A three-dimensional analytical model of background winds interacting with downburst outflows

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Downburst outflows are radially diverging winds near the surface that occur when a negatively buoyant downdraft from a thunderstorm cloud hits the ground. Positive pressure perturbations underneath the downdraft accelerate the air horizontally (i.e., parallel to the surface) and, depending on the pressure perturbation magnitude, can case high-impact near-surface winds. Indeed, wind gusts in intense downbursts can exceed 60 m s^{-1}—comparable to those observed in severe tornadoes. Diameter of a typical downburst downdraft is about 1 km and the maximum horizontal wind speeds in the outflow are found between approximately 50 and 150 m above ground level. In other words, the vertical profiles of horizontal velocity in the outflow resemble the so-called nose-shaped wind profile, i.e., typical of those found in the wall jet region of impinging jets.

A common assumption in studying downbursts is that they either occur in calm atmosphere or the effect of background winds on downburst outflows can be represented through simple vector addition of the two undisturbed flow fields—those being undisturbed downburst outflow and background winds in which downburst is immersed. While the former assumption of often unrealistic, the latter assumption is physically inconsistent with the conservation of momentum of background winds. In other words, if a background wind interacts with downburst outflow at a point A within the outflow, it is unphysical that the magnitude of the background wind at point B, which is downstream from A, is the same as that in point A. The loss of momentum at point A would lead to smaller magnitude of background winds at point B.

This research presents the first three-dimensional analytical model of the interaction between downburst outflows and background (e.g., regional) winds. We model the loss of momentum of background winds as they interact with the downburst outflow using turbulence drag law implemented into steady-state momentum equation without Coriolis, pressure gradient, and viscous force terms. The research presented provides several solutions to this problem that vary in the level of robustness and complexity, but all analytical in nature. For example, the simplest analytical solution models the slowdown of background winds (v) as they traverse a distance L through downburst outflow via:

$$v = v_0 \mathrm{e}^{-\frac{C_D}{\delta} L},$$

where v_0 is the wind speed of undisturbed background winds, C_D is the turbulent drag coefficient that quantifies the exchange of momentum between the two flows, and δ is a characteristic depth of downburst outflow. The results of our analytical models are also compared against wind tunnel measurements of downburst-like impinging jets released into atmospheric boundary layer-like background winds.

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