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The genesis, evolution and decay of tornados from an initial momentary instability: CFD simulations

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SUMMARY

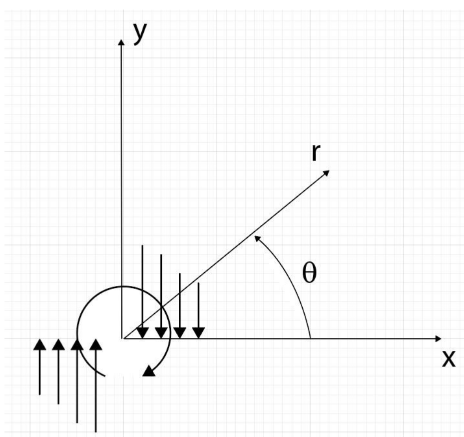
In order gain greater insight into tornado genesis and dissipation, a new instability mechanism is proposed whereby an initial purely vortex instability causes the formation of a tornado, its intensification, and subsequent decay. Computational fluid dynamics (CFD) simulations are performed on the scale of natural tornados, and realistic boundary conditions obtained from atmospheric properties are used in the transient simulations. A 600 m diameter, 600 m high, cylindrical computational domain was used in the simulations. The wall model LES (WMLES) and Spalart-Almaras turbulence models were implemented for comparison of their suitability for tornado simulations. The results show that the initial instability transforms into a tornado-like flow field, which intensify with time and creates an updraft. Starting from an initial axisymmetric, purely tangential velocity profile, and axisymmetric boundary conditions, the flow field transitions to a highly three-dimensional pattern with fluid flowing in in certain regions and flowing out in other regions of the curved side boundary. Even without any externally imposed translation velocity, the eye of the vortex translates and moves away from the axis of the computational domain. The results obtained from the present simulations provide valuable insight into tornado behavior and its influence on the structures in its path.

Keywords: dust devils, tornado genesis, natural scale tornado simulation

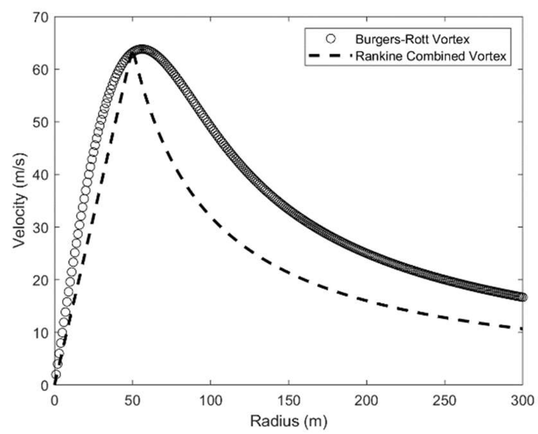
1. INTRODUCTION

Driven by the atmosphere getting warmer over the past few decades, tornados have become common lately. The mechanisms that cause tornados to form and evolve into sometimes destructive forces (Haan et al., 2008; Simiu and Scanlan, 1996) are still not well understood due to the large number of factors involved. Experimental study of tornados is usually conducted on scale models (Ward, 1972; Haan et al, 2008), where the main features of tornados such as swirl, flow in the vertical direction and horizontal translation have been included. There have been a few numerical simulation studies of natural tornados (Lewellen, et al. 2000). The simulations rely on radar date from full scale tornadoes for validation. Numerical simulation of natural tornados is challenging due to their geometric scale and the need to include many factors that influence tornado genesis and evolution. There are two main approaches to numerical simulation of tornados: one favored by atmospheric scientists who try to study aspects such as super cell formation, moisture content, and rain, to virtually create tornadoes. A second approach is confined to the tornado itself and solves the conservation equations of mass, momentum and energy to obtain the flow field information.

The goal of this work is to investigate how tornados evolve under realistic atmospheric conditions when an initial momentary instability is introduced, such as from a transient wind shear. The initial conditions that must be specified for a transient CFD simulation play a crucial role in capturing the essential behavior of tornados. Beyond the basic understanding that instability mechanisms such as horizontal and vertical wind shear create favorable conditions for tornado formation, many specifics are still unknown. In some previous studies, a vortex has been used to introduce an initial instability mechanism. The Burgers-Rott vortex (BRV) that can be used to introduce an initial velocity profile does not have radial and axial velocity components. In the present simulations, we use the BRV for the initial instability. The radial and axial components of the velocity subsequently evolve with time starting from t = 0, governed by the Navier-Stokes equations and the turbulence model equation.
The scope of the study is limited to gas phase (air) only and the incompressible flow regime. Important aspects such as mesh size and mesh distribution, and choice of turbulence model, are addressed.



(a)



(b)

Figure 1. (a) Wind shear as an initial instability mechanism (b) The Burgers-Rott vortex and the Rankine combined vortex (RCV) velocity profiles.

Figure 1 shows how a momentary wind shear that can serve as the source for the formation of a vortex, which can be modeled as a Burgers-Rott vortex (BRV).

2. METHODS

The shape of the computational domain is a circular cylinder (600 m diameter (D) x 600 m height(h)). The bottom boundary is a solid surface representing the ground. The side and the top are open boundaries. Results were obtained using two different meshes for comparison. The structured hexahedral mesh has 3.6 million cells and the unstructured mesh has ~2.3 million cells. The mesh is finer in the boundary layer on the ground.

A primary objective of the present work is to specify the boundary conditions that are closer to the physics of natural tornados. One way to specify the boundary conditions is to have a velocity inlet, for example, on the curved side boundary, and specify a swirl velocity component and a radial velocity component based on a selected swirl ratio (S), that are constant with time. Such a boundary condition specification provides a continuous driving force for the evolution of the tornado starting with the initial conditions. Under this formulation, the tornado will reach a steady state, and will not undergo the birth, growth and decay observed in natural tornados. In some previous studies, a vortex has been used to introduce an initial instability mechanism. The Rankine Combined Vortex (RCV) and the Burgers-Rott Vortex (BRV) have been proposed as possible triggers for spawning tornados.

In the present study, we have implemented an alternate approach that is closer to the properties of the atmosphere, specifically that of the standard atmosphere. Under this boundary condition formulation, after the tornado is born due to an instability, it is driven by the naturally occurring variations of pressure, temperature and density in the atmosphere. Following this reasoning, we have chosen the side boundary and top boundary to be pressure boundaries in the ANSYS FLUENT CFD solver, where the flow may be into the domain or out of it, as obtained from the solution. The bottom boundary is a solid surface (ground) where the no-slip boundary condition is applied.

3. RESULTS AND DISCUSSION

Figure 2 shows pathlines of particles released from two horizontal planes, xy, at z = 10 m, and z = 300 m, respectively, from the ground at elapsed times 1s, 10s, 20s, 40s, 80s, and 120s from the start. One difference between the two sets of particle paths is that the inner region is larger at z = 300 m compared to the z = 10 m during the time interval t = 1 s to t = 40 s. At t = 80 s and 120 s, the particles released from the z = 10 m plane show very irregular particle paths having no well-defined inner region. The corresponding pathline animations show that the flow is largely counterclockwise in the inner region in Figs. 2 (a) to 2 (d). In Figs. 2 (e) and 2 (f), the particle paths are very irregular with no predominant direction of rotation. In the outer region of the z = 10 m particle paths, fluid enters at the top left (~10-O'clock) and exits slightly above that (~12-O'clock) forming an open loop. A small vortex indicated in blue is seen between the inlet and exit. A second difference in the pathline patterns is that the particles released from the xy-plane at z= 10 m, stay nearly in their release plane for cases 2 (a), 2(b) and 2(c) (1s, 10s and 20s, respectively), with little indication of any significant upward, out of plane motion. However, for the same three cases, the particles released from the z = 300 m plane form an inner region with a significant velocity component in the +z-direction. The diameter of this inner region increases from case (a) to case (c).

4. CONCLUSIONS

Insightful and valuable results have been obtained from the present tornado simulations pointing to a possible instability mechanism that can capture the essential features of tornado genesis, evolution and decay. The study involved two different meshes and two different turbulence models to gain understanding of these selections. This work highlights the importance of implementing physically realistic boundary conditions for tornado simulation at the scale of natural tornados. Future work will include studying dust devils on Mars under Mars atmospheric conditions of gas composition, temperature and pressure.

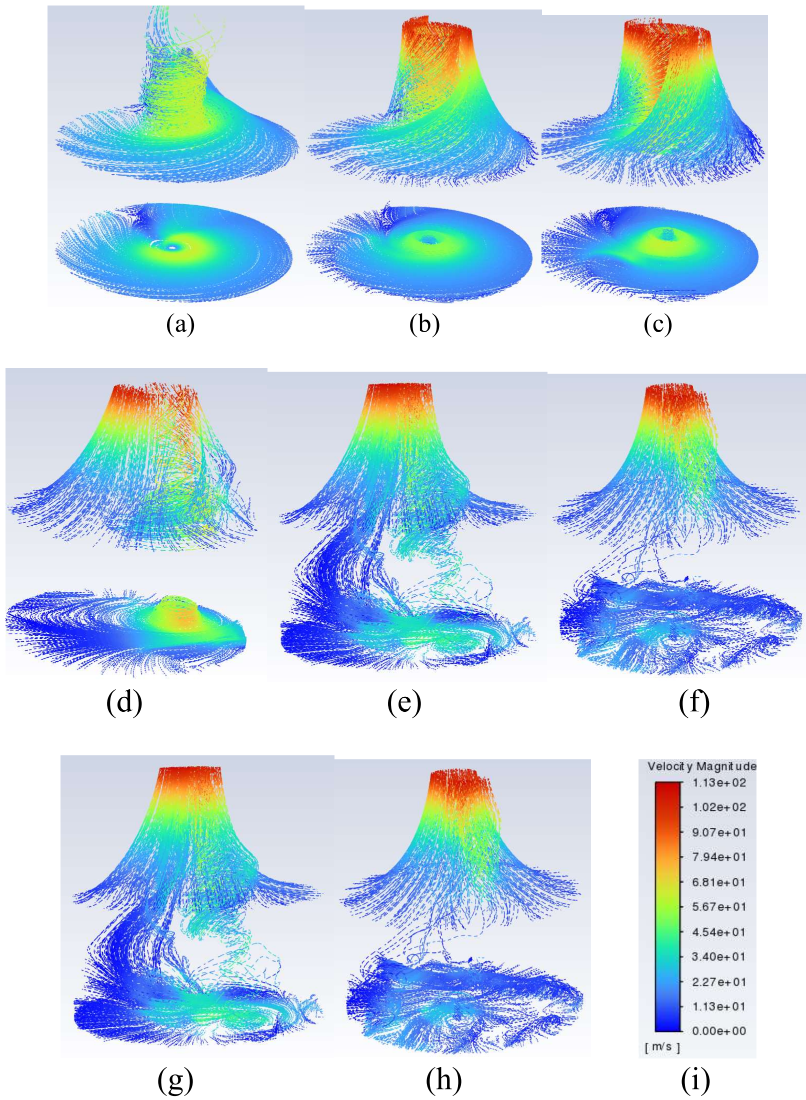


Figure 2. Particle paths. Particles released from xy-planes at z = 10 m, and z = 300 m. Colored by velocity magnitude. (a) t = 1 s, (b) t = 10 s, (c) t = 20 s, (d) t = 40 s, (e) t = 80 s, (f) t = 120 s. (i) key for pathline color.

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