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High-resolution numerical simulation of a thunderstorm-induced downburst event and comparison with LiDAR wind measurements

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SUMMARY:
Thunderstorms are among the major atmospheric mesoscale threats worldwide. Their simulation is still a challenge for operational and scientific purposes, as well as the forecast of the large damage that might occur at the local scale due to related hazards like windstorms, hailstorms, and intense rainfall. In this research, we focus on the high-resolution numerical simulation of a thunderstorm event using the Cloud Model 1 (CM1). The domain of analysis is the Ligurian Sea, a geographical region prone to the development of deep convection because of the presence of steep orography and strong surface heat fluxes, which can enhance thunderstorm strength and lifetime. The chosen event hit the city of Genoa on August 14, 2018, producing a downburst on the ground that was measured by a scanning lidar, a lidar vertical profiler, and several anemometers and met-stations. Different schemes for the microphysics are tested to compare the numerical outcomes with ground measurements of wind and temperature fields. The surface wind fields produced by the longest-lasting thunderstorm cell, which was characterized by a sustained updraft and a strong downdraft due to the interaction of the cloud with the complex orography, are shown in the results and compared with the measured vertical wind profiles.

Keywords: thunderstorm, downburst, cloud model

1. INTRODUCTION

Despite the theoretical knowledge in the field, mesoscale atmospheric events are still challenging in terms of predictability. Large uncertainties are often associated with the forecast of thunderstorm evolution and, more specifically, with the likelihood of hazardous phenomena. In accordance with the last IPCC report (Pörtner et al., 2022), extreme weather events are expected to further worsen soon in many parts of the world because of human-induced global warming. These two aspects explain the great interest of the scientific community in investigating the mechanisms that play a role in triggering thunderstorms and how a warmer world could affect deep convection (Gallus et al., 2018).

This work is performed to investigate the mechanisms that underlie deep convective development and intensification in the Ligurian Sea, a region affected, mostly during the late summer and autumn, by severe convective episodes. A thunderstorm event hitting the city of Genoa in the morning of August 14, 2018, during the collapse of the Morandi Bridge (Burlando et al., 2020), is chosen as case study to perform high-resolution numerical simulations. The main final goal of this research is to study the role that complex regional orography could play in the enhancement of the thunderstorm outflow at the ground and in the evolution and strengthening of the whole convective system. Simulations with different schemes for the microphysics are performed and the numerical outcomes are compared with the available ground measurements.

2. METHODOLOGY

We used the Cloud Model 1 (CM1, Bryan and Fritsch, 2002), release 21.0 (cm1r21.0, April 2022), which is a non-hydrostatic idealized numerical model designed for high resolution simulations, mostly for severe storms that contain deep moist convection. In this work, the equations are numerically solved using the Large Eddy Simulations (LES) approach, adopting the parameterization of Deardorff for the subgrid turbulence. Among the available options in the microphysics parameterization, we tested 5 schemes: Morrison et al. (2005), NASA-Goddard version of the LFO scheme (Lin et al., 1983), Thompson et al. (2004), NSSL 2-moment (Mansell et al., 2010) and the Predicted Particle Property bulk microphysics (Morrison and Milbrandt, 2015).

The atmospheric sounding reported in Burlando et al. (2020) is used to initialize the atmosphere, with open-radiative boundary conditions. The storm is generated by using a 3D warm bubble (Hannah, 2017), centered at 0.5 km above the sea level, with a horizontal and a vertical radius of, respectively, 10 km and 1 km. All the simulations run for a period of 90 minutes after the warm bubble release in the atmosphere.

The domain of analysis is squared, 289 km $\times$ 289 km $\times$ 20.3 km in the x, y, and z directions, respectively. The horizontal grid spacing is stretched and varies from almost 1.8 km at the boundaries to 0.05 km in the innermost part of the domain, for a total of 600 x 600 grid points. Along the vertical, the grid resolution is 25 m up to an altitude of 500 m and 0.2 km from 2.3 km to the top of the atmosphere, while the grid is stretched in between 500 m and 0.2 km for a total of 126 vertical levels. The orographic data have been downloaded from the SRTM database (https://www2.jpl.nasa.gov/srtm/), with an original spatial resolution of 90 m, while we used the ERA5 reanalyses (0.25° $\times$ 0.25°), and observations from the Copernicus Marine Service dataset for the surface properties (i.e., Sea Surface Temperature and ocean mixed layer depth).

3. RESULTS

After the sensitivity analysis was performed with the 5 aforementioned microphysical schemes, the simulation carried out using Thompson's scheme turned out to be the most accurate in reproducing the flow fields at the ground, based on the comparison with LiDAR measurements (see below). Accordingly, for the sake of simplicity, in the following only the results corresponding to this simulation are shown.

Fig. 1 shows the wind field at 12.5 m above ground level (AGL) simulated by CM1 at time steps corresponding to 40, 45, 50, and 55 min. Within this 20-minute interval, the downburst is released at the ground, spreads out, and slowly dissipates. At 40 min, the downburst is barely affected by the orography and spreads out over the sea in an almost circular shape. Interestingly, the widest and strongest sector of the downburst is to the east of the touchdown, which corresponds to the direction of storm motion. Moreover, behind the primary vortex ring, which corresponds to the most external part of the downburst, some trailing vortices appear in the form of secondary radial outflow speed up. In the next time steps, the downburst keeps on spreading, but its shape is no longer circular due to the orography. According to the simulations, the downburst reaches the position of the Morandi Bridge (red square) only 10 min after the touchdown, with velocities in the order of 10-12 m/s.

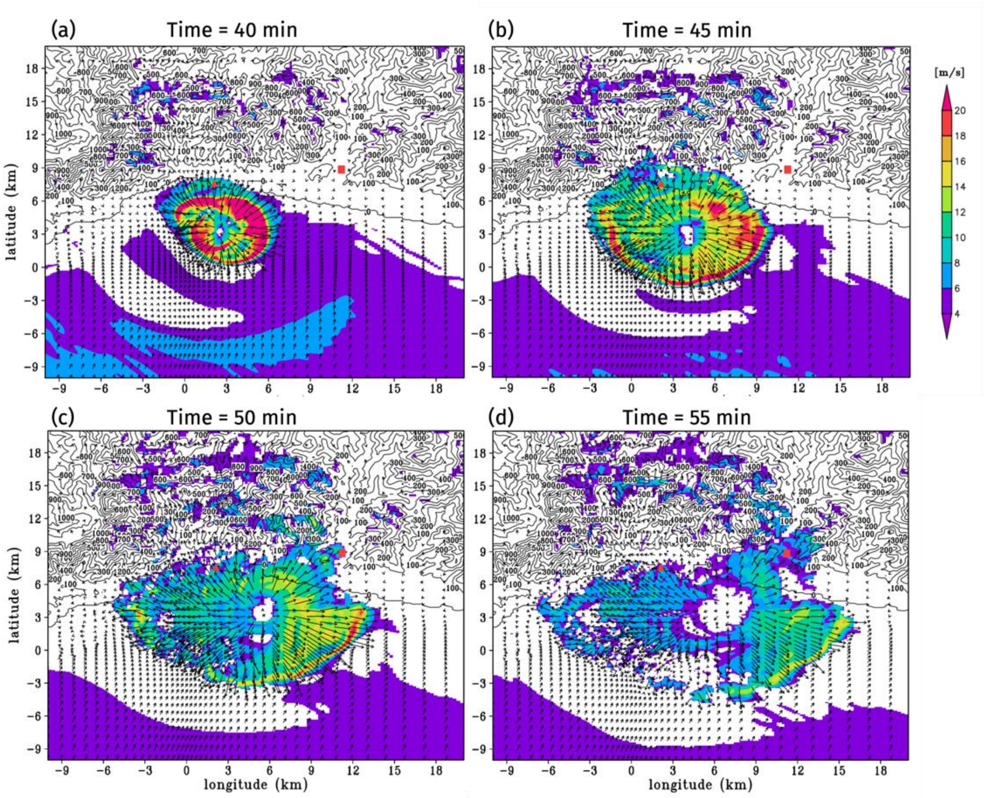

Figure 1. Surface (12.5 m AGL) wind field magnitude (shaded contours) and vectors for times 40 (a), 45 (b), 50 (c), and 55 min (d). The red square is the Morandi Bridge. The red triangle is the LiDAR profiler.

Fig. 2 shows the comparison between the wind speed (top panel) and direction (bottom panel) measured by the LiDAR vertical profiler (blue and orange dots), which is installed in the position of the red triangle reported in Fig. 1, and simulated by CM1 in the same position (green lines and dots) after bilinear interpolation among the 4 closest grid points. The figure shows that CM1 is able to capture the signature of the downburst both in terms of magnitude and evolution over time.

4. CONCLUSIONS

This paper describes the numerical simulation of a real downburst that occurred in the Mediterranean by means of the CM1 cloud model. The maximum horizontal resolution is 50 m, and the time-space evolution of the entire thunderstorm seems to be properly described using the LES strategy. Other anemometric and LiDAR measurements in addition to those shown in this paper are available and will be used for further validation of the simulation and reported in the extended version of this paper.

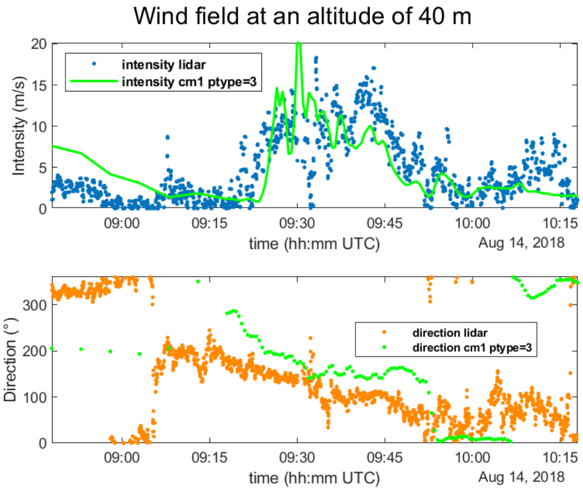

Figure 2. Comparison between measured and simulated wind speed and direction at 40 m AGL. The position of the LiDAR corresponds to the red triangle in Fig. 1.

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