

FOG CLIMATOLOGY AND STABILITY INDEX
FOR PLOVDIV 1991–2018

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Abstract

Fog can cause large economic losses for public services and in particular aviation where the cost of flight delays and rescheduling is estimated to hundreds of millions of euros per year. Despite the continuous improvement of weather prediction fog diagnosis and forecasting remains a challenge. In the US alone, 74% of the fatal car crashes are associated with recorded low visibility but without fog warning in the forecast. Today the operational fog forecasting is mainly done with “in-house” developed tools, which is understandable due to the fog life cycle peculiarity. The aim of this work is to investigate the fog climatology for Plovdiv, Bulgaria, for the period 1991–2018 and to use it for calculation of a threshold value of stability index, which can be implemented as an operational forecast tool. One fog case in January 2013 is selected for numerical weather prediction simulations with the WRF model for the city of Plovdiv. It was found that while the index with its site specific threshold value describes well the fog evolution, the WRF model has large deviations in temperature compared to the observations during daytime.

Key words: fog climatology, fog index, WRF simulations

Introduction. Fog prediction is a challenging process because of fog’s local nature. In large cities fog is frequently combined with decreased air quality due to the presence of inversion layers. ASHLEY et al. [1] study the fatal car crashes in the US caused by low visibility for the period 1994–2011. They report that approximately 500 fatal crashes each year occur when fog is reported. It was also

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found that during the period 2007–2011 74% of the fatal crashes associated with low visibility were on days with no warnings for fog in the forecast, which shows the importance of correct fog forecasting. HOLTSLAG et al. [2] examine empirical methods as alternative forecasting tools, and conclude that Fog Stability Index (FSI), based on radiosonde profiles and optimised for stations in the Netherlands, results in an improvement of the forecast skills. The FSI is found to give better forecast scores than the NWP model, especially after optimisation for site specific conditions. STOYCHEVA and EVTIMOV [3] made fog climatology for Sofia for the period 1992–2014 and proposed a Sofia-Cherni vrah Stability Index (SSI), based on Brunt–Väisälä frequency concept to estimate the strength of the static stability of the atmosphere over Sofia. The index is found to separate fog and no fog intervals. In STOYCHEVA et al. [4] a comparison of SSI and an index computed using the Weather Research and Forecasting (WRF) model (SSI_w) shows a high correlation but also model underestimation for selected fog case study in Sofia. The assimilation of surface and upper-air observations in the WRF model resulted in 10% improvement of the SSI_w being a result of moderate improvement of the vertical temperature profiles. From 2019, the observation and NWP model based SSIs for Sofia are implemented and used in pre-operational settings for fog monitoring at the National Institute of Meteorology and Hydrology (NIMH).

Holtslag et al. [2] investigated the behaviour of Fog Stability Index (FSI) for 12 stations in the Netherlands compared to NWP output and have found that after optimization for the specific location the FSI gives better results in comparison to NWP (MM5) direct output. Despite the improvements of horizontal and spatial resolution, microphysics and initial data NWP models were found to have significant disadvantages for forecasting fog mainly because of the small scale of the phenomena and local effects which can remain unresolved by the model (JACOBS et al. [5]). Inaccurate surface conditions such as temperature, relative humidity associated with the error in the initial conditions were found to be a main factor for unsatisfactory NWP fog forecasts (MANAFOV et al. [6], PITHANI et al. [7]). STEENEVELD et al. [8] compared the performance of WRF and HARMONIE models for two fog cases – one in Autumn and one in Spring, in the Netherlands. The WRF is evaluated to better predict the fog type and timing. The boundary layer parameterization scheme is found to be the most important for fog onset, while for fog dissipation microphysics plays a key role. These two models are found to have more difficulties to predict radiation fog rather than cloud-base lowering fog (ROMÁN-CASCÓN et al. [9]) because of the inaccuracy of simulated surface temperature. On the other hand, cloud-base lowering type of fog is thicker or more prolonged than observations have shown. For radiation fog WRF is found to be very sensitive to spin-up (ROMÁN-CASCÓN et al. [10]) and initial conditions. The horizontal resolution increase does not improve the fog forecast significantly and instead, the data assimilation is found to be more important. Increased model vertical resolution leads to earlier fog onset (PHILIP

et al. [11]), more heterogeneous and more frequent fog in the forecasts because of better model representation of boundary layer conditions. The different model parameterizations for fog forecasting are evaluated by STEENEVELD et al. [12] and it was shown that the most important parameters for adequate representing the fog life cycle are those about soil conductivity and turbulent boundary-layer mixing. Utilizing soil moisture content for radiation fog with prior precipitation greatly improves the forecast (KIM et al. [13]) and is recommended for the operational forecasts. The aim of this study is to prepare the fog climatology and to propose a fog index for Plovdiv, Bulgaria.

Fog index for Plovdiv. In this study the proposed by Stoycheva and Evtimov [3] SSI is applied. Plovdiv is situated 150 km south east of Sofia and Cherni vrah peak is not representative for the upper air flow in this region thus the closest station Rozhen in the Rhodope mountains is used. A modified index is proposed using surface observations from Plovdiv and Rozhen. The index is named Plovdiv Stability Index (PSI) and is defined as:

$$(1) \quad \text{PSI} = \sqrt{((1 + (T_{1746} - T_{154})/16)/(1 + T_{1746}/273.15))},$$

where T_{1746} is the surface air temperature at Rozhen (1746 m asl) in °C and T_{154} is the temperature at Plovdiv (154 m asl). The PSI scaling factor of 16 reflects the altitude difference between Plovdiv and Rozhen (1600 m) assuming a temperature gradient of 10 °C/1000 m. Plovdiv (154 m asl) is located in the plain between Balkan (to the north) and Rhodope (to the south) mountain ranges. Rozhen is 90 km to the south of Plovdiv in the Rhodope mountains at altitude 1746 m asl. Rozhen is closer to Plovdiv than Cherni-vrah (130 km to the west) and is recommended by experienced forecasters as a better representation of the advection at altitude from south and southwest during fog conditions in Plovdiv.

Observations and data. The surface synoptic observations are provided by the National Institute of Meteorology and Hydrology (NIMH). Data from the synoptic weather station in Plovdiv, Bulgaria (42°8'N, 24°48'E; 154 m asl) are used for fog registration. The observations in the synoptic station are in 00, 06, 12, 18 GMT (main synoptic observations) and in 03, 09, 15 and 21 GMT (intermediate synoptic observations). The temporal resolution of the data is 3 h and for the purpose of this work the temperature, past and present weather phenomena and horizontal visibility are extracted. The data analysis is based on the number of every 3-hour fog registrations, not just fog cases. Fog duration is measured by the number of consecutive registrations of fog multiplied by 3. A software is developed to read and analyse the data and to fix gaps in observations based on past phenomena in the next observation. Temperature from the synoptic weather station in Rozhen (41°41'N, 24°44'E; 1746 m asl) is used to calculate PSI. The temperature from the station in Plovdiv is used to calculate the equivalent potential temperature (EPT) (HOLTON et al. [14]). EPT is used as a criterion for static stability of the atmosphere and for changing of the air mass. Rapid change of the

surface EPT indicates a change of the air mass, while the absence of diurnal cycle indicates lack of dynamics, which favours the fog development.

Results. Fog climatology for Plovdiv: 1991–2018. To investigate fog parameters and time distribution a period of 28 years is chosen. The seasonal climatology is done for: 1) winter season – from November to February (NDJF), 2) spring season – March to May (MAM), 3) summer season – June to August (JJA) and 4) autumn season – September to October (SO). The fog in Plovdiv is predominantly seasonal with 91.4% of the registrations during winter (not shown). For comparison in Sofia winter fog is 97.2% of all registrations (STOYCHEVA and EVTIMOV [15]). In spring the fog registrations are 3.66%, with 0.59% and 4.34% for summer and autumn, respectively. In the summer fog occurs after the passage of cold fronts as the humidity increases and the temperature drops, while during the winter season fog develops during strong and prolonged temperature inversions under the influence of anticyclones. Figure 1a presents the fog distribution by four horizontal visibility intervals (WMO-Codes): a) 0–50 m, b) 50–200 m, c) 200–500 m, and d) 500–1000 m. The peak fog registrations are 999 with visibility between 50 and 200 m and combined with the registrations with visibility below 50 m (329) gives 53.5% total. Thus the more common fog in Plovdiv is with horizontal visibility below 200 m. The diurnal cycle of fog registrations is well defined with a maximum number of cases at 06 UTC (509) and minimum between 12 and 15 UTC (158). This diurnal cycle is to be expected as in the afternoon hours the visibility tends to increase due to radiative forcing. Figure 1b presents the distribution of fog duration. It is seen that the peak is for fog cases with duration up to 3 h (339) and after that the number of cases decreases by a factor of about 2 up to 15 h fog duration (31). During the study period there are 12 fog cases, which last longer than 45 h, one of them is with duration 141 h and is the longest registered for the period 8–14 January 2008.

Plovdiv Stability Index 1991–2018. In order to use PSI as an indicator for fog onset and dissipation it is necessary to investigate and quantify its changes for different visibility ranges. A software is developed to analyze the data from Plovdiv and Rozhen from 1991 to 2018 and to calculate PSI in seven visibility ranges up to 50 km. The PSI median for fog registrations with visibility between 0 m and 1000 m has the value of 1, which will be used as fog threshold. In the visibility range: 1) 0–200 m PSI is 1.01, 2) 200–500 m PSI is 0.96, and 3) 500–1000 m PSI is 0.91. PSI values tend to decrease with increase of visibility reaching 0.52 at 50 km. Figure 2a shows a box and whisker plot of PSI for fog and no fog cases for each month in the winter season. The difference on a monthly basis is well seen as the 25 percentile for fog has around the same value as the 75 percentile for no fog. The values are higher in January and December compared to February and November for both fog (F) and no fog (noF) cases. Fog is not the only weather phenomenon that causes low visibility. Heavy rain, drizzle, snow as well as smoke and dust can also result in visibility reduction. A box and whiskers

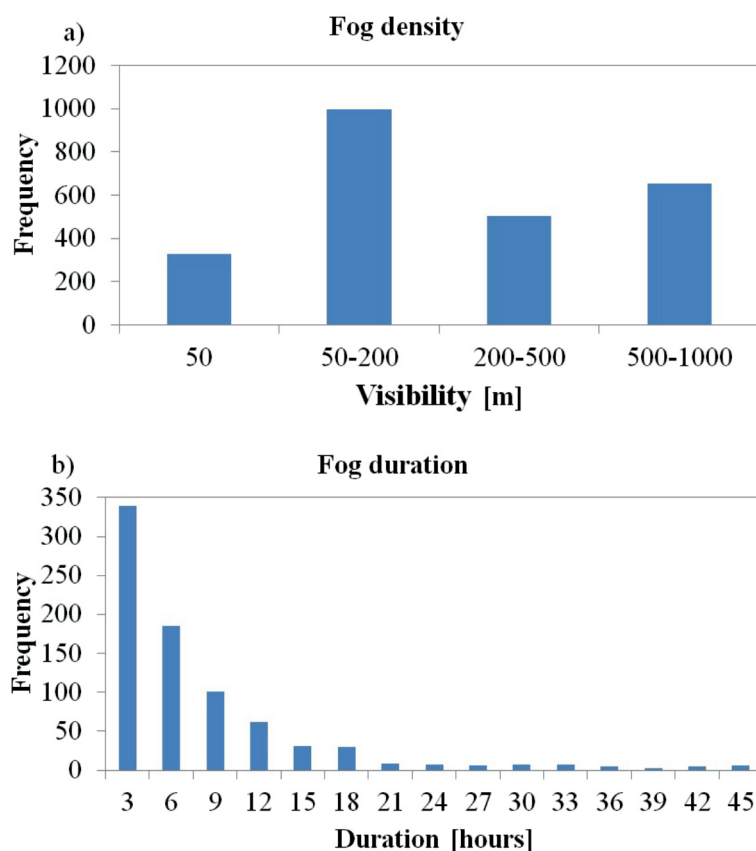


Fig. 1. Fog registrations (every 3 h). a) Distribution of fog registrations by visibility; b) Distribution of fog duration

plot presented in Fig. 2b shows the PSI values for: a) visibility below 1000 m due to fog (left box), 2) visibility below 1000 m due to other phenomena (middle box) and 3) visibility 1–50 km (right box). It is clearly seen that the highest PSI values correlate with low visibility due to fog. There is no overlap between left and middle boxes, which indicates statistically significant phenomena separation by PSI, i.e. fog versus snow or drizzle. The 25 percentile of the left box is with value 0.9 while the 75 percentile of the middle box is 0.88. The PSI 75 percentile value for the visibility range 1 to 50 km (right box) is 0.8 thus it can be concluded that the PSI range during fog has unique values and can be used for guidance in operational forecasting.

Discriminant analysis. Further, an evaluation of PSI is made via discriminant analysis by grouping PSI (independent variable) with F/noF indicator (grouping variable). Table 1 presents the percentage of all cases correctly assigned to each group – F and noF, based on the discriminant analysis. PSI and RH are investigated separately and then combined. While PSI alone has a higher per-

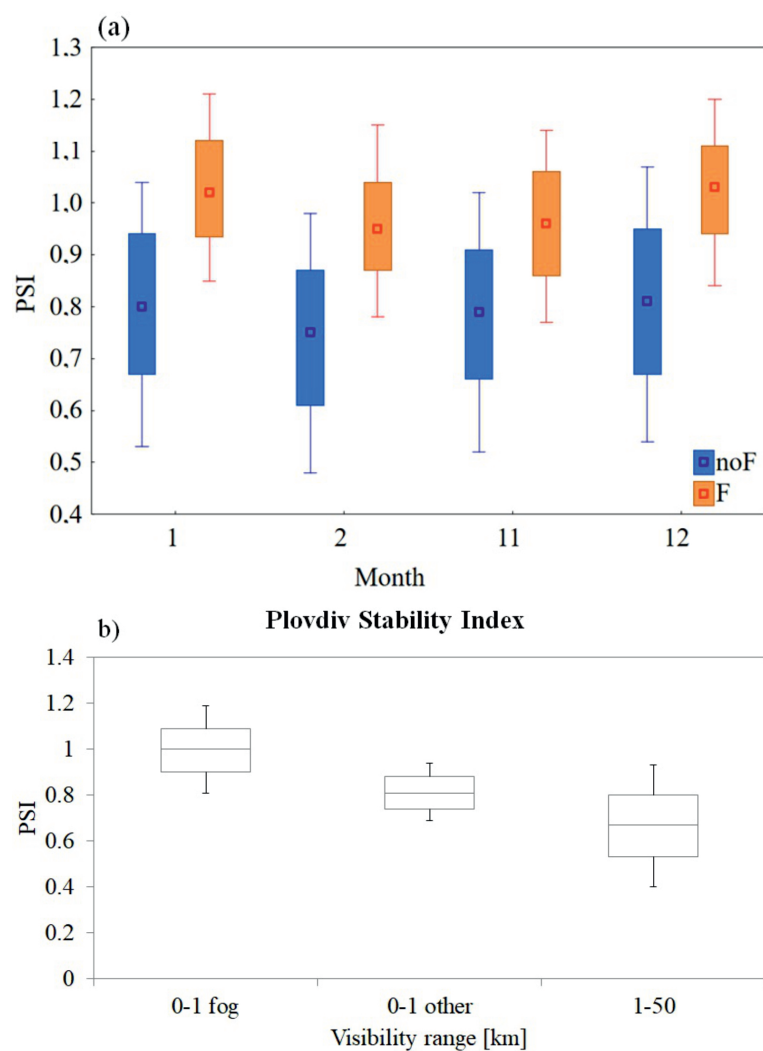


Fig. 2. a) Monthly box and whisker plot of PSI for winter season; b) Box and whisker plot of PSI and 10, 25, 75, and 90 percentiles for visibility: 1) left 0–1000 m (fog), 2) middle 0–1000 m (other), and 3) right 1001–50 000 m (no fog)

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POD for F/noF groups for the period 1991–2018 calculated from:
(1) PSI only, (2) RH only, and (3) combination of PSI and RH

POD	PSI	RH	PSI + RH
noF	79.7%	67.4%	78.7%
F	85.2%	98.1%	93%

centage of correct guesses for noF cases in comparison to RH – 79.7% and 67.4%, respectively, RH alone shows better results for F cases. The combination of both smooths the differences, giving probability of detection (POD) of 93% for F and 78.7% for noF. These better results of the combination of PSI and RH are driven by the combining factors of stability of the surface layer from PSI and the surface relative humidity. The discriminant analysis shows that the combination of PSI and RH is a reliable tool for fog prediction.

Case study: 1–3 January 2013. The case study presents a radiation-advection fog (radiation cooling combined with warm air advection at 1500 m) in the period 1–3 January 2013. Figure 3 shows PSI for Plovdiv from 1 to 3 of January 2013 calculated from observations (PSI) and WRF temperature profiles (PSI_W). The black dashed line is the PSI threshold value for fog. The PSI value increases with fog onset on 2 January reaching a maximum value of 1.22 and is above the fog threshold of 1.00. It is seen that PSI from observations describes the fog onset and dissipation very well, while PSI_W has low values and reaches the threshold only once at 06 UTC on 2 January. The correlation coefficient of PSI and PSI_W is 0.75. The significantly lower values are due to absence of daytime inversions in model temperature profiles (see Fig. 3b). The equivalent potential temperature is used to characterize the air mass over the station and it indicates the change in air mass after 6 UTC on 3 January, which is when the fog dissipates. The mean values of PSI confirm that it has overall higher values for the fog periods compared to periods with no fog. For the whole period of the case study, PSI_W has 20% lower values than PSI from observations. For the fog periods it is 18% lower and for the periods without fog 25%.

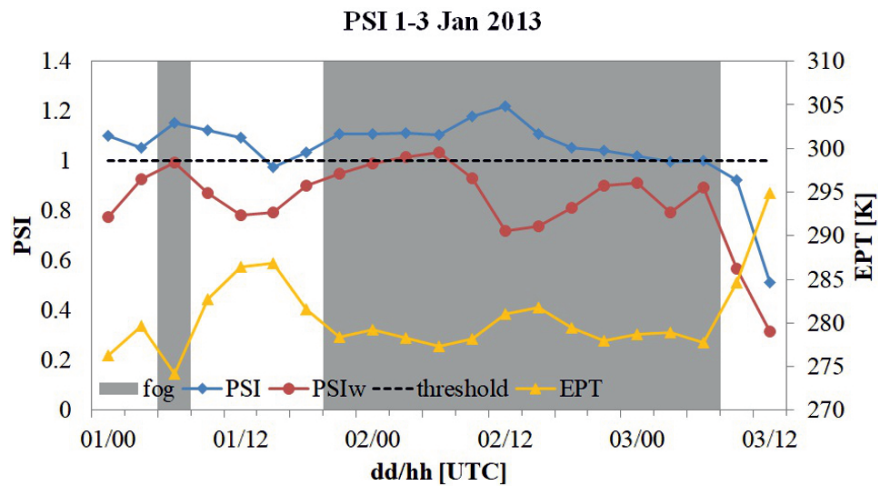


Fig. 3. PSI calculated from observations (blue line), from WRF T profile for Plovdiv (red line). Equivalent potential temperature (orange line) and fog periods (grey area). Black dashed line indicates the PSI threshold for fog

Discussion and conclusions. From the climatology it can be concluded that for Plovdiv fog is: 1) mainly a winter phenomenon with 91.4% of total registrations, and 2, that it has well-defined diurnal cycle with maximum frequency at 06 UTC. For the period 1991–2018 most of the fog cases are with duration of 3 to 6 h and 53.5% of the reports are for horizontal visibility below 200 m. Further, a threshold value of Plovdiv Stability index (PSI) for fog occurrence is derived from observations for the period 1991–2018.

The PSI is found to have a statistically significant skill in horizontal visibility separation with respect to weather phenomena. For a radiation-advection fog case study on 1–3 January 2013 the PSI value increases with fog onset on 2 January reaching a maximum value of 1.22 and is above the 1.00 threshold during the fog. Fog dispersion on 3 January at 06 UTC results in PSI decrease below the threshold of 1.00. The correlation coefficient of PSI and PSI_W is 0.75.

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