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Lightning and Radar Characteristics of Tornadoes in Landfalling Hurricanes

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1. Introduction

Motivation

- Tropical cyclone (TC) tornadoes are associated with low-skill forecasts (Martinaitis 2017), which may be improved through greater understanding of their lightning and radar signatures;
- These low-skill forecasts are due to the marginal structure of TC tornadic mesocyclones, which are low-topped supercells (Edwards et al. 2012);
- TC tornadic mesocyclones have weaker low-level rotation and reduced lightning flashes, although these results are based on studies with limited sample sizes (e.g., Nowotarski et al. 2021).

Research Questions

1. **Are there differences in lightning and low-level rotation between tornadic and non-tornadic TC mesocyclones before and during tornadogenesis in a large climatology?**
2. **How do low-level rotation observations compare between TC and non-TC tornadic mesocyclones before and during tornadogenesis in a broad sample of cases?**

2. Data and Methods

Datasets

- **Tornadic and non-tornadic mesocyclone data:**
  1) **TC tornadic mesocyclones:** SPC TC tornado data from 2013–2020 (N = 379; Edwards 2022) including subjectively extended tracks for up to 1 hr before tornadogenesis (N = 141; Sandmæl et al. 2022);
  2) **TC non-tornadic mesocyclones**: Subjectively identified rotating, non-tornadic cells within the same radar scan as tornadoes from 2017–2018 (N = 5840; Sandmæl et al. 2022);
  3) **Non-TC tornadic mesocyclones:** SPC tornado data from 2013–2020 (N = 5840; Schaefer and Edwards 1999) including subjectively extended tracks for up to 1 hr before tornadogenesis (N = 992; Sandmæl et al. 2022);
- **Lightning data:** Earth Networks Total Lightning Network (ENTLN) data using wideband (1 Hz to 12 MHz) detection with time-of-arrival technique;
- **Low-level rotation data:** 0.5°-tilt maximum azimuthal shear data (i.e., across-azimuth gradient in radial velocity) from WSR-88D radar.

Methods

- For each TC tornadic, TC non-tornadic, and non-TC tornadic mesocyclone track point, we collected: 1) lightning and azimuthal shear (where available) within a 10-km radius of each point and 2) lightning within 750-km radius of TC for first two subsets;
- Compared differences between:
  1. Local-scale lightning associated with TC tornadic and non-tornadic mesocyclones;
  2. Low-level rotation before and during TC tornadic, non-TC tornadic, and TC non-tornadic mesocyclones;
  3. TC-scale lightning before, during, and after tornadic and non-tornadic mesocyclones.

3. Results: Are There Differences in Lightning Near TC Tornadic and Non-Tornadic Mesocyclones?

Overview

Compare the number and location of flashes immediately surrounding TC tornadic and non-tornadic mesocyclones.

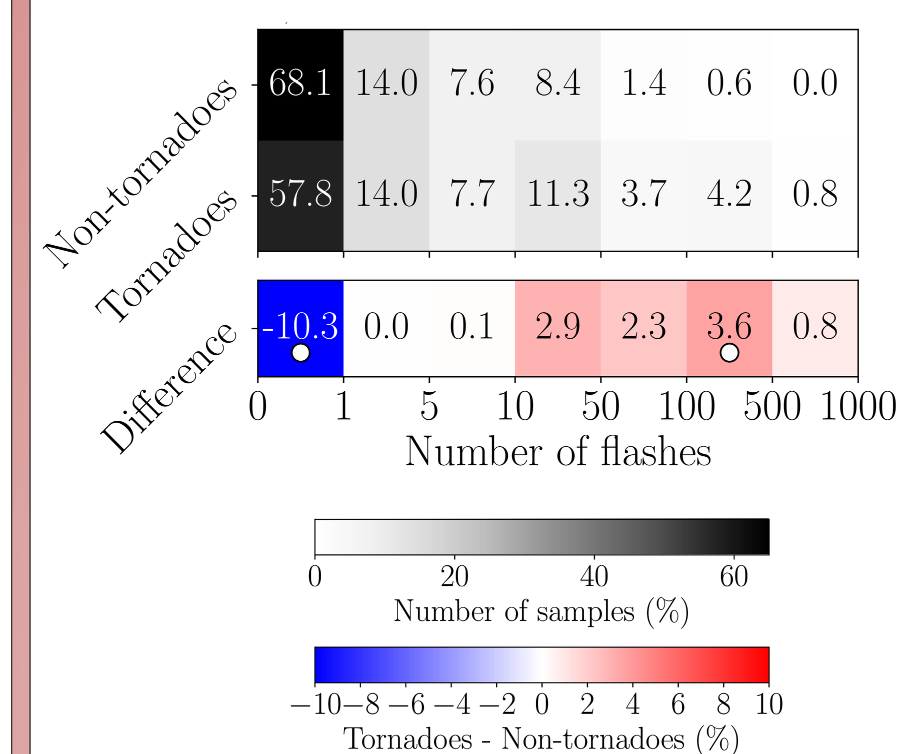

Fig. 1: Heat map of flashes (%) within 10 min before and a 10 km radius of TC non-tornadic mesocyclones, tornadogenesis of TC tornadic mesocyclones, and their difference. Percentages are calculated relative to the total number in each subset. Grid boxes with a white dot show statistically significant differences between the tornadic and non-tornadic subsets.

Synopsis

1. Most TC tornadic and non-tornadic mesocyclones are not associated with lightning (Fig. 1);
2. Mesocyclones with ≥100 flashes over a 10 min period are more likely to be tornadic (Fig. 1);
3. Flashes near TC tornadic mesocyclones are concentrated to their northeast at tornadogenesis, whereas flashes are less frequent and more symmetrically distributed about TC non-tornadic mesocyclones (Fig. 2).

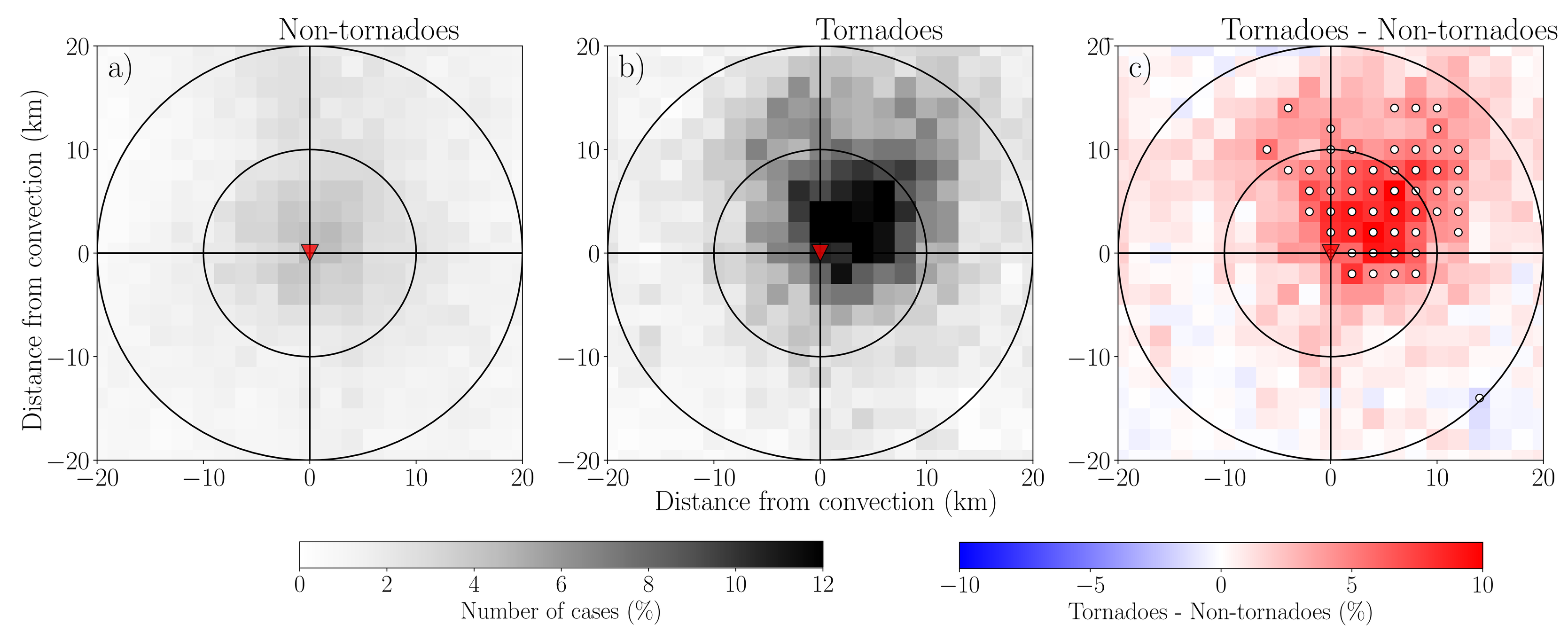

Fig. 2: Percentage of cases on a 2-km × 2-km grid with ≥1 flashes within 10 min before (a) TC non-tornadic mesocyclones, (b) tornadogenesis of TC tornadic mesocyclones, and (c) their difference (tornadic - non-tornadic mesocyclones) shown relative to tornadogenesis or non-tornadic mesocyclone location. Range rings are shown at 10-km intervals. The small white circles denote bins with statistically significant differences between the tornadic and non-tornadic subsets.

4. Results: Does the Low-Level Rotation of TC Tornadic Mesocyclones Differ From TC Non-Tornadic and Non-TC Tornadic Mesocyclones?

Overview

Evaluate how radar-derived low-level rotation differs between TC tornadic mesocyclones, TC non-tornadic mesocyclones, and non-TC EF0/EF1 tornadic mesocyclones before and during tornadogenesis.

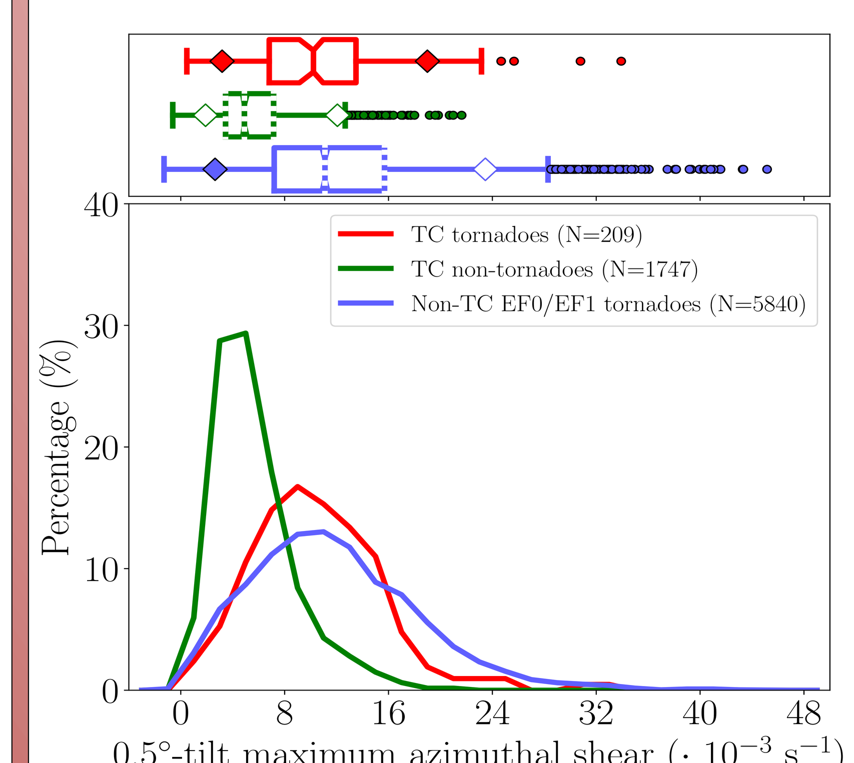

Fig. 3: Histogram and box-and-whiskers plot showing 0.5°-tilt maximum azimuthal shear (· 10^{-3} s^{-1}) for TC non-tornadic mesocyclones, and TC tornadic and non-TC EF0–1 tornadic mesocyclones at tornadogenesis. Dotted lines in the box-and-whiskers indicate when the median, 25th, or 75th percentiles are significantly different from the TC tornadic mesocyclone subset, while white-filled diamonds are used to show significant differences for the 5th or 95th percentiles.

Synopsis

1. Stronger low-level rotation for TC tornadic mesocyclones at time of tornadogenesis compared to TC non-tornadic mesocyclones (Fig. 3);
2. Weaker low-level rotation for TC tornadic mesocyclones compared to non-TC tornadic mesocyclones at 1 hour prior to tornadogenesis (Fig. 4);
3. More rapid broadening of low-level rotation distribution for TC tornadic mesocyclones leads to marginal differences with non-TC tornadic subset at time of tornadogenesis (Figs. 3 and 4);

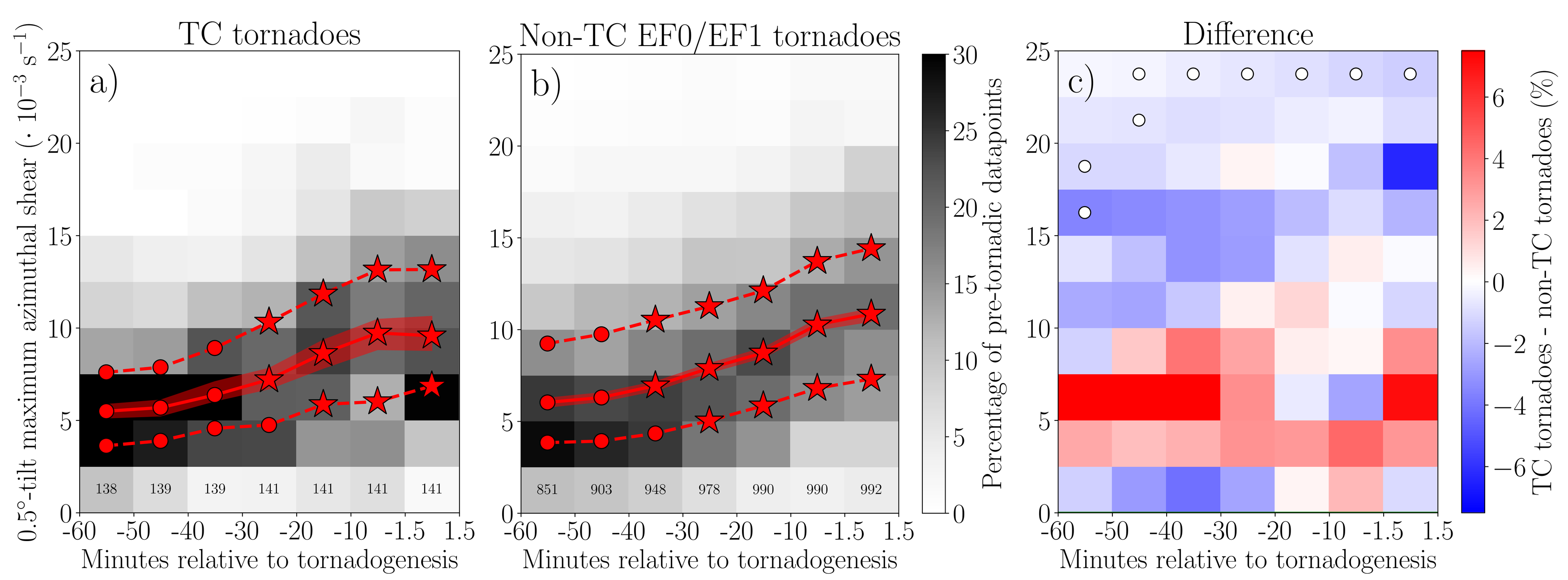

Fig. 4: Heat map of minutes relative to tornadogenesis versus 0.5°-tilt maximum azimuthal shear (·10^{-3} s^{-1}) for (a) TC tornadic mesocyclones, (b) non-TC tornadic mesocyclones, and (c) their difference (TC tornadic - non-TC tornadic mesocyclones). Percentages are calculated relative to the total number of points within each time bin with the sample size of each bin written near the bottom of the y-axis. The red solid line, shading, and dashed lines show the median, its 95% confidence interval, and the interquartile range, respectively. Stars in panels (a–b) denote significant differences in the 25th, 50th, or 75th percentiles between the 50–60-minute bin and the time bin of each star. White circles in denote significant differences from 0 for a given grid box in panel (c).

5. Results: How Does TC-Scale Lightning Evolve Before, During, and After Tornadogenesis?

Overview

Analyze whether there are differences in where lightning occurs throughout the TC at before and during the time of tornadic versus non-tornadic mesocyclones.

Synopsis

1. TC tornadic mesocyclones at time of tornadogenesis are located closer to downwind edge (i.e., in direction of advective TC wind) of stronger lightning maximum compared to TC non-tornadic mesocyclones (Fig. 5);
2. Lightning maximum shows more lightning before tornadogenesis and distinct propagation away from TC in tornadic subset (Fig. 6).

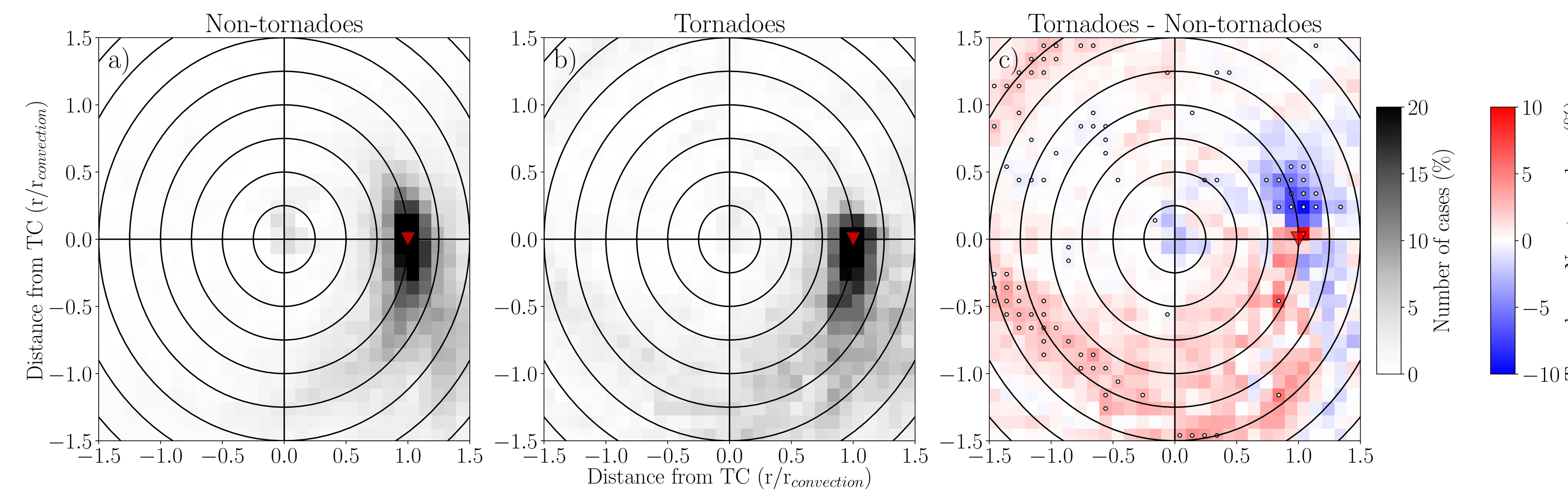

Fig. 5: Percentage of cases with ≥1 flashes on a $0.1r/r_{convection} \times 0.1r/r_{convection}$ grid normalized by the TC-relative radius of (a) non-tornadic mesocyclones, (b) tornadogenesis of tornadic mesocyclones, and (c) their difference (tornadic - non-tornadic mesocyclones). The location of each tornadic or non-tornadic mesocyclones and flash have been rotated around the TC such that each is always to the right. White circles show bins with statistically significant differences between the tornadic and non-tornadic subsets in panel (c).

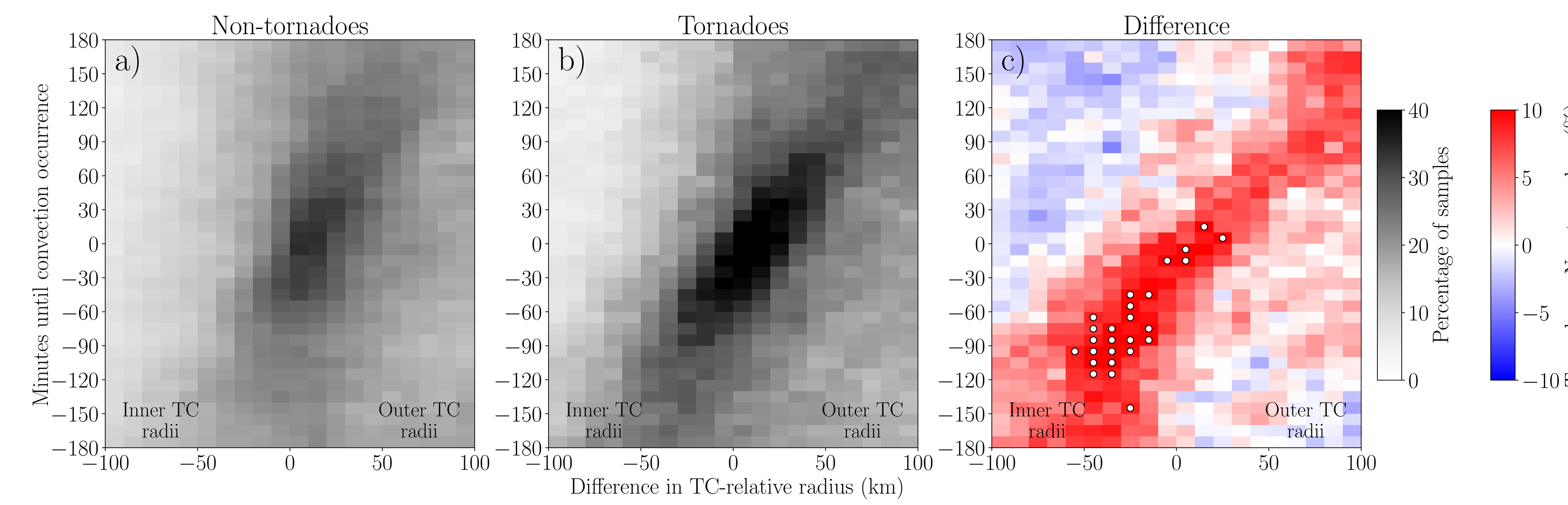

Fig. 6: Percentage of cases with ≥1 flashes in a joint histogram of difference in TC-relative radius (km) versus minutes until (a) non-tornadic mesocyclones, (b) tornadogenesis of TC tornadic mesocyclones, and (c) their difference (tornadic - non-tornadic mesocyclones). All flashes within a 90° TC-relative azimuth of non-tornadic and tornadic mesocyclone subsets are aggregated. White dots show bins with statistically significant percentage differences between the tornadic and non-tornadic mesocyclones in panel (c).

6. Summary and Discussion

- We investigated radar and lightning characteristics of TC tornadic mesocyclones compared to TC non-tornadic and non-TC tornadic mesocyclones;
- Our most important conclusions were:
  1. While most TC tornadoes and non-tornadic mesocyclones are not associated with lightning, large numbers of flashes particularly to the northeast of the mesocyclone tend to occur at the time of tornadogenesis (Panel - Results: 3.);
  2. TC tornadic mesocyclones are characterized by stronger low-level rotation compared to non-tornadic mesocyclones that typically increases in the hour before tornadogenesis (Panel - Results: 4.);
  3. Compared to TC non-tornadic mesocyclones, TC tornadic mesocyclones at the time of tornadogenesis often occur closer to the downwind edge of a stronger TC-scale lightning maxima that more distinctly propagates away from the TC center (Panel - Results: 5.);
- Together, these results suggest that forecasters should consider lightning both local to mesocyclones and throughout the TC as well as trends in radar-derived rotation to improve real-time identification of tornadoes.

7. Acknowledgements

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