Meteorological precursors of significant tornado in Italy for the period 2000-2017

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ABSTRACT

The torndado occurrence in Italy is relatively frequent, although their intensity is generally not comparable to the USA. During the past years, only few works have analysed the precursors of tornadoes and their climatology in Italy, despite of the importance and the risks associated with these events. For this reason, a focus on some of parameters related to tornadoes has been necessary. In this study, the temporal evolution of three important meteorogical precursors, wind shear, calculated between 0-1 and 0-6 km, and CAPE, the latter in terms of WMAX, is analysed by means of two different reanalyses (ERA-INTERIM and ERA-5) for the period 2000-2017 during which 32 events of significant tornadoes occurred. The study focus on three different seasons, Spring, Summer and Autumn, while Winter is not considered in this study because of the lack of a relevant number of events in this season. The analysis shows that WMAX seems play the most important role immediatly before the tornadogenesis, with a clear difference from the reference climatology, especially in ERA-5 reanalysis, where this difference is detected for each season. 0-1 km wind shear, calculated at the reanalysis timestep immediatly before the event, denotes higher values compared to 0-6 km wind shear, but their departure from the climatology is not so evident in both precursors.

1. Introduction

Tornadoes are relatively common in Italy, occurring mostly on flat terrains in the north and along the coasts in the south of the peninsula (**??**). Intensity of tornadoes is rated using the Enhanced Fujita Scale (**?**), which classifies them into six categories on the basis of the damages to vegetation, buildings and vehicles (from EF0, producing only light damage, to EF5, producing almost complete destruction.

The occurrence of significant tornadoes is not so frequent in Italy, although some of them have caused fatalities and significant damages in the past, such as the tornado (EF3) in the Taranto area, in November 2016, when a worker in the ILVA complex died and caused 60 millions euros of damage (**?**) or the Tornado (EF4) between Mira and Dolo that, in July 2015, caused one death and 20 millions euros of damage **?**. However, in general, the probability of significant tornadoes in Italy is much lower than in the USA and in other European coutries (Miglietta and Matsangouras 2018).

There are several studies to identify parameters linked to tornado events and to define good forecast precursors. This task is not simple because of the difficult to create a complete database of the past events. In this work, EF2+ tornadoes in the Italian region for the period 2000-2017 are analyzed by means of two different reanalyses of the European Centre for Medium Range Weather Forecasts (ECMWF): ERA-INTERIM (**?**) and ERA-5 (https://www.ecmwf.int/en/newsletter/147/news/era5-reanalysis-production).

A previous work - see **?** - provides the support to an approch based on reanalysis output showing patterns that are qualitatively similar to other analysis by means of satellite observations as shown in **?**. In particular, three parameters were considered: wind shear (magnitude vector difference between 0-1 km and 0-6 km, here referred to as WS01 and WS06) and MUCAPE (Most Unstable Convective Available Potential Energy), expressed in terms of vertical velocity in the simple parcel theory (WMAX). These three parameters give a *"good first guess"* of the possible de-

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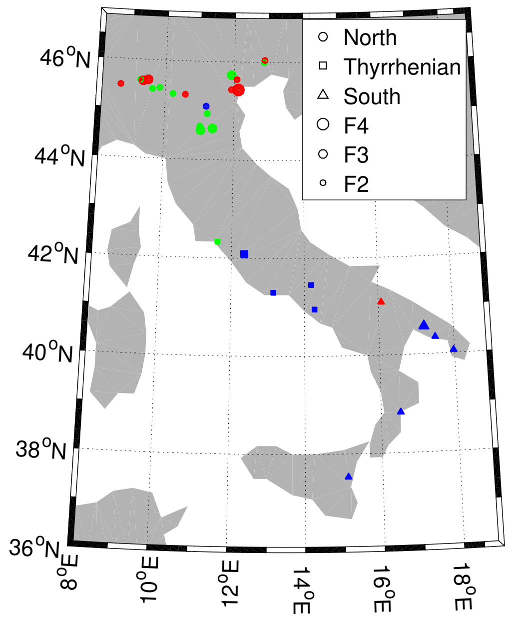

FIG. 1. Map with the location of significant tornadoes (category EF2 or stronger) considered in this study in the period 2000-2017. Colors of dots denote season (green for spring, red for summer and blue for autumn) and their size the three different recorded category of tornadoes (EF2-EF3-EF4). The different markers represent the three different macro-regions: bubbles for north Italy, squares for Tyrrhenian area and triangles for the southern regions.

velopment of severe weather conditions, when these parameters show high values (**??**). Brooks (2013) shows that higher values of WS and CAPE characterised the USA severe weather conditions compared to Europe. However, the European region is affected by a higher probability of severe conditions, probably related - as the author speculates - to the frequency of convective initiation. Moreover, the probability of occurrence of tornadoes exhibits a stronger dependence of the value of WS06 than of CAPE. Several papers highlight that the main difference between the two regions is in the CAPE values, that are lower in the environmental conditions of European tornadoes (**???**). **?** consider different weather conditions (dry, non tornadic thunderstorms and tornadic thunderstorms) and a large set of parameters: WS01 and WS06, SBCAPE (Surface Based CAPE), Storm Relative Helicity (SHR) and some composite parameters, such as the Supercell Composite Parameter (SCP) and the energy helicity index (EHI). They have found that high values of SBCAPE cannot explain the development of tornadoes and waterspouts but are useful to differentiate between dry conditions and the remaining part of sounding classes, so that SBCAPE represents a good indicator for convection. Moreover, they show a direct proportionality between high values of WS06 and tornado intensity. The same relation is found between high values of WS01 and strong tornadoes. In **?**, high values of MLCAPE (mixed layer CAPE) are associated with tornadic supercell, and a monotonic increase of CAPE values, switching from non tornadic to tornadic supercell, is detected. This difference with Rodriguez and Bech's conclusions is probably linked to generally higher CAPE values in the USA severe weather conditions, as written above. Supercells also reveal higher WS01 magnitude compared to nontornadic supercells and non-supercell storms.

The aim of this study is to evaluate these parameters (WS01, WS06 and WMAX) in order to check their temporal evolution in the hours before the tornado time and their potential role to trigger the tornadogenesis. A relationship between these precursors is provided and box and whisker plots are produced in order to compare different model timesteps, on which the precursors are calculated (see section 2), just before the event, and to check possible differences with climatology().

The data set used and the methodology are indicated in Section 2, while the results of the analysis and the discussion about them are provided in Section 3.

2. Data and Methods

The data set used for the analysis of the tornado events was created from Miglietta and Matsangouras (2018), which is based on the European Severe Weather Database (ESWD) - managed by the European Severe Storm Laboratory (ESSL) - , the regional agencies (e.g. Arpa) and even the amateur reports, that provide an important contribution to the scientific research on tornadoes. Only significant events (EF2+) were included in this data set and some of them were removed because of the lack of the precise time of the occurence of the tornado.

A total of 32 EF2+ events were analyzed (Table 1), 11 for Spring April-May-June) and Summer (July-August-September) and 10 for Autumn (October-November-December). The strongest event (EF4) was recorded in Mira, in the Veneto region, on 8th July 2015. In general, the distribution of tornado events in Italy differs according to the macro-region. Winter was not considered, since only two EF2+ tornadoes are recorded during this season. In the Northern part of the country, tornadoes are typical in Spring and Summer, while, in the Tyrrhenian and Southern regions, they are more common in Autumn (Fig.1). This regional distribution per season is in line with other results in previous studies (Giaiotti et al. 2007; Miglietta and Matsangouras 2018.

1) The reanalyses

The analysis of the meteorological precursors is based on two global reanalyses, ERA-INTERIM and ERA-5,

TABLE 1. List of the 32 tornadoes considered in this study for the period 2000-2017. The tornadoes are divided per season.

Season	Flag	Location	Coordinate (lon-lat)	Time(yyyy/mm/dd hh:mm)	Scale
Spring					
	(1)	San Giorgio di Piano (North)	11.39 44.64	2013/05/03 15:15	EF3
	(2)	Castelfranco Emilia (North)	11.05 44.59	2013/05/03 14.45	EF3
	(3)	Riese Pio (North)	11.92 45.73	2009/06/06 13:45	EF3
	(4)	Nonantola (North)	11.03 44.68	2014/04/30 13:15	EF2
	(5)	Montalto di Castro (Tyrrhenian)	11.61 42.33	2014/04/19 12:00	EF2
	(6)	Gallignano (North)	9.84 45.44	2012/04/08 13:00	EF2
	(7)	Monza (North)	9.27 45.58	2000/04/15 15:45	EF2
	(8)	Mirandola (North)	11.23 44.93	2013/05/03 15:15	EF2
	(9)	Castelletto di Leno (North)	10.22 45.32	2017/06/06 15:00	EF2
	(10)	Casaletto Vaprio (North)	9.63 45.41	2017/06/06 13:30	EF2
	(11)	Orcenico Superiore (North)	12.87 45.99	2009/06/06 14:30	EF2
Summer					
	(12)	Mira (North)	12.12 45.43	2015/07/08 15.30	EF4
	(13)	Grezzago (North)	9.50 45.59	2015/08/08 14:15	EF3
	(14)	Brianza (North)	9.35 45.57	2001/07/07 10:30	EF3
	(15)	Guidizzolo (North)	10.58 45.32	2007/07/09 15:00	EF2
	(16)	Cadoneghe (North)	11.92 45.43	2001/07/07 13:30	EF2
	(17)	Aurava (North)	12.88 46.04	2014/08/13 16:30	EF2
	(18)	Cremona (North)	9.77 45.30	2006/08/01 01:00	EF2
	(19)	Montecchio (North)	12.53 42.85	2004/08/13 12:15	EF2
	(20)	Galliate (North)	8.70 45.48	2003/08/29 13:00	EF2
	(21)	Morgano (North)	12.07 45.64	2015/09/14 15:30	EF2
	(22)	Minervino Murge (South)	16.08 41.08	2012/09/02 17:15	EF2
Autumn					
	(23)	Ladispoli (Tyrrhenian)	12.35 42.08	2016/11/06 16:00	EF3
	(24)	Taranto (South)	17.21 40.56	2012/11/28 09:50	EF3
	(25)	Frattaminore(Tyrrhenian)	14.27 40.96	2016/10/07 11:30	EF2
	(26)	Melara (North)	11.20 45.09	2014/10/13 13.40	EF2
	(27)	Terracina (Tyrrhenian)	13.15 41.30	2017/11/05 16.45	EF2
	(28)	Monacizzo (South)	17.50 40.34	2014/11/12 04:10	EF2
	(29)	Ognina (South)	15.11 37.53	2014/11/05 10:00	EF2
	(30)	Gallipoli(South)	17.98 40.06	2013/11/19 11:15	EF2
	(31)	Roccelletta Borgia (South)	16.51 38.83	2004/11/12 12:00	EF2
	(32)	Fontegreca (Tyrrhenian)	14.18 41.46	2014/12/28 02:00	EF2

provided by the ECMWF, at different resolutions. ERA-INTERIM has approximately a 80 km resolution on 60 vertical levels from the surface up to 0-1 hPa, while ERA5 provides hourly estimates of meteorological and climate variables and is based on a 30km grid resolution with 137 levels from the surface up to a height of 80km. The period 2000-2017 was selected because of the availability of ERA-5 data, that is predently limited to this temporal range. Time step used to extract data is six hours.

2) THE METEOROLOGICAL PRECURSORS: WIND SHEAR AND WMAX

Two possible environmental precursors were considered in this study: Wind Shear and MUCAPE. The Reanalysis output does not provide the wind shear, so it was indirectly calculated from the components of wind speed. The MUCAPE was converted in WMAX, the vertical velocity as described in the simple parcel theory.

(i) Wind Shear One of the most important parameters during extreme meteorological conditions linked to tornado events is the vertical wind shear, that is the variation of horizontal winds with height, associated with the horizontal vorticity, a fundamental element, in particular for mesocyclonic tornado. In fact, the vertical vorticity is required for tornadogenesis and it is generated by tilting of horizontally oriented components of vorticity. Tilting (defined below) is the second term in the equation that describes the evolution of the vertical vorticity in terms of advection of vertical vorticity, tilting or twisting and solenoidal term. The tilting term, derived from the above mentioned equation, can be defined as

$$-\left(\frac{\partial w}{\partial x}\frac{\partial v}{\partial z} - \frac{\partial w}{\partial y}\frac{\partial u}{\partial z}\right)$$

where u,v,w are the wind components.

The reanalysis product doesn't provide the wind shear, so an indirect calculation of wind shear, in terms of magnitude of the vector difference between the surface (1000 hPa level) and about 1 km (850 hPa level) and 6 km (500 hPa), was done by mean of u and v components of wind vector. The method is shown in Appendix 1.

(ii) WMAX In the reanalyses provided by the ECMWF, CAPE is calculated by considering parcels of air departing at different model levels below the 350 hPa level. CAPE is a parameter linked to the availability of potential energy during convection and it is proportional to the area bounded by the environmental temperature trace and the pseudoadiabat, relative to a saturated parcel lifted from the level of free convection (LFC) to the equilibrium level (EL). It is defined as

$$CAPE = g\int_{LFC}^{EL} Bdz$$

where B is the buoyancy force and is defined as

$$B = \frac{dw}{dt}$$

It is useful to convert the CAPE unit of measurement (J/kg) into metre per second to have the same units for both parameters. The maximum vertical velocity (WMAX) at the EL, as calculated in the simple parcel theory, is derived from CAPE and it is defined as

$$WMAX = \sqrt{2 * CAPE}$$

It is important to highlight that there is a bi-univocal correspondence between WMAX and CAPE.

(iii) The precursor indices In order to obtain comparable parameters, a process of standardization of the meteorological precursors was developed. So the single index (I) was obtained as

$$I = \frac{X - \overline{X}}{\sigma}$$

where X is the value of the precursor (Wind Shear or WMAX, in this case), The mean value $\overline{X}$ and the standard deviation σ are computed separately for each tornado considering the 18 values of the precursors at the same time and calendar day at which the event occurred in the 18 years 2000-2017. Therefore, $\overline{X}$ and σ have different values for each individual tornado and for the ERA-5 and ERA-Interim datasets. In the tables at the end, the seasonal values of $\overline{X}$ and σ are shown for both reanalyses.

For every tornado, four timesteps - those occurred just before the event - have been selected in order to check the temporal evolution of the precursors, so a temporal range of 18-24 hours is covered because of the 6 hours resolution of the reanalyses. The time step closest to the time of the tornado is denoted as timestep-1. Please, notice that, in the remaining sections, the two precursors are always referred to as indices.

3. Results and discussion

1) A comparison between wind shear and WMAX precursors

The relationship between WMAX, WS01, WS06 and the characteristics of the tornadoes at the timestep-1 is shown in fig.2

The colors of the dots represent the tornado events for the three seasons in the examined period, green for spring, red for summer and blue for autumn. The markers are representative of the three macro-regions: North (bubbles), Thyrrenian area (squares) and South (Triangles). The different size of the markers indicates three different intensities: EF4, EF3 and EF2.

The WS01 panel, on the left in Fig. 2, is consistent with the idea that high values of WS01 play an important role in the tornadogenesis, as it can be seen from the greater aggregation of markers at the top of the panel. In fact the 50% of WS01 indices are over the value of 2, in contrast to WS06 index, for which only the 15% of the values is over this threshold. At the same time, the CAPE, although shows few large values, is not characterized by negative of them. A particular relationship between high values of the three parameters and the tornado intensity (represented from the size of the markers) is not clear.

2) Temporal evolution of wind shear and WMAX

In order to check the behaviour of the precursors, their values at timestep-1 to4 have been analysed separately (figures 3-5). Then red line inside the box denotes the the

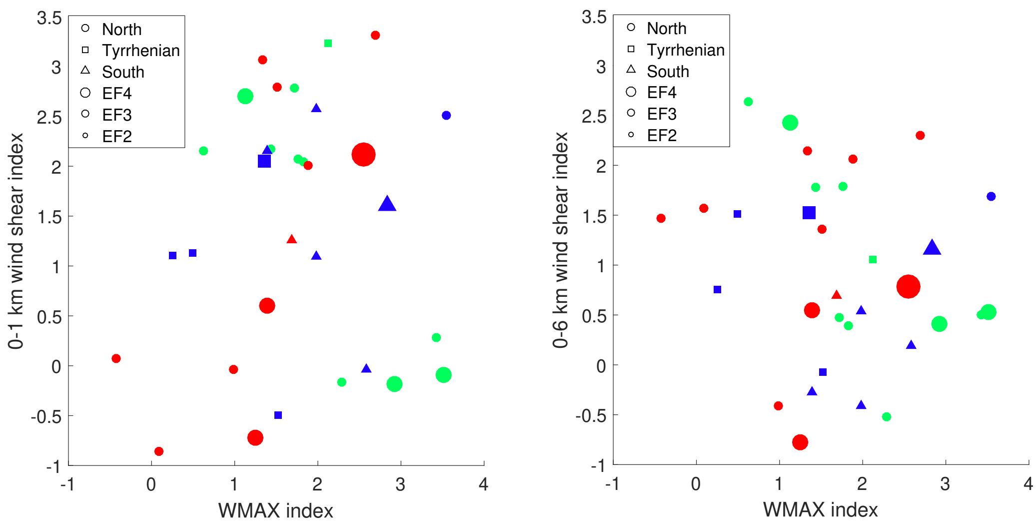

FIG. 2. Relationship between WMAX and WS01 (on the left) and WS06 (on the right) based on ERA-5 reanalysis. Colors of dots denote season (green for spring, red for summer and blue for autumn) and their size the three different recorded category of tornadoes (EF2-EF3-EF4). The different markers represent the three different macro-regions: bubbles for north Italy, squares for Tyrrhenian area and triangles for the southern regions.

median, and the bottom and top edges of the box represent the 25th and 75th percentiles, respectively, while the whiskers are calculated as +/–2.7σ.

Fig.3 shows the temporal evolution for WS01 per each season. The boxplot analyses for ERA-INTERIM and ERA-5 reanalyses are reported on the left and on the right sides of the figure, respectively. The boxplots show generally a tendency to increasing values of the precursor as the timesteps become closer to the event. In particular, in autumn this increase assumes an almost linear shape, especially for ERA-INTERIM reanalysis, where the difference between the first timestep before the event (timestep 1) and the last one (timestep 4) is statistically significant (the Mann-Whitney test at the 5% significance level has been used). No significant difference is detected for the other seasons in both reanalyses.

In Fig.4, the same kind of analysis of Fig.3 is shown for WS06 precursor. Also in this case, an increase of the values of precursor as the time lag of the occurrence of tornadoes decrease is suggested by the figures. The timestep 1 is statistically different only in Spring for both reanalyses.

The timestep 1 in autumn for WS01 in ERA-INTERIM reanalysis differs from the reference climatology, calculated on the analysed period, and this is the only case where a difference from the mean of events is detected for the Wind Shear precursors. The chosen values of the whiskers is +/- 2.7σ, so there is about 99.3 % coverage if the data are normally distributed. It is important to highlight that with a lower value of whiskers (e.g. 95% coverage) this differences could increase, especially for the timestep-1.

Fig.5 is referred to the WMAX parameter. Similarly to the other boxplots for WS, WMAX seems to increase when close to the event time. The significativity was found only in one case, in Autumn, for ERA-INTERIM dataset. But, in ERA-5 data set, WMAX, calculated at timestep 1, differs from climatology for each season, while in ERA-INTERIM denotes this difference only in Autumn.

These departure from climatology decrease, stepping away from the event time, in all reanalysis data sets . This suggests that the temporal scale of the development of tornado conditions is lower than daily scale.

When all 32 events togheter are considered, the difference between the timestep 1 and timestep 4 becomes significant for all three precursors in every reanalysis dataset, so, the lack of significance in some seasonal cases, is likely caused by the small amount of events.

Moreover, in general, as can be seen in the tables in the appendix, the ERA-5 reanalysis shows higher values for the Wind Shear and WMAX climatologies compared to ERA-INTERIM data set. Therefore, it's possible to suppose that ERA-5 better reproduces the magnitude of the precursors, especially for WMAX parameter, immediatly before the event time.

4. Conclusions

In spite of the short length of the considered period the analysed data allow to achieve useful information on the meteorological conditions associated with tornadoes over Italy.

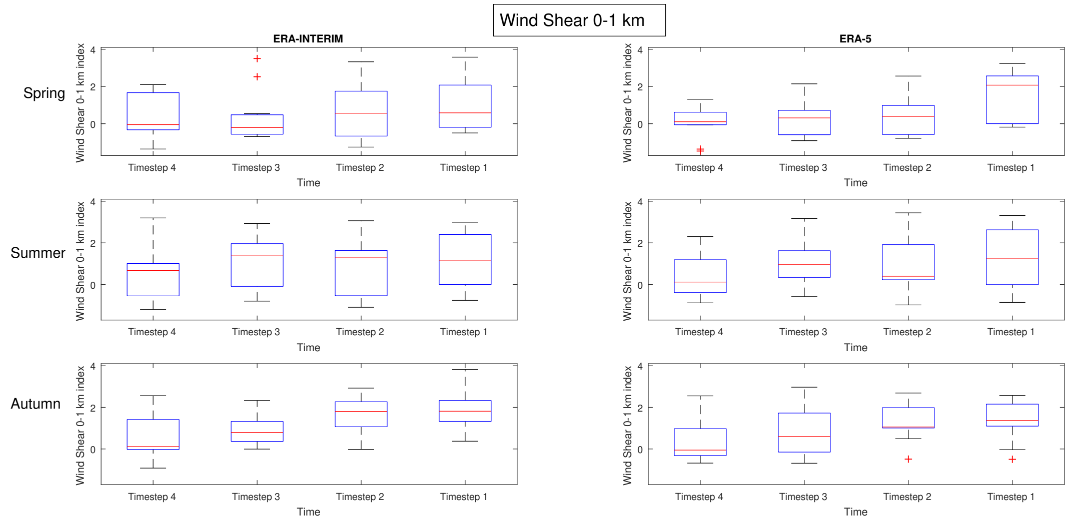

FIG. 3. Boxplots for Wind Shear 0-1 km. The red line, inside the box, represents the median, the upper and lower limit of the boxes the 25th and 75th percentile, while the value considered for the whiskers is approximately +/–2.7σ, The red crosses represent the outliers. Each panel refers to a different season: spring (top), summer (middle), autumn (bottom). Timestep-1 is the latest available step before the occurrence of the tornadoes. Former steps 2, 3 and 4 are 6, 12 and 18 hours before timest-1, in this order.

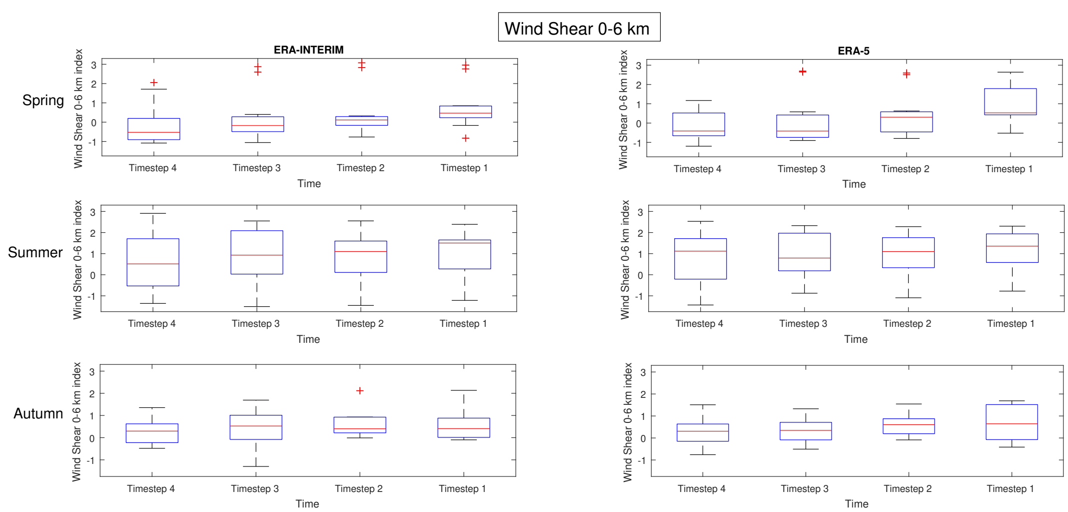

FIG. 4. Same as figure 5 except it refers to the Wind Shear 0-6 km precursor

- The geographic distribution of significant Italian tornadoes agrees with previous studies (Giaiotti et al 2007; Miglietta and Matsangouras 2018). Tornadoes occur prevalently in spring and summer for northern regions and in late summer and autumn for the tyrrhenian coast and southern regions;

- High values (over the value of 2) of Wind Shear Index, calculated between 0-1 km, are reported in 50% of the cases. On the contrary, only the 15 % of tornado show WS06 values over this threshold.

- Considering the temporal evolution in the 18-24 hours before the event, although all parameters seems to show an increase in values, as the event is approaching, they don't show a statistically significant (at 5% level of significance) difference between timstep-1 (immediately before the tornado) and timestep-4 (from 18 to 24 hours before the tornado).

- If the whole list of tornadoes (32 events) is considered, the difference between the two timesteps becomes significant.

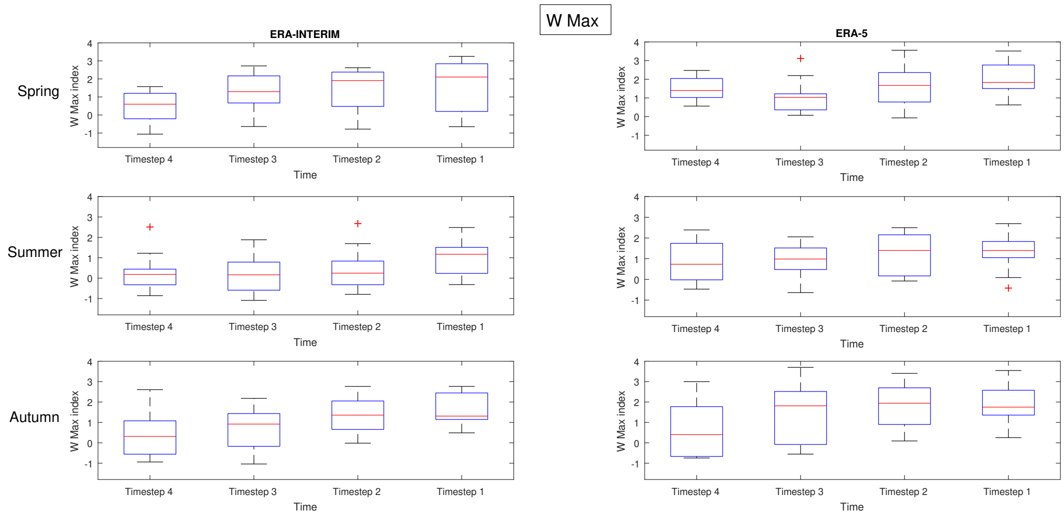

FIG. 5. Same as figure 5 except it refers to the WMAX - max. of vertical velocity - precursor

- The WMAX parameter calculated at the closest timestep to tornado time differs from the climatology in each season for ERA-5 reanalysis, while only the Wind Shear, calculated between 0-1 km in autumn, for ERA-INTERIM data set, differs from climatology. This suggests that WMAX denotes a better performance, as precursor, compared to Wind Shear.

- ERA-5 data set shows, generally, higher values of the two precursors and higher significance of their anomalies, especially close to event time.

In conclusion, WMAX seems to represent the best parameter between the three analysed precursors. For wind shear variable, the 0-1 km Wind Shear calculated shows a better response compared to the 0-6 km Wind Shear. A better and more robust analysis of the three precursors will be provided by future availability from 1950, which will allow to consider a wider sample of recorded tornadoes than that considered in this preliminary study.

APPENDIX

Calculation of Wind Shear

For the computation of the wind shear, the four grid points surrounding the location of the event are identified and among them the point located upwind is selected. The meteorological wind direction (0° to 360°), detected at 500 hPa, is considered.

The Wind Shear is calculated as the magnitude vector difference between 0-1 km and 0-6 km:

$$|W_i| = \sqrt{U_{diff}^2 + V_{diff}^2}$$

where W_i is the magnitude of ith vector difference and U_{diff} and V_{diff} are the components of difference vector calculated as

$$U_{diff} = (u1_h - u1_s, u2_h - u2_s, \ldots\ldots, ui_h - ui_s)$$

$$V_{diff} = (v1_h - v1_s, v2_h - v2_s, \ldots\ldots, vi_h - vi_s)$$

where the ui_h and vi_h are the wind speed components - provided from Reanalyses - at 500 or 850 hPa while ui_s and vi_s at the surface (1000 hPa).

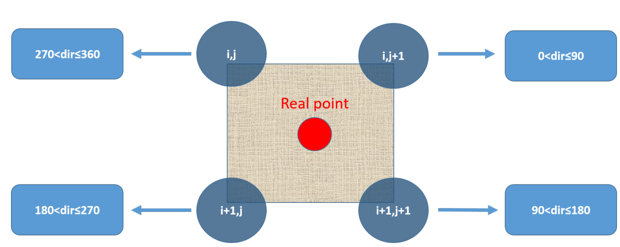

FIG. A1. The box of the 4 reanalysis grid points closest to the real geographic point where the tornado is occurred. If the wind direction is between]0°-90°], the grid point at the top right corner is considered, if it is between]90°-180°], the grid point at the bottom right of the corner is considered, etc.

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TABLE A1. Mean ($\overline{X}$) and standard deviation(σ), calculated on the period 2000-2017, for the closest reanalysis timestep to the event time for Wind Shear 0-1 km in ERA-INTERIM dataset. The flags represent the 32 tornado events, as shown in Table 1.

Spring			Summer			Autumn		
Flag	$\overline{X}$	σ	Flag	$\overline{X}$	σ	Flag	$\overline{X}$	σ
(1)	4.03	2.80	(12)	3.77	1.89	(23)	4.40	2.86
(2)	4.15	2.76	(13)	1.40	0.85	(24)	6.79	4.78
(3)	2.79	1.77	(14)	2.67	1.63	(25)	4.00	2.51
(4)	4.30	3.25	(15)	2.22	2.14	(26)	3,69	2.76
(5)	2.95	2.36	(16)	3.10	1.66	(27)	3.94	2.76
(6)	2.36	1.82	(17)	3.09	1.83	(28)	4.61	2.75
(7)	3.80	2.28	(18)	3.13	1.70	(29)	3.96	2.52
(8)	4.15	2.76	(19)	1.82	1.17	(30)	4.22	2.97
(9)	2.30	1.56	(20)	1.87	1.34	(31)	3.44	2.52
(10)	2.37	1.48	(21)	4.83	2.94	(32)	5.20	2.98
(11)	3.04	1.70	(22)	4.65	2.53			

TABLE A2. Mean ($\overline{X}$) and standard deviation(σ), calculated on the period 2000-2017, for the closest reanalysis timestep to the event time for Wind Shear 0-1 km in ERA-5 dataset. The flags represent the 32 tornado events, as shown in Table 1.

Spring			Summer			Autumn		
Flag	$\overline{X}$	σ	Flag	$\overline{X}$	σ	Flag	$\overline{X}$	σ
(1)	4.50	3.17	(12)	4.81	2.18	(23)	5.83	3.60
(2)	4.87	3.20	(13)	2.78	3.29	(24)	7.51	5.22
(3)	4,65	3.44	(14)	3.20	2.12	(25)	4.91	2.44
(4)	5.64	3.43	(15)	2.36	1.68	(26)	5.89	4.25
(5)	4.55	2.12	(16)	5.02	2.99	(27)	4.83	3.53
(6)	3.39	2.21	(17)	3.54	3.14	(28)	5.62	3.52
(7)	3.47	2.04	(18)	4.09	2.01	(29)	5.37	2.46
(8)	4.87	3.88	(19)	2.73	1.96	(30)	3.96	3.86
(9)	3.70	2.94	(20)	2.47	1.68	(31)	6.53	4.34
(10)	3.59	2.65	(21)	6.71	4.83	(32)	7.65	4.16
(11)	4.87	3.27	(22)	4.98	1.96			

TABLE A3. Mean ($\overline{X}$) and standard deviation(σ), calculated on the period 2000-2017, for the closest reanalysis timestep to the event time for Wind Shear 0-6 km in ERA-INTERIM dataset. The flags represent the 32 tornado events, as shown in Table 1.

Spring			Summer			Autumn		
Flag	$\overline{X}$	σ	Flag	$\overline{X}$	σ	Flag	$\overline{X}$	σ
(1)	11.59	5.56	(12)	13.59	8.05	(23)	14.29	7.19
(2)	11.40	5.34	(13)	11.17	6.27	(24)	13.78	6.51
(3)	10.86	6.58	(14)	14.10	8.11	(25)	11.65	6.49
(4)	10.87	5.94	(15)	11.33	6.72	(26)	12.33	7.59
(5)	11.42	6.55	(16)	14.02	8.05	(27)	13.15	7.23
(6)	12.54	7.52	(17)	11.70	6.48	(28)	11.83	6.25
(7)	14.13	8.34	(18)	11.07	5.54	(29)	12.17	7.73
(8)	11.40	5.53	(19)	8.69	5.46	(30)	13.77	8.10
(9)	11.25	5.83	(20)	12.70	7.29	(31)	11.80	5.31
(10)	11.44	5.75	(21)	12.69	7.63	(32)	16.36	5.57
(11)	10.59	7.21	(22)	12.05	6.54			

TABLE A4. Mean ($\overline{X}$) and standard deviation(σ), calculated on the period 2000-2017, for the closest reanalysis timestep to the event time for Wind Shear 0-6 km in ERA-5 dataset. The flags represent the 32 tornado events, as shown in Table 1.

Spring			Summer			Autumn		
Flag	$\overline{X}$	σ	Flag	$\overline{X}$	σ	Flag	$\overline{X}$	σ
(1)	12.74	6.79	(12)	15.86	8.50	(23)	16.48	8.83
(2)	12.89	6.84	(13)	13.61	8.38	(24)	15.78	7.02
(3)	11.15	8.04	(14)	16.23	8.07	(25)	12.09	5.87
(4)	13.00	6.68	(15)	13.54	6.97	(26)	14.94	8.72
(5)	14.21	8.50	(16)	15.59	8.14	(27)	14.11	8.83
(6)	12.32	7.29	(17)	12.60	6.43	(28)	13.64	6.71
(7)	13.60	7.96	(18)	11.94	4.92	(29)	12.88	6.51
(8)	13.14	7.14	(19)	9.82	4.51	(30)	13.63	9.03
(9)	12.32	6.33	(20)	13.55	8.65	(31)	13.58	7.76
(10)	12.58	5.81	(21)	15.01	8.17	(32)	18.61	8.29
(11)	11.63	7.50	(22)	11.53	7.82			

TABLE A5. Mean ($\overline{X}$) and standard deviation(σ), calculated on the period 2000-2017, for the closest reanalysis timestep to the event time for WMAX in ERA-INTERIM dataset. The flags represent the 32 tornado events, as shown in Table 1.

Spring			Summer			Autumn		
Flag	$\overline{X}$	σ	Flag	$\overline{X}$	σ	Flag	$\overline{X}$	σ
(1)	9.13	10.97	(12)	17.80	15.57	(23)	11.12	12.59
(2)	9.78	11.53	(13)	23.74	19.69	(24)	10.49	11.42
(3)	17.01	15.38	(14)	14.68	16.70	(25)	15.18	14.50
(4)	8.14	9.55	(15)	17.87	13.39	(26)	5.74	7.96
(5)	4.25	6.08	(16)	17.61	16.09	(27)	10.70	14.18
(6)	8.20	7.37	(17)	22.31	17.11	(28)	8.20	8.92
(7)	6.95	6.24	(18)	16.37	16.54	(29)	10.25	14.16
(8)	9.13	10.97	(19)	17.31	16.91	(30)	10.93	13.61
(9)	16.79	13.17	(20)	10.96	13.16	(31)	9.37	12.06
(10)	16.35	13.13	(21)	10.36	12.58	(32)	5.81	7.30
(11)	16.95	15.41	(22)	21.96	18.81			

TABLE A6. Mean ($\overline{X}$) and standard deviation(σ), calculated on the period 2000-2017, for the closest reanalysis timestep to the event time for WMAX in ERA-5 dataset. The flags represent the 32 tornado events, as shown in Table 1.

Spring			Summer			Autumn		
Flag	$\overline{X}$	σ	Flag	$\overline{X}$	σ	Flag	$\overline{X}$	σ
(1)	10.98	13.99	(12)	24.63	23.48	(23)	10.91	11.84
(2)	9.20	13.29	(13)	26.25	22.09	(24)	6.89	10.42
(3)	21.03	16.98	(14)	23.82	21.62	(25)	17.32	16.05
(4)	9.92	11.65	(15)	24.28	22.53	(26)	7.03	15.60
(5)	5.67	9.45	(16)	24.50	24.90	(27)	14.36	17.38
(6)	4.59	7.40	(17)	18.73	16.08	(28)	6.83	9.34
(7)	5.67	9.12	(18)	21.16	18.32	(29)	8.73	14.09
(8)	9.97	13.02	(19)	5.11	12.16	(30)	8.17	10.43
(9)	19.46	19.06	(20)	19.75	23.78	(31)	10.09	15.36
(10)	20.20	19.34	(21)	10.50	13.36	(32)	2.17	3.28
(11)	19.97	18.91	(22)	15.84	15.19			