RESEARCH ARTICLE

10.1002/2013JD021243

Key Points:

- An atmospheric microburst was reproduced in laboratory
- Turbulence and entrainment were investigated by analyzing the experimental data
- Measurements giving high temporal and spatial resolutions were performed

Correspondence to:

E. Ferrero,
enrico.ferrero@mfn.unipmn.it

Citation:

Ferrero, E., L. Mortarini, M. Manfrin, M. Solari, and R. Forza (2014), Physical simulation of atmospheric microbursts, *J. Geophys. Res. Atmos.*, 119, 6292–6305, doi:10.1002/2013JD021243.

Received 3 DEC 2013

Accepted 9 MAY 2014

Accepted article online 13 MAY 2014

Published online 3 JUN 2014

Physical simulation of atmospheric microbursts

E. Ferrero¹, L. Mortarini², M. Manfrin³, M. Solari¹, and R. Forza³
¹Department of Sciences and Technological Innovation, University of Piemonte Orientale Amedeo Avogadro, Alessandria, Italy, ²Institute of Atmospheric and Climate Sciences, CNR, Turin, Italy, ³Department of General Physics, University of Torino, Turin, Italy

Abstract A laboratory simulation of atmospheric microbursts is presented. The physical model of the atmospheric phenomenon is reproduced at a reduced scale in a rotating tank (TURLab, Italy), the similitude is based on the Froude number. Different experiments were carried out varying the Rossby number, and the analysis of four significant cases is presented. The velocity, vorticity, and turbulent kinetic energy fields are evaluated together with the swirling strength analysis. The comparison with the natural prototype is eventually shown and discussed.

1. Introduction

Microbursts are a well-known atmospheric intense phenomenon, they have been the subject of several observational and numerical studies since the pioneering work of Fujita [1978]. Fujita [1985] defines a downburst as a short-lived strong downdraft that induces a highly divergent outburst. Generally, a microburst is defined as a small-scale downburst with its outburst and winds extending for about 4 km or less. In spite of its small horizontal scale, an intense microburst could induce straight or curved damaging winds with speeds as high as 75 m s^{-1} . Due to the intense wind shear accompanying them, microbursts can be specially dangerous to aircraft during takeoff and landing procedures [Elmore *et al.*, 1986]. For this reason the understanding of their formation and development is extremely important for risk assessment purposes.

Fujita [1990] describes three field studies (NIMROD (1978), JAWS (1982), and MIST (1986)) performed in order to characterize the microburst structure and their time evolution. During these campaigns, the meteorological aspects of the microburst have been measured by several ground-based anemometers (from 27 to 81, depending on the campaign) and by up to five Doppler radars. The results of these measurements improved our understanding of the microbursts physical properties and were followed by further experiments and numerical simulations. Ignoring both the complex cloud microphysics and the large-scale atmospheric processes, numerical or physical microbursts modeling can be performed, allowing a detailed analysis of the flow structure close to the ground, where the highest wind velocities are usually detected. In the numerical simulations, the thermal forcing is usually parameterized using a spatiotemporal variable function that is decoupled from the microphysics and the moisture advection [Orf *et al.*, 1996]. Proctor [1988, 1989] carried out a numerical simulation of an isolated microburst and investigated its dynamics and structure with a time-dependent, three-dimensional model (TASS). The model solves the equations for the momentum, pressure deviation, potential temperature, and six coupled continuity equations for the water substances (vapor, rain, snow, hail, nonprecipitating cloud droplets, and ice crystals). The equation set is approximated with quadratic-conservative centered space differences on a three-dimensional staggered grid. He found that the surface friction plays an important role in the burst front propagation [Proctor, 1988], and he performed a sensitivity analysis of the environmental parameters that can predict the development of wet microbursts: the vertical distribution of ambient temperature and humidity, the horizontal width of the precipitation shaft (downdraft), the magnitude of the precipitation loading, the type, and duration of the precipitation [Proctor, 1989]. Orf and Anderson [1999] studied the effects of traveling microbursts in unidirectional sheared environments using a $k - \epsilon$ model.

The availability of less expensive platforms for parallel computing has now made the Large Eddy Simulation (LES) strategy more appealing and not so prohibitive as in the past. This was accomplished with the idealized conditions typical of subcloud modeling in which the cooling forcing that generates the microburst is parameterized following Orf *et al.* [1996]. Nicholls *et al.* [1993] performed a LES of a microburst producing thunderstorm. The thunderstorm is initiated when a thermal within a developing mixed layer reaches the

Figure 1. The rotating tank.

lifting condensation level and strong latent heating occurs. A microburst is subsequently produced as condensate from the thunderstorm falls beneath the melting level. Recently, *Anabor et al.* [2011] performed a LES of an idealized microburst where some of the principal features of microbursts dynamics, such as the horizontal spread of strong surface winds and the formation of a vortex ring at the leading edge of the cold outflow, were replicated.

Computational Fluid Dynamics (CFD) models were also used to investigate the macroscale flow dynamics of an impinging jet with application to downbursts [Kim and Hangan, 2007]. *Mason et al.*

[2009] developed a dry two-dimensional nonhydrostatic model implemented within the CFD commercial code ANSYS CFX11.

Experimental investigations of microbursts were conducted by *Alahyari and Longmire* [1994]. They developed a method to improve the measurement of currents in variable density flows by Particle Image Velocimetry (PIV) that was based on the matching of the refractive indices of two fluids while maintaining density differences up to 4%. *Yao and Lundgren* [1996] studied the microburst dynamics in its transition from a vortex dominated flow to a radial gravity current in its late stages in a glass walled cubic tank (0.61 m on each side). They performed hot film velocity measurements near the ground at different radial positions from the burst center. Realistic estimates of the wind field were obtained from the measurements by means of a previously developed scaling law. The scaling is based on a characteristic length defined as the equivalent spherical radius of the heavier fluid before the release and a characteristic time defined as a function of the characteristic length and the reduced gravity.

In this work different microbursts in reduced scale have been reproduced in the rotating water tank of the University of Turin. The evolution of the velocity field has been measured by means of the PIV technique. The atmospheric phenomenon has been simulated in Froude number, Fr , similarity. Consequently, the governing parameters were the temperature difference between the vertical current and the ambient water, the burst depth and its vertical velocity. Further, the influence of rotation on the current has been investigated by accounting for different values of the Rossby number. Four experiments with different values of the above mentioned governing parameters giving the same Froude number are presented. For each experiment the mean velocity profiles and the turbulent kinetic energy are shown. The presented experiments mainly differ from the ones previously cited because they include the rotation effect on the density current. Further, while preserving the Fr number similarity with the real atmosphere, they account for different values of the governing parameters. The turbulent structures propagating with the flow and responsible of the entrainment process are analyzed comparing the evolution of the vorticity field with the swirling strength analysis [Adrian et al., 2000; Ferrero et al., 2009]. To compare the experiments with the natural phenomenon, the reduced scales are then brought back to the natural prototype scale.

2. Experimental Setup

The hydrodynamic laboratory of the University of Turin (TURlab) is equipped with a large rotating turntable, 6 m in diameter, on which a cylindrical tank 5 m in diameter is placed (Figure 1). The tank can be filled with either salty or fresh water up to the height of 0.80 m and can rotate at a maximum angular velocity of 20 rpm. This setup is able to reproduce both laminar and turbulent flows in stratified and nonstratified natural fluids, taking into account the influence of the environment rotation.

A two-dimensional PIV system allows to measure the Eulerian flow field, the turbulent structure of the flow has been characterized evaluating the statistical moments of the velocity fluctuations [Fincham and Spedding, 1997; Bernero and Fiedler, 2000].

Figure 2. Lateral view of the experimental setup.

The experiments were carried out creating a negative buoyancy in the tank, i.e., by cooling down the surface water. The constant temperature difference between the surface water and the inner water generated a strong convergence producing a stationary vertical downward current. A Dalsa Pathera 1M60 camera with a 1024×1024 pixel resolution, displaced frontally with respect to the laser sheet, was used for the flow acquisition (Figure 2). Two different procedures were used to cool down the water. The first methodology was realized using a cylindrically shaped thick layer of ice (with a diameter of 0.17 m and a height of about 0.07 m) created inside a water-filled container cooled in a refrigerator. Though being very simple this method showed some drawbacks: the irregularities of the ice surface influenced the vertical current formation, producing a nonhomogeneous flow. The ice layer also caused strong reflections of the laser sheet that perturbed the acquired images and its floating on the water made the centering on the laser sheet and camera difficult. The insemination of the water coming from the melting process was also critical, since in the refrigerator the tracer particles dropped on the container bottom and did not remain homogeneously distributed in the flow. Due to the difficulties in creating the density current, a second series of experiments was performed using a different approach. A liquid nitrogen reservoir (about 10^{-3} m^3) was placed on the water surface (Figure 3). The temperature reduction due to nitrogen evaporation first cooled the water in contact with the reservoir and then frozen it in a very well-shaped cylindrical form. In this way the ice layer was made by the water filling the tank, and hence, it was homogeneously inseminated by the tracer particles.

In our laboratory experiment the dynamics of the burst is mainly governed by the Froude (Fr) and Rossby (Ro) numbers:

$$Fr = \frac{W}{\sqrt{g'H}}; \quad Ro = \frac{W}{fH} \quad (1)$$

where W is the velocity scale, $g' = g \frac{\Delta T}{T}$, T the temperature, g the gravity acceleration, H the vertical length scale, and f the Coriolis parameter. While W and H are easily determined, with the chosen cooling methodologies, the precise measurement of the sinking water density (or temperature) and, consequently, of its cooling rate is not straightforward. We estimated the density difference between the vertical current and the ambient water "a posteriori" using the flow vertical velocity and the conservation of mechanical energy. We can write the Bernoulli equation at the downburst top and at half of the column height, where the vertical

velocity has its maximum. At the top, being null the vertical velocity, we have only two terms: the atmospheric pressure and the potential energy. At half height, the hydrostatic pressure for the ambient water balances the kinetic term entailing the maximum vertical velocity (this will be explained in the following). Then, equating the Bernoulli equations at the two levels leads to the following expression for the relative density difference:

$$\frac{\delta \rho}{\rho} = \frac{1}{\frac{g'H}{w_{\max}^2} - 1} \quad (2)$$

Figure 3. Front view of the experimental setup.

Table 1. Model Parameters

Model Parameters	Case 1	Case 2	Case 3	Case 4
H (m)	0.12	0.10	0.12	0.12
$\Delta\rho/\rho$	$2.2 \cdot 10^{-4}$	$4.5 \cdot 10^{-4}$	$5.8 \cdot 10^{-4}$	$4.5 \cdot 10^{-4}$
W (m s ⁻¹)	0.016	0.021	0.026	0.023
f (s ⁻¹)	0	0.	0.014	0.023
Fr_m	1	1	1	1
Ro_m	∞	∞	15	8
ζ_m	∞	∞	240	70
Re	1900	2100	3100	2800

It is worth noticing, that the term $\sqrt{gH}$ represents the limit velocity (w_{lim}) for a falling body and w_{max} cannot exceed it unless $\delta\rho$ is negative. When $w_{max} \ll w_{lim}$, equation (2) reduces to

$$\frac{\delta\rho}{\rho} = \left(\frac{w_{max}}{w_{lim}} \right)^2 \quad (3)$$

Equation (3) shows that the density difference between the ambient fluid and the burst can be estimated by the ratio of the maximum and limit velocities. Different experiments with different values

of the physical parameters were carried out. Here we show four test cases, whose characteristics are summarized in Table 1. The Fr and Ro numbers are shown together with the Reynolds number (Re), twice the rotation frequency f and a nondimensional number ζ , defined as $\left(\frac{Ro}{Fr} \right)^2$. Both Fr and Ro depend on a velocity scale (W) that in our experimental setup cannot be evaluated a priori but is estimated as the maximum of the vertical velocity absolute value. On the other hand, their ratio is independent from W and only depends on the setup. The Re values are comparable with those typical of the density currents (see for instance, *Cenendese and Adduce*, [2008]). Each data set is made of 501 images providing 501 velocity fields of approximately 80×80 grid points. The acquisition rates span from 17 to 27 s⁻¹, with equivalent acquisition times ranging, respectively, from about 29 s to 18 s.

It can be observed that in all the four cases Fr_m (the subscript m stands for model) is equal to one. Since Fr_m is the ratio between the flow velocity and the gravity wave velocity, a value of one reflects the balance between the two velocities. Table 2 reports the natural prototype parameters, estimated from the works present in the literature. The Fr value for the real case is 0.4, hence, in the atmosphere the burst vertical velocity is lower than the gravity waves velocity.

During the whole measuring time the cooling sources were maintained on the water surface. Therefore, except for a transitory phase of about 10–30 s, the reproduced microbursts can be considered almost stationary for more than 10 min and their Froude numbers considered constant throughout the experiment. This is different from what happens in nature, where the atmospheric microbursts are short lived and their Froude number decreases with time [*Wolfson*, 1988]. However, the stationary conditions of the laboratory measurements allow us to analyze a well-developed vertical current and to perform a statistical analysis of the velocity fields.

3. Results

3.1. Mean Flow

In Figure 4 we present the mean velocity field ($\sqrt{u^2 + w^2}$) for the four cases in Table 1. The fields are evaluated averaging 501 frames, corresponding, respectively, to time intervals of 27.83 s, 18.56 s, 29.47 s, and

23.86 s, depending on the acquisition frame rate. Even if the vertical current is always clearly identifiable, the four cases present different behaviors of the velocity field. Case 1 shows an almost symmetrical averaged velocity field, the current develops on the edges of the horizontal domain and tends to become almost homogeneous on the x axis around $z \sim 8$ cm. At $z \sim 25$ cm the flow starts feeling the influence of the tank bottom and separates. The interaction of the current with the bottom boundary creates pressure gradients that generate an outflow. The scalar field in Figure 4b (case 2) is similar to Figure 4a, but the larger density difference generates a strong downburst that does not reach the horizontal homogeneity; the flow is faster on the boundaries and slower in the center. Case 3 (Figure 4c) is similar to case 1 but with larger velocity. The rotation seems to decrease the horizontal velocity gradient between the ambient and the current. Compared to cases 1 and 2, the current in case 3 is wider, suggesting an enhancement of the entrainment process. Figure 4d shows a

Table 2. Prototype Parameters

Parameter	Prototype
H (m)	2000
ΔT (K)	9
T (K)	302
W (m s ⁻¹)	10
f (s ⁻¹)	10^{-4}
Fr_p	0.41
Ro_p	50
$\Delta T/T$	0.03

Figure 4. Mean velocity fields corresponding to the four runs: (a) case 1, (b) case 2, (c) case 3, and (d) case 4.

velocity field rather different from the other cases. There are not two distinct maxima close to the bottom on the current edges but one single maximum in the middle of the domain. In case 4, different from case 3, the effect of the rotation is evident: the current appears squeezed and the outflow is very limited, its dynamics probably disrupted by the rotation.

Figure 4 shows that averaging over x is not feasible, because the current is horizontally homogeneous only for some cases and only in a small portion of the vertical domain. In our opinion the maxima or minima of the velocity components are the values that best characterize the microburst. Figures 5 and 6 show the vertical profiles of the mean horizontal velocity absolute value maximum, $|u_{\max}|$ and the mean vertical velocity minimum $\overline{w_{\min}}$ for the four cases. $|u_{\max}|$ is evaluated averaging in time the u component absolute value at each quote, while $\overline{w_{\min}}$ is the average of the w component minimum at each quote.

Figures 5a–5c describe the same behaviors. Near the top $|u_{\max}|$ has a local maximum where the flow convergence is stronger. In the middle it reaches a constant value that, in absence of background flow, may represent the entrainment/detrainment velocity, and then it increases toward the bottom reaching its maximum, representing the outflow, at ~ 0.025 m. Case 4 (Figure 5d) shows a similar trend at the top but for $z < 0.08$ m the dynamics induced by the rotation becomes dominant and the flow has an almost constant horizontal velocity with no evident outflow. The Rossby number in the experiments (Ro_m in Table 1) is much lower than in nature (Ro_p in Table 2).

The vertical coordinate of the $|u_{\max}|$ minima for cases 1–3 is an approximated estimate of the outflow current depth: Figures 5a–5c (together with Figures 6a–6c) show that this depth is the same for the three cases, i.e., ~ 0.025 cm. Later in the paper this important parameter will be rescaled at the prototype scale.

Cases 1–3 in Figures 6a–6c show a layer of increasing vertical velocity at the top followed by a layer where $\overline{w_{\min}}$ is constant. Close to the bottom the vertical velocity decreases toward zero. The joint analysis of the

Figure 5. $|u_{\max}|$ vertical profiles for the four runs: (a) case 1, (b) case 2, (c) case 3, and (d) case 4. The horizontal dotted lines mark out the boundaries among the three zones.

$\overline{w_{\min}}$ profiles and the $|u_{\max}|$ profiles for the first three cases suggests to identify three different zones in the flow field:

1. A top layer where the cooling process determine a strong convergence region and where the horizontal flow is gradually converted in vertical flow.
2. A central layer that begins where the horizontal and vertical velocities reached their minimum. Here both the velocity components are constant and the flow is mainly vertical; the small u velocity component is only due to the entrainment/detrainment processes.
3. A bottom layer where the presence of the bottom creates an outflow.

The dotted lines in Figures 5 and 6 mark out the boundaries among the three zones. $\overline{w_{\min}}$ for case 4 (Figure 6d) shows a more organized behavior if compared with the $|u_{\max}|$ profile. The vertical velocity increases from the top, it reaches a maximum at the middle of the domain, and then it decreases without showing a constant region. It seems that in the lower part of the domain the horizontal velocity due to rotation slows down the vertical component and disrupts the microburst dynamics.

Indeed, the comparison of the two rotating cases (case 3 and case 4) shows that not always the flow feels the rotation effect. While in case 3 this effect is negligible, in case 4 its influence is evident. Being the Froude number the same for all the experiments, the differences between the two cases with rotation seem to be related to the Ro number. In particular, it can be argued that a critical value for the number ζ exists in the range between 70 and 240. Above this value the rotation seems not to influence the current dynamics.

3.2. Entrainment, Vorticity and Swirling Strength

It is well known that turbulent entrainment governs the spreading and the mixing rate of free shear flows like mixing layers, wakes, and jets. As suggested by Bettencourt da Silva and Nunes Dos Reis [2011] turbulent entrainment takes place across a sharply contorted turbulent/nonturbulent (irrotational) interface [Antonia and Krogstad, 2001]. Furthermore, exchanges of mass, momentum, and passive or active scalar quantities,

Figure 6. $\overline{w_{\min}}$ vertical profiles for the four runs: (a) case 1, (b) case 2, (c) case 3, and (d) case 4. The horizontal dotted lines mark out the boundaries among the three zones.

e.g., heat, take place along these interfaces. As recognized by *Corrsin and Kistler* [1955] the entrainment development depends on the presence of coherent vortices. At the turbulent/nonturbulent interface, these induce large-scale engulfing motions generating the entrainment [Townsend, 1966; Bisset *et al.*, 2002; Hunt *et al.*, 2006, 2008, 2009]. However, also the small-scale eddy motions seem to play an important role [Corrsin and Kistler, 1955; Mathew and Basu, 2002; Westerweel *et al.*, 2005].

To identify where the entrainment takes place, it is useful to analyze the turbulence structure. Propagating in a flow with a very low Reynolds number, we expect the buoyancy current to develop turbulence in correspondence of maximum shear and close to the bottom. Figure 7 shows the two-dimensional turbulent kinetic energy (TKE) fields, calculated as $\sqrt{\frac{1}{2}(\sigma_u^2 + \sigma_w^2)}$, for the four cases listed in Table 1. Analogously with the mean field, cases 1–3 are very similar, while case 4 has a different behavior. Figures 7a–7c show that turbulence develops on the edges of the current and increases toward the bottom of the tank. The maxima of TKE are measured at the end of the central layer, ($z \sim 0.025$ m), where the vertical velocity start decreasing and the outflow generates. Moving from case 1 (Figure 7a) to case 3 (Figure 7c) the convergence zone presents increasing levels of TKE, due to the increasing density differences. Figure 7d shows that, in presence of strong rotation, turbulence mainly develops in the center of the downburst, while in the bottom boundary layer the TKE is lower than in the central part. The TKE maximum occurs at almost half of the vertical domain, where probably the interaction of the buoyancy current with the rotating flow is higher. These characteristics are in agreement with the behavior of the mean flow (Figure 4d). As a consequence of rotation, the current is narrower and the highest values of both mean flow and turbulence are attained in the core of the downburst.

Through the TKE analysis it is possible to identify the turbulent/nonturbulent interfaces from a statistical point of view, but for the understanding of the microbursts dynamics and of the entrainment phenomenon it is necessary to study the evolution of the vortices. There is a wide literature dealing with vortex structure identification. *Jeong and Hussain* [1995] proposed a definition of vortex in an incompressible flow in terms

Figure 7. TKE fields corresponding to the four runs: (a) case 1, (b) case 2, (c) case 3, (d) case 4.

of the eigenvalues of the symmetric tensor $S^2 + \Omega^2$ where S and Ω are, respectively, the symmetric and antisymmetric parts of the velocity gradient tensor.

In the shear-driven boundary layer the presence of large organized structures, like streaks or rolls, has been recently demonstrated by many authors. Direct observations of these structures are limited [Drobninski *et al.*, 1998; Adrian *et al.*, 2000; Drobninski *et al.*, 2004; Hommema and Adrian, 2003] due to the difficulty of obtaining measurements in the shear-driven boundary layer. More evidence of them can be found from LES [Moeng and Sullivan, 1994; Lin *et al.*, 1996, 1997; Drobninski and Foster, 2003; Etling and Brown, 1993]. To identify and to trace the turbulence structures, we considered the joint analysis of the vorticity and the swirling strength, i.e., the imaginary portion of the complex eigenvalue of the local velocity gradient tensor. Adrian *et al.* [2000] demonstrated that the maximum (or minimum) of vorticity is a necessary but not sufficient condition for the identification of a vortex. To select coherent structures among the vortex extremes, they proposed the swirling strength method. To perform the swirling strength analysis, we evaluated a two-dimensional form of the velocity gradient tensor in the measurement plane:

$$D = \begin{bmatrix} \frac{\partial u}{\partial x} & \frac{\partial u}{\partial z} \\ \frac{\partial w}{\partial x} & \frac{\partial w}{\partial z} \end{bmatrix} \quad (4)$$

where D either has two real eigenvalues ($\lambda_{r1}, \lambda_{r2}$) or a pair of complex conjugate eigenvalues ($\alpha \pm i\lambda$). Vortices are unambiguously identified by plotting isoregions of $\lambda > 0$ [Adrian *et al.*, 2000]. It is worth noticing that this analysis is independent of the frame of reference and does not reveal regions where the vorticity is significant but coherent structures are not present. The swirling coefficient field appears to be less noisy than the vorticity field because the latter is influenced by the presence of local shear layers.

In Figures 8 and 9 the instantaneous vorticity fields together with the swirling strength contours are reported for cases 1 and 4. We consider the component normal to the laser sheet plane. Generally, it can be observed that vorticity develops mainly in two regions of the flow, the edge of the microburst in the vertical

Figure 8. (a–c) Vorticity and (d–f) swirling strength instantaneous fields for case 1 evaluated at $t = 13.83$ s, $t = 14.11$ s, and $t = 14.39$ s.

Figure 9. (a–c) Vorticity and (e–f) swirling strength instantaneous fields for case 4 evaluated at $t = 11.85$ s, $t = 12.09$ s, and $t = 12.33$ s.

Figure 10. Swirling strength contour plot for case 2. The picture depicts the temporal evolution of the turbulent structures inside the burst ($x \sim 0.076$ m).

the edges, positive and clockwise on the left, negative and counterclockwise on the right. This indicates the presence of entrainment of ambient fluid into the current. The outflow presents negative (positive) vorticity in the left (right) branch close to the bottom due to the shear generated in the boundary layer. Above this layer the vorticity changes its sign showing the tendency to form symmetric vortices at the two sides. Unfortunately, the horizontal dimension of the measurement field does not allow us to study the complete evolution and spreading of the vortex ring on the ground but only its initial stages. Figures 8b and 8c show the vorticity field ~ 0.28 s and ~ 0.56 s after Figure 8a, respectively. It can be observed that the intensity decreases and the structures initially generated disappear. The same as in Figure 8 but for case 4 is reported in Figure 9. The effect of the rotation is particularly evident in the last stage (Figure 9c) which shows that the vorticity structures are destroyed. The rotation seems to make the flow two-dimensional, and as a consequence, all the vertical turbulent structures are damped [Ferrero *et al.*, 2008].

In Figure 8 (case 1), it can be observed that some structures develop along the edges of the density current and are transported by the vertical flow. It may be interesting to notice that sometimes these structures follow the flow even when it diverges horizontally. If we identify the entrainment with the presence of turbulent structures, we can conclude that it develops only on the boundaries between the current and the fluid at rest. The pattern shown in Figure 9 (case 4) is quite different from that of the case without rotation. As a matter of fact, maxima of λ appear not only in the burst edges but also inside of it. Thus, in this case, entrainment seems to develop in the inner regions of the flow as well.

To investigate the coherent structures evolution in the flow, it is possible to plot the swirling strength temporal evolution on a fixed x point considering the λ contour plot in a time- z reference. We consider two distinct points on the x axis, one well inside the burst ($x \sim 0.076$ m) and another one on the burst edges ($x \sim 0.036$ m). Figure 10 shows the evolution of the coherent structures inside

Figure 11. Swirling strength contour plot for case 2. The picture depicts the temporal evolution of the turbulent structures on the burst edge ($x \sim 0.036$ m). The arrows indicate two instants when the boundary layer separates.

flow and in the boundary layer generated by the horizontal flow. In this case vorticity of opposite sign with respect to those of the boundary layer is present at higher levels due to the shear between the horizontal flow and the environment fluid at rest. For case 1, vorticity is not present in the middle of the vertical flow but only along the burst edges indicating a shear between the vertical flow and the fluid at rest. In Figure 8a, in which the well-developed downburst current is reported, it can be observed an opposite sign of the vorticity along

a column with a mainly vertical motion for case 2. If we focus on the time interval between 4 s and 15 s, we see three different structures propagating. They become evident at the end of the convergence zone ($z \sim 0.08$ m) and move with almost constant vertical velocity increasing their strength during the descent. At $z \sim 0.025$ m they start decelerating until they reach the tank bottom where they are responsible of the vortex ring formation. Figure 11 depicts the swirling strength temporal evolution on the burst left edge

Figure 12. Case 1 mean entrainment field.

divergence. This analysis agrees with the results of the swirling strength, indicating that the entrainment is mainly localized along the current edges. Furthermore, if we identify the horizontal flow of opposite sign with the outflow, the detrainment zones can also be detected.

As far as the entrainment is concerned, it can be eventually concluded that it is very low and limited to the edge regions of the flow in the cases without rotation. On the contrary, it is more developed and it takes place also in the inner of the current when the rotation is present.

3.3. Comparison With the Natural Prototype

We recall that the main parameters for the natural prototype are listed in Table 2. In order to compare our simulation results with the natural prototype we converted the measured values into the prototype scale

($x \sim 0.036$ m), where the movement of the structures is more complex. At the top, in the convergence region, the swirling strength is almost uniform, the turbulent structures have no vertical velocity, they move toward the burst center. In the central layer the deep λ stripes indicate the area where the entrainment is stronger. On the tank bottom, at $t \sim 4$ s and $t \sim 10$ s, two structures leaving the ground can be seen, these may refer to two instants when the boundary layer separates and the flow moves upward.

In order to deeper investigate the entrainment in the vertical current we consider the horizontal velocity fields normalized by its maximum (Figures 12 and 13). Since there is no horizontal background flow, we can identify this quantity as an indicator of the inflow/outflow, at least above the flow

Figure 13. Case 4 mean entrainment field.

on the base of the Froude number similarity. Imposing the equivalence of the model and prototype Froude numbers, we find

$$Fr_m = \frac{W_m}{\sqrt{g'_m H_m}} = Fr_p = \frac{W_p}{\sqrt{g'_p H_p}} \quad (5)$$

where m and p refer to the model and prototype parameters, respectively, and

$$g'_m = g \frac{\Delta \rho}{\rho}, \quad g'_p = g \frac{\Delta T}{T} \quad (6)$$

As a consequence, the velocity reduction scales verifying this equation is

$$\frac{W_p}{W_m} = \frac{(H_p g'_p)^{1/2}}{(H_m g'_m)^{1/2}} \quad (7)$$

while the time reduction scale is

$$\frac{t_p}{t_m} = \frac{H_p/W_p}{H_m/W_m} = \frac{(H_p g'_m)^{1/2}}{(H_m g'_p)^{1/2}} \quad (8)$$

Using these reduction scales, we calculated the velocity fields in the scale

Table 3. Comparison Between Model and Prototype

	Prototype	Case 1	Case 2	Case 3	Case 4
$ w_{\max} $ (m s ⁻¹)	25	24	24	24	25
$ u_{\max} $ (m s ⁻¹)	35	19	23	24	16
$\frac{ u_{\max} }{ w_{\max} }$	1.4	0.8	0.9	1.0	0.7
h_{outflow} (m)	500	500	590	660	-
f (s ⁻¹)	10 ⁻⁴	0	0	2 10 ⁻³	3 10 ⁻³

of the prototype, starting from the measurements carried out in the water tank experiments. In Table 3 the results obtained for the four experiments are summarized together with the prototype values derived from Anabor *et al.* [2011] LES.

As far as the vertical velocity is concerned, all the cases give approximately the same value which agrees with that

of the prototype. On the contrary, the horizontal velocity maxima are different and underestimate the prototype value. An interesting parameter is the ratio between horizontal and vertical velocity maxima. In the prototype this value is greater than 1, meaning that the outflow velocity is higher than the one of the downburst. This feature is not captured by the experimental data. The disagreement may be due to the value of Fr , being 1 in the experiment and 0.4 in the real case. A value less than 1 indicates that the (vertical) flow velocity is less than the wave propagation velocity, while in the experiments is the same.

The outflow height is well reproduced by case 1, while in case 2 it is overestimated. In case 3, characterized by moderate rotation velocity, it is also overestimated. As a matter of fact, the rotation yields the flow to get horizontal components, as it can be observed in Figures 4c and 4d. In case 4 the outflow current is not present. The average time of the analysis in section 3.1 corresponds, in the prototype scale, to a time interval between 309 s and 526 s, while the time intervals between the different analysis of the vorticity and swirling strength evolutions, Figures 8 and 9, are 3 s and 4 s, respectively.

4. Conclusions

Four laboratory experiments simulating the atmospheric microburst phenomenon in a rotating water tank are presented. Different experiments were carried out in Froude number similarity and studied with a high-resolution PIV system. To the authors knowledge, it is the first time that the influence of the rotation on a vertical density current is studied at this scale. The descending flow was created cooling the water surface with both a single ice block and a reservoir of liquid nitrogen. The latter provided a more regular and homogeneous flow and proved to be more suitable for the PIV measurement system. The spatial and temporal evolutions of the velocity field were investigated evaluating the mean and turbulence statistics of the flow together with the vorticity field. The analysis of the swirling strength allowed the visualization of the turbulent structures and their movements on the current boundaries and along the tank bottom. The comparison of the four experiments showed that the variations of the total height of the fluid column and of its density difference with the ambient water seem not to produce remarkable differences in the flow dynamics. On the contrary, the flow rotation drastically changes the nature of the current. For higher values of the Rossby number the horizontal velocity gradients are strong enough to contrast the gravity force and prevent the burst formation. Turbulence structures are also damped in the presence of strong rotation. The flow appears shrunked, and, while in the nonrotating cases the turbulent entrainment takes place mainly on the burst edges, at high Rossby number it involves also the inner flow region.

Finally, the comparison with the natural prototype shows that some features of atmospheric microbursts are well reproduced even if the outflow maximum velocity in the experiment is always less than the maximum of the vertical velocity absolute value, while in the real case $|u_{\max}| = 1.4|w_{\max}|$. This may be a consequence of the Froude number chosen for the experiments.

Acknowledgment

The authors would like to thank Umberto Rizza for useful discussions.

References

- Adrian, R. J., C. D. Meinhart, and C. Tomkins (2000), Vortex organization in the outer region of the turbulent boundary layer, *J. Fluid Mech.*, 422, 1–53.
- Alahyari, A., and E. K. Longmire (1994), Particle image velocimetry in a variable density flow: Application to a dynamically evolving microburst, *Exp. Fluids*, 17, 434–440.
- Anabor, V., U. Rizza, E. L. Nascimento, and G. A. Degrazia (2011), Large-eddy simulation of a microburst, *Atmos. Chem. Phys.*, 11, 9323–9331.
- Antonia, R., and P. Krogstad (2001), Turbulence structure in boundary layers over different types of surface roughness, *Fluid Dyn. Res.*, 28, 139–157.

- Bernero, S., and H. Fiedler (2000), Application of particle image velocimetry and a proper orthogonal decomposition to the study of jet in a counterflow, *Exp. Fluids*, 29(suppl.), S274–S281.
- Bettencourt da Silva, C., and R. J. Nunes Dos Reis (2011), The role of coherent vortices near the turbulent/non-turbulent interface in a planar jet, *Philos. Trans. R. Soc. A*, 369, 738–753.
- Bisset, D. K., J. C. R. Hunt, and M. M. Rogers (2002), The turbulent/non-turbulent interface bounding a far wake, *J. Fluid Mech.*, 451, 383–410.
- Cenendese, C., and C. Adduce (2008), Mixing in a density-driven current flowing down a slope in a rotating fluid, *J. Fluid Mech.*, 604, 369–388.
- Corrsin, S., and A. L. Kistler (1955), Free-stream boundaries of turbulent flows, *Tech. Rep. TN-1244*, NACA, Washington, D. C.
- Drobinski, P., and R. C. Foster (2003), On the origin of near-surface streaks in the neutrally-stratified planetary boundary layer, *Boundary Layer Meteorol.*, 108(2), 247–256.
- Drobinski, P., R. A. Brown, P. H. Flamant, and J. Pelon (1998), Evidence of organized large eddies by ground-based Doppler lidar, sonic anemometer and sodar, *Boundary Layer Meteorol.*, 88(3), 343–361.
- Drobinski, P., P. Carloti, R. K. Newson, R. M. Banta, R. C. Foster, and J.-L. Redelsperger (2004), The structure of the near-neutral atmospheric surface layer, *J. Atmos. Sci.*, 61(6), 699–714.
- Elmore, K. L., J. MacCarthy, W. Frost, and H. P. Chang (1986), A high resolution spatial and temporal multiple doppler analysis for a microburst and its application to aircraft flight simulation, *J. Clim. Appl. Meteorol.*, 25, 1398–1425.
- Etling, D., and R. Brown (1993), Roll vortices in the planetary boundary layer: A review, *Boundary Layer Meteorol.*, 104, 359–369.
- Ferrero, E., R. Genovese, A. Longhetto, M. Manfrin, and L. Mortarini (2008), Experimental study of higher-order moments in shear-driven boundary layers with rotation, *J. Fluid Mech.*, 598, 121–139.
- Ferrero, E., L. Mortarini, M. Manfrin, A. Longhetto, R. Genovese, and R. Forza (2009), Boundary-layer stress instabilities in neutral, rotating turbulent flows, *Boundary Layer Meteorol.*, 130, 347–363.
- Fincham, A., and G. Spedding (1997), Low-cost, high resolution DPIV for measurement in turbulent fluid flows, *Exp. Fluids*, 23, 449–462.
- Fujita, T. T. (1978), Manual of downburst identification for project NIMROD, *SMRP Research Paper*, 156, 104 pp.
- Fujita, T. T. (1985), The downburst, microburst and macroburst, satellite and mesometeorology research project SMRP, *Research Paper* 210, Dept. of Geophysical Sciences, Univ. of Chicago.
- Fujita, T. T. (1990), DOWNBURSTS: Meteorological features and wind field characteristics, *J. Wind Eng. Ind. Aerodyn.*, 35, 75–86.
- Hommema, S. E., and R. J. Adrian (2003), Packet structure of surface eddies in the atmospheric boundary layer, *Boundary Layer Meteorol.*, 106(1), 147–170.
- Hunt, J. C. R., I. Eames, and J. Westerweel (2006), Mechanics of inhomogeneous turbulence and interfacial layers, *J. Fluid Mech.*, 554, 499–519.
- Hunt, J. C. R., I. Eames, and J. Westerweel (2008), Vortical interactions with interfacial shear layers, in *Proceedings of IUTAM Conference on Computational Physics and New Perspectives in Turbulence, Nagoya, September 2006*, edited by Y. Kaneda, Springer, Berlin, Germany.
- Hunt, J. C. R., I. Eames, J. Westerweel, P. A. Davidson, S. Voropayev, J. Fernando, and M. Braza (2009), Eddy dynamics near sharp interfaces and in straining flows, in *Proceedings of European Conference Maths in Industry, July 2008*, Springer, Berlin, Germany.
- Jeong, J., and F. Hussain (1995), On the identification of a vortex, *J. Fluid Mech.*, 285, 69–94.
- Kim, J., and H. Hangan (2007), Numerical simulations of impinging jets with application to downbursts, *J. Wind Eng. Ind. Aerodyn.*, 95, 279–298.
- Lin, C. L., J. C. McWilliams, C.-H. Moeng, and P. P. Sullivan (1996), Coherent structures and dynamics in a neutrally stratified planetary boundary layer flow, *Phys. Fluids*, 8(10), 2626–2639.
- Lin, C. L., C.-H. Moeng, P. P. Sullivan, and J. C. McWilliams (1997), The effect of surface roughness on flow structures in a neutrally stratified planetary boundary layer flow, *Phys. Fluids*, 9(11), 3235–3249.
- Mason, S. M., G. S. D. F. Wood, and D. F. Fletcher (2009), Numerical simulation of downburst winds, *J. Wind Eng. Ind. Aerodyn.*, 97, 523–539.
- Mathew, J., and A. Basu (2002), Some characteristics of entrainment at a cylindrical turbulent boundary, *Phys. Fluids*, 14, 2065–2072.
- Moeng, C.-H., and P. Sullivan (1994), A comparison of shear and buoyancy driven planetary boundary layer flow, *J. Atmos. Sci.*, 51, 999–1022.
- Nicholls, M., R. Pielke, and R. Meroney (1993), Large eddy simulation of microburst winds flowing around a building, *J. Wind Eng. Ind. Aerodyn.*, 46–47, 229–237.
- Orf, L. G., and J. R. Anderson (1999), A numerical study of traveling microbursts, *Mon. Weather Rev.*, 127, 1244–1257.
- Orf, L. G., J. R. Anderson, and J. M. Straka (1996), A three-dimensional numerical analysis of colliding microburst outflow dynamics, *J. Atmos. Sci.*, 53, 2490–2511.
- Proctor, F. H. (1988), Numerical simulations of an isolated microburst. Part I: Dynamics and structure, *J. Atmos. Sci.*, 45, 3137–3160.
- Proctor, F. H. (1989), Numerical simulations of an isolated microburst. Part II: Sensitivity experiments, *J. Atmos. Sci.*, 46, 2143–2165.
- Townsend, A. A. (1966), The mechanism of entrainment in free turbulent flows, *J. Fluid Mech.*, 26, 689–715.
- Westerweel, J., C. Fukushima, J. M. Pedersen, and J. C. R. Hunt (2005), Mechanics of the turbulent–nonturbulent interface of a jet, *Phys. Rev. Lett.*, 95, 174501.
- Wolfson, M. (1988), Characteristics of microbursts in the continental United States, *Lincoln Lab. J.*, 1(1), 49–74.
- Yao, J., and T. S. Lundgren (1996), Experimental investigation of microbursts, *Exp. Fluids*, 21, 17–25.