Journal of Atmospheric and Solar-Terrestrial Physics 133 (2015) 87–97

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

Study of fog in Bulgaria by using the GNSS tropospheric products and large scale dynamic analysis

A. Stoycheva [a], G. Guerova [b,*]

[a] National Institute of Meteorology and Hydrology, Bulgarian Academy of Sciences, 66 Tsarigradsko Shose Blvd., 1784 Sofia, Bulgaria
[b] Faculty of Physics, Sofia University "St. Klement Ohridski", 5 James Bourchier Blvd., 1164 Sofia, Bulgaria

ARTICLE INFO

Article history:
Received 19 February 2015
Received in revised form
12 August 2015
Accepted 12 August 2015
Available online 20 August 2015

Keywords:
Fog
Mixing ratio
Temperature
Visibility
Global Navigation Satellite Systems (GNSS)
GNSS tropospheric products
Integrated Water Vapour

ABSTRACT

The fog formation, development, and dissipation are studied by employing the synergy between surface observations and vertically Integrated Water Vapor (IWV) from Global Navigation Satellite Systems (GNSS). Selected are three fog cases in February and November 2012 and the fog development in 4 locations in north Bulgaria is analysed. It is found that the IWV tends to decrease during fog formation, and densification. Increase of IWV leads to fog dispersion and can be a result of evaporation or advection of new humid air mass. The mixing ratio also decreases during the fog formation and increases during dissipation but has a distinct diurnal variability, which limits its short range forecasting potential. IWV is found to have a very high sensitivity to both air mass transformation and/or advection at altitude. In one case it is found that the arrival time of a new air mass at altitude is of key importance for further fog development or suppression. The change of the air mass leads to change of the diurnal cycle of surface parameters like temperature thus controlling the fog life cycle. Further complication of fog diagnosis is introduced by a dynamic component, reflecting the orography difference in west and east part of Bulgaria. The behaviour of the IWV and mixing ratio can be a valuable additional tool in decision making processes for very short range fog diagnosis and prognosis. For monitoring fog life cycle hourly or sub-hourly data-sets will be an advantage.

1. Introduction

Fog occurs when the visibility is reduced to less than 1000 m by water droplets suspended in the air (International Meteorological Vocabulary, 1966). The fog layer varies in depth, from the lower few meters in the boundary layer up to 1000 m. Fog usually forms near the surface under clear skies in stagnant air associated with anticyclonic condition after nocturnal surface cooling and temperature decrease to the dew point temperature (Welch et al., 1986).

However, fog is found to form as a result of multiple processes occurring simultaneously and interacting nonlinearly with each other. These interactions result in a nontrivial set of key fog parameters leading to fog formation, while other combinations prevent fog formation (Haeffelin et al., 2010). The mechanisms of fog formation, development, and dissipation are very complex and have been extensively studied and reviewed in Gultepe et al. (2007). Several different approaches are used to study fog. Among them are: (1) statistical methods (Bocchieri et al., 1974; Murtha, 1995; Vislocky and Fritsch, 1997; Pasini et al., 2001; Wantuch, 2001; Marzban et al., 2007; Bremnes and Michaelides, 2007), (2) hydrometeor analysis (Eldridge, 1971; Pilié et al., 1975; Roach et al., 1976; Meyer et al., 1980; Bott, 1990; Wendisch et al., 1998; Yuskiewicz et al., 1998; Gultepe and Isaac, 2004; Gultepe et al., 2006), (3) remote sensing from ground and space (Hunt, 1973; Ellrod, 1995; Cermak and Bendix, 2008; Ellrod and Gultepe, 2007; Eyre et al., 1984), (4) fog resolving and mesoscale Numerical Weather Prediction (NWP) models (Brown, 1980; Turton and Brown, 1987; Bott et al., 1990; Duynkerke, 1991; Nakanishi, 2000; Pagowski et al., 2004; Bergot et al., 2005), and (5) fog climatology (Peace, 1969; Martin, 1972; Hardwick, 1973; Bendix, 2002; Tardif and Rasmussen, 2007; Muraca et al., 2001; Witiw and Baars, 2003). A number of field studies were conduced deploying extensive set of instruments in United States (CEWCOM project, 1977), Canada (Gultepe et al., 2009) and Europe (Haeffelin et al., 2010). A major EU funded project targeting improvement of the fog forecast was the COST Action 722 "Short range forecasting methods of fog, visibility and low clouds" (COST 722, 2004–2008).

During COST 722, 1-D and 3-D research NWP models as well as probability forecasts were considered. 1-D models include precise parametrisations of radiative, turbulent and surface processes and

* Corresponding author at: Department of Meteorology and Geophysics, Physics Faculty, Sofia University, 1164 Sofia, Bulgaria
E-mail address: guerova@phys.uni-sofia.bg (G. Guerova).

http://dx.doi.org/10.1016/j.jastp.2015.08.004
1364-6826/

rely on detailed and continuous near surface observations of temperature, humidity, wind, radiation, and visibility. However, application of 1-D models remains local and they are better suited for forecasting local parameters, such as visibility, ceiling, and boundary layer parameters (Bergot, 2005). The state-of-the-art 3-D NWP models were found to have significant shortcomings for forecasting fog, visibility, and low clouds, mainly because the local effects and boundary layer processes over the various scales cannot be resolved (Jacobs et al., 2008). Due to limitations of the models at present the National Meteorological Service (NMS) relay on "in-house" developed empirical forecasting tools, based on operational work well tested in the practice. Those tools are based on observations from: (1) surface meteorological network (SYNOP) (Hyvarinen et al., 2008), (2) satellite MSG-SEVERI-based product like Layer Precipitable Water (Wirth and Alexander, 2008), and (3) combination of surface and satellite products (Tzanos and Guidard, 2008).

In Bulgaria, fog studies (Latinov et al., 2005) were conducted as a part of COST 722. Examined are observations of relative humidity (RH), temperature (t), wind direction, and wind speed at four levels (700 hPa, 850 hPa, 925 hPa, and surface) at Sofia synoptic station. It was found that the maximum in the frequency of the long lasting fog (24–48 h) is in December. Usually, they form over night and in early morning before 09 UTC. In November, compared to October, there are less fogs, but with longer duration. A resent study by Stoycheva and Evtimov (2015) shows that a typical fog conditions in Sofia are mainly in anticyclonic conditions when relative humidity is above 90–95% and temperature between -5 °C and $+5$ °C. Favourable places for fog formation in Bulgaria are the Danube plane, Thracian plain, Black Sea coast and high valleys like Sofia. The main types of fog, occurring there, are: radiation fog – usually in the planes and valleys during cold season as a result of radiative cooling during anticyclonic circulation; advection fog – mainly at the Black Sea coast when warm and moist air from the sea surface is advected over a cold coastal surface; and most common type for prolonged fog mixed radiation-advection fog, a combination of radiation cooling in the first fog stages in conjunction with warm advection at a given altitude. The temperature increase at 850 hPa plays a critical role for development of temperature inversion layer in the lower troposphere (Latinov et al., 2005). The inversion layer thickness in combination with temperature increase has impact on duration of mixed fog episodes as for example in the case III studied here.

In the last 20 years a new method for atmospheric monitoring using the Global Navigation Satellite Systems (GNSS) has been successfully developed (Guerova et al., 2015). Use of GNSS tropospheric products to study fog was first proposed by Lee et al. (2010). They analyse the relationship between Integrated Water Vapor (IWV), derived from GNSS, and visibility during dense fog cases on the South Korea coast. For a radiation fog case they report: (1) decrease of the mixing ratio and IWV as the fog settles and (2) increase of IWV during dissipation. Mixing ratio is limited in its ability to detect the vertical inflow of the water vapour accompanying the cloud water, but IWV can reflect the process owning to the inflow of the cloud water and the water vapour during advection fog. In the case of mixed fog, mixing ratio, and IWV cannot directly detect the process due to cancellation within each term. They also show that radiation fog is more suitable for detection with IWV.

The aim of this work is to investigate the added value of GNSS tropospheric products in operational fog forecasting. The objectives are: (1) to combine the observation data-set proposed by Lee et al. (2010) with detailed synoptic analysis of the air masses and (2) to apply it to study three fog cases in Bulgaria in 2012. In Section 2 are presented the data-sets used. Section 3 presents detailed analysis of the weather conditions and their impact on fog formation and dissipation. The discussion is given in Section 4 and the summary and the conclusion are given in Section 5.

2. Methodology

2.1. GNSS tropospheric products

Since 2012, GNSS tropospheric products are archived in the Sofia University Atmospheric Data Archive (SUADA, Guerova et al., 2014). The SUADA is developed to facilitate the use GNSS data for meteorologic and climatic studies in Bulgaria and Southeast Europe. Archived are GNSS tropospheric products from five different GNSS processing (IGS, EUREF, CODE, ZenithGEO, Bulipos, see Guerova et al., 2014 for details). In this work we use data from the GNSS network operated by the ZenitGEO company. The network consists of 30 GNSS stations. The GNSS stations used in this work are: Vidin, Oryahovo, Ruse and Silistra (grey markers in Fig. 1).

The GNSS tropospheric product provided by ZenithGEO is Zenith Total Delay (ZTD) with temporal resolution of 5 min (300 s). In order to derive the IWV from ZTD surface observations of temperature and pressure are required following Bevis et al. (1992) and Emardson et al. (1998). As a first step the Zenith Hydrostatic Delay (ZHD) is computed using

$$ZHD = (2.2768 \pm 0.0014)\frac{p_s}{f(h,\theta)}, \tag{1}$$

where

$$f(h,\theta) = 1 - 0.00266\cos(2\theta) - 0.00028\,\mathrm{h} \tag{2}$$

and p_s is local surface pressure, h is the height and θ is the latitude variation of the gravitational acceleration. Then the Zenith Wet Delay (ZWD) is obtained:

$$ZWD = ZTD - ZHD. \tag{3}$$

Finally, the Integrated Water Vapour is computed:

$$IWV = \frac{10^6}{(k_3/T_m + k_2)R_v}ZWD, \tag{4}$$

where k_2, k_3 and R_v are constant and T_m is the weighted mean atmospheric temperature.

It is to be noted that the surface observations are with temporal resolution of 3 h thus the derived IWV is also every 3 h. An altitude correction is applied to the surface observations to derive the pressure and temperature at the altitude of the GNSS station (Guerova et al., 2014).

The derived from GNSS IWV is a measure of the vertically integrated water vapour amount i.e. it is a cumulative characteristic of the water vapour content of the air mass above the station. It is to be noted that it is not possible to distinguish the water vapour in the lower (below 850 hPa), middle (850–500 hPa), and upper (above 500 hPa) troposphere.

2.2. Surface observations

In this study we use the surface (synop) observations of (1) 2 m air temperature (t), (2) 2 m relative humidity (RH), (3) visibility, (4) fog phase and type, and (5) air pressure at surface. They are collected manually every 3 h by National Institute of Meteorology and Hydrology. The visibility is measured by qualified observer, which makes visual estimation based on the location of the visibility markers of the stations. The synop stations are: Vidin, Oriahovo, Ruse, and Silistra. The stations are in the Danubian plain, along Danube River at altitude under 200 m. Vidin is placed in west Bulgaria, Oriahovo, Ruse, and Silistra are 90, 250, and 350 km