J. Wind Eng. Ind. Aerodyn. 138 (2015) 13–26

Contents lists available at ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/jweia

High-resolution full-scale measurements of thunderstorm outflow winds

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ARTICLE INFO

Article history:
Received 8 October 2013
Received in revised form
8 December 2014
Accepted 18 December 2014
Available online 9 January 2015

Keywords:
Thunderstorm outflow
Wind profiles
Radar observations
Profile evolution

ABSTRACT

Efforts to understand thunderstorm outflow winds have been ongoing for years in the wind engineering community given the design wind speed for regions away from the hurricane-prone coastline is governed by this phenomenon. These efforts have largely consisted of laboratory and numerical simulations using both impinging jets and thermodynamic-allowing models, while full-scale observations have remained fairly sparse. The limited body of research has illustrated significant differences between the mean characteristics of thunderstorm outflow winds and “standard” boundary layer winds, yet the evolution of the wind profiles remains poorly understood. Using high-resolution full-scale data collected with two mobile Doppler radars, this research provides a deeper understanding of the evolutionary characteristics of thunderstorm outflow winds and wind profile data. The unique scanning strategy that enables the collection of the dual-Doppler wind profiles also allows for the analysis of the vertical structure of the outflow. Three outflow events are investigated with particular emphasis place on the profile evolution and driving meteorology of each event.

1. Introduction

For most regions away from hurricane-prone coastlines, thunderstorms produce the majority of extreme winds and wind-induced damage. The dominance of these atmospheric phenomena has been identified in the wind climate of several regions in the United States (Twisdale and Vickery, 1992) as well as other countries (Holmes, 2001; Letchford et al., 2002). Thunderstorms, including the extreme winds they can produce, contribute not only to financial loss and property damage, but also to human casualties (Ashley and Mote, 2005; Mohee and Miller, 2010; Schoen and Ashley, 2011). Insured losses from extreme wind-producing derecho events have even rivalled the insured losses of some of the most damaging hurricanes in the United States (Ashley and Mote, 2005). Long span structures, such as transmission lines, are particularly susceptible to thunderstorm winds with a reported 65% of transmission line failures being the result of either tornadoes or non-tornadic convective winds (Holmes, 2001; Behncke and Ho, 2009).

While thunderstorm winds generally occur as a thermodynamically (or dynamically) induced downdraft impinges on the surface and travels away from the parent storm as outflow (Wakimoto, 2001), a variety of thunderstorm types and mechanisms can produce damaging outflow winds. For example, mesoscale vertical vorticity maxima (or mesovorticies; Trapp and Weisman, 2003; Wakimoto et al., 2006) associated with bow echoes have recently been implicated in accelerating outflow winds to the level of producing F1 damage (Wakimoto et al., 2006). While such studies have contributed to the broad understanding of thunderstorm outflow dynamics and sources of severe wind, the lack of near surface data and a focus on larger atmospheric scales have limited the information that can be incorporated into design considerations (Letchford et al., 2002). Much of the current understanding of thunderstorm wind characteristics relevant to design is based primarily on laboratory experiments and numerical simulations of an isolated downburst.

1.1. Thunderstorm outflow wind profiles

Both impinging jet and cooling source models (among others) have shown that thunderstorm outflow wind profiles differ substantially from the synoptic boundary layer wind profile for which most structures are designed (Kim and Hangan, 2007; Mason et al., 2010). Not only are higher wind speeds found closer to the surface in thunderstorm outflows, but wind shear can also vary greatly from that of the synoptic boundary layer. Also, by comparing instantaneous wind profiles to storm maximum profiles Mason

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http://dx.doi.org/10.1016/j.jweia.2014.12.005
0167-6105/

et al. (2009, 2010) showed that the wind speed does not peak simultaneously through the depth of the profile. The elevation and magnitude of the wind speed maximum are also both time and space dependent (Kim and Hangan, 2007; Lin et al., 2007; Mason et al., 2009; Vermeire et al., 2011a, 2011b; Orf et al., 2012). Spatial variation has also been investigated by examining wind profiles at various distances from the downdraft center. Several impinging jet laboratory experiments and numerical models have shown maximum wind speeds occurring near the surface between 1 and 1.5 downdraft diameters from the center of the downdraft (Wood et al., 2001; Choi, 2004; Kim and Hangan, 2007). Maxima in the wind speed profiles were attributed to translation of a ring vortex and have been seen in other numerical studies (Lin et al., 2007; Vermeire et al., 2011a; Orf et al., 2012). Outside of this distance, the profile maximum was weaker in magnitude and occurred at higher elevations. In addition to these basic characteristics, several numerical studies also investigated sensitivities of the wind profiles to other parameters. Mason et al. (2009) noted that an increase in surface roughness resulted in a change of the wind maximum to a higher elevation within the profile and decreased its magnitude. Similar results were noted in Proctor (1989).

Most of the field observations that are present in the literature were collected as part of aviation safety studies and contain little information regarding the near surface wind field (Wood et al., 2001). Two such studies were Project NIMROD (Fujita, 1978; Wakimoto, 1982) and JAWS (Hjelmfelt, 1988). One dataset from NIMROD yielded cross sections through the center of a downburst (Fujita, 1981). The resulting radial velocity profiles revealed peak wind speeds only 50 m above the surface just over 1 km away from the downdraft center. It should be noted that 50 m was the lowest level at which data were available. Using radar data collected during the Joint Airport Weather Studies (JAWS) project, Hjelmfelt (1988) analyzed the radial velocity profiles of eight microbursts. It was noted that profiles matched the profile predicted by a wall jet. Thunderstorm outflow wind profiles have also been investigated using data from tall, instrumented towers where multiple parameters were shown to influence the shape of the wind speed profile, including the distance from the parent thunderstorm at which the outflow was sampled as well as averaging times applied to the raw wind time histories (Choi, 2004; Lombardo et al., 2014). Significant evolution of the envelope gust profile was noted in several events studied in Lombardo et al. (2014) where the peak 3 s gust was transferred downward over very short time scales.

1.2. Project SCOUT

The limited full-scale data and numerous simulations suggest the wind profile and turbulence characteristics of thunderstorm winds differs from those expected in synoptic winds, yet more full-scale measurements for validation are still needed, especially with respect to thunderstorm wind profiles (Letchford et al., 2002; Holmes et al., 2008). To address this need, Texas Tech University (TTU) designed and executed a field project (Project SCOUT) using mobile Doppler radars and surface measurement stations to collect engineering-relevant data in thunderstorms known to be capable of meeting the United States National Weather Service criterion for severe wind (wind speeds greater than 26 m s^{-1}). While the majority of historical research has focused on the characteristics of isolated microbursts, Project SCOUT targeted specific types of organized thunderstorms, such as supercell thunderstorms, bow echoes, and other mesoscale convective systems (MCS), to increase the likelihood of sampling severe wind in the relatively small deployment domain as well as to provide enough lead-time to construct a quality deployment.

The objective of this research is to present the initial findings of wind profile measurements from 3 different thunderstorm outflow events collected during Project SCOUT and to discuss the meteorological context of each event. In doing so, mean and evolutionary characteristics of the outflow wind profiles will be documented. Given the novelty of the dual-Doppler wind profile technique employed here, a secondary objective will be to provide validation of this technique as applied to non-stationary thunderstorm outflow data.

2. Data collection

2.1. TTUKa Doppler radars

Wind Speed and direction profiles were computed from data acquired with the TTUKa mobile Doppler radars. These systems are capable of collecting raw data with 15 m range resolution and a 0.49° half-power beamwidth. While the range resolution is constant along the beam, the azimuthal resolution is a function of the beamwidth and the range from the radar. For example, at 5 km range from the radar the azimuthal spread is 42.8 m. Both TTUKa radars are capable of performing horizontal scans, or Plan-Position Indicator (PPI; constant elevation, multiple azimuths), and vertical scans, or Range-Height Indicator (RHI; constant azimuth, multiple elevations). The implementation of a pulse compression technique combines the sensitivity achieved using a relatively long pulse without sacrificing range resolution. One consequence of transmitting within the Ka band is the tendency of the emitted signal to attenuate in regions of higher precipitation. This effect was seen multiple times throughout the project and occasionally resulted in data voids within areas of heavy precipitation. Once received by the radar, the return signal is processed to recover the standard radar moments of reflectivity, radial velocity and spectrum width. While the reflectivity and spectrum width fields provide valuable information, only the radial velocity data will be considered further.

2.2. Radial velocity data

A single Doppler radar is only capable of resolving the along-beam component of the wind velocity. This velocity is called the radial velocity and is typically represented as positive and negative values for outbound and inbound radial velocities, respectively. If the individual radar is not aligned with the wind direction, then the full horizontal wind vector is not measured. The radial velocity data (and those of any Doppler radar) are subject to spatial and temporal averaging which, for a given range, azimuth and elevation, occurs over the resolution volume. The size of this volume depends on the pulse and antenna characteristics of the radar as well as the range from the radar. Given the characteristics of the TTUKa radars, the size of the resolution volume for typical SCOUT deployments was 15 m in range and less than 35 m in azimuthal spread. Thus, a radial velocity measurement represents the mean scatterer (typically liquid hydrometeors) motion within the resolution volume over the sampling time. The sampling time for each azimuth (elevation) angle of a PPI (RHI) is on the order of 0.01 s for the TTUKa radar systems. The temporal resolution of a complete PPI or RHI depends on the antenna scan speed and the spatial extent of the scan. For Project SCOUT the scan speeds were kept constant at 30° s^{-1} for PPIs and 6° s^{-1} for RHIs. Therefore, an RHI from 0 to 45° in elevation would take 7.5 s to complete.

2.3. Dual-Doppler velocity data

In order to resolve the full horizontal wind vector, radial velocities from two radars synchronously scanning the same region must be synthesized. In an ideal dual-Doppler deployment, the angle separating the two radar beams (or the crossing angle) should be close to 90° such that orthogonal components of the wind are being resolved.