

SEVERE WEATHER WARNINGS FOR SOFIA, BULGARIA:
MAY – SEPTEMBER 2010–2019

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Abstract

Severe weather monitoring and forecasting is the prime task of the National Meteorological Services according to World Meteorological Organization Guidelines (WMO). Since 2009 Bulgarian National Institute of Meteorology and Hydrology (NIMH) issues 48 h ahead severe weather warnings as a contribution to the European warning system (METEOALARM). A total of 243 days with warnings for heat, thunderstorms and intense rain were issued for the period May–September 2010–2019. The monthly maximum for heat is 42 days in July, for thunderstorms it is 26 days in June, and for intense rain it is 27 days in June. Objective circulation classification is conducted which shows that the majority of heat warnings are associated with Anticyclonic and West flow circulation types. About 40% of thunderstorm warnings are of Cyclone type followed by 28.6% of Cyclonic Directional types. For rain warnings, most of the days are with Cyclone type (46.2%) and Cyclonic Directional types (27.5%). Analysis of Global Navigation Satellite Systems (GNSS) derived Integrated Water Vapour (IWV), from the Bulgarian station in Sofia, shows consistently higher values for the days with METEOALARM warnings for heat, thunderstorm and rain.

Key words: severe weather warning, METEOALARM, heat, thunderstorms, intense rain, objective circulation classification, GNSS, Integrated Water Vapour

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Introduction. Nowcasting severe weather has been ongoing in Europe and Bulgaria with the METEOALARM website serving as an important warning tool [1]. The METEOALARM is a part of the European Multi-service Meteorological Awareness Project, developed by EUMETNET. The METEOALARM website issues hazardous weather information from National Meteorological and Hydrological Services (NMHSs) within the WMO across 38 European countries. Hazardous weather warnings cover 12 phenomena: wind, snow or ice, thunderstorm, fog, high temperature, low temperature, coastal event, forest fire, avalanches, rain, flooding, and rain flood. The awareness level is colour-coded with yellow for moderate, orange for severe and red for extreme weather events. Mediterranean cyclones are often the driver of severe weather events in Southeastern Europe that include heavy rainfall and flooding, thunderstorms with intense lightning activity, windstorms and dust storms, tornadoes, storm surges, and landslides, and compounding effects [2]. According to FLAOUNAS et al. [3] the most important factors for Mediterranean cyclone dynamics are upper-tropospheric forcing, baroclinic instability and southward deviations of the polar jet. That causes air masses with high potential vorticity to intrude into the Mediterranean area, which is a trigger for baroclinic instability similar to extratropical cyclones over open oceans [3]. In the last two decades GNSS tropospheric products in Near Real Time (NRT), delivered within 90 minutes observation threshold, became an established remote sensing method for operational Numerical Weather Prediction and monitoring IWV [4]. Advancement in GNSS processing and the high spatiotemporal coverage facilitated application in short term weather forecasting (nowcasting, WMO [5]) of convection, heavy precipitation, hail, thunderstorms, fog [6], and foehn [7]. Relation between precipitation and IWV was first reported by BENEVIDES et al. [8] for the Lisbon region in Portugal. Precipitation probability was found to be 70% for IWV values higher than 42 kg/m^2 . More importantly, they report a close to linear increase of precipitation probability with an incremental increase of IWV. CALORI et al. [9] analyzed GNSS IWV and hail storms for Mendoza province in Argentina and reported that the positive IWV anomalies tend to be associated with hail registrations while the negative IWV anomalies result in precipitation only. INOUE and INOUE [10] report a time lag of 15–30 minutes for 40% of lightning strokes and maximum of IWV in Kanto District, Japan. GUEROVA et al. [11] used stepwise discriminant analysis to derive classification functions for thunderstorm nowcasting based on GNSS IWV and 8 Instability Indices for Sofia, Bulgaria. A machine learning approach is used by LOS et al. [12] for thunderstorm nowcasting of GNSS tomography-based vertical wet refractivity profiles and IWV in Poland. The results show that wet refractivity below 7 km one-two hours ahead of the thunderstorm and IWV one-three hours ahead and to the west of the thunderstorm are amongst the most significant parameters with predictive potential. The aim of this manuscript is to analyze severe weather in Sofia, Bulgaria registered in METEOALARM and its link to objective circulation classification

of Mediterranean cyclones and GNSS derived IWV.

Data and methods. Since 2009, NIMH has issued operational METEOALARM warnings for 11 parameters namely, strong wind, intense precipitation, thunderstorm, snow storms, extreme high temperature and heat waves, extreme low temperatures and cold waves, fog, sea waves and landslides, operationally [13]. METEOALARM warnings in Bulgaria can be used as an indicator for subjective evaluation for severity of the meteorological events in different months and years. For example, a study by STOYCHEVA et al. [14] reports that for a 4-year period NIMH issued more than 500 weather warnings.

For objective circulation classification the Cost733class software version 1.2 (Cost733class v1.2, PHILIPP et al. [15]) is used. The Cost733class v1.2 includes over 20 classification methods. Based on a previous study by STOEVE et al. [16] we select Jenkinson–Collison Type (JCT) method, which is threshold-based classification method with circulation types defined by using a numerical threshold for circulation indices. The main advantage of threshold-based classifications is that they discriminate between synoptically significant types [15]. The assignment of cases is automated by using threshold values for three indices (zonal and meridional flow and vorticity) that result in three states (low, intermediate and high) and 26 circulation types. To derive JCT circulation types JENKINSON et al. [17] automated scheme is applied to daily 850 hPa geopotential height fields from ERA5 reanalysis [18]. The JCT26 is computed for domain Southeast Europe and includes 8 directional types, West (W), South-West (SW), North-West (NW), North (N), North-East (NE), East (E), South-East (SE) and South (S), 8 Anticyclonic directional types (AW, ASW, ANW, AN, ANE, AE, ASE and AS), 8 Cyclonic directional types (CW, CSW, CNW, CN, CNE, CE, CSE and CS) as well as Cyclonic (C) and AntiCyclonic (AC) type.

In this work the GNSS tropospheric products are from stations Sofia – Plana (SOFI, altitude 1164 m asl). GNSS derived IWV is computed as follows:

$$(1) \quad IWV = \frac{10^6}{(k_3/T_m + k'_2)R_v} \left(ZTD - 0.0022768 \frac{p_s}{1 - 0.00266 \cos(2\theta) - 0.00028h} \right)$$

where, ZTD is Zenith Total Delay, $k'_2 = (17 \pm 10)$ [K/hPa], $k_3 = (3.776 \pm 0.004)10^5$ [K²/hPa] are constants and $R_v = 461.51$ [J/(kg K)] is the gas constant for water vapour, $T_m = 70.2 + 0.72t_s$ [K] is the weighted mean atmospheric temperature, h [km] is the height and θ is the latitude variation of the gravitational acceleration. The pressure difference between the GNSS and WRF model altitude is calculated using the polytropic barometric formula.

Results. For the period May–September 2010–2019 NIMH issued a total of 243 days with warnings for heat, thunderstorms and intense rain for Sofia. The yearly heat maximum of 21 days is in 2012 (Fig. 1a) from which orange code warnings are 8 and yellow code warnings are 13. As seen from Fig. 1b, the yearly

thunderstorm maximum of 16 days with both orange and yellow code warnings is in 2018, where one day is with orange code and 15 days are with yellow code warnings. The yearly rain maximum of 20 days with both orange and yellow code warnings is in the same year 2018 (Fig. 1c). There were 3 days of orange code warnings for rain, and 17 days with yellow code warnings. For the period 2010–2019 the monthly heat maximum of 42 days is in July with both orange and yellow code warnings as follows: 34 yellow and 8 orange (Fig. 1d). As seen from Fig. 1e, the monthly thunderstorm maximum of 26 days of yellow and orange code warnings is in June with 24 yellow and 2 orange warnings. The monthly rain maximum is split between May and June, both with 26 and 27 days of warnings (Fig. 1f). June can be considered with more rain if it is taken into consideration that there are more days with the stronger orange code than in May. In June there are 4 days of orange code warnings and 23 days of yellow code warnings. In May there is one day of orange code warnings and 25 days of yellow code warnings.

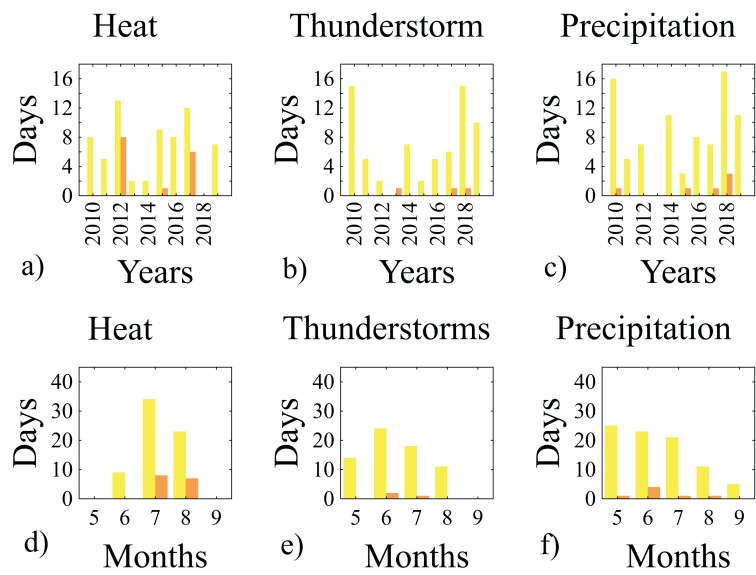


Fig. 1. Yearly (a, b, c) and monthly (d, e, f) warnings climatology from May to September 2010–2019 in Sofia. a) and d) heat, b) and e) thunderstorm, and c) and f) rain. The colour indicates the code of the warning

The frequency distribution of circulation type associated with a severe weather warning issued represents well the climatic characteristics of the investigated warm part of the year in Bulgaria. Figure 2 presents the JCT26 circulation types for days with heat, thunderstorm and rain warnings issued for Sofia from May to September 2010–2019, respectively. For heat days the dominating circulation is Anticyclonic (A) with a total of 27 days from which 22 days are with yellow

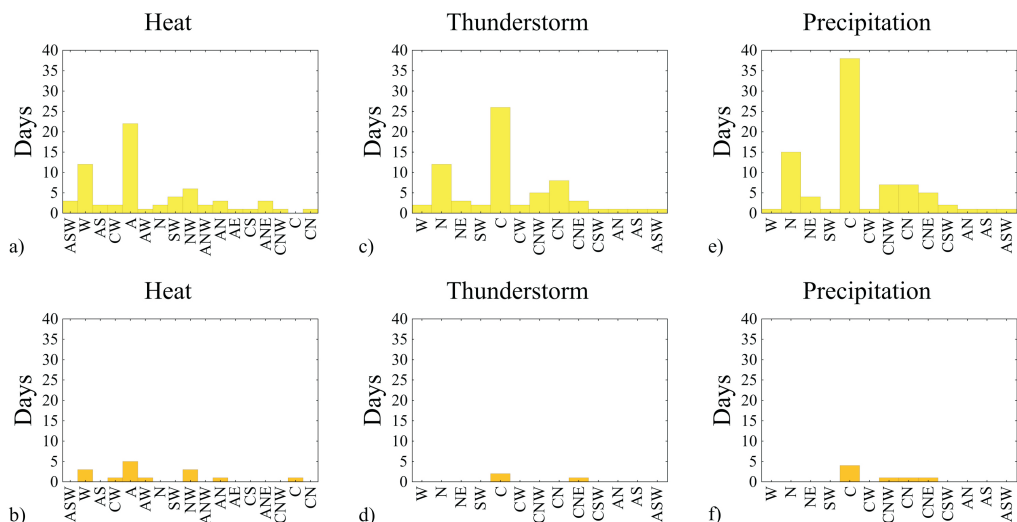


Fig. 2. Objective circulation classification for days with warnings from May to September 2010–2018 in Sofia. a) and b) heat yellow and orange code. c) and d) thunderstorm yellow and orange code. e) and f) rain yellow and orange code

(Fig. 2a) and 5 days are with orange code warnings (Fig. 2b). This is around 33.3% of all the heat warnings. Second is the West (W) type, which is with 15 days of warning (12 days – yellow and 3 days – orange) or 18.5% of all the heat warnings. For the W type there is an Anticyclone over South Africa, which brings hot tropical air over South Europe. The third circulation with 11% is the North-West (NW) with 9 days from which 6 days with yellow and 3 days with orange code. For NW circulation type an anticyclone is over West Mediterranean with the hot air advected from West Europe to Southeast Europe. In Fig. 2c and d are presented the days with yellow and orange thunderstorm warnings. The dominating circulation type is Cyclonic (C) with a total of 28 days from which yellow codes are 26 days (Fig. 2c) and orange codes are 2 days (Fig. 2d). This gives around 40% of all the thunderstorm warning to C type. Second is the North (N) circulation type, which is for 12 days with yellow code only, i.e. 17%. The thunderstorms registered for N circulation type are due to cold front passage over Bulgaria and low pressure system east of Bulgaria over the Black sea. The third is the Cyclonic North (CN) circulation type with 8 days all with yellow code, which is 11.4%. For CN type the cyclone is over Asia Minor and the thunderstorms develop in the cold air mass behind the cold front as a result of radiated heating and topography. For the days with yellow and orange rain warnings, presented in Fig. 2e and f, the dominating circulation is Cyclonic with a total of 42 days from which 38 days are with yellow code and 4 days are with orange code. This makes 46% of all rain warning days. The second circulation type is the North (N) with

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Circulation groups associated with heat (line 2), thunderstorm (line 3) and rain (line 4) warnings in the period from May to September 2010–2019. For Directional (D), Cyclonic Directional (CD) and Anticyclonic Directional (CD) groups as well as Cyclone (C) and Anticyclone (A) types

Warning type	D	CD	AD	C	A
Heat	37%	21%	–	33.3%	
Thunderstorm	27.1%	28.6%	40%	–	
Rain	23.1%	27.5%	46.2%	–	

15 days, all with yellow code. This is 16% of all rain warnings. The third place is split between Cyclonic North (CN) and Cyclonic North-West (CNW) circulations type, each with 8 days from which 7 days yellow code and one day with orange code. CN and CNW are with 8.8% of all rain warning days. For CNW circulation type the cyclone centre is located north of Bulgaria over Ukraine and the intense rain is associated with passing of cold atmospheric front.

Table 1 presents a summary of the circulation groups associated with heat, thunderstorm and rain warnings for May–September 2010–2019. When the days with heat warnings are separated according to the group most of the days are in the Directional group. There are 30 days, which is 37% of the total heat warnings. The dominating direction is West (W) with 15 days, followed by North West (NW) with 9 days. The Anticyclone type is with 27 days, which is 33.3% of the heat warnings and the Cyclonic Directional group is with 17 days, which is 21%. For thunderstorm warnings, most of the days are with Cyclone type. There are 28 days, which is 40% of the total thunderstorm warnings. The Cyclonic Directional group is with 20 days, which is 28.6% and the Directional group is within 19 days, which is 27.1%. For rain warnings, most of the days are with Cyclone type. There are 42 days, which is 46.2% of the total rain warnings. The Cyclonic Directional group is within 25 days, which is 27.5% and the Directional group is within 21 days, which is 23.1%.

Figure 3 presents comparisons between monthly mean IWV for the days without warnings (green bar) and days with yellow and orange code warnings for: a) heat, b) rain, and c) thunderstorm from May to September 2010–2018. IWV is higher in days with yellow and orange code warnings than in days with no warnings for all the studied categories namely heat, thunderstorm and rain. For heat the difference is most distinguished in June with monthly mean IWV 23.7 kg/m² for days with no warnings (green bars in Fig. 3a), versus mean IWV of 27.1 kg/m² for days with yellow code (yellow bars in Fig. 3a). As seen from Fig. 3a there was no orange code issued for heat for June. For rain in May the mean

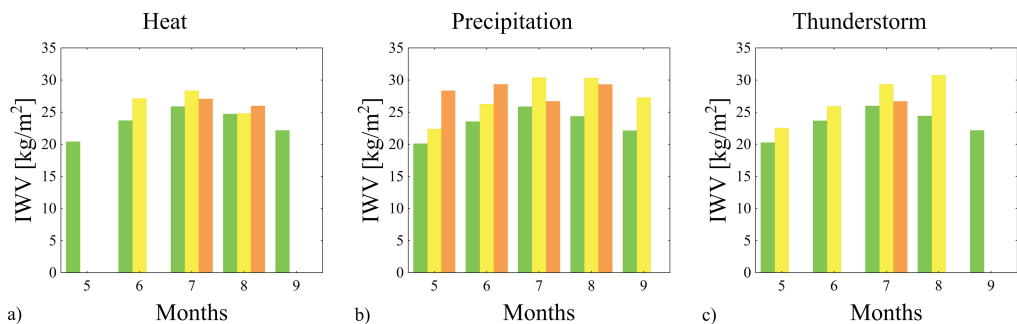


Fig. 3. Monthly mean IWV for a) heat, b) rain, and c) thunderstorm warnings. The colour indicates the code of the warning. The green colour bars are for the monthly average IWV for the days without warning

IWV difference is most distinguished, especially during orange code days (Fig. 3b). Monthly mean IWV climbs up to 28.35 kg/m^2 in orange coded days and is 20.09 kg/m^2 in no warning days (green bars in Fig. 3b). For yellow coded days IWV is 22.40 kg/m^2 . The smallest IWV difference is in July. For orange code days the monthly mean IWV is 26.70 kg/m^2 , versus 25.86 kg/m^2 for no warning days. Yellow code days monthly mean IWV in July for rain climbs up to 30.38 kg/m^2 . For thunderstorm warnings August is most distinguished with monthly mean IWV of 24.4 kg/m^2 for no warning days (green bars), versus 30.7 kg/m^2 for days with yellow METEOALARM code.

Discussion and conclusions. In this paper we present an analysis of the METEOALARM warning issued by the National Institute of Meteorology and Hydrology (NIMH) for the warm part of the year May–September 2010–2019 in Sofia, Bulgaria. NIMH issued a total of 243 days with warnings for heat, thunderstorms and intense rain. The monthly heat maximum of 42 days is in July with 34 yellow and 8 orange warnings which correlates with climate – the absolute temperature maximum in Bulgaria was reached in July. For thunderstorm warning June is with a maximum of 24 yellow codes and 2 orange codes. For rain the maximum is in June with 27 days followed by May with 26 days. With respect to objective circulation classification the majority of heat warnings (37%) are of Directional type (W, NW, N, NE, E, SE, S, SW) followed by Anticyclone type (33.3%). About 40% of thunderstorm warnings are of Cyclone type followed by 28.6% Cyclonic Directional types (CW, CNW, CN, CNE, CE, CSE, CS, CSW). For rain warnings, most of the days are with Cyclone type (46.2%) and Cyclonic Directional types (27.5%). Analysis of GNSS derived IWV for the days with METEOALARM warnings for heat, thunderstorm and rain shows consistently higher values when compared with the days without warnings.

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