was computed only for depths of 1 and 100 meters.)

Sinclair (45) measured vertical lapse rates from the 7 to 31 foot level in three dust devils, and they ranged from 63 to 101 times the dry adiabatic. Data between the 17 and 31 foot levels indicated an inversion of up to 31°C/100m in the leading edge of the dust devil. This is attributable to the fact that the dust devil tends to lean forward. Therefore, along a vertical line, warmer temperatures arrive first at the upper (31') level, and then increase downward.

Since dust devils frequently occur when lapse rates at eye level exceed the autoconvective, dust devils and inferior mirages may be observed simultaneously. Dust devils may in fact occur "within" an inferior mirage. When this occurs, Ives (32) indicates that the mirage is disrupted near the base of the vortex and the dust devil appears to "eat a hole" in the mirage.

2.33 Favorable Air Flow

Sinclair (46) reported that dust devil activity was enhanced in a location downwind from the mountains. Application of the vorticity equation flow over a mountain barrier indicates that the net result is cyclonic curvatuve in the flow pattern (26). Low-level cyclonic curvature would result in a positive vertical velocity (because of friction) which should indeed enhance the overturning of strongly superheated air in the boundary layer. It is interesting to note that Graham (25), while studying fire whirlwinds, appears to have reached this same conclusion. (Graham fails to mention whether the favorable location is upwind or downwind from the ridge crest. He only states that the most favorable location is near the top of the ridge with strong winds over the top of the ridge.)

It would appear likely that, in addition to cyclonic curvature, the presence of lee wind eddies would be a significant enhancing factor in initiating dust devils. On the other hand, it would appear that winds over a ridge would merely be an enhancing factor and should by no means be imposed as an absolutely necessary requirement for dust devil formation.

2.34 Abundant Surface Material

Some investigators have mentioned abundant surface material, in the way of dust, loose debris, etc., as one of the factors favoring dust devils; however, it does not seem that this is a valid requirement. Probably what they meant was that abundant surface material was a near necessity for sighting dust devils and this is then certainly a valid requirement. As was mentioned earlier in the discussion of damage caused by dust devils (Section 1.5), and particularly in connection with aircraft safety, dust devils do not necessarily contain dust or debris in sufficient quantities to make them readily visible. Yet there can be little doubt that the basic circulation thus encountered is nearly identical to one which is rendered visible by the surface material drawn into its circulation. In fact, an "invisible" dust devil is made visible upon passing over an area of abundant surface material. However, it is possible that the electrical properties of the system could change with varying densities of debris.

From a strictly theoretical point of view, it would seem that a perfectly smooth unbroken surface would be more conducive to dust devil formation. The exposed surface area for a surface covered with small clods, pebbles, debris, etc., would be considerably larger than that of a perfectly flat smooth surface. Therefore, any given amount of incident solar radiation would be spread over this larger surface area, in turn reducing the surface temperature - and the temperature gradient in the boundary layer.

2.35 Level Terrain

This is another interesting point which has not been elaborated upon in the literature. Theory would provide at least one positive and one semipositive argument on this subject. First it is obvious, and has been frequently shown in micrometeorological studies, that a slope inclined more nearly perpendicular to the incident solar beam will receive more radiant energy, become generally warmer in daytime, etc.

On the other hand, it may be possible that any significant slope would be sufficient for superheated (light) air to "rise up the slope" and escape, say at a ridge, in a larger and less violent manner of convection. By the same token, if a favorable slope tended to converge to a point rather than a ridge, it would seem that dust devil activity would be enhanced at the summit. As was noted in Section 2.1, Geiger (22) has noted that a favorite point of origin is at roadside slopes, and at the edge of a plateau.

It would appear, therefore, that one should not be too hasty in including level terrain as a rigid condition favoring dust devil formation, but should consider instead a number of factors such as inclination, orientation, length, physical shape, etc., of a slope, before eliminating it as having potential for formation of dust devils.

2.4 Triggering Devices

As we have seen, it is not uncommon for density to increase markedly with height in the boundary layer, and since the entire layer of superheated air cannot rise at once it has been postulated by a number of authors that some triggering device may be necessary to produce an initial disturbance allowing the superheated air to "break" through the boundary layer and begin to rise. If a disturbance allows an unusually large volume of warm air to rise from the surface, it will rise in a columnar form. Such a column necessarily produces a chimney like draft, since the air composing it is warmer and therefore lighter than the adjacent air on the outside. Once established, such a column of warm air will maintain and perpetuate itself so long as the air that is forced into its base is warm and light (30).

The dust devil may be triggered by some chance happening, perhaps at a pile of rock at the edge of a wood, at the confluence of extreme heat sources such as a road intersection, or by air set in motion by the activity of small animals (23). Ives (32) has noted that in some instances the path of a jackrabbit or a coyote across the desert is marked by a succession of small dust devils, indicating that the movement of these animals has created eddies of sufficient magnitude to trigger the dust devils. Thus, the creation of eddies (relative vorticity) by some means or other, seems necessary, or relief of the temperature extremes will be by non-rotating plumes that will not be so readily noticed nor be of concern.

2.5 Size and Shape

A typical dust devil is shaped roughly like a cone, with the apex near the ground and the base some distance above ground level. They are generally several yards in diameter at the base and may narrow for a short distance upward then expand again, like two cones apex to apex.

The height of dust devils varies over wide ranges, but normally they are only visible up to heights of from one-hundred to three-hundred feet (31). Frequently, however, tropical and subtropical dust devils may have a visible height in excess of 5,000 feet (21). Sinclair (46) has detected the invisible disturbance at altitudes up to 12,500 feet above ground level. The detectable disturbance at that level has a diameter of from one-fourth to as much as one mile.

From observations on the "high plains" Warn (59) reported base diameter variations of from one to fifty feet (with a few ranging up to one-hundred fifty feet), an estimated height range (visible height) of twenty-five to four-hundred fifty feet with no consistent ratio between diameter and height. Fortner et. al. (19) reported "dust whirls" up to a mile in diameter in Japan but these appear to be associated with cold frontal activity.

2.6 Dust Size and Distribution

Dust devils are, of course, made visible by the dust and debris drawn into their intense circulation, and as pointed out earlier they may form or drift over areas with such a limited supply of loose surface material that they are "invisible" aloft and detectable only through observation of the surface vegetation (grass, trees, etc.), or through physical measurement. The load of dust in a well-developed dust devil may be quite large (35); however, the only indication of the order of magnitude of the dust load comes from the observation of a "stationary" dust devil observed by Ives (32) near Altar, Sonora, Mexico. This dust devil hovered over a spot where a railroad embankment was under construction and removed about a cubic yard of sand per hour for four hours.

The centrifugal action of the vortex has the effect of keeping the larger particles in the outer portions of the vortex making a graduation of progressively smaller particles toward the center. Sinclair's measurements on the Arizona Desert (46) indicated dust particles within dust devils ranged from 10-100 microns in diameter. His measurements also verified the fact that dust density decreases rapidly with height. This is due to the expansion of the vortex with height and the consequent relative dispersion of the particles, i.e., the initial concentration is spread over an expanding area as the vortex expands. He has gathered samples of dust borne up by the dust devil at altitudes of up to 15,000 feet.

Ludlam (36) indicates that if dust devils extend up to the condensation level there is not normally any rotation to be seen in the cumulus cloud formed at the top. There appears to be very few recorded observations of dust devils forming clouds or extending to cloud bases; however, a report from the Middle East describes a "spout connecting to the cloud base" (33). It appears that this was an unexperienced dust devil observer.

Under favorable conditions a number of dust devils may be visible at one time. The report from the Middle East indicated thirty well-developed dust devils visible within a radius of about four miles, and Warn (59) simultaneously viewed up to 16 within a radius of fifteen miles.

2.7 Duration

Although favorable conditions for dust devil formation persist over deserts for several hours during the middle of summer days, few dust devils have been observed to last for even a fraction of that time. Typical observed lifetimes are of the order of seconds or minutes. It should be pointed out that dust devils are usually observed only when sufficient surface debris is available to make them visible. Their actual existence, however, is not dependent upon a source of visible debris. Consequently, populations may be greater and durations considerably longer than indicated from visual observations. Population and duration figures must be interpreted with this in mind.

Sinclair has undoubtedly conducted the most intensive and well-planned study of dust devils on record. His results of a dust devil census conducted over both flat desert terrain and populated areas showed that, of 2152 medium (10-50 ft. diameter) and large (50-100 ft. diameter) dust devils, 95% had a visible life cycle of four minutes or less (48).

According to Flower (18), the duration of the majority of the cases he observed was of the order of several minutes, but not over 20 minutes and one-fourth of all cases lasted less than 30 seconds. There have, however, been a number of cases where these "average" lifetimes have been greatly exceeded. In Utah, for example, a dust devil some 2,500 feet high was observed continuously for seven hours along a thirty-five mile path (23); another near Cairo, Egypt lasted for five and a half hours (17).

Until recently, the literature has occasionally contained a rule of thumb between the altitude of the visible dust devil column and its lifetime (7, 32, 35, 38). This rule stated that the dust devil would last an hour for each thousand feet of height, provided it didn't travel out of the favorable geographical environment or into a cloud shadow. However, it appears that this rule is frequently incorrect.

It appears that a dust devil can continue to exist, if stationary, until it exhausts the available supply of heated air, or if in lateral motion, until it travels out of a favorable environment. For stationary dust devils, a life cycle of approximately eight hours might be possible; however, few have been observed to last more than a couple of hours.

2.8 Direction of Rotation

The direction of dust devil rotation has nurtured considerable controversy in years gone by. It was correctly postulated that dust devils had lower pressure in their centers; therefore, it was felt that cyclonic rotation should result, as had been observed with large-scale systems. Authors pointed out that there was some difficulty in actually determining, with certainty, which direction the vortex was rotating, and that a clockwise rotation viewed from ground level would appear counterclockwise if viewed from above. Results of early investigators (18, 58) even indicated that large dust devils had a preference for cyclonic rotation.

It is most meaningful to indicate sense of rotation as cyclonic or anti-cyclonic. These are meteorological terms which are valid whether viewed from above or below, and there is no ambiguity when considering data from both the northern and southern hemispheres.

Sinclair (49) reasoned that since there is usually a direct relationship between dust devil height and diameter, one might use either one or both to distinguish large or small dust devils. He shows that if diameter is used to distinguish a large or small dust devil, all the information from available past records indicates a preference for cyclonic rotation for the largest and smallest dust devils. For intermediate diameters, there appears to be no significant preference for direction of rotation. On the other hand, if height is used as a criterion for dust devil size, the data show there is a slight preference for anticyclonic rotation for tall dust devils and considerable preference for cyclonic rotation for short ones. For all heights between 20 ft. and 2000 ft., there is in general little preference for either direction of rotation. The chi-square test indicated these features to be statistically significant at the 5% level.

Sinclair (49) then presents data (Table 2) from a number of independent sources and geographical areas which show that if size classifications are disregarded, dust devils have no preferred direction of rotation. Only for the

Table 2. Observations of dust devil sense of rotation.

Direction of Rotation	Flower (1936)	CDOP	McDonald (1960)	Sinclair	Williams (1948)	Brooks (1960)	Durward (1931)	Total
Cyclonic	199	53	9	60	9	100	30	460
Anticyclonic	175	35	29	84	12	0	0	365
Total	374	88	38	144	21	100	30	825

very largest - or smallest - dust devils might this conclusion be questioned. Table 2 contains data from five independent sources (the questionable data of of Brooks and Durward are clearly evident). The data labelled CDOP (Cooperative Dust Devil Observation Program) were gathered by Institute of Atmospheric Physics personnel and other interested persons in the Tucson area during 1960-63. The McDonald (1960) data were collected by Professor James E. McDonald in the southwestern United States. Flower (1936) made his observations in Egypt and Iraq; Williams (1948) examined dust devils near

Inyokern, California. Sinclair's data were taken in the desert near Tucson during 1960-62. It is believed that as more data are collected, the entire frequency distribution of dust devil size (with respect to diameter or height) will not be significantly dependent on sense of rotation.

Sinclair has further indicated that the frequency of cyclonic and anticyclonic dust devils is about the same in any given area at the same time.

It may be shown from the basic equations of motion that large-scale low pressure areas acquire cyclonic vorticity and large-scale high pressure areas acquire anticyclonic vorticity due to the influence of the earth's rotation (coriolis effect); however, when the radius of the vortex becomes small the coriolis effect becomes small and insignificant compared to the other terms of the equation. Sinclair (49), in an order of magnitude analysis, shows that near and within the dust devil the coriolis acceleration may be three to five orders of magnitude smaller than the accelerations produced by the pressure gradient force. At large distances from the visible dust column these analyses show the effect of the coriolis acceleration to be insignificant by orders of magnitude.

It appears, therefore, that the triggering device which creates an eddy of sufficient size to start the "chimney" of the dust devil also determines its sense of rotation. The incoming surface air is therefore initially directed to one side of the vortex and as the angular momentum thus established tends to remain constant, a correspondingly vigorous whirl is developed (30) and the initial sense of rotation persists.

Observers have noted dust devils which have almost come to the end of their existence, then revived themselves after coming into contact with an obstacle, but now rotating in the opposite direction (23,32). It would seem likely in these cases that the rotation of the dust devil may have been completely stopped momentarily and then triggered again, by an eddy from the obstacle.

2.9 Lateral Speed and Direction of Movement

Field observations indicate that the trajectory of a dust devil is largely controlled by local topography if little or no wind is present, i.e., they seek higher terrain. However, when the local wind reaches 3 or 4 mph, the wind and not the topography becomes the main controlling factor (32). For example, Murchie (38) reports dust devils working their way uphill while bucking a 3 mph prevailing downslope breeze. Ives (32) noted that dust devils in bowl-shaped basins follow a regular spiral course on windless days. They start in the center of the basin and spiral outward (uphill) in a counter-clockwise fashion (although the vortex itself rotated either cyclonically or anticyclonically). He also noted that when a dust devil reaches the peak of a topographical "hump" it will tend to remain there (even if the "hump" is minor in size).

It will not usually descend a slope, even if aided by a wind. It will, however, move across a slope with little deviation, unless influenced by a local wind. When a dust devil encounters a small topographical depression (such as a ditch or small wash) it usually "jumps" the depression, and the plan view trajectory remains straight for all but acute incident angles.

If a dust devil migrates to or originates over a small topographical hump, it may remain there for an extended period, usually removing all loose dust and other light debris from the immediate vicinity. This commonly occurs in flat desert areas over large anthills. An extreme case was observed during the construction of a railroad embankment near Altar, Sonora, Mexico. In mid-morning, a large dust devil suddenly appeared at the end of the embankment and remained there for four hours. The dust devil was broken up by parking a bulldozer at the end of the fill.

More frequently, however, dust devils move slowly and erratically in a fairly definite direction, appearing to move from one patch of superheated air to another. The net travel of a migratory dust devil is about the same (with respect to speed and direction) as that of the local wind, although the base tends to wander (31,32).

Sinclair (48) in his census of over two thousand dust devils noted that the translational speeds were approximately 8-15 mph. The magnus effect has been noted to affect the path of dust devils, in that their path curves toward the side that is moving forward (36), especially as they die down. That is, when the rotation is clockwise, the lateral course of the dust devil as it dies out is counterclockwise, and vice versa. This turning from the direction of the wind has been observed to continue until in its final moment the dust devil sometimes for an instant stands directly against the wind (22). (The magnus effect produces a force which acts at right angles to the approach velocity and is a result of fluid flow about a solid rotating cylinder.)

3. QUANTITATIVE MEASUREMENTS OF METEOROLOGICAL VARIABLES

3.1 Instrumentation

Prior to the observations of Sinclair in the early '60's, there had been only limited quantitative measurements made within dust devils. Many of these earlier measurements were the result of chance, such as a dust devil passing over an instrumented site. Both these measurements and those that were deliberately made within dust devils were almost without exception non-representative because the instruments used were not sufficiently responsive or sensitive to give satisfactory measurements of the meteorological variables within dust devils.

However, in recent years there has been an increasing awareness of the need for smaller, more sensitive, and responsive instruments in many fields. This has been particularly true in the area of temperature measurements. The development of small sensitive and responsive electrical sensors, connected to equally sensitive and responsive recorders has presented the experimenter with the instrumental capability of satisfactorily measuring the temperature profile within a dust devil.

Similarily, in the area of wind measurements, instrumentation capabilities have advanced tremendously in recent years, prompted to a large degree by the increasing concern with air pollution. At any rate, the principles of sensitive, responsive wind instruments have been set forth and it is now possible to buy or design instruments with small moments of inertia, small overshoot, and very short distance constants, i.e., instruments capable of accurately measuring the wind profiles within the dust devil. When connected to an equally sensitive and responsive recorder, it is also possible to obtain sufficient readings over a short period of time to "map" a representative wind profile along the horizontal and vertical axes.

Techniques, principles, and sensors for measuring small, rapid, fluctuations in atmospheric pressure have not developed to the degree or at a pace comparable to the advancements in the fields of temperature and wind measurement. Pressure instruments of sufficient range, response and sensitivity to measure the pressure profile encountered in dust devils had in fact received very little attention prior to Sinclair's investigations. This no doubt was the fact that prompted Sinclair to design and construct a small, highly responsive pressure instrument, which he called a microbarophone (48). The microbarophone has a sensitivity of approximately 0.1 mb which can be reached in approximately 0.16 sec. Although he obtained reasonably good results with this instrument, he has made suggestions for further improvement.

There have been reports of electrical field and space charge measurements in the vicinity of dust devils. These observations have resulted as a matter of chance, however, and it once again appears that the instruments used were not sufficiently sensitive and responsive to give more than a general idea of the actual electrical profiles which may be associated with dust devils. There appears to be no present effort to design instruments and make measurements of this kind, but the measurements currently available will be presented in a later section (3.6). From a consideration of the measurements already made, the lifetime, size, and translational velocities likely to be encountered, interested experimenters will be able to make an intelligent determination of the physical size, magnitude of range, response, and sensitivity needed to design instruments which will accurately record or map the electrical properties of dust devils.

3.2 <u>Horizontal and Vertical Velocity Profiles</u>
It is interesting to briefly review the early observations and efforts to measure the wind field within dust devils. Brooks (6) noted that the horizontal rotation and upflow within a dust devil usually exceed 20 mph but that this undoubtedly varies somewhat with the size of the dust devil.

By watching pieces of paper and other debris, Flower determined that dust devils rotated at a rate of six to thirty-six revolutions per minute (18). Fixed recording stations recorded velocities that changed from near zero to 50 to 90 mph in one-half to one and a half minutes; however, these values are highly questionable due to the slow response and large overshoot of most instruments of this type. Engineering computations applied to damage caused by large dust devils in one instance indicated that damage did not exceed that expected for linear winds of 150 mph (32).

Ives (32) approximated the vertical velocities within dust devils by noting that small animals were often swept aloft by dust devils. He then obtained the free fall velocities of the species by dropping them from a tower, and assumed that the vertical velocities in the dust devil were at least equal to the free fall velocities of the animals. He found the free fall velocity of kangaroo rats to be of the order ot 25-30 mph while cottontail rabbits and jackrabbits attained velocities of 35 mph or greater.

Sinclair (50) presents the quantitative results of four dust devil penetrations on the Arizona Desert near Tucson. These results are reproduced in Figures 4, 5, 6, and 7. The pressure units can be converted to millibars by use of 1 "pressure unit" = $5x10^{-2}$mb. The tilt angle refers to the number of degrees that the mobile recording system was tilted away from vertical and indicates where corrections have been applied and/or where the data may have a tilt angle error.

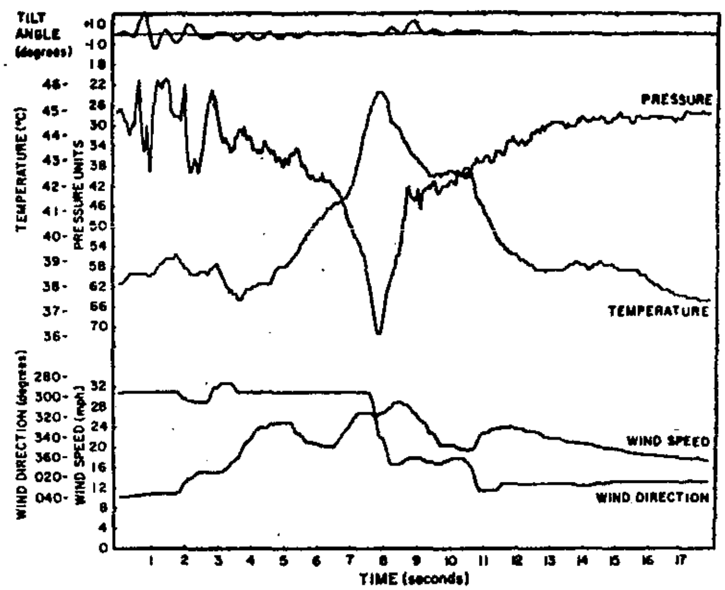


Figure 4. Temperature, pressure, and horizontal wind velocity measurements through a dust devil on August 2, 1960, 1230 MST. From Sinclair (50).

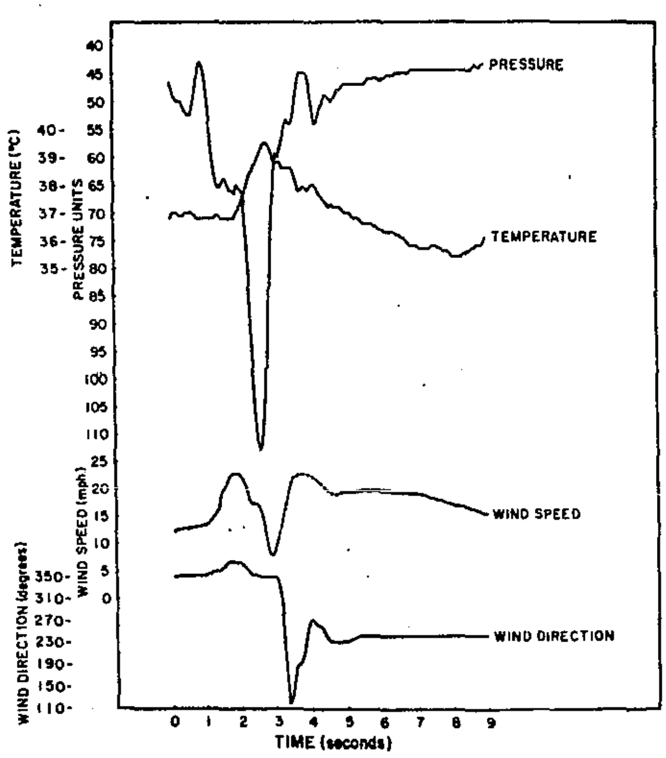


Figure 5. Temperature, pressure, and horizontal wind velocity measurements through a dust devil on July 19, 1960, 1305 MST. From Sinclair (50).

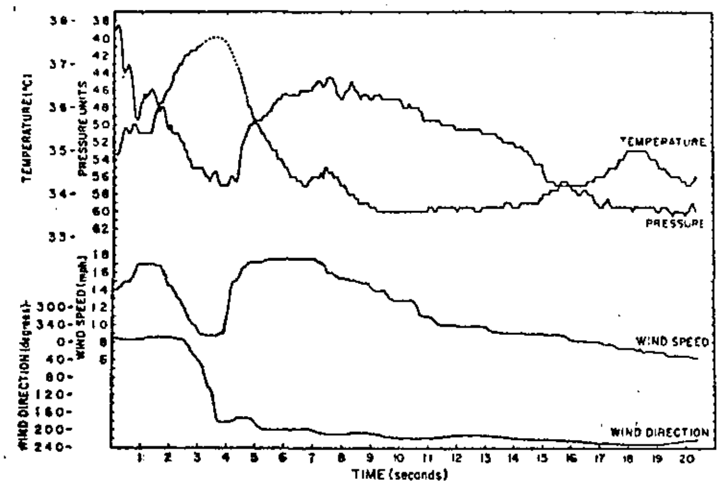


Figure 6. Temperature, pressure, and horizontal wind velocity measurements through a dust devil on July 14, 1960, 1330 MST. From Sinclair (50).

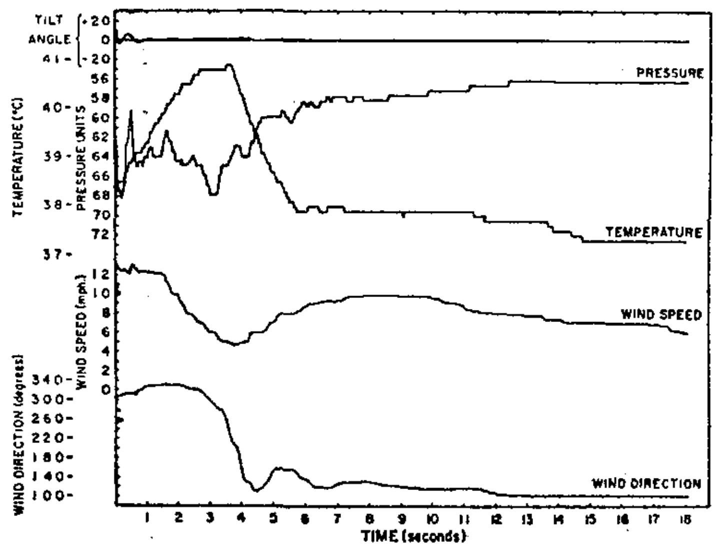


Figure 7. Temperature, pressure, and horizontal wind velocity measurements through a dust devil on August 30, 1960, 1435 MST. From Sinclair (50).

All four dust devil penetrations show the anticipated warm core, low pressure center. The temperature rise varied from almost 9°C for the largest dust devil (Figure 4) to 3.5°C for the smallest one (Figure 7). An interesting temperature feature of the two most intense dust devils, shown in Figures 4 and 5, is that the temperature gradient is less steep in the rear than in the front of the dust devil, where front refers to that portion of the dust devil which passed over the mobile recording system first. This may be related to the difference in wind fields in these two regions but further measurements are needed before this can be determined. The dashed portion of the temperature trace in Figure 6 indicates a partial loss of data as a result of a temperature range change during the dust devil penetration.

An experimental study of atmospheric convection in the lowest 100m, under conditions of strong surface heating and light winds was carried out by Myrup (39). Using an instrumented light aircraft, measurements were made of the fluctuating temperatures and vertical air speeds over a desert dry lake during the daytime. It was found that the atmospheric active regions (rising thermal plumes) characteristically have an asymmetric temperature distribution with the warmest temperature usually found close to the upwind side of the active region. There are indications of a slightly asymmetric temperature distribution in the data presented by Sinclair (50).

The total pressure drop varied from 2.3 mb (Figure 4) for the largest dust devil to 0.6 mb (Figure 7) for the smallest dust devil. The largest pressure drop is shown in Figure 5 and is equal to 3.5 mb. Because the pressure instrument is underdamped, these total pressure drops are somewhat in error due to excessive "overshoot". By impressing a continuous sinusoidal pressure oscillation on the instrument with a pressure generator, it was found that at 0.5 cps the instrument had a maximum "overshoot" of 30%. Consequently, the pressure pulse shown in Figures 4 through 7 should be reduced by about 1/3. Therefore, the largest actual pressure drop as shown in Figure 5 would more likely be 2.4 mb. For continuous correction of the pressure trace, the pressure generator data showed that smoothing the trace using a running mean over 0.9 second intervals resulted in a smoothed pressure trace that was a good approximation to the actual pressure trace.

Because of the relatively slow response of the Windial, the wind data are probably most accurate in the time interval preceding the passage of the dust devil center. The dust devil center is assumed to be near the pressure minimum and the closely related temperature maximum. In general, the wind speed traces show two maxima, one on either side of the low pressure center. The exception shown in Figure 4 may be the result of an off-center penetration of an eccentric vortex (note that the wind direction change was only 90 degrees). In the other cases, the change in wind direction seems indicative of a center penetration of a symmetrical vortex. The dashed portion of the wind speed trace in Figure 5 is the best estimate of what actually happened. (The actual record was missing as a result of the slow response of the Windial. The Windial did not immediately respond to the change in wind direction, with the result that the propeller turned backwards at a rate of more than 20 mph.)

More recent surface measurements by Sinclair (46), which included temperature, pressure, and wind velocity measurements at two levels simultaneously, revealed that the tangential flow is consistent with a Rankine vortex. He also found that the dust devil is non-hydrostatic since the vertical velocities exceed the theoretical velocities which would be obtained when the buoyancy equation was applied to the observed temperature profile.

Sinclair's upper-air measurements by sailplane (50) indicated that the vertical velocity structure extended to a considerable distance above the visible dust column (often to altitudes in excess of 12,000 feet above ground level). The vertical motion experienced above dust devils of this size was found to range from a few hundred feet per minute to 2,000 feet per minute, i.e., from a few mph to over 20 mph. The size of the updraft region increased with height and was found to have diameters ranging up to a mile at altitudes of around 12,000 feet above ground level.

Sinclair's measurements revealed that there is strong radial inflow near the surface which diminishes as the visible dust column is approached. In the region of the dust column, the air is spiraling upward much in the form of a helical vortex. As the center of the dust column is approached, a downward vertical circulation is encountered in a core surrounding the symmetry axis. As a result, the vortex features of the dust devil have a marked similarity with other atmospheric and some laboratory vortices.

3.3 Temperature and Pressure Profiles

As indicated in Section 3.2, Sinclair has shown there is a sharp maximum of temperature and a sharp minimum of pressure at the center of the dust devil. He found (47) that one can expect a total pressure drop of 2 to 3 mb from the immediate environment (within a radial distance of 10 to 100 m) to the center of the dust devil. This is equivalent to a pressure gradient of some 50 mb per mile. Sinclair recorded a maximum pressure drop of 3.5 mb in a distance of 30 feet; however, substantially larger gradients will undoubtedly be encountered when accurate tornado pressure measurements are made.

3.4 Moisture Profile

There appears to have been little, if any, effort to measure the moisture profile in the vicinity of dust devils. There may be several reasons for this: (1) instrumental limitations; and (2) investigators may have felt it was a relatively unimportant parameter, especially in view of the difficulties of measurement posed by instrumental limitations. Probably the smallest, most sensitive, and responsive instruments currently available are the thermocouple and resistance type psychrometers. However, it would require some investigation to determine if there were any method currently available to satisfactorily measure the moisture profile in dust devils. An added difficulty would be the very low moisture to be measured.

From the data presented in sections 3.2 and 3.3, one would intuitively suspect, however, that the relative humidity in the rising column of air just outside the vortex would be slightly higher than the environmental relative humidity near the ground, and that the relative humidity would increase with height in the area of vertical updraft due to lifting. By the same token, one would expect relative humidity to decrease downward within the downdraft area due to compression.

3.5 Inclination of The Vertical Axis

Geiger (22) indicates that the vertical axis is usually vertical or inclined slightly forward with height (forward with respect to the lateral movement). Murchie (38) states that when the surrounding wind fields are turbulent, dust devils often contort themselves into curves, corkscrews, or leaning angular figures, sometimes scores of them in one apparently coordinated ballet. He has seen them lay nearly horizontal, "steamrollering across the Mexican desert, now bounding over the hillocks, now tilting vertically to rise a thousand feet, now leaning downward again before the dry hot wind".

3.6 Electrical Measurements

Freier (20) was making electrical field measurements in the Sahara Desert in September 1959 when a dust devil passed within about 100 feet of the field mill. The dust devil was estimated to be between 300 and 600 feet high and about 25 feet in diameter. The recorded profile he obtained is shown by the solid line in Figure 8. It shows a maximum potential gradient depression of about 440 volts per meter. The two negative excursions with a tendency to go positive between them suggest a sort of dipole structure for the dust devil with negative charge above (inverted thunderstorm).

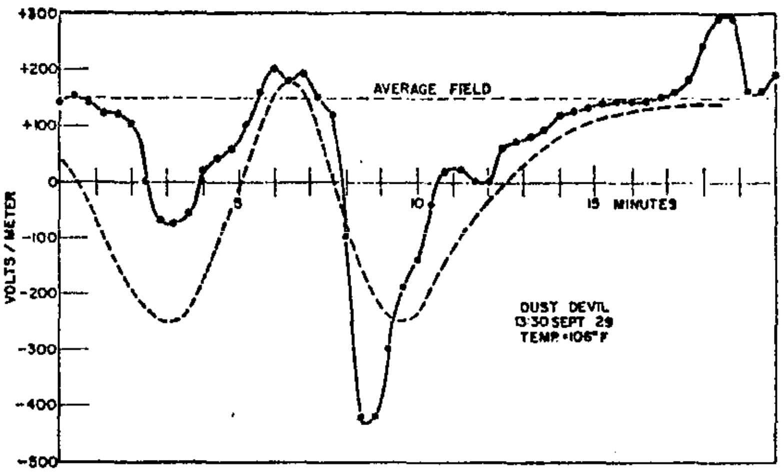


Figure 8. A reproduction of the record for the electric field due to a dust devil. Positive values of the field imply positive charge above. The dashed curve corresponds to a dipole of 1.7×10^9 esu cm at a height of 21.4 meters following a similar course. From Freier (20).

The dashed curve in Figure 8 is the theoretical trace of a dipole of $1.7\text{x}10^9$ esu cm at a height of 70 feet following a course similar to that taken by the dust devil. However, this theoretical dipole would only have a translational velocity of 0.16 m/sec instead of the approximate 4 m/sec velocity of the observed dust devil. Crozier (13) presented a similar observation; however, in this case the dust devil was about 4/10 of a mile away at its closest point, it was estimated to have a visible diameter of 60 feet, and height of 350 feet. The transcribed potential gradient was depressed for about 10 minutes and showed a maximum depression of about 111 volts per meter.

Both Freier and Crozier have recorded roughly W-shaped potential gradient records. Crozier suggests the first minimum may be attributable to an increase of ground speed or a diminishing intensity of the dust devil. It would appear that Sinclair's more recent observation of a central downdraft in the vortex may be the key to explaining the W-shape of the potential gradient field. This thought becomes particularly promising when one remembers that the "eye" of the dust devil is relatively free of dust and debris.

Bradley and Semonin (5) were making electrical field measurements over Illinois in an instrumented, light weight, single-engine, aircraft when they spotted several dust devils and were able to obtain measurements by flying through the dust devils. Freier's observation had indicated a dipole charge distribution with negative charge on top. The aircraft measurements, at around 500 feet above ground level, confirmed the suggested negative charge aloft, although the potential gradient measurements did not indicate a dipole charge distribution. The observations indicated negative space charges in excess of 400 elementary charges per cm^3 as indicated in Figure 9.

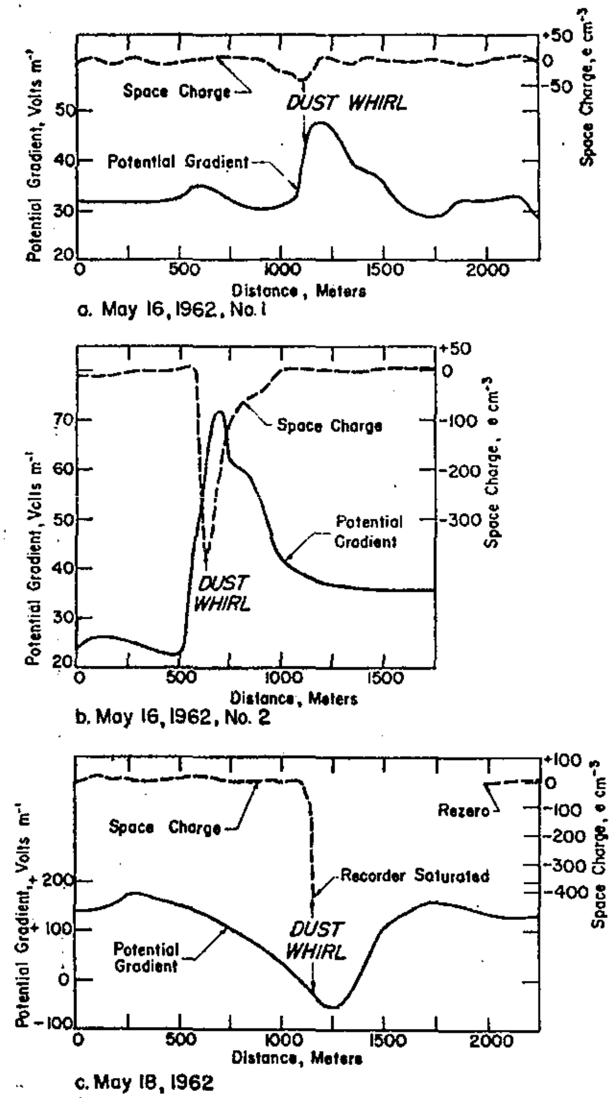


Figure 9. Space charge and potential gradient observed at a height of 500 feet in three dust devils. From Bradley and Semonin (5).

Freier and Crozier made no mention of the capability of their instruments but they were both some distance from the centers of the dust devils. Bradley and Semonin undoubtedly penetrated the invisible upper portions of the dust devils they measured, and they indicated that the response times of the potential gradient probes and the space charge filter were not rapid enough to clearly define the horizontal extent of the space charge concentrations or potential gradient perturbations. Their recordings are, therefore, probably conservative estimates of the space charge and potential gradient. All of these gentlemen appear to agree that if the electrical properties of dust devils are to be understood, there is need for a great deal of additional pertinent data.

3.7 <u>Energy</u>

Battan (1) has analyzed the dust devil from energy considerations and concludes that the kinetic energy of a dust devil results from a reduction of the internal and potential energy of the air involved. From these energy considerations he has graphed a theoretical horizontal pressure gradient and horizontal wind velocity profile with respect to a core of radius r_o in solid rotation and an outer shell in which the velocity varies inversely as the distance (Figure 10). It will be noted that the velocity profile thus computed indicates

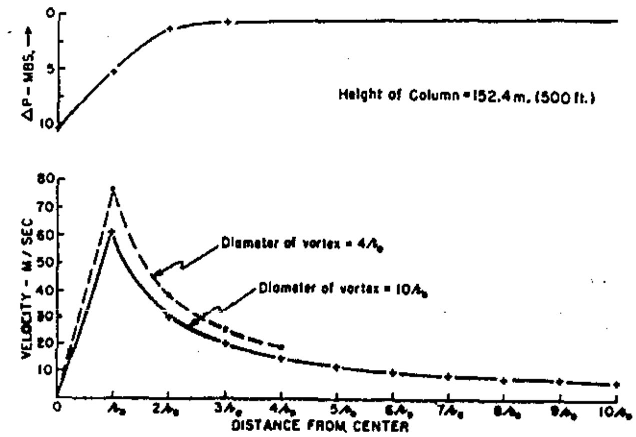


Figure 10. Calculated profile of velocity and pressure in a dust devil. The pressure profile was calculated for the case of diameter of vortex equal to $10r_o$. From Battan (1).

a maximum velocity of about 60 mps (134 mph), for an environment to core center pressure drop of 10 mb. This is a pressure drop about 3 times the maximum observed by Sinclair with a wind velocity some 5 times greater than the associated wind speed observed by Sinclair (Figure 5).

4. THEORETICAL MODELING

4.1 Laboratory Modeling

The Apache Indians may have been the first to artificially produce dust devils. It is said that they produced dust devils by firing the spines of a column-like cactus (saguaro?) which is common in the southwestern United States (6).

More recently, Dr. Barcilon, of Harvard University (16), produced a laboratory model simulating a dust devil. It is a few inches in diameter and about 10 feet high. He postulates two basic conditions necessary to produce a natural dust devil: (1) superheated surface air; and (2) a gentle breeze of 2-5 mph having a velocity that varies horizontally.

The laboratory model is produced by placing a small pile of ammonium chloride on a heated circular platform about six feet in diameter then slowly rotating a tall cylinder of screen about the platform. Before the screen column is set in motion, the heated ammonium chloride gives off a white smoke that slowly whirls and curls upward. Soon after the screen begins to revolve, the smoke becomes a tight, rapidly twisting whirlwind. There have been no quantitative measurements presented to indicate whether the temperature, pressure, and velocity profiles compare with those of a natural dust devil.

4.2 Mathematical Modeling

Smith (51,52) has done considerable work toward mathematical modeling of an intense vortex near a solid boundary (such as the earth's surface). This work appears primarily directed at tornado modeling; however, the profiles derived appear rather representative of dust devil profiles. The radial, tangential and vertical velocity profiles have been derived from numerical integration of the primitive equations of motion, assuming a modified Rankine vortex to exist at a distance from the boundary layer where pressure and centrifugal forces are in balance. The equations have also been non-dimensionalized for easier manipulation and interpretation of the results. The graphed results of the tangential and vertical profiles obtained are shown in Figures 11 and 12. In these figures R is the non-dimensional radius, Z is the non-dimensional height coordinate, and C is the ratio of radius of maximum velocity to depth of model layer (i.e., the radius R and the height Z of any given dust devil is modeled by unit radius and unit height in Figures 11 and 12).

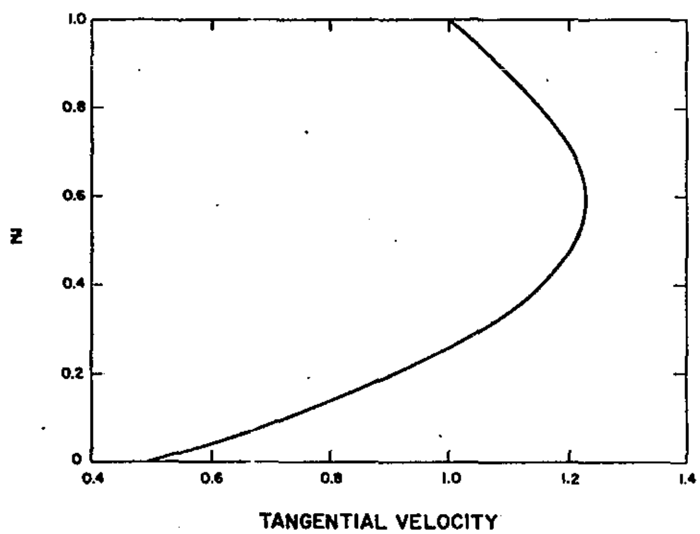


Figure 11. The dimensionless tangential velocity component vs. Z at R = 1, in the case C = 6. From Smith (52).

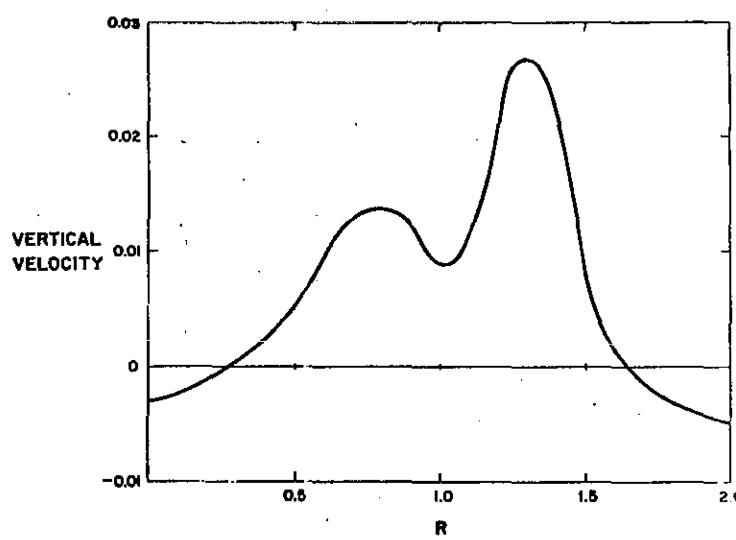


Figure 12. The dimensionless vertical velocity component at the top of the model layer vs. R derived numerically in the case C = 6.

The tangential velocity profile indicates that the tangential velocity is unity at the top of the model, increasing downward to about .6 the height of the model then decreasing to one-half unity at the surface. The vertical velocity profile indicates a downdraft (negative vertical velocity) at the center of the vortex (R=0), and increasing to a maximum a short distance beyond unit radius, then dropping markedly to less than zero (downdraft) at twice unit radius, i.e., the maximum vertical velocity is outside of the vortex, while downdrafts are present both inside and outside the vortex.

These figures show a marked similarity to the actual profiles measured by Sinclair (46). The vertical velocity profile, however, appears rather erratic and nonrepresentative near unit radius. Later (and yet unpublished) work by Smith (51), representing a slight change in the variables, smoothed out this oscillation as well as increasing the magnitude of the updraft near unit radius and the downdrafts in the center and at about twice the unit radius of the vortex, i.e., in the new model the vertical velocity at the center of the vortex is about -.03, rising to .01 at R=0.5, rising only slightly to .02 at R=0.8, then rising quickly to a maximum of 0.06 at R=1.1, and dropping sharply to -0.06 at R=1.6.

This model shows even better agreement with Sinclair's measurements.

5. CONCLUSIONS

There is a tremendous change in the meteorological parameters across a horizontal and vertical cross-section of the dust devil--it represents a very sizeable amount of atmospheric energy when it releases the highly unstable superheated air from the boundary layer. Consequently, it may play a significant role in the heat transfer processes that take place in the atmosphere, particularly in the desert regions during months of large incident solar angles.

There are many valid reasons for studying the dust devil. It may cause significant damage, yet it is much easier to find the dust devils, make measurements in the surrounding environment and within the vortex, than is the case with the tornado, thunderstorm or hurricane, yet in many respects it has been shown that these circulations show striking similarities. Therefore, it is not unreasonable to assume that a complete analysis and understanding of the dust devil would provide new insights into the processes involved within - and our ability to predict the behavior of - these other larger, more destructive and relatively elusive, atmospheric circulations.

The dust devil is a natural atmospheric phenomena that may play a significant role in the energy balance of the atmosphere. Until it is fully described and understood, it will be impossible to accurately understand and calculate this important factor. Significant steps have been taken toward making a complete analysis of the dust devil, but there is much that remains to be done.

One nagging question continues to hound the author -- is the dust devil an appropriate or representative name for the phenomena defined and discussed? The atmospheric sciences have advanced to the state where we recognize and differentiate between tropical and extratropical cyclones, yet we use the term "dust devil" to denote a phenomena that may, at times, contain little, if any, visible dust. Its circulation and influence undoubtedly extends far beyond its visible dust extremities. In addition, the term carries no connotation of the original source of the (thermal) energy driving the system. Whirlwind, too, fails to define the original source of energy and fails to differentiate our "dust devil" from the other small-scale rotational systems. Thermal whirlwind fails to distinguish between those caused by fires and those initiated by insolation. Possibly as a matter of last resort - insolational whirlwind - would be a more appropriate name than dust devil.

REFERENCES

1 Battan, L. J. "Energy of a Dust Devil". J. of Met., Boston: AMS 15(2): 235-237, April 1958.

2 Beard, J. "I Learned About Flying From That". Flying, New York: Ziff-Davis, Aug. 1961, 52.

3 Biter, C. J., and Stinson, R. J. "Deviations Between the Surface Wind and the Geostrophic Wind on the Antarctic Continent". Paper presented at the AMS Conference on Modern Methods of Weather Forecasting and Analysis, Chicago, Ill., March 23-25, 1966.

4 Blacktin, S. C. Dust, Cleveland: Sherwood, 62, 103, 104, 1934.

5 Bradley, W. E., and Semonin, R. G. "Airborne Electrical Measurements in Dust Whirls". J. Atmospheric Sci., 20: 622-623, 1963.

6 Brooks, C. F. "Why The Weather?". New York: Harcourt, Brace; 1938, 98-99.

7 Brooks, E. M. "Local Circulations and Local Winds". Compendium of Meteorology, Boston: AMS, 1951, 678-679.

8 Brooks, H. B. "Rotation of Dust Devils". J. of Met., Boston: AMS, 17: 84-86, 1960.

9 Byers, H. R. General Meteorology, New York: McGraw-Hill, 1944, 148-149. 586.

10 Byers, H. R. Synoptic and Aeronautical Meteorology, New York: McGraw-Hill, 1937, 271.

11 Byram, G. M. et. al. "The Possible Relation of Air Turbulence to Erratic Fire Behavior in the Southwest". Fire Control Notes, 12, 3, 1951.

12 Cordeiro, F. J. B. The Atmosphere: Its Characteristics and Dynamics, New York: Spon and Chamberlain, 1910, 89-90.

13 Crozier, W. D. "The Electric Field of a New Mexico Dust Devil". J. of Geophysical Res., Wash., D. C.: The American Geophysical Union, 69: 5427, Dec. 1964.

14 De Mastus, H. L. "Pressure Distrubances in the Vicinity of Dust Devils". AMS Bulletin, Boston: AMS, 35, 497-498, 1954.

15 Donn, W. L. Meteorology, New York: McGraw-Hill, 1951, 182-183.

16 Anon. "Dust Devils Produced". Science News, Wash., D. C.: Science Service, 90:234, 1966.

17 Flora, S. D. Tornadoes of the United States. Norman: Univ. of Oklahoma, 1953: 153-154.

18 Flower, W. D. Sand Devils. Great Britain, Meteorological Office, Professional Notes, 5, No. 71, 1-16, 1936.

19 Fortner, L. E., Jr. et. al. "Day of the Fuhjin, March 1963". Met. Soc. of Japan, Tokyo, Journal. Ser 2, 42(4): 269-273, Aug. 1964.

20 Freier, G. D. "The Electric Field of a Large Dust Devil". J. of Geophysical Union, 65(10): 3504, Oct. 1960.

21 Garbell, M. A. Tropical and Equatorial Meteorology, New York: Pitman, 1947, 99, 209.

22 Geiger, R. The Climate Near the Ground. Cambridge, Mass.: Harvard University, 1959, 9-12, 52-74, 129-130.

23 Geiger, R. The Climate Near the Ground. Cambridge, Mass.: Harvard University, 1965, 91f.

24 Glaser, A. H. "Tornado Studies". Texas Agricultural and Mechanical College, Dept. of Oceanography and Meteoro., Contract CWB 8696, Final Report, Jan. 1956. 24 p.

25 Graham, H. E. "Fire Whirlwinds". AMS Bulletin, 36, 3, 99-103, 1955.

26. Grant, C. G. Dust Devils in the Sub-Arctic, Weather, 4, 1949, 402-403.

27 Haltiner, G. J., and Martin, F. L. Dynamical and Physical Meteorology. New York: McGraw-Hill, 356-357, 1957.

28 Heninger, S. K. A Handbook of Renaissance Meteorology. Durham, N. C.: Duke, 118-119, 1960.

29 Hissong, I. N. "Whirlwinds at Oil Tank Fire, San Luis Obispo, California". Monthly Weather Review, 54, 161-163, 1926.

30 Humphreys, W. J. Physics of the Air. New York: McGraw-Hill, 151-155.

31 Huschke, R. E. Glossary of Meteorology. Boston: AMS, 1959.

32 Ives, R. L. "Behavior of Dust Devils". AMS Bulletin, Boston: AMS, 28, 168-174, 1947.

33 Jones, W. P. et. al. "Dust Devils". Indian J. of Met. and Geophysics, Delhi 6(1): 67, Jan. 1955.

34 Kendrew, W. G. Climatology, Oxford: Clarendon, 70, 1949.

35 Koeppe, C. E., and De Long, G. C. Weather and Climate. New York: McGraw-Hill, 138, 1958.

36 Ludlam, F. H., et. al. Cloud Study. London: John Murray, 1960, 77.

37 Mawson, Sir Douglas The Home of the Blizzard. Philadelphia: Lippincott, 1915, 111-112.

38 Murchie, G. The Song of the Sky. Cambridge, Mass.: Riverside, 154-155, 1954.

39 Myrup, L. O. "The Structure of Thermal Convection in the Lower Atmosphere Under Conditions of Light Winds and Strong Surface Heating". Doctoral Dissertation, University of California, Los Angeles, 1965.

40 Ockenden, C. V. "A Contribution to Forecasting in Iraq; Small Rotary Systems in Advance of a True Cold Front". London, 1940.

41 Ohman, O. L., and Pratt, R. L. Yuma Winter Microclimate. U. S. Army Natick Laboratories. Natick, Mass., Project reference: 1V025001A129, 1966.

42 Petterssen, S. Introduction to Meteorology. New York: McGraw-Hill, 95, 1958.

43 Ross, J. "Dust Devil Observed at Coalburn, Lanarkshire, (Scotland)". Meteorological Magazine, London, 85 (1009), 215-216, July 1956.

44 Shaw, P. J. R. "Local Winds in the Mawson Area". Antarctic Meteorology, New York: Pergamon, 3-4, 1960.

45 Sinclair, Peter C., "A Quantitative Analysis of the Dust Devil". Doctoral Dissertation, University of Arizona, 1966.

46 Sinclair, P. C. "A Quantitative Analysis of the Structure and Behavior of Desert Dust Devils". Paper presented at the 47th Annual Meeting of the AMS, January 25, 1967, New York, N. Y.

47 Sinclair, P. C. "Measurements of Temperature, Pressure, and Wind Velocity in Dust Devils". AMS Bulletin, Boston: AMS, 42:132, 1961.

48 Sinclair, P. C. "Microbarophone for Dust Devil Pressure Measurement Techniques". J. of Applied Met., Boston: AMS, 4(1): 116, 1965.

49 Sinclair, P. C. "On the Rotation of Dust Devils". AMS Bulletin, Boston: AMS 46(7): 388-391, 1965.

50 Sinclair, P. C. "Some Preliminary Dust Devil Measurements". Monthly Weather Review 92, 8, 363-367, 1964.

51 Smith, R. C. "Flow in the Boundary Layer Beneath an Intense Vortex Such as a Tornado". Paper presented at the 47th Annual Meeting of the AMS, January 25, 1967, New York, N. Y.

52 Smith, R. C., and Smith, P. "Theoretical Flow Pattern of a Vortex in the Neighbourhood of à Solid Boundary". Tellus, 17, 2, 213-219, 1965.

53 Anon. "Soaring Weather". Aviation Weather. Washington, D. C.: Federal Aviation Agency and Dept. of Comm. Weather Bureau. Government Printing Office, 1965; 262.

54 Sutton, O. G. Micrometeorology. New York: McGraw-Hill, 1953, 106-113.

55 Taylor, G. F. Elementary Meteorology. New York: Prentice-Hall, 219-220, 1954.

56 Valtat, B., et. al. (all, M'et'eorologie Nationale, Paris), Le "Ph'enom'ene de Loewe" en Terre Ad'elie. ("Loewe phenomenon" in Ad'elie Land). La M'et'eorologie, Paris, Ser. 4, No. 57:77-112, Jan./March 1960.

57 Van Nostrand's Scientific Encyclopedia, Princeton, N. J.; Van Nostrand, 546, 1958.

58 Wallington, C. E. Meteorology for Glider Pilots. New York: Pitman, 159, 1961.

59 Warn, G. F. "Some Dust Storm Conditions of the High Plains". AMS Bulletin. Boston: AMS, 33, 241, 1952.

60 Williams, N. R. "Development of Dust Whirls and Similar Small-Scale Vortices". AMS Bulletin, Boston: AMS 29, 106-117, 1948.

ADDITIONAL WORKS

The following items were not used because of unavailability or lack of a suitable translation.

Arakawa, H. (Met. Res. Inst., Tokyo), "Phugoid Motion of Whirlwinds in the Atmosphere". Geofisura Purae Applicata, 22(3/4):171-173, April/June 1952.

Combier, Ch. "Sur La constitution des vents de sable en Syrie". (On the formation of sand storms in Syria.) Acad'emie des Sciences, Paris, Comptes Rendus, 200:1232-1233, 1935.

Embree, C. R. "Dust Whirl on a Quiet Day", Syracuse, N. Y., March 28, 1957. Monthly Weather Review, Washington, D. C., 85,(3):88, March 1957.

Koschmieder, H. "Uber Tornadoes Und Tromben". ("On Tornadoes and Whirlwinds") Die Naturwissenschaften, 25(41):663-664, 1937.

Koschmieder, H. "Zur Trombenbildung". ("On Tornado Formation".) Archiv fur Meteorologie, Geophysik und Bioklimatologie, Ser. A, 4:203-219, 1951.

Lacaze, Jean. "Aspect convectif des tourbillons de sable d'axes verticaus". ("Convective aspect of vertical dust whirls".) Acad'emie des Sciences, Paris, Comptes Rendus, 231 (23):1329-1331, Dec. 6,1950.

Lacaze, J. "Les tourbillons de sable du Sahara". ("Sand devils in the Sahara".) Puy de Dome. Observatoire, Bulletin, No. 1:19-22, Jan/March 1958.

Lacaze, J. "Tourbillons Atmospheriques d'axes verticaux: tourbillons de sable, Pt. 2". ("Vertical atmospheric vortices: sand whirls, Pt. 2".) Journal de M'ecanique et de Physique de l' Atmosphe're, Paris, Ser. 2, 1(1):25-41, Jan/March 1959.

Lacaze, J. "Tourbillons atmosph'eriques d'axes verticaux". ("Vertical atmospheric vortices".) (Sand whirls.) Journal Scientifique de la M'et'eorologie, Paris, 10(40):133-147, Oct. Dec. 1958.

Long, R. R. "Tornadoes and Dust Whirls". Johns Hopkins Univ Dept. of Mechanics, Contract Nonr-248(31) Project NR 082-104, Tech. Report #10; and Contract CWB-9919, Technical Report #13, Sept. 1960.

Normand, C. W. B. "On Dust-raising Winds". India, Meteorological Dept., Memoirs, Vol. 22, Pt. 7:575-581, 1913-1921.