9th Asia-Pacific Conference on Wind Engineering
Auckland, New Zealand
3-7 December 2017

A Model of Tangential Wind-speeds in Dust-Devils

N.A. Hawkes and R.G.J. Flay

Department of Mechanical Engineering
University of Auckland, Auckland 1142, New Zealand

Abstract

Dust-devil wind-speeds are modelled for a dataset from NASA Report DAC-63098. The model suggests dust-devils act as heat-engines which convert Convectively Available Potential Energy (CAPE) available within the super-adiabatic boundary layer into rotational kinetic energy at an efficiency proportional to the height of the super-adiabatic layer. The model successfully predicts the peak tangential wind-speeds measured at the ground.

Introduction

The report DAC-63098: "Study of Dust Devils as Related to the Martian Yellow Clouds" [1] was produced in 1969 to justify ascribing "Yellow Clouds" seen in the Martian atmosphere as arising from dust-devils, rather than from some more problematic possibility such as acid condensation, based on field-trials performed in preparation for the Mars landings, under contract NASw-1620.

Since then heat-engine analyses of dust-devils have been published [2-4] based on a heat-engine driving vortex flows that runs from the ground to the top of the convective layer, with a hot reservoir at the air temperature at the ground and a cold reservoir at the average temperature of the convective slab, or modelled implicitly via CAPE.

Our recent paper [5] suggests that this view can be usefully modified by making these assumptions:

- the cold reservoir is immediately above the coherent concentrated vortex, in the turbulent plume that forms when the vortex core breaks down;
- the core break-down occurs rapidly when no vertical acceleration is present to concentrate vorticity against radial diffusion;
- vertical acceleration in the core arises from lapse-rate divergence between the core and the atmosphere. If the core cools more slowly than the atmosphere, then vertical acceleration results as the rate of release of CAPE increases with height.

The assumptions above are supported by analysis of vortex wind-speeds in published laboratory experiments [6] and field observations of dust-devil height [7] but more analysis was needed to demonstrate that this theory can usefully model vortex wind-speeds in the atmosphere. This is attempted here.

The Field Trials

Field experimental studies of dust-devils were made in the Mojave Desert of Southern California, at a site called El Mirage Dry Lake, in 1968. This site is flat, devoid of vegetation and lies about 160 km from Santa Monica at an elevation of 944 m.

An area of 500 m by 300 m was cleared, with a measurement station set up at the centre. The area was repeatedly scraped to provide loose dust to make any passing dust-devils visible. Surveyed stakes were set up at intervals within the area, to aid estimates of dust-devil distance, so height and diameter could be obtained by angulation.

Measurements were taken of atmospheric temperature profile; atmospheric wind-speed and direction; atmospheric vorticity and for each dust-devil:- time of occurrence, location, duration, maximum tangential and vertical wind-speeds, diameter, dust and billow heights, direction of rotation and general meteorological conditions.

Temperature measurements were taken from the surface to a height above the super-adiabatic layer. Measurements were taken at the ground and at 0.3, 1, 2, 4, 8 and 14 m from the measurement station mast, and at 77, 150, 300, 920 and 1540 m from a light aircraft. The thermometers used were calibrated to +/- 0.1 °C.

The experimenters drove ahead of the dust-devils by car, in order to place mobile instruments into them as they passed. Peak dust-devil wind-speeds near the ground were measured by two-axis hot-wire anemometer in this way. Diameters were measured by angulation from photographs and peak tangential and vertical wind-speeds taken from the histories of the anemometers.

Original Analysis of the Data

Statistics for temperature and lapse rate were derived relating to a three layer atmospheric model, with a strongly super-adiabatic layer from the ground up to some 5-10 metres immediately above it, a super-adiabatic layer extending some hundreds of metres above that and a sub-adiabatic layer beyond.

Correlations were sought between temperature statistics for these layers and statistics for the dust-devils encountered. Many interesting results were derived but the variation of tangential wind-speed with atmospheric conditions and radius was not convincingly explained.

Re-analysis of the Data

The measured temperature versus height profile immediately preceding each dust-devil arrival was entered into RAOB software, which is a package for manipulating radiosonde data to produce SkewT/log-P diagrams and associated statistics, including analysis of Convectively Available Potential Energy or "CAPE" [8] with height. RAOB gives better facilities to visualise and measure lapse rates and CAPE than were available in 1968. The very notion of CAPE is of later date than the report.

81 temperature profiles were entered into spreadsheets, along with the maximum tangential and vertical wind-speeds (as measured near the ground) for the associated dust-devil. All dust-devils with a diameter of at least 1m, recorded in the trials running from 28/3/1968 to 12/9/1968, covering 11 days of field observations, were entered.

Figures for height above the ground were converted to atmospheric pressure, for entry into RAOB, using the 1976 Standard Atmosphere Calculator, with temperature offset to reflect the average recorded ground-level air temperatures (17°C offset gives 904.86 mb @ 944 m altitude, etc.)

The results were analysed to see whether the maximum tangential velocities recorded in the dust-devils could be predicted from the atmospheric temperature profiles, through considering various models of the vortices as heat-engines.

Data Excluded

Of the 81 dust-devils recorded, some were excluded from the analysis for the following reasons:

- Devil 4 arrived after a significant period of shading by passing cloud. The temperature profile is disturbed.
- Devils 14,22,23,48 and 52 have no data for tangential velocity.
- Devils 44,45,46 and 72 show profiles with significant adiabatic or sub-adiabatic layers immediately above the ground, with the expected super-adiabatic layer above them. This seems to throttle the vortex at birth with wind-speeds being much reduced.

These 10 devils are excluded so 71 dust-devils form the dataset for modelling.

Modelling

Different criteria for estimating the likely height of the coherent vortex – relating to diameter, vertical acceleration and breakdown – were investigated by inspection of scatter diagrams in searching for a persuasive correlation. The criterion that the authors call H produces the best correlation to Vtmax as measured. It assumes vortex breakdown occurs rapidly at a height (H) where the difference between the core lapse rate (with the core assumed to be adiabatic) and the atmospheric lapse rate, is less than $0.2℃/km$, i.e.

$$LR(H)_{atm} < 10℃/km$$

Estimating H for deeper super-adiabatic layers, associated with more powerful dust-devils, involved interpolation between data points – for instance in the case of a layer 450 m deep, the nearest data points in the profiles are at heights of 300 m and 920 m. This was done by assuming a monotonically varying profile through the data points below and above, then selecting a value of H where the average lapse rate to the data-point below is greater than $10℃/km$ and the average lapse rate to the data-point above is less than $9℃/km$, by inspection of Skew-T/Log-P plots of the temperature profiles.

The model of [2] and a modification of this model based on CAPE given by [4], were further modified by assuming the cold reservoir resides in the plume above at height H, to give estimates of the mean tangential wind-speed at the core-edge. The results of these models are somewhat similar but do not produce convincing correlations to the measured wind-speeds, as shown in figures 1 and 2.

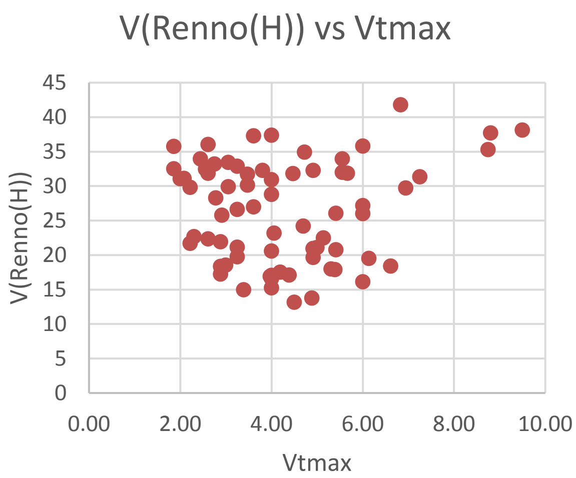

Figure 1. Renno et al. [2] model with cold reservoir in the plume

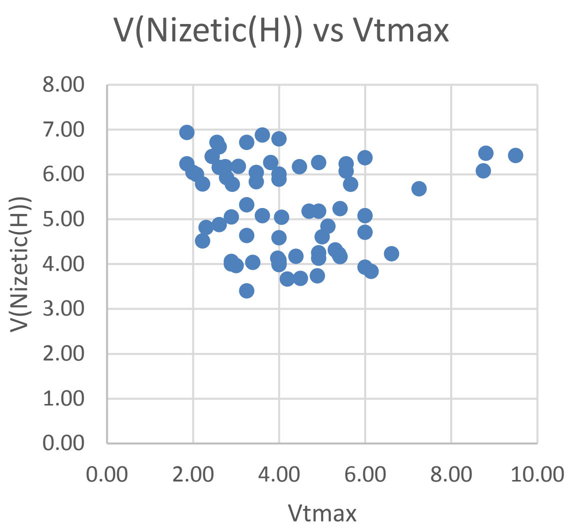

Figure 2. Nizetic [4] model with cold reservoir in the plume

These models assume the dust-devil is in a steady-state balance between ground-heating and mechanical work.

Instead, the authors suggest that rotational kinetic energy in the core arises from the conversion of pre-existing CAPE in a stationary boundary-layer (i.e. not moving with the wind) immediately above the ground, gathered by dust-devils moving with the wind-field above it.

This gathering breaks the relationship between power from heating and rate of mechanical work. If the dust-devil converts CAPE released in the core into rotational kinetic energy, with mass flow rate $\dot{m}$ entering the vortex core at the bottom and exiting into the plume at the top then

$$\dot{KE_r} = K1.\dot{m}.V_t^2 = \dot{m}(CAPE(H).\eta) \text{ (W)} \quad (1)$$

- K1 is a constant for a consistent flow structure
- η is the conversion efficiency of the vortex

CAPE(H) is calculated based on air temperature at the ground and the resulting virtual potential temperature differences, up to H

$$CAPE(H) \equiv \int_0^H g.\frac{T_{v,parcel}-T_{v,env}}{T_{v,env}}\, dz \text{ (J/kg)} \quad (2)$$

If CAPE(H) is assumed to be converted entirely into rotational kinetic energy (with vertical velocity ignored) in a core in solid body rotation (a Rankine model vortex) then,

$$KE = \frac{1}{2}I\omega^2 \text{ and } I = \frac{mR^2}{2} \quad (3)\ (4)$$

At the core edge $$\omega = \frac{V_t}{R} \quad (5)$$

So $$KE = \frac{1}{4}mV_t^2 \quad \text{(J)} \quad (6)$$

Equating CAPE and KE per unit mass of air, using equations (1),(2) and (6), for the mean flows in the core edge, then gives K1=1/4

$$V_t^2 = 4.CAPE(H).\eta$$

so $$V_t = 2\sqrt{CAPE(H).\eta} \quad (7)$$

Buoyancy vortices commonly occur with 1-cell or 2-cell structures [9]. For a 2-cell vortex, wind concentration occurs at a ratio of approximately 2, relative to the flows above in the core, arising from the Drowned Vortex Jump (DVJ) flow structure at the ground, as shown in figure 3.

Wind concentration occurs as a result of inertial overshoot beyond the point of cyclostrophic balance in the airflows turning the corner from radial inflow to vertical outflow. The area of maximum wind concentration from conservation of angular momentum is at point 3 in figure 3. The flows then recover to cyclostrophic balance at point 1 in the core, with radial pressure gradient from buoyancy balanced by centrifugal force.

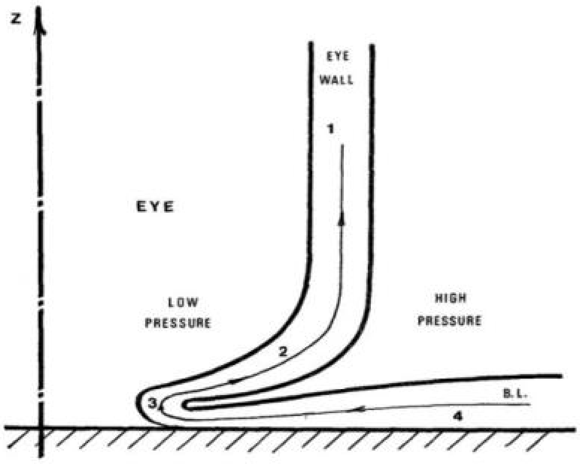

Figure 3. DVJ structure in a 2-cell vortex [10]

So assuming that maximum tangential wind-speeds at the ground (V_g) are proportional to mean tangential wind-speeds in the core:

For a 2-cell vortex:
$$V_g \approx 4\sqrt{CAPE(H).\eta_v} \quad (8a)$$

For a 1-cell vortex, wind concentration is approximately 1 so $$V_g \approx 2\sqrt{CAPE(H).\eta_v} \quad (8b)$$

The predictions of (8a) and (8b) were then used to model peak tangential wind-speeds at the ground as V(m), making the following specific assumptions:

- vortex height is H, as previously defined
- $\eta_v = K2.H$
- K2 is a constant for all dust-devils in the dataset, chosen to give best fit to the measured maximum tangential wind-speeds at the ground (Vtmax)
- all convection is dry, with no condensation
- Dust-devils 12,17,56,71,and 78 are assumed to be 1-cell vortices - with the remainder being 2-cell vortices. This is arbitrary but is consistent with field reports that most but not all dust-devils appear to be 2-cell vortices

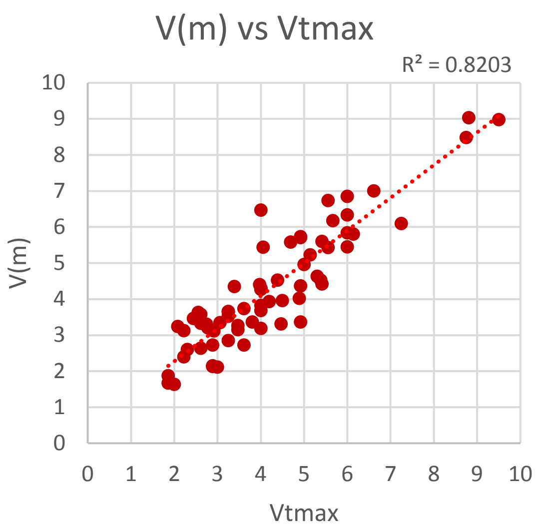

Figure 4. Gathered CAPE(H) with cold reservoir in the plume

The correlation shown in figure 4 (R^2=0.82) suggests the following:

- The dust-devils convert gathered CAPE (gathered in moving over the boundary layer) into rotational kinetic energy.
- A dust-devil goes through a rapid break-down to a turbulent plume at a height H, with the plume taking no apparent part in driving the vortex flows. Therefore the base of the plume can be taken as the cold reservoir of the heat-engine driving the vortex flows.
- H is the height at which the divergence between the atmospheric lapse-rate and the adiabatic core lapse-rate falls below $0.2°C/km$.
- The conversion efficiency is proportional to H for H<500 m, $\eta_v \approx 1.5\%$ for H=500 m. It may be that efficiency will tend to an upper bound for taller dust-devils.
- Dust-devil tangential wind-speeds are not dependent on diameter across a range from 1-15 m.
- 5 out of 71 dust-devils appear (from their tangential wind-speeds) to be 1-cell vortices with the remainder (93%) being 2-cell vortices.

The gathering of pre-existing CAPE incidentally explains why such dust-devils are seen to decay if they stop moving, since they would then denude the local stores of CAPE in the boundary layer. It may be that taller dust-devils can develop to more closely approach the steady-state heat-engine envisaged by [2] but would presumably still involve a cold reservoir in the plume above.

This model ignores the kinetic energy embodied in the vertical velocity of the core and in the velocity of the potential vortex flows surrounding the core and assumes the plume above plays no part in driving the vortex flows.
These are admitted simplifications of the fact that nonetheless seem to yield a useful prediction of tangential wind-speeds at the ground.

This model differs from the CAPE model of [4] which assumes a steady-state, with power from heating balanced by mechanical work-rate and CAPE to the height of the convective layer being converted to kinetic energy at low mechanical efficiency. This cannot be tested using this report as data was not collected up to the height of the convective layer.

No correlation was found between CAPE(H) and vertical peak wind-speeds in these dust-devils. This is surprising given that the vertical speed of general convection is expected to be proportional to the square root of CAPE released [8]. It is not clear why this is the case.

Conclusions

The modelling suggests short dust-devils act as heat-engines which convert pre-existing Convectively Available Potential Energy (CAPE) available within the super-adiabatic boundary layer into rotational kinetic energy at an efficiency proportional to the height of the super-adiabatic layer, with a structure which is otherwise consistent with [5]. The model successfully predicts the peak tangential wind-speeds of individual dust-devils as measured at the ground.

Acknowledgement

The report DAC-63098 is particularly well-suited for this purpose but was not easily available after the lapse of years. We wish to record our gratitude to Professor Robert N. Meroney, for his invaluable help in tracking it down and making it available.

References

[1] Ryan J. Study of Dust Devils as Related to the Martian Yellow Clouds 1969; DAC-63098

[2] Renno N, Burkett M, Larkin MP. A simple thermodynamical theory for dust devils. Journal of the Atmospheric Sciences; J.Atmos.Sci. 1998; 55: 3244-3252

[3] Renno N. A thermodynamically general theory for convective vortices. Tellus Series A-Dynamic Meteorology And Oceanography 2008; 60: 688-699

[4] Nizetic S. Analytical approach for estimating the pressure drop potential in convective vortex heat engines. Trans Can Soc Mech Eng 2014; 38: 81-91

[5] Hawkes NA, Flay RGJ. Dust Devil Heights and Windspeeds 2016; AWES 18

[6] Mullen JB, Maxworthy T. A laboratory model of dust devil vortices. Dynamics of Atmospheres and Oceans 1977; 1: 181-214

[7] Hess G, Spillane K. Characteristics of dust devils in Australia. Journal of Applied Meteorology 1990; 29: 498-507

[8] Rennó NO, Ingersoll AP. Natural convection as a heat engine: A theory for CAPE. Journal of the Atmospheric Sciences 1996; 53: 572-585

[9] Church C, Snow J, Baker G, Agee E. Characteristics of tornado-like vortices as a function of swirl ratio: A laboratory investigation. Journal of the Atmospheric Sciences 1979; 36: 1755-1776

[10] Maxworthy T. A vorticity source for large-scale dust devils and other comments on naturally occurring columnar vortices. Journal of the Atmospheric Sciences 1973; 30: 1717-1722