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Strong tornado and waterspout climatology of Greece

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Abstract
Tornadoes and waterspouts are extreme weather events, associated with deep convection and severe thunderstorm activity. Strong tornadoes are defined those of an F2/EF2 of the Fujita/Enhanced Fujita tornado intensity scale or T4 of the TORRO scale or greater. Strong waterspouts are considered in this study are those occasionally moving to land becoming damaging tornadoes equivalent of an EF1 or T2 intensity or greater. A total of 45 strong tornado and waterspout events have been reported in the last 20 years in Greece, a period of systematic tornado recording and developing of the first Greek tornado database (2000-19). An analysis of climatological features of strong tornado and waterspouts is presented in term of spatiotemporal patterns of their occurrence. Meteorological conditions associated to strong tornado environment are also studied by examining of synoptic circulation types, wind, thermodynamic parameters and indices.

1. Introduction
Tornado research in Greece has been developed during the last decades including a systematic effort for data collection and the development of the first comprehensive Greek database (GTD). This ongoing initiative is following the European tornado research initiaves including the European Conferences on Severe Storms (ECSS) forum, the Tornado and Storm Research Organization (TORRO) (Doe, 2016), the European Severe Weather Database (ESWD) established by the European Severe Storms Laboratory (ESSL) (Groenemeijer and Kühne, 2014) and the International Centre for Waterspout Research (ICWR) (Sioutas et al., 2009).

Based on GTD, ESWD and ICWR databases an increased tornado research literature has been developed including tornado meteorological conditions studies, spatiotemporal distributions of occurrence, tornado and waterspout climatologies, waterspout forecasting and considerable case studies (Sioutas 2003; Sioutas et al., 2009; Sioutas, 2011; Sioutas et al., 2013; Matsangouras et al., 2013; Sioutas et al., 2018). This research offered useful information to a variety of end users, including weather forecasters, state authorities and services, manufacturers, insurances and the public.

2. Scope and objectives of the study
Strong tornadoes are defined those of an F2/EF2 of the Fujita/Enhanced Fujita tornado intensity scale or T4 of the TORRO scale or greater. Strong waterspouts in this study are considered those associated with severe thunderstorms occasionally moving to land becoming damaging tornadoes equivalent of an EF1 or T2 intensity level or greater.

The primary objectives of this study are:

- Analysis of climatological features of strong tornadoes and waterspouts of Greece, in term of spatiotemporal patterns of frequency of occurrence.
- Probability cluster analysis using the Optimized Hot Spot Analysis tool in ArcGIS and the local spatial autocorrelation statistic Gi*.
- Examine the meteorological conditions associated to strong tornado and waterspout occurrences based on synoptic flow patterns, wind parameters and thermodynamic environment parameters.

3. A strong tornado and waterspout climatology for Greece

3.1. The Greek tornado database (GTD)

Summarizing the 20-year data of the Greek tornado database (GTD) (2000-2019):

- A total of about **1700 tornado events** reported **in 1150 days** during the 20-year period 2000–19 (October).
- **Tornadoes** in **302 days** with **317 events**. *Maximum tornado activity was reported the year 2016 with 26 events*.
- **Waterspouts** in **690 days** with **1160 events**. *Maximum waterspout activity in the year 2014 with 144 events.*
- **Funnel clouds** in **167 days** with **235 events**. *Maximum funnel activity was reported the year 2014 with 55 events.*

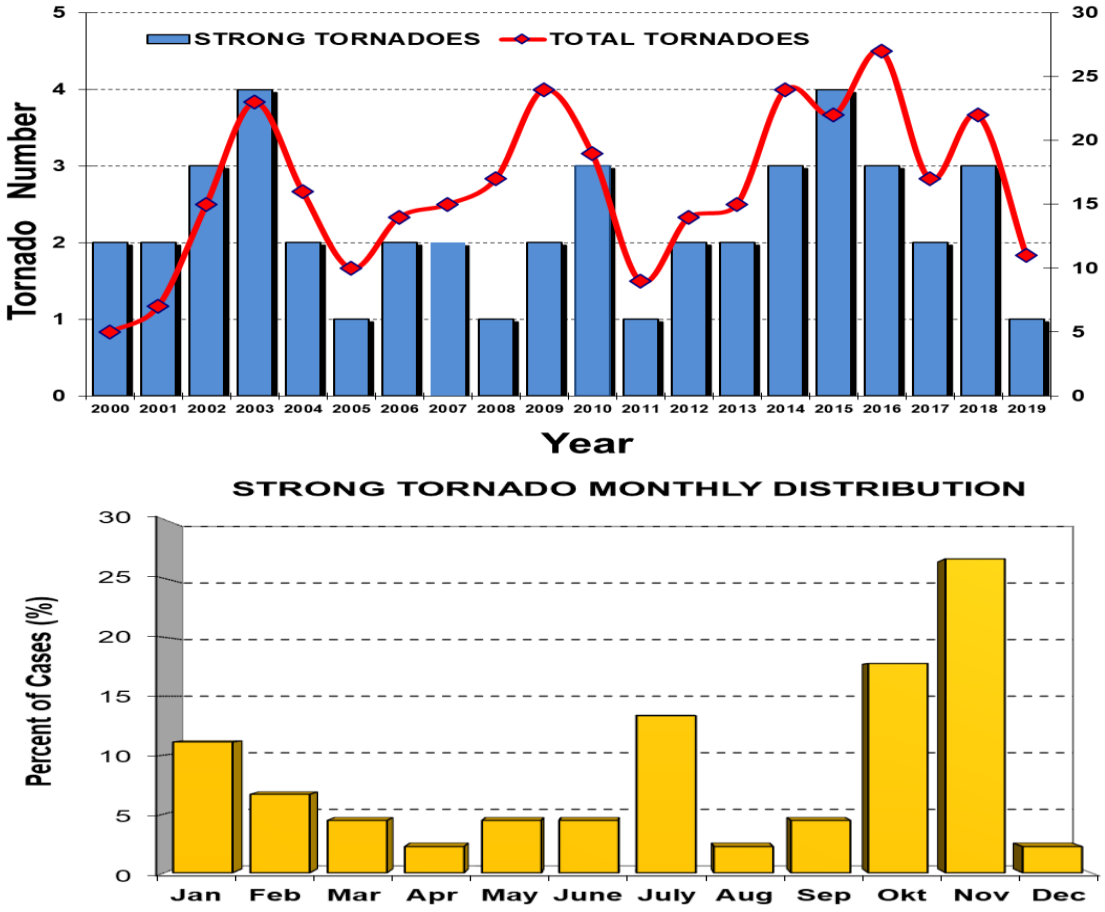

Fig. 1. Annual (upper) and monthly (below) distributions of strong tornadoes in Greece.

3.2. Spatial distribution of strong tornadoes and cluster analysis

A total number of 45 strong tornado and waterspout occurrences have identified in the 20-year Greek tornado data base (2000-2019 October). They are distributed in various areas, with most frequent those of western Greece. Coastal and low elevation areas are generally prone to tornado and also to strong tornado development. Considering annual cycle, northern Greece appears maximum during summer and southern Greece during winter and vice versa. Western Greece exhibits a longer seasonality lasting from Autumn through Winter up to Spring. Considering spatial frequency of strong tornado and waterspout days, the maximum is located in Ilia prefecture, northwest Peloponnese,

followed by Kerkyra island in the northern Ionian Sea and then Rhodes in the south-eastern Aegean Sea.

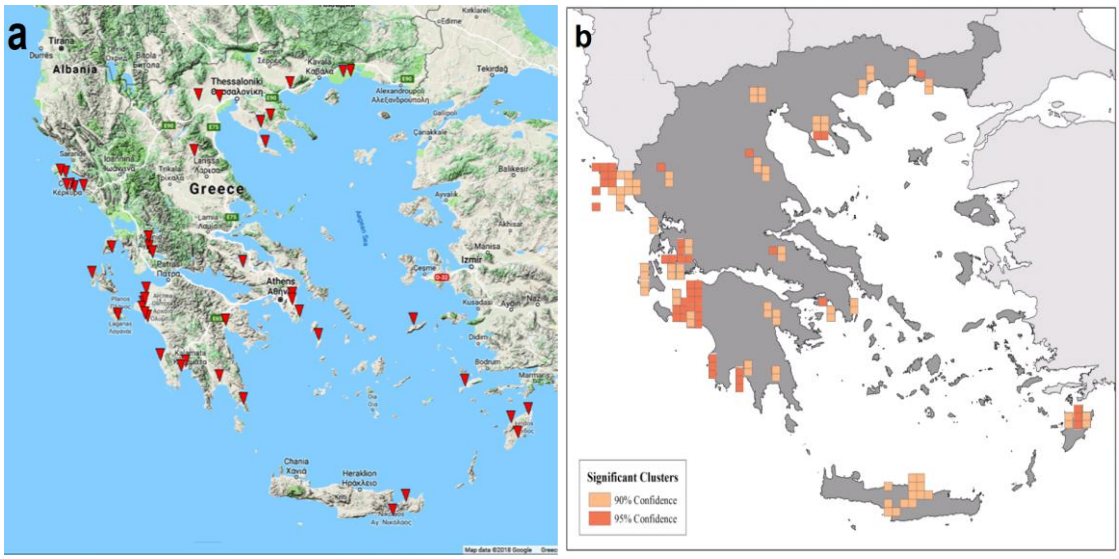

Fig. 2. a) Strong tornado locations and b) Hot spot cluster analysis of tornadoes in Greece.

In Figure 2b, a cluster analysis is displayed performed using the Optimized Hot Spot Analysis tool in ArcGIS. This helps identify clusters of events in a point dataset using the local spatial autocorrelation statistic Gi*. It shows, with two levels of confidence, locations most likely to experience a tornado event.

4. Synoptic and thermodynamic strong tornado environment

A four synoptic typing scheme prevailed on strong tornado days with their distribution displayed in Fig. 3. Southwest flow (SW) is the dominant type with a percentage of 35.3% of the strong tornado days, followed by short wave trough (SWT) with 29.4%, closed low (CLOSED) with 23.5% and long wave trough (LWT) with 11.2%.

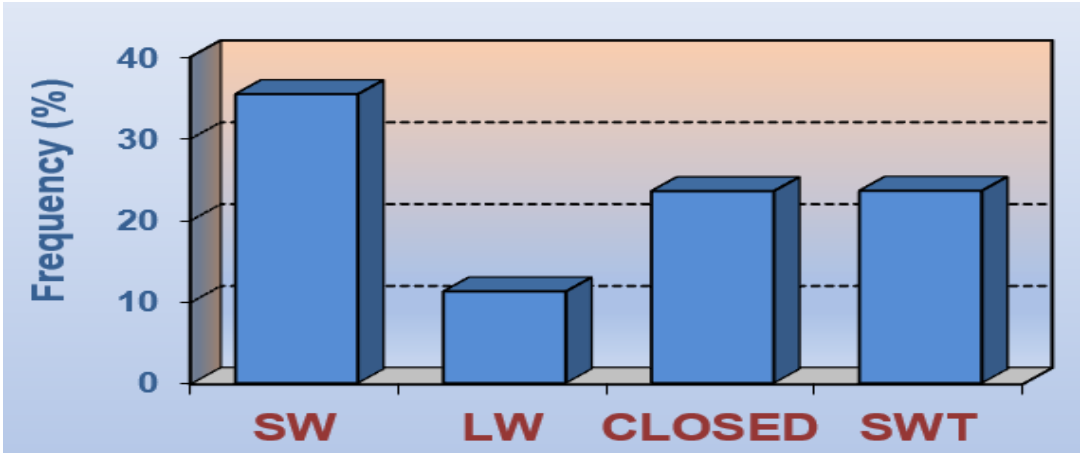

Fig. 3. Synoptic circulation types on strong tornado days in Greece (2000-19).

The thermodynamic environment on strong tornado and waterspout days was also studied based on a large number of parameters and instability indices.

- Storm Relative helicity (SRH) vs Convective Available Potential Energy (CAPE) represent contribution of both low level shear and buoyancy (Fig 4a).

- Energy-Helicity Index (EHI), represents a dimensionless parameter combining CAPE with 0-3 km SRH (Fig 4b).

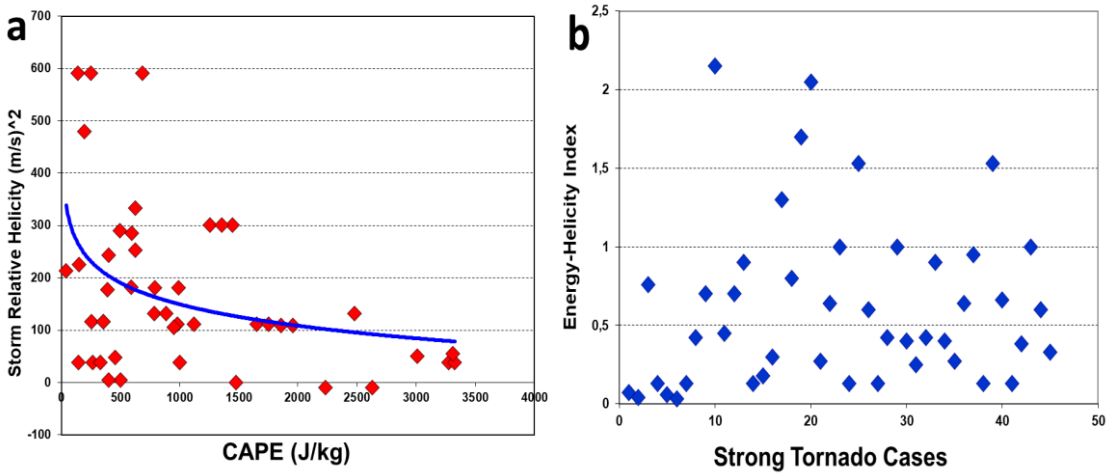

Fig. 4. a) 0-3 km Storm Relative Helicity (SRH) vs Convective Available Potential Energy (CAPE) and b) and Energy-Helicity Index, for strong tornadoes in Greece (2000-19).

5. Results and future

- Tornado occurrence in Greece based on the 20-year period 2000-19 database, stands at: 19% tornadoes, 67% waterspouts and 14% funnel clouds.
- Strong tornadoes in Greece are rather rare, with a yearly frequency of about to 2-3 cases, with western parts of Greece appeared hit most frequently.
- Climatological studies indicated western Greece and coastal areas as most strong tornado and waterspout prone areas in term of spatiotemporal patterns, frequencies and distributions.
- Further analysis will include topography and other geographical features, mapping and statistical analysis of the data, regional climate and climate change influences.

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