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Preliminary contribution
Prethodno priopćenje

FOG EVENT CLIMATOLOGY FOR ZAGREB AIRPORT

Klimatologija događaja magle na zračnoj luci Zagreb

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Abstract. This work presents a comprehensive study of climatology of fog events at Zagreb Airport. The data used in the study consists of observations from 1994 to 2015, in form of METAR reports. Fog events are classified into five types based on the physical mechanism of formation. The results show a decrease in the annual number of fog events at Zagreb Airport during the last 22 years. Fog is more frequent in the period between September and February, which can be designated as fog season. During spring and summer fog is a relatively rare phenomenon. Fog is usually quite dense; events with a minimum visibility of over 200 m occurred in only 29% of cases. Radiation fog is the dominant type of fog. The analysis has also shown that advective fog is very rare during summer, while precipitation fog and cloud base lowering fog occur only during fall and winter. All fog types except evaporation fog have a similar distribution of duration. Radiation fog and advective fog are the densest types; precipitation fog is the least dense type. A closer analysis of radiation fog has provided data on the annual/diurnal distribution of frequencies of onset and dissipation, wind during onset or dissipation, and persistence.

Key words: Fog, climatology, classification of fog, visibility, Zagreb airport

Sažetak. U ovom radu opsežno je predstavljena klimatologija događaja magle na zračnoj luci Zagreb. U radu su korišteni podaci iz METAR izvještaja, u razdoblju od 1994. do 2015. Događaji magle su klasificirani u pet vrsta prema fizikalnom mehanizmu nastanka. Rezultati pokazuju smanjenje godišnjeg broja događaja magle na zračnoj luci Zagreb u protekle 22 godine. Magla je češća u razdoblju između rujna i veljače, koje se može nazvati sezonom magle. Za vrijeme proljeća i ljeta pojava magle je relativno rijetka. Magla je obično prilično gusta; događaji s minimalnom vidljivošću većom od 200 m čine samo 29% slučajeva. Prevladavajuća vrsta magle je radijacijska. Analiza pokazuje da je advektivna magla vrlo rijetka za vrijeme ljeta, dok oborinska magla i magla spuštanja podnice oblaka nastaju samo ujesen i zimi. Sve vrste magle, osim magle isparavanja, imaju sličnu raspodjelu trajanja. Radijacijska i advektivna magla su najgušće vrste; oborinska magla je najmanje gusta. Pomnija analiza radijacijske magle pružila je podatke o godišnjoj/dnevnoj raspodjeli učestalosti početka i završetka događaja magle, vjetra za vrijeme početka i završetka te perzistencije.

Ključne riječi: Magla, klimatologija, klasifikacija magle, vidljivost, zračna luka Zagreb

1. INTRODUCTION

The occurrence of fog represents a major problem in traffic, which is especially emphasized in air traffic due to safety concerns. Long lasting fog events at airports can cause significant flight delays due to poor visibility and low cloud ceiling. These delays are associated with considerable costs, as flights have to be diverted to nearby airports. Accurate fog forecasts at airports are therefore of major importance for airlines and the aviation industry as a whole. As an example, Allan (2001) in his study estimated that improved forecasts during low ceiling visibility events at three major airports in New York City area could save up to $240,000 per event. Although no such studies exist for Zagreb, it is reasonable to assume that more accurate fog forecasts would also lead to substantial savings, despite the fact that there is much less traffic at Zagreb Airport when compared to airports in the New York City area.

Fog represents one of the areas of meteorology where scientific understanding is still limited (Gultepe, 2007). Although synoptic and mesoscale forcing play a role, local microphysical processes in the atmospheric boundary layer are the deciding factor in fog formation. Because of this complexity, forecasting fog is a difficult task. Operational numerical weather predictions models, although being continuously improved and upgraded, are too cumbersome to offer anything but rough guidance (Teixeira and Miranda, 2001; Klaić, 2015), so the forecaster often has to use his own experience and particular knowledge of local meteorological conditions in the forecasting process. Studying the climatology of fog can therefore add to the forecaster's knowledge and experience, which can in the end lead to improved forecasts of low visibility and ceiling (Hyvärinen et al., 2007). Until now, there were few published articles on fog climatology for continental parts of Croatia - e.g. comprehensive study by Makjanić (1953) - but there were some graduate theses dealing with fog in Zagreb region. Lisac (1953), Brzoja (2012) and Leko (2014) analyzed the occurrence of fog with respect to meteorological and other parameters in their graduate theses. Klaić (2015) analyzed the performance of the WRF-ARW high-resolution NWP model in simulating fog. For Zagreb Airport, Ivatek-Šahdan (1997) did an analysis of horizontal visibility. In the surrounding region, Veljović et al. (2014) did an analysis of fog events at Belgrade Airport, which shares a lot of climatological features with Zagreb. A similar study was made by Stolaki et al. (2009) for Thessaloniki Airport in Greece.

The main purpose of this study is to provide the aviation forecaster with a detailed climatological analysis of fog events at Zagreb International Airport. Fog events are classified into five different types according to the physical processes of formation of fog and analyzed by using common statistical methods. An attempt is made to better understand the general behavior of each fog type and the meteorological features influencing their formation.

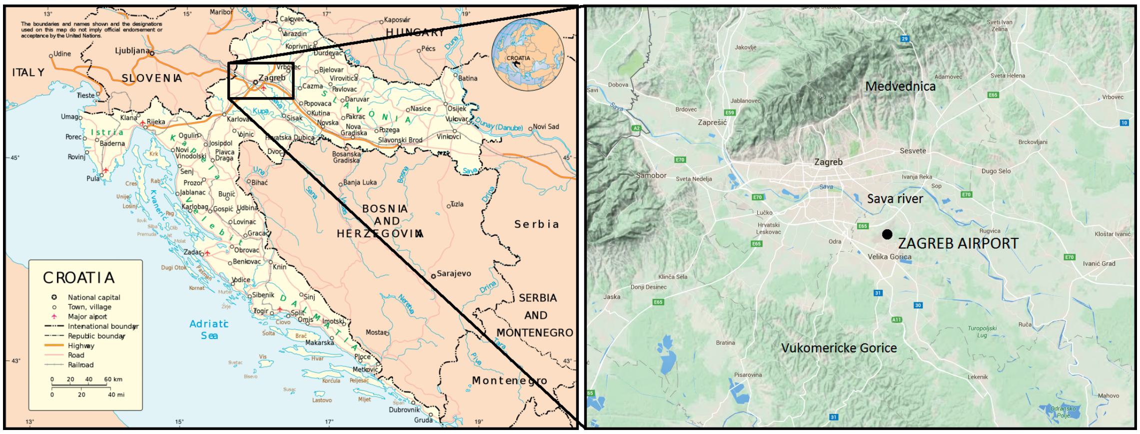

Figure 1. Location of Zagreb Airport.

Slika 1. Položaj zračne luke Zagreb.

2. LOCATION AND DATA

Zagreb Airport is located roughly 10km southeast from Zagreb city center, near the suburban village Pleso and town of Velika Gorica (Figure 1). Exact geographical coordinates of the airport are 45°44’35’’ N, 016°04’08’’ E, and its elevation is 108 m AMSL. The airport is situated in a fog-prone plain south of the Sava River, which is a major source of humidity. In addition, the area east of the airport is dotted with small ponds that also serve as significant humidity sources. The terrain surrounding the airport is very flat and covered predominately by grasslands and small forests. Underground waters in the region reach near the surface, which is also a factor that contributes favorably to fog development (Sijerković, 2012). As demonstrated by Brzoja (2012), the meteorological station at Zagreb Airport recorded more days with fog per year than two urban stations in the city of Zagreb in the period between 1981 and 2008. The only larger mountain in the near vicinity of the airport is Medvednica, which is located 20 km to the north-northwest. Its highest peak, Sljeme, is at 1,035 m AMSL. Another topographical feature in the vicinity of the airport is the wooded low hill range of Vukomericke gorice, located approximately 15 km south-southwest of the airport. Its highest peak is at 243 m AMSL. Zagreb Airport is the largest airport in Croatia, having served 2,587,798 passengers in 2015 with 39,854 registered flights (*Statistics for 2015*).

METAR, also known as the Meteorological Aerodrome Report, is the standard type of weather report used for reporting meteorological conditions at airports. A typical METAR report contains data for wind speed and direction, visibility, weather phenomena (if any), cloud cover and height, air and dewpoint temperature and barometric pressure. The data used in this study consists of half-hourly METAR reports from Croatia Control’s climatological database. It should be noted that visibility data in each METAR are estimates made by the human observer, situated near the end of the runway with an excellent view of the surroundings. Other meteorological parameters needed in fog type analysis used from METAR reports are: wind speed, weather phenomena, height and amount of clouds and temperature and dew point. In aviation, all meteorological reports are standardized to UTC time. Zagreb local time is UTC+1. The dataset used in this study covers a 22-year period spanning from Jan 1, 1994 to Dec 31, 2015. This is not consistent with standard climatological practice of analyzing data in 30-year timespans, but having in mind the forecasting needs previously outlined, this limited dataset should nevertheless provide valuable data for analysis.

3. FOG TYPE ANALYSIS PROCEDURE

Fog type analysis procedure used in this study closely follows the procedure outlined by Tardif and Rasmussen (2007), so it will be only briefly described here. Fog is commonly described as observed horizontal visibility below 1 km due to suspended water droplets or ice crystals in the atmosphere. Mist is described as observed horizontal visibility above 1km and below 10 km, but in aviation meteorology the limit is only 5 km.

A fog event is defined by using the *M-of-N* concept (Setiono et al., 2005), which was adopted by Tardif and Rasmussen (2007) and slightly refined in this work. Here a fog event is defined when visibility is less than 1 km in at least two out of five consecutive METAR reports, or if reported visibility is 2 km or less in at least three METAR reports and less than 1

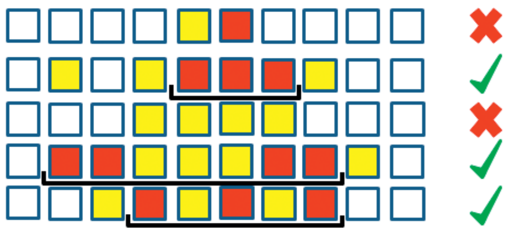

Figure 2. Examples of fog event definition in time series of half-hourly METAR reports (criteria described in text). White boxes: reports with no fog or mist, yellow boxes: reports with visibility between 1 and 2 km, red boxes: reports with visibility less than 1 km. A fog event (underlined in black) was found in data displayed in rows 2, 4 and 5.

Slika 2. Primjeri definicije događaja magle u vremenskim nizovima polusatnih METAR izvještaja (kriteriji su opisani u tekstu). Bijeli kvadrati: Izvještaji bez magle ili sumaglice, žuti kvadrati: izvještaji s vidljivošću između 1 i 2 km, crveni kvadrati: izvještaji s vidljivošću manjom od 1 km. Događaj magle (podcrtano crnom bojom) je pronađen u podacima u nizovima 2, 4 i 5.

km in one of these three reports. These reports with low visibility need not be consecutive - 'breaks', i.e. periods with visibility greater or equal to 1 km lasting up to two hours, are allowed. This principle ensures two important conditions are met: firstly, occurrences of fog lasting less than an hour are excluded from the analysis, and secondly, fog events with fluctuations visibility are not artificially split into two or more separate events. This logical test is then run through a segment of 5 consecutive METAR reports, one seg-

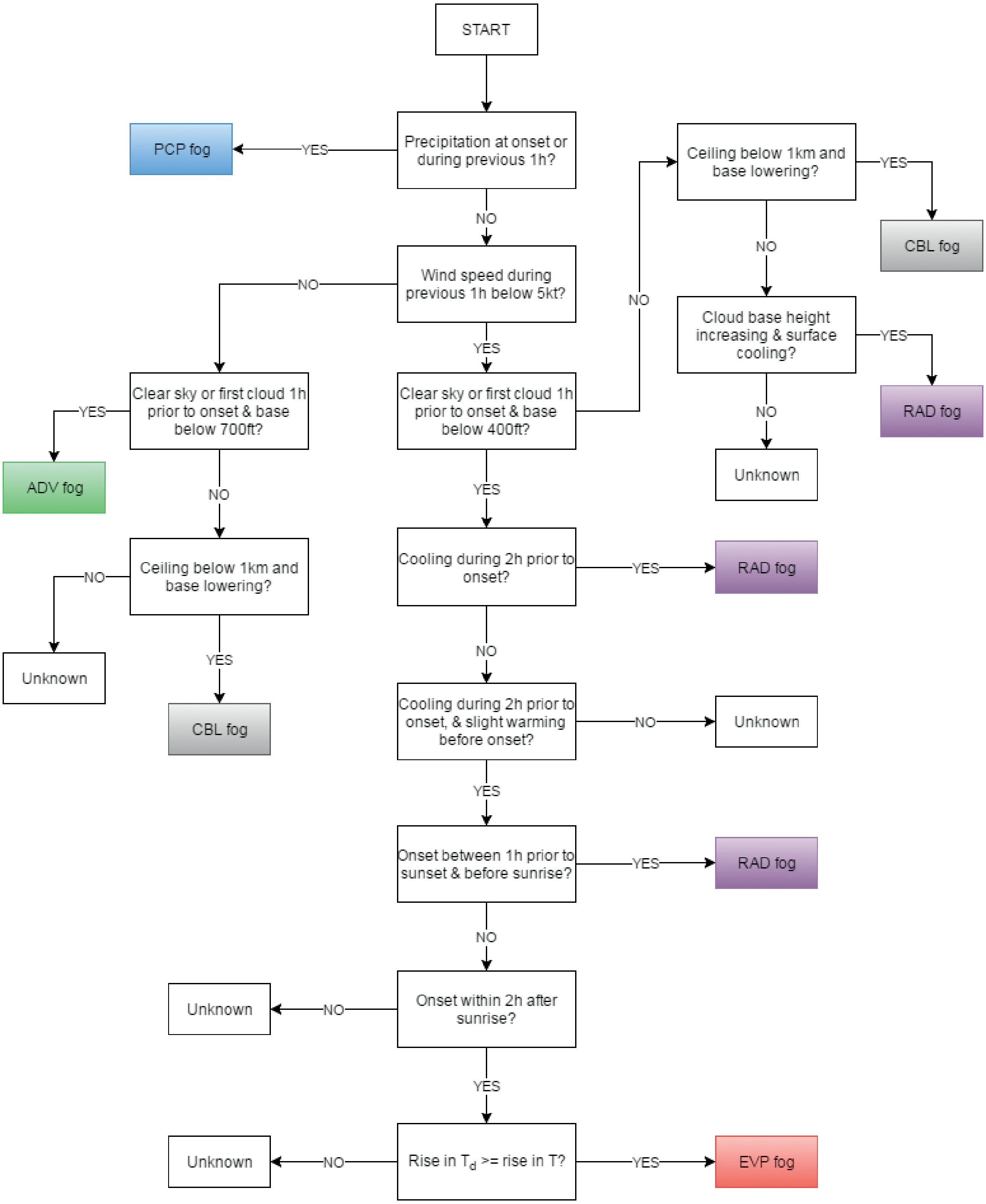

Figure 3. Flowchart diagram illustrating the fog type classification algorithm used in this study (Tardif and Rasmussen, 2007).

Slika 3. Dijagram toka s algoritmom klasifikacije vrsta magle korišten u ovom radu (Tardif i Rasmussen, 2007).

ment at a time (somewhat similar to calculating sliding averages). Figure 2 shows some examples of fog events defined in this way.

Obtained fog events are classified into five types - the defining characteristic for each type is the physical mechanism of fog formation, which is derived from an objective analysis of the behavior of meteorological parameters before onset of each event. According to the classification scheme used by Tardif and Rasmussen (2007), these five types are: 1) radiation fog, 2) advection fog, 3) precipitation fog, 4) evaporation fog and 5) stratus lowering fog. Fog events that could not be identified by this algorithm were designated as unknown type. However, in this study there were some differences applied. These are: 1) for radiation fog, the temperature decrease query was broadened to a 2-hour timespan before onset; 2) for advection fog, the wind speed threshold was set to value greater or equal to 5 kt; 3) for stratus lowering fog, the timespan of cloud base lowering was reduced to 3 hours; 4) for evaporation fog, the onset time was redefined as up to 2 hours after sunrise, instead of one hour. Detailed algorithm with flowchart and used thresholds is provided in Figure 3. These changes were introduced because the initial analysis, made by using the original classification scheme, resulted in the number of fog events of unknown type being too large - over 20% of total number. This was considered to be unacceptable, so the conditions for classification were further refined and finely tuned as described above, to acknowledge specific characteristics of local fog behavior and produce more clear results. After this step the number of fog events of unknown type was reduced to 6%. It should be noted that the original classification scheme was also used by Stolaki et al. (2009), van Schalkwyk and Dyson (2013) and Veljović et al. (2014).

Tardif and Rasmussen (2007) found that on the eastern US coast radiation fog occurs more often at stations that are further away from the sea, while on the coastal stations it is a relatively rare phenomenon. Schalkwyk and Dyson (2013) found that radiation fog constitutes 51% of all fog events at Cape Town Airport, in the period 1997-2010. According to results from Stolaki et al (2009), radiation fog is the second most numerous type of fog at Thessaloniki Airport with 29% of cases. Judging from these results, it would seem that radiation fog is more common at locations with more continental characteristics, while advective fog is more common at maritime locations.

4. RESULTS AND DISCUSSION

a. General characteristics of fog

The algorithm previously described found that there were 1336 fog events in the 22-year period from 1994 to 2015 (approximately 60 events per year). Figure 4 shows the total number of fog events at Zagreb Airport per year in the period 1994-2015. Although there are significant variations in the yearly number of events - maximum is 79 events in 1998, minimum is 40 events in 2012 - the general trend shows a slight decrease in the yearly frequency of fog. It amounts to 0.30 events per year, which means that the yearly frequency of fog events during the 22-year period has decreased by 6.6 events in total. Mann-Kendall test shows that this trend is statistically significant at the 95% confidence level. This finding is consistent with the results of both Brzoja (2012) and Ivatek-Šahdan (1997), who also found a slight decrease in the yearly number of days with fog.

An important feature of fog is its annual variation in frequency. From the monthly distribu-

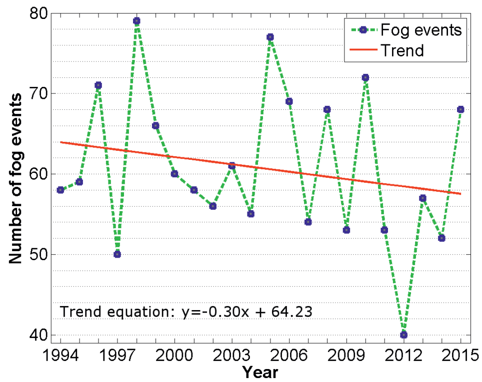

Figure 4. Yearly number of fog events at Zagreb Airport, 1994-2015. Blue dots represent the yearly number of events, with the linear trend shown with a red line.

Slika 4. Godišnji broj događaja magle na zračnoj luci Zagreb, 1994-2015. Plave točke predstavljaju godišnji broj događaja, a crvena linija linearni trend.

tion of the number of fog events (Figure 5) it can be seen that June and July have the lowest frequency of fog events. Starting from August and into September there is a marked increase in the number of fog events leading to a maximum in late fall and early winter. In February fog is significantly less frequent than in January, and this change starts the gradual drop in the monthly number of fog events. Judging from the data, it can be concluded that the period spanning from September to February (fall/winter) can be designated as 'fog season' at Zagreb Airport. This is the period of year during which fog is a frequent phenomenon. During spring and summer on the other hand, fog occurs rarely, but nevertheless it is not so rare to be considered an extreme event. Table 1, which shows the average monthly number of fog events at Zagreb airport in the period from 1994 to 2015, supports the previously mentioned findings. A quick comparison with the results of Veljović et al. (2014) shows that fog behaves similarly at Zagreb and Belgrade airports. This is not surprising since both locations have a similar climate according to Köppen classification - Cfb (Zagreb) and Cfa (Belgrade).

Figure 6 shows the monthly distribution of duration of fog events, measured in hours. It should be noted that the y-axis on the chart has been limited to 25 because in November, December and January there were cases of fog that lasted much longer than 25 hours. It can be seen that fog events during fall and winter are longer lasting than fog events dur-

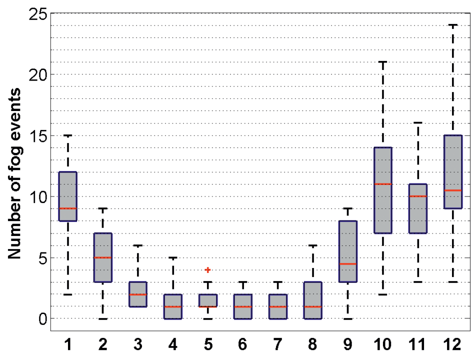

Figure 5. Monthly distribution of the number of fog events at Zagreb Airport during the period 1994-2015. Red crosses mark outliers.

Slika 5. Mjesečna raspodjela broja događaja magle na zračnoj luci Zagreb, 1994-2015.

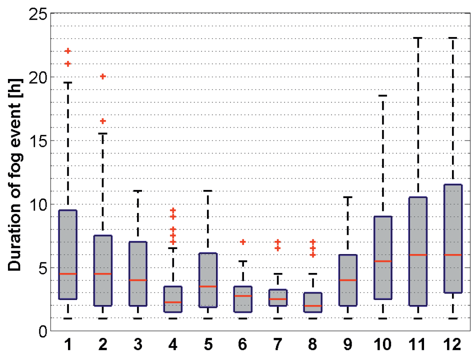

Figure 6. Monthly distribution of duration of fog events at Zagreb Airport, 1994-2015. Red crosses mark outliers.

Slika 6. Mjesečna raspodjela trajanja događaja magle na zračnoj luci Zagreb, 1994-2015.

Table 1. Average monthly number of fog events at Zagreb Airport, 1994-2015.

Tablica 1. Prosječan mjesečni broj događaja magle na zračnoj luci Zagreb, 1994-2015.

Month	Jan	Feb	Mar	Apr	May	Jun
# of events	9.7	4.9	2.5	1.5	1.3	1.2
% of total	16.0	8.1	4.1	2.5	2.1	2.0
Month	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
# of events	0.9	1.9	5.1	10.8	9.5	11.4
% of total	1.5	3.1	8.4	17.8	15.6	18.8

ing spring and summer. The reason for this is that insolation is weak during the fall and winter (weakest on December 21), which causes fog events to dissipate later in the day in this period. A notable exception to this rule can be observed in the data for May, which shows that fog is longer-lasting in this month, when compared to March or June.

Figure 7 shows the monthly distribution of total recorded visibility within fog events at Zagreb Airport. As can be seen, there is a difference between spring/summer and fall/autumn. During spring and summer fog is less dense - occurrences of visibility less than 200 m are rare, and median values are usually between 300 and 400 m. During fall and winter fog becomes denser, as median values drop to 200 m. It should be noted that median values for minimum visibilities during fog events (not shown here) are close to 200 m throughout the entire year.

Figure 8 shows the relative distribution of fog events by duration (above) and visibility (below). Raw data can be found in Tables 2 and 3. Here it is useful to recall that as a consequence of the event definition described in the

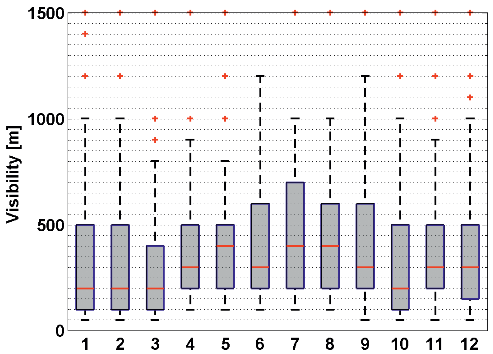

Figure 7. Monthly distribution of total recorded visibility within fog events at Zagreb Airport, 1994-2015. Red crosses mark outliers.

Slika 7. Mjesečna raspodjela zabilježene vidljivosti za vrijeme događaja magle na zračnoj luci Zagreb, 1994-2015.

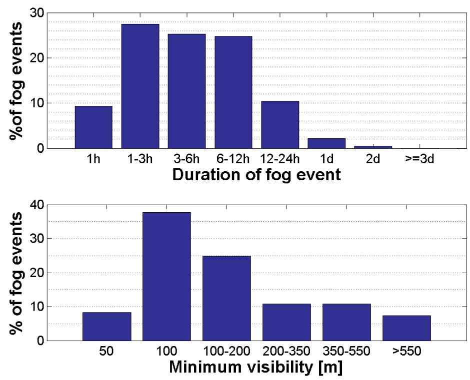

Figure 8. Relative frequency of fog events by duration (above) and minimum visibility (below) at Zagreb Airport, 1994-2015. In the second panel, first two bars correspond only to visibilities that are equal to 50 and 100, respectively.

Slika 8. Relativna učestalost događaja magle po trajanju (gore) i minimalnoj vidljivosti (dolje) na zračnoj luci Zagreb, 1994-2015. Na donjoj slici, prva dva stupca obuhvaćaju samo vidljivosti koje su jednake 50 i 100 m, redom.

Table 2. Number of fog events by duration at Zagreb Airport, 1994-2015.

Tablica 2. Broj događaja magle po trajanju na zračnoj luci Zagreb, 1994-2015.

Duration	1h	1-3h	3-6h	6-12h
# of events	125	367	338	331
% of total	9.3	27.5	25.3	24.8
Duration	**12-24h**	**1d**	**2d**	**>=3d**
# of events	139	29	6	1
% of total	10.4	2.2	0.4	0.1

Table 3. Number of fog events by minimum recorded visibility at Zagreb Airport, 1994-2015.

Tablica 3. Broj događaja magle po minimalnoj vidljivosti na zračnoj luci Zagreb, 1994-2015.

Visibility [m]	**50**	**100**	**100-200**
# of events	111	504	332
% of total	8.3	37.7	24.8
Visibility [m]	**200-350**	**350-550**	**>=550**
# of events	145	145	99
% of total	10.9	10.9	7.4

introductory chapter, fog events lasting only one METAR report (~30 minutes) are omitted from the analysis. Fog events lasting between 1 and 12 hours are the most numerous, and they make for over 77% of the total number of events. Fog events lasting an hour are rare, just as those lasting between 12 and 24 h - each category amounts to around 10% of total number. Fog events lasting more than a day are very rare. During the entire 22-year period there were 29 events that lasted more than one day, 6 events that lasted more than two days, and only one event that lasted more than three days. This result is consistent with findings of Ivatek-Šahdan (1997). The same figure also shows the relative distribution of fog events by minimum recorded visibility. It can be seen from the histogram that the majority of fog events at Zagreb Airport have minimum visibility between 50 and 200 m. In total they make for over 71% of fog events. Fog events with minimum visibility of over 200 m make the rest. Those events with minimum visibility of 100 m are the most numerous (38% in total).

b. Characteristics of fog by event type

According to the distribution of fog events by type (Figure 9 and Table 4), radiation fog (RAD) is the dominant type of fog at Zagreb Airport, with 950 (71%) recorded cases. This result is in agreement with the aforementioned hypothesis, as Zagreb is situated approximately 115 km away from the Adriatic Sea, with the Dinaric mountain range situated in between. Its climate is therefore highly continental in character. All other fog types, including the unknown cases, make for 29% of recorded events. They are roughly evenly distributed by quantity, with the cloud base lowering fog being the most numerous. Evaporation fog is the rarest type of fog that occurs at Zagreb airport, with only 43 recorded cases. Unknown cases represent 6% of total fog events. This confirms the validity of changes introduced in the original classification scheme devised by Tardif and Rasmussen.

Figure 10 shows a chart displaying the total number of fog events recorded per each month. A comparison with Figure 5 shows that the yearly distribution of total fog events is very similar to the yearly distribution of radiation fog (RAD) events. The only exception is December, when frequency of other fog types shows a notable increase. Advective fog (ADV) occurs mostly in the colder part of the

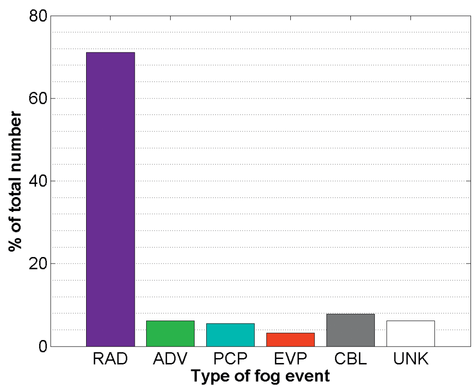

Figure 9. Fog events by type at Zagreb Airport, 1994-2015. Fog type classification based on Tardif and Rasmussen (2007).

Slika 9. Događaji magle po vrsti na zračnoj luci Zagreb, 1994-2015. Klasifikacija prema Tardif i Rasmussen (2007).

Table 4. Number of fog events by event type at Zagreb Airport (according to algorithm shown in Fig. 3), 1994-2015.

Tablica 4. Broj događaja magle po vrsti na zračnoj luci Zagreb (prema algoritmu prikazanom na slici 3), 1994-2015.

Type	RAD	ADV	PCP	EVP	CBL	?
#	950	83	73	43	104	79
%	71.1	6.2	5.5	3.2	7.8	6.2

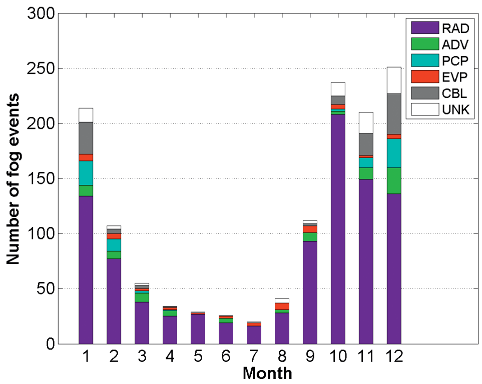

Figure 10. Total number of each type of fog event at Zagreb Airport, per month. Fog type classification based on Tardif and Rasmussen (2007).

Slika 10. Ukupan broj događaja magle svake vrste po mjesecima na zračnoj luci Zagreb. Klasifikacija prema Tardif i Rasmussen (2007).

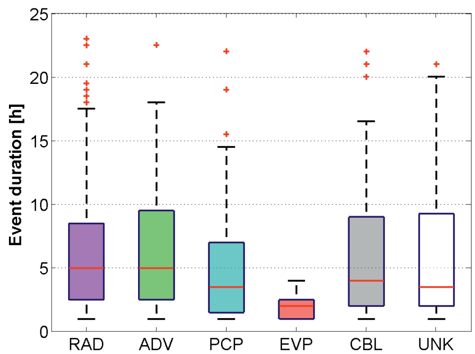

Figure 11. Distribution of event duration by event type at Zagreb Airport, 1994-2015. Red crosses mark outliers.

Slika 11. Raspodjela trajanja događaja po vrsti na zračnoj luci Zagreb, 1994-2015.

year (October-April), and during late spring and summer (May-August) it is a very rare phenomenon. Precipitation fog (PCP) is also most often encountered during the colder part of the year, and in the period from May to September it is practically non-existent. Evaporation fog shows no clear yearly distribution, which is a surprise result since it could be expected that this type would be very rare during early winter (high humidity but weak insolation) and late summer (strong insolation but low humidity). Cloud base lowering fog (CBL) has a similar yearly distribution as precipitation fog, which is to be expected since conditions favoring its formation (stratiform cloudiness, low ceiling) are most often encountered during fall and winter.

The analysis of the distribution of event duration (Figure 11) shows that evaporation fogs have the shortest duration, while all other types share a similar distribution, with the median values ranging between 4 and 5 hours. Distribution of minimum visibility (Figure 12) shows that radiation and advection types are the densest; for both types the 75th percentiles lie at the value of 200 m. The largest variability of minimum visibility can be found in precipitation and evaporation types, with the distribution for precipitation fog being somewhat more skewed towards larger values. A comparison of these results with characteristics of fog in Thessaloniki (Stolaki et al., 2009) shows that radiation fog is the densest type at both airports, while precipitation fog has the highest variability in minimum visibility. The minimum visibility distribution for advective fog shows that this type has a higher variability in Thessaloniki.

c. Some characteristics of radiation fog

Since radiation fog is the prevailing fog type at Zagreb Airport, it is enticing to study it in more detail. This section will deal with some peculiar characteristics of radiation fog.

As can be seen from Figure 13, the majority of radiation fog events lasted between 1 and 12 hours. Between 1994 and 2015 there were few radiation fog events that lasted one hour (less than 10%), and also few events that lasted between 12 and 24 hours (slightly over 10%). Radiation fog events that last longer than 24 hours are very rare; the longest fog event in this period was a 76-hour event from 2011, that began on 16 November, 1530 UTC and ended on 19 November, 1930 UTC. In total there were 20 radiation fog events lasting more than one day, 3 events lasting more than 2 days and only one lasting more than three days. After compared to the same results for all fog types (29/6/1) it can be seen that for long-lasting fog events, radiation process is dominant at their beginning. The distribution of minimum visibility for radiation fog shows that the majority of events have minimum visibility of 200 m or less.

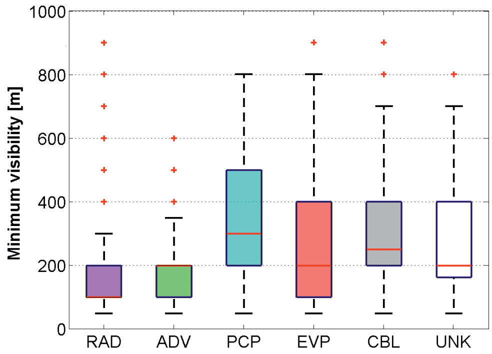

Figure 12. Distribution of minimum visibility by event type at Zagreb Airport, 1994-2015. Red crosses mark outliers.

Slika 12. Raspodjela minimalne vidljivosti po vrsti događaja na zračnoj luci Zagreb, 1994-2015.

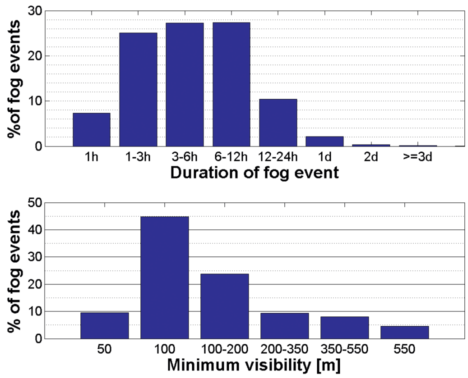

Figure 13. Relative frequency of radiation fog events by duration (above) and minimum visibility (below) at Zagreb Airport, 1994-2015.

Slika 13. Relativne učestalosti događaja radijacijske magle po trajanju (gore) i minimalnoj vidljivosti (dolje) na zračnoj luci Zagreb, 1994-2015.

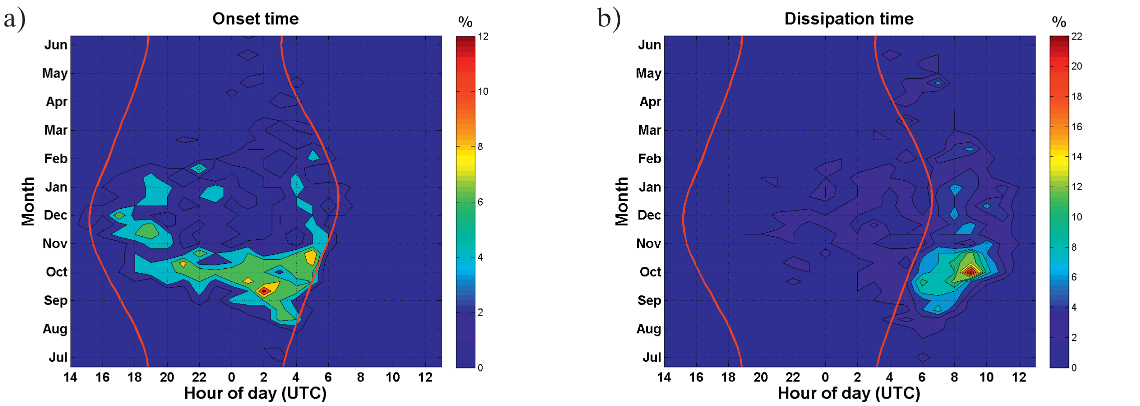

Figure 14. Frequency (%) distributions of **a)** the onset of radiation fog and **b)** the dissipation of radiation fog, as a function of the time of the day and the month of the year, at Zagreb Airport, 1994-2015. Red curves mark the times of sunset and sunrise during the year.

Slika 14. Raspodjele učestalosti (%): **a)** početka događaja radijacijske magle and **b)** završetka događaja radijacijske magle, kao funkcija vremena u danu i mjeseca u godini, na zračnoj luci Zagreb, 1994-2015. Crvene krivulje označavaju vremena zalaska i izlaska sunca kroz godinu.

Seasonal and diurnal frequency distributions of onset and dissipation of radiation fog are presented in Figure 14. The increased frequency of fog occurrences in the so-called 'fog season' is clearly visible in September and October. During August and September radiation fog usually forms at the end of the night - fog events that begin before 0000 UTC are almost non-existent in this period. During October, the probability of fog onset is almost equally distributed during the night. Late fall and early winter have two maxima of probability of fog onset - one at the beginning of the night, and the other at its very end. As far as fog dissipation is concerned, during late summer and early fall fog most often dissipates 2-3 hours after sunrise. In late fall and winter no clear pattern can be discerned from the data shown. There are even some cases during winter where radiation fog dissipated during the night, before sunrise. This is something that is of interest for further study, as it would be useful to know whether these occurrences of early dissipation are a result of changing mesoscale conditions, such as changes in wind or cloudiness, or something else is involved.

Windroses for radiation fog onset (1h before) and dissipation are shown in Figure 15. The data includes 950 radiation fog events in the 22-year period, however only a portion of cases had a recorded wind speed that was not calm (no wind at all) or with variable direction (as defined for METAR reports) - 34.5% for onset and 28.4% for dissipation. The small number of cases where some wind was present during dissipation, and the very small number of cases where wind speeds were 3 m/s knots or above both suggest that radiation fog at Zagreb Airport is seldom dissipated by turbulent mixing induced by advection. It would appear that heating by solar radiation is the dominant process in fog dissipation. From the limited data available it can be seen that during onset of radiation fog, southwesterly wind directions are dominant. During dissipation, southwesterly and westerly wind directions are dominant. An interesting find is the distribution of cases where strong wind (3 m/s or above) was recorded during dissipation - these cases can happen both in situations with southwesterly wind, as well as in situations with northeasterly wind.

Another noteworthy characteristic of fog is its persistence, which is sometimes considered by operational forecasters as a valuable fog predictor. A typical example of using persistence is a situation when synoptic and mesoscale conditions remain unchanged for two or more consecutive nights. If fog was observed during the previous night, then certain meteorological parameters (such as humidity, insolation, vertical profiles of wind and temperature etc.) and their subtle changes during the day are considered to ascertain the likelihood of fog onset and duration during the upcoming night. The yearly variability of persistence of radia-

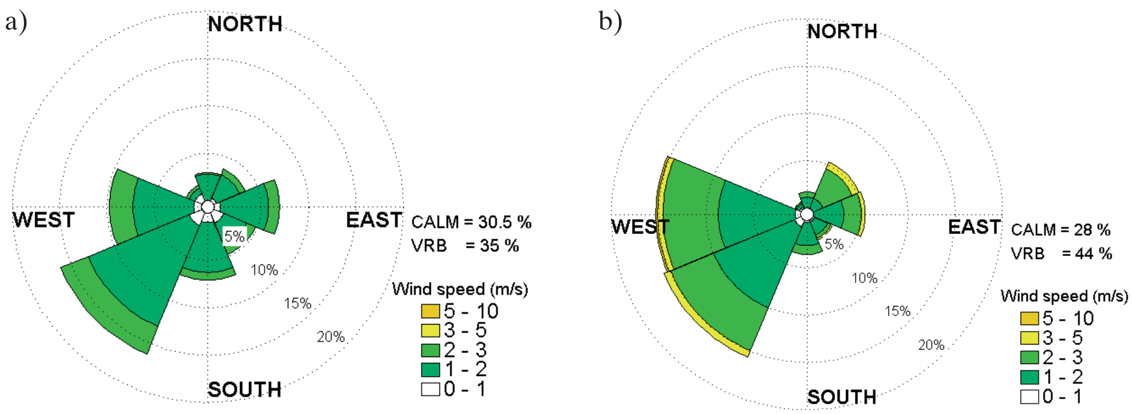

Figure 15. Wind roses for **a)** 1h before onset of radiation fog and **b)** the dissipation of radiation fog at Zagreb Airport, 1994-2015. For a fog event to be classified as radiation type, wind speed up to one hour before onset cannot be 5 knots (2.5 m/s) or higher.

Slika 15. Ruže vjetrova za: **a)** 1 sat prije početka događaja radijacijske magle i **b)** trenutak završetka radijacijske magle na zračnoj luci Zagreb, 1994-2015. Da bi se magla klasificirala kao radijacijska, brzina vjetra unutar sat vremena prije početka ne smije biti 5 čvorova (2.5 m/s) ili veća.

tion fog at Zagreb Airport (Figure 16) roughly follows the yearly variability of the number of fog events (Fig. 5). Persistence is more likely when fog is more frequent. During spring and summer persistence is highly unlikely, as shown by the fact that during the period 1994-2015 there was no persistence at all during April, June and July. This means that during these months, if fog was observed during a certain night and barring extreme weather events, the forecaster can be highly confident in the prediction that there will be no fog during the upcoming night. May again jumps out as an anomalous month, in which the probability of persistence is considerably high when compared to adjacent months of April and June. It remains to be seen whether this spike in persistence is in any way related to probable causes of longer-lasting fogs during May, which were discussed in chapter 5 a). In August and September persistence becomes more likely, and reaches its maximum probability of 44% in October. In November persistence drops to 30%, and remains approximately at these levels until it drops again to 11% in February, which marks the end of the 'fog season'.

Figure 17 shows the probability of persistence of radiation fog by various categories of event duration and minimum visibility. The distribution of persistence by event duration shows that persistence is more probable for longer-lasting fog events. The analysis has shown that this rule of thumb does not apply to events that last longer than 24h. These events have a markedly decreased likelihood of persistence, which is a find that can be useful in forecasting. Forecasters' experience suggests that radiation fog events lasting more than one day often end by dissipating and elevating into a stratus cloud. This low cloud ceiling does not scatter during the day and persists into the following night, thereby preventing renewed formation of fog. The distribution of persistence by minimum visibility also shows a possible correlation, as denser fog events persist more often.

5. CONCLUSION

This work represents the first systematic approach to studying fog climatology at Zagreb Airport. Its purpose is twofold - firstly, to analyze basic climatological features of fog events at Zagreb Airport, and secondly, to provide operational forecasters with statistical data that could help in fog forecasting.

When compared to worldwide averages, the region around Zagreb is prone to formation of fog. 1336 fog events were recorded in the period from 1994 to 2015, which equals to approx-

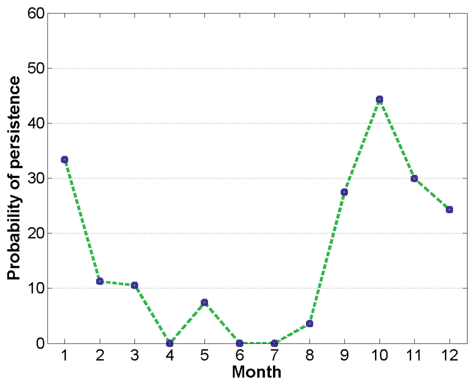

Figure 16. Yearly variation of probability of persistence (probability that radiation fog persists in two consecutive days) of radiation fog at Zagreb Airport, 1994-2015.

Slika 16. Godišnja varijabilnost vjerojatnosti perzistencije (vjerojatnost da će radijacijska magla perzistirati u dva uzastopna dana) radijacijske magle na zračnoj luci Zagreb, 1994-2015.

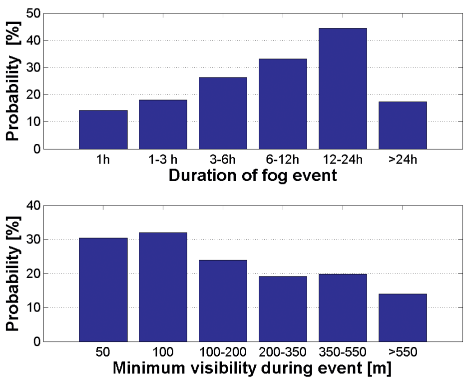

Figure 17. Probability of persistence of radiation fog by duration (above) and minimum visibility (below) at Zagreb Airport, 1994-2015. In the second panel, first two bars correspond only to visibilities that are equal to 50 and 100, respectively.

Slika 17. Vjerojatnosti perzistencije radijacijske magle po trajanju (gore) i minimalnoj vidljivosti (dolje) na zračnoj luci Zagreb, 1994-2015. Na donjoj slici, prva dva stupca obuhvaćaju samo vidljivosti koje su jednake 50 i 100 m, redom.

imately 60 events per year. Over the long-term, fog events are becoming less frequent. By analyzing monthly occurrences of fog, it has been determined that the period from September to February can be identified as ‘fog season' in Zagreb. October, November, December and January are months with the highest frequencies of fog. Spring and summer exhibit very little fog, although its formation during this period is not an uncommon phenomenon. Likewise, fog events during fall and winter last longest, while spring and summer events are usually short-lasting, with the exception of May.

After classifying fog into five different types according to the classification outlined by Tardif and Rasmussen (2007), it was found that radiation is the dominant process in formation of fog at Zagreb Airport. Other fog types (advective, cloud base lowering, precipitation, evaporation) are not often encountered, and they are usually more frequent during fall and winter. Radiation fog, as the most interesting type to study, shows a diverse distribution by event duration. It is usually very dense - the majority of radiation fog events have a minimum visibility of less than 200 m. Radiation fog forms most often during October, and in this month the frequencies of onset are distributed evenly throughout the night. During fall, radiation fog dissipates usually around 2-3 hours after sunrise, and during winter no clear rule has been found in the analysis. Obtained windroses for time of dissipation suggest that radiation fog at Zagreb Airport is seldom dissipated by turbulent mixing induced by advection. It would appear that heating by solar radiation is the dominant process in fog dissipation. Radiation fog is also most persistent during October and least persistent during spring and summer. April, June and July show no persistence at all. An analysis that includes the event duration and minimum visibility shows an apparent correlation between both properties of radiation fog and its persistence - denser and longer-lasting events seem to be more persistent. An exception can be considered in radiation fog events that last longer than 24h, as these events have a low probability of persistence.

In general, the study has produced valuable results that will help elucidate some aspects of the behavior of fog at Zagreb Airport. More importantly, it will be helpful to operational forecasters in fog forecasting, which is a task considerably more challenging for the needs of the aviation industry.

REFERENCES

Allan, S.S., Gaddy, S.G., Evans, J.E., 2001: Delay causality and reduction at the New York City airports using terminal weather information systems. Massachusetts Institute of Technology, Lincoln Laboratory, Project Rep. ATC-291, 48 pp.

Brzoja, D., 2012: Analysis of occurrence of fog in the wider Zagreb region. Master's thesis, University of Zagreb

Climate atlas of Croatia. Meteorological and Hydrological Service of Croatia, Zagreb, 2008

Gultepe. I., Tardif, R., Michaelides, S.C., Cermak, I., Bott, A., Bendix, J, Müller, M.D., Pagowski, M., Hansen, B., Ellrod, G.P., Jacobs, W., Toth, G., Cober, S.G., 2007: Fog research: A review of past achievements and future perspectives. *Pure and Appl. Geophys.,* 164(6-7), 1121-1159

Hyvärinen, O., Julkunen, J., Njetosvaara, V., 2007: Climatological tools for low visibility forecasting. *Pure and Appl. Geophys.,* 164, 1383-1396

Ivatek-Šahdan, S., 1997: Horizontal visibility at Zagreb-Pleso Airport. Master's thesis, University of Zagreb

Klaić. M., 2015: Analysis of influence of katabatic flows on formation of fog around Zagreb. Master's thesis, University of Zagreb

Leko, N., 2014: The influence of air pollution and synoptic circulation on fog formation in Zagreb. Master's thesis, University of Zagreb

Lisac, I., 1953: Formation and types of fog, with a short overview of fog in Zagreb. Master's thesis, University of Zagreb

Makjanić, B., 1959: Climatology of Zagreb-Lučko Airport. *Croatian Meteorological Journal,* Vol.3 No.3

Setiono, R., Pan, S-L., Hsieh, M-H., Azcarraga, A., 2005: Automatic knowledge extraction from survey data: Learning M-of-N constructs using a hybrid approach. *J. Oper. Res. Soc. Amer.,* 56, 3-14.

Sijerković, M., 2012: Meteorological Postcard from Turopolje (Turopoljska meteorološka razglednica). Public College of Velika Gorica, Velika Gorica, 246 p.

Statistics for 2015. Retrieved from http://www.zagreb-airport.hr/about-us/statistics/statistics-for-2015

Stolaki, S.N., Kazadzis, S.A., Foris, D.V., Karacostas, Th.S., 2009: Fog characteristics at the airport of Thessaloniki, Greece. *Nat. Hazards Earth Syst. Sci.,* 9: 1541-1549

Tardif, R., Rasmussen, R.M., 2007: Event-based climatology and typology of fog in the New York City region. J, App. Meteorol. Climatol., 46: 1141-1168

Teixeira, J., Miranda, P., 2001: Fog prediction at Lisbon Airport using a one-dimensional boundary layer model. Meteorol. Appl., 8: 497-505

Van Schalkwyk, L., Dyson, L.L., 2013: Climatological Characteristics of Fog at Cape Town International airport. *Weather and Forecasting,* 28(3): 631-646

Veljović, K., Vujović, D., Lazić, L., Vučković, V., 2014: An analysis of fog events at Belgrade International Airport. Theor. Appl. Climatol., 119: 13-24