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Numerical simulations of Po Valley tornado-like-vortices using Cloud Model 1: Quantifying flow-field dynamics

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SUMMARY:
Tornadoes constitute a significant but substantially underrepresented hazard in the Po Valley, where historical events have induced severe localised wind loading on the built environment. This study aims to develop a high-resolution numerical modelling framework to reveal intricacies of tornadogenesis mechanisms in the Po Valley, using Cloud Model 1 (CM1). Quasi-realistic CM1 LES configurations enable explicit resolution of the tornadic flow field, allowing for quantification of wind-speed distributions, dynamic pressure perturbations, stress tensors, and vortical structures – essential for improving resilience to tornadic winds. Full-scale simulations will be carried out on the Po Valley, by CM1 and then by CFD-LES techniques. Contributions to Italian wind engineering have offered no distinct, recurring focus on tornadic winds; consequently, this research study aims to enable future assessment of tornado-induced wind loading and regional wind risk.

Keywords: Tornadic Wind, Cloud Model 1, Po Valley

1. INTRODUCTION

Contrary to assumptions, tornadoes are not a rare occurrence in the Po Valley, and localised events comprised of significant (EF-2+; i.e., gusts over 60 m s^{-1}) tornadoes do manifest (Groenemeijer and Kühne, 1983). Most significant Po Valley tornadoes stem from supercell thunderstorms, the most vigorous morphology of convective storm responsible for the vast majority of severe tornadoes worldwide. Despite ever increasing exposure and vulnerability to tornadic wind events in Po Valley, the non-synoptic mechanisms that foster tornadogenesis, augment tornadic flow, and cause extensive damage, are respectively poorly understood. Tornadoes have caused substantial economic and societal impacts in the Po Valley (e.g., Zanini et al., 2017), yet research attention remains limited.

Computation Fluid Dynamics (CFD) simulations of laboratory scale tornado-like-vortices (TLVs) have been critical in quantifying tornadic-wind loading stress on multiple archetypes (e.g. low-rise structures, port infrastructure etc), tangential velocity modelling with varying surface roughness, and validifying/refuting real-world tornadic observations (e.g., Kuai et al., 2008). However, such highly idealised laboratory studies fail to instigate realistic TLV genesis and thus do not represent the "true" origins of the tornado flow field. Extremely (or "ultra") high-resolution Cloud Model 1 (CM1) large-eddy simulation (LES) studies (e.g., Markowski, 2024) have progressively revealed previously unrecognised kinematic, and thermodynamic process governing tornadogenesis/tornadic-wind production, often challenging robust conceptual models. These simulations explicitly resolve full-scale TLV genesis and evolution, predominantly employing upper-echelon base-state tornadic environment inputs, atop horizontally homogenous virtual ground.

This research study aims to quantify the mechanisms responsible for tornadogenesis and tornadic-wind generation in the Po Valley, by conducting full-scale TLV ensemble simulations using

CM1 and CFD techniques. Tornadic environment inputs for CM1 are derived from real-world atmospheric profiles associated with selected Po Valley tornadic events. Outputs from CM1 are then employed as inputs for CFD simulations.

2. METHODOLOGY

2.1. Cloud Model (CM) 1 setup

In the present stage, George Bryan's Cloud Model 1 (CM1) version 21.1 (Bryan and Fritsch, 2002) is being utilised to conduct high-resolution simulations of Po Valley TLVs. CM1 is a three-dimensional, fully compressible, non-hydrostatic, time-dependent, cloud-resolving numerical model; a necessity for instigating realistic TLV genesis.

The CM1 computational domain spans 120 km x 120 km x 18 km, and contains 780,000,000 grid points. Constant horizontal grid spacing of 60 m is used, enabling adequate resolving turbulent structures. The vertical grid is a constant 25 m in the lowest 2.25 km above ground level (AGL), and then smoothly stretched from 25 m at 2.25 km, to 275 m at 18 km. A LES approach is used in conjunction with the Deardorff (1980) turbulent kinetic energy sub-grid-scale (SGS) closure scheme. The pressure solver employs compressible, Klemp-Wilhelmson time-splitting, with horizontally explicit and vertically implicit differentiations. Air parcels are forward-integrated in time using the Runge-Kutta second-order and fifth-order advection scheme (scalars and velocities). The large time step Δt for model dynamics is 0.9 s, and the acoustic time step Δt_a is (0.9/10) s, with an allocated adaptive step setting. Cloud microphysics are computed using the Morrison et al. (2009) dual-moment explicit moisture scheme. Lateral boundary conditions are open-radiative. The top boundary is free slip. The bottom boundary is semi slip, providing insight into boundary-layer frictional effects on tornadic flow relevant to wind engineering applications. Po Valley topography is incorporated in the CM1 simulations using NASA's Shuttle Radar Topography Mission (SRTM) global elevation data at 90 m (3 arc-second) resolution.

Convection is initiated using artificial updraught nudging. An ellipsoidal vertical velocity perturbation is stationed at 1500 m AGL, with a horizontal radius of 8000 m, and vertical radius of 1500 m. The vertical velocity ramps up to 14 m s^{-1} until t = 1350 s, before ramping down to 0 m s^{-1} at t = 1700 s. CM1 GrADS outputs are first visualised using the National Centre for Atmospheric Research Visualisation and Analysis Platform (VAPOR; Visualization and Analysis Systems Technologies, 2023), for 3D volume rendering and iso-surfaces. 2D plan view and cross-sectional quantification plots are constructed using Python.

2.2. Atmospheric profile inputs

Vertical profiles of the atmosphere associated with significant Po Valley tornadic events are extracted using Weather Research and Forecasting (WRF) model version 4.7.1 initialised with ERA5 reanalysis data. 101 vertical levels are used, and an inner domain of 1 km horizontal resolution is stationed over Italy's Po Valley. The planetary boundary layer is represented by the Mellor-Yamada-Nakanishi-Niino 2.5 scheme with eddy diffusivity mass flux. Extracted profiles include vertical distributions of temperature, moisture, horizontal wind components and associated vorticity. These profiles are horizontally homogenised and lightly smoothed prior to being applied as initial conditions in CM1.

3. PRELIMINARY RESULTS

Preliminary results from a CM1 supercell simulation at coarser resolution are presented in Figure 1. Figure 1a shows the 3D volume rendering of the cloud field, and reveals classic supercell structure. The mesocyclone – the supercell's helically rotating updraught (red arrows) – is driven by a strong non-hydrostatic vertical pressure perturbation gradient force. The associated horizontal gradients in vertical velocity are able to tilt boundary layer horizontal vorticity into the vertical, which helps promote low-level rotation conducive for tornadogenesis. In Figure 1b, trajectories are initialised at the eastern boundary of the subdomain, and are coloured by the horizontal wind magnitude (U; $\mathrm{m\,s^{-1}}$). Near-surface air parcels (z = 50 m) enter the domain from the east as a coherant inflow jet with horizontal winds exceeding 20 $\mathrm{m\,s^{-1}}$. Wind speeds continually intensify up to 30–35 $\mathrm{m\,s^{-1}}$ as they approach the mesocyclone.

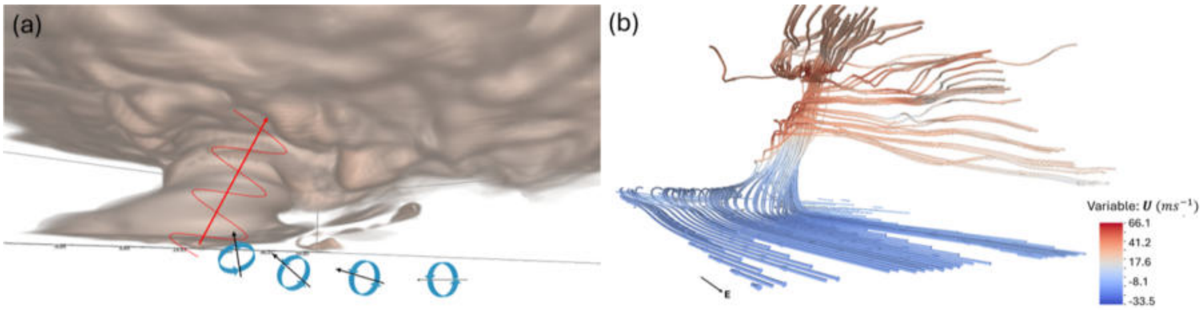

Figure 1. (a) Volume rendered cloud field, with red arrow(s) illustrating the supercell's mesocyclone (updraught) and blue and black arrows indicating the presence of strong horizontal vorticity and associated vorticity vector. (b) Lagrangian air parcel trajectories, within a subdomain of a preliminary CM1 simulation at 400 m horizontal resolution. View is looking to the NW. 3D rendering is constructed using VAPOR.

Results from a WRF simulation of the 22 July 2023, Alfonsine, Emilia-Romagna International Fujita 3 (IF3) tornadic environment are presented in Figure 2. The hodograph depicts a strongly sheared environment with strong storm-relative winds supportive of supercell development, and by extension tornadogenesis (Brooks, 2013). Figure 2 is characterised by an effective bulk wind difference of 49 m s^{-1}, effective storm relative helicity (ESRH) of 418 m^2 s^{-2}, 0–1 km SRH of 172 m^2 s^{-2}, and 0– 3 km SRH of 357 m^2 s^{-2}. The conglomeration of kinematic parameters and thermodynamic parameters (not shown), fosters a significant tornado parameter (STP) of 5.06. An STP value greater than 1 is indicative of an environment with increased probabilities of significant EF-2+ tornado occurence.

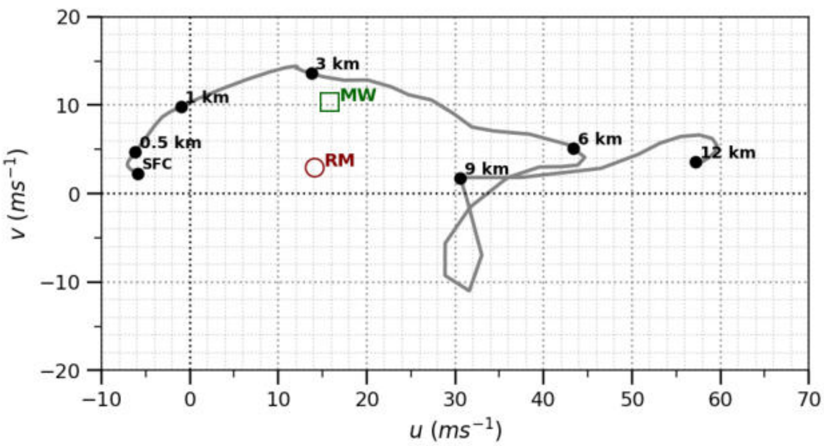

Figure 2. Hodograph extracted from the Alfonsine, Emilia-Romagna, IF3 tornadic environment simulated by WRF. RM denotes the velocity of the right moving supercell, and MW denotes the mean wind vector.

4. CONCLUDING REMARKS

This research study presents a high-resolution numerical framework designed to investigate tornadogenesis and tornadic-wind generation in the Po Valley, a region where tornado risk remains underrepresented in both atmospheric science and wind engineering literature. By employing CM1 LES, configured with real-world environmental inputs derived from Po Valley tornadic events, this framework enables explicit resolution of low-level tornado-scale flow-field dynamics. Although full-resolution simulations are yet to commence, due to computational resource allocation, planned analyses will focus on quantifying wind speed distributions, dynamic pressure perturbations, stress tensors, and vortical structures, encompassing the flow-field and directly informing wind-engineering applications. Additionally, CM1 outputs aim to provide physically consistent inputs for subsequent CFD analyses.

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