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Estimating fog-top height through near-surface micrometeorological measurements

Carlos Román-Cascón [a,*], Carlos Yagüe [a], Gert-Jan Steeneveld [b], Mariano Sastre [a], Jon Ander Arrillaga [a], Gregorio Maqueda [c]

[a] Dept. de Geofísica y Meteorología, Universidad Complutense de Madrid, Madrid, Spain
[b] Meteorology and Air Quality Section, Wageningen University, Wageningen, The Netherlands
[c] Dept. de Física de la Tierra, Astronomía y Astrofísica II, Universidad Complutense de Madrid, Madrid, Spain

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ABSTRACT

Fog-top height (fog thickness) is very useful information for aircraft maneuvers, data assimilation/validation of Numerical Weather Prediction models or nowcasting of fog dissipation. This variable is usually difficult to determine, since the fog-layer top cannot be observed from the surface. In some cases, satellite data, ground remote-sensing instruments or atmospheric soundings are used to provide approximations of fog-top height. These instruments are expensive and their data not always available. In this work, two different methods for the estimation of fog-top height from field measurements are evaluated from the statistical analysis of several radiation-fog events at two research facilities. Firstly, surface friction velocity and buoyancy flux are here presented as potential indicators of fog thickness, since a linear correlation between fog thickness and surface turbulence is found at both sites. An operational application of this method can provide a continuous estimation of fog-top height with the deployment of a unique sonic anemometer at surface. Secondly, the fog-top height estimation based on the turbulent homogenisation within well-mixed fog (an adiabatic temperature profile) is evaluated. The latter method provides a high percentage of correctly-estimated fog-top heights for well-mixed radiation fog, considering the temperature difference between different levels of the fog. However, it is not valid for shallow fog (~ less than 50 m depth), since in this case, the weaker turbulence within the fog is not able to erode the surface-based temperature inversion and to homogenise the fog layer.

1. Introduction

Fog is a troublesome phenomenon affecting the daily life of humans. Among these problems, numerous flight cancellations, delays and landing diversions to other airports are caused by foggy conditions at airports (Fabbian et al., 2007; Stolaki et al., 2012). This implies substantial costs to aerial companies and airports, comparable to the cost related to damage by tornadoes (Gultepe et al., 2007). However, fog is still poorly reproduced by Numerical Weather Prediction (NWP) models (Bergot et al., 2007; Román-Cascón et al., 2012; Price et al., 2015; Steeneveld et al., 2015). In the case that they are represented, numerical models have problems simulating the fog vertical extension (e.g. Guedalia and Bergot, 1994; Román-Cascón et al., 2012; Shi et al., 2012), specially for shallow fog and, in part, due to the limited vertical resolution of models.

Furthermore, it is important to have good estimations of observed fog-top height for validation of model simulations, since comparisons between observed and simulated fog thickness cannot be performed in many cases due to the lack of fog-top observational data. Moreover, there is no doubt about the importance of an accurate information of fog thickness for data assimilation of NWP models, due to the significant impact of this parameter on the radiation budget close to the surface (Rémy and Bergot, 2009). It is also crucial to improve the nowcasting of fog dissipation, since the clearing of deeper radiation fog requires more time than for shallower fog. Finally, the knowledge of the fog-top height can be a quite meaningful information for aircraft pilots when they are landing in foggy conditions, specially in potential emergency cases without Instrument Landing System (ILS). Most airports have regulatory meteorological instrumentation composed by surface visibilimeters, a ceilometer (measuring cloud base and cloud cover) and standard meteorological instrumentation, but all these data are not enough to provide information about fog-top height.

Despite the numerous potential applications of this variable, its numerical value is not always clear. Many studies cannot provide

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* Corresponding author at: Facultad de Ciencias Físicas Universidad Complutense de Madrid Avda. Complutense s/n CP 28040, Spain.
E-mail address: carlosromancascon@ucm.es (C. Román-Cascón).

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information about observed fog-top height due to the lack of measurements in the vertical. In many cases, temperature and humidity data from atmospheric soundings are used to estimate fog thickness (e.g. Koracin et al., 2001; Liu et al., 2011; Boers et al., 2013; Bari et al., 2015). However, these soundings are not always available, or their temporal frequency is not sufficient to cover the whole fog cycle. In other cases, remote sensing instruments are used to estimate the fog top. Dabas et al. (2012) studied the ability of using reflectivity measurements from sodar to estimate fog-top height, while Boers et al. (2013) derived visibility from radar reflectivity for a case study of radiation fog. Ceilometers detect cloud-base height of low clouds (e.g. Dupont et al., 2012), but they are not useful to provide information about fog-top height. All these instruments are usually expensive and sometimes their vertical resolution is not appropriate compared to the fog thickness.

On the other hand, data or products from satellite have been widely used to detect fog or low clouds in numerous fog analyses (e.g. Reudenbach and Bendix, 1998; Van der Velde et al., 2010). Ellrod (1995) developed a technique to approximate fog thickness from brightness differences of two IR channels. Thereafter, Brenguier et al. (2000) related cloud thickness with liquid-water path from remote sensing using an adiabatic model, assuming liquid water content (LWC) increasing from cloud base to the cloud top. In these cases, difficulties appear when trying to differentiate between fog and low clouds (Cermak and Bendix, 2008; Yi et al., 2015). Thus, Bendix et al. (2005) proposed the determination of low stratus thickness and top height of clouds (fog) from MODIS daytime data in order to differentiate between low clouds and fog. Alternatively, Cermak and Bendix (2011) developed a method for the determination of low-stratus thickness from MSG-SEVIRI data. However, most of these methods have to estimate liquid water path from satellite, and in some cases their accuracies exceed the high vertical resolution required for fog studies. Besides, thin cirrus can also obstruct the detection of fog and the availability of the data needed for these approaches can be limited in some cases, for example during night-time conditions.

In any case, fog is defined as a visibility threshold (surface horizontal visibility < 1000 m, (DOC/NOAA, 1995)), but unfortunately, only a few works have the opportunity of using visibilimeters deployed at different heights to determine the fog top (e.g. Guedalia and Bergot, 1994).

In this work, on the one hand we have found a clear linear correlation between surface turbulence and fog-top height. Thus, regression equations are derived relating friction velocity and buoyancy flux at surface with fog thickness data. These relations are statistically calculated by using data from numerous radiation fog events at two sites: the Cabauw Experimental Site for Atmospheric Research (CESAR) in The Netherlands and the Research Centre for the Lower Atmosphere (CIBA) in Spain. A potential applicability of this method could provide a continuous estimation of fog-top height during radiation-fog events with the deployment of a unique sonic anemometer close to the surface.

On the other hand, statistics are performed in order to evaluate the estimation of fog thickness through temperature measurements in the vertical. The temperature homogenization within well-mixed fog is a well-known process which causes temperature convergence at the levels where the fog is present (Nakanishi, 2000; Porson et al., 2011; Ye et al., 2015). Furthermore, Price (2011) suggested that temperature convergence did not occur for shallow fog, although he was not able to demonstrate this issue, since his statistical observational study did not include fog thickness. Herein, we compare observed fog thickness (through visibility measurements at several heights) with estimations of fog-top height based on differences between temperature measured at several levels. We have found how the performance of the method strongly depends on the fog thickness and it is not valid for shallow fog. However its application is also limited for deeper fog (~200 m depth). To conclude, a long-lasting event of radiation fog is analysed at CESAR in order to determine the applicability and skill of these methods during a complete fog cycle.

The study is organized as follows: section 2 presents information about the observational data and experimental sites. Section 3 shows the results for both methods and their evaluation for a case-study at CESAR. Finally, a short discussion and conclusions are presented in Section 4.

2. Data and methodology

This work uses data from two different experimental sites: the Cabauw Experimental Site for Atmospheric Research (CESAR, Beljaars and Bosveld (1997)) and the Research Centre for the Lower Atmosphere (CIBA, Cuxart et al. (2000)).

CESAR is located in The Netherlands (51°58.22 N, 4°55.57 E, −0.7 m above sea level (asl)), over a flat and quite humid terrain surrounded by grass, water canals and pasture. It is 40 km south from the North Sea and very close to the moderately-high populated area of Utrecht-Amsterdam. A 213-m mast stands at CESAR (Fig. 1) with many meteorological instruments from different institutes. However, only a few of them (indicated in Fig. 1) were necessary for this study.

CIBA site is located in the Northern Spanish Plateau (41°48.92 N, 4°55.92 W, 850 m asl), over *Los Montes Torozos*, which is a homogeneous and extensive plateau (800 km^2). CIBA site is located over a quite dry terrain surrounded by crop areas (pasture, cropland and shrubland), far from the sea, mountains or high populated areas. The height of the mast at CIBA is 100 m, instrumented at different levels (see details in Fig. 1).

Due to the permanent basis of the meteorological devices at the two experimental sites, the instruments differ between one place and another, as well as the heights where they were installed. At CIBA, a METEK-USA-1 sonic anemometer was available at 1.5 m above ground level (agl), measuring at a frequency of 20 Hz and using 5-minutes averages for the calculation of the buoyancy flux or friction velocity from wind components and temperature. At CESAR, a GILL R3 sonic anemometer is installed at 3 m agl, measuring at a frequency of 10 Hz, while the surface fluxes and turbulent parameters are calculated from 10-minutes averages. Sonic anemometers measurements at both places are validated from analyses of time series and outliers are removed (gap-filled in the case of CESAR in some cases), besides the automatic malfunctioning checking of dataloggers. Tilt corrections are also applied to the data and finally, turbulent parameters at both places are averaged into 10-minutes data for the calculations performed in the present work.

Temperature measurements are obtained from Theodor Friedrichs 3032.02 (Pt 100) at CIBA and from E & E thermocouples (Pt 1000 − Pt 500) at CESAR. Finally, BIRAL SWS-100 visibilimeters (at both places) were used to provide horizontal visibility data, based on the atmospheric extinction coefficient, which is proportional to the liquid water content of the air. These instruments were deployed at different heights (2, 10, 20, 40, 70, 140 and 200 m agl at CESAR and 2, 30, 70 and 100 m agl at CIBA). They were configured to measure with a maximum visibility range of 20 km. Due to the necessity of visibility measurements at several heights to carry out this study, data from fog events within the period comprising from April 2011 to December 2013 and from 24 December 2014 to 14 January 2015 were used at CESAR and CIBA respectively (Table 1). The starting dates of these periods coincide with the installation of the commented visibility devices at each site.

In this work, fog is defined when the surface visibility (2 m agl) is lower than 1000 m (as defined in DOC/NOAA (1995)). An independent fog event is then defined when data-slots reporting fog are separated more than 2 h. However, only fog events with more than 2 h of persistence and with 60% of data slots reporting fog are considered, in order to avoid short-lived, patchy and non-well established fog events. Similar procedures have been used in previous works (Menut et al., 2014; Román-Cascón et al., 2015). Finally, only radiation-fog or cloud-base