Fog Case Studies using the GNSS Tropospheric Products in Bulgaria

Anastasiya STOYCHEVA, Guergana GUEROVA, Bulgaria

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SUMMARY

Fog forecasting is an old problem which is still a challenge despite the continuous improvement of weather prediction. In this work, we use the GNSS tropospheric product to derive Integrated Water Vapour (IWV). GNSS – IWV is combined with surface observations of temperature, mixing ratio, visibility, and pressure to study the fog dynamics in Bulgaria for three cases in 2012. The results showed a high value of the mixing ratio and relative minimum in the GNSS - IWV before the fog formation. During fog the changes of GNSS - IWV can be linked to change of visibility. Detection of advected warm humid air at 850 hPa can explain the behaviour of GNSS - IWV during prolonged fog periods. Concerning the fog dissipation, our results show a minimum of mixing ratio followed by increase of temperature and rapid increase GNSS – IWV. This confirms the studies of Lee and al. (2010) in South Korea. Usually, this is linked with the inflow of new air mass with higher humidity, lower temperature. This new air mass destroys the inversion layer formed during the fog episode.

1. INTRODUCTION

The significant development of numerical models in recent decades has not yet led to significant progress in fog forecasting. The lack of parameterization of the specific processes in the boundary layer, leading to the formation, development and dissipation of fog is one of the reasons for poor forecasting results. The difficulty in the study of fog is on a scale larger than its own, since it is the result of the combination of a number of general and local factors, is another reason for low fog forecasting rates. In this light, regional studies of fog, especially for operational purposes are undoubtedly relevant.

In Bulgaria, the systematic study of the fog began Stefanov's work (1959), which examines the impact of weather conditions on the horizontal visibility. Again on the visibility, but focusing on statistic-climatologically point of view is the work of Kostova (1959). Analyzing the spatial-temporal distribution of low clouds in Bulgaria, Subev and Tanev (1970) emphasize the priority formation of ground fog in the morning hours of the season from October to March. Martynov (1974) investigated the synoptic conditions for fog formation, seasonal and daily behaviour and classification of fogs in the Bulgarian part of the Danube River. The climate regime of fog over the Sofia airport was investigated by Godev and Korchev (1971), which offered a statistical method for its prediction. Peculiarities of cloudiness over Sofia field are reviewed by Martynov and Gabrakova (1965), and the temperature regime of Martynov and Bogachev (1978). Active studying fog in Bulgaria continues until around the end of the 70s of last century, after which there is 30-35 years period of silence on the subject.

Since the beginning of the new century, slowly began to renewed interest on the fog in Bulgaria. Latinov et al. (2005) address the specificities of the occurrence of fog in Sofia and two other weather synoptic stations in the last quarter of 2004 as a part of COST 722. The 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 are examined. It was found that the maximum in the frequency of the long lasting fogs is in December. Most of them last between 24 and 48 hours. Usually, they form over night and in early morning till 09 UTC. In November, compared to October, there are less fogs, but with longer duration. Stoycheva and Evtimov (2014) conducted a detailed statistical Sofia's fog diagnostics for the period 1992 to 2012, also deals and distribution of the fogs in their duration. This study (Stoycheva and Evtimov, 2014) shows that a typical fog conditions in Sofia are mainly in anticyclonic conditions when relative humidity is above 90 - 95 % and temperature between -5º C and +5º C. From 2015 is the work of Manafov and Guerova (2015) associated with numerical experiments of meteorological conditions with fog at Sofia Airport in 2011-2014.

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 is 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.

Using IWV from GNSS, Stoycheva and Guerova (2015) are found a very high sensitivity of IWV to both air mass transformation and/or advection at altitude. As an additional tool for diagnostic of these air mass transformation processes, the behaviour of IWV can be combine with other air mass characteristic parameters. In our study we use the equivalent potential temperature as such parameter and following its changes we try to add some useful hints for fog diagnostics.

In this study we use in addition the equivalent potential temperature. It is a conservative characteristic of dry adiabatic and moist adiabatic up or down movement of the air parcels, and equiadiabatic elevation as well. It is approximately constant at isenthalpic evaporation, under isobaric heating it increases and in the isobaric cooling it decreases (Belinskii, 1948). Therefore equivalent potential temperature can be used for identification of the air mass. Sanders (1999) propose a new method for ground analysis using ground potential temperature to distinguish fronts baroclinic through and nonfrontal baroclinic areas. Hoffman (2008) analyzed the average annual and seasonal ground-potential temperature in the continental United States, southern Canada and northern Mexico with adjacent coastal waters and identifies strengths and baroclinic temperature zones. Turton and Broun (1987) and also Bergot and Guedalia (1994) demonstrate the importance of advection in the formation and evolution of fogs and its importance for increased attainment in model prediction of fog. Stoycheva and Evtimov (2015) use the equivalent potential temperature for surface analysis and as an indicator of a possible change of air masses for one prolonged period of fog in Sofia during first half of January 2014.

This work demonstrates the GNSS meteorology method for fog study. Data for integrated water vapour from one typical for fog formation GNSS stations in Bulgaria together with data from ground measurements and surface and altitude synoptic maps were used for the study of three typical synoptic situations with fog. We calculate also the equivalent potential temperature and adding it to detailed synoptic analysis carried out demonstrates the high sensitivity of the IWV to advection or transformation of the air mass before, during and after the formation of fog. Thus, IWV along with the equivalent potential temperature is emerging as an effective complementary tool to study the dynamics of the fog.

2. METHODOLOGY

2.1 GNSS tropospheric products

Since 2012, GNSS tropospheric products are archived in the Sofia University Atmospheric Data Archive (SUADA). The SUADA is developed to facilitate the use IWV data for meteorological and climatic studies in Bulgaria and Southeast Europe. Archived are GNSS observations, from five different GNSS processing strategies. In this work we use data from the GNSS network operated by the ZenitGEO Company. The network consists of 30 GNSS stations (grey markers in figure 1). In this work is used the GNSS station Oriahovo. The GNSS tropospheric product is Zenith Total Delay (ZTD) with temporal resolution of 5 min (300 s). In order to derive the IWV surface observations of temperature and pressure are used as described in Guerova et al., 2014. It is to be noted that the surface observation are with temporal resolution of 3 hours thus the derived IWV product is also every 3 hours. 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. 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. IWV is a cumulative characteristic of the water vapour content of the air mass above the station.

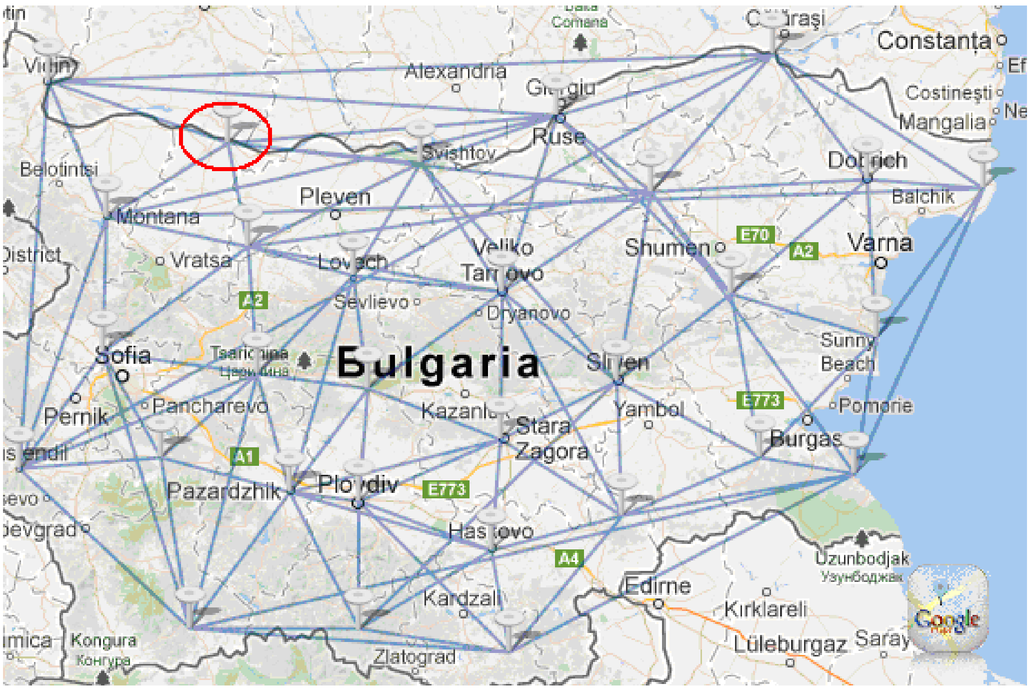

Figure 1. Map of GNSS station location in Bulgaria (grey markers) and Oriahovo SYNOP station (in red circle).

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 4) air pressure at surface. They are collected manually every 3 hours by National Institute of Meteorology and Hydrology. The SYNOP station Oriahovo is placed on the Danubian plain, along Danube River at altitude 29 m and coordinates 43^{o} 41’N - 23^{o} 58’E (circled in figure 1).

3. FOG CASE STUDIES

The atmospheric condition before and after the fog are analysed in this study. This allows us to follow the air mass transformation before, during and after the fog. In addition, by combining several days with fog the air mass transformation can be traced and regional and local difference analysed. Selected are 3 fog episodes in 2012 in Oriahovo, Bulgaria: case I, 21-23 February 2012: case II, 10-13 November: and case III, 25-30 November 2012. February is one of the coldest months of the year in Bulgaria and the fog in 2012 is cold and its duration is 48 hours. The transition between autumn and winter in Bulgaria takes place in November. Increase of the relative humidity, decrease of the temperature and change of the air masses are factors that determine the decrease of the visibility (Latinov, 2001). In November positive temperatures are often recorded in Bulgaria. The fog cases II and III in November are warm fog and its duration are 45 and 51, correspondingly.

3.1. Case study I: 21-23 February 2012

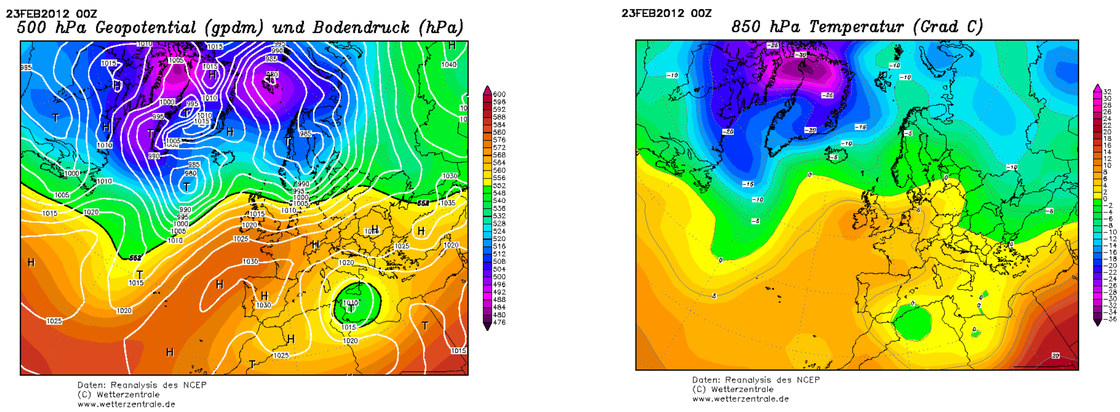

Figure 2. 23 February 2012 00 UTC, Left plot: 500 hPa geopotential height (colour scale) and sea level pressure (white contours). With ”H” and ”T” are marked the local high and low pressure centres, correspondingly. Right plot: Temperature at 850 hPa.

The fog case I is a radiation type. In the period 21 to 23 February the Balkan Peninsula is under the influence of large anticyclone. At 06 UTC on 22 a local high pressure centre (1030-1035 hPa) is formed over Romania (figure 2, left). The extended high pressure system blocks a Mediterranean cyclone and its trajectory is south-southwest, passing south of Italy and occluding over Malta. Until 15 UTC on 22 February low and mid-level clouds (850-700 hPa) are detected over the study region. On 23 February at 500 hPa a ridge from north-northwest is developed over Bulgaria. At 850 hPa after development of a thermal ridge the temperature increased from -2º C on 21 to 4º C on 23 February 2012.

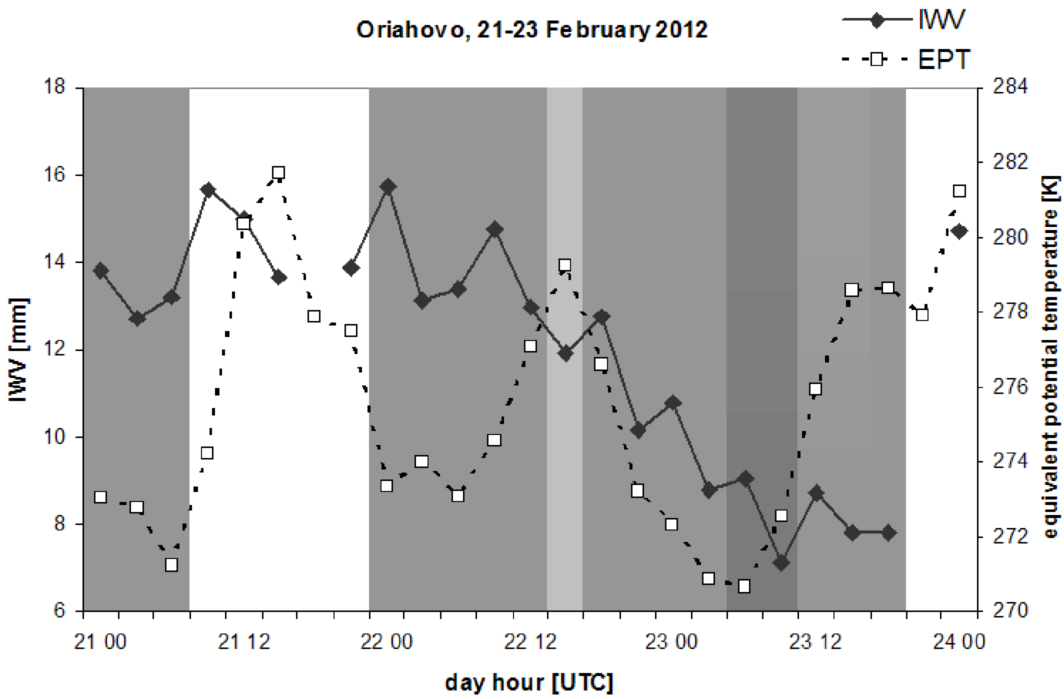

Figure 3. Case I, 21-23 February 2012: visibility (grey bars), IWV (black line with dots) and equivalent potential temperature (dashed black line with white dots) for station Oriahovo; (due to missing IWV data the IWV line is discontinued).

In Oriahovo, the fog lasts for 42 hours. After 00 UTC on 22 February a decreasing IWV trend is registered and with a minimum at 09 UTC on 23 results in visibility 0 m (figure 3). The well pronounced diurnal trend of the equivalent potential temperature (EPT) has minimum at the same time. This is quite expected because of connection between low values of EPT and strong stability of the air mass during fog. The maximum of EPT is during 15-hour period (from 21 Feb at 09 UTC to 22 Feb at 00 UTC) of quite good visibility (between 1100 and 8000 m). The average of EPT for the studied period is 276 K. During the 27 hours with fog we detect low than 276 K means of EPT. The fog dissipation results in a factor of two IWV increase from about 8 mm to 15 mm. The lowest visibility is recorded on 23 February and this is as a result of the discussed development of high ridge at 500 hPa leading to slight increase of temperature at 850 hPa. It is well known from synoptic practice in Bulgaria, that small temperature increase at 850 hPa and light wind from south result in fog development and decrease of visibility.

3.2. Case study II: 10-13 November 2012

The fog case II is of mixed type starting with radiation fog part IIa and continuing with advection type part IIb. After passage of a trough on 9-10 November on 11 November a

thermal and pressure ridge are formed at 500 hPa over Bulgaria (figure 4). At surface the center of an anticyclone is located north-northeast of the Black Sea. Fog is reported at Oriahovo, where the periods with visibility less than 1 km are for 45 hours totally. The fog dissipates on 13 November 2012 after cold air advection in the surface anticyclone circulation.
In Oriahovo, both the radiation (IIa) and advection (IIb) part of the fog are very well seen. The IIa part of the fog is formed at 03 UTC on 11 November and lasts for 12 hours. Before the fog formation diurnal temperature range (not shown here) is factor of two higher that once the fog is formed. In addition, a decrease of IWV (figure 5) is seen during the part IIa of episode. After 12 UTC on 11 November the fog is dispersed and interestingly the IWV increases from 8 mm to 15 mm within 6 hours. This rapid IWV increase is linked to humid air advection at altitude from west. This air mass transformation leads to the second part of the fog episode. During the IIb part of the episode the IWV variation is dependant on the changes at higher levels (1000 – 3000 m) thus the changes on the low levels are masked.
The diurnal EPT amplitude during the two parts of the fog (IIa and IIb) is smaller than this one before fog formation at 03 UTC on 11 November and in the end of studied episode, after 13 November at 12 UTC. Besides of lower temperatures detected during fog hours, this behaviour could be influenced by above discussed advection of warm air mass at the altitude (figure 4, right). So, the inversion in low layers becomes stronger which reflect on the low values of EPT. It is quite well seen that the air mass before and after two part of the fog and during the fog (IIa and IIb) as well, are different, because of different average of the EPT which is almost 291 K in fog and 294 K in non fog time. Further investigations along those lines to get more clear correlation between EPT and IWV behaviour as a two different parameters detect changes in air mass.

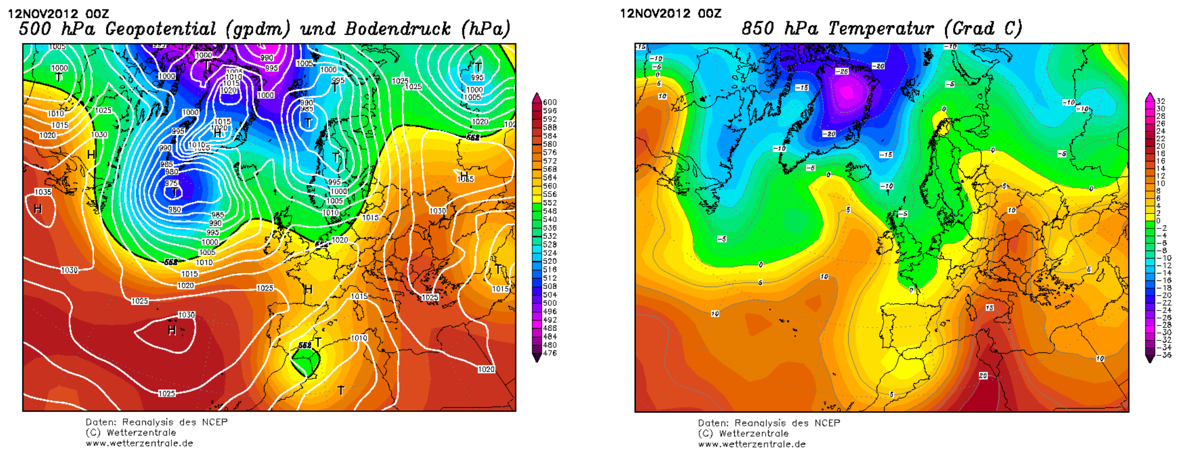

Figure 4. 12 November 2012 00 UTC, Left plot: 500 hPa geopotential height (colour scale) and sea level pressure (white contours). With ”H” and ”T” are marked the local high and low pressure centres, correspondingly. Right plot: Temperature at 850 hPa.

It can be concluded, that IWV is a good indication of new air mass advection at altitude and the fog formation is very sensitive to the time of the advection. This sensitivity is linked to the influence of the upper levels on the diurnal variation of surface parameters like temperature thus reflecting the nocturnal radiative cooling. Also, the advection of new humid air mass, detected by IWV in combination with behaviour of EPT at the ground level give us an additional tool for analyzing current situation by two different integrated characteristics connected with main parameters for air mass – humidity and temperature and in some stage pressure.

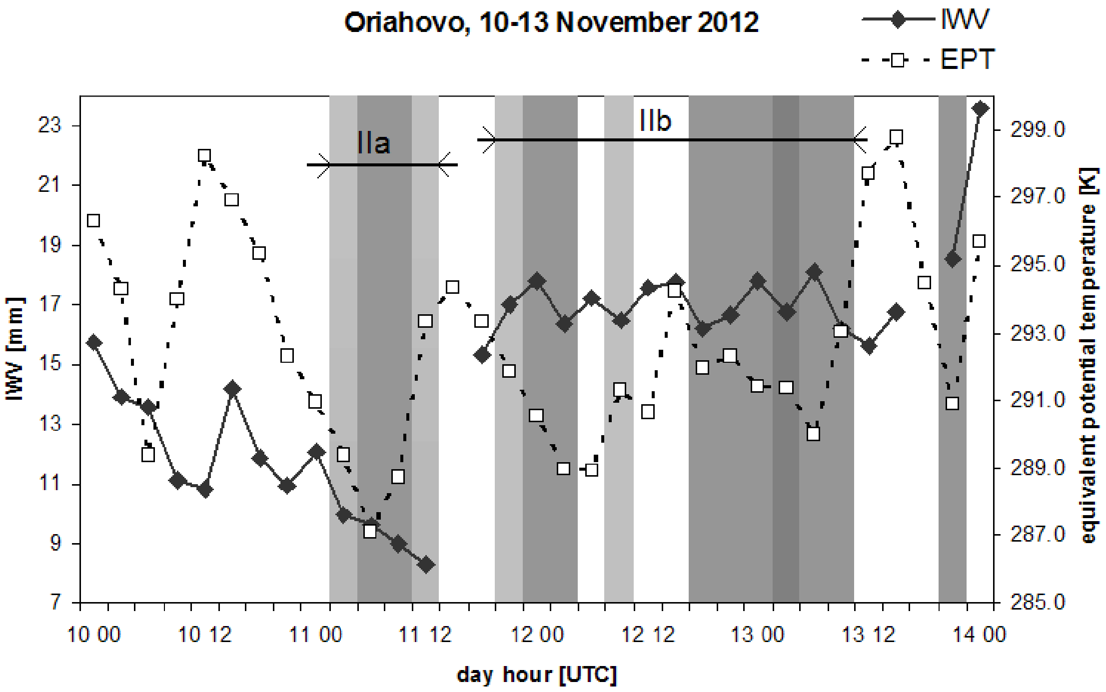

Figure 5. Case II, 10-13 November 2012: visibility (grey bars), IWV (black line with dots) and equivalent potential temperature (dashed black line with white dots) for station Oriahovo; (due to missing IWV data the IWV line is discontinued).

To confirm the changes of the air mass in Oriahovo the EUMETSAT (http://eumetsat.org/) cloud cover products and EUMeTrain (http://eumetrain.org/) data archive were examined into detail.

3.3. Case study III: 25-30 November 2012

The case III is a mixed type fog with three phases IIIa, IIIb and IIIc. On 25-26 November the anticyclone formed over the Balkan Peninsula facilitating the radiation fog (IIIa) formation. On 27-28 November in the front part of a though warm air is advected at 850 hPa over the region. The resulted in temperature increase is from 0-4º C on 26 November to 10-12º C at 00 UTC on 29 November (figure 6, right) and the phase IIIb fog is formed. At 12 UTC on 29 November, the passage of an atmospheric disturbance results in small temperature decrease. This disturbance results in radiation fog formation (IIIc) at 00 UTC on 30 November in Oriahovo.

In case III the IWV are high due to two main reasons: 1) at the end of November the humidity in Bulgaria is often high, due to the significant sunshine decrease and the considerable night cooling, which favours condensation during the nights and mornings thus fog and low cloud formation (Latinov, 2001) and 2) the dynamic of atmospheric processes increases and the humid Mediterranean incursions become more frequent. Such humid Mediterranean air mass is well detected in case IIIb.

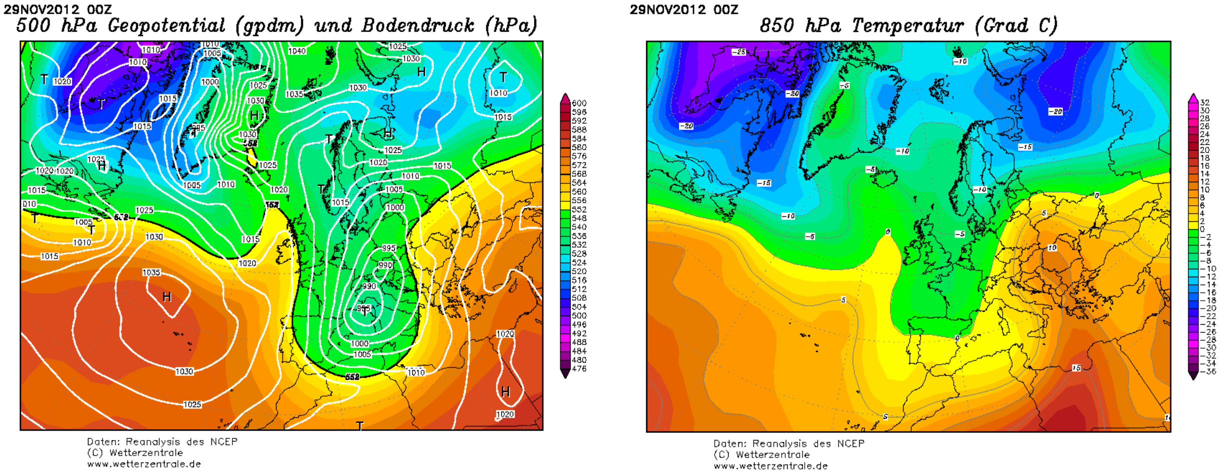

Figure 6. 29 November 2012 00 UTC, Left plot: 500 hPa geopotential hight (color scale) and sea level pressure (white contours). With "H" and "T" are marked the local high and low pressure centres, correspondingly. Right plot: Temperature at 850 hPa.

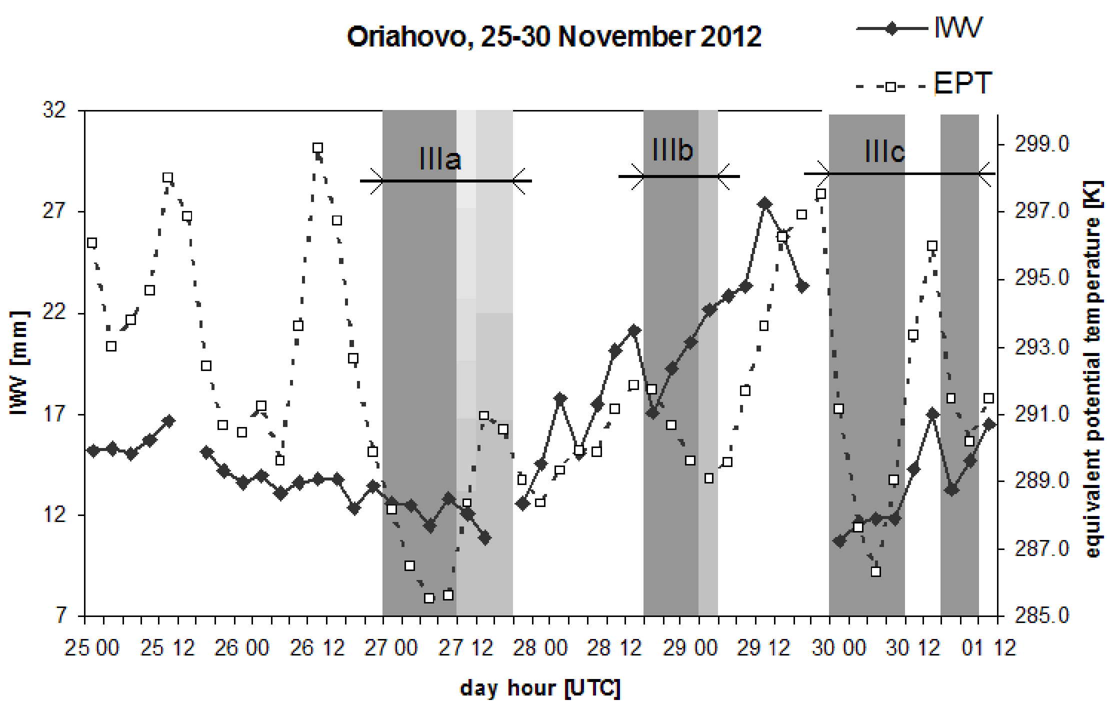

Figure 7. Case III, 25-30 November 2012: visibility (grey bars), IWV (black line with dots) and equivalent potential temperature (dashed black line with white dots) for station Oriahovo; (due to missing IWV data the IWV line is discontinued).

In case III the fog life cycle in Oriahovo has three distinguished parts clearly visible in IWV behaviour (figure 7). The first fog is formed in the night of 27 November following the radiative cooling and nocturnal temperature drop. It is to be noted, that the IWV shows a tendency to decrease after fog formation and significant drop in EPT to lowest value of 285.5 K for whole studied period. The second fog formation part IIIb in Oriahovo is after sharp jump of IWV from about 15 mm to 20 mm within 6 hour associated with humid Mediterranean air mass. In case IIIb the IWV behaviour during the fog is not indicative for close to surface air mass transformations. Never the less the slight increase of EPT, till end of the part IIIb the EPT's values stay below the 293 K average for the period. The retreat of the humid Mediterranean air leads to drop of IWV from 24 mm at 18 UTC on 29 November to 11 mm over 6 hour time period. Such drop is seen again in EPT values when second minimum is detected. The last part IIIc of fog is in the cold air mass settled after the passage of the atmospheric disturbance. The clear sky and calm conditions facilitated the radiative cooling and fog is formed again. It is to be noted, that the fog duration is 18 hours with short period of visibility improvement around midday.
In this case III we can find that the altitude advection of humid and warm air mass show tendency of correlation with low EPT values but further investigation is need to be done.

4. DISCUSSION

In this work we use observations from IWV in combination with surface observations of temperature, relative humidity and visibility, and calculated equivalent potential temperature to study the fog formation, development and dissipation at a favourable for fog formation location in north Bulgaria. Three fog cases were selected in February and November 2012. Given is a detailed description of the synoptic conditions leading to fog formation. Improvement of fog diagnosis and prognosis can be expected by using IWV as a very sensitive tool for transfer of water vapour into cloud water during fog formation and development, especially in radiation fog stage. The IWV sensitivity to warm and humid air advection in mixed fog type shows promise for the operational forecasting. Demonstrated it this study is that IWV has high sensitivity to the new air mass advection. The behaviour of the IWV and equivalent potential temperature can be a valuable additional tool in decision making processes for very short range fog forecast in the operational practice. In this work 3-hourly data-sets are used. For monitoring fog dynamics hourly or better sub-hourly data-sets will be an advantage. Access to the real-time GNSS tropospheric products will be additional motivation for development of operational tool using this new data-set. The work will continue with extending the study to other locations in Bulgaria and more cases as a contribution to working group two of the COST Action ES1206 "Advanced Global Navigation Satellite Systems tropospheric products for monitoring severe weather events and climate (GNSS4SWEC)".

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BIOGRAPHICAL NOTES

Anastasiya Stoycheva is an operational weather forecaster at the National Institute of Meteorology and Hydrology – Bulgarian Academy of Science, Sofia, Bulgaria. She received a MSc degree in meteorology from Sofia University and submitted her PhD thesis at the Department of Meteorology and Geophysics of the Sofia University, Sofia, Bulgaria. Her research interest cover weather forecasting, especially fog forecasting, intense precipitation and all ranges of hazards events in general.

Guergana Guerova is an associate professor at the Department of Meteorology and Geophysics of the Sofia University, Sofia, Bulgaria. She received a MSc degree in meteorology from Sofia University and PhD in applied physics from University of Bern. Her research interest cover monitoring short and long-term variation of GNSS derived water vapour in particular for studying fog, intense precipitation, hail storm and heat waves. She is Marie Curie IRG Fellow (2011-2014) and vice chair of COST Action ES1206 GNSS4SWEC (2013-2017).

CONTACTS

Anastasiya Stoycheva
National Institute of Hydrology and Meteorology – Bulgarian Academy of Science
Tsarigradsko shosse 66
Sofia
BULGARIA
Tel. +359 887 942024
Email: anastassia.stoycheva@meteo.bg