A Climatology of Tropical Tornadoes Over Puerto Rico

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1. This study analyzes 15 confirmed tornado cases in Puerto Rico, focusing on recurring atmospheric patterns

- Since the 1950s, **over 25 tornado events** have been documented on the island of Puerto Rico, with most classified as EF0 or EF1.
- The **Doppler radar's elevation** at ~2,959 feet (0.9 km) limits its ability to capture critical data below 1 km, **hindering the detection of tornado signatures** and reducing lead time for warnings.
- This study conducts a **climatological analysis of 15 confirmed tornado cases** to identify recurring **synoptic, mesoscale, and microscale patterns**.
- Findings indicate that most tornadoes are concentrated in the **northwestern part of the island.**
- **The research aims to:**
    - Enhance tornado forecasting capabilities
    - Improve early warning systems
    - Reduce risks for Puerto Rico's vulnerable communities.

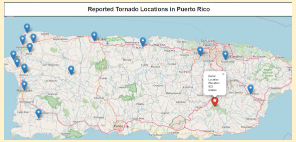

Fig. 1: Map of Puerto Rico showing the locations of the 15 tornado cases analyzed in this study and relative location of radar. A notable concentration of cases is observed in the island's northwestern region.

2. Radar imagery, ERA5 reanalysis data, and ERA5 proximity soundings were utilized to examine atmospheric conditions during the tornado events, providing an analysis of the existing conditions

Radar Analysis:
- NOAA's **Weather and Climate Toolkit** (WCT) was used to analyze radar products.
- **Reflectivity (dBz)** evaluated storm mode and motion.
- **Radial velocity (kt)** identified potential areas of possible rotation and velocity signatures.

Reanalysis Data:
- **ERA5 reanalysis data** from the **NCAR Research Data Archive (RDA)** was used for atmospheric analysis.
- Plots generated included:
    - **2-m temperature and dew points** (in Kelvin) with **low level wind vectors**.
    - **Geopotential heights** and wind vectors at **250 hPa, 500 hPa, 850 hPa, and 1000 hPa.**

Focus Areas:
- **1000 hPa plots centered on Puerto Rico** for local environmental conditions. **Higher-level geopotential height** plots covered **broader synoptic patterns** across the Atlantic Basin.
- **Satellite Imagery**:
    - **NASA Earthdata Worldview** provided satellite imagery at event times to contextualize atmospheric conditions.
- **Atmospheric Parameters**:
    - The **"thundeR - ERA5 sigma levels browser"** explored ERA5 data across sigma levels.
    - **Proximity Skew-Ts** were generated to analyze:
        - Wind shear profiles.
        - Moisture and instability near event times.

3.After analyzing reanalysis and observational data, cases were categorized based on similarities in their respective setups

EVENT TYPE	EVENTS	JUL - SEP	OCT - DEC	JAN - MAR	APR - JUN	EF/F - RATING	MEAN SURFACE - 1 KM SHEAR (KNOTS)	MEAN SURFACE - 6 KM SHEAR (KNOTS)	MEAN MU CAPE (J/kg)	MEAN SURFACE-2 KM RH (%)	PRECIPITABLE WATER (in)	SCP (>2)
I) AIRMASS THUNDERSTORMS	6	5	1	0	0	EF-0 (5) F-1 (1)	9.75	7.37	1944.17	77.30	1.91	0
II) TUTT+WEAK UPPER LEVEL DYNAMICS	5	4	1	0	0	EF-0 (5)	8.88	7.85	1919.40	81.60	1.84	0
III) STRONG UPPER LEVEL DYNAMICS	3	0	1	2	0	EF-0 (3)	5.69	20.1	622.67	76.00	1.77	0
IV) TUTT+STRONG UPPER LEVEL DYNAMICS	1	0	0	0	1	EF-1 (1)	11.00	23.50	1457.00	72.00	1.70	2.20
V) SURFACE LOW PROXIMITY	2	1	0	1	0	EF-0 (1) F-0 (1)	8.55	23.72	934.5	68.00	1.78	0

Table 1: Summary of Event Types and Associated Parameter Means for Tornado Cases.
Note: Overlapping Meteorological Setups: Two Air Mass Thunderstorm cases also displayed the influence of a weak TUTT, contributing to sustained convection. Additionally, one Surface Low Proximity case was influenced by strong upper-level jet dynamics.

4. Tornadoes in Puerto Rico Exhibit Non-Classical Environments

- **Event Characteristics:**
  Most tornadoes were EF0 or EF1, concentrated in the island's northwestern region.
- **Radar Limitations:**
  Doppler radar elevation (~2,959 ft) restricts detection of low-level (<1 km) tornado signatures, reducing warning lead time.
- **Storm Forcing Mechanisms:**
  Convection was driven by orographic lifting, sea breeze convergence, and daytime heating.
- **Upper-Level Forcing:**
  TUTTs and subtropical jets provided upper-level divergence, enhancing convection.
- **Post-Frontal Systems:**
  Frontal boundaries introduced moisture pooling and temperature gradients.
- **Localized Dynamics:**
  Tornado genesis was influenced by sea breeze, fronts, outflow boundaries, and column stretching near terrain transitions.
- **Topographic Influence:**
  Storms consistently intensified downwind of mountain ranges due to terrain-driven dynamics.
- **Overall Mean Shear Environment:**
    - Surface-to-1 km shear: **8.77 knots** (below the midlatitude threshold >15 knots).
    - Surface-to-6 km shear: **16.51 knots** (below the midlatitude threshold >25 knots).
- **Overall Mean Moisture and Instability:**
    - Boundary Layer Relative Humidity: **74.98%**
    - Precipitable Water: **1.8 inches**
    - MU CAPE: **1,375.55 J/kg**
- **Non-Classical Tornado Setup:**
  SCP values were generally 0.0 (except for the Arecibo case), indicating the absence of large-scale supercell dynamics.
- **Future Work**
    - Compare parameter values to climatological values for given date and season.
    - Simulate tornado events using WRF to study atmospheric interactions across scales.
    - Develop a probabilistic forecast algorithm tailored for tropical islands, incorporating multi-scale parameters.
- **Broader Impacts**
    - Collaborate with NWS WFO San Juan
    - Leverage high-resolution modeling resources to advance understanding of tropical island tornado genesis.
    - Enhance tornado forecasting and early warning systems for Puerto Rico's vulnerable communities.
    - Reform forecasting frameworks for tropical environments.

5. References:

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I) Air Mass Thunderstorm: Sample Case Bayamón 9/30/2019

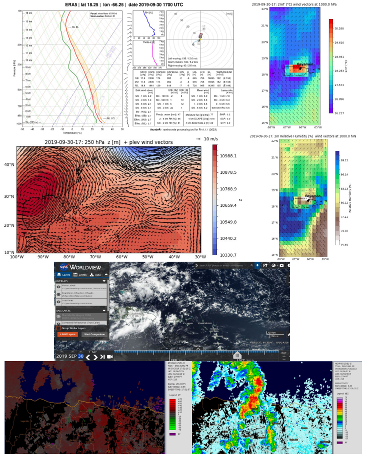

Fig. 2: Bayamón Tornado Case The ERA5 proximity Skew-T diagram (top-left) shows a high-CAPE, low-shear environment. Surface temperature (°C) (top-right) highlights warmer conditions near the tornado's location with south-south easterly flow. The 2-meter relative humidity (below temperature) reveals slightly drierconditions compared to the surrounding environment. At 250 hPa, geopotential heights and wind vectors (bottom-right) emphasize local forcing mechanisms with minimal synoptic influence. Worldview satellite imagery and Weather and Climate Toolkit radar products show the storm cell responsible for the tornado, with weak rotation on radial velocity (kt) and reflectivity (dBZ).

II) TUTT + Weak Upper Level Dynamics: Sample Case Aguada 7/16/2023

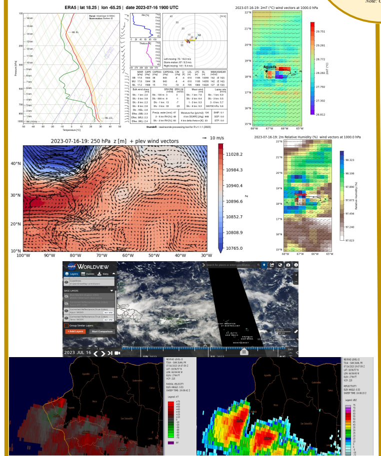

Fig. 3: Aguada Tornado Case The ERA5 proximity Skew-T diagram (top-left) highlights moderate CAPE and weak shear. Surface temperature (°C) (top-right) shows warmer conditions in western Puerto Rico with northeasterly winds, while 2-meter relative humidity depicts moist conditions near the tornado. The 250 hPa geopotential heights and wind vectors reveal a weak TUTT west of Puerto Rico. Worldview satellite imagery complements the reanalysis data. Radar products show a weak velocity couplet (kt) and non-supercell storm mode (dBZ).

III) Strong Upper Level Dynamics: Sample Case Las Piedra 3/16/2023

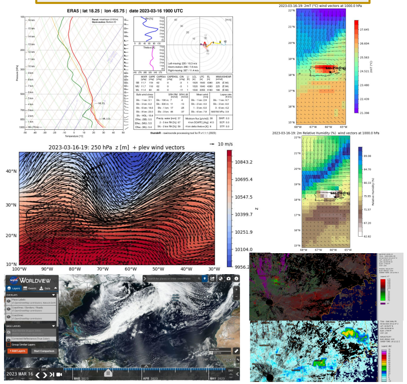

Fig. 4: Las Piedras Tornado Case: The Skew-T diagram (top-left) indicates low CAPE and dry conditions in the lowest 2 km. Surface temperature (°C) (top-right) highlights warmer northern Puerto Rico with westerly flow and a temperature gradient due to an approaching cold front. The 2-meter relative humidity confirms relatively dry conditions in the tornado's vicinity. At 250 hPa, a deep trough and strong subtropical jet north of Puerto Rico are visible. Satellite imagery shows the approaching front. Radar products reveal a weak velocity couplet (kt) and a weak storm cell (dBZ).

IV) TUTT + Strong Upper Level Dynamics: Sample Case Arecibo 5/01/2022

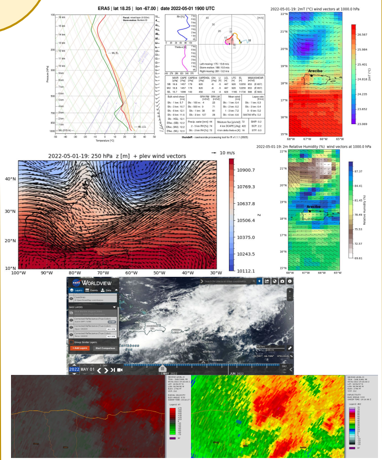

Fig. 5: Arecibo Tornado Case: The Skew-T diagram (top-left) shows moderate CAPE, veering winds, and moist low levels. Surface temperature (°C) (top-right) highlights warm northwestern Puerto Rico with easterly flow and cooler conditions from an approaching frontal system. The 2-meter relative humidity indicates pooling moisture near the tornado. The 250 hPa plot shows a TUTT west of Puerto Rico and a subtropical jet. Satellite imagery reveals post-frontal system approaching from the west. Radar products depict broad rotation (kt) and a supercell-like structure (dBZ).

V) Surface Low Proximity: Sample Case Trujillo Alto 3/26/2017

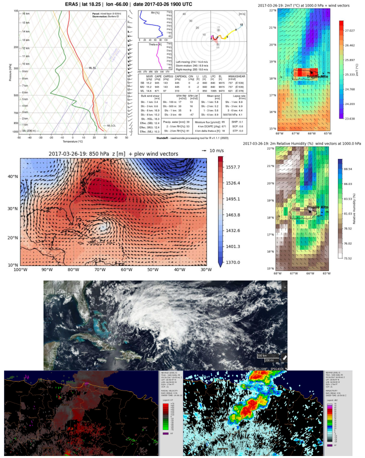

Fig. 6: Trujillo Alto Tornado Case: The Skew-T diagram (top-left) shows low CAPE, speed shear, and moist low levels. Surface temperature (°C) (top-right) highlights significantly warmer northern Puerto Rico with southerly flow. The 2-meter relative humidity suggests slightly drier conditions near the tornado compared to the surrounding environment. The 250 hPa plot shows an anomalous surface low northwest of Puerto Rico with a dipping subtropical jet. Satellite imagery confirms the surface low. Radar products indicate tight rotation (kt) and a non-supercellular structure (dBZ).