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Fog characteristics at the airport of Thessaloniki, Greece

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Abstract. A statistical approach in order to study fog event characteristics occuring at the airport of Thessaloniki, Northern Greece is presented in this work. To achieve this, the seasonal and diurnal characteristics of fog are investigated using 35 years (1971–2005) of observations of meteorological parameters such as: visibility, air temperature, dew point temperature, air relative humidity, wind vector, precipitation, and cloud base height and coverage. Hourly surface observations of fifteen (15) years (1991–2005) are used to identify fog events induced by various physical mechanisms. Fog events are classified into fog types through the application of objective criteria that are derived upon fog formation processes and under the influence of various physiographic features. The temporal variability of different fog type occurrences are examined and the events are characterized according to their duration and intensity.

The results are somehow affected by regional and local factors. Fog is mainly formed in winter time (∼64%) with an enhanced likelihood to appear also in late autumn (19%). The highest frequency of the fog events occurs around sunrise or 1 to 2 h before of it. The mean duration of the events is about 4.5 h. Most of them (75%) are dense (visibility <400 m). The overall fog phenomenon is a combination of various types, such as: advection fog, radiation fog, cloud-base lowering fog and precipitation fog. Advection fog (30%) and radiation fog (29%), which are the most common types, occur predominantly in winter and early spring time. With respect to the former type, it seems that, in many cases, already formed fog is advected from the nearby *Anthemountas* valley. Moreover, a considerable number of fog events (22%) result from cloud-base lowering, and they frequently occur in late autumn and mid winter.

1 Introduction

The limited visibility associated with the appearance of fog is responsible for several losses in time, money and even human life in all forms of transportation, including navigation, aviation and land transportation. Concerning aviation, fog occurrences arise issues related to safety of flights, disruptions in air traffic, delays and significant financial losses to large airway companies. There has been an increasing concern in understanding the complexity and physical character of the phenomenon as well as in examining potential methods of forecasting it, since public safety and economy, are strongly affected by it (Michaelides and Gultepe, 2008).

Our understanding of the physics of fog remains incomplete though, due to the time and space scales involved in numerous processes influencing fog formation, development and dissipation. Because of this complexity the accurate forecasting of fog always remains a difficult task (Gultepe, 2007). Apart from using empirical and statistical techniques or numerical prediction models and satellite imagery, analysis of climatological data can bring an added-value to fog forecasting. Studying the climatology of fog, serves as a basis for the better understanding of the various conditions that led to fog formation in the past, so fog occurrences may be predicted in the future when similar conditions are met. Contributing to this direction, synoptic scale features also give a better insight in the synoptic conditions that prevail before fog formation, thus adding to the knowledge that is needed in aiding the forecasting of fog.

Fog formation, development and dissipation depends mostly on the thermodynamical and microphysical structure of the atmospheric boundary layer. In order to better understand this structure, measurements during various field experiments have been obtained over the last 200 years (i.e. Wells, 1814; Willett, 1928; Fuzzi et al., 1998; Tardif and Rasmussen, 2007). PARISFOG and TOULOUSEFOG are the most recent field experiments. Radiosondes, tethered

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balloons and remote sensing techniques were used in the experiments which involved surface and vertical measurements of various meteorological parameters including turbulence and surface fluxes (for PARISFOG), downward longwave and shortwave fluxes (for both experiments), aerosol and fog microphysics measurements. Moreover, lots of efforts have focused on the study of fog through 1-D, 2-D and 3-D numerical models (Fisher and Caplan, 1963; Zdunkowski and Nielsen, 1969; Brown and Roach, 1976; Oliver et al., 1978; Brown, 1980; Welch et al., 1986; Forkel, 1987; Tardif and Rasmussen, 2007). Most of these studies were related to radiation and sea fog. Therefore, basic research is still needed with respect to the numerous processes influencing fog, such as, nucleation, radiative processes, surface turbulent fluxes, mesoscale circulations, pollution, complex coastline and topography. In addition, efforts have also been made in order to study the synoptic conditions favorable for fog formation. From a geographical standpoint these mainly concerned the USA (Tardif and Rasmussen, 2007, 2008).

In Greece, there is scarce information on fog occurrence. The limited studies that were carried out (Angouridakis, 1973; Angouridakis and Flocas, 1983; Foris, 2002; Houssos et al., 2008) are focused on examining the climatology of fog and the synoptic conditions favoring it, with a particular focus on Northern Greece. Fog has been one of the major and troublesome weather phenomena at the International Airport of Thessaloniki, therefore it deserves particular attention.

The objectives of the present study are: the climatological analysis of fog features, including the frequency of occurrence, duration and density, the identification of the fog events and the classification of them into specific types and their temporal characteristics. Moreover, an attempt is made to understand the general behavior of each fog type and the meteorological features influencing their formation in the complex environment of Thessaloniki's airport. The area of interest, the dataset used in this study and the various analysis procedures applied to identify and characterize fog events are presented in Sect. 2. The climatology, the temporal variability and the behavior of fog are described in Sect. 3, while Sect. 4 contains an analysis of the characteristics of the various fog types. A brief summary and the conclusions are presented in Sect. 5.

2 Dataset and analysis procedure

Thessaloniki's International Airport is located 15 km southeast of Thessaloniki center in a fog-prone coastal region with several geomorphological complexities (valley; mountain; coastline; presence of urban and rural areas) and with significant aerosol load (Petrakakis et al., 2005; Kazadzis et al., 2007).

Limited efforts have been made in order to study fog at the area. In this respect, Angouridakis (1973) studied the relationship of weather types and fog occurrences in Thessaloniki. Angouridakis and Flocas (1983) proposed a linear equation used for forecasting radiation fog in Thessaloniki, by estimating the fog point temperature introduced by Saunders (1950) in relation to several meteorological parameters corresponding to 12:00 and 18:00 UTC hours on the previous to forecast day, and comparing it with the one estimated by Saunders's method. Foris (2002) studied the climatology of fog at the airport for the period 1971–2002 and identified the most common fog types that occur in the area, radiation and advection fog. Last, Houssos et al. (2008) examined the characteristics of atmospheric circulation favoring the formation of fog in Thessaloniki, by applying an objective analysis on 138 long duration fog events of the period 1959–2002. The above studies do not provide sufficient information to identify all fog types forming at the airport area, the mechanisms influencing their formation, or their space-time characteristics.

2.1 Datasets used

The main dataset used is half-hourly METARs (Météorologique Aviation Régulière) and Special Meteorological aviation reports (SPECIs) information from the airport's Meteorological Station (40.31° N, 22.58° E), which is situated at 800 m distance from the sea at 7 m a.m.s.l. METAR is a routine weather report issued at half-hourly intervals. It is a description of the meteorological elements observed at an aerodrome at a specific time. SPECI is a special weather report issued when there is a significant change (deterioration or improvement) of one or more meteorological elements at the aerodrome, such as surface wind, visibility, cloud and weather.

Half hourly land surface observations of visibility, temperature, dewpoint temperature, wind speed and direction, precipitation, and cloud base height and coverage, for a 35-year period (1971–2005) are used for the study of fog climatology and its behavior. A 15-year period (1991–2005) of the same dataset is used for the identification and classification of the fog events.

Figure 1 shows a map of the location and topography of the airport. The existence of the nearby *Anthemountas* valley and of the *Chortiatis* mountain (∼1200 m) should be noticed.

2.2 Methodology

One of the first classifications of fog into types, was made by Willett (1928), later modified by Byers (1959), who identified eleven (11) fog types. Both researchers based their classifications on the formation mechanisms and weather scenarios that were associated with fog. In between, George (1951) proposed a classification of fog into six (6) types.

The classification of fog events presented in this article, is based on the classification methodology followed by Tardif and Rasmussen (2007). Many physical factors interacting and counteracting are involved with fog formation processes.

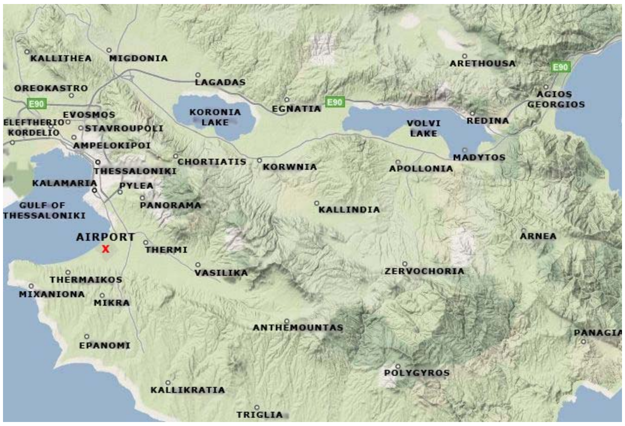

Fig. 1. Relief map of the region around Thessaloniki's airport (from http://maps.google.com).

Therefore, since the classification is made with the use of half hourly surface observations solely, we restricted our classification to broadly defined fog types. The classification methodology of Tardif and Rasmussen (2007) was applied to hourly observations of visibility, air temperature, wind speed and direction, precipitation, and cloud base height and coverage, for a 15-year period (1991–2005). During this period 282 fog events were recorded and for each of them a fog type was assigned. The fog events classification is based on the use of criteria that are applied to the hourly values of the above meteorological variables for a period of 5–8 h before fog onset. The criteria and thresholds for some of the variables were derived based on references in Tardif and Rasmussen (2007), so that the primary physical mechanisms responsible for fog formation of each type are taken into account. These criteria are presented in detail in Table 1. The above procedure led to the identification of four fog types: advection fog, radiation fog, cloud-base lowering fog and precipitation fog. There were few advection-radiation fog events that were identified but they were included in the radiation fog category. Those events that did not meet any or all of the criteria and could not be classified under the four fog types, were characterized as unknown.

Table 1. Criteria applied in the classification of fog events into the four types identified and associated primary mechanisms responsible for fog formation of each type.

Fog type	Criteria
Advection	– Wind speed $\geq 2\,\mathrm{m\,s^{-1}}$ – Clear sky one hour before or height of cloud base <200 m – Sudden decrease in visibility – Onset like a wall approaching the station
Radiation	– Wind speed $<2\,\mathrm{m\,s^{-1}}$ – Clear sky one hour before or height of cloud base <100 m if followed by fog onset at the surface – Cooling before onset or slight warming at the hour before fog onset if preceeded by cooling – Formation during the night
Cloud-base lowering	Gradual lowering of the height of base with initial height of cloud base lower than 1 km
Precipitation	Precipitation recorded at fog onset or 1 h before

3 Results

3.1 Climatological characteristics of fog

According to the international definition, fog corresponds to a reduction of horizontal visibility to less than 1000 m due to the existence of water droplets in suspension with the base touching the surface (AMS Glossary, 2000). A fog event is defined here as the phenomenon during which visibility is lower than 1000 m, but can also include short intervals during which visibility is temporarily slightly higher (Foris, 2002). Under this definition, 635 fog events were identified for the 35-year period. Dense fog is also studied in this work and it is defined as the reduction of visibility to less than 400 m. In the following sections the annual, seasonal and diurnal variability of fog occurrences' characteristics are presented and a further insight into the general features of the four fog types is given.

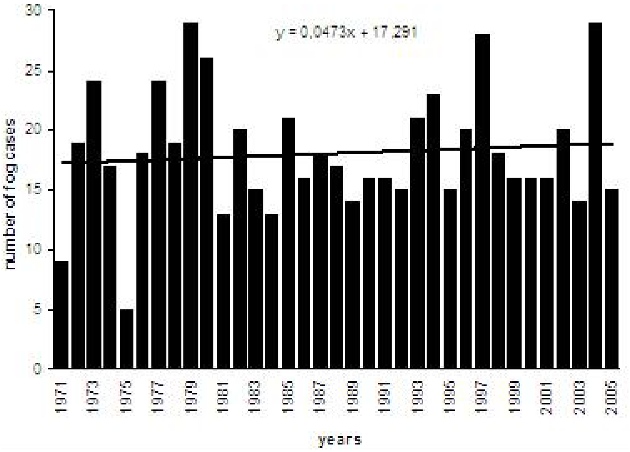

Fig. 2. Annual distribution of fog events for the 1971–2005 period.

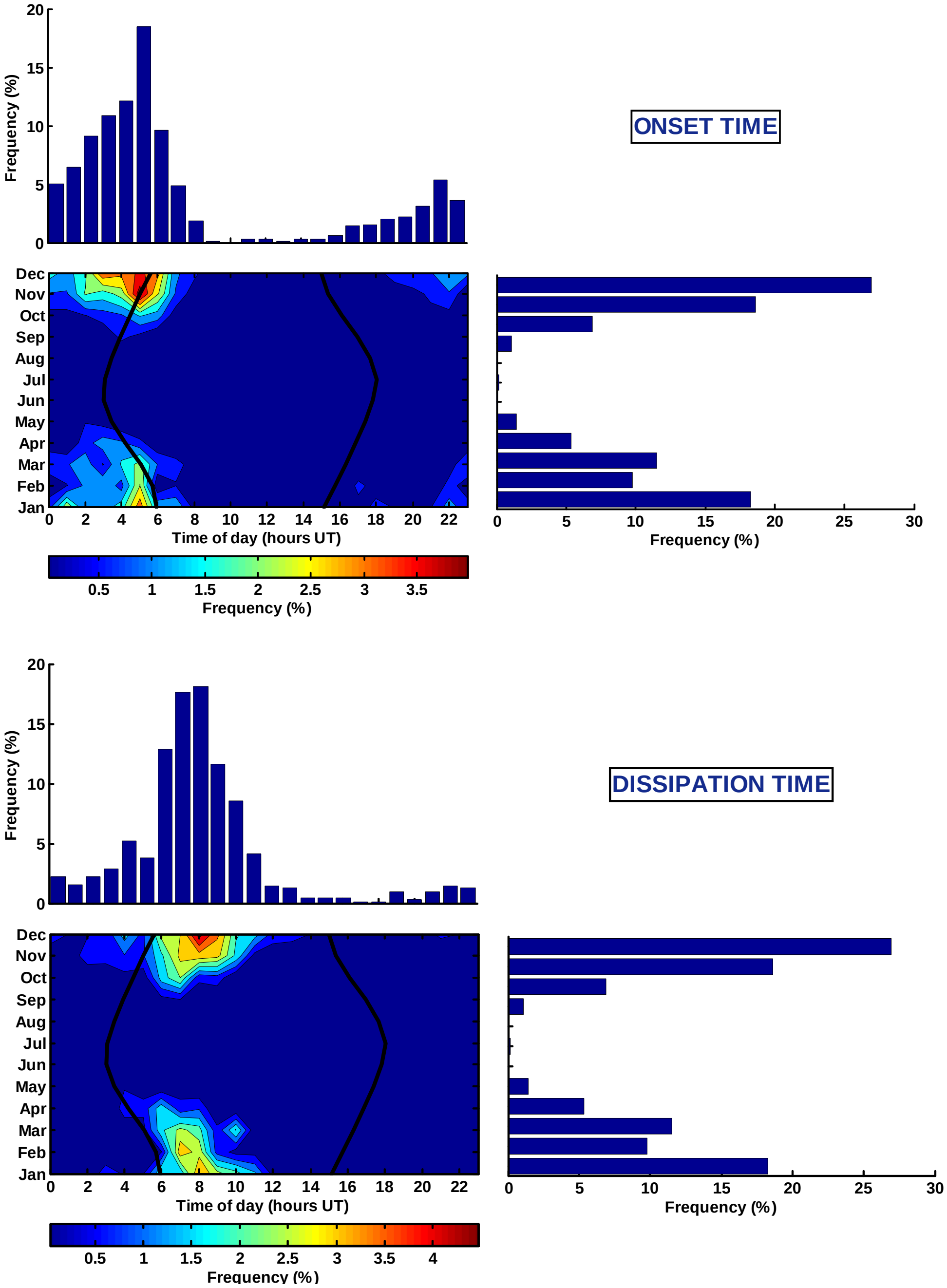

Fig. 3. Frequency distributions of **(a)** the onset of fog and **(b)** the dissipation of fog, as a function of the time of the day and the month of the year. Times of sunrise and sunset (solid lines) are indicated. The corresponding monthly distribution of fog event frequencies is shown on the right, and the frequency distribution with respect to the time of day is shown in the top panel of the figure. The data cover the 1971–2005 period.

3.1.1 Annual, seasonal and diurnal fog events' characteristics

The annual average number of the fog events for the 35-year period (1971–2005) reached 18 events. The highest number of fog events is 29, which occurred in 2004, whereas the lowest (5) occurred in 1975 (Fig. 2). A positive trend is somehow encountered, which is not significant at the 95% statistical level (Wilks, 1995). On a monthly basis, December is the most fog prone month (27%), whereas the highest fog frequency of occurrence period is the one from November to January, encountering the 64% of the total events. Fog is a phenomenon most common in winter, since in summertime no fog is observed at the airport. The above features are also illustrated in Fig. 3a, which presents the seasonal and diurnal characteristics of fog onset. Dense fog events follow the same annual and monthly distribution with December being the most fog prone month, whereas there is a decline in dense fog occurrence frequency from winter to spring season. By examining the surface air temperature on the fog onset and dissipation time, it comes out that fog is warm in 94% of the events. In the 61% of the total number of the events the surface air temperature at the time of fog formation is lower than that at the time of fog dissipation, since, as it is discussed later, one of the reasons for fog dissipation is the solar radiation. Certainly this is not always the case: nocturnal fogs formed in late evening, lasting overnight and dissipating early next morning, usually indicate dissipation temperatures lower than the formation temperatures.

On a diurnal basis, the highest frequency of fog onset is observed on the early morning hours, between 04:00 and 06:00 UTC, while when the day sets in, frequencies are declining. Events occuring during the period November-January, initiate around sunrise or 1 to 2 h before of it. Moreover, there are some fog cases occurring before midnight (∼22:00 UTC). Thus, on a diurnal basis, it is evident that fog forms on the early morning hours and frequently around sunrise.

Another noteworthy feature is the wind direction distribution at fog onset. In more than half of the fog events, calm conditions were prevailing. Wind direction between 90° and 135° (E-SE) under light winds, is also frequent. These cases are related to the *Anthemountas* valley breeze circulation, which is either transferring the already formed fog at the valley to the airport area, or provides the airport area with cold air from the valley. Thus, the topography of the area is considered as one of the most favorable factors for fog formation, since *Chortiatis* mountain lies to the east-southeast of the area of interest (Fig. 1). Moreover, the valley circulation of the *Chortiatis* mountain could be the reason for fog to be induced before sunrise. At that time, the valley floor is still cold and the denser cold air follows a downward movement, descending from the slopes of the surrounding hills, thus transfering the air from the valley to the airport area. The airport area is supplied with moisture by the nearby sea, which, in combination with the cool air originating from the valley, condenses into fog droplets.

The distribution of the timing of fog dissipation for the totality of fog events is shown in Fig. 3b. There is a general tendency for fog to dissipate 1–4 h after sunrise. During the November-January period, fog is dissipated around 2 h after sunrise. Solar warming, along with turbulent mixing caused by the temperature rise, seem to be the main driving factors for the dissipation of fog. By examining the conditions observed around the time of the dissipation of all events it is revealed that calm conditions prevail in 65% of the fog events. Additionally, 74% of the events are characterized by a stable or decreasing relative humidity amount, whereas, 61% of them are associated with an increasing air temperature. When wind blows, the most frequent directions observed are the W-NW (in 16% of the events) and the E-SE (in 11% of the events), the last originating from the *Anthemountas* valley. For both directions there is a light breeze, strong enough to dissipate fog, along with the heating aid of the solar radiation.

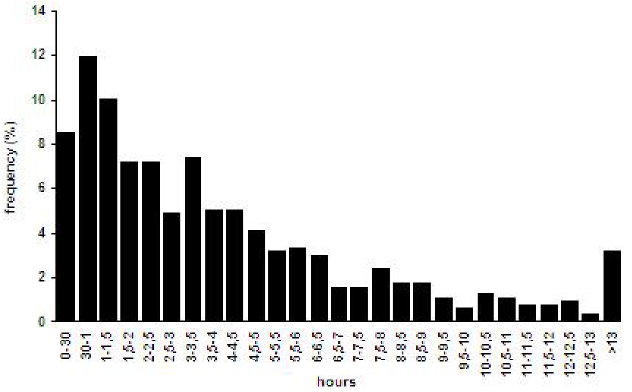

Fig. 4. Distribution of fog events duration compiled for the totality of events (635). Data cover the 1971–2005 period.

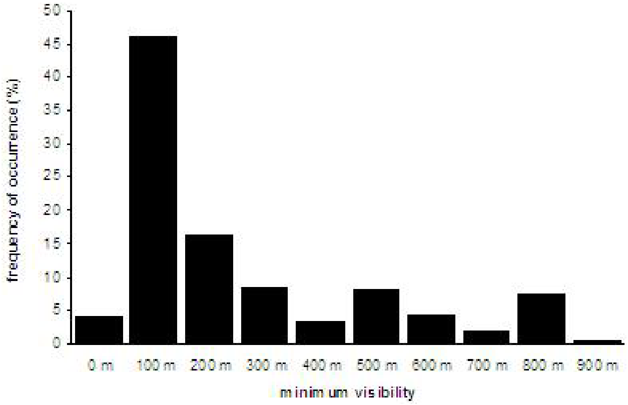

Fig. 5. Minimum visibility distribution frequencies compiled for the totality of fog events for the 1971–2005 period.

3.1.2 Fog duration and density

Fog intensity is further examined by studying the duration and the degree of fog density. The mean fog event duration is 4.5 h, while 34% of the events lasted 2–5 h (Fig. 4). The most long-lasted fog event occurred on the 15 December 1989 and lasted more than 2 days (51.5 h). On the other hand, 9% of the events last 15 to 30 min, while less than 8% last more than 10 h. On average, most long-lived fog events occur during the December-February period. In Fig. 5, the distribution of minimum visibility is presented. From this figure it is clearly demonstrated that the very dense fog events, that is, the events with the recorded minimum visibility to be lower than or equal to 400 m, correspond to more than 75% of their totality. This finding is quite important, somehow demonstrating the seriousness of the fog problem at the International Airport of Thessaloniki. Therefore, it can be concluded that despite the type of fog and season, the fog events occurring at the aerodrome are dense.

4 Fog types

4.1 Seasonal and diurnal variability of fog types onset and dissipation

Results indicate that advection and radiation fog are the most common fog types occurring at the area. The same result was derived by Foris (2002), whereas Angouridakis (1973) found that 38.8% of the fog cases he studied for Thessaloniki were formed due to the prevalence of radiation weather types. Indeed, the overall frequencies of advection and radiation fog correspond to 30% and 29% of the total number of events, respectively. Also, fog related to the lowering of the cloud base occurs with a frequency of 22% of all events, whereas fog in precipitation occurs with a frequency of only 5%. Last, 14% of the events were classified as unknown.

The behavior of each of the fog types was further examined by studying the temporal distributions of fog onset and dissipation frequencies. To study the intraannual distributions of each fog type, the percentage of fog events in each month was calculated. The monthly frequency of advection fog shows a bimodal distribution with a marked peak during late autumn – mid winter (November, December and January) and a second maximum in spring (March–April period). December is the month with the highest frequency of occurrence of this type, as 32% of all advection fog events occur this month. Frequencies are minimized during the rest of the year. On a diurnal time scale and for the first peak, in November and January, advection fog most frequently occurs 1–2 h before sunrise, whereas in December it occurs mostly 1 h after sunrise. During the secondary peak, fog occurs mainly 2 h before sunrise in March and 4 h before sunrise in April. Most frequently, advection fog tends to dissipate 1–2 h after sunrise in mid and late autumn (October–November), whereas in mid-winter dissipation occurs around 2.5 h after sunrise. In spring, dissipation occurs around 2.5 h after sunrise.

Radiation fog is most frequently occuring during the period November–January (60% of the fog events of this type), whereas a considerable amount of fog cases occur in early spring (18% in March), with a gradual decrease in frequency thereinafter. The rest of the period is characterized by a minimum of radiation fog occurrence. On a diurnal time scale, radiation fog occurs mostly 1 to 3 h before sunrise, whereas there were a few cases that fog has formed much earlier (at around 21:00 to 23:00 UTC). More specifically, December and January fog onset occurred 1–3 h before sunrise, while during the March–April period the highest fog onset frequency was recorded at sunrise and 1 h before of it. It seems that the air near the surface needs the timelength of the night so that it is cooled sufficiently inducing, along with adequate moisture, fog formation. On the other hand, fog dissipation typically occurs 2 to 4 h after sunrise in January, whereas in March it occurs 2 to 5 h after sunrise. For November and December, the most frequent dissipation hour is around 2 h after sunrise. The temporal distribution of cloud-base lowering fog shows that it occurs in mid-autumn, with a peak of occurrence during the December-January period (59% of the fog events of this type). At the end of winter and in spring (11%), there is a gradual decrease in fog occurrence, whereas a minimum of occurrence is recorded in September. The vast majority of fog events resulting from the lowering of the cloud base in January began during the nocturnal hours, e.g. 2–5 h before sunrise. On the other hand, in December fog onset is most typically occuring 1 h before sunrise, while for the same month, there is a significant number of events (37%) forming between 20:00 and 22:00 UTC. In March, fog onset occurs mainly at 01:00 UTC and in October, 1 h after sunrise. The dissipation, on a temporal basis, in the January–March period occurs 2 h after sunrise. December's fog dissipation time is distributed throughout the night, but two peaks are prominent; the first peak occurs 2 h and the second peak 4 h after sunrise.

The monthly distribution of precipitation fog events shows a maximum frequency of occurrence in February (43%) and November (29%). A decrease in occurrence is observed during the period December–January. On a diurnal basis, precipitation fog onset is distributed almost throughout the day, except for the day period before and after noon during which the occurrence of any type of fog is rare. More significant frequencies, though, are observed during night hours. The vast majority of precipitation fog during the November–December period dissipates between 10:00 and 13:00 UTC. Dissipation time in the period January–February is mainly observed 1 h after sunrise.

The superposition of fog types leads to fog events being distributed throughout the year, with the absence of them during summer. Diurnally, fog onset mainly occurs during the second half of the night and the early morning hours. In general, strong wind flow favors fog to dissipate. However, for the case of Thessaloniki airport it is to be noted that such conditions rarely exist during the dissipation of the fog events. Thus, independent of fog type, calm wind conditions exist during dissipation, which takes place after the sun has rised sufficiently enough so that the solar radiation heating to take effect.

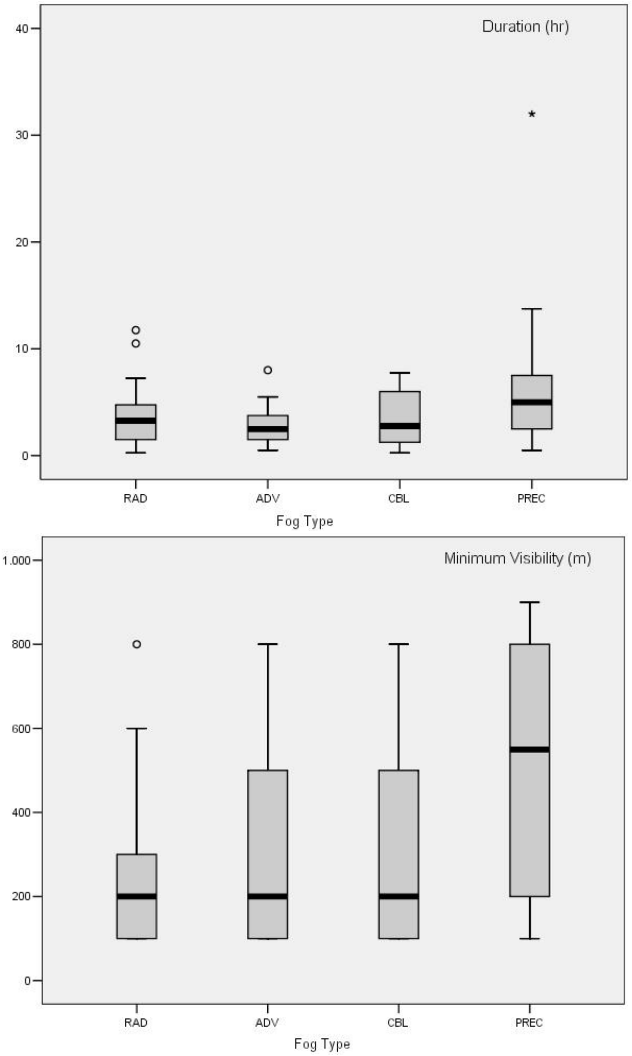

Fig. 6. Distributions of **(a)** fog event duration and **(b)** minimum visibility during fog events, for each fog type, over the 1991–2005 period. Distributions are illustrated using box plots, defined using the 5th (lower whisker), 25th (lower edge of box), median (horizontal line within box), 75th (upper edge of box), and 95th (upper whisker) percentiles. Outliers are marked with a circle and extreme cases are marked with an asterisk.

4.2 Fog type density and duration of events

Other parameters of interest in determining the behavior of each fog type are the density and duration of the events. The density is examined by studying the minimum visibility observed during the fog events of every type. The distributions of event duration and minimum visibility compiled over the totality of fog events corresponding to the 1991–2005 period are shown for each fog type in Fig. 6. Results show that 75% of radiation fog events last less than 5 h, while there is a limited amount of events (5%) that last more than 7 h. A possible explanation for the short duration of radiation fog is that, as shown previously, fog of this type forms a few hours before sunrise and as soon as sun rises solar radiation influence prohibits the events from lasting long, since with heat they shortly dissipate. Moreover, at this time of the day, the nocturnal inversion established influencing fog formation breaks, as soon as the temperature rises near the surface and some turbulent motions begin to build up. These motions mix the air, causing radiation fog dissipation. Advection fog is the fog type that lasts the least, between 1 to 3 h, since 75% of the events last less than 4 h. The *Anthemountas* valley circulation in combination with the appropriate cooling – in degree and time – of the air near the surface for fog to form, may account for such a short fog duration. Although the valley circulation is taking effect in the beggining of the night, the cooling of the ground to the degree that favors the condensation of water vapor, needs more time. Up to 75% of the fog events due to cloud-base lowering last, the maximum, 8 h, whereas a good proportion of events (25%) last only 1 h. Precipitation fog lasts longer in relation to the rest of the fog types, given that 75% of the events last up to 9 h, and about 5% last more than 10 h. Such a characteristic can be attributed to the fact that precipitation fog is mainly associated with frontal activity, which is a synoptic phenomenon that lasts longer than the local ones affecting the duration of fog.

Regarding fog density, radiation fog leads to a greater proportion of dense fog conditions, with 75% of the events having minimum visibility lower than 300 m. More than half of the precipitation fog events are related to minimum visibilities greater than 600 m. Therefore fog of this type is not dense according to the definition of density given in this work. Fog events due to advection and lowering of cloud base have similar density. This accounts to the fact that the main characteristics of these two types are similar. In half of the events of these types minimum visibility less than 200 m is recorded, whereas in more than 75% of the events, the minimum visibility is 500 m.

5 Summary and conclusions

The identification of the general characteristics of fog forming under a complex topography was the main focus of this study. Fog events were categorized into 4 types using criteria that were based on the primary physical mechanisms responsible for fog formation. The characteristics of each type and the fog as a whole were examined in terms of density, duration and their temporal variability. It was shown that fog more frequently forms during the November-December-January period, whereas in summertime it is absent. During the aforementioned three month period, fog mainly forms during the second half of the night and the early morning hours, and frequently around sunrise, whereas it dissipates 1–4 h after sunrise. The combination of solar heating, the turbulent mixing due to the heating effect and the calm wind conditions – that prevail for the majority of the fog events – leads to the increase of temperature and the decrease of relative humidity which aid the fog dissipation. Fog events last on average 4.5 h and the severity of visibility reduction is rather high.

The complex topography highly influences the fog formation, due to a valley breeze, originating from *Anthemountas* valley, which descends from the slopes of the surrounding hills to the airport area, transferring already formed fog or providing the area with cold air from the valley. This is usually the main cause for advection fog to occur, which, along with radiation fog, are the most frequent fog types occurring at the examined area. Both fog types usually form during late autumn – mid winter, but fog events in early spring occur often. Advection fog typically forms 1–2 h before sunrise and in some cases in the middle of the night, 4 h before sunrise. Radiation fog occurs mostly 1–3 h before sunrise with a few cases forming much earlier. The dissipation time of these types varies, according to the season, between 2 and 5 h after sunrise. Cloud-base lowering events are mainly confined to the December-January period, with isolated events occurring in late winter and early spring. Fog onset for the two month period is mainly recorded 1 h before sunrise, whereas in spring around midnight (01:00 UTC). The temporal distribution of dissipation is bimodal, with two peaks 2 and 4 h after sunrise. Precipitation fog, though not frequent in the area, typically occurs in February and November and its onset time is distributed almost along the whole day.

Each fog type has specific duration and visibility reduction. The precipitation fog events last, in average, the longest, followed by cloud-base-lowering, radiation and, finally, advection fog. Radiation fog produces the densest conditions, while precipitation fog the less dense ones. The visibility is reduced significantly for the advection fog and cloud-base-lowering fog types, with the minimum visibility not exceeding 500 m for the majority of the events.

The work herein can serve as a basis for future investigations of the factors influencing the lifecycle of the various fog types forming at the airport of Thessaloniki. It also lays the foundation for a focused analysis of the vertical structure characterizing fog types and the synoptic conditions associated with their occurrence. This will be the subject of future work. To this direction there is a high need of conducting field measurements of various meteorological variables at the exit of the *Anthemountas* valley. Fog climatological characteristics related to topographic features of Thessaloniki's airport presented in this study, can be beneficial to those involved in weather forecasting in the complex area of the airport, in their efforts to produce improved and reliable forecasts. The implementation of a local numerical forecast system at the airport is already the main focus of future efforts. Moreover, it could also provide the means for an appropriate feasibility study concerning the applicability or not of any fog dispersion program.

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