

FOEHN CLIMATOLOGY AND INDEX FOR SOFIA 1993–2014

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Abstract

Foehn is an extreme weather event caused by high wind gusts and its forecasting is still a challenge. The foehn in Bulgaria is observed on the northern slopes of the mountains. The foehn in Sofia occurs after the air mass passes over Vitosha and Lulin mountains. Foehn days in Sofia are selected using as criteria the surface temperature, relative humidity and wind direction. For the period 1993–2014 there are 136 foehn days. For 55.9% the wind gust is between 14 and 19 m/s corresponding to yellow Meteoalarm code, 14.7% are with gusts 20–29 m/s (orange code), and 1.5% are with gusts over 30 m/s (red code). For the foehn days the upper-air flow at mountain peak Cherni Vrah is in 47.4% of the days from 202° direction and in 36.8% from 225°. Orange code days are 55.0% with wind direction 225° at Cherni Vrah, while for red code it is 180°. Cherni vrah-Sofia Stability Index is computed and found to have high sensitivity to foehn/no foehn conditions. The case studies in 2010 show that the Index decreased by 20% with foehn start, and increased by up to 29% after the foehn. For the foehn days a manual circulation classification is created with 4 circulation classes. The circulation class I with Mediterranean cyclones passing over Hungary, results in 51.3, 65.0 and 100.0% of the days with yellow, orange and red code, respectively.

Key words: foehn, meteoalarm warning, foehn index, GNSS tropospheric products, stochastic model, binary logistic time series regression

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Introduction. The warm and dry wind blowing on the lee side of a mountain, is observed in mountainous regions globally and is referred to as foehn. Foehn gusty wind is an extreme weather event and its forecasting is still a challenge for operational weather forecasting. Due to its local occurrence the number of foehn studies is limited to the mountain regions. Studying the Altdorf foehn [1, 2] conclude that: 1) there is not a pronounced long-term trend in the foehn frequency over 150 year period, 2) there is considerable year to year variability with an average of 60 foehn registrations per year and a maximum of 114 registrations (1872) and a minimum of 27 registrations (1955), and 3) the foehn frequency has a pronounced seasonal cycle. A review of the Andean foehn (zonda) in Argentina [3] covers: 1) empirical observational methods, 2) synoptic elements for forecasting, 3) probabilistic method, and 4) Numerical Weather Prediction models and concludes that “as in the European Alps, the skills of experienced forecasters familiar with the local and regional situations are still an important prerequisite for a successful forecast”. NORTE [4] defines zonda wind categories based on the maximum gust as follows: 1) moderate with the maximum gust less than or equal to 18 m/s, 2) severe for maximum gust between 18 and 25 m/s, 3) very severe with gust between 25 m/s and 33 m/s, and 4) extremely severe with the gust greater than 33 m/s. The foehn in Bulgaria is observed on the northern slopes of the mountains, as a result of a warm air mass advection from the south and southwest. Its occurrence is highest north of the Vitosha and the Balkan Mountains. One way to facilitate the operational weather forecasting is via development of indices which provide guidance for particular meteorological phenomena.

A probabilistic method, developed by MeteoSwiss, using two pressure gradients across the Alps and a pressure tendency, called Widmer’s foehn index [5], is reported to be reliable for 36 h forecast [2]. OTERO et al. [6] aim at obtaining an index for predicting the probability of zonda occurrence from using radiosonde data at Mendoza (Argentina). Surface zonda wind events are selected based on an objective classification method. A principal component analysis is used to identify the leading patterns of the vertical structure of the atmosphere before a zonda occurrence. The entry matrix for the analysis includes: 1) temperature, and 2) dew point temperature anomalies for the standard levels between 850 and 300 hPa [6]. The analysis yielded six significant components explaining 94% of the variance. A zonda/no zonda index is estimated combining temperature and dew point temperature profiles with regional climatology. The zonda index efficiency is reported to be 74.7% and increased to 87.8% when surface observations were added.

In operational forecasting in Bulgaria the first index developed by STOYCHEVA and EVTIMOV [7] named Cherni vrah-Sofia Stability Index (SSI) is based on Brunt–Vaisala frequency concept and estimates the strength of the static stability of the atmosphere over Sofia during fog. This index is currently being tested in an operational environment.

In the last two decades atmospheric remote sensing using Global Navigation Satellite Systems (GNSS) became widely used for monitoring high temporal and spatial variability in atmospheric water vapour. GNSS atmospheric remote sensing in Bulgaria started with development of the Sofia University Atmospheric Data Archive (SUADA, [8]). SUADA data is used for case studies of thunderstorm diagnosis for Sofia [9] as well as fog. The GNSS derived water vapour is an integral characteristic of the air mass above the station and its temporal variation provides additional information about air mass transformation during foehn. This study aims to provide quantitative evaluation of the atmospheric conditions leading to foehn in Sofia with particular focus on the foehn events with issued Meteoalarm warning.

Observations and data. Foehn criteria. To select the days with foehn, observations from the SYNOP Sofia station for the period 1993–2014 are analysed. Synoptic observations are made every 3 hours following the standards and recommendations of the World Meteorological Organization. The proposed by [10] quantitative criteria for foehn selection are used to select the foehn days. They are as follows: 1) south wind ($112\text{--}247^\circ$) and its increase by at least 5 m/s in 3 hours, 2) sharp increase of the temperature by 5 °C or more in 3 hours, and 3) decrease of relative humidity by more than 20% in 3 hours. As a part of European extreme weather alert, the Meteoalarm system is developed for EUMETNET, the Network of European Meteorological Services. The National Institute of Meteorology and Hydrology (NIMH) started to issue Meteoalarm warnings in 2010. The Meteoalarm provides information about the possible occurrence of severe weather, such as heavy rain with risk of flooding, severe thunderstorms, strong winds, heat waves, forest fires, fog, snow or extreme cold with blizzards, avalanches or severe coastal tides. The alarm is coded in three colours – yellow, orange and red and presented on the website maps [12]. In calm conditions the colour code is green. NIMH issues wind gust warnings as follows: 1) yellow 14–19 m/s, 2) orange 20–30 m/s, and 3) red above 30 m/s. In this work a manual circulation classification for foehn days in Sofia presented in [13] is used. It is based on analysing the synoptic conditions using the archive of National Centres for Environmental Prediction [11].

Modified Cherni vrah-Sofia Stability Index and Equivalent Potential Temperature. In this study the proposed by [7] Cherni vrah-Sofia Stability Index (SSI) is used. SSI is defined as:

$$(1) \quad SSI = \sqrt{\frac{1 + \Delta T/17}{1 + T_{ch.vrah}/273.15}},$$

where ΔT is the temperature difference between Cherni vrah and Sofia NIMH, and $T_{ch.vrah}$ is surface air temperature at station Cherni vrah in degrees Celsius. The scaling factor of 17 reflects the altitude difference of Sofia-Cherni vrah which

is 1700 m. In this work a modified SSI (SSI^*) is proposed to take into account that during the foehn conditions the temperature lapse rate is higher than 10°C for 1 km. The modified SSI^* is calculated with scaling factor 22 as follows:

$$(2) \quad SSI^* = \sqrt{\frac{1 + \Delta T/22}{1 + T_{ch.vrah}/273.15}}.$$

The scaling factor 22 is selected based on assumption of super-adiabatic temperature lapse rate. BYRAM and HACKMAN [18] report that super-adiabatic lapse rate for foehn registration is Switzerland. The super-adiabatic lapse rate during foehn is the result of dry adiabatic lapse rate warming during air descent on the lee side of the mountain in combination with surface heating in the lower troposphere in the afternoon hours. In addition, Equivalent Potential Temperature (EPT) is calculated following [14, 15].

GNSS tropospheric products. In this work we use GNSS tropospheric products from station Sofia – Plana (SOFI). The International GNSS Service (IGS) tropospheric products for SOFI are produced with Bernese GPS Software 5.0 using precise point positioning. The IGS processing strategy is presented in [19]. The tropospheric product from GNSS processing used in this work is Zenith Total Delay (ZTD). In [8] a detailed description of Integrated Water Vapour (IWV) computation and pressure difference correction is presented.

Results. Foehn in Sofia: 1993–2014. Figure 1a shows the number of foehn days in Sofia per year. The years with the maximum number of days are 1999 and 2014 followed by 2005 and 2012, while the minimum are during 2005 and 2012. There is a tendency to reduce the number of days with foehn after 2003. The average number of days for the period 1993–2003 is 7.2, while for 2004–2014 it is 5.2, i.e. 2 days less. This is explained in [16]. As seen in Fig. 1b the month with the highest number of foehn days is March (26) followed by December (14), January and February (12). Figure 1c shows the number of foehn days depending

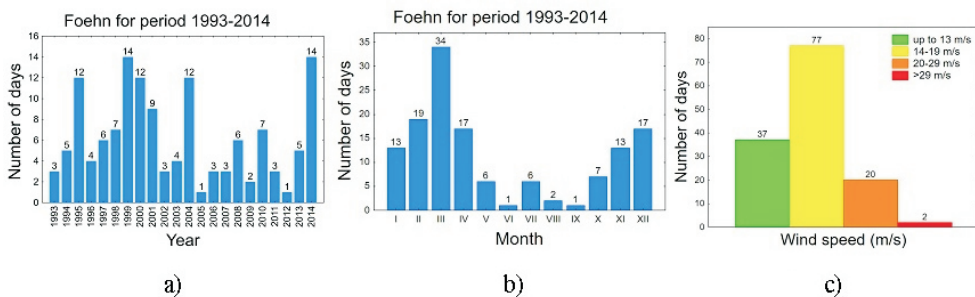


Fig. 1. Number of days with foehn in Sofia for the period 1993–2014: a) per year, b) per month, and c) per wind gust code: green (below 14 m/s), yellow (14–19 m/s), orange (20–30 m/s) and red (over 30 m/s)

on the wind gusts in Sofia. In 56.6% of the days it is between 14 and 19 m/s, corresponding to yellow Meteoalarm code. In 14.7% the average wind gust is 20–30 m/s, which corresponds to the orange code, and in 1.5% of the days it is above 30 m/s (red code). The wind gusts over 30 m/s were observed only twice. The highest registered wind gusts are 30 m/s in 1997 and 2000. In the period studied by [10] the maximum wind gust is 35–37 m/s. The prevailing wind gusts are between 15 and 20 m/s with no clear distinction of the wind gusts by years, i.e. for one year it varies with a wide range.

SSI (SSI*), EPT and IWV during foehn. The SSI is developed to analyze fog conditions in Sofia. It is found that SSI increases with fog formation and decreases with fog dissipation. In this work SSI and modified SSI* are computed for foehn registrations in the period 1993–2014. The index is suitable for this type of weather events as it takes into account differences in the temperature gradient. Unlike fog, where SSI values are higher than 0.8, during foehn they are lower than 0.8. In Fig. 2a the SSI (black line) and EPT (grey dashed line), are presented for year 2010. The grey bars are the wind gusts following Meteoalarm coding. As seen in Fig. 2a, SSI is in the range from 0 to 1 but for each measurement it could not be calculated. This is the reason to propose the modified index SSI* with scaling factor 22. The SSI* takes into account that the temperature gradient rises by more than $1^\circ/100$ m during foehn, i.e. it accounts for super-adiabatic temperature lapse rate. A clearly seen tendency is that during foehn SSI* decreases and reaches its minimum value and then, with its increase, the foehn ends. Very high sensitivity of SSI* is seen for the foehn free intervals between 8 and 10 November 2010 (Fig. 2a) but also others. In many of the foehn days SSI* increase starts before the foehn's end, which can be used for early guidance in operational forecasting. The statistics for the 22-year period of SSI* during foehn conditions gives:

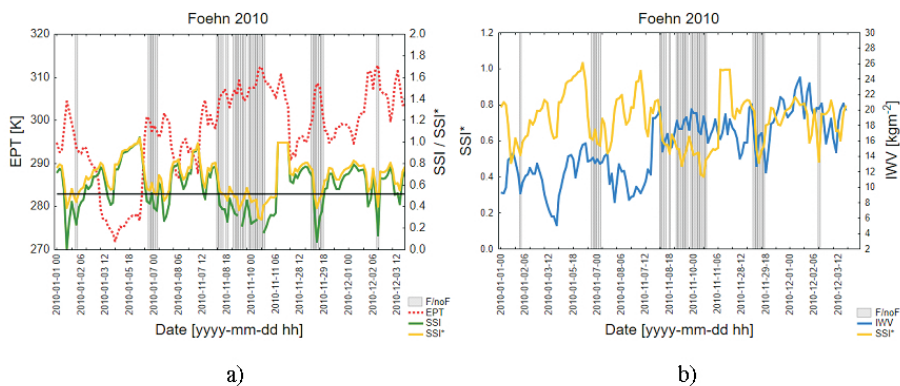


Fig. 2. a) SSI (green line), SSI* (yellow line), EPT (red dashed line), grey bars for Meteoalarm code for 2010, and b) IWV (blue line), SSI* (yellow line), and grey bars for the Meteoalarm wind gust

1) lowest value of 0.11, 2) highest value of 0.83, 3) mean of 0.52, and 4) 25 and 75 percentile of 0.46 and 0.6. It is clearly seen that SSI^* values below 0.52 (black horizontal line) are obtained also for days without foehn. This is an indication that SSI^* alone could not be used to distinguish between foehn/no foehn conditions. In most of the foehn events EPT (dashed red line in Fig. 2a) reaches its maximum value during foehn.

The first study of the Integrated Water Vapour (IWV) during foehn is made by [17]. For five foehn events in 2010, SSI^* has local minimums during foehn and demonstrates high sensitivity for foehn free intervals on 8 and 9 November (Fig. 2b). The IWV minimum corresponds to SSI^* minimum only on 2 January 2010. For the remaining four events in 2010, the IWV temporal variability before, during and after the foehn does not have a clear tendency. Thus, it is confirmed that the SOFI station does not register the air mass, which is transformed by passing over Vitosha mountain. The GNSS station location and the IWV values suggest that the air mass is likely passing around Vitosha mountain and not drying substantially.

Wind direction at Cherni vrah. To study the upper-air flow the surface observations at Cherni vrah situated at about 2300 m a.s.l. are used. In particular, the wind direction at Cherni vrah is investigated for the foehn days in Sofia for the period 1993–2014. As shown in Table 1 the major wind directions at Cherni vrah are 202° and 225° (southwest), with 41 and 39 days (41.8% and 39.8%), respectively. The wind direction at Cherni vrah from 157° to 180° is recorded for 11 days (about 11.2%) and 7 days (7.1%) with wind direction $247\text{--}270^\circ$. Further, the wind direction at Cherni vrah is analyzed based on the Meteolarm criteria,

Table 1

Wind direction at Cherni Vrah, Number of Days (NoD) and percentage for yellow code (lines 2 and 3), orange code (lines 4 and 5) and red code (lines 6 and 7) warning of Meteolarm system. The period is 1993–2014

Wind direction Ch.vrah	below 180°	180°	202°	225°	above 225°
NoD total	1	10	41	39	7
%	1.0	10.2	41.8	39.8	7.1
yellow code					
NoD	1	4	36	28	7
%	1.0	5.3	47.4	36.8	9.2
orange code					
NoD	–	4	5	11	–
%	–	20.0	25.0	55.0	–
red code					
NoD	–	2	–	–	–
%	–	100.0	–	–	–

T a b l e 2

Number of Days (NoD) and percentage with foehn in Sofia by classification type I, II and III orange code (lines 4 and 5) and red code (lines 6 and 7) warning of Meteoalarm system.
The period is 1993–2014

Type	Ia	Ib	Ic	Id	IIa	IIb	IIIa	IIIb	I	II	III
NoD	18	5	6	10	8	6 * 29	4				
yellow											
%	23.7	6.6	7.9	13.2	10.5	7.9	25.0	5.3	51.3	18.4	30.3
NoD	10	2	–	1	2	1	3	1			
orange											
%	50.0	10.0	–	5.0	10.0	5.0	15.0	5.0	65.0	15.0	20.0
NoD	2	–	–	–	–	–	–	–			
red											
%	100.0	–	–	–	–	–	–	–	100.0		

used by operational weather forecasters in NIMH, for issuing warnings for yellow, orange and red code (Table 1, rows 4–9). For yellow code in Sofia the predominant wind direction at Cherni vrah is 202° with 47.4% of the days followed by 225° with 36.8%. Fifty-five percent of the days with orange code in Sofia are with wind direction at Cherni vrah 225° and all foehn events with red code are with the wind direction at Cherni vrah 180° . The manual circulation classification of the foehn days with yellow, orange and red code is presented in Table 2. The circulation class I results in 51.3%, 65.0%, and 100.0% of the days with yellow, orange and red code, respectively. In particular, class Ia is responsible for all days with red code, 50.0% of the days with orange, and 23.7% of the days with yellow code.

Conclusions. The 22-year foehn climatology of Sofia valley gives 136 foehn days selected by using quantitative criteria based on observed surface temperature, humidity and wind direction. Foehn is investigated with respect to Meteoalarm warning code criteria for wind gusts, applied in operational weather forecasting in Bulgaria. In 55.9% of the foehn days the wind gusts are between 14 and 20 m/s, corresponding to yellow code. In 14.7% the gusts are 20–30 m/s, which corresponds to the orange code, and in 1.5% it is above 30 m/s (red code). The modified Sofia-Cherni vrah Stability Index (SSI*) tends to decrease, reaching its minimum value, during foehn and increase with the foehn end. For the majority of foehn events the SSI* increase marks the foehn end and can be used for early guidance in operational forecasting. The mean SSI* value during foehn is 0.53 but it is also obtained for days without foehn, which is an indication that SSI* alone could not be used to distinguish between foehn/no foehn conditions. The upper-air flow at mountain peak Cherni Vrah shows the major wind directions 202° and 225° (southwest) in 41.8% and 39.8% of the foehn days in Sofia, respectively. Further, the wind direction at Cherni vrah is analysed based on the Meteoalarm

criteria and for yellow code wind gusts in Sofia the predominant wind direction at Cherni Vrah is 202° with 47.4% of the days followed by 225° with 36.8%. 55.0% of the days with orange code are with wind direction at Cherni Vrah 225° , and for all foehn events with red code the wind direction at Cherni Vrah is 180° . For the foehn days a manual circulation classification is created with four circulation classes. Circulation class I, Mediterranean cyclone passing over Hungary, results in 51.3, 65.0 and 100.0% of the days with yellow, orange and red code, respectively. A detailed case study for 2010 shows that SSI* has very high sensitivity to foehn/no foehn conditions, and for all events in 2010 it has local minimums during foehn. The IWV on the other hand does not show clear tendency before, during and after the foehn, and confirms previous findings that it registers the air mass passing around the Vitosha mountain.

REFERENCES

- [1] GUTERMANN T., B. DURR, H. RICHNER, S. BADER (2012) Föhnklimatologie Altdorf: die lange Reihe (1864–2008) und ihre Weiterführung, Vergleich mit anderen Stationen, <http://e-collection.library.ethz.ch/eserv/eth:6318/eth-6318-01.pdf>.
- [2] RICHNER H., P. HACHLER (2013) Understanding and Forecasting Alpine Foehn. In: (F. K. Chow, S. F. J. De Wekker, B. J. Snyder Eds) Mountain Weather Research and Forecasting (Chapter 4), Springer Atmospheric Sciences, 219–260, https://doi.org/10.1007/978-94-007-4098-3_4.
- [3] NORTE F. A. (2015) Understanding and Forecasting Zonda Wind (Andean Foehn) in Argentina: A Review, Atmospheric and Climate Sciences, **5**(3), 163–544.
- [4] NORTE F. A. (1988) Características del viento Zonda en la Región de Cuyo, PhD Thesis, Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, <http://www.prmarg.org/tesis-doctorado>.
- [5] WIDMER R. (1966) Statistische Untersuchungen über den Föhn im Reusstal und Versuch einer objektiven Föhnprognose für die Station Altdorf, Vierteljahres Schr. Naturforsch. Ges. Zurich, 331–375.
- [6] OTERO F., F. NORTE, D. ARANEO (2018) A probability index for surface zonda wind occurrence at Mendoza city through vertical sounding principal components analysis, Theoretical and Applied Climatology, **131**(1–2), 213–225.
- [7] STOYCHEVA A., S. EVTIMOV (2014) Studying the fogs in Sofia with Cherni vrah - Sofia Stability Index, Bulgarian Geophysical Journal, **40**, 23–32.
- [8] GUEROVA G., T. SIMEONOV, N. YORDANOVA (2014) The Sofia university atmospheric data archive (SUADA), Atmospheric Measurement Techniques, **7**(8), 2683–2694.
- [9] GUEROVA G., T. DIMITROVA, S. GEORGIEV (2019) Thunderstorm classification functions based on instability indices and GNSS IWV for the Sofia Plain, Remote Sensing, **11**(24), 2988.
- [10] HRISTOV P., A. TANEV (1970) The Climate of Sofia, Sofia, Nauka i Izkustvo, 278 pp.

- [11] National Centre for Environmental Prediction GFS model, <http://www.wetterzentrale.de/topkarten/fsres.2eur.html>, accessed 30 June 2021.
- [12] EUMETNET, MeteoAlarm – early warning system for severe weather in Europe, <http://www.meteoalarm.org>.
- [13] STOEV K., G. GUEROVA (2020) Foehn classification and climatology in Sofia for 1975–2014, *Időjárás – Quarterly Journal of the Hungarian Meteorological Service*, **124**(4), 483–497.
- [14] BELINSKI B. A. (1948) *Dynamic Meteorology*, St. Petersburg, Hydrometeoizdat, (in Russian).
- [15] HOLTON J. R. (1972) *An Introduction to Dynamic Meteorology*, New York, Academic Press, 319 pp.
- [16] STOEV K., P. POST, G. GUEROVA (2022) Synoptic circulation patterns associated with foehn days in Sofia in the period 1979–2014, *Időjárás – Quarterly Journal of the Hungarian Meteorological Service*, **126**(4), 545–566.
- [17] STOEV K., G. GUEROVA, K. VASSILEVA (2017) Use of GNSS tropospheric products to study the foehn in Sofia, *Proceedings of the 6th International Colloquium Scientific and Fundamental Aspects of the Galileo Programme*, 1–4.
- [18] STEINACKER R. (1981) Analysis of the temperature and wind field in the Alpine region, *Geophysical & Astrophysical Fluid Dynamics*, **17**(1), 51–62.
- [19] BYRAM S., C. HACKMAN (2014) IGS final troposphere product update. In: Poster presented at IGS workshop.

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