VERTICAL TRANSPORT OF DESERT PARTICULATES BY DUST DEVILS

AND CLEAR THERMALS*

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ABSTRACT

While the vertical and horizontal transport of natural surface material by dust devils is not in itself a critical environmental problem, the transport and downwind fallout of toxic or hazardous materials from dust devil activity may be a contributing factor in the development of future ecological-biological problems. Direct quantitative measurements of the dust particle size distribution near and within the visible dust devil vortex and analyses of the upper level clear thermal plume have been made to provide estimates of the vertical and horizontal transport of long half-life radioactive substances such as plutonium. Preliminary measurements and calculations of dust concentrations within dust devils indicate that over 7×10^3 tons of desert dust and sand may be transported downwind from an area 285 km^2 during an average dust devil season (May - August). Near the ground these dust concentrations contain particles in the size range from approximately $1 \text{ }\mu\text{m}$ - $250 \text{ }\mu\text{m}$ diameter. Since the vertical velocity distribution greatly exceeds the particle(s) fall velocities, the detrainment of particles within the vortex is controlled primarily by the spatial distribution of the radial (v_r) and tangential (v_θ) velocity fields.

Above the visible dust devil vortex, a "clear" thermal plume may extend upward to 15,000 - 18,000 ft MSL. A new airborne sampling and air data system has been developed to provide direct measurements of the dust concentration and air motion near and within the upper thermal plume. The air sampler has been designed to operate isokinetically over a considerable portion of the low-speed flight regime of a light aircraft. A strapped down, gyro-reference platform and a boom-vane system is used to determine the vertical air motions as well as the temperature and turbulence structure within the thermal plume.

1. INTRODUCTION

In the past, resuspension and transport models of toxic or hazardous material such as plutonium have not fully taken into account the convective transport component. This latter component could be especially significant if the convective elements are large enough to provide deep layer mixing. These conditions often exist during the summer months in the southwest U.S. where large desert thermals and dust devils (Figure 1) provide an effective heat and momentum transport mechanism through a convective mixing layer that may extend to 20,000 ft MSL (Sinclair¹). Previously, the removal and vertical transport of surface material by dust devils has not been considered significant other than from the fact that it is this material that makes the dust devil visible and therefore amenable to study. On the other hand, if the soil particles contain highly toxic plutonium particles or act as host particles, the deep layer mixing associated with dust devil activity may result in a significant horizontal transport of plutonium particles downwind of the contaminated area.

Because this situation presently exists at a number of locations, it appears timely to assess the magnitude and hence the importance of the dust devil transport component with respect to the total wind blown resuspension and transport of desert sand and dust. The unique feature of the dust devil transport mechanism is the significant altitude(s) the particles may be lifted to prior to their downwind dispersion by the horizontal flow. Depending on the particular size spectrum of the surface particle distribution, the particles may be lifted to 5-6 km before beginning their downwind journey from the source area. Consequently, many small particles may be transported great distances by dust devils and related convective processes that take place

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continuously over many years before the decrease in the long radioactive and biological half-life of substances such as ^{239}Pu ($T_{1/2} = 2.4 \times 10^4$ years) limits the problem.

In order to numerically assess the importance of this problem, a surface and airborne sampling program has been initiated at the Lawrence Livermore Laboratory in cooperation with Colorado State University. While this program is still in the design and development phase, some initial calculations were performed on the results of a previous dust devil research program in Arizona (Sinclair¹) and of several ground measurements of the dust devil particle size spectrum on the Nevada Test Site. Some preliminary results of these transport calculations are outlined in this paper along with supporting data on the dust devil structure and morphology.

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11. DUST DEVIL LOWER STRUCTURE

Measurements by Sinclair^{1,2} of the temperature, pressure, and wind velocity near and within the visible vortex have been used to formulate a quantitative dust devil model. A schematic model of the dust devil lower structure is shown in Figure 2. The warm air is confined essentially within the dust column which surrounds the low-pressure center. As a first approximation, the pressure field is assumed symmetrical about the dust devil axis with the central pressure about 3 mb below the environmental pressure at the same height. The two horizontal cross sections through the dust devil represent conditions at the measurement levels (7 and 31 ft). The tangential velocity field is represented by a Rankine vortex which agrees very closely with the measurements. The radial field of motion is generally inward toward the dust devil axis as illustrated by the two flow lines (relative air trajectories) which depict the air spiraling inward and upward. The relatively dust-free downcurrent surrounding the axis is readily apparent. This hollow tube structure has frequently been observed and photographed by the author and noted by other investigators. It is shown here in its most distinct stage of development, but is probably present in varying degrees in all dust devils, even though not so visually evident. Thus, the observational model represents a two-cell structure: a spiral descending vortex core with a surrounding region characterized by a rapidly ascending toroidal vortex. Many of these features are found in other atmospheric vortices [the hurricane and possibly the tornado (Rossman³)], experimental vortex flows (Ward⁴), and unpublished results of the author, and theoretical vortex models (Donaldson and Sullivan⁵; Kuo⁶).

The dense dust region near the ground is characteristic of many dust devils. Here the horizontal pressure field in conjunction with the surface

friction promotes strong radial inflow, and hence even the largest particles are confined to relatively small orbits. As the particle is accelerated upward, however, the tangential velocity component appears to increase rapidly with an accompanying decrease in the radial component, which results in large particle orbits and hence a larger dust column diameter. Consequently, very close to the ground the dust column in many cases has a convex shape. This feature has been visually observed and photographically recorded by the author and also by Koschmieder⁷.

Because of the large vertical and horizontal wind speeds near the ground, a significant portion of the surface particulates are dislodged and resuspended to considerable elevations within the dust devil. A photomicrograph slide of some of the larger particles is shown in Figure 3. The large black dot in the upper left hand corner represents a diameter of 250 μm . Only the large particles are in focus. In addition to the sand particles, the dust devil literally vacuums up any other surface debris that happens to be in its path. This material may be a small piece of wood (2500 μm in length) as shown in Figure 3 or a sage bush (1 m dia) or a much heavier object such as a cardboard box. These materials are easily supported by the $10\text{-}20 \text{ msec}^{-1}$ vertical motion field that exists just above the ground within the dust devil vortex.

III. DUST PARTICLE DISTRIBUTIONS

During the preliminary planning stages of the current dust devil-thermal resuspension program, additional dust particle samples were obtained in the GNM area of the Nevada Test Site (NTS). The samples were obtained by exposing several petri dishes on a small diameter pole as the dust devil passed the observer. Again, as in the Arizona samples, the sampling technique leaves much to be desired in terms of providing adequate collection efficiencies for the small particles. However, it offers a lightweight and portable particle collection technique which provides sufficient quantitative data for the design of more sophisticated ground and airborne sampling programs and instrumentation.

The petri dishes were coated with vasoline in order to retain all particles which impacted the collection surface. The vasoline while acting as a convenient dust particle trap, complicated subsequent analysis by not permitting direct particle counting and sizing systems to be employed. Consequently, the particles were removed from the vasoline by washing in benzedrine and then centrifuging before placement on a glass slide for viewing on a Quantimet A-100 particle analyser. Great care is necessary in this washing and preparation of the particles for the viewing slide. Too much agitation of the particles during this washing and centrifuging phase will result in the removal of clays and small particles from larger particles thereby providing an artificial bias at the lower end of the particle size spectrum.

A. Particle Number and Mass Distribution

The dust particle number and mass distribution from a small dust devil are shown in Figure 4. The particle sizes (diameter) vary from approximately 0.4 μm to almost 350 μm with a median diameter near 1.2 μm . The cross-section of the irregular particles are determined by the particle analyser (picture

point = $0.2 \mu\text{m}$) which expresses these measured areas in terms of an equivalent spherical diameter. Because of more significant collection efficiency errors in the sub-micron tail of the particle distribution, larger deviations from the actual distribution must be expected in this region. The collection efficiency errors arise from the turbulence and large vertical and horizontal variations of the wind within the dust devil vortex. A comparison with Koval's⁸ data appears to indicate that the petri dish particle collection technique may be more accurate than one would expect from collection efficiency theory as applied to the dust devil vortex. For example, in the same GMX area, Koval's⁸ particle measurements with a Climet particle counter result in a particle number distribution very similar to the dust devil distributions in the $0.63 - 9.45 \mu\text{m}$ diameter size range. His measurements were made under non-dust devil conditions where the dust resuspension was due to meso-synoptic scale gusty surface winds ($u_* = 0.54 \text{ msec}^{-1}$ and $\sigma_w = 0.75 \text{ msec}^{-1}$). Both particle distributions show a median diameter of approximately $1.2 \mu\text{m}$. In general, however, the dust devil resuspends a greater percentage (5-15%) of larger particles. Of course, part of this difference can also be attributed to the petri dish small particle collection efficiency errors for particles less than $10 \mu\text{m}$ in diameter.

The mass distribution shown in Figure 4 indicates a mass median diameter of approximately $80 \mu\text{m}$, with 70% of the mass due to particles with diameters greater than $50 \mu\text{m}$. This compares rather closely with the mass median diameter of $95 \mu\text{m}$ for an Arizona dust devil. The difference in the maximum particle diameters, $350 \mu\text{m}$ for GMX and $275 \mu\text{m}$ for Arizona, is due primarily to the larger particle distribution typical of the GMX desert pavement surface. A secondary cause of the difference in the distributions appears to be due to the larger number of smaller particles collected and counted in the GMX site. While

these smaller particles act relatively little to change the mass distribution and hence the mass median diameter, they are especially significant in this comparison since it had been deduced earlier from the Arizona samples that sub-micron particles may not be resuspended by dust devil activity.

These comparisons suggest that: (1) dust devils remove essentially the same number of small particles ($<10 \mu\text{m}$ dia.) that are removed by larger scale resuspension mechanisms and (2) small to medium size dust devils are capable of removing and vertically transporting sand particles as large as approximately $350 \mu\text{m}$ from a wide range of desert surfaces. The last point is significant with respect to the distinct difference between the desert pavement surface of GCMX and the more typical desert surface found in Arizona and the Southwestern U. S. In the GCMX area, the exposed soil surface is covered by pebbles; the soil mass median diameter is about $300 \mu\text{m}$ with slightly over 30% of the mass associated with particles $>2000 \mu\text{m}$ in diameter (Tamura⁹). The distribution of mass with particle size is quite different, however, in sheltered areas beneath desert shutters where the mass median diameter is about $175 \mu\text{m}$ with only 1.8% of the mass associated with $>2000 \mu\text{m}$ in diameter.

The preliminary measurements of the particles entrained by dust devils also indicate that very few soil particles with diameters of 200 to $1000 \mu\text{m}$ and above are being removed and transported to heights of at least 1 meter. Gillin¹⁰ has suggested that under turbulent wind conditions the known ballistic effect results in a dislodgement process that is capable of removing a representative number of all particles in the soil surface layer. That is, this dislodgement process "results in a particle size distribution that is dictated by the size distribution of the soil particles". While this may be true for smaller grain soils, it appears that the lack of large desert pavement particles at $z = 1$ meter is due to insufficient

dislodgement forces or centrifuging of the large particles by the vortex flow. Without additional data on the particle distribution in the saltation layer, the question concerning sufficient dislodgement forces cannot be directly answered.

We can, however, indirectly assess the significance of the centrifuging action of the vortex on the particle distribution. With some idea of the dust particle size distribution, one may determine (with certain simplifying assumptions) whether the necessary radial inflow, for particle orbits to remain within the sampled dust column, is realistic in light of the dust devil wind velocity measurements (Sinclair¹). Since the dust particles are more dense than air, all particles would be centrifuged out of the rotating column (which we know does not take place) unless acted upon by some outside force. This outside force is in the form of an aerodynamic drag force acting on each particle and is produced by the radial component of the converging airflow. For simplicity, the vortex flow is considered laminar with no dust particle interaction. In addition, the horizontal projection of the dust particle trajectories are approximated by closed circular orbits with the tangential velocity (v) of the dust particles the same as that of the air. Figure 5 shows the distribution of the force and velocity components acting on the dust particle relative to a cylindrical coordinate system fixed to and moving with the dust devil which is moving with a constant velocity (relative velocities are denoted by the subscript r).

The dashed circular lines represent the circular orbits of the dust particles (P) and the solid converging lines represent the air flow. The horizontal relative velocity (V_{hr}) of the air has a tangential component (V_t) which represents the particle velocity, and a radial inflow component (u_r) relative to the dust particle at the radius r .

The necessary centripetal acceleration ($F_c = \frac{mv^2}{r}$, where m is the particle mass and r the radial coordinate) for the particle to remain in a circular orbit must be produced by the aerodynamic drag (D) of the radial inflow relative to the dust particle. For Reynolds' numbers (R_e) less than about 1.0, Stokes drag law

$$D_s = 3\pi\mu u_r \quad (1)$$

is valid (where μ is the dynamic viscosity of the air, d is the particle diameter, and u_r is the relative radial velocity). For $R_e > 1.0$ the general drag law

$$D = \frac{1}{2} \rho u_r^2 C_D A \quad (2)$$

must be used (where ρ is the air density, C_D the drag coefficient, and A is the particle cross-sectional area normal to the relative air velocity (u_r). Near the edge of the dust column, the radial inflow velocity at $z \approx 2$ m is at least -13 msec^{-1} and the dust particle measurements indicate a size range of $0.4 \text{ } \mu\text{m} - 400 \text{ } \mu\text{m}$ (diameter). Since the question here is directed at the large particle end of the particle distribution, we will only consider those particle diameters from $500 \text{ } \mu\text{m} - 10^4 \text{ } \mu\text{m}$ which distinguish the GCM desert pavement from the smaller grain desert surfaces. These particles result in $30 < R_e < 400$, and consequently the general drag law must be employed. Hence for a particle in circular orbit ($F_c = D$):

$$\frac{mv^2}{r} = \frac{1}{2} \rho u_r^2 C_D A \quad (3)$$

or

$$r = \frac{4}{3} \frac{\rho v^2 r^2}{\rho C_D u_r^2} \quad (4)$$

where ρ_d is the dust particle density. Thus for a particular velocity distribution and particle size, the radius at which the dust particle is in a circular orbit (hereafter referred to as the equilibrium radius) is given by Eq. (4). Measurements within the dust column (Sinclair^{1,2}) indicate that the dust column is confined within a region where the mean velocity (v_r) profile is essentially linear. Considering the motion (v_r) within the dust column as one of solid rotation, Eq. (4) becomes:

$$r = C' \frac{\rho_d u_r^2}{d} \quad (5)$$

where $C' = \frac{3}{4} \frac{C^2}{\rho_d}$ where $C = \frac{v}{r}$ and $C_D = C_D(R_e)$. Under these simplifying assumptions, it is then possible by use of Eq. (5) to determine an equilibrium radius for a particular radial inflow (u_r) and particle size (d). For example, for a medium size dust devil, a particle 85 μm in diameter may have an equilibrium radius at the limit of the dust column ($r = 2 \text{ m}$) for $u_r = 3 \text{ m sec}^{-1}$. This result agrees rather well with respect to the particle and wind velocity distribution measured in medium size dust devils (Sinclair²). However, for sand particles the size of the GCM desert pavement (500 $\mu\text{m} - 10^4 \mu\text{m}$) a similar medium size dust devil would require a radial velocity (u_r) of approximately 15 - 65 m sec^{-1} to confine these large particles within the 4 m diameter dust column. Since these velocities are 5 - 20 times larger than those previously measured, it must be concluded that even though particles of this size range are dislodged through the saltation process they will be very quickly centrifuged out of the vortex and deposited on the ground in close proximity to their original location. Furthermore, it also seems unlikely that even within the largest dust devils these particles will be confined within the visible dust boundary. In some cases, an enlarged and more diffuse region just above the

ground (Fig. 1) may be due to particles which have been centrifuged, because of their density and/or turbulent motions, out of the main vortex. It is concluded therefore that in the case of a soil surface such as the desert pavement in the GNM area, the soil particle distribution does not dictate the particle size distribution at $z = 1-2\text{m}$ within a dust devil. This conclusion also appears to be true at lower heights because of the unrealistically large radial velocities required to confine all of the larger particles of the desert pavement within the visible dust boundary. However, the dislodgement forces may be sufficient to move these particles within the saltation layer. Additional data is required, however, before the dislodgement possibility can be answered.

B. Particle Concentration Distributions

The dust devil particle size distribution is shown in Figure 6 in terms of $\Delta N / \Delta \log D$, where N is the number density (number per cm^3) and D is the equivalent (spherical) particle diameter, i.e., $\Delta N / \Delta \log D = [\text{No. of particles per } \text{cm}^3]$. For comparison, airborne particle size distributions for various surfaces and wind conditions are also shown for: (1) a sparsely vegetated region on the AEC Hanford reservation (Sehmel¹¹), (2) a desert pavement region on the AEC Nevada (GNM) Test Site (Koval⁸), and (3) an eroding Nebraska field (Gillette, et al¹²). The Hanford data represent the airborne particle distribution at heights of 0.3 m (○) and 1.0 m (△) during April 4-26, 1972--total of 10 hours of wind speed greater than 8 msec^{-1} . Koval's⁸ data were obtained with a Climet optical (particle) counter at a height of approximately 1.0 m for the following mean wind and maximum gust (G) wind conditions: (●) $6.7/18 \text{ msec}^{-1}$, (▲) $2.4/44.0 \text{ msec}^{-1}$, and (□) $1.9/33.6 \text{ msec}^{-1}$. Gillette's¹² data represent airborne samples taken at the beginning of a prefrontal dust

storm where the wind velocity at 1.5 m was 4.2 msec^{-1} (Ø) and 10.6 msec^{-1} (ψ). The dust devil particle measurements were made within a medium sized dust devil (dia. $\sim 3\text{m}$) at a height of 2 m where the maximum wind speed was approximately 10 msec^{-1} .

While the data plots in Figure 6 represent different particle collection or counting techniques and soil types, it appears evident that the dust devil is capable of removing and suspending a greater portion of the larger diameter particles. Sehmel's¹¹ data, of which the two $\Delta N/\Delta \log D$ curves shown in Figure 6 represent the two lowest levels, show as expected that the particle concentration of large particles increases as the height decreases. This increase is such as to produce an inflection in the $\Delta N/\Delta \log D$ curve. We anticipate that more detailed measurements of the particle distribution below $10 \mu\text{m}$ dia. for the dust devil will reveal $\Delta N/\Delta \log D$ distribution curves that are very similar in shape to Sehmel's¹¹ particle concentration distributions. The dust devil distributions will, however, contain much greater concentrations of the larger particles primarily because of the large vertical velocity field within the dust devil vortex. Thus, it seems reasonable that the dust devil measurements will not only reflect higher concentrations for all particle sizes at significant heights above the ground but will also have distribution curves more characteristic of the soil surface than those obtained from less convective wind regimes. The apparent "minimum" or significant change in slope of the concentration ($\Delta N/\Delta \log D$) at approximately $10 \mu\text{m}$ dia. is not explainable with the available data, and therefore it must await the analysis of more complete data on the simultaneous measurement of both soil and aerosol particle distributions.

IV. VERTICAL MASS FLUX NEAR THE GROUND

The dust devil particle distributions indicate a mass loading of approximately 5 gm m^{-3} at a height of 1 - 2 m above the ground. In comparison, mass loadings for cities are of the order of $100 \text{ } \mu\text{gm m}^{-3}$ while midwest dust storms range from approximately 0.1 mgm m^{-3} (Gillette¹²) for developing Nebraska storms to values greater than 20 mgm m^{-3} within well-developed Texas dust storms (Shinn¹⁴). The extremely high mass loadings within the dust devil suggest that, provided their frequency of occurrence is sufficient, a significant component of the vertical mass flux of desert surface particulates may be due to dust devil activity. Furthermore, due to the large vertical velocities and vertical extent of the upper dust devil plume, mixing throughout a deep layer will occur for almost the entire particle distribution.

A realistic test of this hypothesis requires some statistical knowledge of the following dust devil features:

- (1) Diurnal and seasonal frequencies of occurrence
- (2) Dust devil duration
- (3) Vertical mixing depth of the dust
- (4) Dust particle distribution and concentrations
- (5) Environmental wind distribution

Sinclair^{1,13} has presented the largest and most complete set of observations of dust devil frequency of occurrence, duration and vertical extent. These studies which are critical with respect to the radioactive dust transport problem show for a typical desert region (285 km^2) of the Southwestern United States that:

1. Daily frequencies range from 20 to 162 dust devils with a mean of 85. Similar observations within the CMX site of Area 5 of NTS

indicate frequencies of approximately 1 dust devil per minute during the most active part of the day.

2. Dust devil duration is variable depending on size and generally ranges from 0.5 to 10.5 min. with an upper limit near 15 min. Two reports, from other areas, of durations of 2-7 hours can be considered extremes.
3. Sailplane measurements of the "clear" dry thermal regions above visible dust devils show that the vertical mixing depth of the warm boundary layer extends to altitudes as great as 16,000 feet MSL for the larger size dust devils.
4. Meso-synoptic scale situations conducive to dust devil formation usually exhibit very little wind shear with height. The Arizona Studies (Sinclair¹) indicate that winds are less than 10 - 15 kts at all levels from the surface to 500 mb. Consequently, for the smaller particles, the low terminal velocity combined with the deep vertical mixing is more significant with respect to downwind transport than the mean transport due to the environmental wind. The downwind transport possibilities will be only briefly mentioned here, with more definite modeling results dependent on the success of the current NTS field measurement program.

From these available data (Sinclair^{1,2,13}) four dust devil size categories were established with the following mean features for a height (z) of 2 meters,

Dust Devil Size	Diameter (m)	Duration Δt (sec)	Vertical Extent $\bar{z}$ (m)	Vertical Velocity $\bar{w}$ (m sec ⁻¹)
Small	3	60	750	3
Medium	9	100	2300	6
Large	23	240	3000	10
Extra Large	46	360	3800	12

For each dust devil size, the mean vertical mass transport ($\bar{T}$) of surface particulates was calculated from:

$$\bar{T} = \bar{\rho}_d \bar{w} \bar{A} \quad [\text{gm sec}^{-1}] \quad (6)$$

where $\bar{\rho}_d = 5.3 \text{ gm m}^{-3}$ represents a mean mass loading, $\bar{w}$ a mean vertical velocity, and $\bar{A}$ a mean cross-sectional area of the dust devil. For example, for the small (size) dust devil:

$$\bar{T}_s = \bar{\rho}_d \bar{w} \bar{A} = 5.3 \text{ gm m}^{-3} \times 3 \text{ msec}^{-1} \times 6.8 \text{ m}^2 = 108.1 \text{ gm sec}^{-1} \quad (7)$$

The dust devil cross-sectional area for each size category has been corrected for the negative vertical motion in the core area (Sinclair^{1,2}).

The total (mean) dust particle mass transport for a small dust devil is then:

$$(\bar{T}_s)_t = \bar{T}_s \times \Delta t = 108.1 \text{ gm sec}^{-1} \times 60 \text{ sec} = 0.72 \times 10^{-2} \text{ tons} \quad (8)$$

The total mean daily transport $(\bar{F}_s)_t$, from small dust devils which have a mean daily occurrence of 25 per day is then:

$$(\bar{F}_s)_t = 0.72 \times 10^{-2} \text{ tons} \times 25 \text{ D-D/day} = 18.2 \times 10^{-2} \frac{\text{tons}}{\text{day}} \quad (9)$$

For a mean dust devil season of 45 d.y.s, the total mean seasonal dust transport is simply:

$$(\bar{F}_s)_{yr} = 18.2 \times 10^{-2} \frac{\text{tons}}{\text{day}} \times 45 \text{ days} = 8.2 \text{ tons} \quad (10)$$

Following a similar analysis for the medium, large, and extra large dust devil leads to a total mean daily transport of 157 tons and a total mean yearly transport of $157 \text{ tons day}^{-1} \times 45 \frac{\text{days}}{\text{season}} = 7 \times 10^3 \text{ tons/season}$.

The mass flux for each dust devil class represents the transport per unit area, i.e., for the small dust devil class:

$$\frac{\bar{F}_s}{A} = \bar{p}_d \bar{w} = 1590 \mu\text{g m cm}^{-2} \text{ sec}^{-1} \quad (11)$$

The results of these calculations for all dust devil classes are tabulated in Table 1. These data show that although there are relatively few extra-large dust devils, they are responsible for 95% of the dust transport for a single dust devil and for 75% of the total mean daily and seasonal dust transports. For comparison, duststorm data are also included in Table 1. These data show that the vertical flux for a single dust devil (flux/DD) in $\mu\text{g m cm}^{-2} \text{ sec}^{-1}$ exceeds that of even a well-developed dust storm by two to five orders of magnitude. However, because of the dust devil limitations with respect to duration and total areal coverage, the well-developed duststorm mean daily dust transport ($\text{tons}/10^2 \text{ mi}^2$) exceeds that of a typical dust devil source region for the same time period. For example, the small dust devil represents an areal coverage of approximately 100 m^2 and a duration time of 60 sec. Using 285 km^2 (10^2 mi^2) as a reference area, we know that only 0.18 tons are transported vertically by a mean number (35 DD/day) of dust devils as compared to 100×10^3 tons for a duststorm covering the same area (Table 1). As a result, the dust devil and duststorm mean daily dust transport differ by a factor of approximately 10^7 due to the duration time and area ratios of:

$$\text{time: } \frac{7 \text{ hrs}}{60 \text{ sec}} = \frac{25.2 \times 10^3}{60} = 5 \times 10^2 \quad (12)$$

$$\text{area: } \frac{285 \text{ km}^2}{100 \text{ m}} = 2.85 \times 10^6 \quad (13)$$

which results in a total time-area difference factor of $(5 \times 10^2) (2.85 \times 10^6) = 10^9$.

The small dust devil flux, however, is larger approximately by a factor of 10^2 which results in a net difference in total mean daily dust transport of approximately 10^7 , i.e., 0.18 tons (small dust devil) vs. 1700×10^3 tons (dust-storm at $21 \mu\text{gm cm}^{-2} \text{ sec}^{-1}$). The total dust devil transport, however, differs only by a factor $30\text{--}10^4$ for the dust storm flux, i.e., 160 tons vs. $(6 \text{ to } 1700) \times 10^3$ tons (Table 1). Note, however, that the dust devil transport still exceeds that of the duststorm initial stages as measured by Gillette, *et al.*¹²

The important point to be emphasized here is that a typical dust devil source region may provide a significantly greater atmospheric dust mass loading than that resulting from duststorms not reaching well-developed stages. Since the dust devil probably represents the extreme end of the continuum of convective elements, the vertical flux from less intense "clear" elements, which represents the larger part of the convective spectrum, could materially add to the mass transport by dust devils. Because of the much higher frequency of these "clear" convective thermals, the total mass transport from a typical desert region may approach more closely that of even a well-developed duststorm.

In addition, since the dust devil and "clear" thermal activity during a typical summer season (June-August) will occur daily, for example, throughout the southwestern desert regions and the cultivated farming areas of the midwest, there will be essentially a continuous vertical dust transport from many thousands of square miles. On the other hand, it seems reasonable that when duststorms occur, they will at any one time be responsible for dust resuspension in an area at most only one-tenth the total available area. For the entire U.S.

this factor may even be an order of magnitude smaller. Consequently, the vertical transport of surface particulates by dust devils and thermals may closely approach or equal that same transport by well-developed duststorms.

V. DEEP LAYER MIXING

A. Dust Devil Vertical Structure

The primary importance of the vertical transport of surface particulates by dust devils is not only related to the large mass loadings (5 gm m^{-3}) but it involves also the possibility that the particles may be vertically transported to the top of the convection layer. During the summer months, the upper boundary of the convection layer may reach 500 mb over the desert of the Southwest. Quantitative measurements from an instrumented sailplane (Sinclair¹) of the dust devil structure within this convective regime have revealed that the "clear" upper portion of the dust devil can extend throughout the depth of the convective layer. This was substantiated by penetrating the dust devil updraft-downdraft regions at various altitudes and measuring the temperature and vertical motion. These individual penetrations were then used to develop a composite model of the dust devil upper structure (Figure 7).

The composite model shows essentially the same updraft-downdraft and temperature features as the individual penetration cases. At each mean altitude there is a central region of strong upward motion (approximately 3 msec^{-1}) on the axis which is surrounded by a distinct region of descending motion slightly less in magnitude. The mean temperature profiles indicate, as in the individual cases, positive ΔT 's within the updraft region (approximately 0.35°C on the axis) and in some cases negative values within the surrounding downdrafts. The dotted outline shown in Figure 7 represents a hypothetical boundary for the width of the mean updraft. In addition, the heights and width characteristic of the dust column of large desert dust devils is shown near the base of the mean updraft region. Note that this height is to be regarded as a mean height with the possibility that in extreme cases the dust

may still be visible at altitudes of 6000-9000 ft. above the ground (Woodward¹⁵). The rapid widening of the updraft region from the ground to approximately 6000 ft. is believed to take place in the following manner. As the upward moving column of warm air proceeds through the plume and vortex stages, mixing between the thermal and the environment results in a mutual exchange of both vertical momentum and heat. Malkus¹⁶ has termed this mixing process "gross entrainment". As the upward vertical momentum is mixed into the unstable environment, an upward vertical velocity is imparted to the environment. Due to the vertical instability of the disturbed environment, the air has a positive buoyancy, and it therefore continues to accelerate upward. Thus, in the initial stages of growth as the vortex penetrates to successively higher levels, the gross entrainment acts to "trigger" the inherent instability of the surrounding environment in the lower levels and thereby results in the rapid widening of the initial updraft. Therefore, the origin of the updraft region at about 6000 ft. (Figure 7) is not necessarily at the ground, but may have partly had its origin someplace within the atmospheric layer between the surface and 6000 ft. Because gross entrainment implies mixing both into and out of the warm updraft, relatively cool environmental air is mixed into the updraft. This acts to decrease the temperature and hence the buoyancy of the updraft. In addition, the net or dynamic entrainment (air from the environment that is mixed into and remains within the updraft) of vertical momentum acts to decrease the upward motion of the warm buoyant air. Thus, the mixing tends to broaden the updraft region with height, as well as to reduce the buoyancy of the updraft.

H. Particle Transport

It is evident from the composite model of the dust devil upper structure (Figure 7) that surface particles as large as 200-300 μm can be transported

vertically to at least 10,000 ft. MSL by large desert dust devils. Consequently, a large portion of the surface dust and sand particle distribution can be removed from the surface layer and lifted vertically to altitudes from which downwind transport becomes significant. To obtain an estimate of the downwind dust transport capability of dust devils, the total vertical mass flux of various sized dust devils were analysed with respect to the upper level desert wind regime. Figure 8 shows the total daily dust fallout or vertical dust transport with respect to the downwind fallout distance of the various size particles. The dust devils were sized according to mean values: diameter, height, vertical velocity, and duration taken from earlier field measurements and observations (Sinclair^{1,2,13}). To obtain the total daily dust fallout from the vertical mass flux, a mean daily dust devil count in an area of 285 km^2 was used for the various designated sizes. The downwind fallout distance was calculated using the particle size spectrum deduced from earlier measurements (Sinclair¹) and a mean environmental wind of 5 msec^{-1} . The latter approximation appears quite valid for the Tucson, Arizona area during the particular period of study. Each curve in Figure 8 represents a particular dust devil size, and each point on a curve refers to the various classes of particle sizes from $5 \text{ }\mu\text{m}$ to $240 \text{ }\mu\text{m}$, i.e., $5\text{-}10 \text{ }\mu\text{m}$, $10\text{-}20 \text{ }\mu\text{m}$, $30\text{-}40 \text{ }\mu\text{m}$ $230\text{-}240 \text{ }\mu\text{m}$. For example, the first point on the left of each curve represents the $230 \text{ }\mu\text{m}\text{-}240 \text{ }\mu\text{m}$ particle size range, and the points to the far right for each curve represent the $5 \text{ }\mu\text{m}\text{-}10 \text{ }\mu\text{m}$ size range. The peaks for each curve represent the size range which includes the median mass diameter of $95 \text{ }\mu\text{m}$. Thus, for example, the downwind fallout distance (mi) for $5 \text{ }\mu\text{m}\text{-}10 \text{ }\mu\text{m}$ diameter particles may exceed $500 \text{ mi}\text{-}2500 \text{ mi}$ depending on the dust devil size which controls the initial height from which the simple terminal velocity fallout calculations were performed. The curves of Figure 8

are skewed toward greater fallout distances for increasing dust devil size. This is due to the lifting of particles to greater heights in the larger dust devils. Consequently, the settling time of the entire particle spectrum is increased. Hence, with a constant environmental wind these particles are transported further downwind than those that start out at much lower altitudes in the smaller dust devils. The particular ordinate spacing of the curves for the four dust devil sizes was produced not only by the differences in each dust devil size, but also by the mean number of dust devils which occurred on a particular day during the observing period. Also, note that while the dust devils were observed over an area of approximately 285 km^2 the downwind fallout distances are plotted as if all the dust devils occurred along a common source line which was selected perpendicular to the downwind transport direction.

The data, on one hand, present an upper limit to the total daily dust fallout from dust devils in this particular area, since it is assumed that all of the dust reaches the top of each dust devil before it begins its trajectory. On the other hand, the dust particle spectrum used for all four dust devil sizes is valid only for a medium size dust devil. This is the reason that all four curves have the same general shape. Consequently, the total dust fallout from the small dust devils may be overestimated while that from the large and extra-large dust devils may be underestimated. The latter possibility tends to offset much of the overestimate due to the assumption of no particle loss through the dust devil lateral boundaries. However, there are still other considerations that must be taken into account. For example, the extra-large dust devils are certainly more intense, developing higher wind speeds which may increase the saltation process and thereby remove from the surface both a greater number and/or larger sand or dust particles. While

this would probably change the entire particle size spectrum, the higher tangential flow fields in the vortex may tend to centrifuge the larger particles out of the dust vortex near the ground. On the other hand, larger radial flow components occur for the larger dust devils which would tend to confine these larger particles within the dust devil vortex. Consequently, these results can only be considered a rough first approximation to what actually occurs. A specifically designed measurement and analysis program is necessary before these and other compensating particle transport effects can be adequately determined.

These calculations (Figure 8 and Table 1) indicate that a dust devil source region of 285 km^2 area may result in large daily and seasonal downwind dust fallout. However, not much of the total mass is confined within that part of the particle spectrum that exceeds 100 miles fallout distance. That is, most of the mass transport reaches the ground in a fallout distance less than approximately 50 miles. The small dust devils transport approximately 0.1% of the total mean daily dust transport, and less than 10% of their total daily dust flux is transported further than 10 miles from the dust devil source region. Only the $5 \text{ }\mu\text{m}$ - $10 \text{ }\mu\text{m}$ particles that are lifted high in the "clear" thermal plume above the visible dust devil, exceed fallout distances of 10^3 miles. These particles, however, contribute only 0.03% of the total mass transported by dust devils in the three largest size categories. On the other hand, these particles ($5\text{--}10 \text{ }\mu\text{m}$), as well as the accompanying sub-micron particles, are the important ones with respect to human and animal inhalation.

While these first results appear significant with respect to the seasonal transport of dust downwind of a dust devil source region, there are three factors that can greatly enhance the amount and the distance of the dust transport.

(1) Leapfrog Transport Mechanism

The above calculations of dust transport have been based on the assumption that after the particles leave the top of the various size dust devils they settle to the ground at their terminal velocity. This is probably not the case, even during mild convective activity. The Arizona dust devil census data (Sinclair¹) and cross-country sailplane flying experience indicate that one can expect, in desert regions on an average convective day, dust devil and/or clear thermal separation distances of approximately 1-15 mi, with an average of about 5 miles. The separation appears to be governed strongly by the dust devil size distribution and surface vegetation and terrain. Consequently, some of the dust particles which are lifted more than a few hundred feet above the ground will probably experience a number of vertical transport cycles within other dust devils or clear thermal plumes which are embedded in the downwind convective layer (Figure 9). As a result of this leapfrog mode of transport, the downwind fallout distance of each dust devil size category (Figure 8) may be significantly increased. The Arizona dust devil data indicate that the desert convective activity extends over a period of approximately 6 daylight hours. This means that the dust fallout distance could be increased by approximately 67 miles for each dust devil size category. Percentage wise this is a significant increase for all categories except for the smallest particles. A more significant increase may result from the transport of dust particles from the smaller to the larger dust devils and/or

clear thermal plumes (Figure 9). For example, 5 μm to 10 μm dust particles that leave the top of a small dust devil may have their downwind fallout distance increased from approximately 500 miles to 2600 miles by a simple leapfrog cycle with an extra-large dust devil. The leapfrog process applies to all particle sizes and convective element size categories.

(2) Cumulus Cloud Transport

Frequently, cumulus clouds form above the dry convective plumes of dust devils and clear thermals. Dust particles entering a cumulus cloud base may be transported another 5,000 feet to 40,000 feet above the top of the dry convective layer. Dust particles entering cumulus humilis type clouds will probably be lifted 5,000 feet-10,000 feet above cloud base. This results in a significant increase in the initial altitude from which the particles begin their downwind trajectories. If the dust particles act as condensation nuclei, the water droplets will evaporate within approximately 10 min-20 min, which is the average life cycle of this type of cumulus cloud. On the other hand, dust particles that enter the bases of cumulus clouds that develop into congestus and cumulonimbus types will probably be rained out in the precipitation fallout. Thus, these particles will be returned to the general location from which they originated. However, dust particles which escape this precipitation rainout may reach the upper level outflow of the anvil region and thereby be carried many miles downstream within this ice crystal region. Under such conditions, the dust particle size distributions would all be shifted significantly toward larger downwind fallout distances (Figure 3). On the other hand, dust devil activity is usually low during strong convective situations which produce large cumulonimbus type clouds. Consequently, other processes during these situations appear to be more important with respect

to the vertical transport of surface dust. This conclusion, however, should not be interpreted to mean that the vertical transport of large quantities of surface material by cumulonimbus clouds does not take place. On the contrary, large masses of surface dust material are imbedded in the inflow during certain stages of large convective storms. Our experience in measuring the air motion at cloud base and within these storms indicates that these cloud systems are capable of transporting considerable surface dust material to altitudes where subsequent downwind fallout distances should be significant with respect to the transport of radioactive material. It would appear that this mode of radioactive dust transport also should be carefully studied.

However, smaller cumulus clouds which do not develop precipitation size droplets could increase the downwind dust fallout distances for all particle sizes by the following percentages:

<u>Dust Devil Size</u>	<u>Downwind Fallout Distance Increase</u>
small	200% - 400%
medium	60% - 120%
large	50% - 100%
extra-large	40% - 80%

As a result, medium, large and extra-large dust devils in conjunction with fair weather cumulus cloud activity could be responsible for downwind fallout distances of 2,000 to 4,000 miles for particles as large as 20 μ m (Figure 8). During the Arizona dust devil field research, cumulus clouds were observed each day. As the cloud cover increased, the dust devil activity decreased (Sinclair¹³). However, due to the large percentage increases of downwind fallout distance from the added vertical dust transport capability of relatively small cumulus clouds, there exists a cross-over point above which

the cumulus cloud transport component exceeds the effect of decreased number of dust devils due to the overlying cloud cover.

VI. AIRBORNE MEASUREMENT PROGRAM

The Lawrence Livermore Laboratory and Colorado State University are presently working on a joint dust devil measurement program at the AEC Nevada Test Site. The program is designed to determine quantitatively the vertical flux of dust within the visible dust devil, the "clear" thermal region above, and the horizontal dust flux in the region downwind. This information coupled with the downwind ground particle sampler data and the surface particle measurements will complete the study of the dust transport cycle by dust devils and provide data for establishment of a dust transport budget. From this transport budget, one can then ascertain the magnitude of the dust devil transport of radioactive material within and out of the Test Site boundaries. Large "clear" convective elements will also be investigated in order to assess the importance of these large convective elements to the dust mass loading of a desert atmosphere. In the initial analysis of this dust transport question, it became readily apparent that airborne measurements are necessary to properly establish the possible dispersion of radioactive material by dust devils. For example, surface measurements alone would not be capable of determining the downwind dust transport from a specified experimental area. That is, one cannot simply measure the dust vertical flux within the dust devil near the ground and the dust fallout downwind and arrive at a suitable model for the dust devil transport mechanism. This conclusion is based on the following considerations: (1) some of the particles are centrifuged out of the vortex at relatively low altitudes, (2) some of the particles undoubtedly are mixed out of the clear thermal region at various altitudes above the visible vortex and (3) dust devil activity in the downwind sampling area may seriously bias the downwind ground particle sampler data.

The above arguments clearly establish the requirement for airborne

measurements of the vertical flux and transport of desert particulates by dust devils. The airborne sampling requirements dictate the use of a low-speed and very maneuverable aircraft. We have selected a two-place, 150 hp Shinn 2150A aircraft (Figure 10) for the dust devil penetrations from 50 ft. to 18,000 ft. MSL. The airborne sampler (Figure 11) is a new design which incorporates several features of an earlier design by Raynor¹⁷. In order to obtain a representative sample of the particles within the dust devil, the sampler inlet diameter (0.75 in.) has been maximized such that the flow rate remains compatible with the vacuum pump capability and the aircraft true airspeed. That is, the vacuum pump is automatically adjusted to provide isokinetic sampling at all airspeeds and altitudes. The entrance cone acts as a deceleration chamber for the air and the particles before the latter are collected on a 90 mm diameter Nuclepore filter located at the rear of the removable entrance cone. The entrance cone is attached to a middle cylindrical chamber which also supports the vacuum pump at the rear. Thus, the air flows in essentially a straight line directly through the entrance cone, the filter, the middle cylindrical section, and finally out the rear of the vacuum pump. The middle cylindrical chamber is attached to a rotary section which can slide laterally (spanwise) along the airfoil section which supports the entire air sampling unit. On the pilot's command, the sampler entrance cone rotates toward the cockpit and at the same time slides laterally toward the entrance hole in the aircraft canopy. The sampler rotates and moves horizontally such that the entrance cone can be removed and the filter quickly changed. The sampler then automatically "backs" away from the cockpit and turns into the airflow by the time it reaches the end of the airfoil track (Figures 10 and 11). The sampler was designed with these particular features to allow frequent and rapid filter changes while in flight. This capability

will allow us to estimate the vertical variation of the dust particle distribution with the dust devil.

A complete air data system and gyro-reference platform is carried in the rear cockpit of the aircraft. This system senses and records on digital cassette tape the total temperature, ram and static pressure, rate of climb, roll, pitch, and α and β vane angles. The α - β vane system (Figures 10 and 12) senses angle of attack and yaw changes with light weight, fast response plastic vanes. The measurement system is designed to be independent of the aircraft sensitivity to atmospheric motions and/or pilot induced motions. The measurement technique (Sinclair^{18,19}) requires knowledge of the motion relative to the airplane ($V_{a,p}$) and the motion of the airplane relative to the ground ($V_{p,g}$) in order to calculate the atmospheric motion with respect to the ground ($V_{a,g}$) i.e.

$$V_{a,g} = V_{a,p} + V_{p,g} \quad (14)$$

Using the small angle approximation, the vertical component ($W_{a,g}$) can be expressed as:

$$W_{a,g} = W_{p,g}(\alpha) + V_T \alpha + V_T \dot{\alpha} - V_T \ddot{\alpha} + \int_0^t a_z dt + L\ddot{\alpha} \quad (15)$$

where V_T is the true air speed; α the angle of attack, α , β , and γ the pitch, yaw, roll angles, respectively; $\int_0^t a_z dt$ the rate of climb of the aircraft; $W_{p,g}(\alpha)$ the vertical motion of the aircraft at time $t = 0$; $\dot{\alpha}$ the pitch rate; and L the accelerometer center displacement from the angle of attack measurement point. The flow vanes and pitot system are mounted on a nose-boom in front of the aircraft to minimize the affects of propellor, fuselage, and wing induced flow fields. The true airspeed is calculated from measurements of total pressure, static pressure, and total temperature. The static temperature

and true airspeed are determined by use of the compressible, subsonic flow equations (Sinclair ¹⁸):

$$\frac{P_t - P_s}{P_s} = \left(1 + \frac{\gamma-1}{2} M^2\right)^{\frac{\gamma}{\gamma-1} - 1} \quad (16)$$

$$\frac{T_t}{T_s} = 1 + \frac{\gamma-1}{2} \eta M^2 \quad (17)$$

$$V_t = T_c^{\frac{1}{2}} [gR / (1 + \frac{\gamma-1}{2})]^{\frac{1}{2}} \quad (18)$$

where: P_t = total pressure; P_s = static pressure; M = Mach number; T_t = total temperature; T_s = static temperature; η = recovery factor; γ = ratio of specific heats of air, c_p/c_v ; V_t = true airspeed.

The air data system will provide vertical motion data necessary for the calculation of the vertical transport of surface particulates. In addition, the turbulence and buoyancy data will be useful in modeling the dust devil upper structure and the accompanying particle transport. This information, in conjunction with the dust devil census data, the environmental wind flow, and the surface particle radioactivity can be used to develop conceptual and numerical models of the downwind transport of radioactive material. Additional measurements of downwind convective activity, dust devil spacing, and cumulus cloud occurrence can be used to assess the importance of the leapfrog and cumulus cloud transport mechanisms.

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Table 1
DUST DEVIL (D-D) VERTICAL MASS FLUX

Wind System D-D Size	Flux/D-D ($\mu\text{g cm}^{-2} \text{ sec}^{-1}$)	Single D-D Dust Transport (Tons)	Total Mean Daily Dust Transport (Tons)	Total Mean Seasonal Dust Transport (Tons)
Small	1.6×10^3	0.01	0.18	8.
Medium	3.2×10^3	0.30	13.	570.
Large	5.3×10^3	2.4	25.	1100.
Extra-Large	6.4×10^3	48.	120.	5400.
TOTAL	1.6×10^4	50.	160.	7000.
<u>Duststorm</u>				
Initial Stages	$(0.6 \text{ to } 10) \times 10^{-5}$		0.8 to 8	2.4 to 24
Well-Developed	0.07 to 21		$(6 \text{ to } 1700) \times 10^3$	$(17 \text{ to } 5000) \times 10^3$

ILLUSTRATION CAPTIONS

- Figure 1 A Typical Desert Dust Devil
- Figure 2 A Schematic Model of the Dust Devil Lower Structure. The motion is with respect to a coordinate system fixed to the dust devil, which is moving from right to left in the diagram. The vertical (w) and tangential (v) velocity profiles are characteristic of the measurements at the 7 and 31 ft levels. The assumed axial symmetric pressure field represents approximately a 3-mb pressure drop from the environmental pressure (P_0) to the dust devil center, i.e., the pressure interval is 1 mb with $P_0 > P_1$.
- Figure 3 Photomicrograph of the Large Particle Distribution Within the Dust Devil Vortex at a Height of 2 Meters.
- Figure 4 Dust Particle Number and Mass Distribution From a Small Size Dust Devil
- Figure 5 Force and Velocity Diagram for a Dust Particle in Circular Orbit
- Figure 6 Airborne Particle Size Distributions
- Figure 7 A Composite Model of the Dust Devil Upper Structure. The dashed lines refer to the mean temperature deviations (ΔT) and the solid lines represent the mean vertical velocity (w). The notations (UW) and (DW) refer to the upwind and downwind side, respectively, of the dust devil.
- Figure 8 Total Daily Dust Fallout From A Typical Dust Devil Source Region
- Figure 9 Schematic of the Leapfrog Transport Mechanism: The radioactive dust particles that leave the top or sides of the dust devil that is initially responsible for their vertical transport, may be drawn into other convective elements (dust devils, clear thermal plumes, and/or cumulus clouds) and transported back to the same or to even greater initial altitudes.
- Figure 10 Dust Devil Research Aircraft
- Figure 11 Airborne Particle Sampler and Boom-Vane System
- Figure 12 α - β Vane-Pitot Static Turbulence Sensor System

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