DOI:10.28974/idojaras.2022.4.5

IDŐJÁRÁS

Quarterly Journal of the Hungarian Meteorological Service
Vol. 126, No. 4, October – December, 2022, pp. 545–566

Synoptic circulation patterns associated with foehn days in Sofia in the period 1979–2014

Krasimir Stoev [1,2,*], **Piia Post** [3], and **Guergana Guerova** [1]

[1] *Sofia University "St. Kliment Ohridski"*
Physics Faculty, Department Meteorology and Geophysics
5 James Bourchier blvd., BG-1164 Sofia, Bulgaria

[2] *National Institute of Meteorology and Hydrology*
66 Tsarigradsko shose Blvd., 1784 Sofia, Bulgaria

[3] *Institute of Physics University of Tartu, Estonia*

**Corresponding author E-mail: krasimir.stoev@gmail.com*

(Manuscript received in final form September 12, 2021)

Abstract— Foehn is a well-known example of local atmospheric circulation and is an extreme weather event for wind gusts. It can cause rapid snowmelt in spring or spread of forest fire in summer, as well as significant economic losses. The foehn in Bulgaria is observed on the northern slopes of the mountains. For the period 1979–2014, 261 foehn days are registered north of the Vitosha mountain, where Sofia valley is located. The average annual number of foehn days is 8.1, 8.3, and 4.5 for the periods 1985–1994, 1995–2004, and 2005–2014. After 2004, the average annual number of days with foehn decreases, and the lowest maximum wind gusts are registered. To check whether atmospheric circulation changes, could be the reason for this change two objective circulation classifications and a manual one are used to study the foehn occurrence in the Sofia valley. Based on the GrossWettertypen (GWT) catalogue of circulation patterns produced by the COST Action 733 and ten circulation types of the Jenkinson-Collison (JCT) catalogue of weather types the largest number of foehn days occur at the SW, W, and NW circulation patterns. GWT and JCT classifications with 26 types confirm the foehn occurrence during the W and SW flows, but add two more cyclonic types, the CW and CSW. For the foehn days in March 1979–2014, best agreement was found with the manual circulation classification with 26 types. A comparison between the decades 1995–2004 and 2005–2014 shows a substantial decrease in western and northwestern circulation types during the foehn days. An analysis of circulation types for all days confirms an overall reduction of W and NW circulation types after 2004.

Key-words: foehn climatology, manual classification, objective circulation classification

1. Introduction

Foehn is a well-known example of local atmospheric circulation with warm and dry wind blowing on the leeward side of the mountains. This severe weather event caused by wind gusts can trigger rapid snowmelt in spring, forest fire spread in summer, or disruption in air traffic all year. On the Balkan Peninsula, the foehn events are closely linked to the development of cyclonic vortices in the presence of a strong flow. The Mediterranean Sea is a well-known area, where cyclones form. Mediterranean cyclones and their formation, frequency, trajectories, and influence on the weather and the climate of the Balkan Peninsula have been studied by many authors (*Stanchev*, 1954; *Pisarski*, 1955 (a,b); *Blagoev*, 1961; *Martinov*, 1967; *Peiter,* 1975; *Radinovic,* 1987). *Bocheva et al*. (2007) report that the monthly and annual distribution of the cyclones generated over the Mediterranean for the period 1980–2001 show the highest cyclone frequency during winter (from December to March). The cyclonic activity decreases in April, when cyclones appear three times less frequently than in March. From May to September, cyclogenesis is a rare phenomenon. The number of cyclones strongly increases in November, being four times higher than in October. *Marinova et al.* (2005) find that: 1) after 1990, the cyclogenesis season over the Mediterranean Sea is two months shorter, and it is located mainly over the central part of the sea and 2) the largest number of Mediterranean cyclones pass over the southern part of the Balkan peninsula. The first study of the Mediterranean cyclone trajectories was by *Van Bebber* (1891). Since then, the main paths of the Mediterranean cyclones and their seasonal variability have been studied by many authors (*Pisarski,* 1955 (a,b); *Popova et al.*, 1975; *Martinov*, 1983; *Jansa et al.,* 2001; *Bartholy et al.,* 2009, *Catrina et al.,* 2019). Three main trajectories are reported, namely: 1) through Croatia and Hungary (NW), 2) through the Adriatic Sea and the Balkan Peninsula toward the Black Sea (E), and 3) southern parts of the Balkan Peninsula toward Asia Minor (SE then E).

The foehn in Bulgaria is observed on the northern slopes of the mountains, as a result of advection of the warm air from the south and southwest. Its occurrence is the highest north of the Vitosha and the Balkan Mountains. Among the highest foehn occurrence is the Sofia valley, located at the foot of the north slopes of the Vitosha mountain. *Stoev* and *Guerova* (2020) present a manual classification of the meteorological conditions leading to foehn in the central meteorological station in Sofia. For the period 1975–2014, there are 298 foehn days classified in four manual circulation types. The circulation type associated with a Mediterranean cyclone has the highest frequency (52%). Foehn climatology gives an average annual number of 7.5 foehn days, and the lowest annual number of days (4.5) is registered in the last decade 2005–2014. Wind gusts over 14 m/s require issuing of a warning code, following the Meteoalarm warning system. For the period 1993–2014, in 79.6% of the foehn cases, wind gusts in Sofia range between 14 and 20 m/s (which corresponds to the yellow

Meteoalarm code), 15.8% are with gusts between 20–30 m/s (orange code), and 4.6% are with gusts 30 m/s (red code). A mediterranean cyclone trajectory over Hungary results in 52, 65, and 100% of the days with yellow, orange, and red codes, respectively.

Manual circulation classifications have two major limitations, namely: 1) they are labor intensive, i.e., require many person hours, and 2) the results are not consistent among investigators, i.e., they are not reproducible (*Yarnal,* 1993). The COST Action 733 "Harmonization and Applications of Weather Types Classifications for European Regions" (2005–2010, http://cost733.met.no/index.htm) aimed to develop a classification technique scalable to any European region for a wide range of applications. A general numerical approach was required to assess and compare atmospheric circulation classification and typical weather regimes in Europe to reach this goal. The COST Action 733 produced an extensive, consistent catalogue of atmospheric circulation type classifications based on different methodological concepts. A set of 33 methods or algorithms, ranging from manual classifications to data mining and machine learning methods, have been used to classify daily circulation patterns (*Philipp et al.*, 2016; *Tveito et al.*, 2016). A comprehensive dataset of classification catalogues, time series of type numbers or names representing atmospheric states for 12 European domains has been compiled using a specially developed open-source software package (*Tveito* et al., 2016). They are categorized into 1) weather type classifications - grouping several weather variables to create classes of atmospheric states and 2) circulation classifications - based only on circulation variables like atmospheric pressure, geopotential height, or large-scale wind components (*Philipp et al.,* 2016). The COST 733 weather type classifications have been applied to various phenomena, including heavy precipitations, freezing rains, droughts, floods, snow avalanches, and many more (*Tveito et al.*, 2016). Two weather type classifications have been conducted in Bulgaria for heavy precipitations (*Neykov et al.,* 2016) and freezing rains (*Nikolov et al.,* 2016).

This study aims to find the synoptic-scale atmospheric circulation patterns for foehn days in Sofia, with an ultimate goal to understand better the role of atmospheric circulation changes in the decreased number of foehn days. Former manual classification of foehn days' weather charts provides the grounded choice of two objective classifications for this purpose. In Section 2, the circulation classifications are presented. Foehn climatology and objective circulation classification using two threshold-based methods are applied for Sofia valley. Summary and outlook are given in Section 4.

2. Method and data sets

2.1. Objective circulation classifications

The Cost733class software version 1.2 (*Philipp et al.,* 2016) is used to classify atmospheric circulation. The Cost733class is a software package to create, compare, visualize, and evaluate weather and circulation type classifications. The software includes more than 20 automated methods and is licensed under GPL with documentation and software download available on the cost733wiki. For this study, two circulation classifications are selected: the GrossWettertypen (GWT) and the Jenkinson-Collison Type (JCT) classification. Both GWT and JCT are threshold-based classification methods 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 (*Philipp et al.*, 2016). The assignment of cases to the classes is done objectively and is automated by using threshold values for pre-defined indices discriminating between the types. Use of three indices result in three states (low, intermediate, and high) and 27 circulation types. For 9 or 18 circulation types, a smaller number of indices/states is required (*Philipp et al.,* 2016). The indices represent: 1) large-scale flow directions, i.e., zonal and meridional and 2) vorticity, i.e., high/low central pressure. The indices are derived from one circulation map, thus, the method is not suitable for multi-parameter datasets requiring two or more circulation maps to be classified together (*Philipp et al.,* 2016).

The GWT circulation types are derived by calculating correlations with raw or normalized correlation coefficients (*Beck*, 2000; *Beck et al*., 2007) and prototype fields of a zonal flow, meridional flow, and cyclone in the center of the domain (*Beck et al.,* 2007). The JCT circulation types (*Jenkinson* and *Collison*, 1977) are derived using an automated scheme for the Lamb weather types (*Lamb,* 1972). Daily 850 hPa geopotential height fields from ERA5 reanalysis with horizontal resolution of 31 km (*Hersbach et al.,* 2020) are classified into circulation types for the period 1979–2014. The calculations produced catalogues of classifications, where each day is specified by one circulation type from every classification. At first prototypical patterns of an idealized zonal and meridional flow and a low pressure in the center of the field are defined. The correlations of the real geopotential fields with these patterns are calculated. These correlations give the indices of zonality, meridionality, and vorticity of the atmospheric flow at that day. The spatial resolution of the fields is 0.5°. The circulation classifications are computed for a regional domain covering Southeast Europe (D10, 7° E – 30° E and 34° N – 49° N).

Both classifications are calculated for 10 and 26 types. In *Figs. 1* and *2,* maps of GWT and JCT with 10 types (GWT10, JCT10) and 26 types (GWT26, JCT26) are shown, respectively. Circulation classification with ten types (*Fig. 1a* and *1b*) includes 1) eight main directional types (W, SW, NW, N, NE, E, SE, and S), 2) one cyclonic type (C), and 3) one anticyclonic type (AC). For the 26 circulation types (*Figs. 2a* and 2*b*), there are two additional groups: 1) eight anticyclonic directional types (AW, ASW, ANW, AN, ANE, AE, ASE, and AS), and 2) eight cyclonic directional types (CW, CSW, CNW, CN, CNE, CE, CSE, and CS).

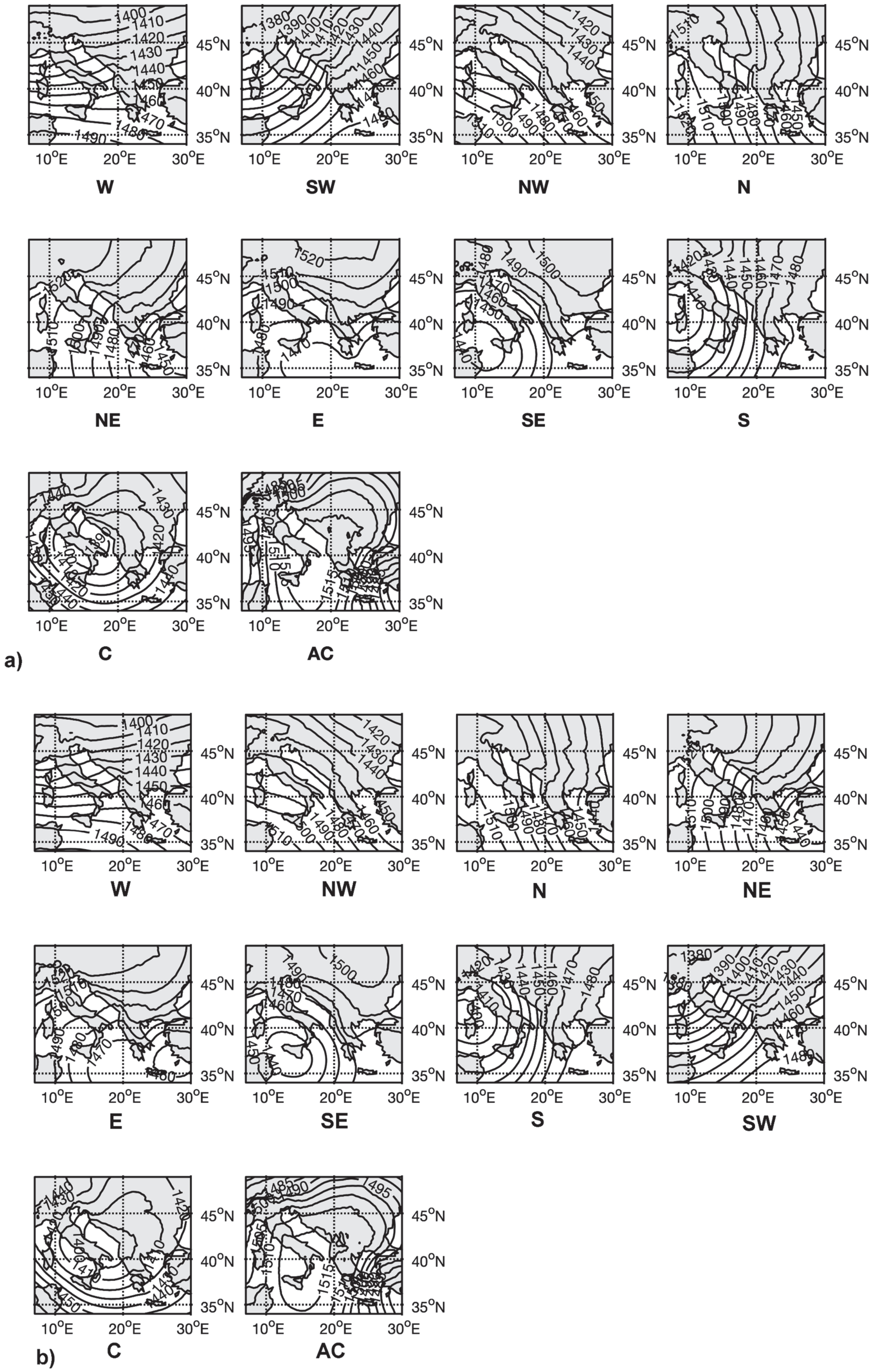


Fig. 1. Maps of the 850 hPa geopotential height of the GWT10 (a) and JCT10 (b) circulation types.

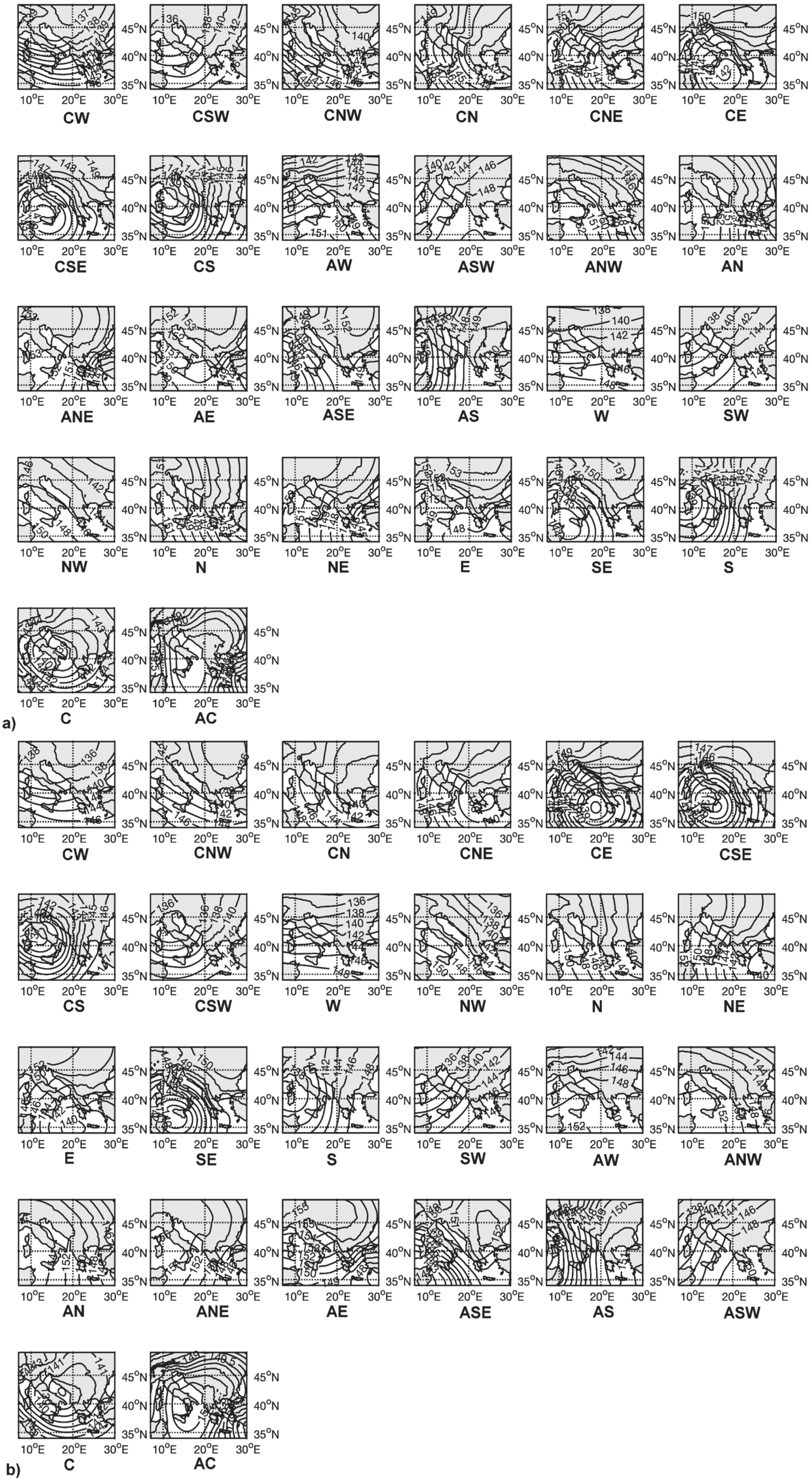


Fig. 2. Maps of the 850 hPa geopotential height of the GWT26 (a) and JCT26 (b) circulation types.

2.2. Manual circulation classification for foehn in Sofia

A manual circulation classification titled Bulgaria Foehn Type (BFT, *Stoev* and *Guerova,* 2020) is developed for foehn situations in Sofia for the period 1975–2014. The BFT classification is produced by an experienced operational forecaster using the National Centres for Environmental Prediction reanalysis data archive (NCEP, www.wetterzentrale.de/topkarten/fsres.2eur.html). Analyzed fields are: 1) surface pressure maps, 2) 500 hPa geopotential height maps (AT500), 3) 850 hPa geopotential height and temperature maps (AT850), and 4) 700 hPa relative humidity maps (AT700). The BFT has four major types: 1) type I: a Mediterranean cyclone that moves west of Bulgaria, 2) type II: cyclogenesis over Hungary and a cold front approaching the western part of the Balkan Peninsula, 3) type III: a cyclone centered over the North Sea, its periphery moves over Central Europe and 4) type IV: a cyclone centered over Scandinavia, moves through the Baltic area towards the southern part of European Russia also known as a *diving* cyclone.

2.3. Surface observations

To determine the days with foehn, observations of 35 years from the central meteorological station of the National Institute of Meteorology and Hydrology in Sofia are analyzed. Synoptic observations are made every 3 hours, at 00, 03, 06, 09, 12, 15, 18, and 21 UTC. Observations are made according to the standards and recommendations of the World Meteorological Organization (WMO). The following meteorological elements are used in this work: 1) wind speed and direction, 2) air temperature and maximum temperature at 2 m, and 3) relative humidity at 2 m. Quantitative criteria proposed by *Hristov* and *Tanev* (1970) are applied for foehn occurrence, such as 1) wind direction between SE and SW and wind speed increase by more than 5 m/s in 3 hours, 2) sharp rise of the temperature by 5 °C or more in 3 hours, and 3) relative humidity decrease with more than 20% in 3 hours.

2.4. Conditional foehn probability

The conditional foehn probability (F) for a selected circulation type is the probability that the foehn will occur given the knowledge of all events for this circulation type (A). If events A and F are dependent, then the probability of the intersection of A and F (the probability that both events occur) is defined by

$$P(A \text{ and } F) = P(A)P(F|A).$$

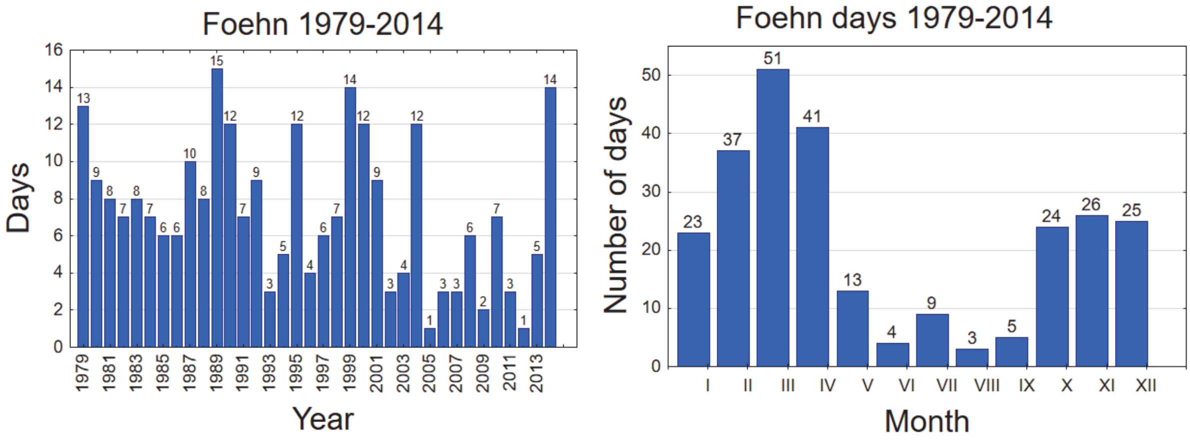
Thus the conditional probability for foehn circulation type $P(F|A)$ is $\in(0,1)$ and is given with

$$P(F|A) = \frac{P(A \text{ and } F)}{P(A)}.$$

3. Results

3.1. Foehn climatology of the period 1979–2014

For the period 1979–2014, there are 261 foehn days in Sofia. The annual foehn climatology presented in *Fig. 3a* shows that the number of foehn days per year ranges from 1 to 15. As reported in *Stoev* and *Guerova* (2020), the average annual number of foehn days is 8.1, 8.3, and 4.5 for the period 1985–1994, 1995–2004, and 2005–2014, respectively. After 2004, a decrease of the average annual number of days with foehn is found and the lowest maximum wind gusts are registered. In Section 3.3, the reason for this decrease is studied in detail. Monthly foehn climatology for the period 1979–2014 is seen in *Fig. 3b*. The largest number of foehn days are in March (51) followed by April (41) and February (37). The period September-May has 92% of the foehn days, while 17% of the foehn days are alone in March. This motivates the detailed discussion of those selected periods in Section 3.2.



a) **b)**

Fig. 3. a) Annual number of foehn days and b) monthly number of foehn days for the period 1979–2014 for Sofia, Bulgaria.

3.2. Atmospheric circulation patterns associated with foehn in the period 1979–2014

Two objective circulation classifications are used, namely GWT and JCT, with 10 and 26 classification types for the region of Southeast Europe. Due to the topography of the Balkan Peninsula, the circulation types are based on the field of the 850 hPa geopotential height. Mean sea level pressure classification has been computed, but it was difficult to distinguish the predominant synoptic patterns, therefore it was not used in this study. To facilitate the comparison, the results are presented based on the number of classification types.

3.2.1. Foehn in the period 1979-2014: 10 circulation types

In this section, a comparison between circulation classifications with ten types is offered. It is to be noted, that the comparison is made for all days and foehn days only for the period September-May. This period is selected based on the foehn climatology (*Stoev* and *Guerova*, 2020), which shows a minimum of foehn days in the period June-August of 1975–2014.

For the period 1979–2014, GWT10 gives four main types (not shown), namely: 1) type NW (2747 days), 2) type N (2565 days), 3) type W (2365 days), and 4) type SW (1590 days). A characteristic feature of the type NW is that the cyclone center is located northeast of the Balkan Peninsula. A cold atmospheric front passes over Bulgaria, and the flow is from the northwest. For type N, the air mass advection is from the north, with the cyclonic vortex located east of the Balkans. In types W and SW, the transport of air masses over the Balkan Peninsula is from the west-southwest. For type W, the cyclone center is over Central Europe, and for type SW – over the Alps. As seen from the blue bars in *Fig. 4a*, for the period September-May of 1979–2014, there are four main circulation types, namely: 1) W with 20% of occurrence (1918 days), 2) NW with 19% (1836 days), 3) N with 16% (1555 days), and 4) SW with 14% (1431 days). For March (*Fig. 4b*) the main GWT10 atmospheric circulation types are: 1) W (21%, 244 days), 2) NW (20%, 228 days), 3) N (17%, 128 days), and 4) SW (11%, 129 days).

For the foehn days, GWT10 gives only three main circulation types, namely: 1) W with 5 % of occurrence (132 days), 2) SW with 32% (83 days), and 3) NW with 14% (36 days). A common feature of the atmospheric circulation, which specifies the weather over the Balkan Peninsula to type W and SW, is the cyclonic circulation with warm air advection from W or SW. As seen from the red bars in *Fig. 4a*, for the period September-May of 1979–2014, three main circulation types are leading to foehn in Sofia, namely: 1) W with 50% of occurrence (122 days), 2) SW with 34% (83 days), and 3) NW with 12% (32 days). The main circulation type with foehn in March (red bars in *Fig. 4b*) is W with 60% (31 days). Visual comparison of *Figs. 4a* and *4b* leads to the conclusion that the days with foehn in Sofia are associated with three main GWT10 circulations types W, SW, and NW. It is to be noted, that the N type of GWT10 circulation classification does not lead to foehn.

For classification scheme JCT10, there are four main general atmospheric circulation types for the period 1979–2014 (not shown): 1) type W with 2053 days, 2) type N with 2020 days, 3) type AC with 1906 days, and 4) type NW with 1889 days. The characteristic feature of JCT10 type W is a cyclone situated over Central Europe. For JCT10 type N, the air mass advection is from the north with a cyclone east-southeast of the Balkan Peninsula, over Asia Minor. The JCT10 type NW circulation is a cyclonic field with a cold atmospheric front passing over the Balkan peninsula and connecting to a cyclone over Belarus and Ukraine. The JCT10 type AC is an anticyclonic circulation over the Balkan Peninsula. As seen from *Fig. 4c* (blue bars), the main JCT10 circulation types for the period September-May of 1979–2014 are: 1) C with 11% (1264 days), 2) AC with 11% (1215 days), 3) E with 11% (1197 days), 4) NE with 11% (1191 days), and 5) type SE with 10% (1066 days). The characteristic feature of JCT10 type C is a Mediterranean cyclone crossing the Balkan Peninsula. For type E, the cyclone is located above the Eastern Mediterranean. For March in 1979–2014 (blue bars on figure 4d), the two main JCT10 types with about 15% of occurrences are C (168 days) and NE (159 days). The SE type is with 11% (119 days), while N, NW, and E types are with 10% and 109, 112, and 116 days, respectively.

For the period 1979-2014, the JCT10 circulation leading to foehn in Sofia is W with 42% of occurrence (109 days) and SW with 31% (80 days). The general characteristic feature of the atmospheric circulation, which determines the weather over the Balkan Peninsula in these types, is cyclonic circulation, the predominant flow of warm air masses from west-southwest with a large pressure gradient. For September-May of 1979–2014 (*Fig. 4c*), the main circulation types leading to foehn in Sofia are type W with 40% of occurrence (101 days) and type SW with 30% (78 days). The main JCT10 circulations leading to foehn for March of 1979–2014 (red bars on *Fig. 4d*) are type W with 60%, type SW with 20%, and type C with 10%.

From *Figs. 4a* and *c*, an interesting comparison can be made between GWT10 and JCT10 for the foehn cases. Both classifications have the largest number of foehn days for type W but with a 10% difference. For SW and NW types of GWT10 and JCT10, this agreement is within 5%. For JCT10, the fourth significant type is the C with about 10% difference. This pattern is best seen for the visual comparison of the red bars in *Figs. 4b* and *d*. In *Table 1,* conditional probability for the foehn event for circulation classification GWT10 and JCT10 is presented for the period 1979–2014. Classification types W and SW have the largest probability for foehn. However, there is a difference for the third major circulation type, which is NW for GWT10 and C for JCT10. NW type for JCT10 comes as the fourth most probable type.

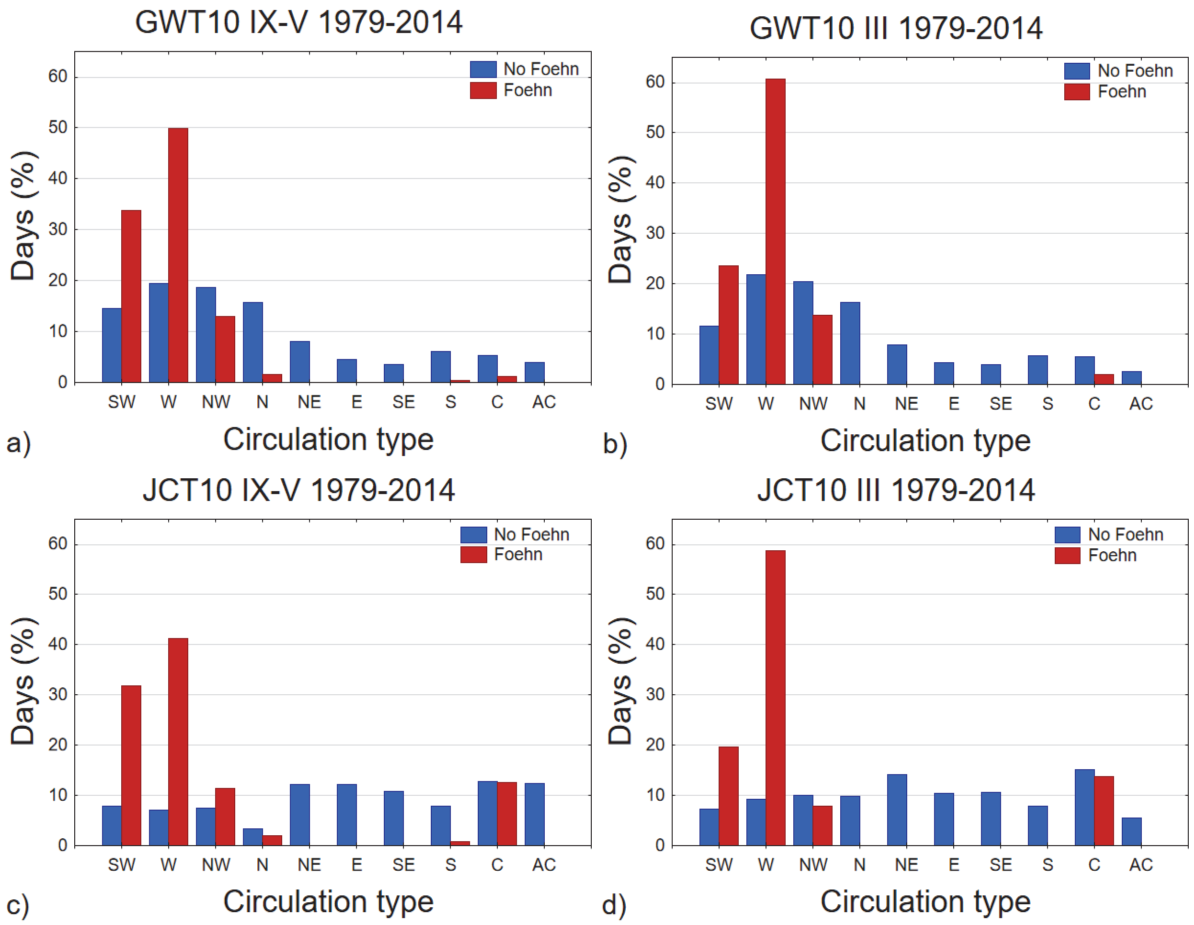


Fig. 4. Relative frequencies of circulation types for all days (blue bars) and foehn days (red bars). GWT10 a) September-May of 1979–2014 and b) March of 1979–2014. JCT10 c) September-May of 1979–2014, and d) March of 1979–2014.

Table 1. Conditional probability of the foehn for circulation classification GWT10 (column 2) and JCT10 (column 3) for the period 1979–2014

Type	P(GWT10)	P(JCT10)
SW	0.052	0.056
W	0.056	0.053
NW	0.013	0.016
N	0	0.004
NE	0	0
E	0	0
SE	0	0
S	0.002	0.003
C	0.005	0.022
AC	0	0

3.2.2. Foehn in the period 1979–2014: 26 circulation types

For the period 1979–2014, GWT circulation classification with 26 types for the 850 hPa geopotential height gives three significant types: 1) ANW with 1348 days, 2) AN with 1220 days, and 3) AW with 970 days. A characteristic feature of AN and ANW types is that the main cyclonic center is above Northern Europe, and an anticyclone is above the Western and Central Mediterranean, respectively. For AW type, the cyclone is over Western Europe and the anticyclone is over the Central Mediterranean. As seen from the blue bars on *Fig. 5a*, for the period September-May of 1979–2014, three main circulation types stand out: ANW with 9% (882 days), AW with 8% (756 days), and AN with 7% (710 days). GWT26 for March gives three main types of circulation: ANW with 10% (107 days), W with 8% (94 days), and AW with 8% (87 days). For GWT26 circulation type W, the cyclone is located over Central Europe and the Baltics (not seen in *Fig. 2a*), with westerly flow over the Balkan Peninsula (seen in *Fig. 2a*).

On the other side, the synoptic conditions leading to foehn in Sofia give four main GWT26 types: 1) CW with 68 days (26%), 2) W with 47 days (18%), 3) CSW with 44 days (17%), and 4) SW with 35 days (14%). A common feature of the atmospheric circulation, which determines the weather over the Balkan Peninsula, is cyclonic circulation with warm air mass flow from the southwest-west. During the September-May period, the largest number of foehn days is registered, and four main GWT26 types are leading to foehn: CW, W, CSW, and SW with 25%, 19%, 18%, and 14%, respectively. As seen from red bars in *Fig. 5b*, for March only, the maximum foehn frequency of 31% is for GWT26 circulation type W, 16% is for CW, and 14% is for CSW and AW.

JCT26 circulation types registered in the period 1979–2014 are as follow: 1) 1906 days (15 %) for type AC, 2) 1402 days (11%) for type C, 3) 1380 days (10%) for type W, and 4) 1330 days (10%) for type N. For the September-May period (blue bars in *Fig. 5c*), type AC has 1316 days (13%), type C – 1172 days (12%), and type W – 1051 days (11%). As seen from *Fig. 5d*, for March only, type W has 156 days (14%), type C – 144 days (13%), and type AC – 106 days (9%).

JCT26 circulation classifications for foehn days is: 30% (77 days) for type W, followed by 20% (53 days) for type SW, 12% (31 days) for type C, and 11% (29 days) for type CW. As in *Fig. 5c*, for September-May type, W has 29% of occurrence (72 days), type SW – 21% (52 days), type C – 13% (31 days), type CW – 11% (27 days), and type CSW – 11% (26 days). For March (*Fig. 5d*), type W is with 51% (26 days), type C with 14% (7 days), and type SW with 12% (6 days).

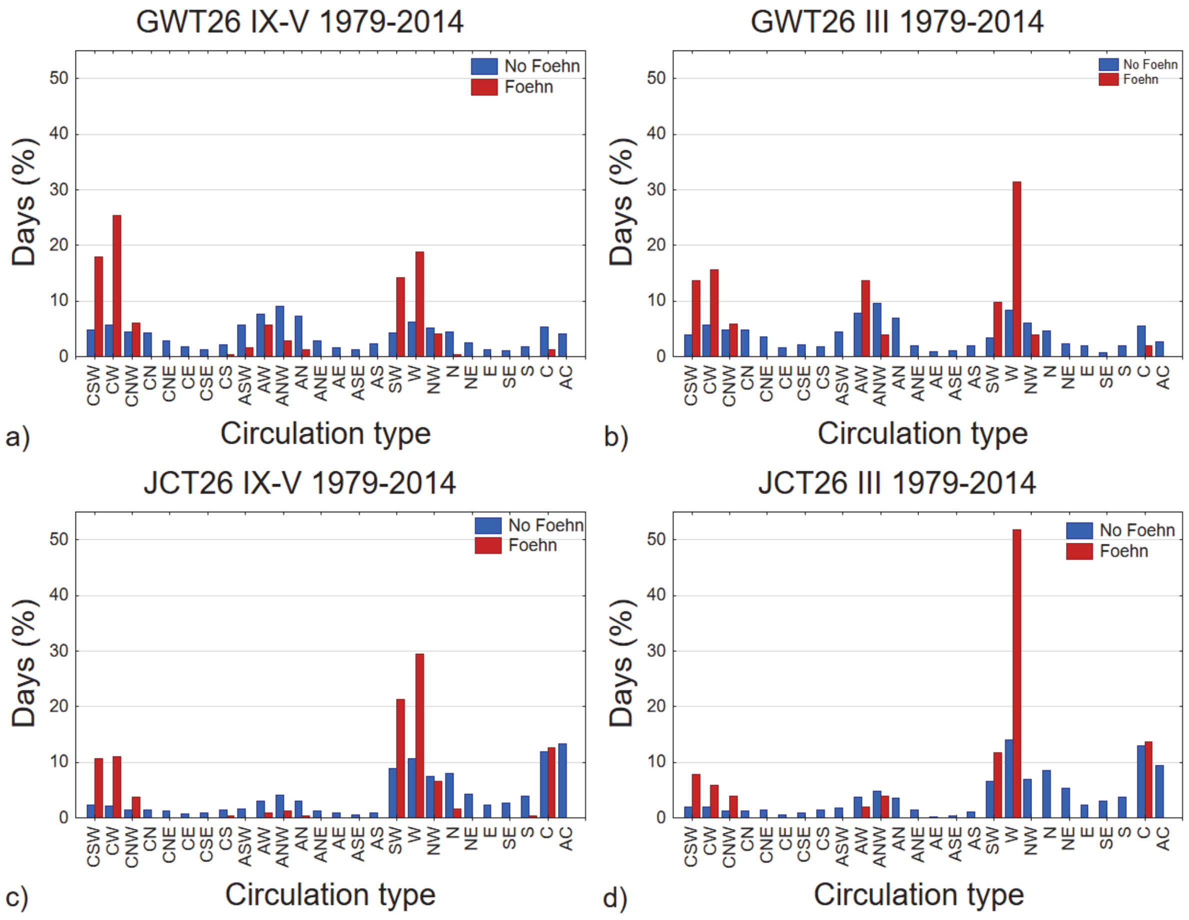


Fig. 5. Relative frequencies of circulation types for all days (blue bars) and foehn days (red bars). GWT26 a) September-May of 1979–2014 and b) March of 1979–2014. JCT26 c) September-May of 1979–2014 and d) March of 1979–2014.

To conclude, the GWT26 classification shows the foehn occurrence for circulation types W, SW, CW, and CSW (red bars in *Figs. 5a* and *b*). A comparison between *Figs. 5a* and *b* show that GWT26 has a similar distribution between eight cyclonic, eight anticyclonic, and eight directional circulation types (blue bars), with dominant SW, W, NW, and N types. This, however, is not the case for JCT26 (*Figs. 5c* and *d*). The prevalent circulation types for September-May and March (blue bars on *Figs. 5c* and *d*) are W, SW, NW, N, C, and AC types. The remaining eight cyclonic and eight anticyclonic types are with contributions less than 5%. JCT26 circulation types that result in foehn are W, SW, C, CSW, and CW with 29, 21, 13, 11, and 11%, respectively, for the period September-May of 1979–2014. The same holds for March, but with the JCT26 W type dominating the foehn days in 51% of the cases. For circulation classification, GWT26 conditional foehn probability (column 2 in *Table 2*) is above 0.05 for types CW, CSW, W, and SW. As seen from *Table 2* for JCT26 with conditional probability above 0.05, types (CW, CSW, W and SW) are the same. There are, however, differences between GWT26 and JCT26 type CNW with conditional probability 0.26 and 0.05, respectively. Notably the largest difference is for type C, where GWT26 probability is 0.002 versus the 0.022 value for JCT26.

Table 2. Conditional probability of the foehn type (column 1) for circulation classification GWT26 (column 2) and JCT26 (column 3)

Type	**P(GWT26)**	**P(JCT26)**
CSW	0.088	0.107
CW	0.103	0.106
CNW	0.026	0.050
CN	0	0
CNE	0	0
CE	0	0
CSE	0	0
CS	0.005	0.007
ASW	0.006	0
AW	0.017	0.007
ANW	0.006	0.005
AN	0.004	0.006
ANE	0	0
AE	0	0
ASE	0	0
AS	0	0
SW	0.077	0.053
W	0.064	0.056
NW	0.015	0.015
N	0.001	0.003
NE	0	0
E	0	0
SE	0	0
S	0	0.002
C	0.002	0.022
AC	0	0

3.2.3. Comparison of objective and manual circulation classifications

In this section comparison between objective and manual foehn classifications is presented. The motivation for this is to select the best objective classification that corresponds to the manual classification, and thus, benefits from the experienced forecaster's analysis. Clearly, manual classification for other extreme events will be very time consuming, thus objective classifications are the best possible option for operational forecasting. *Table 3* presents the comparison between the manual circulation classification BFT and objective classifications GWT and JCT with 10 and 26 types. Here again, for JCT10 and JCT26, the C type stents out for BFT-I, BFT-II, and BFT-III. In addition, the 26 circulation types differ from the 10 types by including CW and CSW types.

Table 3. BFT and corresponding GWT10 (column 2), JCT10 (column 3), GWT26 (column 4), and JCT26 (column 5) circulation types

BFT	**GWT10 (%)**	**JCT10 (%)**	**GWT26 (%)**	**JCT26 (%)**
I	W (22%) SW (22%) NW (5%)	W (16%) SW (22%) NW (5%) C (7%)	CW (14%) CSW (12%) SW (9%) W (8%) C (1%)	CW (6%) CSW (9%) SW (13%) W (10%) C (7%) NW (3%)
II	W (22%) SW (4%) NE (6%)	W (9%) SW (4%) NW (5%) C (3%)	CW (8%) CSW (2%) SW (1%) W (2%) CNW (3%)	CW (3%) CSW (1%) SW (3%) W (6%) C (3%) NW (3%)
III	W (15%) SW (6%) NW (2%)	W (16%) SW (5%) NW (1%) C (1%)	W (7%) CW (4%) CSW (2%) SW (3%) AW (4%)	CW (2%) SW (5%) W (14%) C (1%) AW (1%)
IV	NW (1%) N (1%)	NW (1%) N (1%)	ANW (1%) AN (1%)	AN (1%)

The foehn days for March of 1979–2014 are used to compare the objective circulation classifications GWT and JCT with the in-house developed manual classification BFT. It is to be noted, that the BFT has four main circulation types, and their corresponding GWT and JCT types are shown in *Table 3*. The largest number of foehn days is with circulation types BFT-III and BFT-I, which are associated with the cold front approaching Bulgaria and the Mediterranean cyclone, respectively. As seen from *Table 4*, the GWT10 and JCT10 objective classifications tend to have large differences with the BFT types. For example, BFT-I has 16 days while GWT10 has 1 day, but JCT10 has 17 days. BFT-II, however, has 12 foehn days, and GWT10 agrees, while JCT10 has none. A much better agreement is obtained between BFT and GWT26, and BFT and JCT26. JCT26 has the best agreement with BFT for BFT-II and BFT-IV types. GWT26 has 11 days for circulation type corresponding to BFT-IV.

Table 4. Comparison of number of the foehn days from manual classification Bulgaria Forecast Type (BFT column 2) and corresponding GWT10 (column 3), JCT10 (column 4), GWT26 (column 5) and JCT26 (column 6) for March 1979-2014.

Type	**BFT**	**GWT10**	**JCT10**	**GWT26**	**JCT26**
BFT-I	16 (31%)	1	17	13 (25%)	11 (22%)
BFT-II	12 (23%)	12	-	11 (22%)	11 (22%)
BFT-III	21 (42%)	31	30	16 (31%)	26 (51%)
BFT-IV	2 (4%)	7	4	11 (22%)	3 (6%)
Total	51	51	51	51	51

3.3. Foehn circulation types in the periods 1995–2004 and 2005–2014

As a next step, we investigated the decrease in the number of foehn days from 83 in the period 1995–2004 to 45 in 2005–2014. The number of foehn days for circulation types GWT10 and JCT10 are presented in *Table 5*. For each classification type, the percentage decrease/increase is calculated. For the period 2005–2014, both GWT10 and JCT10 classifications show that the foehn days decrease due to the decreased circulation types W by -65% and -80%, respectively and NW with -25 and -27%, respectively. For GWT10, the circulation type SW also decreased by -25% for the 2005–2014 period. The percentage is calculated considering the number of days from the period 1995–2004 as 100%, subtracting the number of days from the period 2005–2014, and then dividing by the number of days from the period 1995–2004.

Table 5. Circulation types for the foehn days for the periods 1995–2004 and 2005–2014. GWT10 1995–2004 (column 2) vs 2005–2014 (column 3) and percent of decrease/increase (column 4). JCT10 1995–2004 (column 5) vs 2005–2014 (column 6) and percent of decrease/increase (column 7)

Type	**GWT10 1995–**	**GWT10 2005–**	**GWT10 %**	**JCT10 1995–**	**JCT10 2005–**	**JCT10 %**
SW	24	18	-25%	19	19	
P(SW)	0.056	0.039		0.048	0.047	
W	46	16	-65%	45	9	-80%
P(W)	0.046	0.026		0.076	0.017	
NW	12	9	-25%	11	8	-27%
P(NW)	0.015	0.012		0.019	0.017	
N	-	1	+100%	-	1	+100%
P(N)		0.001			0.002	
C	1	1		7	8	+14%
P(C)	0.006	0.005		0.019	0.018	
AC				1	-	
P(AC)				0.002		

Comparison of circulation types GWT26 and JCT26 for the periods 1995–2004 and 2005–2014 is shown in *Table 6*. Both GWT26 and JCT26 confirm the foehn days decrease for the 2005–2014 period due to a decrease of circulation types W by -76% and -82%, respectively and NW with -100% and -71%, respectively. Circulation type CW decreased for the 2005–2014 period by -57% for GWT26 and by -73% for JCT26. CSW and AW also show a decrease for both GWT26 and JCT26.

In *Tables 5* and *6* the conditional foehn probability for circulation classification GWT and JCT with 10 and 26 types are presented, and they also confirm the decrease of the above mentioned types for the period 2005–2014.

Table 6. Circulation types for the foehn days for the periods 1995-2004 and 2005–2014. GWT26 1995–2004 (column 2) vs 2005–2014 (column 3) and percent of decrease/increase (column 4). JCT26 1995–2004 (column 5) vs 2005–2014 (column 6) and percent of decrease/increase (column 7)

Type	**GWT26 1995–**	**GWT26 2005–**	**GWT26 %**	**JCT26 1995–**	**JCT26 2005–**	**JCT26 %**
CSW	15	10	-33%	8	4	-50%
P(CSW)	0.110	0.069		0.121	0.057	
CW	23	10	-57%	11	3	-73%
P(CW)	0.112	0.057		0.132	0.041	
CNW	5	4	-11%	4	3	-25%
P(CNW)	0.04	0.021		0.059	0.052	
ASW	-	2	+100%			
P(ASW)		0.011				
AW	6	2	-67%	1	-	-33%
P(AW)	0.022	0.008		0.009		
ANW	2	5	+60%	-	3	+100%
P(ANW)	0.005	0.015			0.022	
AN	-	1		-	1	
P(AN)		0.003			0.009	
SW	9	6	-33%	11	15	+36%
P(SW)	0.08	0.046		0.040	0.054	
W	17	4	-76%	33	6	-82%
P(W)	0.08	0.022		0.084	0.017	
NW	5	-	-100%	7	2	-71%
P(NW)	0.024			0.212	0.007	
C	1	-		7	8	+14%
P(C)	0.006			0.019	0.018	
AC	-	1		1	-	
P(AC)		0.006		0.002		

3.4. Changes in synoptic-scale circulation in Southeast Europe in three decades

As a next step, we investigated the general atmospheric circulation types over Southeast Europe for three decades: 1985–1995, 1995–2004, and 2005–2014. *Figs. 6a* and *b* show GWT10 and JCT10 for each decade separately. It is seen that for GWT10, there are four main types with more than 10% of the days: NW, N, W, and SW. Interestingly, for the 2005–2014 period there is a decrease of NW and W types in the range of 1–2.5%. It is to be noted, that the two types also show a reduction for the foehn days as reported in Section 3.3. For the 2005–2014 period, the increase of types C, E, and SW have a compensating effect for GWT10. A decrease of W and NW types between 2 and 4% is also seen for JCT10 classification for the 2004–2015 period. This is compensated by a 2% increase of C and 1% increase of AC type.

For the period 2005–2014, GWT26 classification also shows a decrease of the W type and the second type with reduction is ANW. In *Figs. 7a* and *7b* an increase is seen in the percentage of days with the C and AC types for both the GWT26 and JCT26 classifications. For JCT26, there is about a 2% decrease in the number of days with W, NW, and ANW.

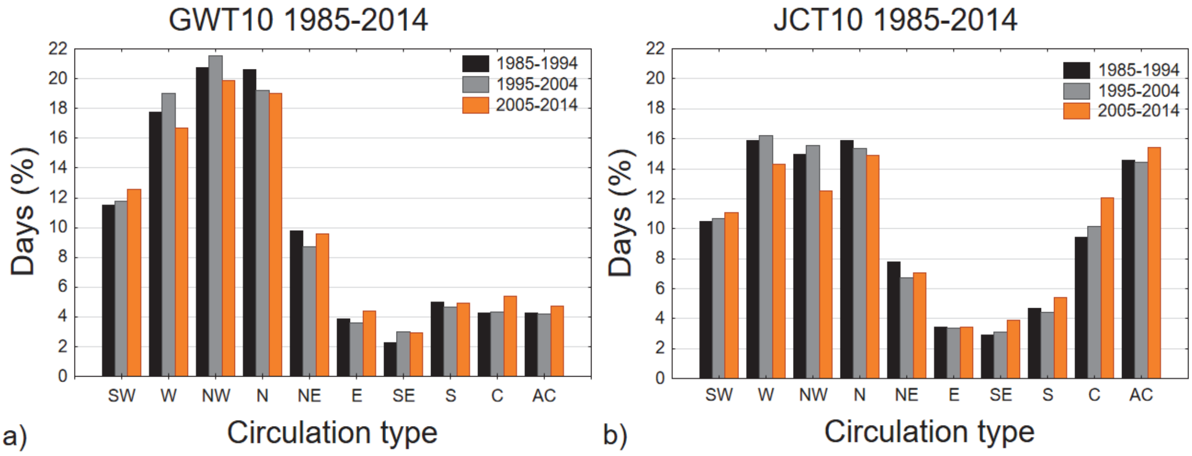


Fig. 6. Relative frequencies of circulation types for the periods 1985–1994 (black bars), 1995–2004 (grey bars), and 2005–2014 (orange bars) for a) GWT10 and b) JCT10.

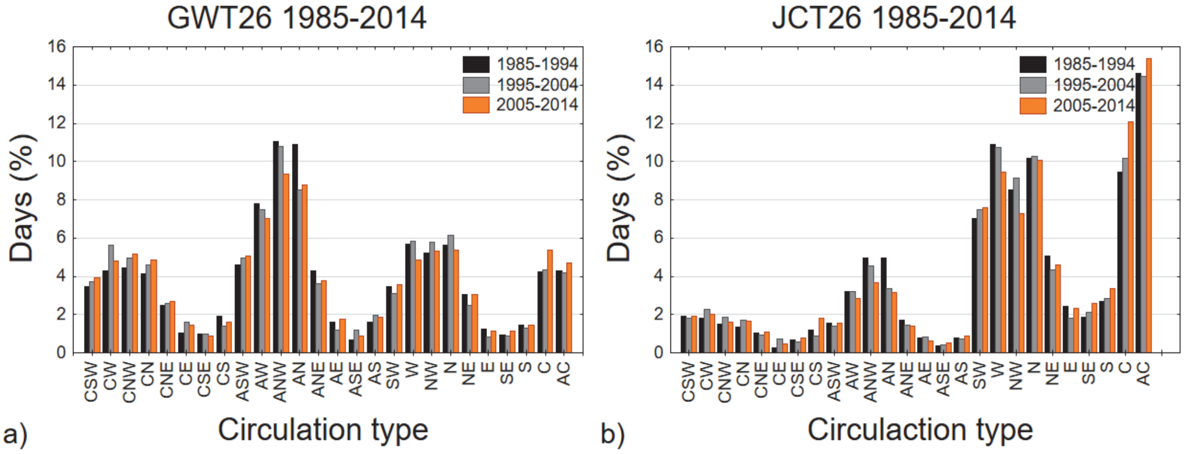


Fig. 7. Relative frequencies of circulation types for the periods 1985–1994 (black bars), 1995–2004 (grey bars), and 2005–2014 (orange bars) for a) GWT26 and b) JCT26.

4. Conclusion

In this study, two threshold-based objective circulation classifications (GWT and JCT) and one manual classification (BFT) were applied for 261 foehn days in the Sofia valley in the period 1979–2014. Threshold-based objective classifications are selected as they are based on the concept of subjectively pre-defined types similar to the manual classification method. Two variants of the objective classifications are selected with 10 (GWT10, JCT10) and 26 types (GWT26, JCT26). A comparison between GWT10 and JCT10 types for the foehn days in the period September-May gives the largest number for types SW, W, and NW. However, they differ by 10% for SW type and 5% for W and NW types. GWT26 confirms the foehn occurrence for circulation types W (25%), SW (19%), CW (18%), and CSW (14%). JCT26 circulation types for foehn days are W (29%), SW (21%), C (13%), CSW (11%), and CW (11%). It is to be noted, that GWT26 has evenly distributed cyclonic, anticyclonic, and directional circulation types with dominant SW, W, NW, and N types in each group. On the other hand, for JCT26, the dominant circulation types are W, SW, NW, N, C, and AC. Eight cyclonic and eight anticyclonic JCT26 types occur in less than 5% of the days. For the foehn days in March of 1979–2014, a comparison between objective circulation classifications and manual classification show a tendency for GWT10 and JCT10 to underestimate or overestimate the BFT types. A much better agreement is obtained for GWT26, and the best agreement is with JCT26.

A previous study showed a decrease in the average annual number of days with foehn in Sofia after 2004. A comparison between the periods 1995–2004 and 2005–2014 gives a decrease of circulation types W by -65% (GWT10) and -80% (JCT10) and NW with -25% (GWT10) and -27% (JCT10). GWT26 and JCT26 confirm the reduction of the foehn days due to the decrease of circulation types W by -76% (GWT26) and -82% (JCT26) and NW with -100% (GWT26) and -71% (JCT26). A general circulation analysis for the period 1985–2014 confirms the decrease of W and NW circulation types for all days in the period 2005–2014.

The findings of this study show that the objective circulation classifications can be used to quantify the foehn occurrence in the Sofia valley. This work is the first step towards developing an objective foehn warning system for operational weather forecasting at the National Institute of Meteorology and Hydrology in Bulgaria.

Acknowledgments: We are very grateful to the National Institute of Meteorology and Hydrology for providing the data from synoptic station Sofia. The COST 733 core group provided the synoptic catalogues and the software used in this study. This research has been supported by the Estonian Research Council (grant no. PSG202).

References

Bartholy, J., Pongrácz, R., and *Pattantyús-Ábrahám, M.,* 2009: Analyzing the genesis, intensity, and tracks of western Mediterranean cyclones. *Theor. Appl. Climatol. 96,* 133–144.

Van Bebber, W., 1891: Die Zugstraßen der barometrischen Minima. *Meteor. Zeit. 8,* 361–366. (In German)

Beck, C., 2000: Zirkulationsdynamische Variabilität im Bereich Nordatlantik-Europa seit 1780. *Würzburger Geographische Arbeiten 95*. (In German)

Beck, C., Jacobeit, J., and *Jones, P.D.*, 2007: Frequency and within-type variations of large-scale circulation types and their effects on low-frequency climate variability in Central Europe since 1780. *Int. J. Climatol. 27,* 473–491.

Blagoev, H., 1961: Patishta na Sredizemnomorskite Tsikloni, *Hydrol. Meteorol.* **1:** 43–51. (in Bulgarian)

Bocheva, L., Georgiev, C.G., and *Simeonov, P.,* 2007: A climatic study of severe storms over Bulgaria produced by Mediterranean cyclones in 1990–2001 period. *Atmos. Res. 83,* 284–293.

Catrina, O., Ştefa, S., and *Crăciun, C.,* 2019: Objective identification of Mediterranean cyclones and their trajectories towards Romania. *Meteorol. Appl. 26,* 429–441.

Hersbach, H., Bell, B., Berrisford, P., et al., 2020: The ERA5 global reanalysis. *Quart. J. Roy. Meteorol. Soc. 146*, 1999–2049. https://doi.org/10.1002/qj.3803

Hristov, P. and *Tanev, A.,* 1970: Nauka i izkustvo, Sofia. (In Bulgaarian)

Jansa, A., Genoves, A., Picornell, M., Campins, J., Riosalido, R., and *Carretero, O.,* 2001: Western Mediterranean cyclones and heavy rain. part 2: Statistical approach. *Meteorol. App. 8*, 43–56.

Jenkinson, A.F. and *Collison, F.P.,* 1977: An initial climatology of gales over the North Sea. Synoptic Climatology Branch Memorandum 62, Meteorological Office, Bracknell.

Lamb, H.H., 1972. British Isles weather types and a register of the daily sequence of circulation patterns 1861–1971. *Geophys. Memoir. 116,* 85L.

Marinova, T., Bocheva, L., and *Sharov, V.,* 2005: On some climatic changes in the circulation over the mediterranean area. *Időjárás 109*, 55–67.

Martinov, M., 1967: Niakoi osobednosti na tsiklogeneza v raiona na Sredizemno more i Balkanskia poluostrov *Hydrol. Meteorol. 6,* 7–21. (in Bulgarian)

Martinov, M., 1983: Synoptical and statistical processing of historical data for Mediterranean depression. WMO, PSMP Report Series 3: 121–144.

Neykov, N., Trifonova, L., Gospodinov, I., and *Neytchev, P.,* 2016: Circulation types and associated precipitations over Bulgaria. In (Eds. *Tveito, O.E., Huth, R., Philipp, A., Post, P., Pasqui, M., Esteban, P., Beck, C., Demuzere, M., Prudhomme, C.*) COST Action 733: Harmonization and application of weather type classifications for European Regions; final scientific report. Augsburg, University of Augsburg. 270–276.

Nikolov, D., Beck, C., Philipp, A., and *Neychev, P.,* 2016: Circulation types associated with freezing precipitation over Bulgaria. In (Eds. *Tveito, O.E., Huth, R., Philipp, A., Post, P., Pasqui, M., Esteban, P., Beck, C., Demuzere, M., Prudhomme, C.*) COST Action 733: Harmonization and application of weather type classifications for European Regions; final scientific report. Augsburg, University of Augsburg. 277–280.

Peiter, E., 1975: Handbook for forecasters in the Mediterranean, Tech. Rep. 344, Environmental Prediction Research Facility, Naval Postgraduate School, Monterey, California.

Philipp, A., Beck, C., Huth, R., and *Jacobeit, J.,* 2016: Development and comparison of circulation type classifications using COST733 dataset and software. *Int. J. Climatol. 36,* 2673–2691. doi: 10.1002/joc.3920

Pisarski, A., 1955a: Sredizemnomorskite Tskiloni i tyahnoto vilyanie na vremeto v Bulgaria, part I, *Hidrologia i Meteorologia .5*, 33-50. (in Bulgarian)

Pisarski, A., 1955b: The Mediterranean cyclones and their influence on the weather in Bulgaria. *Hydrol. Meteorol.* **6**: 3–15. (in Bulgarian).

Popova, T., Runcanu, T., Tanczer, T., and *Sharov, V.*, 1975: Sredizemnomorskie t͡siklony v pole oblachnosti. Gidrometeoizdat, Leningrad. (in Russian)

Radinovic, D., 1987: Mediterranean cyclones and their influence on the weather and climate. WMO, PSMP Report Series 24, 131.

Stanchev, K., 1954: The South cyclones, their passage over the Balkan Peninsula and the weather in Bulgaria. *Hydrol. Meteorol. 5,* 19–39. (in Bulgarian)

Stoev, K. and *Guerova, G.,* 2020: Foehn classification and climatology in Sofia for 1975–2014. *Időjárás 124*, 483–497.

Tveito, O.E., Huth, R., Philipp, A., Post, P., Pasqui, M., Esteban, P., Beck, C., Demuzere, M., and *Prudhomme, C.,* 2016: COST Action 733: Harmonization and application of weather type classifications for European Regions; final scientific report.

Yarnal, B., 1993: Synoptic Climatology in Environmental Analysis. Belhaven Press: London.