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APPLICATION OF GROUND-BASED GNSS METEOROLOGY IN BULGARIA/SOUTHEAST EUROPE: CASE STUDY 2007 HEAT WAVE

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Цветан Симеонов, Керанка Василева, Гергана Герова. ПРИЛОЖЕНИЕ НА НАЗЕМНИТЕ ИЗМЕРВАНИЯ С ГЛОБАЛНИТЕ СПЪТНИКОВИ СИСТЕМИ ЗА ПОЗИЦИОНИРАНЕ В МЕТЕОРОЛОГИЯТА В БЪЛГАРИЯ И ЮГОИЗТОЧНА ЕВРОПА ПРИ ИЗСЛЕДВАНЕТО НА ТОПЛИННАТА ВЪЛНА ОТ 2007 ГОДИНА

Водната пара е най-разпространеният парников газ и се очаква да нараства в атмосферата вследствие на глобалното затопляне. Поради големите си времеви и пространствени нееднородности водната пара е трудна за измерване със стандартните метеорологични уреди. През последните 15 години се наложи нов метод за измерване на интегрираното във височина количество водна пара в атмосферата с помощта на глобалните навигационни спътникови системи (ГНСС), а именно ГНСС метеорология. В Европа методът е широко разпространен, като в момента Националните метеорологични институти получават данни от повече от 1600 наземни ГНСС станции чрез проекта на EUMETNET-E-GVAP. В югоизточна Европа този метод е слабо познат и все още не се използва. Тук за първи път се разглежда денонощният ход на интегрираната по височина водна пара за 8 станции в югоизточна Европа по време на топлинната вълна между 19-ти и 25-ти юли 2007 година. В станциите, разположени край Черно море – Констанца и Варна, водната пара има максимум в 15 ч. по Гринуич, т.е. 3 часа след температурния максимум. Водната пара, измерена в станциите, разположени край Средиземно море (Атина и Дубровник), има подобно поведение. Максимумът в 15 ч. може да се обясни с максимум в развитието на морската бриза, която доставя влажен въздух над сушата. В станции, далеч от морския бряг, като Букурещ и Крайова, максимумът на водната пара е отчетен между 6 и 9 ч. по Гринуич. Разликите в дневния ход на водната пара показват важността на местната циркулация.

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Tzvetan Simeonov, Keranka Vassileva, Guergana Guerova. APPLICATION OF GROUND-BASED GNSS METEOROLOGY IN BULGARIA/SOUTHEAST EUROPE: CASE STUDY 2007 HEAT WAVE

Atmospheric water vapour, the most abundant greenhouse gas, is expected to increase in a warmer climate. Due to its high temporal and spatial variation it is also difficult to sample with the conventional atmospheric observing systems. In the last 15 years, vertically Integrated Water Vapour (IWV) is derived from the GNSS (Global Navigational Satellite Systems) signal time delay: the GNSS meteorology method. GNSS meteorology is well established research filed in Europe and data from over 1,600 ground-based GNSS stations are available to the European National Weather Services via EUMETNET E-GVAP project. In Southeast Europe GNSS is yet to be used for water vapour studies. This first work employes IWV derived from 8 GNSS stations in Southeast Europe to study the water vapour cycle during the 19-25 July 2007 heat wave. At the Black sea coastal stations Constanta and Varna, the peak IWV is at 15 UTC, i.e., 3 hours after the temperature peak. Similarly, IWV peak at 15 UTC is characteristic for the Mediterranean sea station Athens and Adriatic sea station Dubrovnik. The IWV peak at 15 UTC can be explained with the peak of the sea breeze circulation that brings humid air from the sea inland. In contrast, at the inland stations Bucharest and Craiova the peak of IWV is between 6–9 UTC. The differences in diurnal cycle of inland and coastal stations show the importance of local circulation.

Keywords: global navigation satellite systems (GNSS), GNSS meteorology, atmospheric water vapour, heat wave

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1. INTRODUCTION

Atmospheric water vapour is the most abundant greenhouse gas involved in the climate feedback loop. As the temperature of the Earth's surface and atmosphere increases, so does the moisture- holding capacity of the atmosphere and atmospheric water vapour is expected to increase in a warmer climate. The evidence is now indisputable [1] that water vapour released into the atmosphere adds one degree Celsius to global warming for every one degree contributed by man through greenhouse gas emissions.

According to the World Bank [2], as a consequence of climatic change a dramatic decrease in precipitation (–25%) is likely to occur in Bulgaria/Southeast Europe (Bulgaria and 9 neighboring countries). Since 1950 the rate of change of precipitation shows a decrease of about 0.2% per year. Comparing the mean value for annual temperature in 1901–1920 to 1980–2002, warming has increased by 0.5^0 in Southeast Europe. Heat waves have become a common summer feature on the Balkan Peninsula in the last 20 years [3]. During the 2007 summer, three heat waves are reported in the second half of June, July and August [3]. The July 2007 heat wave has the largest geographical extension reaching Bulgaria. In the period 18–25 July 2007, temperature above 40^0 is measured in at least two stations, operated by the National Institute of Meteorology and Hydrology in

Bulgaria. On 23 and 24 July in all 41 stations temperature records are registered. The temperature reached a record of 45.5^0 C in the Sandanski station in South Bulgaria. The heat wave caused wild fires and drought. Coarse-resolution global climate models project that by the mid-century, Bulgaria will become warmer, drier and with more frequent heat waves (data available from the World Bank Climate Portal).

In this work we study the atmospheric water vapour during the July 2007 heat wave in Bulgaria using the Global Navigation Satellite System (GNSS) Meteorology technique. The concept of GNSS Meteorology was first suggested in 1992 by Bevis [4]. As the GNSS signal travels trough the atmosphere its propagation is affected by the atmospheric gases and in particular water vapour, which has high temporal variation up to 20-30% within a day. Thus vertically integrated water vapour data with high temporal and spatial resolution can be derived from the GNSS signal time delay.

In Europe, the exploitation of GNSS for monitoring the troposphere started in 1998. The initial research combined the GPS networks of France, Italy and Spain [5]. Operational provision of ground-based GPS tropospheric products in Near Real Time (NRT) started in 2001 [6]. Currently, 13 European GNSS processing centers deliver tropospheric products from more than 1,600 continuously operating GNSS stations with a maximum of 90 minute latency and hourly update. While in Europe, application of GNSS in Meteorology is well established, in East Europe it is an emerging research field.

This study presents the first results of application of ground-based GNSS meteorology method in Bulgaria/Southeast Europe for monitoring water vapour during the 2007 heat wave. The combination of high water vapour and temperature are lethal [3].

The paper is organized as follows: section 2 presents the radiosounde and the GNSS Meteorology methods and intercomparison for estimation of atmospheric water vapour; the GNSS tropospheric parameters and intercomparison between GNSS and radiosonde is given in section 3; section 4 discusses the diurnal cycle of atmospheric water vapour at 8 GNSS stations during the 2007 heat wave. Conclusions are given in section 5.

2. METHODS

2.1. RADIOSOUNDE METHOD

The radiosounde is a standard technique for in-situ sampling of the atmosphere. The method is approved by the World Meteorological Organization (WMO) and is widely adopted for temperature, pressure, humidity, wind speed and direction.

The National Institute of Meteorology and Hydrology of the Bulgarian Academy of Sciences (NIMH-BAS) performs regular radiosounde observations at 12 UTC in station Sofia. Since 2005 the sounde type is VAISALA RS92KL. The relative humidity sensor is a thin-film capacitor heated twin sensor with measurement range between 0 and 100%, resolution 1% and total uncertainty in sounding 5%.

In this work we use the radiosounde *Integrated Water Vapour* (*IWV*). It is computed using:

$$IWV = \frac{1}{\rho_w} \int_{h_0}^{h_{top}} \rho_{wv}(h)dh \qquad (1)$$

where h_0 is the altitude of the station, where the probe is released, h_{top} is the maximum acheaved hight by the probe during sounding, ρ_w is the density of water, ρ_{wv} is the density of water vapour. *IWV* is measured in millimeters [7].

2.2. GNSS METEOROLOGY

The concept of GNSS Meteorology was first suggested in 1992 by Bevis [4]. As the GNSS signal travels trough the atmosphere, its propagation is affected by atmospheric gases and in particular by water vapour. The magnitude of the atmospheric effects depends on the elevation angle of the satellite and on the current atmospheric situation. There are three major effects, caused by the atmosphere: ionospheric group delay; group wet and dry delay, caused by the troposphere and the stratosphere and the signal attenuation in the troposphere and in the stratosphere [8].

The ionosphere is the highest part of the atmosphere. It is situated between 100 and 500 km from the Earth's surface and consists mainly of ionized gases. The ionosphere has a highly noticeable daily fluctuation, because it is very sensible to sun and space radiation. The refraction index of the atmosphere depends on the wavelength of the signal, but it can be accurately calculated by using the main two frequencies ($L1$ and $L2$) of every GNSS.

The troposphere, the bottom 12 km of the atmosphere, can be described as a combination of dry air and water vapour. Nitrogen, Oxygen, Argon and carbon dioxide are the fundamental gases, which create the troposphere. From them, mainly oxygen, refracts the GNSS signal. The signal refraction in the atmosphere is the main error source in GNSS. The total tropospheric delay of GNSS signal in zenith direction is called *Zenith Total Delay* (*ZTD*). *ZTD* is a result of two major factors - the wet and hydrostatic delays.

The *Zenith Hydrostatic Delay* (or *ZHD*) is the largest of the two and is caused primarily by Oxygen and Nitrogen. *ZHD* causes about 2.1 meters of uncertainty in positioning at sea level and varies with temperature and pressure in a predictable manner. The *ZHD* is calculated, using this formula:

$$ZHD = (2.2768 \pm 0.0024)\frac{p_s}{f(h,\theta)}, \quad (2)$$

$$f(h,\theta) = 1 - 0.00266\cos(2\theta) - 0.00028h, \quad (3)$$

where p_s is local surface pressure and $f(h,\theta)$ is a factor, dependent on height h and the latitude variation of the gravitational acceleration θ.

The second delay is caused by the water vapour and is called *Zenith Wet Delay* (*ZWD*). *ZWD* is much smaller, than the *ZHD* and adds from 1 up to 80 cm to the uncertainty in positioning. Unlike the *ZHD*, it has a large variation in a short time, due to its dependence of temperature, soil moisture and local conditions, which makes it highly unpredictable. The *ZWD* is defined by:

$$ZWD = ZTD - ZHD \quad (4)$$

The *Integrated Water Vapour* (*IWV*) can be extracted from this formula:

$$IWV = \frac{10^6}{(k_3/T_m + k_2')R_v} ZWD \quad (5)$$

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

2.3. *IWV* INTERCOMPARISON: GNSS AND RADIOSOUNDE

Figure 1 shows intercomparison between GNSS derived *IWV* and the radiosonde during the heat wave period. The two methods show similar results. Clearly seen are the sampling differences between the two techniques. While GNSS provides high temporal resolution data (15 minute to 1 hour observations) the radiosonde is limited to only one sample a day. Clearly the large temporal variation between two sounding makes the GNSS data very suitable to study the diurnal cycle of *IWV*.

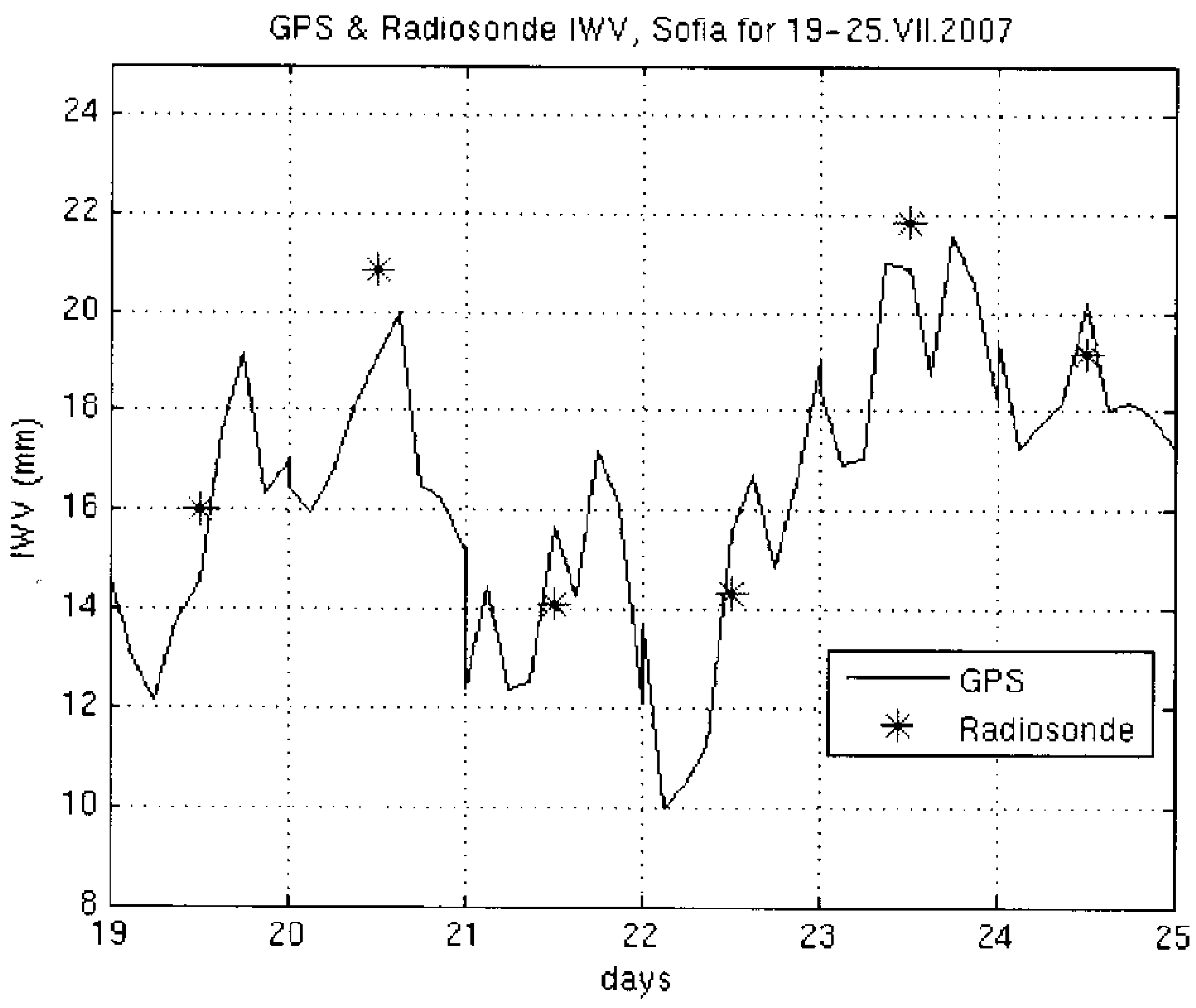

Fig. 1. *IWV* intercomparison: GNSS (solid line) and radiosonde (star).

Table 1 shows a comparison between the GNSS meteorology and the radiosonde method for retrieving information about water vapour. Beside the high temporal resolution, the GNSS has very high spatial coverage, 115 stations in Bulgaria, compared to 1 sounding for the same region. The low vertical resolution of GNSS meteorology is caused by the lack of measuring at different altitudes.

Table 1. Characteristics of water vapour measurement techniques

Criteria	Radiosonde	GNSS
temporal resolution	low (24 hours)	high (15 min - 1 hour)
spatial resolution	low (1 station)	high (115 stations)
vertical resolution	high (profile)	low (integrated quantity)
all weather operation	yes	yes
dataset length	about 50 years	from 1997 (SOFI station), 2009 (114 stations)
ownership	NIMH	IGS (SOFI) and 3 private networks

The radiosonde is an in-situ observing system, providing vertically resolved water vapour profiles in the troposphere. Both methods are all weather operational including cloud cover and precipitation events. While the radiosonde is in operation for more than 50 years the GNSS is only available since mid 1990ies. In addition to the high temporal and spatial resolution GNSS method comes at low cost. The GNSS meteorology is an established observing system providing unique data for the state-of-the-art numerical weather prediction models. It is the only technique that can measure atmospheric water vapour with a reproducibility better than 1% over decades at a reasonable cost [9].

3. TROPOSPHERIC PARAMETERS DURING THE JULY 2007 HEAT WAVE

3.1. GNSS DATA-SETS

In this work two GNSS data-sets are used. The first data-set is from the GNSS station in Sofia, which is suitable for intercomparison with the radiosonde station in Sofia (see section 3.3). The second data-set, with 19 GNSS station is provided by Dr. Keranka Vassileva from the National Institute of Geophysics, Geodesy and Geography. From this data-set 8 stations are in Southeast Europe and are used in section 4 to study the water vapour dynamics during the heat wave. Short description of the two data-sets is given below.

The tropospheric parameters *ZTD*, *ZHD* and *IWV* are derived for GNSS station Sofia (SOFI), Bulgaria. The SOFI station is in operation since 1997 and is part of the permanent EUREF (EUropean REference Frame) Network. The station is routinely processed by EUREF GNSS Processing Centers and tropospheric parameters are available hourly. The station is located in the Plana mountain, 1120m msl., about 20km from Sofia and is equipped with an AR25 Leica antenna and provides data for IGS and EGVAP.

In addition, GPS data from 19 GNSS permanent stations (*AUT1, NOA1, BUCU,COST, DUBR, GLSV, GRAZ, MATE, ORID, PENC, POLV, ROZH, SOFI, SULP, MIKL, WTZR, ZIMM, VARN, CRAI*) from Central and Eastern Europe (figure 2) are processed with the Bernese software, version 5.0 for the period 19-25 July, 2007. Sixteen of them are IGS (International GNSS Service) and EPN (EUREF Permanent network) stations. Seven sessions of 24 hours have been created. Daily station coordinates and station troposphere zenith delays in every 1 hour of each session are estimated. The troposphere model used is Saastamoinen dry model with Niell dry mapping and tilting gradient model. Corrections to the introduced zenith values have been estimated and finally the total zenith delays have been obtained as well as gradient parameters in North and East directions. These daily tropospheric files with estimated zenith total delays are used as input files for estimation of *IWV*.

Fig. 2 . Loca

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Sofia
Varna
Bucharest
Craiova
Constanta
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Athens
Thessaloniki

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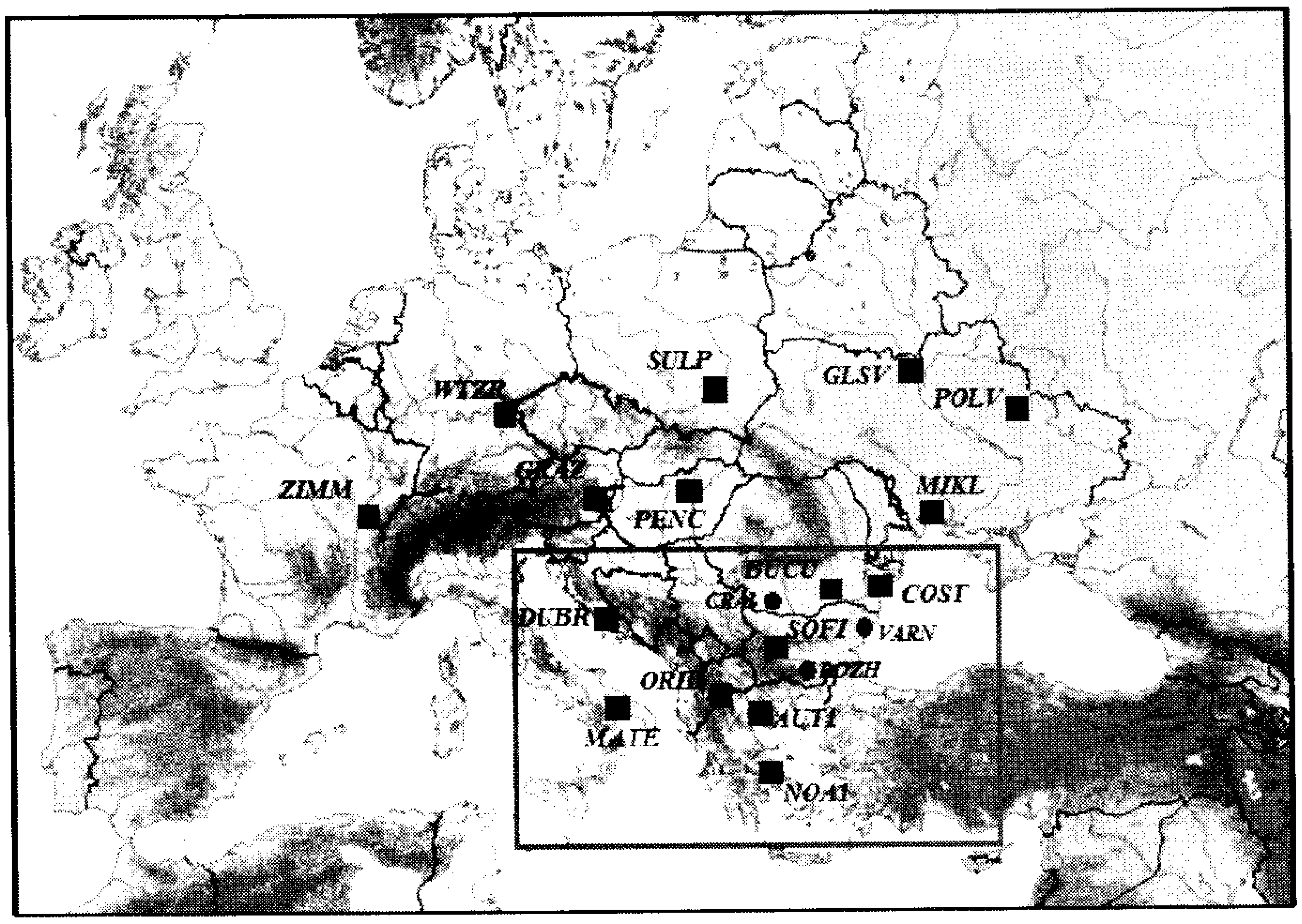

Fig. 2 . Location of the IGS/EPN GNSS permanent stations. In this study are used SOFI, BUCU, COST, CRAI, VARN, AUT1, NOA1 and DUBR, marked with a box.

Table 2. GNSS and meteorological stations coordinates

Station	GNSS altitude[m]	Meteo station altitude [m]	GNSS Longitude	GNSS Latitude
Sofia	1120	595	23^0 23'	42^0 33'
Varna	91	43	27^0 55'	43^0 12'
Bucharest	143	91	26^0 07'	44^0 27'
Craiova	143	195	23^0 45'	44^0 20'
Constanta	46	14	28^0 39'	44^0 09'
Dubrovnik	545	165	18^0 06'	42^0 38'
Athens	538	15	23^0 51'	38^0 02'
Thessaloniki	150	4	23^0 00'	40^0 34'

3.2. GNSS TROPOSPHERIC PARAMETERS: ZTD, ZWD AND IWV

Figure 3a presents *ZTD* for the period 19-25 July 2007 at SOFI station. The *ZTD* is in the range of 2.1m. The *ZHD* temporal variation is almost flat slightly above 2.0m. During the heat wave, the high pressure is dominant over the region, which is the reason for the *ZHD* flatness. The temporal variation of *IWV* is presented in figure 3b. As seen in the figure, *IWV* has a rapid variation, for example at 03 UTC on the 22 July it is about 10 mm and 21 hours later at 00 UTC on 23 July it almost doubles reaching 19 mm. In order to retrieve *ZHD* and *IWV*, temperature and pressure data from the synoptic station Sofia of NIMH-BAS is used. The station is at elevation 595 m msl. therefore, a height correction is applied to accommodate the 625 m altitude difference. The temperature and pressure data are available every 3 hours and this is the reason for degrading the GNSS data, which provides hourly products.

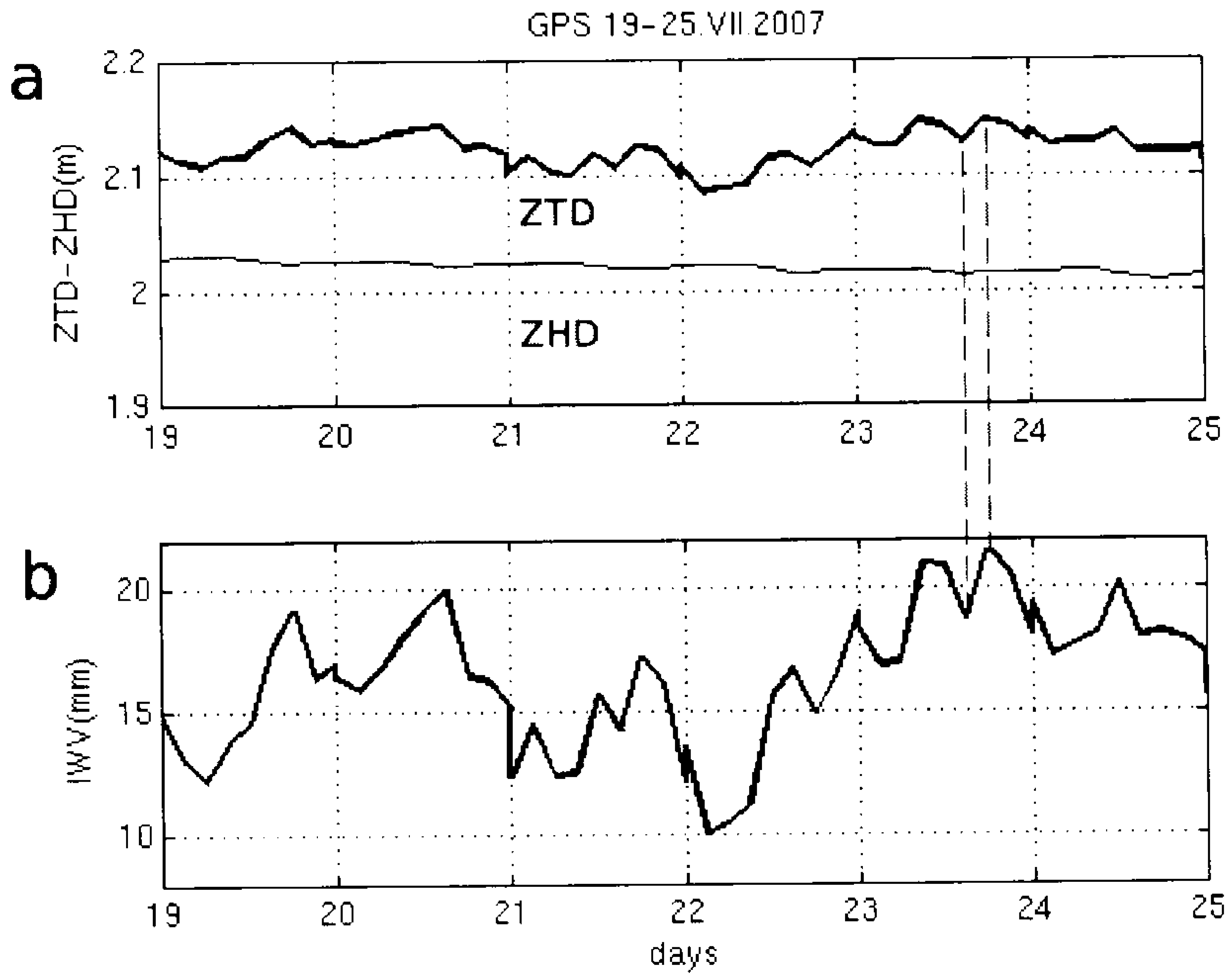

Fig. 3. Temporal variation of: a) *ZTD* and *ZHD*; b) *IWV* at GNSS SOFI station during 19–25 July 2007 heat wave.

4. DIURNAL CYCLE OF *IWV* DURING THE 19-25 JULY 2007 HEAT WAVE IN SOUTHEAST EUROPE

The atmospheric circulation leading to the heat wave is characterized by northerly displacement of the subtropical jet stream (flow at 200 hPa) that allowed subtropical African air to reach the Balkan Peninsula as far as 50^0 N. Clearly seen on figure 4 is a hot air tongue spreading over the Mediterranean sea and the Balkan Peninsula at 00 UTC on 23 July 2007.

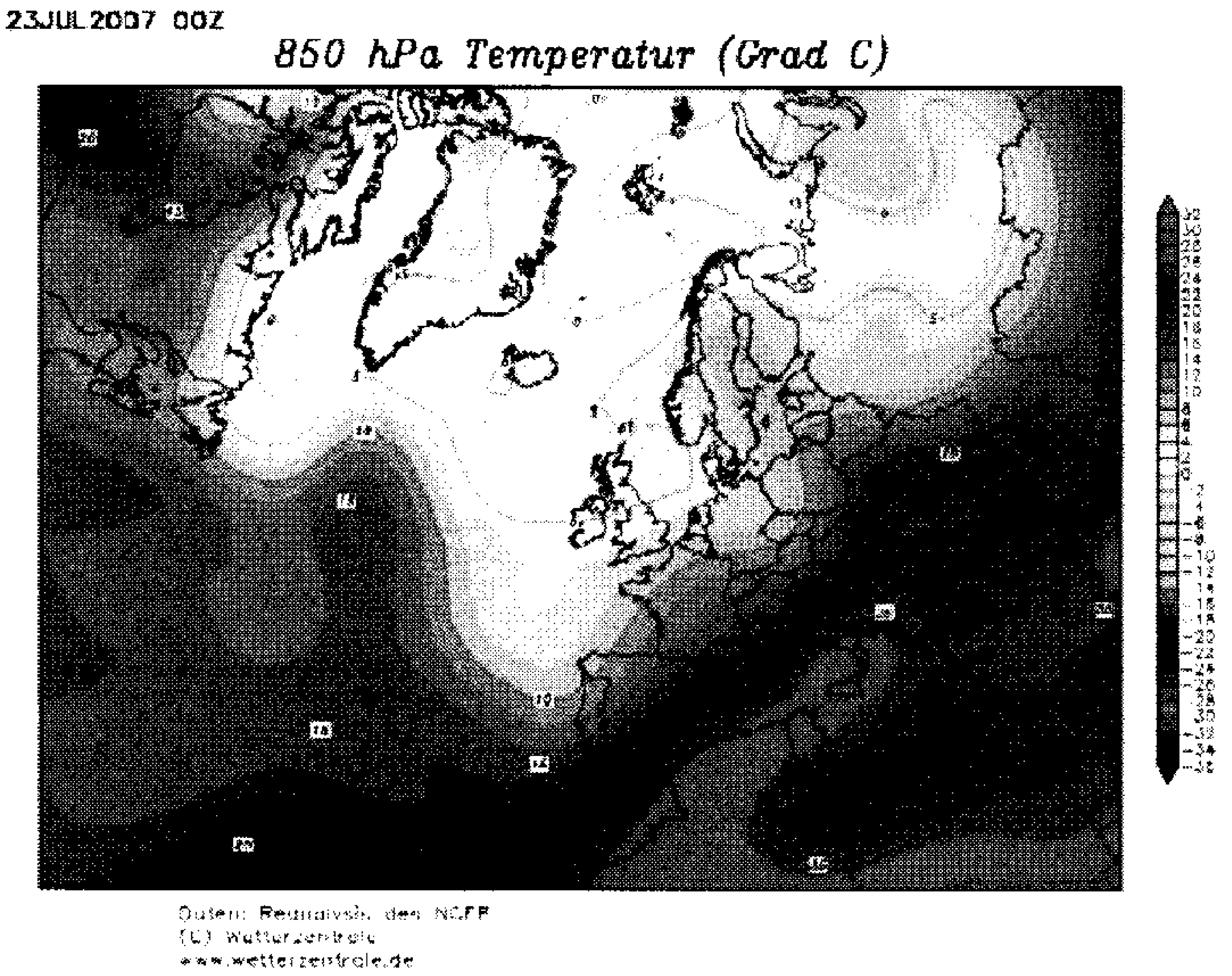

Fig. 4. Temperature at 850 hPa (1.5 km msl.) on 23 July 2007 00UTC.

The diurnal cycle of the temperature and *IWV* is presented in figure 5. At all location the temperature reaches minimum at 3 UTC. At all but 2 locations the temperature peaks at 15 UTC. At the Black sea coastal sites Constanta (figure 5c) and Varna (figure 5d) the temperature peak is at 12 UTC. The diurnal cycle of *IWV* shows substantial differences. For the inland stations in Romania - Bucharest (figure 5a) and Craiova (figure 5b) the peak of *IWV* is between 6-9 UTC and a minimum is at 18 UTC. At the Black sea coastal stations Constanta (figure 5c) and Varna (figure 5d) the *IWV* minimum is around 00 UTC and the peak is at 15 UTC, i.e., 3 hours after the temperature peak. The *IWV* peak at 15 UTC can be explained with the peak of the sea breeze circulation that brings humid sea air inland. Similarly, the *IWV* peak at 15 UTC is also characteristic for the Mediterranean sea station Athens (figure 5e) and Adriatic sea station Dubrovnik (figure 5f). At the Mediterranean sea station Thessaloniki (figure 5f), the *IWV* peak is at 21 UTC, i.e., 6 hours later than the temperature peak. Morland et al. [10] study the diurnal climatology from 2003 to 2007 for station Bern and conclude that the *IWV* diurnal cycle peak occurs about 6 hours later, than the daily temperature maximum. At the inland station Sofia (figure 5h) the *IWV* minimum is at 6 UTC and a broad peak is seen between 12-18 UTC. It is to be noted that the GNSS station in Sofia located in a mountainous area outside of the city at altitude of 1120 m msl. which makes it suitable for study of local *IWV* circulation in mountainous regions.

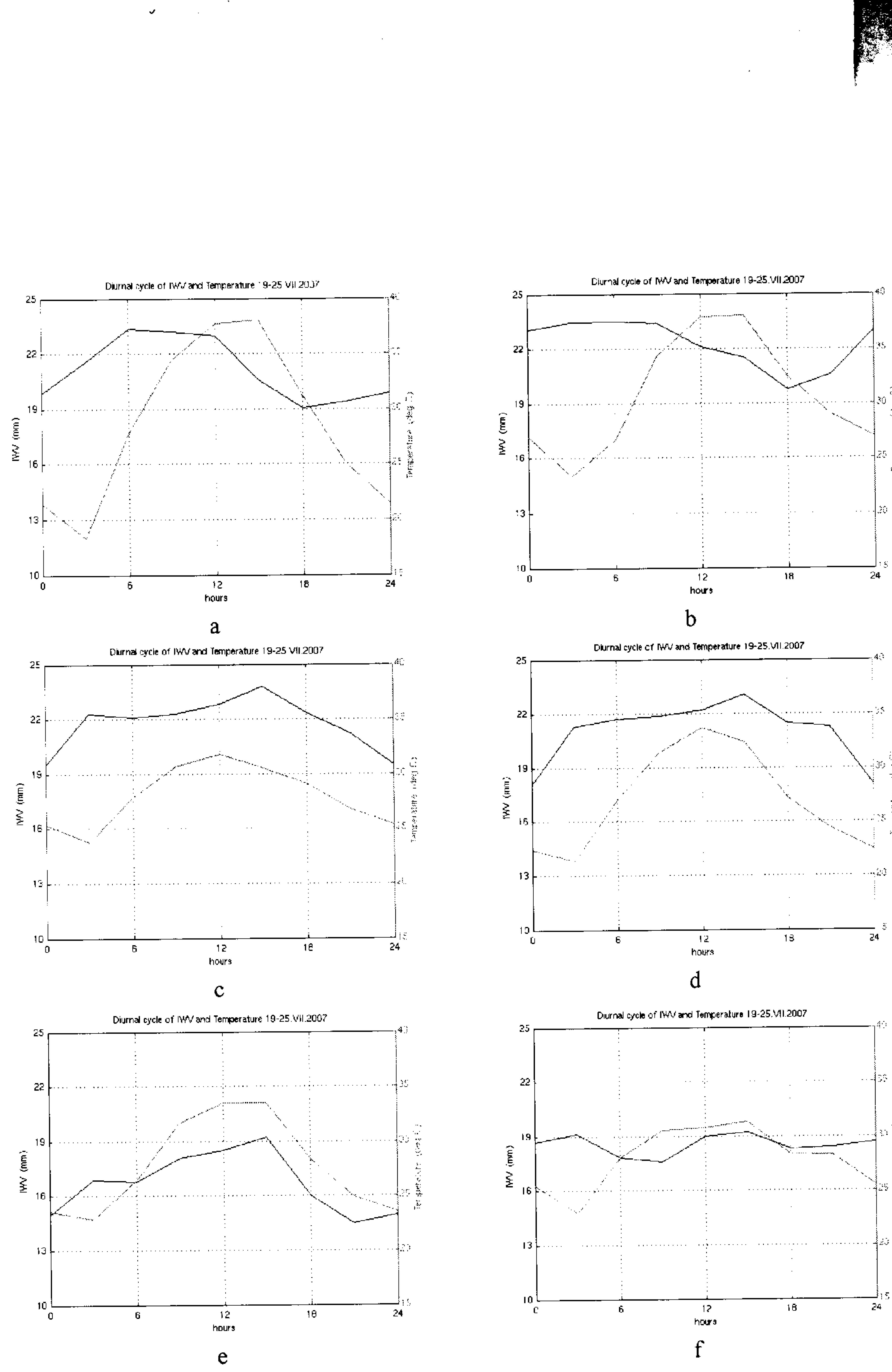

Fig. 5. Diurnal cycle of *IWV* in mm (black line) and temperature in ^{0}C (colored line) for: a) Bucharest, Romania; b) Craiova, Romania; c) Constanta, Romania; d) Varna, Bulgaria; e) Athens, Greece; f) Dubrovnik, Croatia;

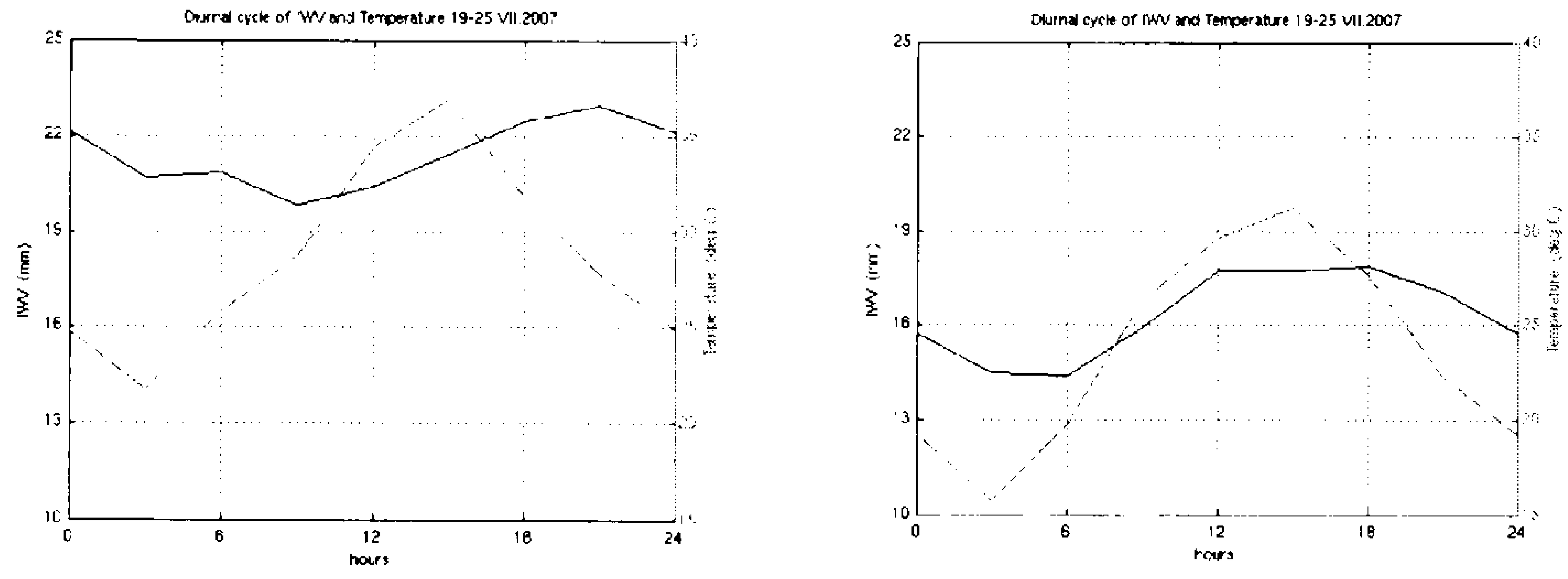

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Fig. 5. Diurnal cycle of *IWV* in mm (black line) and temperature in ^{0}C (colored line) for: g) Thessaloniki, Greece; h) Sofia, Bulgaria.

5. CONCLUSIONS

Heat waves have large adverse social, economic and environmental effects including increased mortality, the destruction of large areas of forests by fire, and effects on water ecosystems and glaciers. They cause increased power consumption and power cuts, transport restrictions and a decreased agricultural production. Heat waves have become a common summer feature in the Southeast Europe thus calling for adequate strategy regarding air quality, transportation, energy production and consumption, agriculture, water management and tourism. The estimated economic losses of the 2007 heat wave in Southeast Europe exceed 2 billion EUR.

Monitoring water vapour during the heat waves is critical as the combination of high temperature and water vapour is lethal. This study presents the first results of application of ground-based GNSS meteorology method in Bulgaria/Southeast Europe. GNSS tropospheric products from 8 stations in Southeast Europe are used to study the diurnal cycle of water vapour during the 19–25 July 2007 heat wave. For the coastal stations at Black sea the peak *IWV* occurs at 15 UTC, i.e., 3 hours after the peak of the temperature and co-insides with the peak of the sea breeze circulation. For the inland stations in Romania the peak of *IWV* is between 6–9 UTC and a minimum is at 18 UTC. A double peak of *IWV* at temperature at 15 UTC is characteristic for the Mediterranean sea station Athens and Adriatic sea station Dubrovnik. The differences in the diurnal cycle of inland and costal stations show the importance of local conditions. While the temperature peak occurs between 12 and 15 UTC at all stations the maximum of *IWV* shows large variations depending on the local environment.

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