A Comparative Ultra-High-Resolution Numerical Study on the Genesis of Island-Induced Clockwise and Counterclockwise Tornadoes in Taiwan

Chih-Ying Chen[1], Chih-Hsien Wei[2], Feng Hsiao[3], Sen Chiao[3], Chuan-Yao Lin[1*]

[1] Research Center for Environmental Changes, Academia Sinica, Taipei, Taiwan

[2] China Airlines, Taipei, Taiwan

[3]NOAA Center in Atmospheric Sciences and Meteorology (NCAS-M), Howard University, Washington, DC, USA

摘　要

在複雜的島嶼環境中，理解控制順時針（CW）和逆時針（CCW）龍捲風形成的獨特動力學過程，對於科學研究和天氣預報而言仍是一項重大挑戰。本研究分析了台灣發生的兩次罕見龍捲風事件：2011年的一次順時針龍捲風和2019年的一次逆時針龍捲風；這兩次龍捲風均非源自超級單體風暴。透過利用天氣研究與預報（WRF）模式進行超高解析度（40公尺）的大渦模擬（LES），我們重現了不同尺度的天氣過程與這兩次龍捲風核心結構之間的相互作用，從而超越了以往基於觀測的研究能力。

模擬結果揭示了龍捲風形成的完整過程，並支持了以下觀點：島嶼引發的龍捲風主要源自於非超級單體對流系統與周圍環境之間的相互作用。結果也顯示了一個自下而上的演變序列：在輻合環境中，由水平風切產生近地面渦旋，隨後渦旋與鄰近中尺度對流單體的上升氣流耦合，並透過渦度拉伸作用得以增強。本研究中龍捲風的順時針（CW）與逆時針（CCW）旋轉特徵，揭示了局部環流如何影響其旋轉方向。這項研究凸顯了高解析度（亞100公尺尺度）模擬在理解這些生命期短暫卻威力巨大的龍捲風之關鍵形成特徵的重要性。

關鍵字：垂直由下而上耦合，非超級單體龍捲，大渦模擬（LES），複雜地形

Abstract

Understanding the distinct dynamical processes governing the formation of clockwise (CW) and counterclockwise (CCW) tornadoes in complex island environments remains a significant challenge for science and weather forecasting. This study examines two rare tornado events in Taiwan: a CW tornado in 2011 and a CCW tornado in 2019. Neither of these tornadoes was part of a supercell storm. Using the Weather Research and Forecasting (WRF) model with ultra-high-resolution (40-meter) Large-Eddy Simulations (LES), we recreated the interactions between different scales of weather and the core structures of both tornado events, surpassing the capabilities of previous observational-based studies.

Our simulations reveal the complete formation process and support the view that island-induced tornadoes arise primarily from the interaction between non-supercell convective systems and the ambient environment. The results also show a bottom-up sequence: a surface-generated vortex forms from horizontal wind shear in the convergent environment, then strengthens via vorticity stretching as it couples with updrafts from neighboring mesoscale convective cells. The clockwise (CW) and counterclockwise (CCW) rotation of tornadoes reveals how local circulation influences rotation direction in this study. This study highlights the importance of high-resolution (sub-100 m) simulations in understanding the key formation characteristics of these short-lived yet powerful.

Keywords: Vertical bottom-up coupling, Non-supercell tornadoes, Large-eddy simulation (LES), Cmoplex Terrain