Phillips, C. and Kim, H.W. and Brown, R.E. (2010) The flow physics of helicopter brownout. In: 66th American Helicopter Society Forum: Rising to New Heights in Vertical Lift Technology, 11-13 May 2010, Phoenix, Arizona.

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The Flow Physics of Helicopter Brownout

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Abstract

The formation of the dust cloud that is associated with low-level helicopter operations in desert environments has been simulated using the Vorticity Transport Model together with a coupled model to represent the entrainment and subsequent transport of particulate matter through the flow. A simple thin-layer theory, supported by simulations performed using the more physically-representative numerical model, is used to explain the formation of characteristic sheet- and filament-like structures in the dust cloud in terms of the interactions between individual vortical filaments and the ground. In parts of the flow, for instance near the ground vortex that is formed under the leading edge of the rotor when in forward flight, the dust cloud becomes more space-filling than sheet-like in character, and the theory suggests that this is a result of the dust distribution having been processed by multiple vortices over a significant period of time. The distribution of the regions on the ground plane from which significant entrainment of dust into the flow takes place is shown to be influenced strongly by the unstable nature of the vortical structures within the flow. It is suggested that the effect of this vortical instability, when integrated over the timescales that are characteristic of the formation of the dust cloud, is to de-sensitize the gross characteristics of the dust cloud to the details of the wake structure at its inception on the rotor blades. This suggests that the formation of the brownout cloud may be relatively insensitive to the detailed design of the blades of the rotors and may thus be influenced only by less subtle characteristics of the helicopter system.

Nomenclature

C_T	rotor thrust, scaled by $\rho A(\Omega R)^2$
g	acceleration due to gravity
R	rotor radius
S_p	source of particulates
S_ω	source of vorticity
μ	advance ratio
$\mu^\star$	thrust-normalised advance ratio, $\frac{\mu}{\sqrt{C_T/2}}$
ν	fluid viscosity
ν_p	particle diffusion constant
ρ	air density
ρ_p	local density of particulates in air
v	velocity of the flow
v_b	velocity of lifting surface
v_g	fallout velocity due to gravity
v_t	threshold velocity
ω	vorticity of the flow
ω_b	bound vorticity

Introduction

A particular problem to helicopter operators in desert or dusty conditions is the possibility of entrainment of dust from the ground into the air when the vehicle is operated close to the ground. This process can cause large clouds of dust to form in the air surrounding the helicopter. The possibility exists, under certain operational conditions, that these clouds might obscure the pilot's view, leading to a loss of situational awareness in a condition known as 'brownout' (see Fig. 1).

Significant effort in a number of university laboratories and research establishments around the world is being expended to try to understand the fundamental physics that underpins the development of the brownout cloud. Some major progress has been made to date and a variety of models now exist that claim to provide some representation of the dynamics of the brownout phenomenon. The crudest current models couple the mean properties of the induced flow below the rotor to some form of uplift and entrainment model. When augmented with some supporting assumptions regarding the supposed 'turbulence levels' within the flow, these models allow the gross characteristics of the dust cloud to be captured.

Anecdotal evidence suggests, though, that different types of helicopter, even under very similar operating

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Presented at the American Helicopter Society 66th Annual Forum, Phoenix, AZ, May 11-13, 2010.

Figure 1: Chinook helicopter landing in dusty conditions. Note the cloud of dust that is being produced below the aircraft; brownout is a distinct possibility should the aircraft decelerate or descend. Image courtesy UK MoD.

conditions, might have distinctly different brownout characteristics. The implication is that the actual dynamics of the brownout cloud is sensitive to properties of the rotor wake that are very much more subtle than the broad characteristics of the flow such as mean outwash velocity, and so on. There may thus be a lower bound on the simplicity of the models of brownout that will ultimately be useful in an engineering context. Indeed, experimental and numerical evidence is mounting to suggest that the brownout characteristics of any particular helicopter are, in fact, extremely sensitive to the fine-scale structure of the wake, so that the geometry and dynamics of the individual vortical structures within the flow, when coupled to the mechanisms of sediment uplift and entrainment from the ground plane, influences very strongly the resultant structure of the dust cloud that surrounds the helicopter under brownout conditions (Refs. 1, 2).

Any useful engineering model should thus be sensitive to these fine-scale effects. The Vorticity Transport Model (VTM) is one of a class of methods that has been shown to provide very accurate, high-resolution predictions of the dynamics of the wake of a helicopter rotor in strong ground effect. When coupled to an Eulerian model for the transport of suspended dust through the flow (Ref. 2), the VTM provides a powerful tool for resolving the fundamental processes at work during the formation of the brownout cloud surrounding the helicopter (see Fig. 2).

The advantage of the Eulerian, or grid-based approach of the VTM over the more commonly-used Lagrangian, or particle-based approach to modelling the dust cloud is that it provides a representation of the dust density distribution that remains linked to the spacing of the underlying computational grid throughout the simulation, whereas the resolution of Lagrangian models tends to deteriorate with time as the particles disperse within the flow. The VTM thus allows a very highly-resolved representation of the link between the rotor-induced flow and the dynamics of the dust cloud to be obtained, and for this connection to be monitored throughout the process whereby the dust is entrained from the ground and eventually swept up into the flow surrounding the helicopter.

The purpose of this paper will be thus to exploit the advantageous properties of a coupled Vorticity/Particle Transport Model (VTM/PTM) in order to examine the dynamics of the wake that is induced by the rotor in ground effect, and in particular to explore in detail the process whereby the wake interacts with a dusty surface in order to generate the cloud of particulate material that can, under certain circumstances, lead to the onset of brownout. The principal contribution of this work will be to resolve this process at the level of the fine-scale, individual vortical structures within the flow and thus to provide insight into the detailed physical mechanisms that are responsible for the generation of the brownout cloud.

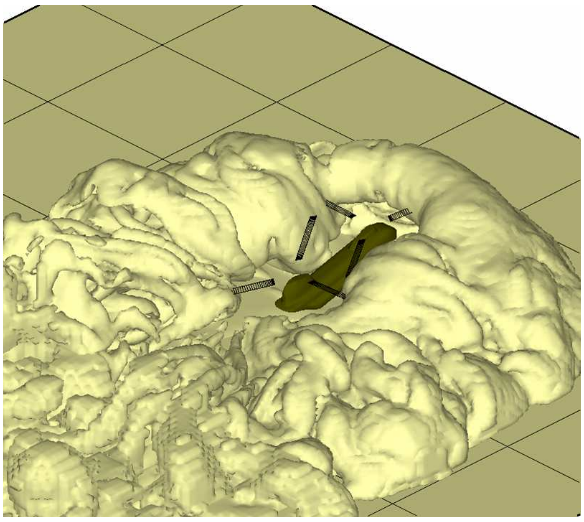


Figure 2: VTM/PTM simulation of the dust cloud that is formed in the air surrounding a generic tandem helicopter during its approach to a desert landing (Ref. 2).

An important qualification is in order, however. The Achilles heel of all current computational models for the onset of brownout is the formalism that is used to represent the entrainment of particulate matter from the surface into the flow. The ultimate goal is possibly to model the dynamics of the entire field of individual particles within the flow, accounting for the effect of the flow on the particles and vice versa, and incorporating all the micro-scale physical effects that are known to bear on the problem. Such models are some way from practicality at present, however, and, arguably, are likely to be of limited engineering utility even once developed. For present purposes, thus, an empirical representation of this process is adopted within the VTM/PTM, based on those approaches that are currently used within the sedimentology community to model the pickup of particle load into the atmosphere or rivers by winds or currents. The basic physical premise of this approach is that particles do not enter the flow until acted upon by a shear field that is sufficiently strong to disturb the particle bed. Although this approach has its deficiencies, fluid dynamic shear at the surface of the ground is undoubtedly one of the fundamental processes that is responsible for entrainment in the context of helicopter brownout. Indeed, VTM/PTM calculations using this relatively simple approach to modelling the entrainment of sediment from the ground into the flow have been shown to provide qualitatively very reasonable predictions of the sand structures that are observed during experiment (Ref. 2).

Given the infancy of our present understanding of the brownout phenomenon, there is no doubt that future developments will result in various necessary embellishments to the approach that is adopted at present to model sediment entrainment from the ground. As such, it must be acknowledged at the outset that the simulations that are presented in this paper will not account for effects, such as bombardment by re-entrant particles, or for porous-flow effects through the strata below the surface, that are regarded as not particularly significant in the sedimentology field but are currently being postulated as important additional mechanisms for particle entrainment in the helicopter context. The approach that is adopted in this paper, in the view of the authors, amounts simply to a sensible implementation of Occam's razor: in other words, to the adoption of the simplest and most robust engineering model that is consistent with presently available evidence.

Vorticity and Particle Transport Models

Brown's Vorticity Transport Model (Refs. 3, 4) has been extended to allow the transport of particles within the airflow surrounding the helicopter to be simulated. The VTM is a finite volume based method which calculates the evolution of the flow field surrounding a helicopter by advancing the solution to the vorticity-velocity form of the unsteady, incompressible Navier-Stokes equation

$$\frac{\partial}{\partial t}\omega + v \cdot \nabla\omega - \omega \cdot \nabla v = S_\omega + \nu\nabla^2\omega \qquad (1)$$

on a structured computational mesh. The velocity, v, is related to the vorticity, ω, by the differential form of the Biot-Savart relationship, $\nabla^2 v = -\nabla\times\omega$. The shed and trailed vorticity arising from the lifting surfaces immersed within the flow is introduced through the vorticity source term S_ω which can be written as

$$S_\omega = -\frac{d}{dt}\omega_b + v_b\nabla \cdot \omega_b \qquad (2)$$

where ω_b is the bound vorticity associated with each lifting surface of the helicopter, and v_b is the velocity of the lifting surface relative to the air.

The dynamics of a large number of particulates within an Eulerian frame of reference is governed by transport equations that can be derived from Newton's second law using classical statistical mechanics (Ref. 2). The transport equation for fine, suspended sediment can be written as

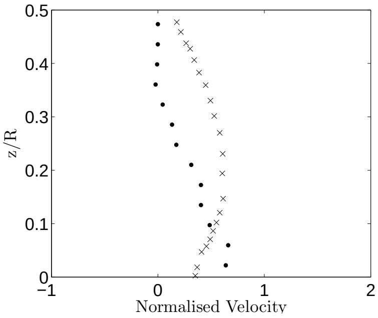
$$\frac{\partial}{\partial t}\rho_p + (v + v_g) \cdot \nabla\rho_p = S_p + \nu_p\nabla^2\rho_p \qquad (3)$$

where ρ_p is the local density of suspended particulate matter in the flow. The source term, S_p, represents the rate of entrainment of particles from the ground plane into the flow field. Once in the flow, the effect of gravity on the dynamics of the particles is captured through the fallout velocity v_g. Although not used for the simulations presented in this paper, other terms can be included on the right hand side of the equation to model more accurately the spin-out of particles from vortex cores and also the scattering of particles as a result of collisions.

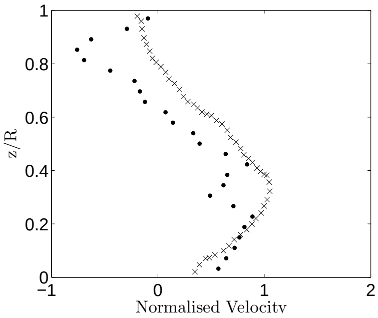
Comparison of Eqs. 1 and 3 shows that the vorticity transport and particle transport equations are very similar in mathematical form. This similarity allows the particle transport equation to be run alongside the vorticity transport equation without significant increase in computational expense (Ref. 2).

The physics of particle transport close to the ground is very complex. Studies within the sedimentology community suggest a process in which, after a threshold velocity v_t in the flow above the ground is reached, the largest particles start to roll and creep along the ground whilst slightly smaller particles hop in a motion called saltation. The movement of these particles disturbs the smallest particles on the ground plane, and these particles can then become suspended within the flow field.

Modelling all these interactions directly is presently well beyond the state of the art. A semi-empirical model is thus used to describe this process and to relate the flow velocity along the ground plane to the amount of dust that becomes suspended in the flow. The approach is essentially to treat the physics of particle entrainment into the flow as a sub-layer type process that occurs at ground level, in other words as a process that occurs over vertical distances that are too small to resolve within the computation itself. Using this approach, the particles escaping from the sublayer and into the flow appear in the particle transport model as a source of particulates S_p which is non-zero only on the ground surface itself. Full details of the entrainment model used at present within the VTM/PTM are given in Ref. 2, but for present purposes, it is assumed that the particle flux derivative, $S_p^* = dS_p/d\overline{v}|_{\overline{v}=1}$, where $\overline{v} = |v_0|/v_t$ and v_0 is the

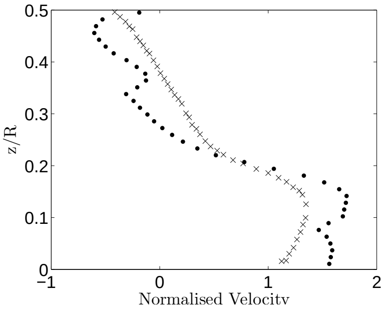


(a) $h/R = 0.5$

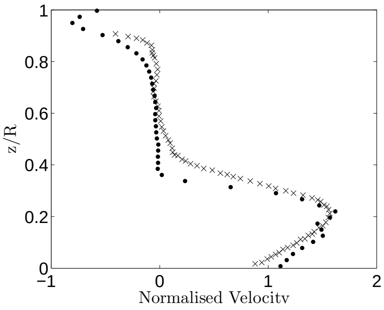


(b) $h/R = 1.0$

Figure 3: Profile of radial velocity at r/R = 0.8. (Crosses correspond to experimental data and dots to VTM predictions.)

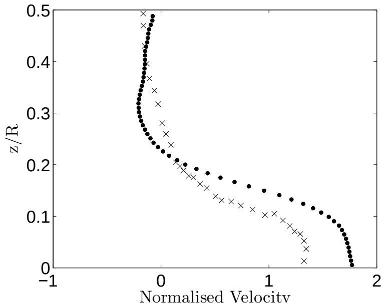


(a) $h/R = 0.5$

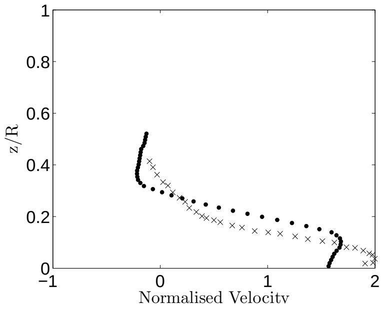


(b) $h/R = 1.0$

Figure 4: Profile of radial velocity at r/R = 1.0. (Crosses correspond to experimental data and dots to VTM predictions.)



(a) $h/R = 0.5$



(b) $h/R = 1.0$

Figure 5: Profile of radial velocity at r/R = 1.5. (Crosses correspond to experimental data and dots to VTM predictions.)

flow velocity just above the ground plane, fully characterises the relevant mechanical properties of the surface below the rotor. Given its physical significance, this derivative is perhaps better termed the *susceptibility to erosion*[1] of the surface, and it should be realised from the outset that a multitude of physical properties of the surface, such as the presence of vegetation or armouring, its moisture content, its chemical composition and electrostatic state, its particle composition and size distribution, amongst others, are hidden within the simple form of this term. The advantage of such an approach, though, is that the susceptibility to erosion should be readily determinable, by empirical means at least, for any surface that is of practical interest.

The non-dimensional particle flux into the flow, $\overline{S}_p = S_p/S_p^*$, in the form used presently in the VTM/PTM, can then be written as

$$\overline{S}_p = \frac{1}{2}\overline{v}^3(1 - 1/\overline{v})(1 + 1/\overline{v}^2) \tag{4}$$

if $\overline{v} > 1$, otherwise $\overline{S}_p = 0$. The particular algebraic form of the right-hand side of Eq. 4 results from adopting the relationship between the particle saltation flux and threshold velocity suggested by White (Ref. 5), and it is entirely plausible that other, similar algebraic forms would suffice equally as well. Indeed, a broad range of plausible such models can be imagined that all satisfy the simple but necessary conditions

$$\begin{aligned} d\overline{S}_p/d\overline{v} = 1 \quad if \quad \overline{v} = 1, \\ \overline{S}_p = 0 \quad if \quad \overline{v} < 1. \end{aligned} \tag{5}$$

It is important to realise though the limitations that adoption of a purely algebraic entrainment model imposes on the characteristics of the resultant model for particulate transport in the flow surrounding the helicopter. Firstly, v_0 is imprecisely defined unless an essentially inviscid flow above the ground plane is assumed. Secondly, the algebraic character of Eq. 4, and in particular its independence of dv_0/dt, although consistent with the equilibrium-flow assumption that is at the core of Eq. 3, cannot be an entirely accurate representation of the saltation process that occurs in the thin layer of particulates just above the ground, particularly when this layer is subjected to *unsteady* forcing by a time-dependent velocity field. It is known, for instance, that it is the particles of intermediate s ize that are responsible for the initiation of saltation, and there is no reason at all to suppose that these particles are necessarily in equilibrium with the airflow to which they are exposed, particularly un-

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[1] The term ‘erodibility’ is already used within the community to denote a related, although less rigorously-defined characteristic of the surface.

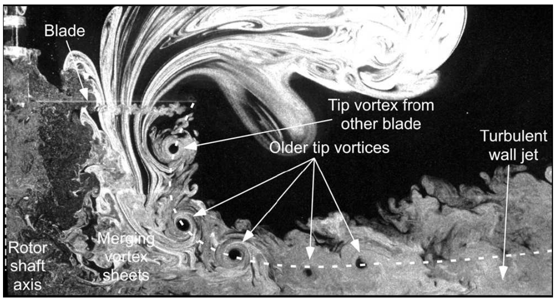
der unsteady flow conditions. Finally, additional processes that have been implicated in the formation of the brownout-related dust cloud such as bombardment (Ref. 1), although responsible for releasing fine matter into the flow in much the same way as saltation, involve particle motions over a vertical extent that is arguably too great to be treated via a sub-layer type model.

Nevertheless, the major advantage of writing the particle flux from the surface in non-dimensional form is that the particle transport equation, Eq. 3, can similarly be written in non-dimensional form, in terms of the non-dimensional particle density $\overline{\rho}_p = \rho_p/S_p^*$. This yields a significant reduction in complexity when interpreting results since the solutions to the *non-dimensional* particulate transport equation are then characterised by only two parameters — namely the threshold velocity v_t and the particle fallout velocity due to gravity, v_g.

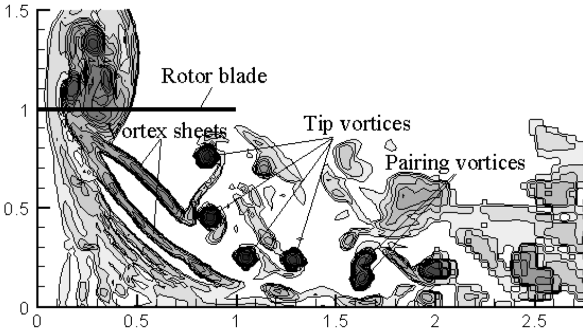
Verification of Flow Fields Produced By Rotors in Ground Effect

Prior to using the VTM to model the particle transport that is associated with brownout, it must first be shown that the VTM can predict accurately the flow field around a rotor when operating in ground effect. Previous investigations by Whitehouse and Brown (Ref. 6) and Phillips and Brown (Refs. 7–9), for example, have shown that the VTM is indeed capable of predicting the various distinct flow regimes encountered during low speed forward flight as described by Curtiss *et al.* (Ref. 10). It has also been shown previously that the VTM matches existing data for the variation of power with height for hovering rotors (Refs. 6, 7).

The ability of the VTM to predict accurately the flow field around a rotor in ground effect has been investigated further by examining the velocities within the wake and the trajectory of the tip vortices that are produced by the rotor blades when in ground effect. Lee *et al.* (Ref. 11) conducted experiments in which digital particle image velocimetry was used to obtain velocity data from within the flow field of a rotor when hovering in ground effect. The VTM has been used to simulate the same two-bladed rotor under the same flight conditions as in this experiment. Figures 3 to 5 show an example comparison of the velocity profiles predicted by the VTM to the experimental data. Shown in the figures are the time-averaged radial velocity profiles found at three different distances ($0.8R$, $1.0R$ and $1.5R$) from the rotor axis. Each figure shows the velocity profile for the rotor hovering at two different heights ($0.5R$ and $1.0R$) above the ground. The time-averaged velocities predicted using the VTM are seen to correspond well to those obtained through experiment and show clearly what is usually interpreted as the formation of a radial wall jet as the wake impinges on the ground.



(a) Smoke flow visualisation of the wake produced by a two-bladed rotor in ground effect. Image from Lee *et al.* (Ref. 11)

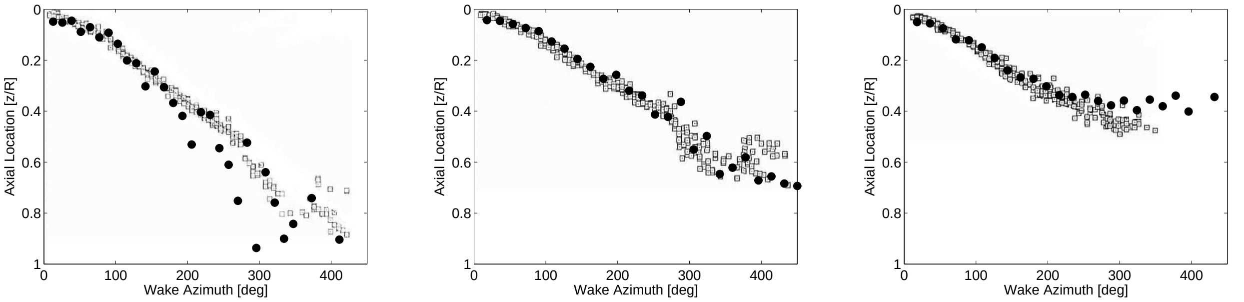


(b) Vorticity distribution from a two bladed rotor in ground effect as calculated using the VTM

Figure 6: Flow field produced by a rotor hovering at one radius above the ground, as predicted by the VTM, compared to that observed through experiment.

Flow visualisation using smoke injection was used during the experiments conducted by Lee *et al.* to highlight the structures found within the wake below the rotor. The qualitative features of the flow field predicted by the VTM are compared to one of Lee *et al.*'s images in Fig. 6. In this figure, instantaneous snapshots of the experimental and numerical flow fields both show the characteristic formation of the tip vortex and vortex sheet structures in the wake below the rotor. The numerical results (Fig. 6(b)) also reveal the onset of vortex pairing in the wake a short distance from the centre of the rotor. The associated instability of the wake is the most likely origin of the disorganised 'turbulent wall jet' that is observed experimentally at significant distances from the rotor.

A more quantitative verification of the predictions of the VTM can be obtained by comparing VTM data for the trajectories of the tip vortices produced by the blades of a rotor in strong ground effect to the experimental data published by Light (Ref. 12). Light's experiment involved using a wide-field shadowgraph method to photograph the tip vortices of a rotor hovering at various heights above a ground board. Quan-

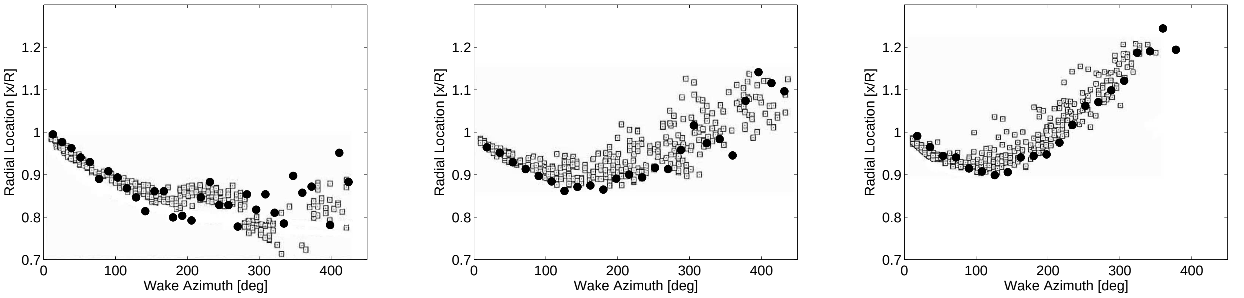


(a) Rotor hovering out of ground effect

(b) Rotor hovering at a height above the ground of $0.84R$

(c) Rotor hovering at a height above the ground of $0.52R$

Figure 7: Axial locations of the tip vortices produced by a hovering rotor. (Dark circles are data predicted by the VTM, squares are experimental data of Light (Ref. 12).)



(a) Rotor hovering out of ground effect

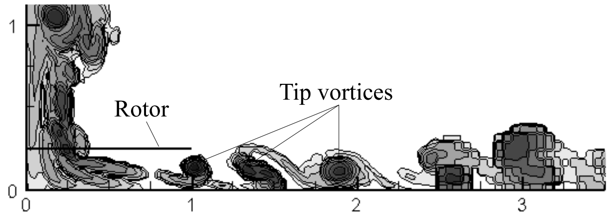
(b) Rotor hovering at a height above the ground of $0.84R$

(c) Rotor hovering at a height above the ground of $0.52R$

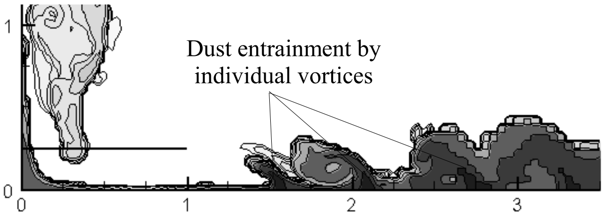
Figure 8: Radial locations of the tip vortices produced by a hovering rotor. (Dark circles are data predicted by the VTM, squares are experimental data of Light (Ref. 12).)

titative data regarding the positions of the vortices were then extracted from the photographs. Figures 7 and 8 compare the axial and radial positions of the tip vortices, as predicted by the VTM, to the data collected by Light. Data are presented for the rotor at three different heights above the ground. Figures 7(a) and 8(a) show the trajectories of the tip vortices when the rotor is out of ground effect, Figs. 7(b) and 8(b) show the trajectories when the rotor is at a height of $0.84R$ and Figs. 7(c) and 8(c) when the rotor is at a height of $0.52R$ above the ground. In all cases there is very good agreement between the vortex positions as predicted by the VTM and those obtained through experiment. The vortices follow a fairly steady trajectory up to a wake azimuth of approximately 200°. After this wake age the vortex positions become more scattered due to the unsteadiness within the wake that is associated with its inherent instability. The VTM is shown to capture well both the orderly development of the wake and this subsequent unsteadiness, lending significant confidence in the ability of the VTM to predict accurately the geometry of the wake that is produced by a helicopter rotor when it is subject to strong ground effect.

There are very limited data available that are of sufficient quality to allow direct verification of any predictions of the entrainment of dust from the ground plane into the flow surrounding the helicopter. Figures 9 and 10 show, nevertheless, a qualitative comparison between the dust distribution as predicted by the VTM and the results from a wind tunnel investigation in which talcum power was used to represent the entrainment and subsequent transport of dust particles in the flow surrounding a model rotor (Ref. 13). A sample of the vorticity distribution and the corresponding dust density distribution as predicted by the VTM is shown in Fig. 9. A comparison of these numerically generated images to the sample snapshot of the experimentally-observed dust distribution shown in Fig. 10 reveals that, qualitatively at least, the VTM reproduces the key features within the flow. Both the numerical and experimental images show the rotor tip vortices to travel along the ground plane, and, as a result of the associated local increase in velocity, a small wedge-shaped region of dust to form in front of each vortex. This comparison suggests, despite the reservations expressed earlier, that the empirical model that is used within the VTM to describe the entrainment of the particles into the flow is capable of representing reasonably faithfully the physics of the particle entrainment process that occurs during the onset and development of helicopter rotor-induced brownout.



(a) Contours of vorticity distribution



(b) Contours of dust density distribution

Figure 9: Vorticity and corresponding dust density distributions in the flow field below a rotor in ground effect as predicted using the VTM.

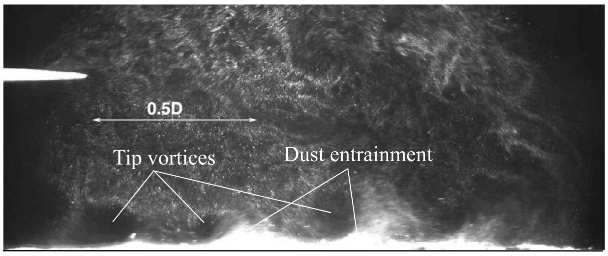


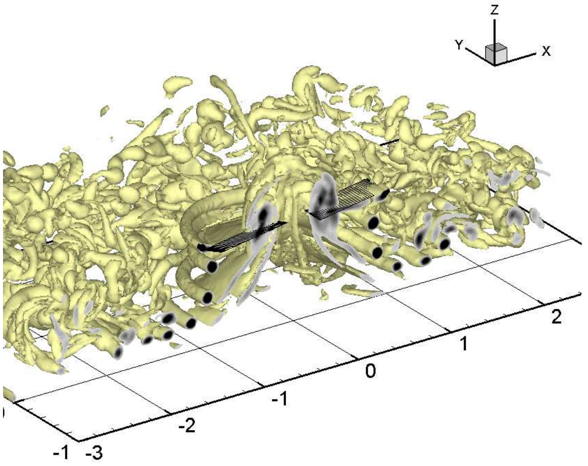
Figure 10: Snapshot showing the effect of the tip vortices on the particle distribution along the ground plane. Image from wind tunnel experiment conducted by Nathan and Green (Ref. 13).

Description of Rotor Configuration

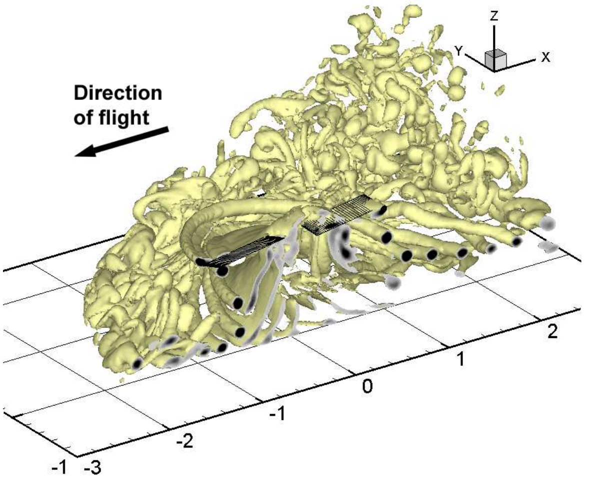
The physics of the formation of the cloud of particulates that is produced by a rotor when hovering in ground effect above a dusty surface was explored numerically by simulating a rotor with the same geometry as that used in the small-scale, brownout-related experiments by Lee *et al.* at the University of Maryland (Ref. 11). This rotor had a solidity of 0.141 and two blades with no twist and a root cutout of $0.15R$. The rotor was simulated, using the coupled VTM/PTM model, at a thrust coefficient of 0.015 whilst flying at at height of 1.0 rotor radii above a flat ground plane. To allow an appreciation of the effect of forward flight on the behaviour of the system, the rotor was simulated in hover and also at a thrust-normalised advance ratio $\mu^\star = 0.5$. In both cases the longitudinal and lateral cyclic were used to trim the tip-path plane of the rotor to be parallel to the ground plane. The presence of the ground was represented by applying a condition of zero through-flow on a flat plane below the rotor. It should be borne in mind that this approach is essentially inviscid, and thus that various features of the flow below the rotor that originate in the viscosity of the air, for instance secondary vorticity production near to the ground as a result of interaction between the rotor flow and the boundary layer on the ground, is not represented using this approach. These mechanisms are particularly important at low Reynolds number, implying a lower limit on the scale of the rotor systems that should be represented adequately using the method adopted here. As the rotor used by Lee *et al.* had a radius of 86mm, it should be realised that there are certain viscosity-related features present in the data from that experiment that obscure *direct* comparison between that work and the results that are presented here.

Figure 11 compares VTM predictions of the structure of the wake that is produced by a rotor with the geometry of that used in the experiments of Lee *et al.*, albeit perhaps at higher Reynolds number, at the two different flight speeds. In this figure, the vorticity distribution in the flow around the rotor is visualised by plotting a surface on which the vorticity in the flow has uniform magnitude. The value of the vorticity magnitude used to produce the figures has been selected to give an impression of the overall structure of the wake — strong vortical structures, such as the individual vortices that are produced at the tips of blades, are clearly resolved, as are weaker structures such as the sheets of vorticity that are produced by the loading gradients further inboard on the blades. It should be noted though that some features of the wake are mis-represented by this method of data analysis. For instance, the natural instability of the structure of the wake results in a highly disorganised and tangled fine-scale distribution of vorticity some distance from the rotor. The plotting technique tends to reproduce these structures as a cloud of disjoint, spheroidal artifacts rather than as a consistent and connected, although nonetheless contorted, collection of vortex filaments.

Nevertheless, the image of the wake produced by the system in hover shows clearly the characteristic pattern of behaviour of the tip vortices of a helicopter rotor when operating in strong ground effect. The vortices initially propagate downwards towards the ground plane before turning outwards, expanding radially as they encounter the presence of the ground, eventually to produce a roughly axisymmetric distribution of vorticity around the rotor. The image of the wake produced by the rotor at $\mu^\star = 0.5$ shows the presence of the characteristic ground vortex that is formed just forward of the leading edge of the rotor at this forward speed. It is clearly evident that the ground vortex is formed by the mutual interaction and roll-up of a number of the tip vortices as their forward motion is retarded by the oncoming free-stream. The

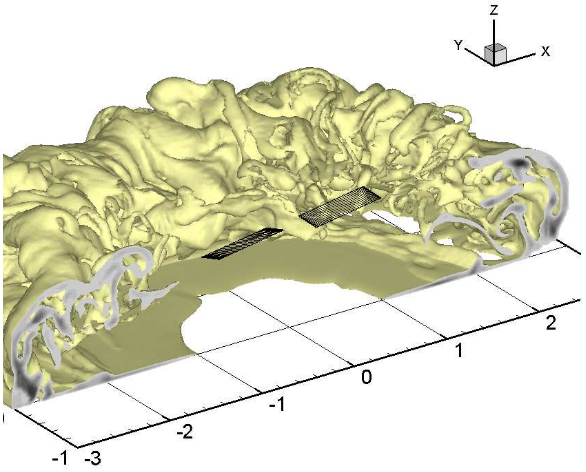


(a) Hover

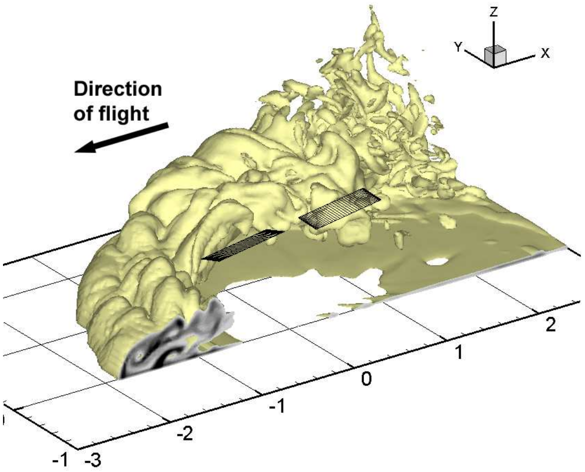


(b) Thrust-normalised advance ratio $\mu^{\star} = 0.5$

Figure 11: Vorticity distribution in the flow field below the two-bladed rotor in ground effect as predicted using the VTM (blade positions represented as hatched surfaces).



(a) Hover



(b) Thrust-normalised advance ratio $\mu^{\star} = 0.5$.

Figure 12: Dust density distribution in the flow field below the two-bladed rotor in ground effect as predicted using the VTM (blade positions represented as hatched surfaces).

vortex adopts a characteristic arc- or bow-shape, with the lateral extremities of the rolled-up system of tip vortices trailing into the flow downstream of the rotor.

What is perhaps less well appreciated, however, given the scant information that is available in the literature, is the very strong influence of the natural instability of the vortex filaments in the wake in disrupting the orderly procession of these vortical structures across the ground plane. The role of this instability in truncating the vertical extent of the wake of a rotor operating out of ground effect, or in precipitating the onset of the vortex ring state in descending flight (Ref. 14), has indeed been far better documented than its influence on the dynamics of the wake of a rotor in strong ground effect. Figure 11 shows that, in both hover and in forward flight, the orderly procession of individual tip vortices across the ground plane is interfered with and disrupted by the rapid growth of large perturbations to their initially almost circular geometry. This process is a consequence of the natural instability of the vortex filaments within the wake to small perturbations to their helicoidal geometry alluded to above, and leads, only a short distance outboard of the rotor, to a wake that consists primarily of a highly disordered and intermixed tangle of vortex filaments. In hover, the final products of this process remain in close proximity to the rotor, their ability to propagate away from the rotor exhausted because the disorder in their orientation excludes any possibility of a lasting and coherent direction to their mutually-induced velocity field. In forward flight, these same structures are convected downstream into the wake behind the rotor by the action of the free-stream.

The key observation from Fig. 11 is thus that, even in hover, the VTM predicts a distribution of vorticity that extends out along the ground plane to only a *finite* distance from the rotor — in other words, a vorticity distribution that is *bounded* in spatial extent. Many other modelling techniques, in contrast, produce a train of roughly circular vortices that travel, more-or-less uninterrupted, out to very large distances from the rotor. The key reason for this fundamental difference in prediction is thought to be the very low level of numerical dissipation that is present in the VTM. This allows the natural vortex instabilities within the wake to grow in a fairly realistic manner within the simulations; certainly there is less risk with the approach that such instabilities be smothered by excessive numerical damping within the algorithm. Even most vortex-filament or free-wake type codes quite often are forced to adopt an unrealistically rapid growth rate for the core size of the vortices in order to maintain the stability of their predicted wake structures. In this context, the core model plays a closely analogous role to numerical dissipation. The finite extent of the 'footprint' of the wake on the ground, even when the rotor is in hover, is key to understanding why most helicopter rotors produce the bounded and dense cloud of particulates, when operating close to a dusty surface, that is so characteristic of the onset of brownout conditions.

It should be borne in mind, however, that Figs. 11 represents the structure of the flow by presenting snapshots, captured at randomly-selected instants of time, of the vorticity distribution that is produced by the rotor. The images represent fairly well the broad characteristics of the vorticity distributions that are encountered in the flow around the rotor at the two advance ratios that were simulated, but, on the other hand, figures such as this allow very little appreciation of the *unsteadiness* in both the vorticity and the particulate distributions that are produced by the rotor. Indeed, it will be argued later in this paper that the unsteadiness in the flow field is fundamentally responsible for the observed structure of the dust cloud. One feature of the evolution of the system that is particularly difficult to represent in a series of static images of the flow, but is very obvious from observing an animated sequences of such images, is that the particulate distribution evolves over timescales that are *significantly* longer than those that are associated with the passage of individual vortical structures through the flow. This observation is key to understanding the link between the dynamics of the dust cloud and the underlying flow of air that is responsible for its creation.

Figure 12, then, portrays the distribution of particulates that is produced in the flow around the rotor by the interaction of the rotor wake with the ground. The distribution of particulates in the flow around the rotor, both in hover and in forward flight, is clearly very complex in stucture. This is somewhat unsurprising, of course, given the disparity in timescales alluded to above, and the consequence thus that the geometry of the dust cloud is the cumulative result of processing by successive flow structures over many rotor revolutions. In hover, the dust cloud is roughly toroidal in shape, but, for this particular system at least, is clearly shell-like with an interior that is relatively devoid of dust. Indeed, in the very centre of the dust cloud there is almost no dust whatsoever except for in a very thin, wedge-shaped layer just above the ground. In forward flight, the shape of the dust cloud is very similar, overall, to the shape of the ground vortex. As in hover, the dust is largely restricted to a shell-like layer that forms the periphery of the cloud, except within the ground vortex itself were the dust distribution still retains elements of a sheet-like structure but is distinctly more space-filling than elsewhere in the flow. At both flight speeds there is evidence of smaller-scale structures in the distribution of dust surrounding the rotor; many of these could be broadly characterised as filamentary or string-like. The reason why the dust cloud adopts a filamentary, shell- or sheet-like structure in parts of the flow, whereas is volume-filling in other parts, can be understood in terms of the particular form of the interaction between the vortical structures and the evolving dust density distribution within the flow, as mediated by the physics of the entrainment process that takes place where the flow meets the ground.

A Simple Theory of Brownout

The particle transport equation, Eq. 3, shows that, in the absence of particulate diffusion, the sediment that is entrained into the flow will follow the velocity field $v + v_g$. It is possible to use the simplification that is induced by this approximation to derive a composite, qualitative model for the evolution of the dust cloud. The validity of the sublayer-type approach to particulate entrainment, along with the possibility of a non-zero flow velocity at the upper edge of the sublayer, is assumed from the outset. In strictest terms, these approximations are most directly compatible with the application of an inviscid, or, at best, a boundary-layer type model, at the interface between the flow and the ground. It follows then, given the algebraic form that is adopted here for the entrainment of particulate matter into the flow, that the source of particulates from the ground plane is confined to those regions where the local velocity just above the ground plane exceeds the threshold velocity v_t. Consider then an infinitesimally thin layer of dust above the ground plane, distributed in a way that is consistent with the distribution of particulate sources. The dust in this layer can enter *into* the flow only at points where the velocity field has non-zero component normal to the ground plane.

The imposition of the zero through-flow condition at the surface implies that the only such points are those at which the flow is (instantaneously) stationary — or, in more rigorous terms, those points in the flow where, following possibly a (local) Galilean transformation (i.e. a combination of translations and rigid-body rotations) so that the velocity field $v + v_g$ is instantaneously time-invariant, the field $v+v_g$ manifests a saddle-type singularity.[2]

The necessary conditions, thus, for particulates to enter the flow are, firstly, that an active source of particulates should exist on the ground plane, and, secondly, that the active source should be connected to a stationary point in the flow through the trajectories of $v + v_g$ along the ground plane itself. As a simple example of the application of this theory, it follows from this thin-layer model that an isolated, steady vortex in a quiescent fluid[3] cannot entrain particulates into the flow if oriented parallel to the ground — it can merely move particulates from one location on the ground plane to another (Fig. 13(a)). A vortex that is convecting along the ground plane, on the other hand, is capable of entraining sediment into the flow since, in a local, Galilean coordinate frame that is co-moving with the vortex, a stationary point appears on the ground plane upstream of the vortex through which particulates can be uplifted into the flow (Figs. 13(b) and (c)). This example serves to suggest the essential role that the unsteadiness of the flow that is induced by the rotor plays in inducing the formation of the dust cloud around the rotor. Forward flight produces, of course, a special case of unsteady flow — this becomes particularly obvious when the system is viewed from the ground-fixed reference frame in which the entrainment model (Eq. 4) strictly applies.

Intriguing too is the fact that the first of these conditions, through the threshold velocity v_t required to activate the source, imposes a lower limit on the strength of the vortical structures in the rotor wake that will induce sediment uplift. The strength of the vortical structures in the rotor wake is, of course, governed primarily by the disc loading of the rotors, but also by the number and twist of the blades and also conceivably by more subtle design features such as the shape of the blade tips[4]. Indeed, several previous studies have shown a sensitivity of the shape and size of the dust cloud to the details of the rotor design (Refs. 9, 15), and the reasoning provided above may indeed provide a useful heuristic that may help to guide efforts to reduce the footprint of the rotor upon the desert surface.

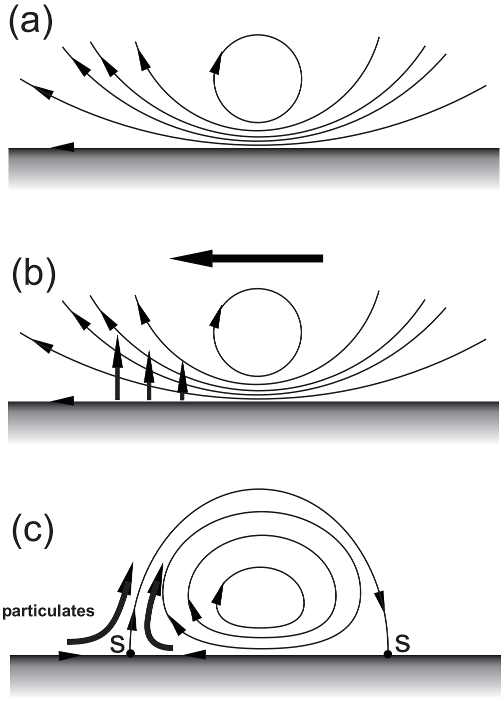


Figure 13: Instantaneous flow trajectories associated with (a) a vortex that is stationary above the ground plane, (b) a vortex that is travelling along the ground plane, and (c) the same moving vortex, viewed in a co-moving reference frame, or, equivalently, a stationary vortex in a free-stream. Routes to particulate entrainment are marked with thick arrows.

The theory can be used quite readily to explain the formation of the sheet- and column-like structures that appear to be characteristic of the dust cloud. Figure 14 illustrates schematically the dust distribution that is formed by the action of a long segment of vortex that travels along the ground plane while remaining essentially parallel to it. Figure 14(a) portrays the trajectories of $v + v_g$, in a reference frame that is co-moving with the vortex. Figure 14(b) shows the location on the ground of the active source of particulates if the vortex is sufficiently strong, and shows this region to be connected, by the trajectories of $v + v_g$ along the ground plane, to a *line* along which the flow is stationary. The flow thus drives sediment along the ground to this line, from whence it enters the flow to form a sheet-like structure as shown in Fig. 14(c). Figure 15(a), on the other hand, suggests a case where the vortex, although inducing a flow pattern that is conducive to sediment uplift, is too weak on its own to activate the particulate source on the ground. Figure 15(b) suggests how interaction with a secondary vortex, and the subsequent distortion of the vorticity field, might bring a segment of the original vortex close enough to the ground for it indeed to activate the particulate source in a small, localised patch. The subsequent evolution of the dust distribution would be as shown in Fig. 15(c), which portrays a stream of par-

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[2] In a steady flow these points would indeed be termed 'stagnation points.' Similar topological features in the velocity field shall be termed 'saddle points' if they occur in the flow away from the ground plane.

[3] Were it able to exist, of course.

[4] Although, see later in this paper.

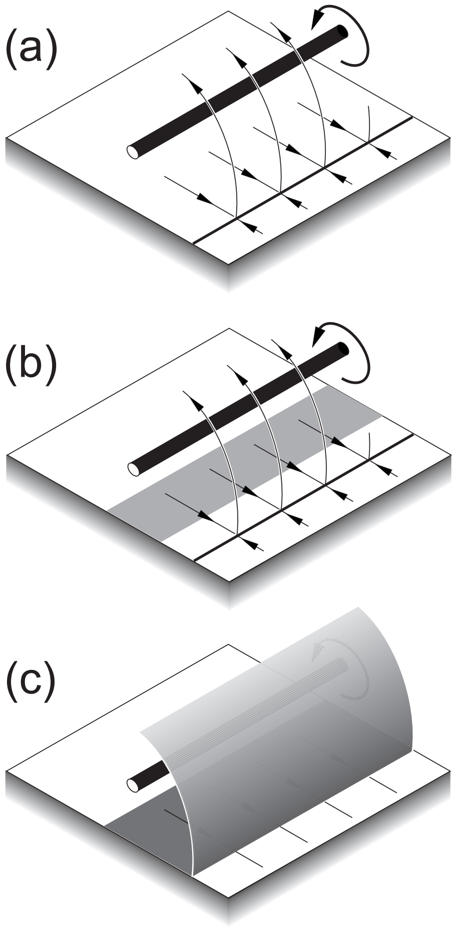

Figure 14: Schematic showing how an extended vortex, moving parallel to the ground, may produce a sheet-like distribution of dust in the flow. Part (a) shows the flow trajectories associated with the vortex, (b) the location of the particulate source on the ground (dark patch) and (c) the resultant dust distribution.

ticulates being drawn out from the source, through the separation line to form a narrow, ribbon-like structure within the dust cloud.

The thin-layer theory as described so far is only capable of explaining the production of features in the dust clouds that are shell-like in topology. Interrogation of numerical simulations of the structure of the evolving dust clouds reveals very clearly the predominance of such structures, yet there are also regions where the dust distribution has evolved to be distinctly more space-filling than shell-like. Careful observation of sequences of snapshots from the VTM/PTM simulations of the evolving dust cloud suggests that this type of dust distribution evolves as a result of the processing of the dust distribution, over relatively long timescales, by the action of multiple, subsequent vortices acting in concert. This process is illustrated in terms of the thin-layer model in Fig. 16, which presents a scenario in which three vortices interact with each other close to the ground plane. Figure 16(a) portrays

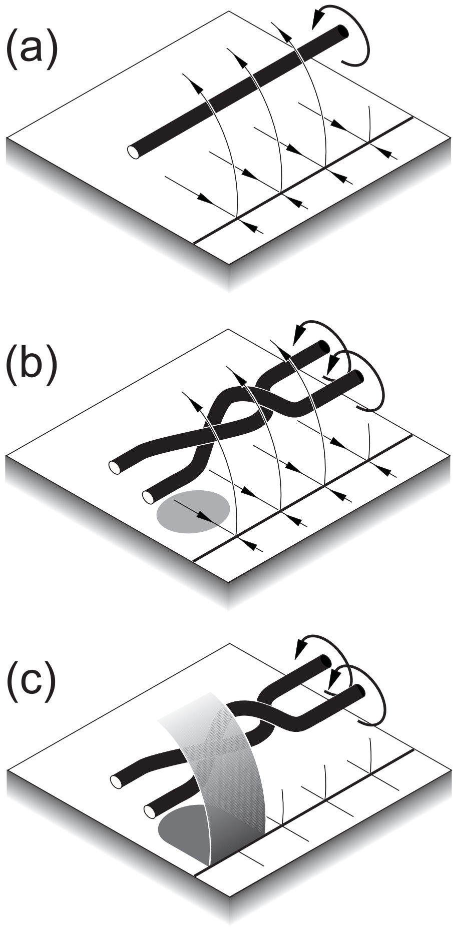

Figure 15: Schematic showing how a vortex system, moving parallel to the ground, may produce a filament-like distribution of dust in the flow. Part (a) shows the flow trajectories associated with a vortex that is too weak to activate the particulate source, (b) how a second vortex may interact to produce a localised particulate source on the ground (dark patch) and (c) the resultant dust distribution.

the vortex closest to the ground as connecting the trajectories in the flow to a source of particulates on the ground plane. The saddle points that are formed in the flow between the vortices act to divide the evolving distribution of particulates into multiple leaves, as illustrated in Figs. 16(b) and (c), eventually resulting in the volume-filling, Swiss cheese-like dust distribution that is shown in Fig. 16(d).

Mechanisms for Sediment Uplift

It is important to bear in mind the limitations of this simple theory for the evolution of structure within the dust cloud. Firstly, finding a co-moving, Galilean reference frame that is applicable for more than an instant over any appreciable portion of a flow as complex as that produced by a rotor in strong ground effect is more easily said than done. Particle diffusion (the last term in Eq. 3) acts to add thickness to the sheet-like structures that are present in the flow, and, indeed, the effects of unsteadiness in the flow over timescales that are too short to resolve will appear as an additional source of particulate diffusion across the trajectories of the flow field.[5] Nevertheless the insights into the formation of the dust cloud that this simple theory does impart suggests that the predictions of the VTM/PTM simulations should be examined more closely in order to try to isolate examples of the interaction of the vortical structures within the rotor wake with the ground, thus to demonstrate the formation of the various structures within the dust cloud via the mechanisms that have been postulated above.

In this vein, Fig. 17 shows a small section of the particulate and vorticity distributions produced during the VTM/PTM simulation of the rotor in hover. In this snapshot, a sequence of arc-like vortices can be seen as they propagate outwards across the ground plane. One of the vortices is sufficiently strong to induce a ridge-like feature in the particulate distribution just above the ground plane. These ridge-like features are thought to be the three-dimensional equivalent to the wedge-like features observed in the experiments of Nathan and Green (Ref. 13) near to the locations of significant sediment uplift into the flow. In the VTM simulations it is very clear that the appearance of these ridge-like features is the precursor to significant, localised uplift of sediment into the flow through a mechanism that is entirely analogous to the formation of the sheet-like structures produced by the thin-layer model. Figure 18 shows a similar section elsewhere in the VTM-predicted flow-field that is produced by the rotor in hover. In this image, two vortices interact strongly just above the ground plane, and their mutually-induced distortion drives a short segment of one of the vortices very much closer to the ground than the remainder of the vortical structure. Although in this case the entire length of the vortex appears able to induce a ridge-like structure along the ground plane through the same mechanism as described above, the locally enhanced entrainment of sediment below the portion of the vortex that is closest to the ground can be seen to result in a stronger, but very localised, tongue-like jet of particulates into the flow. It is believed that these tongue-like formations are the precursor to the filamentary structures that are commonly found within the particulate distribution in the flow surrounding the rotor, and that the processes at the heart of their formation are equivalent to those that lead to the ribbon-like structures predicted by the thin-layer model.

Finally, Fig. 19 shows a close-up of the flow near the ground vortex that is located just forward of the rotor when in forward flight (see Fig. 12 for instance). As de-

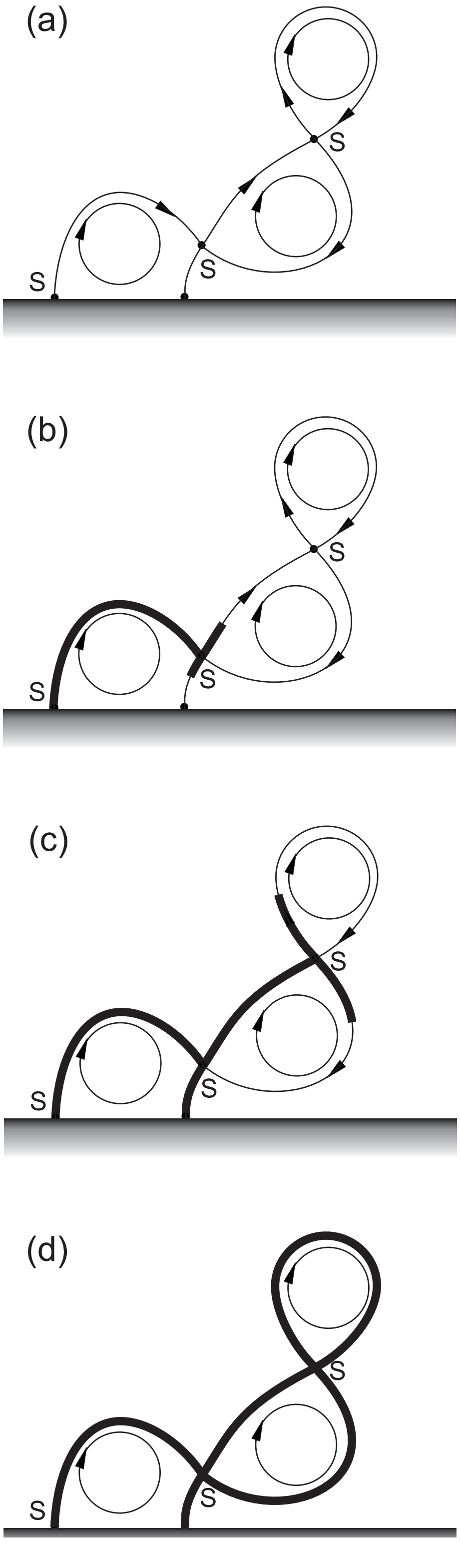

Figure 16: Schematic showing how several vortices may act in concert to produce a space-filling distribution of particulates. Points marked 'S' are stationary or saddle points in the flow. Parts (a) – (d) show subsequent stages in the evolution of the dust distribution.

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[5] This observation should be particularly worrying to those who would attempt to model the brownout problem in terms of the mean properties of the flow.

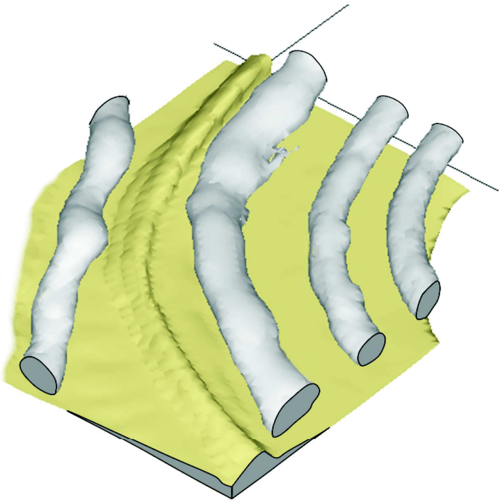

Figure 17: Snapshot of the particulate (yellow) and vorticity distribution (grey) produced during the VTM/PTM simulation of the rotor in hover. A sequence of arc-like vortices propagate across the ground plane; the effect of one on the ground is strong enough to induce a ridge-like feature in the particulate distribution. This feature is the precursor of a sheet-like structure in the dust cloud.

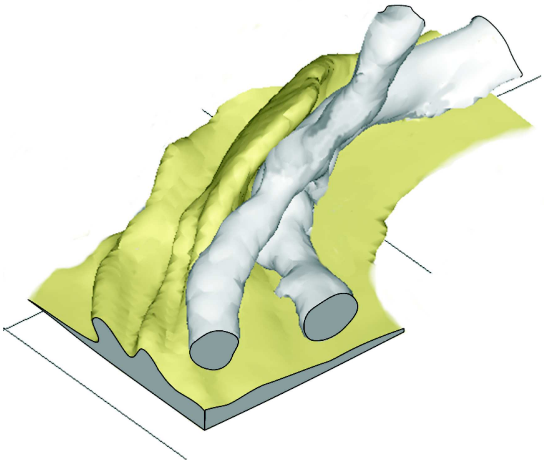

Figure 18: Snapshot of the particulate (yellow) and vorticity distribution (grey) produced during the VTM/PTM simulation of the rotor in hover. Two vortices interact above the ground plane to induce a localised, tongue-like feature in the particulate distribution. This feature is the precursor of a filament-like structure in the dust cloud.

scribed earlier, this vortex is composed of a number of individual, smaller vortices that remain within a very localised region of the flow, but interact with a strong stream of entrained dust that enters the flow from a separation line that is located just upstream of the ground vortex. In orbiting within the ground vortex, these finer vortical structures interact with and mix the particulates within the flow to produce the space-filling distribution of dust that can be seen within the ground vortex itself. The mechanism whereby this distribution is created is thought to be essentially that portrayed in Figure 16, modified to some extent by the apparent diffusion across the flow-lines that takes place because the motion of the vortices is very quick compared to the rate at which the dust cloud itself evolves.

Is Brownout Inherently Unpredictable?

The results presented so far suggest a predictable, generic relationship between the dynamics of the vorticity that is produced by the rotor and the resultant particulate distribution within the flow. Such seems to be the case for the small-scale structures within the flow, at least in qualitative terms. A detailed examination of the *overall* pattern of particulate entrainment from the ground, in simulations of sufficient resolution to capture the fine-scale vortical features within the flow, raises some serious questions though regarding the ability of *any* model, no matter how detailed, to capture anything more reliable or valid than a general description of the formation of the brownout cloud. Indeed it may be the case that, for fundamental physical reasons, the ultimate goal of producing a reliable quantitative estimate of the sensitivity of the shape and size of the cloud to the details of the rotor design may also remain beyond the reach of any conceivable computational method, no matter how fine its resolution or accurate its portrayal of the underlying physics.

The motivation for this rather sweeping statement is revealed in diagrams such as Fig. 20. The images to the left of Fig. 20 show the vorticity distribution, viewed from directly above the rotor when in hover[6] at a height of one *half* a rotor radius above the ground, at three, randomly-selected instants in time. The images to the right of the figure show the corresponding contours of the dust distribution in the flow immediately above the ground plane at the same instants in time. These images thus represent fairly faithfully the locations of maximal sediment uplift from the ground plane into the flow below the rotor.

It is very clear from these images that the regions of maximal uplift of dust from the ground into the flow are indeed very closely correlated with the locations of the individual vortical structures that are present in the flow near to the ground plane. More interestingly, however, two distinct regimes can be identified. Close to the rotor, the sediment is entrained into the flow in a series of concentric waves, and these waves propagate outboard along with the associated tip vortices. In

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[6] In the coordinate system that has been adopted for these diagrams, the rotor has a radius of unity and its axis of rotation is at $0, 0$.

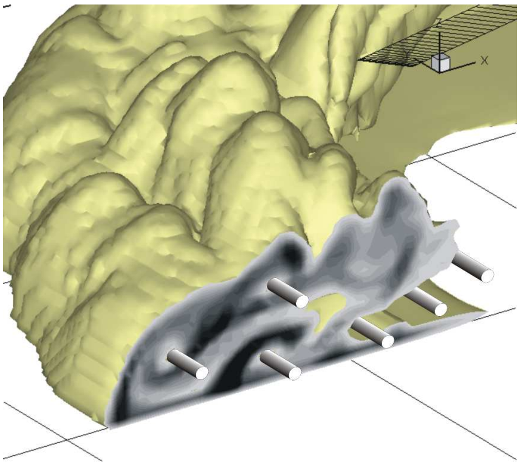

Figure 19: Snapshot of the particulate (yellow) and vorticity distribution (grey) produced during the VTM/PTM simulation of the rotor in forward fight. Compare to Figs. 11 and 12. The positions of several of the vortices comprising the ground vortex are shown schematically. These vortices interact within the ground vortex to produce a space-filling distribution of dust within the flow.

this regime the uplift of sediment could be described as being essentially deterministic and predictable, given that the individual vortices follow a deterministic path across the ground plane, and have been subjected to very little stretching and re-orientation so that their strength is relatively accurately known. Beyond approximately two rotor radii from the axis of rotation, the pattern of sediment uplift is highly granular and small-scale. Although the instantaneous pattern of entrainment appears to be highly variable from time to time, and is thus very likely to be non-deterministic at any coarser scale of resolution of the flow, it is also likely that the amount of dust entering the flow per unit time in this part of the flow could be modelled at coarser scale using some form of stochastic process, for instance one based on the mean turbulence properties of the flow.

The major impediment to accurately capturing the development of the brownout cloud at coarser scale, however, is to be found in the intermediate regime between approximately 1.5 and two rotor radii from the centre of rotation. It is known that the behaviour of the flow in this region has a key effect on the subsequent onset of brownout — containing as it does the region of the ground from which much of the dust that is responsible for the phenomenon is entrained (Ref. 9). Yet this is also the regime in which the individual vortices that are produced by the rotor are still somewhat coherent, but are being rapidly disordered by the tangling and re-orienting mechanisms that are characteristic of their mutual interaction. The figure shows clearly the role of individual vortex tangles and crossings in disrupting the orderly motion of the individual vortices across the ground, thus causing segments of them either to be ejected further above the ground plane or to be compressed closer to the surface than if their dynamics were more orderly. This behaviour is fundamental in leading to a very complex pattern of sediment entrainment into the flow above the ground plane in this intermediate regime. Since the instability that is at the root of these vortex entanglements is sensitive to small changes in initial conditions, the interaction between the rotor wake and the ground would be essentially unpredictable if resolved at any coarser level of detail. This is because the distribution of sources on the ground plane in this regime is insufficiently fine-grained to be captured adequately by a stochastic process based on any coarser representation of the properties of the flow, and insufficiently repeatable to be captured by any deterministic process that is embedded within a simulation that is not capable of resolving in fine detail the evolution of the individual vortical structures within the flow.

Figure 21 shows similar information as presented in Fig. 20 but for the system in hover at *one* rotor radius above the ground, while Fig. 22 presents similar information for the rotor while in forward flight, one rotor radius above the ground, at a thrust-normalised advance ratio $\mu^\star = 0.5$. These figures serve to illustrate the sensitivity of the pattern of dust entrainment from the ground to the operating condition of the rotor. With the rotor in a somewhat higher hover, the region of dust entrainment, near to the centre of the rotor, that is produced by interaction with the portion of the wake which is essentially deterministic in its evolution effectively disappears — this is a result of the vortical structures in the rotor wake having de-stabilised significantly even before they reach and interact with the ground in this case. The predominant feature of the system in forward flight is the intense entrainment of sediment that occurs immediately below the ground vortex. Although confined to a very specific region of the ground plane, the entrainment process on the ground below this flow structure is arguably as complex as in the hovering case, given the intense distortion and disordering of the individual vortex filaments in this region of the flow. Interestingly, the region of highly granular, small-scale vorticity that is observed around the periphery of the wake in hover is entirely absent from the leading edge of the vorticity distribution in forward flight — any such region is confined to the outboard extremities of the ground vortex as it is convected into the flow downwind of the rotor.

These observations motivate very strongly against the use of models that employ an overly simplistic representations of the flow that is induced by the rotor to drive the formation of the dust cloud — and particularly against those mean-flow type models that contain no representation of the vortical structure within the flow whatsoever. Note though that the problem is not necessarily resolved simply by running simula-

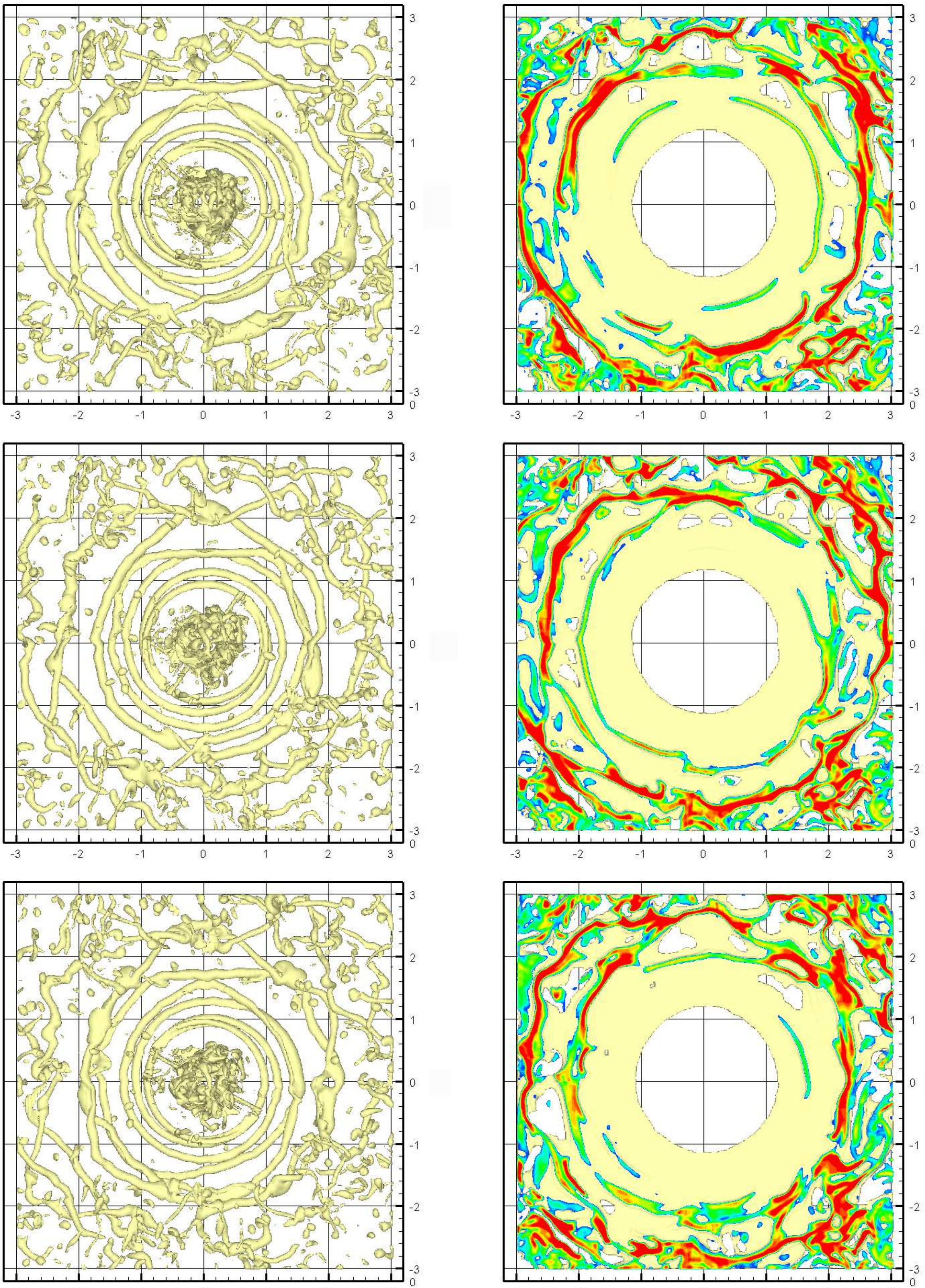

Figure 20: Figure comparing the vorticity distribution in the flow (left) to the regions of maximal particulate uplift from the ground (right: red=highest, blue=lowest) for the rotor in hover at half a rotor radius above the ground. Snapshots at three separate instants of time are shown.

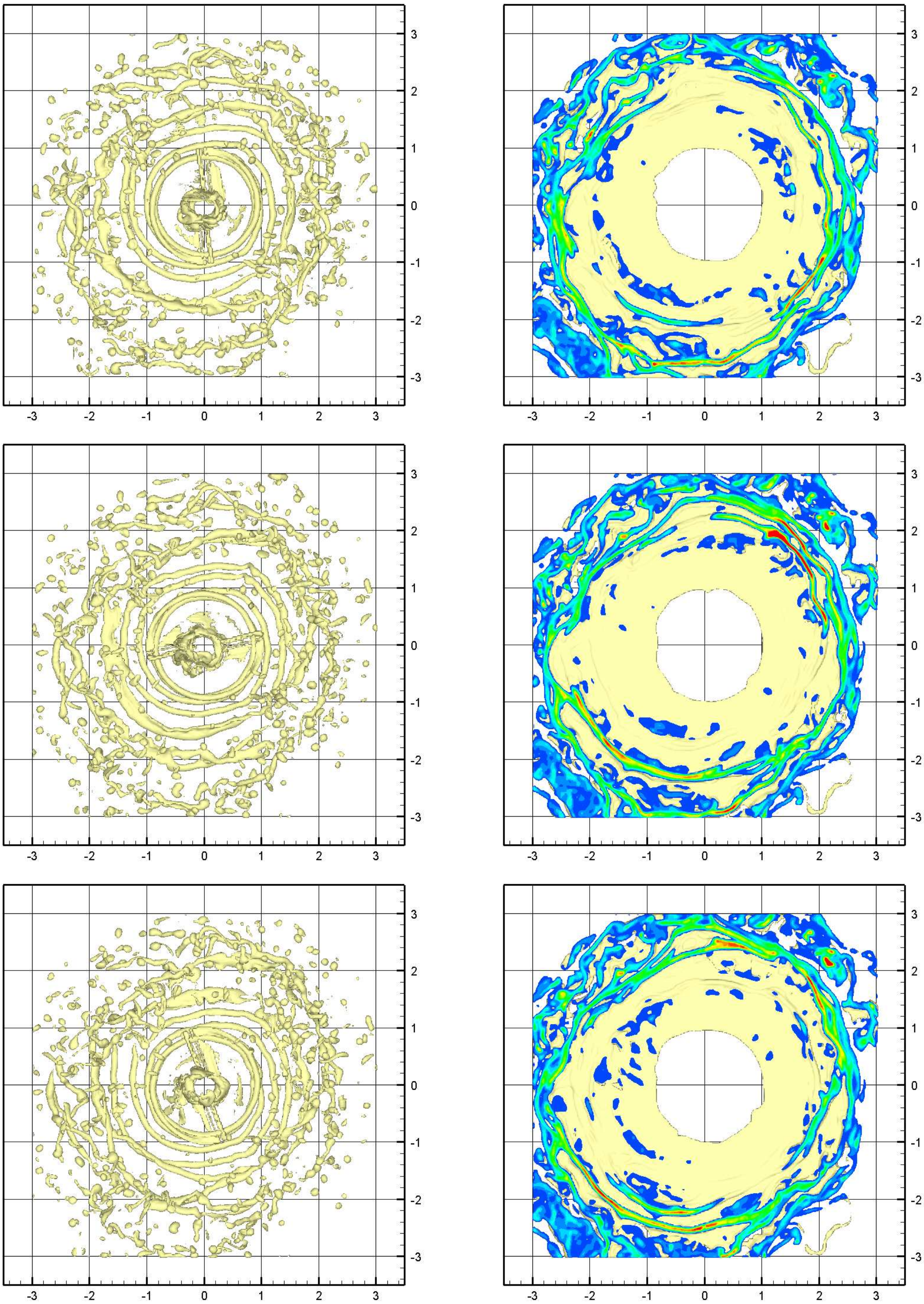

Figure 21: Figure comparing the vorticity distribution in the flow (left) to the regions of maximal particulate uplift from the ground (right: red=highest, blue=lowest) for the rotor in hover at one rotor radius above the ground. Snapshots at three separate instants of time are shown.

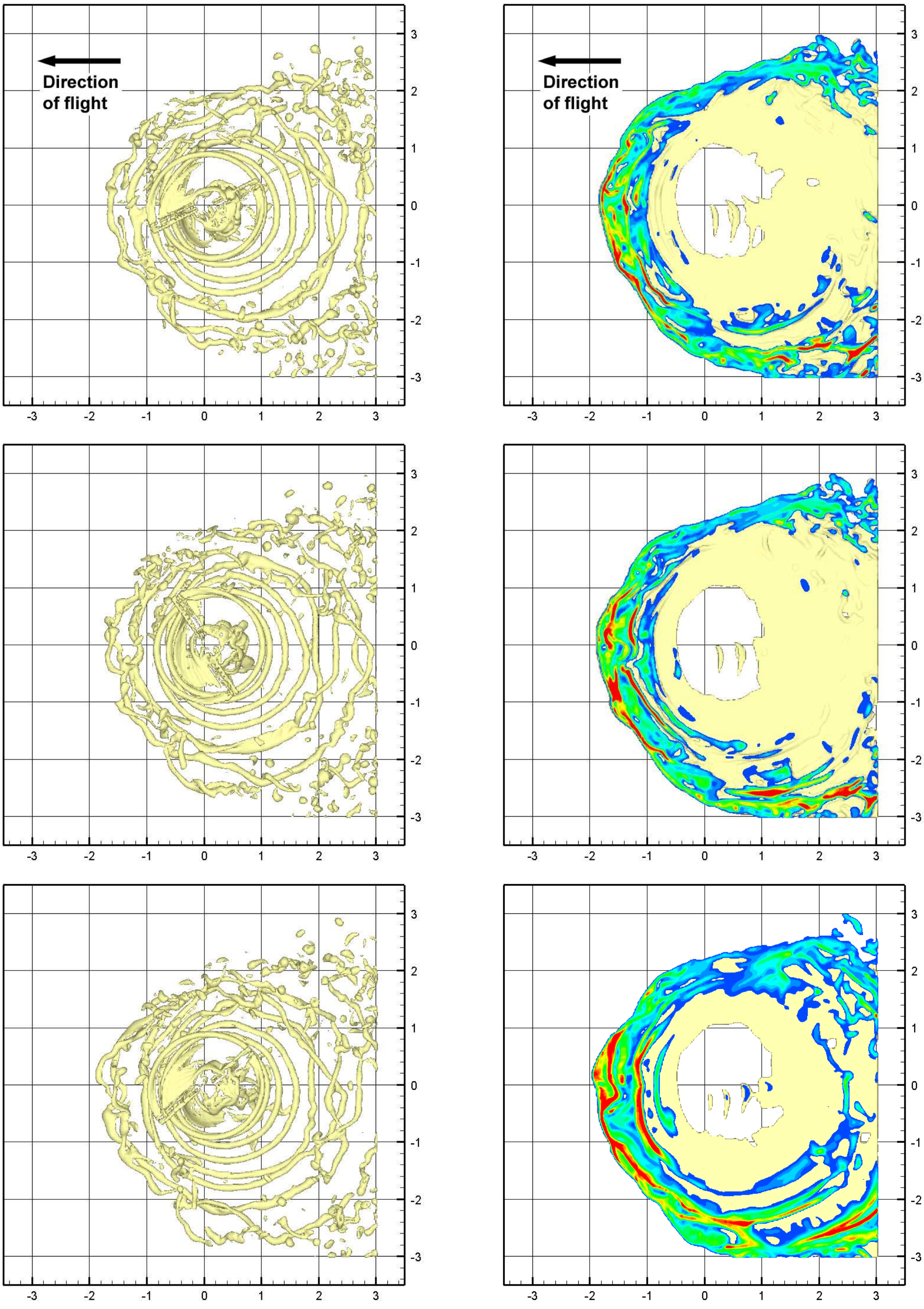

Figure 22: Figure comparing the vorticity distribution in the flow (left) to the regions of maximal particulate uplift from the ground (right: red=highest, blue=lowest) for the rotor in forward flight at $\mu^\star = 0.5$, one rotor radius above the ground. Snapshots at three separate instants of time are shown.

tions at high enough resolution for the evolution of the individual vortex filaments and their interaction with the ground plane to be captured with arbitrarily high accuracy. It was observed earlier that the principal regions of sediment entrainment below the rotor are associated with the interaction with the ground of vortices which are being disordered rapidly by the tangling and re-orienting mechanisms that are characteristic of their mutual interaction. Previous theoretical analysis (Ref. 16) suggests that perturbations to the geometry of the individual vortices, during this regime of their development, grow at exponential rate. This observation implies that small changes to any of the parameters of the system, for instance to the initial or boundary conditions of the simulation, would cause the evolution of the vortices to follow a distinctly different path, with concomitant effect on the history of the particulate source on the ground plane and thus on the entrainment of particulate matter from the ground into the flow. Experience suggests that the integration of the evolving system over the timescales that are associated with the formation of the dust cloud may introduce some 'smearing' of this inherent variability though — so that, for instance, any series of parametric simulations of the distribution of dust within the flow might still produce results that possess some consistency in terms of their gross predictions of the shape and size of the dust cloud, even though they might vary almost arbitrarily in terms of their finer detail.

If this argument is carried further, however, then the consequences are more profound. An alternative, but equivalent view of the disordering process within the wake is that the sensitivity of their evolution to small perturbations to the system causes the individual vortices within the flow to lose information at an exponential rate regarding the circumstances of their original formation. In this view, the sensitivity of the dynamics of the system to small changes in its parameters[7], together with the temporal smearing alluded to above, would act to diffuse the relationship between the details of the wake structure at its inception on the rotor blades, and the eventual effect of the wake on sediment entrainment and dispersal within the system — no matter how finely the system were to be resolved. These issues certainly seem to have bedevilled, at least to some extent, several previous attempts to resolve the effect of parametric variations in the rotor design on the size and shape of the resultant dust cloud (Refs. 9,15). In these studies, the characteristics of the resultant dust cloud have, at best, not borne an obvious or straightforward relationship (and, at worst, have been totally insensitive) to the parameters being varied. The analysis presented here may indeed provide motivation to re-visit the way in which such studies are conducted in future. Extrapolating from the numerical to the physical world, the inherent diffusion within the rotor-air-ground system of the link between cause and effect would have the consequence that, if any modifications to the design of helicopter rotors eventually prove effective in ameliorating the effects of brownout on current operations, then they will most likely turn out to be relatively unsubtle!

Conclusion

The formation of the dust cloud that is associated with low-level helicopter operations in desert environments has been simulated using the Vorticity Transport Model together with a coupled model to represent the entrainment and subsequent transport of particulate matter through the flow. The simulations presented in this paper have been conducted to a level of detail that allows the interactions between individual vortical filaments and the ground, and the subsequent effect on the entrainment of particulates into the flow, to be resolved. A simple thin-layer theory, based on an entrainment model in which the source of particulates into the flow is activated only if the air velocity just above the ground plane exceeds a characteristic threshold velocity, has been introduced. The model shows that the development of the dust cloud is essentially dependent on the formation, on the ground plane, of saddle-type singularities in the velocity field $v + v_g$ through which the particulates can enter the flow. Entrainment of dust into the flow only occurs though if such a singularity is connected to an activated source of particulates via the trajectories of the velocity field along the ground plane. Simulations reveal the dust cloud to have an inherently sheet-like internal structure, and the thin-layer theory suggests that these structures are formed by the action of individual, extended vortex filaments in lifting sediment from the ground plane. Where the vortex filaments are distorted by interaction with other structures in the flow, the source distribution on the ground plane may become localised to the extent that the dust structures that are produced become ribbon-like rather than sheet-like. Analogues of the structures in the dust cloud that are predicted by the thin-layer model are observed in the simulations performed using the more physically-representative VTM/PTM. The dust cloud evolves over timescales which are slow compared to the evolution of the air-flow. In parts of the flow where the dust distribution is processed by multiple vortices over a significant period of time, for instance in the ground vortex that is formed under the leading edge of the rotor when in forward flight, the cloud, although retaining elements of its sheet-like structure, becomes more space-filling in character. The thin-layer theory, supported by the VTM/PTM simulations, suggests that these structures are produced by the action of multiple vortices in concert, the saddle points in their as-

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[7] Or, equivalently, to the noise within the system.

sociated velocity field dividing any nearby sheet-like structures into multiple leaves. These leaves can then evolve over time to produce a space-filling distribution of dust.

The distribution of the regions on the ground plane from which significant entrainment of dust into the flow takes place is shown however to be strongly influenced by the unstable nature of the strongest vortical structures within the flow. The basic physical nature of the flow, as exposed in the simulations presented in this paper, thus implies that minor changes to the set-up of the simulation would produce potentially very different time-histories for the distribution of dust sources on the ground plane. It is suggested that this effect, when integrated over the timescales that are characteristic of the formation of the dust cloud, is to de-sensitize the gross characteristics of the dust cloud to the details of the wake structure at its inception on the rotor blades. This implies that the formation of the brownout cloud may be relatively insensitive to the detailed design of the blades of the rotors and may thus be influenced only by less subtle characteristics of the helicopter system.

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