An updated “climatology” of tornadoes and waterspouts in Italy

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Abstract

Ten years of tornadoes (TR) and waterspouts (WS) in Italy are analyzed in terms of geographical, seasonal, monthly, diurnal, and rating distribution. Starting from the European Severe Weather Database, a comprehensive dataset is developed for the period 2007-2016, which includes 707 WS and 371 TR.

The category of WS includes many weak events but also some intense vortices, able to produce significant damages as they make landfall. WS develop mainly near the Italian coasts exposed to westerly flows (Tyrrhenian and Apulia region Ionian coast); 25% of them makes landfall and becomes TR. The majority of WS develops in autumn (43%), followed by summer (33%). The average density is 0.9 events per 100 km of coastline per year, although there is a strong sub-regional variation, with peaks of around 5 in some spots along the Tyrrhenian coast.

TR originate from WS in about half of cases; the average density of TR is 1.23 events per 10^4 km^2 per year, which is comparable with other Mediterranean regions. The occurrence of TR is more frequent in summer, followed by autumn; however, limiting the analysis to TR originated inland, the number of events is maximum in summer and late spring. The latter result suggests a distinction of "continental" cases, mainly affecting northern Italy in late spring and summer, and "maritime" cases, which affect mainly the peninsular regions in late summer and autumn. The highest density of TR was reported along the coasts of Lazio and Tuscany, in the Venetian plain, in the southern part of Apulia: in these regions, the density of events is comparable with that of the USA states with the highest TR rates. In contrast, the probability of significant TR in any Italian region is much smaller than that of the USA states with the highest risk.

1. Introduction

The occurrence of tornadoes (TR) and waterspouts (WS) in Italy has received little attention so far by both general public and scientists. As TR cover a limited geographical extension and their lifetime is limited to a few minutes, they are generally not recorded by synoptic- and regional-scale station networks, but they are identified mainly using newspaper articles and chronicles. Recently, reports, photographs and videos posted on the internet have made it apparent that the occurrence of these events has been largely underestimated in the past.

Although rare, severe TR occasionally affected Italy, sometimes causing severe damage and even casualties or injuries. The only climatological study of TR in Italy, relative to the decade 1991-2000 (Giaiotti et al., 2007; G07 hereafter), shows that on average about 3 significant events, i.e. Enhanced Fujita 2 or higher rating classes (EF2+), occur in Italy every year (note that the EF scale is designed to be used in the USA and not for European buildings). Some recent review papers about TR activity and impact in Europe have shown that Italy is among the European countries most vulnerable to this hazard, since it was affected by some of the Europe's deadliest recorded TR (Groenemeijer and Kühne, 2014; GK14 hereafter): on 21 September 1897 in Sava and Oria [Apulia region]; on 23 July 1910 in Brianza [Lombardy]; on 11 September 1970 in Teolo, Fusina, Venice (Fujita scale 4 rating class; F4) [Veneto]; on 7 October 1884 in Catania [Sicily]; on 24 July 1930 in Volpago del Montello (F5) [Veneto]. 500 victims were reported for a tornado in Castellamare, near Marsala [Sicily], in 1851, but the nature of the event is uncertain; similarly, some doubts remain about the origin of the event for the case in Brianza in 1910, considering the wide extension of the region affected by damages. Also, Italy ranks first in terms of property loss (258.3 M€), and second for fatalities (753) and injuries (69) associated with TR in Europe in the years 1950-2015 (Antonescu et al., 2017).

In the last years, some intense events have renewed the scientific interest in the topic. A multi-vortex EF3 tornado hit Taranto, in southeastern Italy, on November 28, 2012 (Miglietta and Rotunno, 2016); on July 8, 2015, an EF4 tornado struck the surroundings of Venice (between Mira and Dolo), and caused one death, 72 injuries, and 20 M€ of property loss, completely destroying a villa dating back to the 17^{th} century (ARPAV, 2015). On November 6, 2016, an EF3 tornado, whose path length was estimated at 40 km, was responsible for 30 injuries and 2 casualties near Rome.

The severity of these events suggests the need of an operational warning system dedicated to severe convection and TR. Unfortunately, as in most European countries (GK14; Rauhala and Schultz, 2009), also in Italy warning messages for TR are not issued by either national or regional meteorological services. This situation appears inadequate considering their potential threat and social impact, possibly enhanced in a changing climate. In order to get a better understanding of the relevant mechanisms of development, updated statistics relative to their intensity and distribution appear as preliminary but necessary steps, also considering the strong underreporting in the Mediterranean region (GK14).

In the present study, we face with the latter task, with the aim of updating the 10-year old climatology in G07. The occurrence of TR and WS is here differentiated by region, month, intensity, and time of the day in the period 2007-2016. One may argue that this is a limited period of time; however, one should consider that the number of events and the data reliability decrease going back in time. Indeed, the number of reports has dramatically increased in the last few years, due to the possibility offered by the internet and social networks to share videos and pictures (see Simmons and Sutter, 2011, for USA and Matsangouras et al., 2014, for Greece). This explains the smaller number of reports in 2007-2008, while one can see relatively small inter-year variations in the following years.

The paper is organized as follows. A short review of previous studies of TR in Italy is provided in Section 2. Section 3 reports on the sources of information used in the present study. Section 4 discusses the results. Conclusions and Discussion, including a comparison with the climatology in G07 and with the climatology of other Mediterranean countries, are drawn in Section 5.

2. Previous studies

The documentation of TR affecting the Italian territory starts from ancient Rome, since Giulio Ossequente documented in the *Prodigiorum Liber* the transit of a "turbinis" across Rome in 152 BC, 60 BC and 44 BC. Some of the earliest detailed accounts of TR in Europe refer to Italian vortices: the work of Niccolo Machiavelli (1532) on a tornado in Tuscany on 24 August 1456, that of Geminiano Montanari (1694) on a tornado in Veneto region on 29 July 1686, and that of Boscovich (1749) about a tornado that occurred in Rome on 11 June 1749 (also described in Desio, 1925).

A list of Italian TR mentioned in the literature before 1920 is reported in Peterson (1988). While only 23 TR in the 19th century are documented in scientific papers (Antonescu et al., 2016), in the 20th century some works occasionally described TR and WS affecting Italy (mostly between the two World Wars) - see Baldacci (1966) and Peterson (1998) for a brief summary -: Crestani published some reports mainly based on news agencies (1924a, 1924b, 1925, 1926, 1927, 1929, 1936); some WS were recorded in Garda Lake

(Bernacca, 1956), in northern Lazio (Frugoni, 1925; Baldacci, 1958, 1966), in the strait of Messina, Liguria, near Livorno (Various Authors, 1938), and near Venice (Zanon, 1920; Speranza, 1939); some TR were recorded in Friuli (De Gasperi, 1915). A very detailed description of the tornado affecting the surroundings of Treviso on 24 July 1930 (the only tornado in Italy classified in the highest rating class of the Fujita scale -F5-) was provided in Puppo and Longo (1930). Baldacci (1966) made an interesting photographic documentation on some WS in the Tyrrhenian Sea near Ladispoli and recorded additional WS. The devastating tornado that hit Venice on 11 September 1970, causing 36 casualties, was described in Janeselli (1972), Bossolasco et al. (1972), and Borghi and Minafra (1972). Four TR that struck the coasts of Sicily on 31 October 1964 were described in Affronti (1966). A tornado that caused damages, injuries and one death in Budrio, near Bologna, was described in Visconti (1975). In the last quarter of the 20th century, additional TR were reported in Peterson (1998).

Palmieri and Puccini (1978) provided the first climatology of TR in Italy. They considered 280 vortices between 1946 and 1973, and found that the highest probability of occurrence was along the Tyrrhenian coast (in Lazio region) and was close to the maximum observed in USA (Oklahoma); in contrast, the strongest TR occurred in northern Italy, but their intensity was weaker than that of the strongest USA TR. In the peninsular regions, the peak activity was found mainly in autumn, while in the north the peak occurred in July-August.

After about two decades without any scientific paper on Italian TR, apart from Peterson (1998), a series of works was published about TR in Friuli-Venezia Giulia region, mainly analyzed using Doppler radar data, measures from a mesonetwork, and lightning strokes (Bechini et al., 2001; Bertato et al., 2003; Giaiotti and Stel 2007). These studies suggested that the presence of a thermal boundary at the ground and its interaction with the complex orography of the region could have played an important role in the tornadogenesis of these vortices. Some of the authors of these papers published an updated climatology of Italian TR (G07), including 241 cases between 1991 and 2000. The environment where the TR developed was investigated, showing the vertical wind shear is highest in the lowest 1 km, and potential instability is generally lower than for USA TR.

Recently, some studies focused on southern Apulia. Based on historical chronicles and newspaper archives, Gianfreda et al. (2005) recorded 30 TR between 1546 and 2000 (26 in the last two centuries), responsible for 118 casualties. In the same area, an EF3 tornado struck the surroundings of the city of Taranto and was responsible for one casualty and an estimated property loss of 60 M€ to the largest steel plant in Europe (Miglietta and Rotunno, 2016). A damage survey (Venerito et al., 2013) allowed to reconstruct its path and to estimate the intensity, which were successfully reproduced in numerical simulations (Miglietta et al., 2017a). The simulations showed that, together with the mesoscale environment, the convection triggered by the Sila mountain (Calabria region) was favorable to the development of the tornadic supercell. The positive sea surface temperature anomaly was also found to strongly affect the intensity of the supercell (Miglietta et al., 2017b).

To complete the list of recent publications, we mention a study on numerical simulations of a waterspout near the island of Capraia in September 2003 (Tripoli et al., 2005), and the damage assessment survey of the EF4 tornado near Venice in 2015 (Zanini et al., 2017). The latter study represents probably the first attempt dealing with building types common in Italy.

3. Dataset

The European Severe Weather Database (ESWD; Dotzek et al., 2009), the most comprehensive database of severe weather events over Europe, maintained by the European Severe Storm Laboratory (ESSL), has been the starting point for our analysis. Considering the lack of ESWD data in southern European countries (GK14), we looked for additional data sources in order to include other cases and to provide an additional level of check to the existing reports.

In this effort, we found that many amateur forum and websites contain very detailed information on many events (see Acknowledgements for an incomplete list of amateurs, who provided an invaluable contribution to the present research). Also, several web portals/platforms, used by many web surfers to share and upload pictures and videos (e.g. youtube.com, youreporter.it), gather information on a lot of weak WS and on some TR, which otherwise were not reported.

On the other hand, some confusion arises from traditional newspapers and web magazines, which generally use the term "tromba d'aria" (landspout) to identify also deep convective events of different nature (e.g., downbursts). Thus, the information coming from all the sources was very carefully evaluated: we included in our dataset only the cases clearly documented with photos or videos, whose damage extent and type were compatible with a tornado, or whose description explicitly mentioned the presence of a vortex.

Sometimes, convective features with different characteristics may occur at the same time, hence one should disentangle the respective damage. For example: three TR were documented in Sicily on October 10, 2015, some WS were identified in front of Genoa on October 14, 2016, but in both cases the relevant damages (corresponding to EF2 intensity in the latter event) were associated with intense downbursts. Similarly, on August, 25, 2012, in Verbania, along Lake Maggiore, the damages could not be associated exclusively with a tornado or with a downburst (http://www.meteolivevco.it/tornado-del-25-agosto-2012-verbania/).

Following this analysis, we decide to:

- Remove from our list some events from ESWD, which - we believe – show characteristics (type of damage and/or area affected) more similar to downbursts than to TR, or which were incorrectly classified (e.g., a dust devil was included incorrectly in the list of TR);
- Change or complete the properties of some TR already present in ESWD: based on the documented damages, the rating of some TR was re-evaluated (in the cases of evaluation intermediate between two EF rating classifications, the higher was chosen);
- Include additional 109 TR and 273 WS cases.

Anyway, for the most intense TR, the information in ESWD was found to be complete. The new cases we identified were reported to ESSL for inclusion in ESWD. In conclusion, a total of 371 TR and 707 WS were identified in the period 1 January 2007-31 December 2016, 179 of which belong to both categories (waterspouts making landfall).

4. Results

The results of our analysis are discussed separately for TR and WS. As discussed above, the WS that reach the shore are considered also in the category of TR, although their intensity may be very weak. Following Matsangouras et al. (2017), the occurrence of several WS in a limited region and in a limited period of time (i.e., a few hours) is counted as one event. In contrast, the few cases where inland TR occur in time and space proximity are considered separately, in order to record the different areas affected with damage.

4.1 Waterspouts

4.1.1 Temporal distribution

To our knowledge, the present paper is the first study dealing with the climatology of WS in the seas surrounding Italy. In our 10 years long dataset, a total of 707 events was identified (some of which associated with multiple vortices). Thus, the mean is about 71 events per year, while the median is 64.

Figure 1 shows that the number of yearly occurrences changes considerably during the series (from 31 events in 2007 to 141 in 2014), although the number of cases in 7 years over 10 fits in the range [50-80]. While, as discussed in the Introduction, the lower frequency in the first years of the dataset is probably due to a shortage of reports, the high number in 2014 may be attributed to the peculiar meteorological conditions observed in summer 2014, which favored the intrusion of cooler air in the Mediterranean (see Miglietta et al., 2017c).

Table 1 shows the Pearson correlation coefficient R between the monthly occurrences of WS and, respectively, the monthly values of the North Atlantic Oscillation (NAO) index, the monthly precipitation relative anomaly (fractional bias) and mean temperature anomaly (bias) averaged over all Italian synoptic stations (Brunetti et al., 2006) from June to November (i.e., the period with the highest WS activity; see later). *R* is calculated for each month, between 9 years of data (from 2008 to 2016; 2007 is excluded since the number of WS events is very small in many months). Precipitation above average in July and August, cooler temperatures in July, positive values of NAO index in September are associated with intense WS activity, and the relationships are statistically significant with 95% confidence interval. Considering the whole 6-month period (*R* is calculated between two sets of 54 months of data, 6 months from each of 9 years), the number of events is positively correlated with NAO (R = 0.43) and precipitation (R = 0.39), anticorrelated with temperature (R = -0.31), i.e. in the presence of colder air intrusion into the central Mediterranean basin (all relationships statistically significant). Also, the correlation of WS occurrences with the seasonal precipitation relative anomaly (fractional bias) over the Italian seas is calculated in summer and autumn, showing that correlation is high in summer (R = 0.68) and considering both seasons (R = 0.61), while it is still positive, although not statistically significant, in autumn (R = 0.36).

On average, 24.7% of WS (179 vortices) made landfall. Considering the EF rating of the waterspouts making landfall (WS-to-TR), only 2 cases are classified as EF3 (1.1%), 7 as EF2 (3.9%), 57 as EF1 (31.7%), while most of them are weak WS that disappear a few hundred meters after they make landfall.

About the seasonal distribution, Figure 2 shows that the peak activity of WS occurs in autumn (325 cases, 45.9%) followed by summer (232 cases, 32.8%). The peak in autumn is due to the warm SST combined with cold air intrusions at upper levels, which are frequent in this season. WS occur more rarely in winter (11.4%) and spring (9.6%). The occurrence of WS-to-TR with respect to the total number of WS range from lower frequencies in winter (18.5%) and spring (20.6%) to about 27% in autumn and summer, possibly also due to the different density of inhabitants near the coasts in the two semesters.

About the intensity (not shown), autumn is the most dangerous season with 78% of the total EF2+ events, since the 2 EF3 TR occurred in November, and 5 of the 7 EF2 cases in November (3) and in October (2) (the other 2 EF2 cases occurred in February and in April). More than 50% of the EF1 WS-to-TR occurred in autumn (54.4%), 29.8% in summer, nearly 9% in spring and 7% in winter. Thus, in autumn, WS occur more frequently but the percentage for the most intense events is even higher.

About the monthly distribution (Fig. 3), more than 70% of WS occurs from July to November: the frequency peak is in September (19.2% of the total), followed by August (15.2%), October (14.0%), November (12.7%), and July (9.9%). We should consider anyway that the population density near the coasts increases considerably during summer vacation, thus we possibly expect that the WS are better reported in summer compared to the other seasons.

Regarding the diurnal distribution of WS (Fig. 4a), temporal information is available for 560 cases. We decided to include all cases in order to have a larger data sample, for both WS and TR, independently of their time accuracy (we checked that results do not change appreciably when only the cases with a time accuracy of +/- 2 h were included). In Fig. 4, an event is attributed to the hour t if it occurred within the time interval (t - 30 min, t + 30 min); we checked the results do not change appreciably attributing to t the events in the time interval (t, t + 1 hour). Two third of WS occurred from 09 to 16 UTC. The main peak occurs at 11 and 12 UTC, i.e. around midday local solar time LST (LST=UTC+1) and immediately afterward. Secondary peaks were recorded at 09 UTC and at 15 UTC, while the number of occurrences is minimum at night (possibly due to under-reporting during these hours). This diurnal trend has analogies with the distribution of WS over Japan (Niino et al., 1997) and Florida Keys (Golden, 1973), where distinct peaks were identified in the early morning, near noon, and in the late afternoon. This complex distribution is indicative of the presence of boundaries over coastal waters (which represent the vertical vorticity source necessary for WS development) at different hours, e.g., around or before dawn in the case of land breeze, or around noon and in the late afternoon, as for outflow boundaries from previous convection.

In order to identify the period when WS are stronger, we consider the diurnal distribution of WS sectioned for EF rating classification (Fig. 4b). The distribution is similar to that of Fig. 4a, although the main peak occurs at 09 UTC, and only a secondary peak is recorded at 12 UTC. The strongest events were reported in the morning and, in a minor way, in the afternoon; it is relevant that some EF1/EF2 events were reported at night or in the first hours of the morning, in a period characterized by a minimum of TR reports, which is probably due to the difficulty to identify events in the darkness.

4.1.2 Geographic distribution

The density of WS (Fig. 5) was calculated based on the point density method using ArcGIS 10 software. It calculates the magnitude per unit area from point features (WS reports in our case) that fall within a square neighborhood of 40 km side for each event. This value was selected in order to take into account factors such as the maximum eye view spotting and any geographical biases from the ESWD reports. A few hot spots (up to 22 events) are identified in the coastline from central Liguria to northern Tuscany, and along the northern coasts of Lazio (Baldacci (1958,1966) noted the high frequency of WS in the area), of Campania, and of Calabria. A high number of occurrences was also reported between Sicily and Calabria, near the coast of Molise, in some areas of northern Adriatic (central Veneto and northern Marche) and of southern Apulia. There is only a partial correspondence with the density of population along the coasts (cf. http://aiig.it/wpcontent/uploads/2015/05/documenti/carte_tematiche/italia_densita.pdf).

To explain the distribution of WS, one should consider that most WS move from SW to NE (see the following subsection). Thus, after they develop over the sea, they generally move onshore toward the Tyrrhenian coast, which is exposed to the prevailing westerly currents without any shelter, and move offshore farther from the Adriatic coast.

Figure 6a shows the distribution of WS for each political region. The largest number of events occurred in Sicily (102 cases, 14.4% of the total) and in the regions along the Tyrrhenian and Ligurian Sea, Lazio (98 events) and Liguria (93 cases) over all. A limited number of events affected the eastern regions, apart from Apulia (57 cases), where anyway most of the events occurred along the western (Ionian) coast (see Fig. 5). Surprisingly, a very small number of events affected the very long coast of Sardinia (20 cases, 2.8% of the total), as already noted in Baldacci (1966).

The distribution of WS-to-TR (Fig. 6b) is similar to that of WS, although the number of occurrences in Lazio (36 cases, 20.1% of the total) is much higher than in the other regions (36.7% of the observed WS in Lazio made landfall compared to the Italian average of 24.7%). This can be related to the high-population density along the coasts near Rome. In some Italian regions (Apulia, Campania, Tuscany, Calabria, Liguria, Sicily) the number of occurrences is quite similar (from 18 to 22 cases, around 10-12% of the total), while in the north the largest number of events occurred in Veneto. Combined with Fig.

5, the latter result indicates that the occurrence of WS in the northern Adriatic is generally rare, but some sub-regions may be affected by tornadic events frequently. Also, it is relevant that the largest number of significant WS-to-TR (7 EF2 and 2 EF3) affected Apulia (4 cases), followed by Lazio (2 cases) (one event each in Sicily, Campania and Tuscany).

Figure 7 shows the regional distribution of WS normalized by two factors that may affect the total number of occurrences: the coastline length and the population density. One can see that Lazio and Liguria, which are respectively second and third in the total number of events, rank in the top positions also after normalization by coastline length. In case the data are normalized by population density, Calabria gains the first position, followed by Sicily and Tuscany. Thus, one can see that:

- the high occurrence of WS in Sicily is mainly due to the coastline length;
- Molise, which is the region with the second least number of reports, becomes second after normalization by coastline length (a large number of occurrences was also reported in G07);
- the small population density is responsible, at least in part, for the small number of reports in Sardinia.

Passing to consider the seasonal distribution in each region, Figure 8a shows the presence of three distinct modes: in the northern Adriatic, summer events are more frequent (Veneto, Emilia-Romagna) or as frequent as in autumn (Friuli-Venezia Giulia, Marche); in the central and southern Adriatic and in the main islands, there is a clear prevalence of autumn cases; in the Tyrrhenian sea and Liguria, the frequency of autumn and summer events is similar, with a slight prevalence of autumn cases. To complete the analysis, the month of prevailing occurrence of WS for each political region is shown in Fig. 8b. Again, the net separation between northern region and southern regions is apparent.

4.1.3 Other information on waterspouts

Table 2 shows that multiple vortices were reported in 135 cases, and up to 13 vortices were observed at the same time. Autumn is the season with the largest number of events (51.1% of the total), followed by summer (30.4%), winter (10.4%), and spring (8.1%). The regional distribution of multiple occurrences (not shown) follows approximately the same distribution of the whole dataset shown in Fig. 6, apart from a smaller number of reports in Sicily (8^{th} in the ranking, with 6% of events).

In 73 cases, data on the duration of the vortices are also available. More than the lifetime of a single vortex, these data refer to the whole duration of the event, which means, in case of multiple vortices, from the appearance of the first to the disappearance of the last vortex. The median is 7 minutes, the mean is 11 minutes, which is close to the average lifetime of 12 minutes recorded in Niino et al. (1997) for WS in Japan. In 69 cases, data on precipitation are reported. Of these: 40 events reported heavy rain (in 10 cases also with hail), 22 light/moderate rain, 1 only graupel, 1 only large hail, 5 were dry.

For WS-to-TR, the path length is reported only in 16 cases, with values ranging from 500 m to 41 km (which is also the maximum recorded in Japan; Niino et al., 1997). The average is 9 km, the median is 6 km. The direction of movement is reported in 45 cases: the majority is from WSW-to-SSW (26 cases); 3 from WNW-to-NNW, 4 from N, 2 from NE, 1 from E, 3 from SE, 1 from SSE, 3 from S, 2 cases from W. Six people were killed, and the casualties were concentrated in 4 events; in 13 cases, injured people were reported (for a total of 106 injuries); in 6 cases damages were documented, with a total cost of 80 M€.

4.2 Tornadoes

4.2.1 Temporal distribution

The total number of TR reported in the dataset is 371, 179 of which (48%) originated as WS; however, the fraction of WS-to-TR changes significantly from year to year, ranging from 22% in 2009 to 61% in 2015 (Fig. 9). The mean (37) and the median (36) number of TR per year are almost coincident, and 36 events were exactly recorded in 4 years. Considerations about the climatological background for the peak in 2013 and 2014 and for the smaller number of events in 2007 and 2008 were already discussed in Subsection 4.1.1.

The data on the intensity are available for 351 TR; for the other ones, the information was insufficient to rate them. Considering only the EF1+ (EF1 or stronger) TR, Figure 10 shows that the number of yearly occurrences has small variations, apart from the peak in 2013 and 2014: in 7 over 10 years, the number of EF1+ events is between 10 and 13. This trend is similar to that in the USA, where the weakest events have increased rapidly in frequency with time, while stronger tornadoes have not shown any temporal trend (Simmons and Sutter, 2011). About the EF2+ cases, their occurrence is infrequent: only in 3 years the number of events is higher than 2, with a peak of 7 in 2014. The annual average of EF2+ TR is 2.4 (45% of which are WS-to-TR), which is lower compared to G07 (3.1). EF3 events are rare (6 cases in total, 3 of which occurred in 2013), while only one EF4 tornado was recorded (the Mira-Dolo case mentioned in the Introduction). However, the annual average of EF3+ TR (0.7) is greater than in G07 (0.4).

The highest frequency is associated with EF0 TR (54.7%), many of which are weak WS whose lifetime after landfall is limited to a few seconds, followed by EF1 (38.5%), while significant TR (EF2+) cover only a small fraction (4.84% are EF2, 1.71% EF3, 0.28% EF4). Compared with the distribution of European and USA TR (Fig. 10 in GK14), the TR frequency in Italy decreases faster with increasing intensity. Also, our distribution is somewhat different from that shown for Italy in G07's Fig. 5; in particular, the latter did not show the peak frequency for EF0 TR.

The peak in the seasonal distribution (Fig. 11) occurs in summer (38.3%) followed by autumn (34.8%), spring (18.9%), and winter (8.1%). Most of the autumn and winter TR develop as WS (67.4% and 50%, respectively), while the percentage of WS-to-TR is much lower during summer (44.4%) and in spring (20%). As a consequence, the number of TR originated inland in spring (56) is second only to summer (79), although spring is the season with the minimum number of WS (Fig. 2). These considerations indicate the presence of different mechanisms of development within the category of TR.

The seasonal distribution of TR by EF rating is shown in Fig. 12. EF1 TR occur with the same frequency in autumn and summer, which is about twice the frequency in spring and about 5 times the frequency in winter. The largest number of EF2+ events occurs in autumn (41.7% of the total), and most of these are WS-to-TR (7 over 10). Although only 18.9% of TR occurs in spring (Fig. 11), the percentage increases to 25% for the EF2+ cases. On the opposite, the percentage of summer events decreases from 38.3% in the whole dataset (Fig. 11) to 25% for the EF2+ cases (Fig. 12). Lastly, the percentage of winter TR is the same in the set of EF2+ events and in the whole dataset of TR (8.3% vs 8.1%).

The monthly distribution of TR is unimodal (Fig. 13a), with a peak of 53 events in August and September. The change in distribution is steeper toward the winter months, and gentler toward spring. The minimum number of occurrences is in February, with 8 events. Such a distribution appears similar to that observed in Japan (Niino et al., 1997), which has morphological characteristics similar to Italy, but it is pretty different from that reported for Italy in G07, which shows an abrupt change between July and August (probably due to the “incompleteness” of their database).

Comparing the whole dataset with the distribution of WS-to-TR, it is apparent that only a small percentage of TR generate over sea in May (12%), while most TR originate as WS in November (76%) and October (72%). May is the month with the largest number of TR generated inland (29 events), followed closely by summer months (26-27 occurrences in each month); in contrast, the peak for WS-to-TR is in October. Thus, the distribution of TR generated inland is different from that of WS-to-TR.

Figure 13b shows the monthly distribution of TR by EF rating. EF1+ TR occur with similar frequency in each month from May to November; in contrast, EF2+ TR occur mainly in autumn (note that all 5 cases in November are WS-to-TR) and in late spring-early summer. Only one EF2 case occurred from January to March (originated as a waterspout), and only one in August, which is surprising considering that August is the month with the largest number of TR.

Only 326 events that include the hour of occurrence (independently of the time accuracy) are considered for the diurnal distribution of TS in Fig. 14a (as discussed in Section 4.1.1, results do not change by reducing the dataset to reports with a time accuracy of less than +/- 2 h). Compared with the distribution of WS (Fig. 4a) and WS-to-TR (Fig. 4b), the occurrence of TR shifts from the morning to the afternoon, with the main peak at around 14-15 UTC (15-16 LST), similar to the distribution of TR over Europe (GK14). Around 68% of all events occurred between 9 UTC and 16 UTC (as for WS). The distribution shows a secondary peak at 9 UTC, associated with WS-to-TR (Fig. 4b), which is common with the Japanese TR distribution (Niino et al. 1997).

The diurnal distribution of EF1+ TR in Fig. 14a shows that: the main peak is at 14-15 UTC; all EF3+ events occurred between 14 and 16 UTC, apart from one case at 10 UTC; the occurrence of EF2+ TR is mainly concentrated between 10 and 17 UTC, apart from few cases during the night and early morning (mainly WS-to-TR; cf. Fig. 4b). The latter result is quite different from GK14, which shows several significant TR in the late afternoon and in the evening over Europe. Also, comparing Fig. 14b with Fig. 4b, it comes out that almost all the significant TR generated inland occurred in the afternoon, while most of the significant WS-to-TR occurred in the morning.

4.2.2 Geographic distribution

The geographical distribution of TR, expressed as annual density of TR per 10^4 km^2, is shown in Fig. 15a. TR density was calculated with the same technique described for WS (Subsection 4.1.2). To express the results in terms of annual density per 10^4 km^2, a neighborhood of 100 x 100 km was selected. While the average density of TR per year in Italy is 1.23 per 10^4 km^2, the map shows that they are concentrated in few sub-regions where the density is locally higher than or close to 2: the coastal plains of Lazio, the

Tyrrhenian coast of northern Tuscany and Liguria (mainly WS-to-TR, as shown in Fig. 15b); the southern part of Apulia region; the plain in Veneto region and in Piedmont and Lombardy (TR originated inland, as shown in Fig. 15c). The detailed location of each event is represented in Fig. 15d. Most of the significant TR affected areas with high TR rates (e.g. in Veneto, Lazio and Apulia); however, some EF2+ events, originated inland, occurred in areas of relatively small density of TR, for example in the Po Valley between Emilia Romagna and Lombardy.

The distribution of TR for each political region is shown in Fig. 16. Significant differences can be noted in comparison with the distribution of WS (cf. Fig. 6a). The regions most affected by TR are: those along the Tyrrhenian Sea, in particular Lazio and Tuscany, where most events are WS-to-TR (58 of 80 cases); Sicily, where 50% of the events are WS-to-TR; the eastern Po valley, and Veneto region in particular, where most events originated inland; Apulia, which has the largest number of events (51). The latter results appear consistent with the historical database in Gianfreda et al. (2005), which documented the recursive occurrence of TR in the southern part of region; surprisingly, considering its long coastline, two third of TR generated inland. Normalizing by the extension of each region, Table 3 shows that the regional density can change significantly, reaching a maximum of almost 4 events per year per 10^4 km^2 in Liguria; also, it shows how the concentration of events in the month of maximum activity differs among the regions.

The differences of Fig. 16 with Fig. 6a remark the presence of different mechanisms, depending on the location where TR developed, which can be better identified considering the seasonal/monthly distribution of TR in each region. Figure 17a and 17b show that autumn TR are the most frequent in the extreme southern Italian regions, Sicily and Sardinia; summer and late spring TR prevail in northern Italy and in the central Adriatic; a higher frequency of TR in both autumn and summer was reported along the Tyrrhenian coast and in Liguria. Similarly, Table 4 shows that the EF2+ TR in the Po Valley (Veneto, Emilia-Romagna, Piedmont and Lombardy) occur in summer, and occasionally in spring; they are more frequent in autumn in southern Italy and along the Tyrrhenian coasts, where they develop mostly as WS.

Table 5 shows the regional rate of EF2+ TR per year. The highest rates, recorded in Apulia (0.26 10^{-4} km^{-2} yr^{-1}) and Friuli Venezia Giulia (0.25 10^{-4} km^{-2} yr^{-1}), are comparable, respectively, with those of South Dakota (28^{th} in the ranking of USA states; Simmons and Sutton, 2011). Multiplying the regional rate by the average area A affected in a EF2+ case, one can obtain the probability that a single point in a region is affected by a significant tornado in one year. Following Palmieri and Puccini (1979), we set A = 4 km^2 (also, this is about the area affected by the TR of November 2012 in Taranto; Miglietta and Rotunno, 2016) to obtain the probability of EF2+ occurrences. The highest values in Apulia and Friuli Venezia Giulia, about 1 10^{-4} yr^{-1}, are comparable with that of Minnesota (20^{th} in the ranking of USA states; Simmons and Sutton, 2011). Figure 15d suggests that EF2+ TR are generally confined to small sub-regions, thus the probability of occurrence of significant TR is higher in a few specific areas, like the Ionian coast of Apulia, the plain west of Venice, the Po valley between Emilia Romagna and Veneto.

4.2.3 Other information on tornadoes

Differently from WS, the occurrence of multi-vortices was documented inland only rarely. Only in 8 cases, 2-to-4 vortices were reported for TR originated inland, while in

28 cases a waterspout making landfall was recorded together with simultaneous WS. Data on the lifetime were reported in 51 cases, with values ranging from 1.5 to 30 minutes. The average is about 10 minutes, the median is 5 minutes, which means that data on lifetime were reported in several short events. Data on precipitation are available in 59 cases: heavy rain was reported in 36 cases (in 11 also with hail), light/moderate rain in 12, large/moderate hail in 8, no precipitation in 3.

The path length was reported in 43 cases, and ranges from 150 m to 41 km. The average is about 8 km, the median is 6 km. The mean path width was reported in 15 cases, ranging from 10 m to 700 m (the latter refers to the only EF4 event); the average is 150 m, the median is 100 m. Among these cases, in 9 occasions the maximum width is also available, ranging from 20 m to 1 km. The data about the direction of movement is also present in 60 cases, with a prevalence from WSW-to-SSW (38 cases), followed by 10 cases from the northern quadrant; also, in 8 cases TR moved from S-SE, in 3 from W, in 1 from E.

Damages were recorded in 18 cases, for a total loss of more than 100 M€; 270 people were injured in 23 events and 6 people were killed in 4 WS-to-TR. These data are consistent with the statistics for casualties reported in Japan over 33 years (Niino et al., 1997). However, these values should be considered as a lower limit, considering that these pieces of information are available only for a limited number of events. Also, we remind that the total impact of localized severe convective weather is greater than reported here, considering that most casualties and damages in Italy for this category of events is due to flash floods and downbursts.

5. Discussion and conclusions

In the present paper, ten years of TR and WS in Italy are analyzed. Although limited to the most recent period, the only one including a sufficiently rich data coverage, the dataset is long enough to provide for the first time a comprehensive overview of these events in Italy.

WS are more frequent in autumn, with the peak of occurrences in September, while TR originated inland occur more frequently in late spring and in summer. This classification reflects the distinction of "continental" TR, associated with cold air intrusions mainly affecting northern Italy in summer, similar to those observed in the European continent (Dessens and Snow, 1993; Dotzek, 2001), from the "maritime" TR (Sioutas, 2003), which affect mainly the peninsular regions and generally originate as WS. The diurnal peak in WS activity is around midday, while for TR it is postponed to early afternoon.

Comparing our results with those for the decade 1991-2000 in G07, one can see that:

- the number of TR/WS we found is definitely higher, 909 events in 10 years (707 WS, 179 of which making landfall, and 192 TR originated inland) vs. about 240 in G07;
- the geographic distribution appears similar, confirming that TR occur mainly in flat terrains and in coastal areas, i.e. in the Po Valley, in the Tyrrhenian coasts, and in the Ionian coast of Apulia, while WS are concentrated mainly in the western coasts, i.e. along the Tyrrhenian Sea, in Liguria and Sicily, although our dataset identifies the presence of some spots of relatively intense WS activity also in the central/northern Adriatic coast (Fig. 5);
- the number of significant TR (EF2 or stronger) is smaller in our database (24 vs. 31 cases), although the number of intense events (EF3 or stronger) is greater (7

vs. 3). We believe the reduction in EF2+ cases should be interpreted mainly as the result of our careful preliminary analysis, aimed at removing some spurious cases (downbursts) originally included in the ESWD, and not an indication of a climatic trend (although the reduction in the number of severe convective events and the increase in their intensity is consistent with some recent results for tropical-like cyclones in the Mediterranean; e.g., Cavicchia et al., 2014; Gaertner et al., 2016);

- the seasonality is similar: TR and WS are more frequent in summer and late spring in northern Italy, in autumn in the extreme southern Italian regions, Sicily and Sardinia, while a similar number of events was reported in autumn and summer along the Tyrrhenian coast and in Liguria;
- the percentage of significant TR we found (6.8%) is less than half that in G07; however, the ratio between the intense and the EF1 TR is about the same, which means that *the main difference between the two datasets is in the number of events in the weakest category*.

The density of TR per year in Italy is 1.23 events per 10^4 km^2, which is comparable with other Mediterranean (1.0 in Greece, Matsangouras et al., 2014; 1.5 in Catalonia, Rodriguez and Bech, 2017) and western European countries (1.2 in Belgium, Frique, 2012), but higher than in central-eastern European countries (e.g., 0.7 in Germany, Bissolli et al., 2007; 0.3 in Romania, Antonescu and Bell, 2015) and in countries with morphology similar to Italy (0.5 in Japan, Niino et et., 1997). However, locally the rate is much higher, since yearly occurrences are above 2 per 10^4 km^2 in four regions, and in Liguria are close to 4, i.e. about the value in Florida, the state with the highest TR rate in USA (Simmons and Sutton, 2011). The percentage of significant TR (6.8% of the total) is close to the value reported for Catalonia in Rodriguez and Bech (2017) (6.2%), but it is far less than for USA TR (around 21%; Simmons and Sutton, 2011). As a consequence, the probability of significant TR in any Italian region is much smaller than that of the USA states with the highest risk.

In contrast, the density of WS, of 0.92 events per 100 km of coastline, is lower than in other Mediterranean countries, e.g. 3.8 in Catalonia (Rodriguez and Bech, 2017), 3.0 in Croatia (Renko et al., 2016), and 2.1 in Greece (Matsangouras et al., 2014). Again, the value changes a lot depending on the region (it is close to 3 in Liguria, Lazio and Molise; see Fig. 7).

To complete the present analysis, an investigation of the environmental conditions conducive to TR and WS in Italy is planned. The forthcoming study will focus on synoptic maps and thermodynamic soundings in order to identify the large-scale and mesoscale features typically associated with these events. Also, a dataset covering a longer period should be analyzed, at least for the most intense cases, to make the present statistics more robust.

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	JUN	JUL	AUG	SEP	OCT	NOV	6-MONTHS
WS -PCP	0.2	**0.68**	**0.86**	0.38	-0.08	**0.55**	0.39
WS-TMM	-0.18	-0.64	-0.26	-0.09	**-0.38**	0.07	-0.31
WS-NAO	**0.51**	0.51	0.3	**0.77**	0.26	0.14	**0.43**

Table 1: Pearson correlation coefficient *R* between the number of WS and precipitation relative anomaly (WS-PCP, first row), mean temperature anomaly (WS-TMM, second row), and NAO index (WS-NAO, third row). *R* is calculated on a monthly basis from June to November and on the 6-month period June-November in each year from 2008 to 2016. The maximum for each column is bolded; the correlations statistically significant within 95% confidence interval (1-tailed Student's-t test) are underlined. Data for temperature and precipitation cover all the Italian synoptic stations, being the anomalies relative to the climatology 1961-1990 (courtesy: Michele Brunetti, ISAC-CNR); NAO index data are taken from the Climate Prediction Center of the USA National Weather Service.

NUMBER OF VORTICES	FREQUENCY
2	77
3	33
4	10
5	9
6	1
7	2
10	1
12	1
13	1

Table 2: Number of WS occurrences associated with multiple vortices.

REGION	DENSITY	PEAK MONTH	DENSITY IN PEAK MONTH
Liguria	3.88	AUGUST	1.48
Lazio	2.84	OCTOBER	0.52
Apulia	2.64	OCTOBER	0.46
Veneto	2.17	MAY	0.43
Campania	1.77	JULY	0.66
Calabria	1.66	SEPTEMBER	0.60
Sicily	1.52	OCTOBER	0.43
Friuli-Venezia Giulia	1.40	AUGUST	0.51
Tuscany	1.35	SEPTEMBER	0.30
Molise	0.90	JUNE	0.45
Marche	0.85	JULY	0.32
Piedmont	0.75	JUNE	0.28
Lombardy	0.71	JULY	0.25
Emilia Romagna	0.71	MAY	0.22
Sardinia	0.42	SEPTEMBER	0.08
Abruzzo	0.37	SEPTEMBER	0.09
Trentino Alto Adige	0.16	JUNE	0.16
Basilicata	0.10	MARCH	0.10
Aosta valley	0		
Umbria	0		

Table 3: Spatial distribution of TR in each Italian region (rate of events in 10^4 km^2 per year), month of peak activity (in case of ex aequo, it is considered the one closer to the next in the ranking), and rate of events in 10^4 km^2 in that month.

	AUTUMN	WINTER	SPRING	SUMMER
Lombardy			1/0/0	1/1/0
Friuli-Venezia Giulia				2/0/0
Veneto	1/0/0			1/1/1
Emilia-Romagna			2/2/0	
Apulia	3/1/0	1/0/0		
Campania	1/0/0	1/0/0		
Lazio	0/1/0		1/0/0	
Tuscany	1/0/0			
Sicily	1/0/0			

Table 4: EF2 (first number), EF3 (second number), EF4 (third number) distribution for each season and each political region.

Apulia	0.26
Friuli-Venezia Giulia	0.25
Veneto	0.22
Emilia Romagna	0.18
Campania	0.15
Lombardy	0.13
Lazio	0.12
Tuscany	0.04
Sicily	0.04

Table 5: rate of EF2+ TR per year in each region per 10^4 km^2.

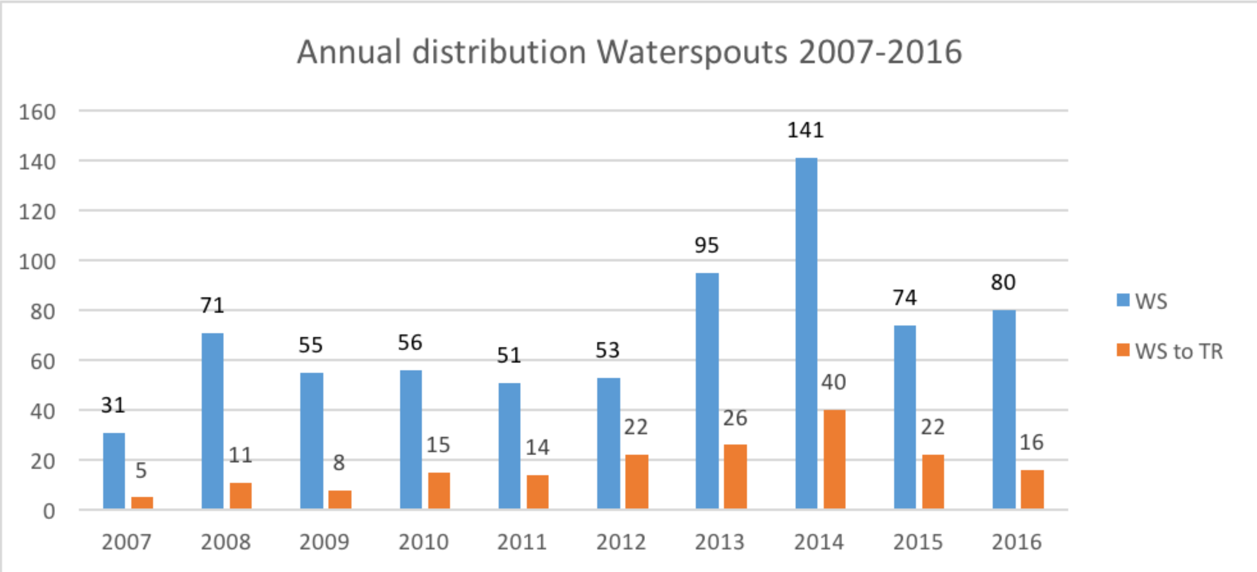


Figure 1: Annual distribution of WS (blue color) reported over Italy from 2007 to 2016. Those making landfall are also shown (WS-to-TR; orange color).

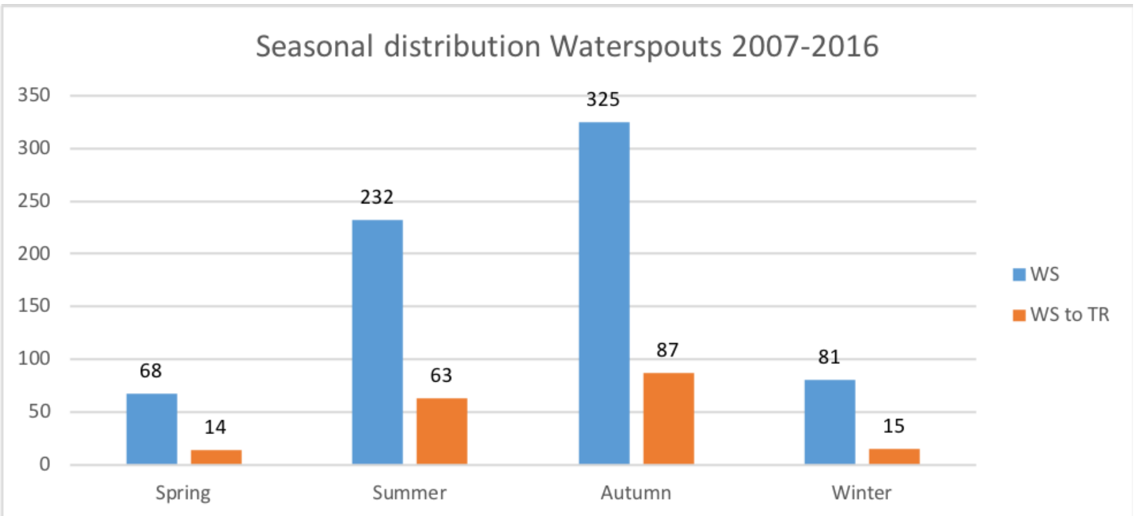


Figure 2: Seasonal distribution of WS (blue color) and WS-to-TR (orange color) over Italy from 2007 to 2016 (spring = MAM, summer = JJA, autumn = SON, winter = DJF). (For one case over 707, the month of occurrence is missing.)

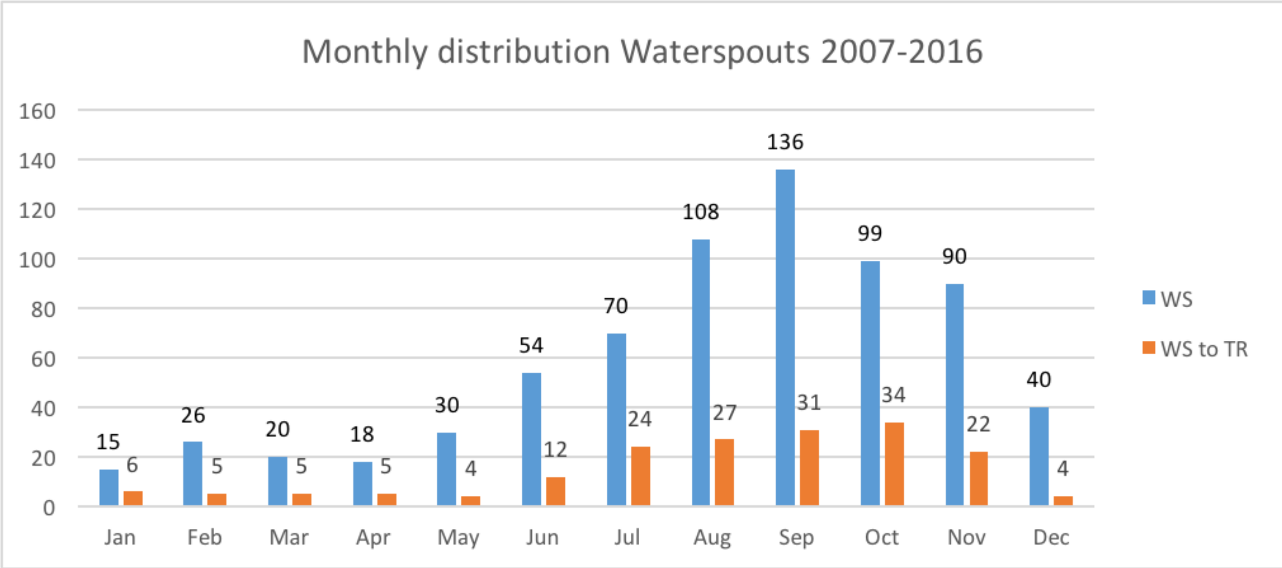


Figure 3: Monthly distribution of WS (blue color) and WS-to-TR (orange color) over Italy from 2007 to 2016.

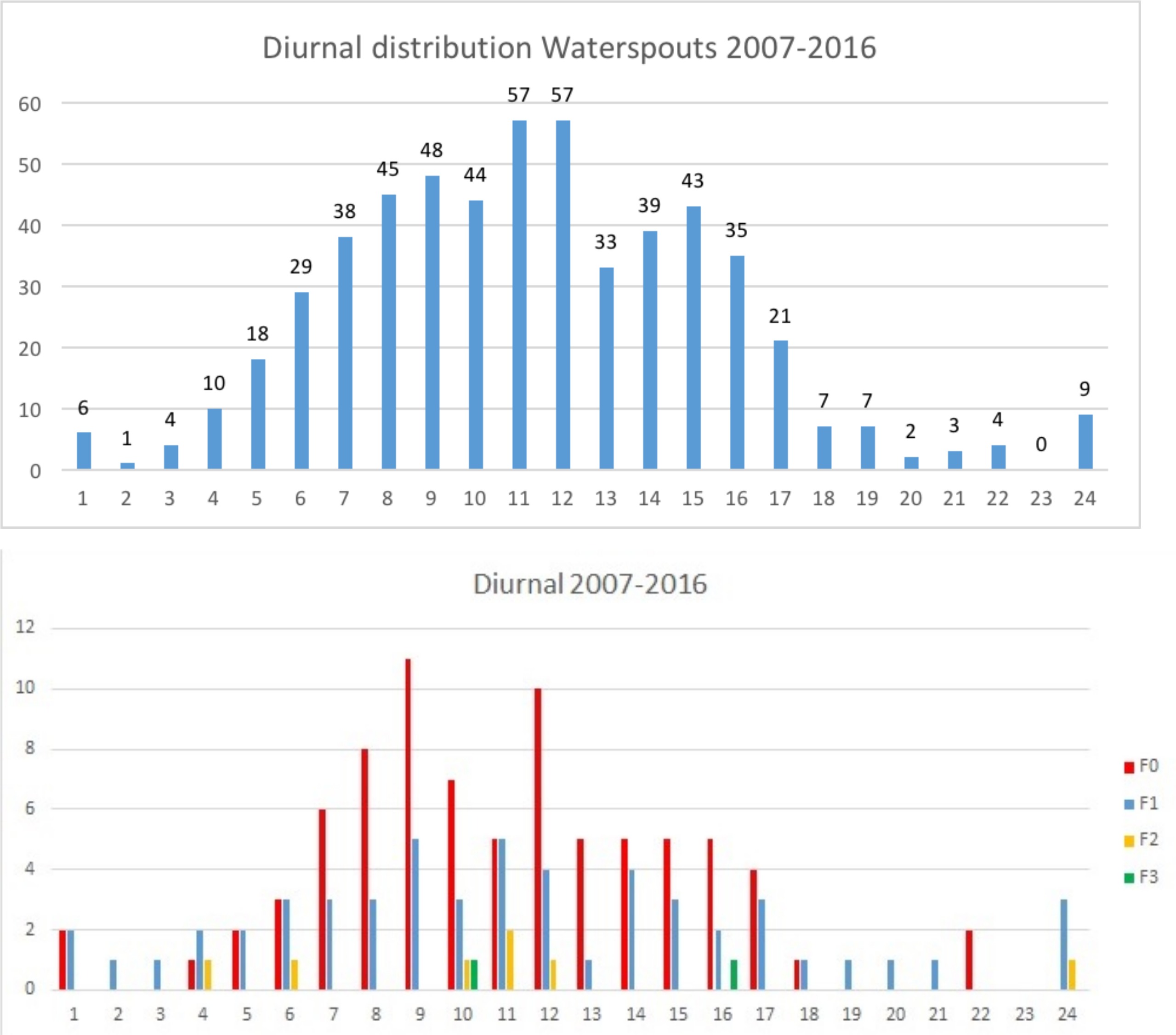


Figure 4: Diurnal distribution of WS over Italy from 2007 to 2016 (a, top) and in terms of EF rating classification (i.e., only WS-to-TR are shown) (b, bottom). The time is in UTC.

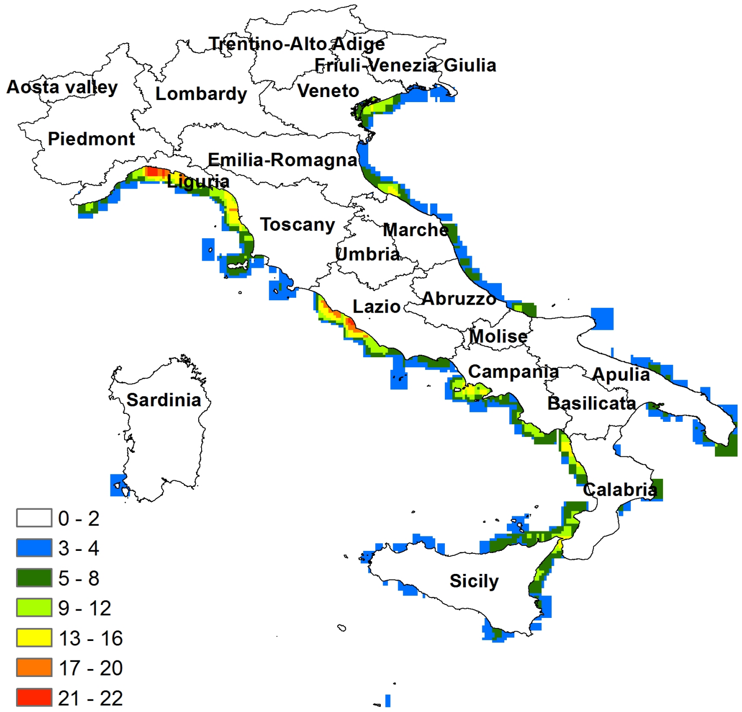


Figure 5: Spatial distribution of WS (yearly density within a square neighborhood of 40 km side along the coast). The density map was calculated with the point density method using ArcGIS 10 software.

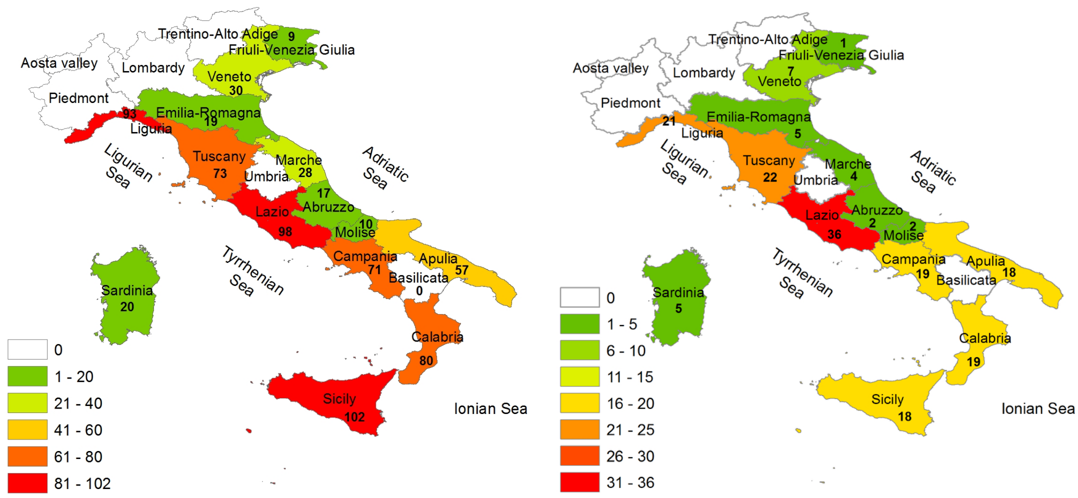


Figure 6: Spatial distribution of WS (a, left) and WS-to-TR (b, right) along the seas surrounding each political region of Italy from 2007 to 2016.

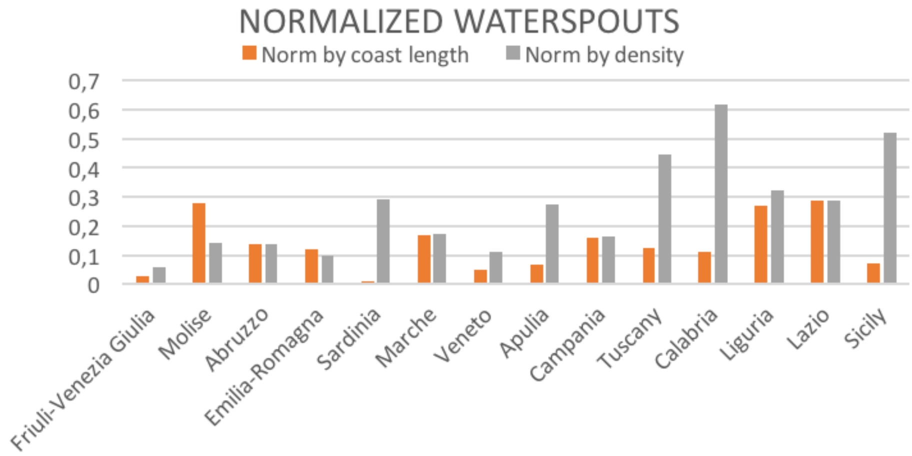


Figure 7: Distribution of WS over Italy (number of events from 2007 to 2016) normalized by the coastline length (events/km^{-1}) and by the population density (events/population/km^{2}). Regions are from left to right following the inverse ranking in the total number of events, i.e. the first on the right side.

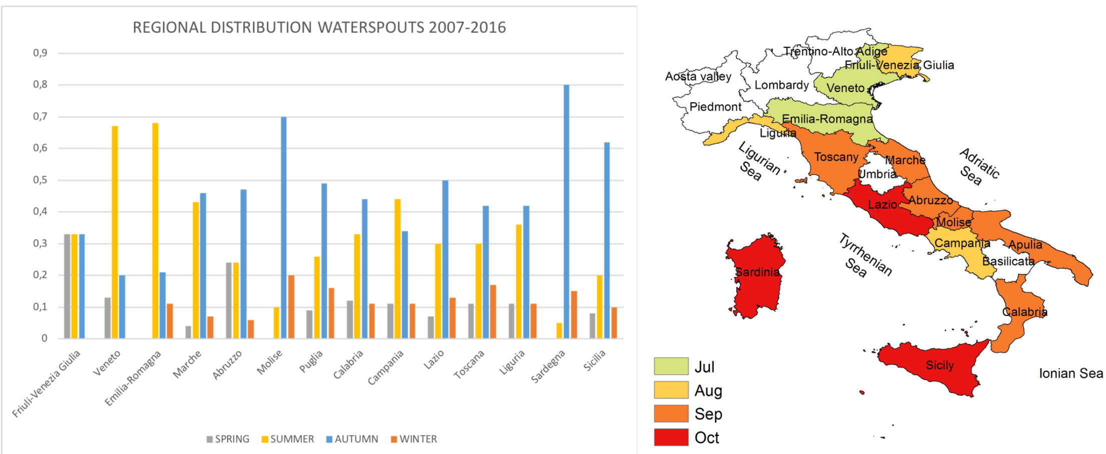


Figure 8: Regional distribution of WS over Italy from 2007 to 2016, in terms of percentage in each season with respect to the total number (regions are from left to right following the coastline clockwise from the northern Adriatic to Liguria; the islands are the last two groups of columns) (a, left); month of prevailing occurrence for each political region (b, right).

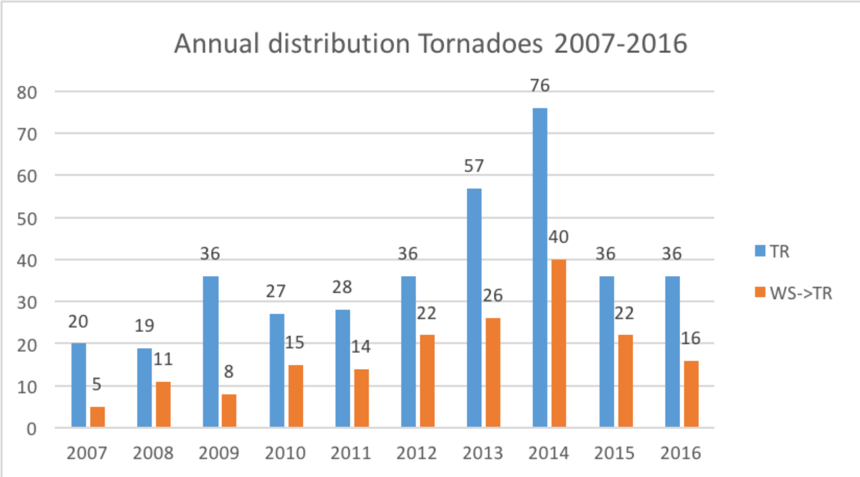


Figure 9: Annual distribution of TR (blue color) over Italy from 2007 to 2016. Those originated as waterspouts are also shown (WS-to-TR; orange color).

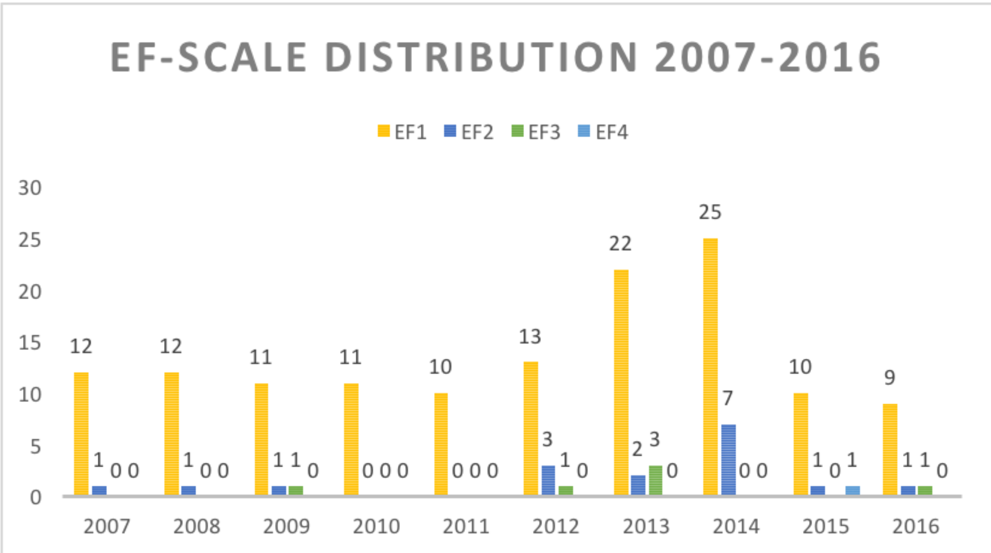


Figure 10: Annual distribution of TR in terms of TR EF rating over Italy from 2007 to 2016.

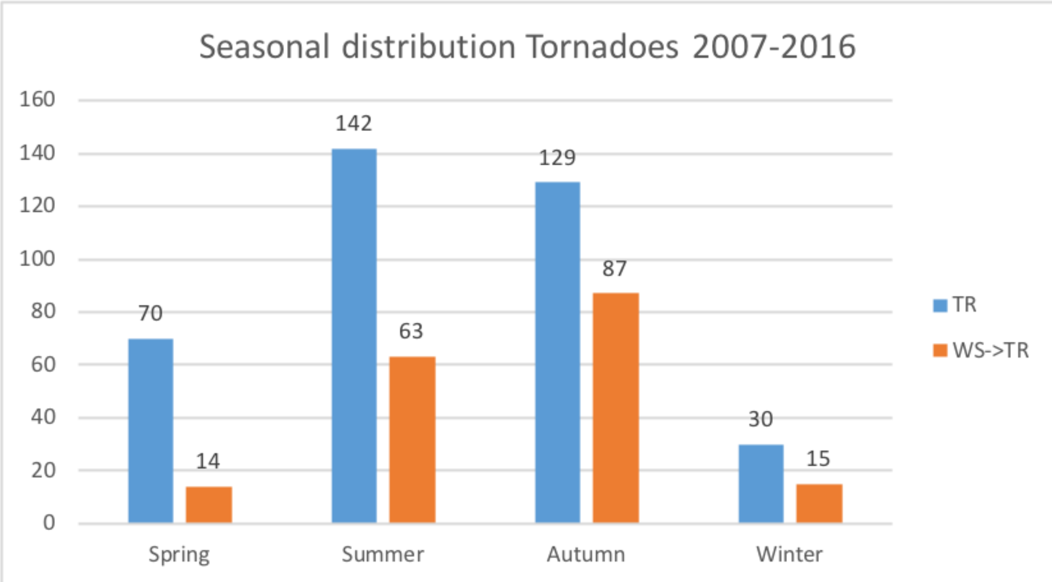


Fig.11: Seasonal distribution of TR (blue color) and WS-to-TR (orange color) over Italy from 2007 to 2016.

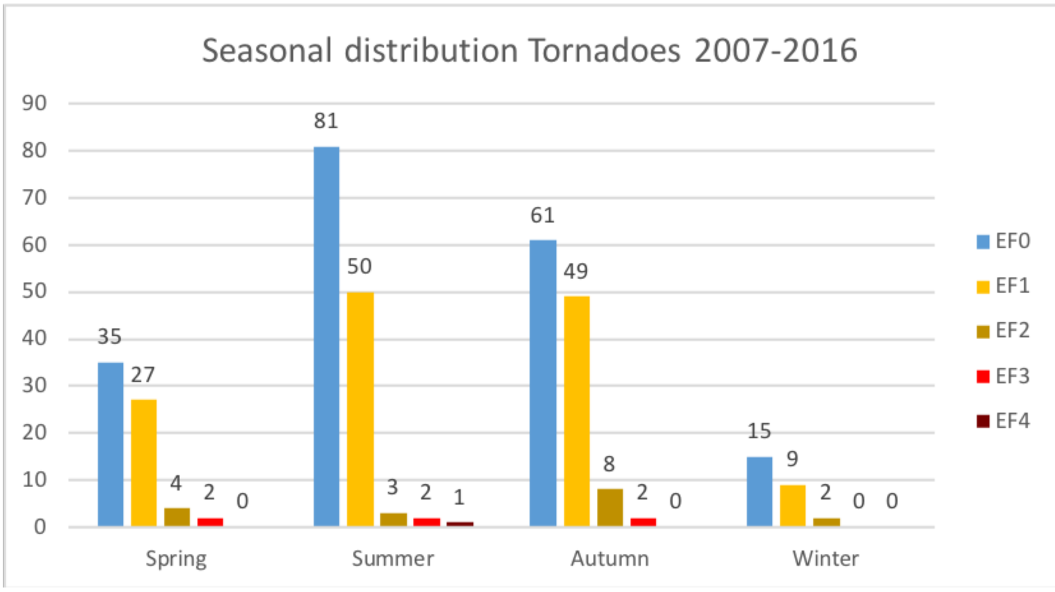
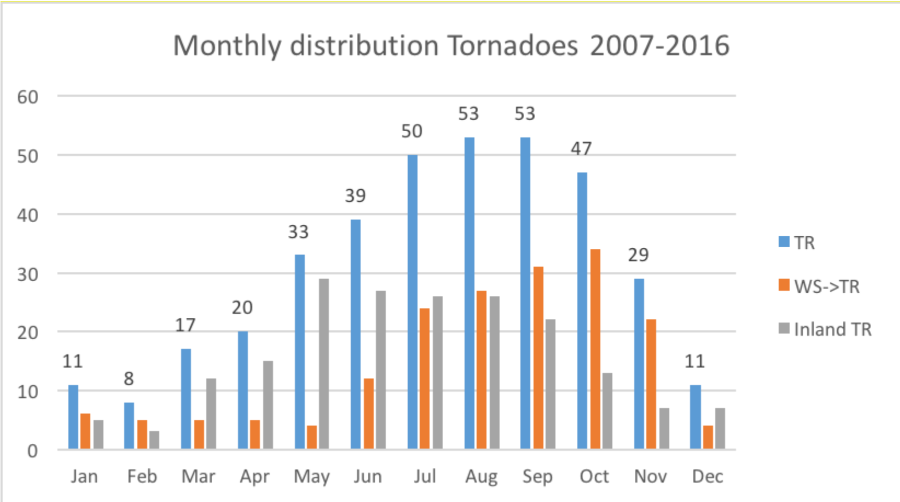


Figure 12: Seasonal distribution of TR over Italy from 2007 to 2016 in terms of EF rating. The smaller number of cases, compared to figure 11, is due to lack of info about the EF rating in some TR.



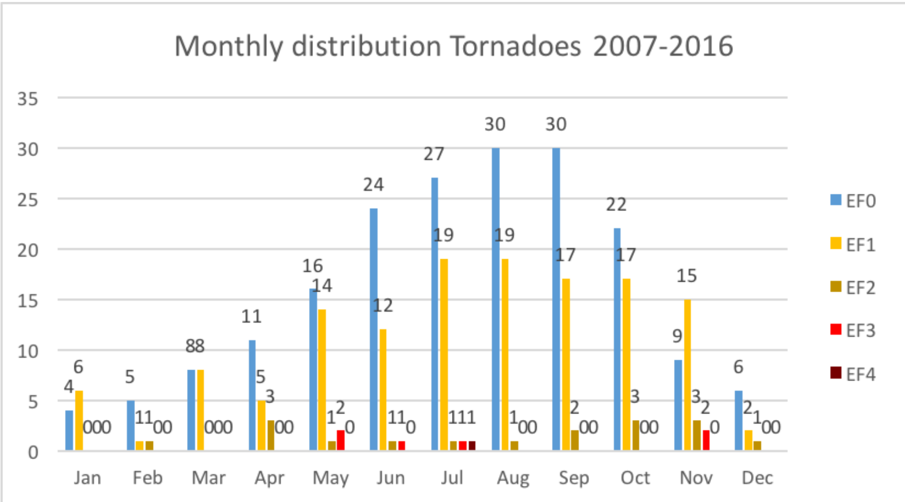


Figure 13: Monthly distribution of TR (blue color), WS-to-TR (orange color), and tornadoes originated inland (grey) in Italy from 2007 to 2016 (a, top); monthly distribution of TR by EF scale rating (b, bottom).

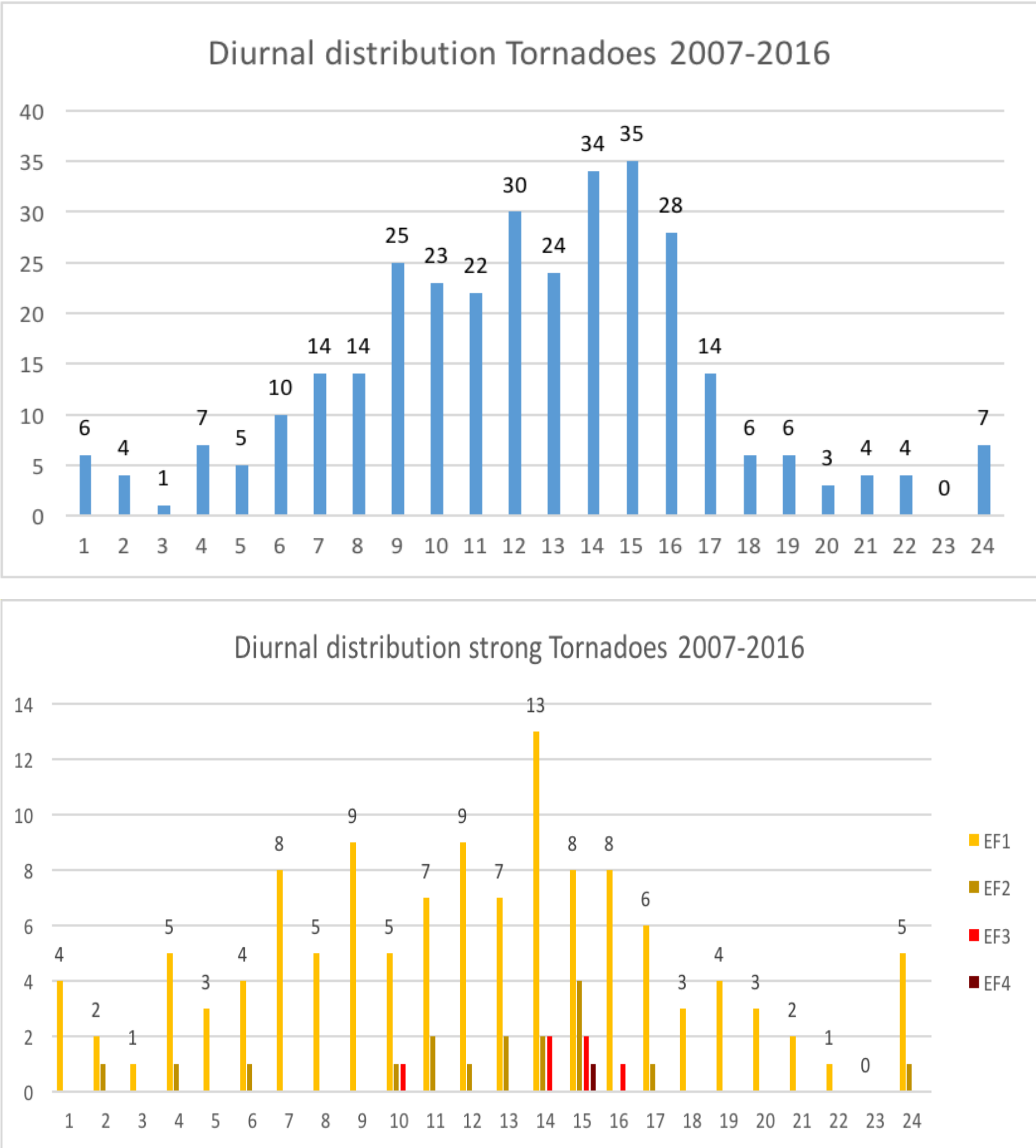


Figure 14: Diurnal distribution of TR over Italy from 2007 to 2016 (a, top), and in terms of EF rating classification (only EF1+) (b, bottom). The time is in UTC.

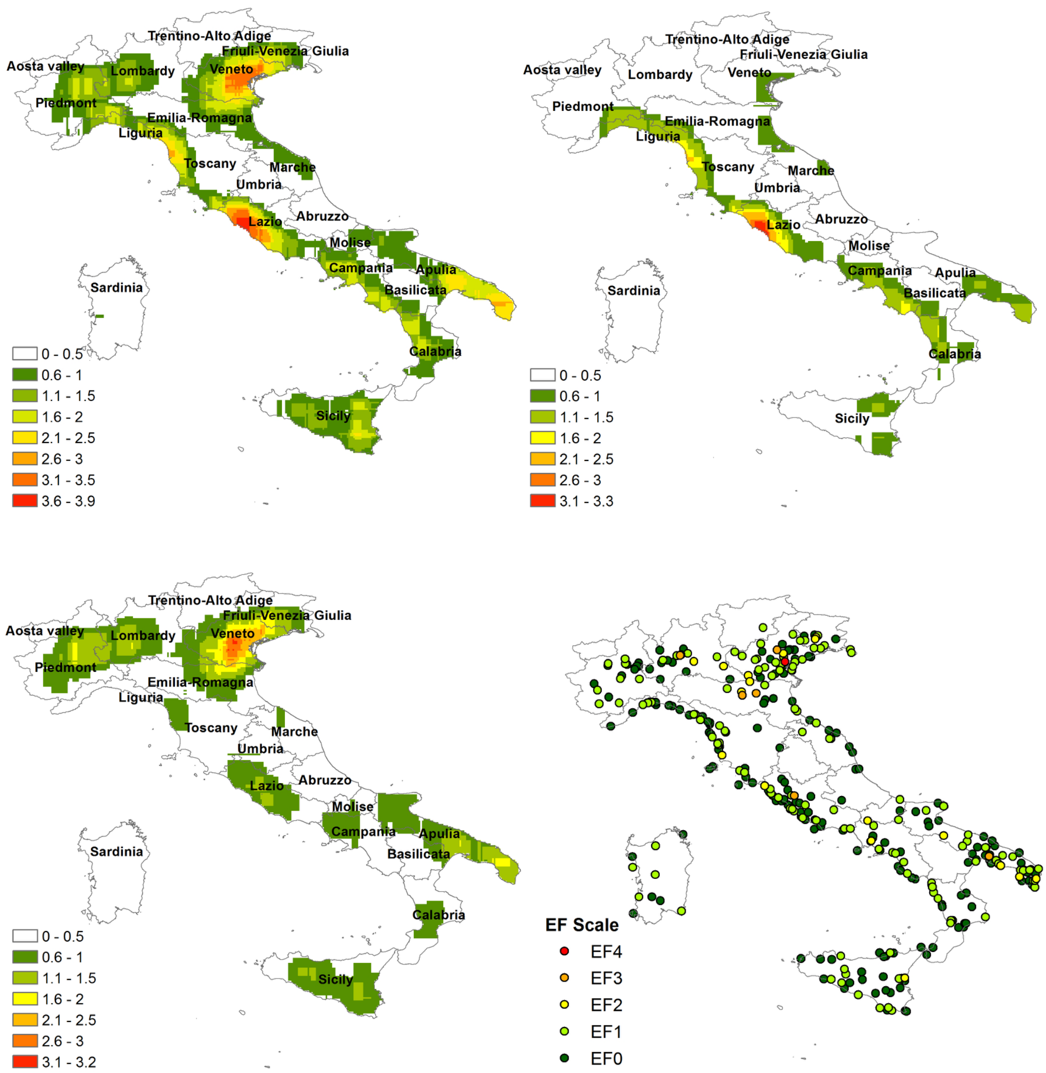


Figure 15: Spatial distribution (yearly density within a square neighborhood of 100 km side) in Italy of TR (a, top left), of WS-to-TR (b, top right), of TR originated inland (c, bottom left); locations where a TR was reported including the information on the EF rating (color) (d, bottom right). The density map was calculated with the point density method using ArcGIS 10 software. Sea points are masked.

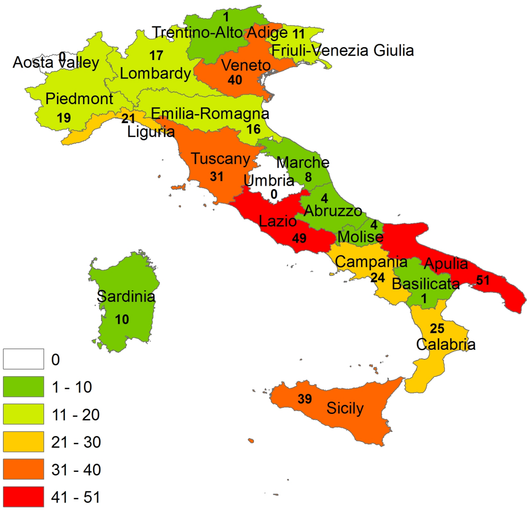


Figure 16: Spatial distribution of TR in each political region of Italy from 2007 to 2016.

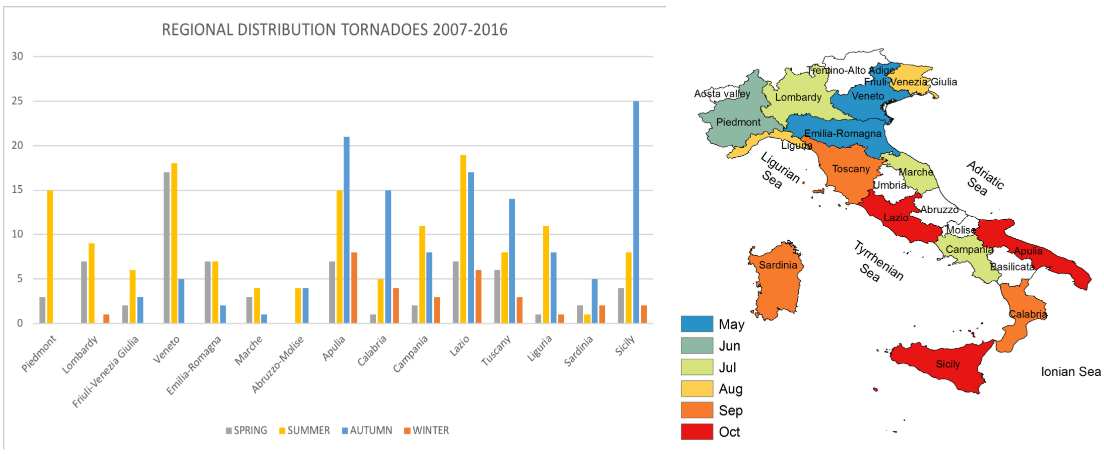


Figure 17: Regional distribution of TR over Italy from 2007 to 2016, in terms of percentage in each season with respect to the total number (a, left); month of prevailing occurrence for each political region (b, right). In (b), in case of ex aequo, it is considered the one closer to the next in the ranking; only regions with 5 or more occurrences are shown.