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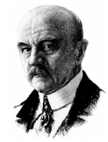

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TORNADIC WATERSPOUT EVENT IN SPLIT (CROATIA) — ANALYSIS OF METEOROLOGICAL ENVIRONMENT

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Abstract: The aim of this paper is the waterspout in Split (φ 43.51 °N, λ 16.45 °E, h = 0 m) observed on January 6, 2016, which swept over the city at 15:40–16:00 CET (14:40-15:00 UTC). There were convective developments in upper-level south-west flow within the cloudiness which followed the low-level cyclone and associated frontal disturbances. There was an intense thermodynamic instability in lower and mid layers of the atmosphere-the passage of the cold front as a main synoptic feature over the warm Adriatic water, pronounced directional and speed wind shear, as well as the presence of jet stream and a pronounced horizontal field of positive divergence above the observed area. The aim of this paper is to investigate synoptic and mesoscale situation, and meteorological conditions which created favourable thermodynamic environment which preceded the waterspout development.

Key words: waterspout, synoptic types, instability indices, the Adriatic Sea, Split

Introduction

A waterspout is a tornado (usually a non-supercell tornado) developed from a cumuliform cloud (Cb, Cu con) over water surface and may as well be connected to well-organized marine supercells and has a circulation qualitatively similar to the one within the supercell cloud (AMS, 2012; Huschke, 1959; Golden, 1971; Golden, 1974; Hagemeyer, 1994; Ćurić, 2001; Browning, 1964; Brady & Szoke, 1988; Davies-Jones, Trapp, & Bluestein, 2001). It is an intensive atmospheric vortex of a small size (funnel cloud[2] diameter ranges from a few to 100 m) and of short lifetime, usually less than 20 minutes (Golden,

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[1] Correspondence to: millennijum@hotmail.com
[2] Funnel cloud is a condensation funnel shaped cloud developing downward from the base of a Cb cloud or other cumuliform clouds. It represents a cloud manifestation of a strong whirlwind and, if a rotation comes into a contact with the surface, the vortex becomes a tornado. It may appear within different convective processes (Bluestein, 1994; Ćurić, 2001).

1973; Golden, 1974; AMS, 2012). Waterspouts are classified into two categories — fair weather waterspouts and tornadic waterspouts (National Oceanic and Atmospheric Administration, 2016a).

Although the mechanism of a waterspout development has been unknown so far, numerous theoretical researches in the form of numerical models suggest that the main cause for a waterspout development lies within a concentrated pre-existing angular momentum of a convective process (Golden, 1971). It is thought that a waterspout develops from a low-level vortex which concentrates the vorticity of a rotating updraft on a cyclonic shear axis into a waterspout. Developing convective cells provide vorticity necessary for shrinking. Vortex presence in the base of cumuliform clouds is a necessary, but not sufficient condition for a waterspout development (Brady & Szoke, 1988; Simpson, McCumber, & Penc, 1986; Wakimoto & Wilson, 1989; Choy & Sprat, 1994; Ćurić, 2001; Wakimoto & Lew, 1993).

Waterspouts usually develop in the vicinity of a gust front and mesoscale convergence lines and shear axis (Ćurić, 2001; Choy & Sprat, 1994; Golden & Sabones, 1991; Simpson et al., 1991). Meteorological environment which favours waterspout development is characterized by high relative humidity, high surface water temperatures and weak tropospheric wind (Hess & Spillane, 1990).

Waterspouts are most frequent over the Florida Keys, southeast part of the USA and the Gulf of Mexico and are described in detail in the Lower Keys Waterspout Project (Rossow, 1970; Golden, 1971; Golden, 1973; Golden, 1974; Golden, 1977). Researches showed that the presence of warm shallow waters in lagoons and bays favoured waterspout development in this part of the USA. Waterspouts are most common in September on the Great Lakes in the USA. A big outbreak was in 2003, from September 27 to October 3, when a record 66 waterspouts were sighted on the Great Lakes. The cause of this outbreak was an above average water temperature of the Great Lakes, as well as the cold air breakthrough with the presence of jet stream (Szilagyi, 2004).

There are numerous research studies dealing with this problem in the region of the Mediterranean (Gianfreda, Miglietta, & Sansò, 2005; Giaiotti, Giovannonni, Pucillo, & Stel, 2007; Gaya, 2001; Matasangouras, Nastos, Bluestein, & Sioutas, 2014; Miglietta & Rottunno, 2016). Renko, Kozarić, and Tudor (2013) recorded a total number of 220 waterspouts in the 2001–2011 period, and the greatest number (65) was recorded in 2010. The most active month in the observed period was August and the most common period of the day for a waterspout to appear is between 8 and 10 hours.

The aim of this paper is the waterspout in Split (Figure 1) (φ 43.51 °N, λ 16.45 °E, h = 0 m), sighted on January 6, 2016 which swept over the city at 15:40-16:00 CET (14:40–15:00 UTC). According to available data about the waterspouts in the Adriatic Sea from 2011 to 2011, 12 cases in total were recorded within 6-day observation period in January. Therefore, this waterspout from January 6, 2016 is a rare meteorological phenomenon for this period of the year (Renko et al., 2013).

Figure 1. Photos of the waterspout in Split, January 6, 2016 and selected life cycle stages (according to Golden, 1974): I) spray-ring stage, II) mature stage, III) mature stage and IV) decay stage (https://www.youtube.com)

The research aim of this paper is to investigate synoptic and mesoscale situation, as well as meteorological conditions which created favourable thermodynamic environment which preceded the waterspout development process. Since this region in Croatia is not covered by meteorological radar, that aspect of research is missing.

Data and methodology

Following data have been used in the analysis of the waterspout:

- Archived data of surface and upper-level structure of the atmosphere (AT 500 mb/ wind at 300 hPa) (http://www1.wetter3.de);
- Synoptic diagrams of selected instability parameters (ML CAPE, LI, Soaring index) (http://www1.wetter3.de);
- Sounding data and wind hodographs from the stations in Zadar and Zagreb (SevereWeather.ch – Create Sounding, 2016);
- Satellite images from geostationary meteorological satellite METEOSAT (EUMeTrain, 2016)
- Storm forecast from ESTOFEX (European Storm Forecast Experiment, 2002) and ESWD (European Severe Weather Database, 2013);
- Surface sea temperature data (SST) provided by MODAS satellite (NRL 7320: Ocean Dynamics and Prediction Branch — Projects, 2016);
- Data obtained from the main meteorological station Split-Marjan (φ 43° 32' N, λ 16° 26' E, h = 122 m (Meteorological and Hydrological Service, 2016) (Figure 2);
- Photos and video recordings of the waterspout taken from various sources-newspaper articles, Internet, eyewitness accounts, etc.

Figure 2. Location of the main meteorological station Split-Marjan (basic map-base layer done by GPS Visualizer (2003–2016), and modified by the author)

The basic starting point of this research is the analysis of the macro- and meso-synoptic circulation, as well as quantifying main thermodynamic instability indices which caused the waterspout development. Taking into account the fact that this waterspout belongs to extraordinary and hazardous meteorological events, that is, atmospheric hazards, research methodology for extreme weather events has been used consequently. In order to get a better understanding of this meteorological phenomenon, a comparison method of a waterspout conceptual model has been used first (Golden, 1971; Golden, 1974), the method of synoptic and mesoscale analysis, as well as synoptic types method (Sioutas, 2011; Sioutas & Flocas, 2003), method of satellite image analysis, radiosounding analysis and wind hodograph analysis, analysis of sea surface temperatures of the Adriatic, method of thermodynamic instability indices analysis and Fujita scale method (*F*-scale) (Fujita, 1981):

$$V_F = 6.3\ (F + 2)^{1.5}, \qquad (1)$$

where V_F denotes the wind speed on F — scale [ms^{-1}]

Results and discussion

ESTOFEX (European Storm Forecast Experiment, 2002) issued a storm forecast valid from January 6, 2016 06 UTC till January 7, 2016 06 UTC. A level 1 warning was issued for certain parts of the Adriatic, mainly including strong wind gusts and large hail, as well as tornado. ESWD (European Severe Weather Database, 2013) recorded three tornado events on January 6, 2016 in the region of Split (φ 43.51 °N, λ 16.45 °E, h = 0 m).

Surface and upper-level (AT 500 mb) atmosphere structure over Europe on January 6, 2016 (Figure 3) had a complex baric topography.

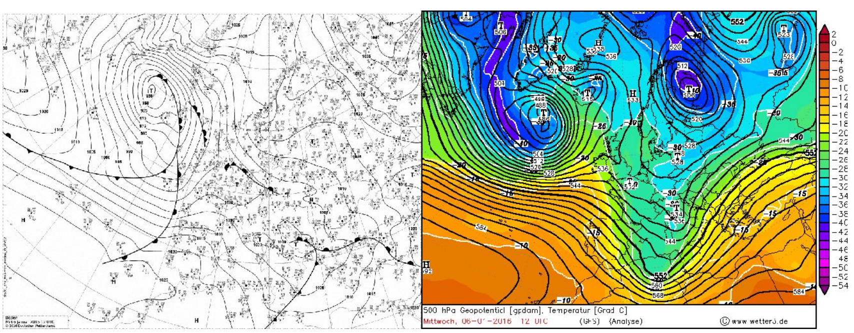


Figure 3. Surface weather map (left) and absolute topography map 500 hPa (right) over Europe, January 6, 2016 at 12 UTC (http://www1.wetter3.de)

At the surface (Figure 3-left), south of Iceland and Greenland, a cyclone with associated frontal systems was formed which deepened while moving eastward. South of this system, around the Azores and Madeira, a vast surface ridge was formed stretching all the way to Morocco and Algeria and isolated high pressure fields were noticed. Within the surface trough, a shallow cyclone over Great Britain and the Gulf of Genoa developed. Over the vast area of East European Plain a large surface ridge developed. Isobaric map of absolute topography AT 500 hPa (geopotential/temperature), in main synoptic periods, reveals a very complex upper-level baric topography (Figure 3-right). Two deep, vast upper-level cyclones with cold cores are noticed. The first cyclone was located south of Greenland and moved towards the east, becoming deeper during the day. Temperatures within the cyclone core were around −40°C. The other cyclone was above the White Sea, was not as deep as the first one and closed by an isotherm of −40°C, which indicated a very cold core. Within this cyclone, there was a deep trough in the form of a short wave which stretched to the West Siberian Plain. An upper-level cyclonic field developed at the end of the trough. During the day, the trough broke off from the cyclone and a separate secondary cyclone was formed. Between these cyclones, there was a vast, deep upper-level trough in the form of a long wave. This upper-level trough was associated with the cyclone whose centre was above the White Sea. At 00 UTC, the trough axis stretched over the Baltic Sea, Germany, Northern Italy, the Gulf of Genoa, and Balearic Islands to the coast of Algeria. This upper-level trough moved zonally towards the east during the day and, within its axis, there was a channel of low geopotential heights which marked the advection of cold air coming from the north. A strong, upper-air south-west flow was pronounced in the front part of the trough within which warm moist and unstable air was coming from Africa. In the period from 12 to 18 UTC, this trough was passing above the Adriatic Sea, which caused subsidence of cold upper-level air. Since the air above the surface was warm and moist, it caused atmospheric instability. This analysis will focus on the study of mesoscale synoptic situation in the area of central Dalmatia which preceded and followed the process of development, formation and intensification of the tornadic waterspout in Split.

Strong tornadic waterspout developed on the sea near Split on January 6, 2016 at 15:50 CET (14:50 UTC). Synoptic situation indicated the presence of a cyclone closed by 1,000 mb isobar with associated frontal systems in the central part of the Adriatic Sea. An upper-level south-west flow developed at 500 hPa level and an upper-level trough with a cold air mass of around -28/30°C was sighted. Therefore, a negative (cold) air temperature advection was present in the upper level. High water temperature of the Adriatic in this time of the year (15-16°C) was being pushed forward by both the cold air descending from upper levels, and the air within the cold front at the surface. A convergence line was formed at the surface and such mesoscale synoptic environment favoured convective initiation and intensification (Figure 4).

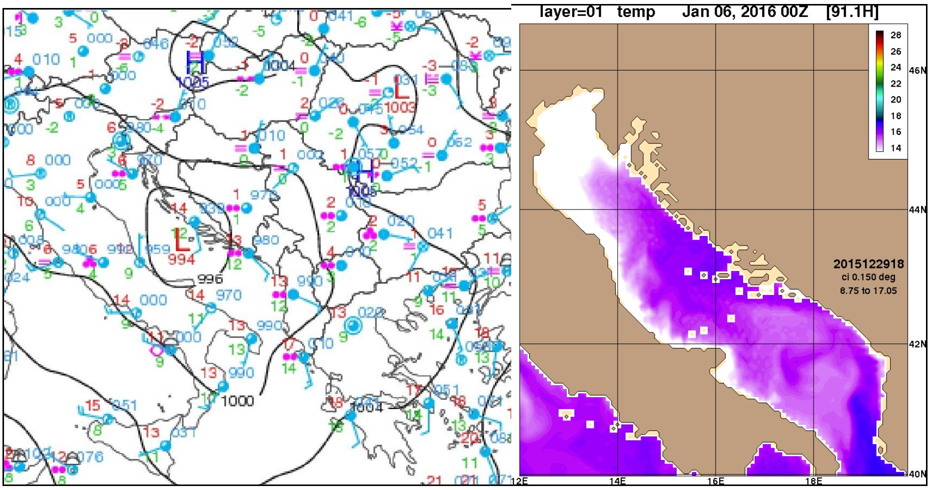


Figure 4. Enlarged SYNOP at 14 UTC (left) and forecasted sea surface temperature (SST) of the Adriatic Sea (right) at 00 UTC, on January 6, 2016 (MétéoCentre: Centre Météo UQAM Montréal 2016) (NRL 7320: Ocean Dynamics and Prediction Branch- Projects, 2016)

On the absolute topography map 700 hPa (Figure 5-left), an area of high relative air humidity over the region of Central Dalmatia closed by an isoline of 90% has been sighted. High values of relative air humidity, surface cyclone and convergence line associated with the passing front, as well as strong updrafts, undoubtedly favour waterspout development. Such high humidity, as well as positive vorticity advection and the presence of horizontal field of positive divergence within the jet stream, indicated a strong ascending air movement and convection. The absolute topography map 300 hPa (Figure 5-right) indicates the presence of a jet stream whose axis was above the Adriatic, that is, above the cyclone and surface frontal zone. Wind speeds on the jet stream periphery ranged from 60 to 100 Kn, while in the axis itself exceeded 160 Kn. A pronounced horizontal field of positive divergence supplied by kinetic energy from the jet stream has been noticed as well. This area of positive divergence at 300 hPa height causes surface air convergence, which favours ideal conditions for a waterspout development.

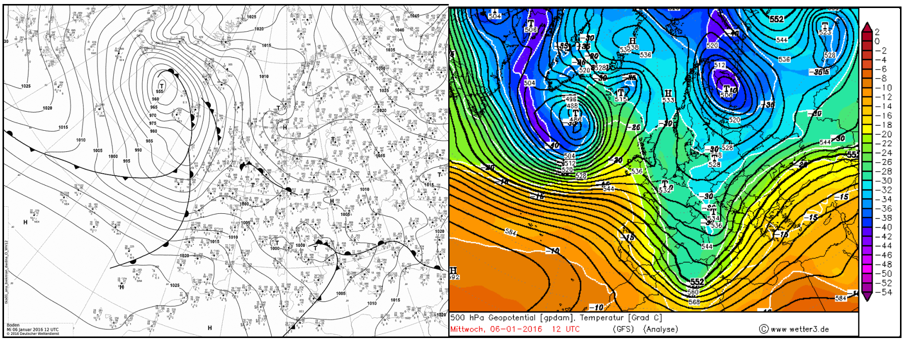


Figure 5. Relative humidity at 700 hPa (left) and absolute topography, jet stream and divergence filed at 300 hPa (right) over Europe, January 6, 2016 at 12 UTC (http://www1.wetter3.de)

According to the circulation on the absolute topography map and the position of upper-level trough related to the features on the surface baric topography (Figure 3), synoptic type determined for this situation is SW (South-west Flow). It can be concluded that in the period of July–November, 2002, two cases of tornadic waterspouts on the Adriatic were recorded considering SW synoptic type. No case of fair weather waterspout was recorded in the observed period considering this synoptic type (Figure 6).

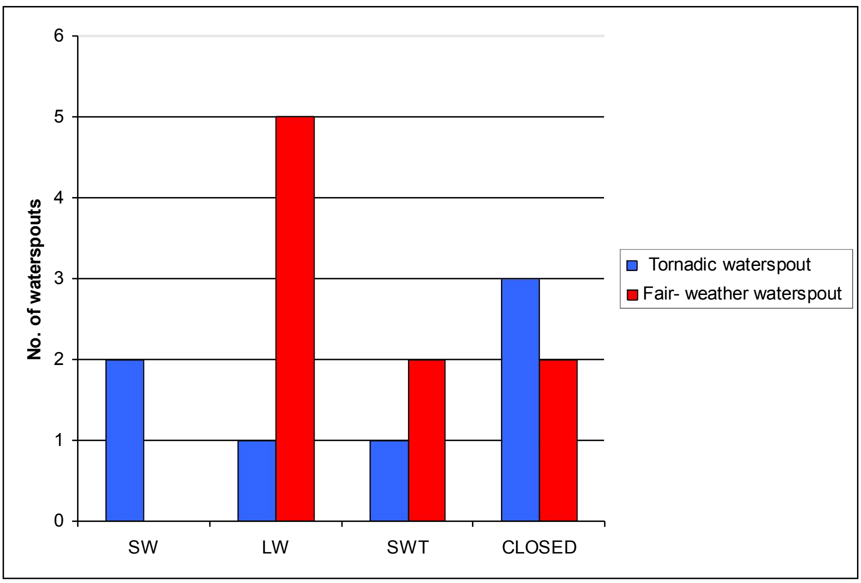


Figure 6. The number of waterspouts in the Adriatic Sea according to the type of synoptic situation-SW (south-west flow), LW (long-wave trough), SWT (short-wave trough) and CLOSED (closed low), July–November, 2002 (according to Sioutas & Keul, 2007)

In order to obtain a better understanding of mesoscale processes which preceded and followed the process of waterspout development, key meteorological parameters forecasted by GFS model for 12 UTC and 18 UTC synoptic periods were analysed. The areas of origin, formation, development and effect were investigated. Estimated data of GFS model[3] (Figure 7) indicate the ML CAPE value of around 500–600 *J/kg* (it is a positive CAPE value-from 0–1,500 *J/kg*). This value of instability parameter was not sufficient for the development of a strong convective process. Estimated value of LI parameter was −2, which indicated marginal instability. Vertical movement in observed area ranged from −38 to −46 hPa/h, which indicated strong convective updrafts, pronounced deep moist convection and formation of cumuliform clouds. Such pronounced vertical movements tilted and stretched low-level rotation formed at the surface and created the waterspout at the base of Cb cloud. A strong SW high level wind (43–47 knots) and the area of positive relative vorticity (18–20 [10 E $-5/s$]) favoured the situation. In this case the argument is approved by the fact that the absolute advection vorticity at 500 hPa geopotential height was positive and had values of 0.1–0.15 [1/(h*h). Soaring index had forecasted values of 25–30 K for this particular area, which indicated frequent rain showers and 40–60% risk of storms. Parameters analysis showed that the whole meteorological situation favoured waterspout development and formation of deep moist convection. Wind parameters and pronounced vertical movement, supported by directional and speed shear, as well as by positive values of relative vorticity and absolute vorticity advection showed the same thing.

[3] Global Forecast System (GFS) is a coupled numeric computer model composed of two parts-the first has a higher resolution and forecasts the weather up to 8 days ahead, and the second has a lower resolution forecasting the weather from 8 to 16 days ahead. It is composed of four separate models-an atmospheric model, an ocean model, a land/soil model, and a sea ice model. The operational weather forecast uses GFS model of 28 km horizontal resolution between grid points. This forecast model was produced by NOAA NCEP (National Oceanic and Atmospheric Administration, 2016b; Models — OpenWeatherMap, 2012–2016).

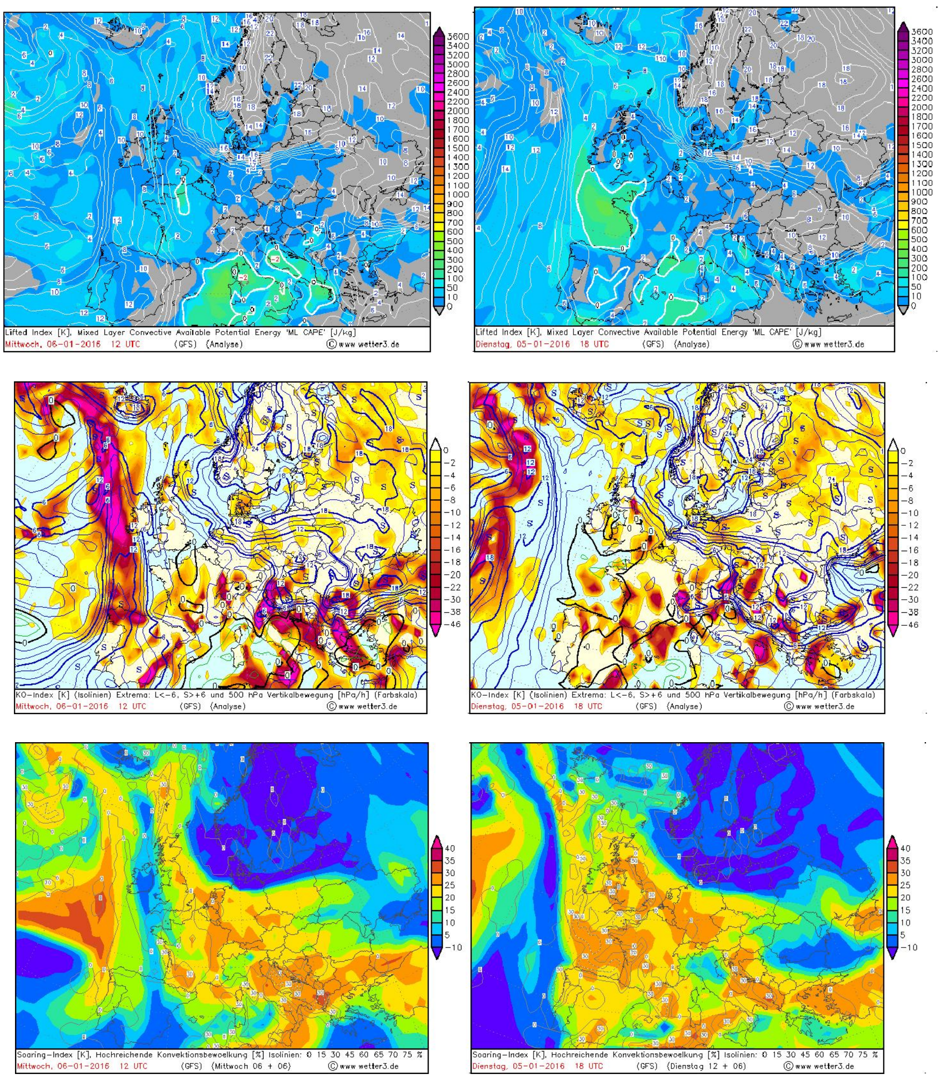


Figure 7. (a–c) Forecasted GFS model parameters at 12 and 18 UTC, January 6, 2016 (a) LI and 'ML CAPE', (b) KO index and vertical movement, (c) Soaring index

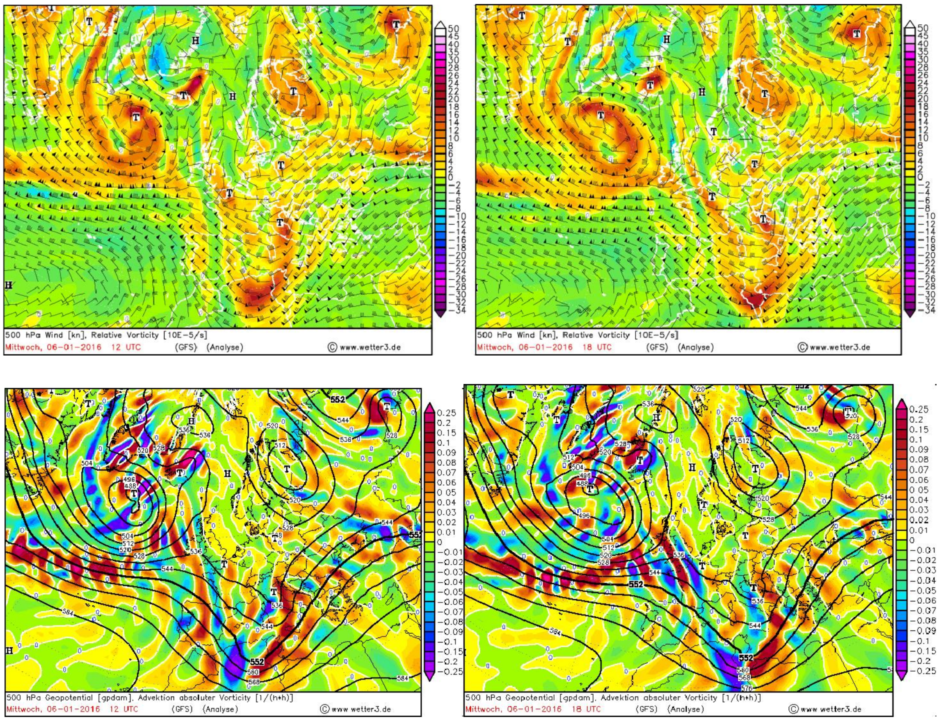


Figure 7 (d–e)**.** Forecasted GFS model parameters at 12 and 18 UTC, January 6, 2016 (d) relative vorticity and wind at 500 hPa, (e) absolute vorticity advection at 500 hPa (http://www1.wetter3.de)

Thermodynamic (skew-t) diagram and wind hodograph for Zadar (14430) and Zagreb (14240) stations were analysed on January 6, 2016 at 12 UTC (Figure 8).

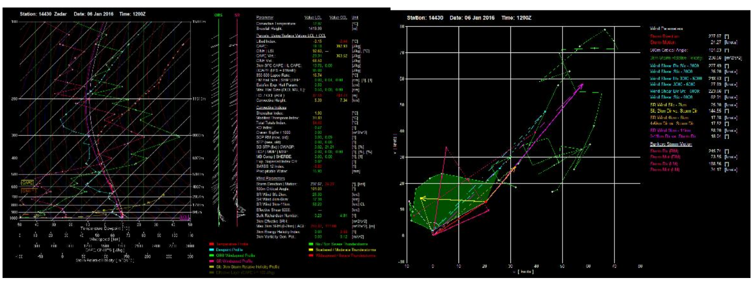


Figure 8. Sounding (skew-t) and wind hodograph for the Zadar station, January 6, 2016 at 12 UTC (SevereWeather.ch — Create Sounding, 2016)

Since the nearest radiosounding data were available for Zadar and Zagreb stations and, bearing in mind that sounding stations should be at a distance of up to 300 km in diameter and ±3 *h* from the waterspout event (Sioutas & Keul, 2007), it can be said that this requirement was fulfilled. Vertical profile of the atmosphere for Zadar indicated marginal instability from the lowest layers, and the CAPE value (392.93 *J/kg*) is indicative of scattered moderate storms. Instability was present at the lowest levels (*LCL/CCL(AGL)* =484.74 *m*), which favoured the waterspout development, while convective height was at 7.34 km, which again indicated the possibility of scattered, but also severe thunderstorms. Since the temperature of the adiabatically rising particle was higher than the temperature of the environment in the 850–600 mb layer, there was a great possibility of scattered thunderstorms to appear. Convective instability indices which indicated a wide spread severe thunderstorm event were TT index (54.40 °C) and SWISS 12 index, with the value of −8.80. Figure 9. shows a comparative survey of estimated values of some instability parameters based on the radiosounding data at 12 UTC and their total mean values for the Adriatic (Sioutas & Keul, 2007).

Wind parameters in this profile indicated the directional and speed wind shear from the surface up to the level of 700 mb (2,854 m). The greatest changes in wind speed and direction were in the 900–800 mb layer, and then the wind speed suddenly increased in the 700 mb layer. The thunderstorm was moving at the speed of 24.27 knots and at the angle of 238 degrees. Active wind parameter was SRH (0–2 km) max 3 km and amounted to 243.02 m^2/s^2 indicating wide-spread severe thunderstorms. Similar results were obtained from the sounding data at the Zagreb station.

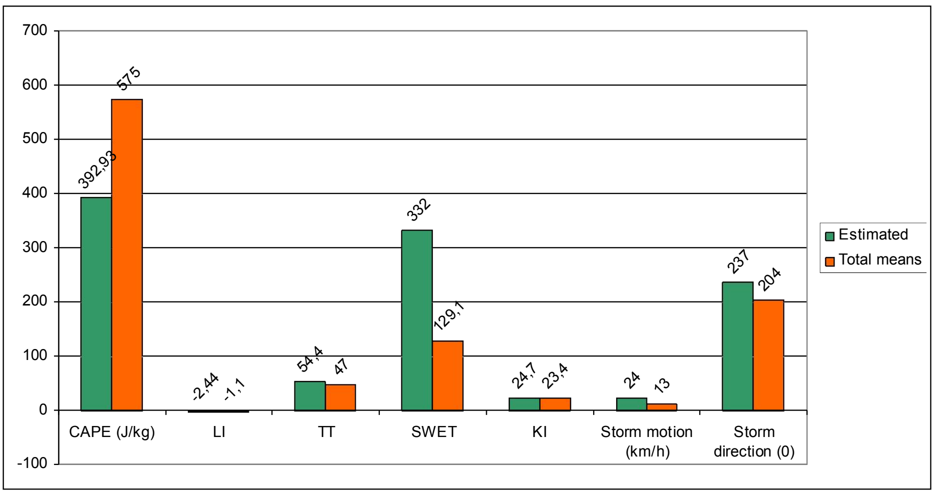
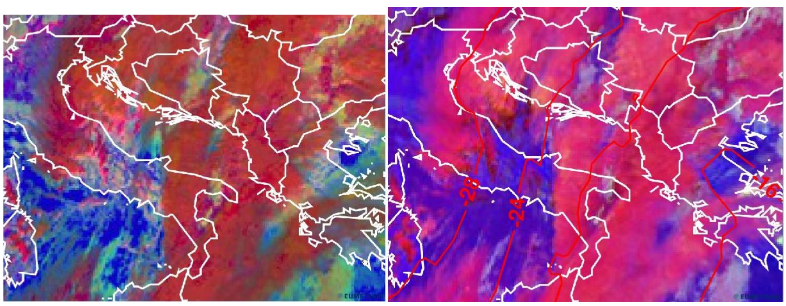


Figure 9. Estimated values of some instability parameters at 12 UTC, January 6, 2016 for the Zadar station (green) and their total mean values for the Adriatic (orange) (according to Sioutas and Keul, 2007)

Various products of the second generation meteorological satellite (METEOSAT) (Figure 10, a, b, c, d) indicate that there was a compact cloudiness in the area of the cyclone and associated frontal systems over the north of the Adriatic and central Dalmatia, which corresponded with the synoptic situation on that day. Convective developments and their north-east movement under the influence of southwest high level flow were sighted. Figure 10 a) indicates the orange parts of the convective cell over the area of Split. Convective cloudiness included ice crystals, which also indicated a strong updraft and a rapid convective cell development under the influence of southwest high level flow. Figure 10 b) with its yellow and red colours indicated the presence of small ice crystals, thick ice clouds and developing convective cell. Yellow-orange colour indicated very cold cloud tops formed by the updraft. Quite low temperatures of the cloud top (isotherm $-24^{\circ}/-28^{\circ}$C at 500 mb) and small ice crystals on the anvil were noticed. Figure 10 c) with its cyan colour indicated high frontal Cb clouds, which corresponded with the synoptic situation.

a) b)



c) d)

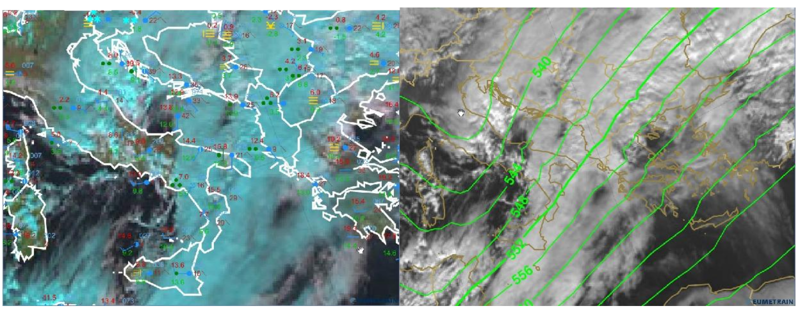


Figure 10. a) Dust RGB, b) Severe Storm RGB+T500, c) Natural Colour RGB+SYNOP, d) VIS0.6+H500, January 6, 2016 at 12 UTC (EUMeTrain, 2016)

Figure 10 d) in the combination of a visible channel (VIS 0.6) is one of the three solar channels and with its white colour indicated thick (white) clouds of a convective cell within the cyclonic cloudiness, and geopotential isolines indicated the 536–540 hPa height in the high level trough.

Discussion and conclusion

A waterspout developed over the Adriatic Sea in the vicinity of the city of Split, on January 6, 2016, at around 15:50 CET (14:50 UTC). This meteorological phenomenon was registered at the main meteorological station DHMZ Split-Marjan (http://klima.hr/razno.php ?id=zanimljivosti&param=zn12012016). There was a convective development in the high level southwest flow within the cloudiness which followed a surface cyclone and associated frontal disturbances. A pronounced thermodynamic instability developed in lower and central layers of the atmosphere-the cold front passage over the warm Adriatic waters as a main synoptic feature, pronounced directional and speed wind shear, as well as the presence of jet stream and pronounced horizontal field of positive divergence over the observed area.

According to the available data from the main meteorological station Split-Marjan (http://klima.hr/razno.php? id=zanimljivosti&param=zn12012016), and the web page (Crometeo, 2016), precipitation amount that day was 20.6 mm with hail occurrence, and the strongest wind gust was 24 m/s from the southwest direction. The cloud base was at 300 meters. The lowest value of atmospheric pressure (sudden pressure drop) of about 977.5 mb (15:58 CET) was registered during the waterspout passage. Air temperature at 2 m height was around 12.6^{0}C. Three waterspouts developed within the frontal cloudiness, the biggest and most destructive entered the land from the sea in the area of Zvoncac (Crometeo, 2016) at 15:55 CET (14:55 UTC). Estimated path length of the waterspout was about 400 m and the funnel width at the ground was estimated at about 50 meters, while close bellow the cloud base at about 100 m. The waterspout had a well-defined funnel moving downward and the reaching the water surface. There were no injured people since the waterspout swept over the thinly populated part of the city. The waterspout caused only a minor damage (Figure 11). The decay and dissipation process of the waterspout started by its collision with the Marjan hill.

Figure 11. A damage segment made by the waterspout in Split on January 6, 2016 (Crometeo, 2016)

Based on field survey analysis and damage estimates, and applying the equation (1), it can be concluded that the waterspout which swept over the city of Split on January 6, 2016 was *F*0 waterspout on the Fujita scale (wind speeds for *F*0 category range up to 33 *m/s*).

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