Atmos. Meas. Tech. Discuss., 7, 2153–2185, 2014
www.atmos-meas-tech-discuss.net/7/2153/2014/
doi:10.5194/amtd-7-2153-2014

Atmospheric Measurement Techniques Discussions
Open Access

The Sofia University Atmospheric Data Archive (SUADA)

G. Guerova, Tzv. Simeonov, and N. Yordanova

Sofia University, Faculty of Physics, Department of Meteorology and Geophysics, 5 James Bourchier Blvd., 1164 Sofia, Bulgaria

Received: 31 January 2014 – Accepted: 18 February 2014 – Published: 5 March 2014

Correspondence to: G. Guerova (guerova@phys.uni-sofia.bg)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Atmospheric sounding using the Global Navigation Satellite Systems (GNSS) is a well established research field in Europe. At present, GNSS data from 1800 stations are available for model validation and assimilation in state-of-the-art models used for operational numerical weather prediction Centers in Europe. Advances in GNSS data processing is making possible to also use the GNSS data for climatic trend analysis, an emerging new application. In Bulgaria and Southeast Europe the use of GNSS for atmospheric sounding is currently under development.

As a first step the Sofia University Atmospheric Data Archive (SUADA) is developed. SUADA is user friendly database and includes GNSS tropospheric products like Zenith Total Delay (ZTD) and derivatives like vertically Integrated Water Vapour (IWV) as well as observations from Radiosonde and surface atmospheric data. Archived in SUADA are: (1) GNSS tropospheric products (over 12 000 000 individual observations) and derivatives (over 55 000) from five GNSS processing strategies and 37 stations for the period 1997–2013 with temporal resolution from 5 min to 6 h and (2) Radiosonde IWV data (over 6000 observations) for station Sofia (1999–2012).

Presented are two applications of the SUADA data for study of long and short term variation of IWV over Bulgaria during the 2007 heat wave and intense precipitation events in 2012.

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 (Dessler and Sherwood, 2009) that water vapour increase adds one degree Celsius to global warming for every one degree through greenhouse gas emissions. Traditionally, the

AMTD
7, 2153–2185, 2014

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

long-term water vapour trends have been estimated using the global Radiosonde (RS) data (Gaffen et al., 1992; Ross and Elliott, 1996, 2001). In the last decade, the use of GNSS tropospheric products has been employed to verify the RS trends, which are not homogeneous due to sensor changes. Gradinarsky et al. (2002) estimate the water vapour trend using GNSS data over Scandinavia and finds to be positive with 0.1–0.2 $\mathrm{mm\,yr^{-1}}$ for the 1993–2000 period. They also report that winter trends are larger, than summer trends for the southern part of the region and opposite for the northern part. Nilsson and Elgered (2008) analyzed data for Sweden and Finland for the period 1993–2006 and confirmed the previous findings. Ning (2012) estimates the linear IWV trends, using 15 year global GNSS data set. The trends are found to be in the range -1.65–$+2.32\,\mathrm{kg\,m^{-2}\,decade^{-1}}$ and the estimated trend uncertainties is of the same order, varying from 0.21–1.52 $\mathrm{kg\,m^{-2}\,decade^{-1}}$.

In addition to climate monitoring, another application of the GNSS tropospheric products is to study development of convective clouds with intense precipitation. Resent studies Graham et al. (2012) in the Bernese Alps in Switzerland and van Baelen et al. (2011) in Black Forest region in Germany use GNSS derived water vapour to study isolated convection development. The first study shows that large transfers of air and water vapour occur from the Swiss plain to the mountains, with up to 50 % increase in GNSS Integrated Water Vapour (IWV) at the Alpine stations, coincident with strong airflow convergence in the same location (Graham et al., 2012). During the intense observation campaign in the region of the Black Forest Mountains in the summer of 2007 van Baelen et al. (2011) study the relationship between water vapour evolution and the life cycle of precipitation systems. They show, that (1) frontal systems seem to develop preferentially where the largest amount of water vapour is available and (2) water vapour has predominant role as a precursor for initiation of local convection. Accumulation of water vapour on the crest of the orography leads to ridge convection and its passing over the orography triggers lee-side convection. De Haan (2008) shows the value of the real-time GNSS-IWV maps for nowcasting by examining two cases studies. The first case is a severe thunderstorm on 8 June 2007 and the second –

two thunderstorm events on 20 July 2007. In both cases the convergence of moist air contains information on the location of developing thunderstorms. For the analysis of the case studies are used several methods – radar observations, GPS IWV maps and surface wind observations. The conclusion is that the real-time GPS IWV maps are of good quality and can be helpful for nowcasting of severe thunderstorms. A nine year study in northern Spain, conducted by Seco et al. (2012), reports that rain events are usually from atmospheric low pressure systems and water vapor entries are caused by Atlantic disturbances. They identify three precipitation patterns associated with different behavior of water vapour during the year. Winter and summer months tend to have characteristic water vapour patterns, while spring and autumn are without clear patterns.

Atmospheric water vapour is also one of the most variable and important parameters for Numerical Weather Prediction (NWP) and forecasting, but is under-sampled in current operational meteorological observing systems. Application of GNSS tropospheric products for NWP was the focus of EU projects WAVEFRONT, MAGIC, TOUGH and COST Action 716. The main achievements of those projects are: (1) set up of near-real time processing with data available with 90 min time lag (Elgered, 2005), (2) quality control of the GNSS tropospheric products, (3) set up of real time GNSS archive. Following their success, the application of GNSS for NWP is now a well-established technique in Europe. Since 2005, E-GVAP (EIG EUMETNET GNSS Water Vapour Programme, EGVAP project, 2014) is in charge of the collection and quality control of operational GNSS tropospheric products for NWP in Europe. More than 12 E-GVAP Analysis Centres (ACs) produce GNSS tropospheric products for over 1800 ground-based GNSS stations, with a target latency of 90 min, and make them available to National Meteorologic Services. The state-of-the-art is data assimilation of hourly-updated ZTD in NWP models. While the production, exploitation and evaluation of operational GNSS tropospheric products for NWP is well established in the northern and western Europe, it is still an emerging research field in eastern and south-eastern Europe.

AMTD
7, 2153–2185, 2014
SUADA
G. Guerova et al.

This manuscript is a first step towards application of ground-based GNSS tropospheric products in operational meteorological and climate observing systems in Bulgaria/Southeast Europe. As a platform for archiving data on an ongoing basis the Sofia University Atmospheric Data Archive (SUADA) was developed. Currently, SUADA includes GNSS tropospheric products and derivatives like IWV from 5 processing strategies and total of 37 stations for the period 1999–2013. IWV from the radiosonde station Sofia in Bulgaria is also archived in SUADA (About SUADA, 2014). The envisaged applications include: (1) cross-validation of ground-based and satellite observations and derivation of systematic biases; (2) validation of numerical models used for research and Numerical Weather Prediction (NWP); (3) study of water vapour distribution in Bulgaria/Southeast Europe; (4) detection of long term water vapour trends in Bulgaria/Southeast Europe and links to heat waves, droughts and changes in the pathway of the Atlantic Cyclones; (5) study how well state-of-the-art climate models, notably the one participating in Intergovernmental Panel on Climate Change (IPCC) AR5 assessment, simulate present climate of Bulgaria/Southeast Europe. SUADA was developed in close collaboration with the Institute of Applied Physics, University of Bern (IAP-UniBe). Since 2001, IAP-UniBe operates the STARTWAVE (STudies in Atmospheric Radiative Transfer and Water Vapour Effects) database. STARTWAVE database (Morland et al., 2006a) was funded in the frame of the NCCR Climate project 2001–2013 (NCCR, 2014). The STARTWAVE database was used for studies covering: (1) validation of two operational NWP models used in MeteoSwiss (Guerova et al., 2003), (2) comparison with the 40 year reanalysis data (ERA40) of the European Centre for Medium Range Weather Forecasting (Morland et al., 2006b) and (3) evaluation of the ECHAM5 climate model. STARTWAVE data was used for instrumental intercomparisons, the major result being detection of day-time bias in the radiosonde observations (Guerova et al., 2005) as well as instrumental problems at the high altitude station Jungfraujoch (Guerova et al., 2003). In Switzerland, a consistent positive IWV trend was found by Morland and Matzler (2007). Analysing IWV during the 2003 heat wave summer, Guerova and Morland (2008) report large positive IWV anomaly in June and large negative anomaly during the heat wave in August.

This paper is organized as follows: Sect. 2 presents the SUADA structure and data-sets; the GNSS Meteorology method is presented in Sect. 3; Sect. 4 presents two case studies of application of GNSS Meteorology for the short-term and long-term variation of the water vapour in Bulgaria. Conclusions are given in Sect. 5.

2 Sofia University Atmospheric Data Archive (SUADA)

2.1 SUADA structure

SUADA is developed using the Structured Query Language (SQL) for relational database management system (Codd, 1970). The SUADA tables are structured as peers with additional relations between them as shown in Fig. 1.

In Fig. 1 the SUADA tables are presented in groups. The first group of tables are "Information tables": INSTRUMENT, STATION, COORDINATE, STATION_ SOURCE and SOURCE (rows 1 and 2 on Fig. 1). The second group of tables are the "Primary tables": MODEL_IN, SYNOP, GNSS_IN and RADIOSONDE_IN (row 3 on Fig. 1). The third group of tables are the "Secondary tables": MODEL_OUT, GNSS_OUT and RADIOSONDE_OUT (row 4 on Fig. 1). The last group of tables are the "Information tables for the web portal": FIELD_DEFINITION, USERS and LOG (row 5 on Fig. 1). A short description of the SUADA tables is given in Table 1. The tables are also accessible from the SUADA web portal.

2.2 SUADA data-sets

2.2.1 GNSS data-sets

Currently SUADA has 5 GNSS data-sets processed with different software and strategies. As seen in Table 2 the GNSS data offer high temporal resolution from 5 min to 6 h

AMTD
7, 2153–2185, 2014
SUADA
G. Guerova et al.

and the IGS station in Sofia Bulgaria (SOFI, marked by red pointer in Fig. 2) is available since 2001. The GNSS data-sets are discussed bellow.

The first SUADA GNSS data-set is IGS-repro1. In 2008, the International GNSS Service (IGS) initiated global GNSS data reprocessing campaign (IGS-repro1, Rebischung et al., 2012; Byun and Bar-Sever, 2009). Nine IGS Analysis Centers contributed to reanalyzing the GPS data collected by the IGS global permanent network since 1994 in a fully consistent way using the latest models and methodology. The IGS-repro1 campaign started after adoption of a new set of antenna phase center calibrations for 65 out of 232 sites of the global IGS network. Archived in SUADA are IGS-repro1 tropospheric products for station SOFI for the period 2001–2007. The ZTD and gradients are processed with JPL GIPSY/OASIS software and are available every 5 min for the period 1997–2007. The estimation approach is as follows: (1) fixed orbits and clocks: IGS Final Re-Analyzed Combined (1995–2007), and IGS Final Combined 2008–Current, (2) earth orientation: IGS Final Re-Analyzed Combined (1995–2007), and IGS Final Combined (2008–Current), (3) transmit antenna phase center map: IGS Standards, (4) receiver antenna phase center map: IGS Standards, (5) elevation angle cutoff: 7°, (6) mapping function (hydrostatic and wet): GMF, (7) data arc: 24 h, (8) data rate: 5 min, (9) estimated parameters: station clock (white noise), station position, wet zenith and (10) delay (3 cm h^{-1} random walk), delay gradients (0.3 cm h^{-1} random walk), phase biases (white noise).

The second SUADA GNSS data-set is CODE-repro2. This is the Center for Orbit Determination in Europe (CODE), at the Astronomical Institute of the University of Bern (CODE Analysis Strategy Summary, 2014), contribution for the second IGS reprocessing campaign (Meindl et al., 2011) initiated in 2013. In SUADA are archived CODE-repro2 tropospheric products with 2 h resolution for SOFI for the period 2001–2010. GNSS data (GPS and Glonass) is processed with Bernese GNSS Software v. 5.3 using (1) ITRF2008 reference frame, (2) elevation cut-off angle 3°, (3) ECMWF-based hydrostatic delay mapped with hydrostatic VMF1 (Dach et al., 2009). In addition to SOFI station archived are also six European IGS stations: Zimmerwald (ZIMM), Switzerland;

Onsala (ONSA), Sweden; Ondrejov (GOPE), Czech Republic; Medicina (MEDI), Italy; Matera (MATE), Italy; Potsdam (POTS), Germany.

The third SUADA GNSS data-set is produced by European Reference Frame (EUREF). EUREF is an European network operating since 1995 with objective to provide a standard precise GNSS-based reference system for Europe. Since June 2001, tropospheric parameters are estimated, by EUREF Local Analysis Centres, on a weekly basis (post-processing mode EUREF-post) with 2 hourly sampling rate for more than 200 GNSS tracking stations of the permanent EUREF network (EUREF tropospheric delays, 2014). On the Balkan Peninsula there are 15 EUREF stations: 5 stations in Greece and Romania each and 1 station in Turkey, Croatia, Macedonia, Slovenia and Bulgaria, totaling 15 stations. The Bulgarian station SOFI is part of the EUREF permanent network since 1997. In SUADA are uploaded SOFI tropospheric products from 2001 to 2004 processed by the BKG (Bundesamt für Kartographie und Geodäsie) Analysis Center in Germany. BKG produces daily tropospheric solutions using fixed coordinates from weekly solution with Bernese software, 10° elevation cut-off angle and elevation dependent weighting. No a priori tropospheric model is used but the zenith total delay is estimated at 1 h intervals for each station and the mapping function is Dry Niell (BKG – EUREF Local Analysis Centre, 2014).

The forth SUADA GNSS data-set is provided by the private company ZenitGEO (Zenitgeo, 2014). Since 2009, the company operates a GNSS network with 30 GNSS stations, evenly distributed over Bulgaria (marked by yellow pointers in Fig. 2). ZenitGEO processes the GNSS data and provides tropospheric products with very high temporal resolution of 5 min (300 s). Currently, IWV is derived for 11 stations (marked by yellow pointers with dots in Fig. 2) namely: Vidin, Oryahovo, Lovech, Veliko Tarnovo, Ruse, Razgrad, Silistra, Shabla, Kyustendil, Pazardzhik and Sliven. It is to be noted that 8 of them are in North Bulgaria. The high temporal resolution of the GNSS product is degraded due to low temporal resolution of the meteorological data-set (see Sect. 2.2.3) therefore in the near future use of NWP model data will be considered (see Sect. 2.2.4). This will also allow to increase the spatial resolution for Bulgaria.

AMTD
7, 2153–2185, 2014
SUADA
G. Guerova et al.

The fifth SUADA GNSS data-set is a targeted processing performed by Keranka Vasilleva (Balkan) for the period 19–26 July 2007. 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 were processed with the Bernese software, version 5.0. Sixteen of them are IGS and EUREF stations. Seven sessions of 24 h have been created. For each session hourly station coordinates and ZTD are estimated. The troposphere model used is Saastamoinen dry model with Niell dry mapping and tilting gradient model. Corrections to the introduced zenith values are estimated and the ZTD and gradients are obtained. Tropospheric products for the stations in Southeast Europe: Sofia (SOFI), Dubrovnik (DUBR), Athens (NOA1), Thessaloniki (AUT1), Craiova (CRAI), Constanta (CONS), Bucharest (BUCU) and Varna (VARN) (marked with green pointers in Fig. 2) are uploaded in the SUADA.

2.2.2 Radiosonde data-set

Atmospheric sounding using a radiosonde is well established method approved by the World Meteorological Organization (WMO). Radiosonde is widely adopted for measurements of vertical profiles of temperature, pressure, humidity, wind speed and direction. In station Sofia, Bulgaria, routine daily sounding are preformed at 12:00 UTC. The station is operated by the Central Aerological Observatory at the National Institute of Meteorology and Hydrology (NIMH). Since 2005 VAISALA RS92KL probe has been used. 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 %.

The radiosonde is widely used for intercomparison with GNSS derived Integrated Water Vapour (IWV). For computing the IWV from the Radisonde profiles (RS-IWV) the following equation is used:

AMTD
7, 2153–2185, 2014

$$\mathrm{IWV} = \frac{1}{\rho_\mathrm{w}} \int_{h_0}^{h_\mathrm{top}} \rho_\mathrm{wv}(h)\mathrm{d}h \qquad (1)$$

where h_0 is the altitude of the station, where the probe is released, h_top is the maximum achieved height 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 (Guerova et al., 2003). Total of 6 376 Radiosonde IWV data for the period 1997–2012 is archived in SUADA.

The collection of the radiosonde data incurs substantial operational cost, which limits the temporal and spatial resolution of this observing system. Radiosonde data is a long-term observation, with time series of over 50 years, which is suitable for global climatic trend analysis, but requires careful quantification of possible systematic biases. Studies in Japan (Ohtani and Naito, 2000), Switzerland (Guerova et al., 2005), France (van Baelen et al., 2005) report bimodal distributions of the GPS and radiosonde residuals. Guerova et al. (2003) report an isolated case of IWV overestimation by the radiosonde related to the passage through low stratus clouds.

2.2.3 Surface observation data-set

Surface observations of: (1) pressure, (2) 2 m temperature, (3) 10 m wind speed and direction, (4) precipitation, (5) cloud cover and (6) current weather are archived in SUADA. The measurements are from the surface observation network (synop) of the National Institute of Meteorology and Hydrology (NIMH) in Bulgaria. The surface data is collected manually every 3 h at 00:00, 03:00, 06:00, 09:00, 12:00, 15:00, 18:00 and 21:00 UTC. The data is available from OGIMET weather information server (Ogimet Weather Information Service, 2014). In addtion, surface observations from 3 stations in Romania (Constanta, Crauiova and Bucuresti) with hourly update and measurements by automatic weather stations are saved. The surface data is used for derivation of IWV from the GNSS tropospheric products as described in Sect. 3. The frequency of

AMTD
7, 2153–2185, 2014

SUADA

G. Guerova et al.

the surface observations is a limiting factor in obtaining high temporal resolution of water vapour. Often the surface data is not collocated with the GNSS station and altitude corrections are applied, which reduce the quality of the product.

2.2.4 Numerical Weather Prediction (NWP) model data-set

As a part of the SUADA project the Weather Research and Forecasting (WRF) model version 3 (WRF, 2014) has been installed on Sofia University PhysOn cluster (PHYSON, 2014). Since February 2013, the model computes daily forecasts of temperature and precipitation for Bulgaria (WRF Weather Forecast, 2014) with horizontal resolution of 9.7 km. The initial and boundary conditions are from the Global Forecast System (GFS) model with horizontal resolution 0.5°.

WRF has been jointly developed by the National Center for Atmospheric Research (NCAR), the Forecast Systems Laboratory and the National Centers for Environmental Prediction of the National Oceanic and Atmospheric Administration (FSL, NCEP/NOAA) and the Center for Analysis and Prediction of Storms (CAPS) at the University of Oklahoma. The model can be run with a spatial resolution between 1 and 10 km. Numerous specific models, such as the Hurricane Weather Research and Forecasting (HWRF) have been created upon WRF. From the first release in 1990 until now the model has evolved (Michalakes et al., 1998) and additional packages have been developed for interactive nesting, upgraded physics, three dimensional data assimilation and simplified parallelization (Michalakes et al., 2004). WRF has large worldwide community with over 20 000 users in over 130 countries.

The near future use of WRF model will be to: (1) replace the synop observations for derivation of GNSS-IWV, (2) verify the model water vapour field with GNSS products and (3) assimilate the GNSS-IWV.

AMTD
7, 2153–2185, 2014

3 GNSS Meteorology

The concept of GNSS Meteorology was suggested by Bevis et al. (1992). The propagation of the GNSS signal through the atmosphere is affected by the atmospheric gases. The magnitude of the atmospheric effects depends on several factors: on the composition of the atmosphere; on the elevation of the receiver (thus on the thickness of the atmosphere); on the elevation angle of the satellite and finally on the amount of water vapour, which depends mainly on the current atmospheric conditions.

There are two contributing factors for the signal path delay in the lower atmosphere–troposphere they are the hydrostatic and the wet delay. The hydrostatic delay is caused by all the gases in the atmosphere, except the water vapour. The hydrostatic delay in direction zenith is called Zenith Hydrostatic Delay (ZHD) and as seen from Fig. 3a is relatively stable in a day timescale. It can be derived, using its dependency on the local atmospheric pressure (Bevis et al., 1992; Emardson et al., 1998):

$$\mathrm{ZHD} = (2.2768 \pm 0.0024)\frac{p_\mathrm{s}}{f(h,\theta)} \tag{2}$$

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

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 contributing factor is the Zenith Wet Delay (ZWD). It is caused by the water vapour in the atmosphere. The ZWD has a large temporal variation in an hour timescale. This is the reason, why the GNSS derived Integrated Water Vapour (IWV) is so valuable with its high temporal resolution (Fig. 3b). The ZWD contributes less then 10 % of the Zenith Total Delay (ZTD). ZWD and IWV can be calculated by using:

$$\mathrm{ZWD} = \mathrm{ZTD} - \mathrm{ZHD} \tag{4}$$

$$\mathrm{IWV} = \frac{10^6}{(k_3/T_\mathrm{m} + k_2)R_\mathrm{v}}\mathrm{ZWD} \tag{5}$$

AMTD
7, 2153–2185, 2014
SUADA
G. Guerova et al.

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

At present, surface pressure and temperature from the synop stations are used to derive the IWV from GNSS (see Sect. 2.2.3). For example, for 11 stations from the ZenitGEO network appropriate surface synop stations from NIMH network (Sect. 2.2.3) are allocated. It is to be noted, that the synop observations are with temporal resolution 3 h, while GNSS tropospheric products are with temporal resolution 5 min thus the derived ZHD, ZWD and IWV are degraded to 3 hourly. In addition, the altitude corrections for temperature and pressure are required for most of the synop stations. For the remaining 19 stations of the ZenitGEO network no appropriate surface stations are available. In near future use of surface pressure and temperature from the WRF model (Sect. 2.2.4) are envisaged.

It is to be noted that IWV decreases with the altitude with the bottom 5.5 km containing 97 % of total atmospheric water vapour content. Thus measuring an integrated quantity at different altitude in the lower atmosphere will depend on location and importantly on elevation above sea level. For representing IWV spatial distribution 2 dimensional maps are suggested by Morland and Matzler (2007). They propose an altitude correction for 500 m a.s.l.:

$$\mathrm{IWV}(0.5) = a \times \mathrm{IWV}(h) \times \exp\left[\frac{h - 0.5}{H}\right] \quad (6)$$

where: IWV(0.5) is IWV at altitude 500 m, IWV(h) is the estimated IWV at altitude h, a is empirically derived coefficients and H is scale height. This correction is applied to 11 stations from the ZenitGEO network at altitude between 36 and 542 m. The produced 2-D maps are used for convection case studies in Sect. 4.1.

4 Case studies

4.1 Short-term variation of IWV: intense precipitation events in 2012

In this work two events with intense precipitation in Bulgaria one associated with frontal passage and one with the development of local convection are presented. The first event is on 25 May 2012 when a cold front passes over Bulgaria. The period 22–29 May is characterized with low pressure field over the Mediterranean area. Prolonged precipitation and thunderstorm are result of the air mass instability or frontal passage. On 24–25 May, a trough can be seen at the 500 hPa map and a cyclonic field near the surface (Fig. 4). On 24 May a cold front, connected with a cyclonic center over the sea of Azov, passes over Bulgaria. On the next day 25 May 2012, another cold front passes Bulgaria from north to south. The intrusion of a cold air mass can be seen on Fig. 5 at 15:00 UTC over North Bulgaria. The water vapour values decrease with 10 mm to 25 mm (Fig. 4).

For the period 24–27 June the weather is dynamic, changeable with unstable air mass, cumulonimbus clouds development and precipitation with different range and intensity. On 26 June a cold front passes over Bulgaria and the temperature at 850 hPa drops from 18 °C at 00:00 UTC to around 10 °C at 06:00 UTC on 27 June 2012. There is a considerable temperature gradient both at altitude and surface and the maximum temperature decreased by 5–6 °C. At 12:00 UTC on 26 June dry air mass was advected from north-west spreading along the Balkan mountain range (Fig. 6). This pathway of cold and dry air is usually associated with intense precipitation of both rain and snow in the spring and autumn seasons. The consecutive two dimensional IWV maps from 26 and 27 June capture well the advancement of the dry air mass. In less than 24 h the IWV in the north Bulgaria decreased by half from above 35 mm at 06:00 UTC on 26 June to 15–20 mm at 03:00 UTC on 27 June. After the cold front passage on 26 June the air mass remains unstable with high relative humidity at level 700 hPa and warming at high altitudes (200 hPa) contributing for the convection development. On 27 June the advected dry air catches the receding humid air mass resulting to isolated

AMTD
7, 2153–2185, 2014
SUADA
G. Guerova et al.

convective cells development with thunderstorms and intense precipitation. Intense rainfall of 74 $L m^{-2}$ for six hours is recorded between 09:00 and 15:00 UTC on 27 June at the Black sea region Kaliakra. The strong north–south gradient of IWV over the Balkan peninsula is confirmed by the Meteosat derived maps (Schroedter-Homscheidt et al., 2008). From the Meteosat maps an isolated convective cell is clearly seen at 15:00 UTC in the infrared cloud cover image. The presented in this paper case studies demonstrate the synergy between GNSS and Meteosat water vapour maps. Future work will be detailed analysis of further 20 convective situations for 2012. This work is 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)".

4.2 Long-term variation of IWV: 2007 heat wave

Heat waves have become a common summer feature in the Southeast Europe (Matzarakis et al., 2007). The July 2007 heat wave has the largest geographical extension reaching Bulgaria. 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 Southeast Europe as far as 50° N. The GNSS-IWV from the IGS repro2 and RS-IWV are used to study the 2007 heat wave. The annual and seasonal mean GNSS-IWV for the period 2001–2010 is compared to the 2007 and is presented in Table 3.

As seen in Table 3, the annual GNSS-IWV in 2007 is 14.0 mm and is similar to the 2001–2010 mean. The seasonal values show that in 2007 the GNSS-IWV is larger in winter (+5 %) and smaller for summer and autumn (–5 and –6 % correspondingly). For comparison the IWV from radiosonde (RS-IWV) station in Sofia is also presented in Table 3. The RS-IWV annual, winter, summer and autumn seasonal mean in 2007 have the same tendency as GNSS-IWV. It is to be noted, that there is a difference between the sampling rate of GNSS and RS the first being each 3 h, while the second is once a day at 12:00 UTC. In addition, the radiosonde station is in Sofia (marked with

AMTD
7, 2153–2185, 2014

red pointer in Fig. 2) and at altitude of 590 m while the GNSS station is in the Plana mountain (marked with blue pointer in Fig. 2) and at altitude 1120 m.

In addition, the monthly IWV anomalies are studied. In Fig. 7 are plotted GNSS-IWV and RS-IWV anomalies. When GNSS-IWV in 2007 (solid line in Fig. 7a) is compared to 2001–2010 (dashed line in Fig. 7a), the following features stand out: (i) IWV decrease in April, (ii) IWV increase in May and (iii) a sharp IWV decrease in July. Clearly seen from Fig. 7b is that the largest negative IWV anomaly is in July about −4 mm from GNSS-IWV and −5 mm from RS-IWV. There is very good correlation of the anomaly from the two techniques despite the different sampling rate and location. The difference between the GNSS-IWV and RS-IWV anomaly is under 0.5 mm in 7 months, between 0.5 and 1 mm in 2 months and about 1 mm in 3 months.

The 2007 winter was 2.4 °C warmer than the 2001–2010 (column 5 in Table 4). The 2007 spring and summer were with 1 and 1.4 °C warmer. In particular, July 2007 was +3.7 °C warmer (Fig. 8) and with less IWV than the 2001–2010 with −16 % and −19 % correspondingly for the GNSS-IWV and RS-IWV. It is to be noted that the annual precipitation amount in 2007 was 25 % higher than the 2001–2010. However the winter was 15 % drier (column 5 in Table 4) and from spring only the month of May has positive precipitation anomaly over 80 mm as seen in Fig. 8. In the summer 2007 the month of July was very dry (about 60 mm less that the 2001–2010 mean).

5 Conclusions

The Sofia University Atmospheric Data Archive (SUADA) is a regional database for Bulgaria and Southeast Europe. GNSS tropospheric products (over 12 000 000 individual observations) and derivatives (over 55 000) from five GNSS processing strategies and 37 stations for the period 1997–2013 are archived in SUADA. The temporal resolution of GNSS data is from 5 min to 6 h. In addition, over 6 000 individual IWV from the radiosonde station in Sofia for the period 1999–2012 are archived in SUADA.

AMTD
7, 2153–2185, 2014

The application of SUADA data is shown in case studies for intense precipitation events in 2012 and during the heat wave in 2007. At 12:00 UTC on 26 June dry air mass was advected from north-west spreading along the Balkan mountain range. Near the Black sea coast the advected dry air catches the receding humid air mass resulting to development of local convection and intense rainfall with 74 $\mathrm{L\,m^{-2}}$. The two dimensional IWV maps capture well the advancement of the dry air mass. In less than 24 h the IWV in the north Bulgaria decreased by half from above 35 mm at 06:00 UTC on 26 June to 15–20 mm at 03:00 UTC on 27 June. The strong north–south gradient of IWV over the Balkan peninsula is confirmed by the Meteosat derived product. The second application of the SUADA data is study of IWV anomaly during the 2007 heat wave in Bulgaria. Despite the difference in the location and sampling rate the two data-set give a negative IWV anomaly in July 2007 about −4 mm from GNSS-IWV and −5 mm from RS-IWV. The July 2007 has less IWV compared to 2001–2010 with −16 % and −19 % correspondingly for the GNSS-IWV and RS-IWV.

This work is first step in application of GNSS tropospheric products for atmospheric sounding in Bulgaria and Southeast Europe. The work will continue with: (1) improvement of the temporal and spatial resolution of the GNSS-IWV notably the ZenitGEO, (2) validation of the NWP model WRF with GNSS data-set for Bulgaria, (3) analysis of additional convective cases in 2012 and (4) analysing diurnal cycle of GNSS-IWV during 18 fog events at Sofia Airport in the period 2011–2012. The work is a contribution to working group two and three of the COST Action ES1206 "Advanced Global Navigation Satellite Systems tropospheric products for monitoring severe weather events and climate (GNSS4SWEC)" 2013–2017.

Acknowledgements. This research is supported by a Marie Curie International Reintegration Grant (FP7-PEOPLE-2010-RG) within the 7th European Community Framework Programme. Sh. Byram from (Earth Orientation Department, United States Naval Observatory, Washington DC) provided GNSS-IGS-repro1 products. Ch. Georgiev and A. Stoycheva from the National Institute of Meteorology and Hydrology provided the Meteosat IWV plots and the detailed analysis of the weather conditions. The tropospheric products are result of collaboration with the ZenitGEO team and Keranka Vassileva.

References

About SUADA: available at: http://suada.phys.uni-sofia.bg/?pageid=185 (last access: 31 January 2014), 2014. 2157

Bevis, M., Businger, S., Herring, T., Rocken, C., Anthes, R., and Ware, R.: GPS meteorology: remote sensing of atmospheric water vapor using the Global Positioning System, J. Geophys. Res., 97, 15787–15801, 1992. 2164

BKG – EUREF Local Analysis Centre: available at: http://www.epncb.oma.be/ftp/center/analysis/BKG.LAC (last access: 31 January 2014), 2014. 2160

Byun, S. and Bar-Sever, Y.: A new type of troposphere zenith path delay product of the international GNSS service, J. Geodesy, 83, 367–373, doi:10.1007/s00190-008-0288-8, 2009. 2159

Codd, E.: A relational model of data for large shared data banks, Commun. ACM, 13, 377–387, doi:10.1145/362384.362685, 1970. 2158

CODE Analysis Strategy Summary: available at: http://igscb.jpl.nasa.gov/igscb/center/analysis/code.acn (last access: 31 January 2014), 2014. 2159

Dach, R., Brockmann, E., Schaer, S., Beutler, G., Meindl, M., Prange, L., Bock, H., Jaeggi, A., and Ostini, L.: GNSS processing at CODE: status report, J. Geodesy, 83, 353–366, 2009. 2159

de Haan, S.: Meteorological applications of a surface network of Global Positioning System receivers, Ph. D. thesis, Wageningen University, 2008. 2155

Dessler, A. E. and Sherwood, S. C.: A matter of humidity, Science, 323, 1020–1021, 2009. 2154

EGVAP project: available at: http://egvap.dmi.dk/ (last access: 31 January 2014), 2014. 2156

Elgered, G., Plag, P., van der Marel, H., Barlag, S., and Nash, J. (Eds.): COST 716: Exploitation of ground-based GPS for operational numerical weather prediction and climate applications, European Commission, Brussels, 2005. 2156

Emardson, T., Elgered, G., and Johanson, J.: Three months of continuous monitoring of atmospheric water vapor with a network of Global Positioning System receivers, J. Geophys. Res., 103, 1807–1820, 1998. 2164

EUREF tropospheric delays: available at: http://www.epncb.oma.be/productsservices/sitezenithpathdelays/ (last access: 31 January 2014), 2014. 2160

AMTD

7, 2153–2185, 2014

SUADA

G. Guerova et al.

Gaffen, D., Elliott, W., and Robock, A.: Relationship between tropospheric water vapor and surface temperatures as observed by radiosondes, Geophys. Res. Lett., 19, 1839–1842, doi:10.1029/92GL02001, 1992. 2155

Gradinarsky, L., Johansson, J., Bouma, H., Scherneck, H.-G., and Elgered, G.: Climate monitoring using GPS, Phys. Chem. Earth, 27, 335–340, 2002. 2155

Graham, E., Koffi, E., and Matzler, C.: An observational study of air and water vapour convergence over the Bernese Alps, Switzerland, during summertime and the development of isolated thunderstorms, Meteorol. Z., 21, 561–574, 2012. 2155

Guerova, G. and Morland, J.: Water vapour anomaly during the 2003 summer in Switzerland, in: AGU Chapman Conference, p. 1, Hawaii, USA, 20–24 October 2008. 2158

Guerova, G., Brockmann, E., Quiby, J., Schubiger, F., and Matzler, C.: Validation of NWP mesoscale models with Swiss GPS Network AGNES, J. Appl. Meteorol., 42, 141–150, 2003. 2157, 2162

Guerova, G., Brockmann, E., Schubiger, F., Morland, J., and Matzler, C.: An integrated assessment of measured and modeled IWV in Switzerland for the period 2001–2003, J. Appl. Meteorol., 44, 1033–1044, 2005. 2157, 2162

Matzarakis, A., de Freitas, C., and Scott, D.: Developments in tourism climatology, in: Commission Climate, Tourism and Recreation, International Society of Biometeorology, 2007. 2167

Meindl, M., Dach, R., and Jean, Y.: International GNSS Service Technical Report, Tech. rep., IGS Central Bureau, 2011. 2159

Michalakes, J., Dudhia, J., Gill, D., Klemp, J., and Skamarock, W.: Design of a Next-Generation Regional Weather Research and Forecast Model, World Scientific, River Edge, New Jersey, 117–124, 1998. 2163

Michalakes, J., Dudhia, J., Gill, D., Henderson, T., Klemp, J., Skamarock, W., and Wang, W.: The Weather Reseach and Forecast Model: software architecture and performance, in: Proceedings of the 11th ECMWF Workshop on the Use of High Performance Computing In Meteorology, edited by: Mozdzynski, G., 25–29 October 2004, Reading UK, 2004. 2163

Morland, J. and Matzler, C.: Spatial interpolation of GPS integrated water vapour measurements made in the Swiss Alps, Meteorol. Appl., 14, 15–26, 2007. 2157, 2165

Morland, J., Deuber, B., Feist, D. G., Martin, L., Nyeki, S., Kämpfer, N., Mätzler, C., Jeannet, P., and Vuilleumier, L.: The STARTWAVE atmospheric water database, Atmos. Chem. Phys., 6, 2039–2056, doi:10.5194/acp-6-2039-2006, 2006a. 2157

Morland, J., Liniger, M. A., Kunz, H., Balin, I., Nyeki, S., Matzler, C., and Kampfer, N.: Comparison of GPS and ERA40 IWV in the Alpine region, including correction of GPS observations at Jungfraujoch (3584 m), J. Geophzs. Res., 111, D04102, doi:10.1029/2005JD00603, 2006b. 2157

NCCR Climate: available at: http://www.nccr-climate.unibe.ch/ (last access: 31 January 2014), 2014. 2157

Nilsson, T. and Elgered, G.: Long-term trends in the atmospheric water vapor content estimated from ground-based GPS data, J. Geophys. Res., 113, D19101, doi:10.1029/2008JD010110, 2008. 2155

Ning, T.: GPS Meteorology: With Focus on Climate Applications, Ph. D. thesis, Chalmers University of Technology, 2012. 2155

Ogimet Weather Information Service: available at: http://www.ogimet.com (last access: 31 January 2014), 2014. 2162

Ohtani, R. and Naito, I.: Comparisons of GPS-derived precipitable water vapors with radiosonde observations in Japan, J. Geophys. Res., 105, 26917–26929, doi:10.1029/2000JD900362, 2000. 2162

PHYSON: available at: http://physon.phys.uni-sofia.bg (last access: 31 January 2014), 2014. 2163

Rebischung, P., J.Griffiths, Ray, J., Schmid, R., Collilieux, X., and Garayt, B.: IGS08: the IGS realization of ITRF2008, GPS Solut., 16, 483–494, 2012. 2159

Ross, R. and Elliott, W.: Tropospheric water vapor climatology and trends over north America: 1973–93, J. Climate, 9, 3561–3574, doi:10.1175/1520-0442(1996)009<3561:TWVCAT>2.0.CO;2, 1996. 2155

Ross, R. and Elliott, W.: Radiosonde based Northern Hemisphere tropospheric water vapor trends, J. Climate, 14, 1602–1612, doi:10.1175/1520-0442(2001)014<1602:RBNHTW>2.0.CO;2, 2001. 2155

Schroedter-Homscheidt, M., Drews, A., and Heise, S.: Total water vapor column retrieval from MSG-SEVIRI split window measurements exploiting the daily cycle of land surface temperatures, Remote Sens. Environ., 112, 249–258, doi:10.1016/j.rse.2007.05.006, 2008. 2167

Seco, A., Ramirez, F., Serna, E., Prieto, E., Garcia, R., Moreno, A., Cantera, J., Miqueleiz, L., and Priego, J.: Rain pattern analysis and forecast model based on GPS estimated atmospheric water vapor content, Atmos. Environ., 49, 85–93, 2012. 2156

AMTD
7, 2153–2185, 2014

Weather Research and Forecasting Model (WRF): available at: http://wrf-model.org/index.php (last access: 31 January 2014), 2014. 2163
WRF Weather Forecast: available at: http://suada.phys.uni-sofia.bg/?pageid=2132 (last access: 31 January 2014), 2014. 2163
van Baelen, J., Aubagnac, J.-P., and Dabas, A.: Comparison of near-real time estimates of integrated water vapor derived with GPS, radiosondes, and microwave radiometer, J. Atmos. Ocean. Tech., 22, 201–210, 2005. 2162
van Baelen, J., Reverdy, M., Tridon, F., Labbouz, L., Dick, G., Bender, M., and Hagen, M.: On the relationship between water vapour field evolution and the life cycle of precipitation systems, Q. J. Roy. Meteorol. Soc., 137, 204–223, doi:10.1002/qj.785, 2011. 2155
Zenitgeo: available at: http://www.zenitgeo.com/homeen.html (last access: 31 January 2014), 2014. 2160

AMTD
7, 2153–2185, 2014

SUADA

G. Guerova et al.

Table 1. SUADA table names and short description.

Table name	Short summary
INSTRUMENT	Instrument name and identification number
STATION	Station name
COORDINATE	Coordinates of the GNSS, synop and radiosonde stations
STATION_SOURCE	Station source information (either instrument or method)
SOURCE	Contact information of SUADA data providers (name, institution, telephones, etc.)
MODEL_IN	Numerical Weather Prediction (NWP) model data
SYNOP	Surface observations from the network of the National Institute of Meteorology and Hydrology
GNSS_IN	Tropospheric products from ground-based GNSS networks or individual station
RADIOSONDE_IN	Data from the radiosonde network or individual station
MODEL_OUT	Processed NWP model data (IWV or other)
GNSS_OUT	Processed GNSS data (IWV, ZHD or other)
RADIOSONDE_OUT	Processed radiosonde data (IWV)
FIELD_DEFINITION	List of abbreviations used in the SUADA tables
USERS	Contact information about SUADA data users (external and internal)
LOG	User log in history

AMTD
7, 2153–2185, 2014

Table 2. GNSS data-sets as of 1 October 2013.

data-set name	tropos. product	available	number of stations	observation frequency	number of observations
IGS-repro1	ZTD	Jul 1997–Dec 2007	1	5 min	823 919
IGS-repro1	ZHD	Jan 2001–Dec 2007	1	3 h	16 619
IGS-repro1	ZWD	Jan 2001–Dec 2007	1	3 h	16 619
IGS-repro1	IWV	Jan 2001–Dec 2007	1	3 h	16 619
CODE-repro2	ZTD	Jan 2001–Dec 2010	7	2 h	411 306
CODE-repro2	ZHD	Jan 2001–Dec 2010	7	6 h	74 943
CODE-repro2	ZWD	Jan 2001–Dec 2010	7	6 h	74 943
CODE-repro2	IWV	Jan 2001–Dec 2010	7	6 h	74 943
EUREF-post	ZTD	Apr 2001–Nov 2004	1	1 h	23 880
EUREF-post	ZHD	Apr 2001–Nov 2004	1	3 h	6539
EUREF-post	ZWD	Apr 2001–Nov 2004	1	3 h	6539
EUREF-post	IWV	Apr 2001–Nov 2004	1	3 h	6539
ZenitGEO	ZTD	Nov 2011–May 2013	30	5 min	11 473 034
ZenitGEO	ZHD	Nov 2011–May 2013	11	3 h	23 233
ZenitGEO	ZWD	Nov 2011–May 2013	11	3 h	23 233
ZenitGEO	IWV	Nov 2011–May 2013	11	3 h	23 233
Balkan	ZTD	19–25 Jul 2007	8	1 h	1160
Balkan	ZHD	19–25 Jul 2007	8	3 h	763
Balkan	ZWD	19–25 Jul 2007	8	3 h	763
Balkan	IWV	19–25 Jul 2007	8	3 h	763

AMTD
7, 2153–2185, 2014

Table 3. Column 1–3 are station name, annual mean for 2001–2010 and 2007 accordingly; column 4–5: winter DJF (December, January and February) mean for 2001–2010 and 2007; column 6–7: spring MAM (March, April and May) mean for 2001–2010 and 2007; column 8–9: summer JJA (June, July and August) mean for 2001–2010 and 2007; column 10–11: autumn SON (September, October and November) mean for 2001–2010 and 2007. The 2007 departure from 2001–2010 mean is given in % in the brackets.

Station	2001–2010	2007	2001–2010	2007	2001–2010	2007	2001–2010	2007	2001–2010	2007
IWV-IGS repro2	mm	mm	DJF	DJF	MAM	MAM	JJA	JJA	SON	SON
SOFI	14.3	14.0	8.0	8.4	12.7	12.7	21.8	20.6	14.8	14.0
Change		−2 %		+5 %		0 %		−5 %		−6 %
IWV-RS	mm	mm	DJF	DJF	MAM	MAM	JJA	JJA	SON	SON
Sofia	15.5	15.1	8.8	9.1	13.6	13.2	23.9	22.5	16.0	15.5
Change		−3 %		+3 %		−3 %		−6 %		−3 %

AMTD
7, 2153–2185, 2014

Table 4. Annual and seasonal mean of IWV, temperature and precipitation for station Sofia, Bulgaria for winter (DJF), spring (MAM), summer (JJA) and autumn (SON) for 2001–2010 and 2007.

Met station	2001–2010	2007	2001–2010	2007	2001–2010	2007	2001–2010	2007	2001–2010	2007
Temperature	[°C]	[°C]	DJF	DJF	MAM	MAM	JJA	JJA	SON	SON
Sofia	8.4	8.8	0.2	2.6	10.7	11.7	20.4	21.8	11.3	9.5
Change		+5 %		+1200 %		+ 9 %		+7 %		−16 %
Precipitation	mm month^{-1}	mm month^{-1}	DJF	DJF	MAM	MAM	JJA	JJA	SON	SON
Sofia	55	69	40	34	55	66	73	86	50	91
Change		+25 %		−15 %		+20 %		+17 %		+82 %

AMTD
7, 2153–2185, 2014

SUADA

G. Guerova et al.

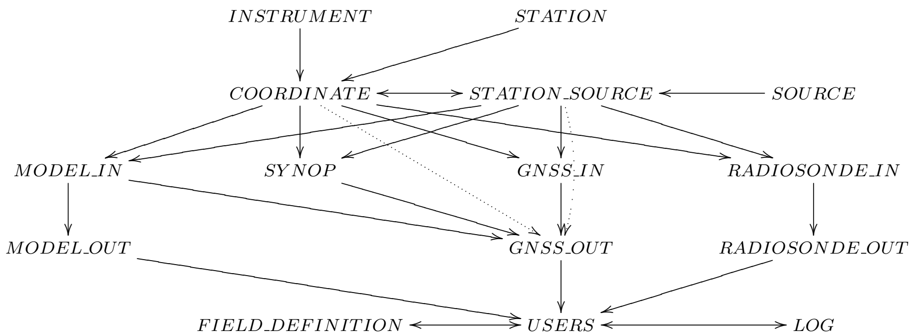


Fig. 1. SUADA data structure and data flow.

AMTD
7, 2153–2185, 2014

SUADA

G. Guerova et al.

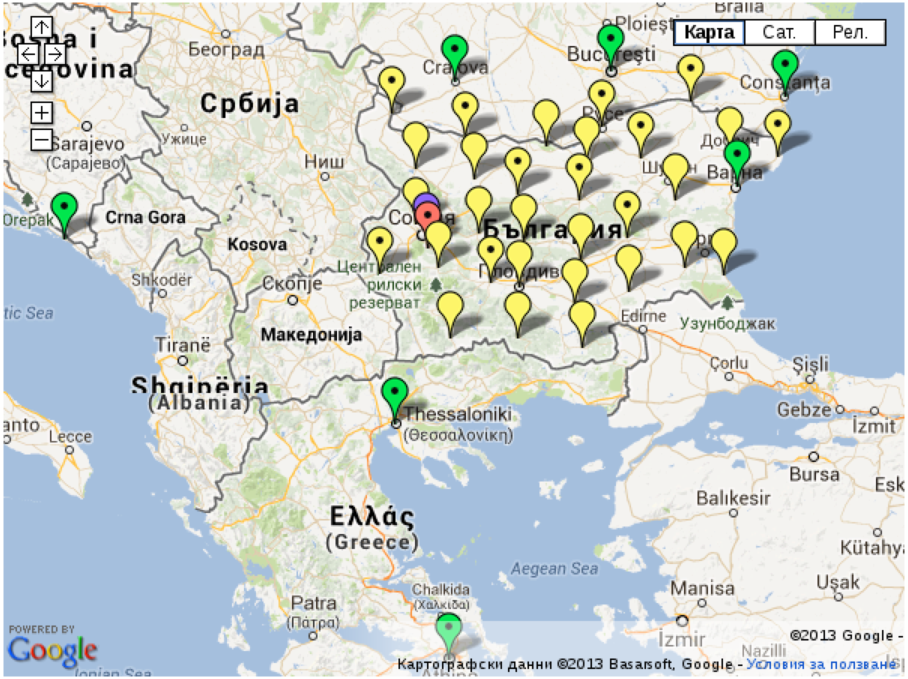


Fig. 2. SUADA GNSS stations in Bulgaria/Southeast Europe.

AMTD
7, 2153–2185, 2014

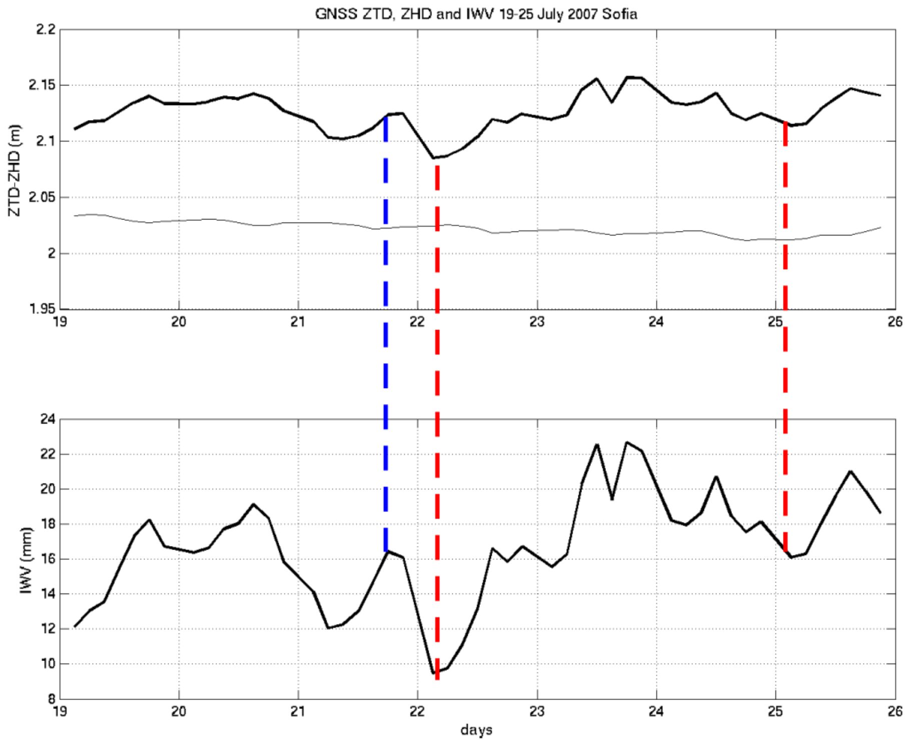


Fig. 3. GNSS Meteorology: ZTD, ZHD and IWV at station SOFI during the 2007 heat wave 19–25 July. **(a)** Zenith Total Delay (ZTD), Zenith Hydrostatic Delay (ZHD) in m, **(b)** Integrated Water Vapour (IWV) in mm. The diurnal cycle of IWV with increase in the afternoon hours and minimum in early morning is well seen.

AMTD
7, 2153–2185, 2014

SUADA

G. Guerova et al.

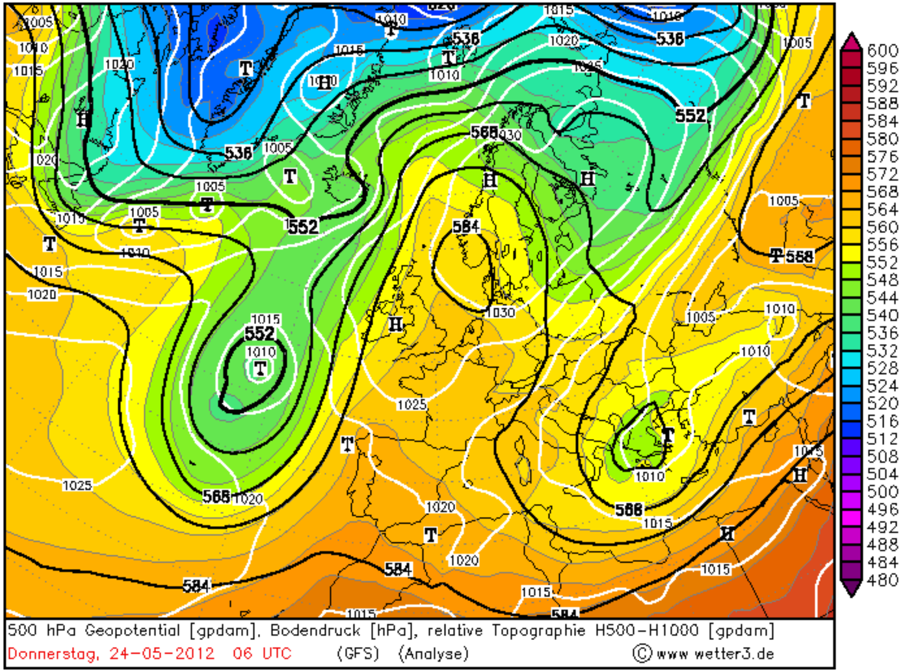


Fig. 4. Geopotential height at 500 hPa (black lines), surface pressure (white lines) and thickness (color map) at 06:00 UTC on 24 May 2012 from the GFS Analysis.

AMTD
7, 2153–2185, 2014

G. Guerova et al.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀I ▶I
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

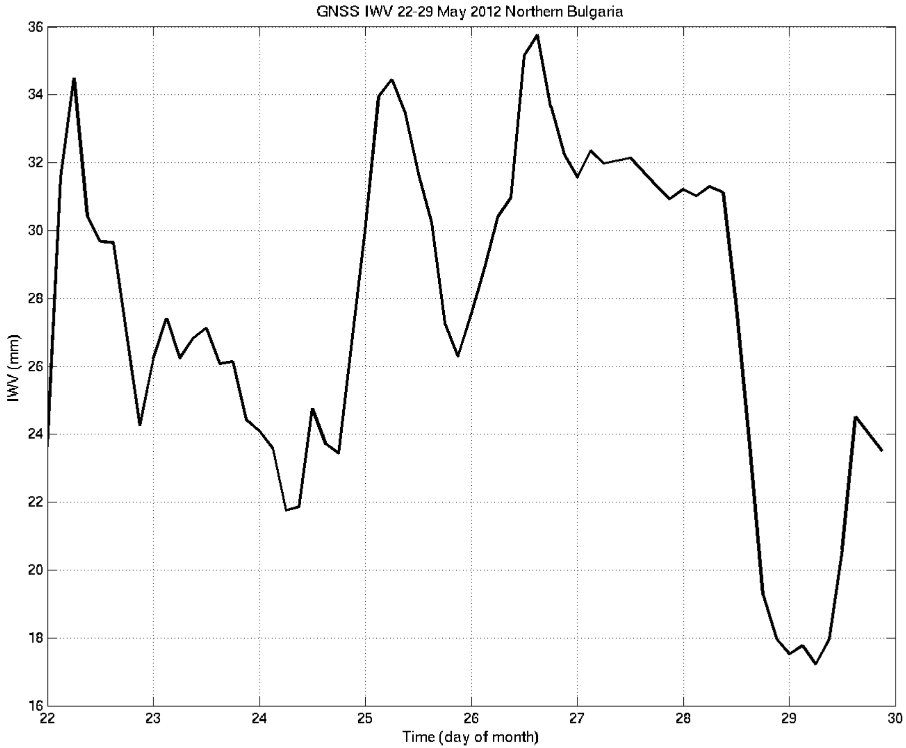


Fig. 5. GNSS-IWV for 22–29 May 2012 at Lovech Bulgaria.

AMTD
7, 2153–2185, 2014

SUADA

G. Guerova et al.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀I ▶I
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

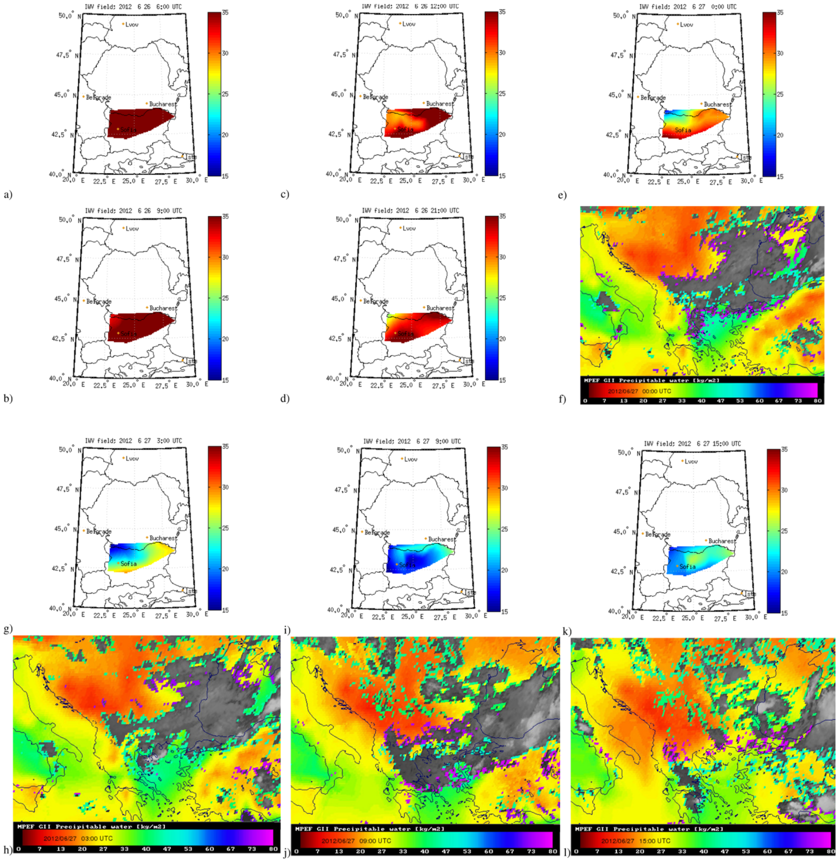
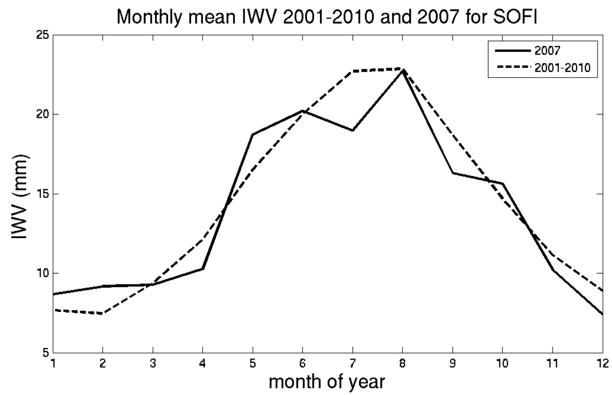


Fig. 6. 2-D IWV maps from GNSS on: 26 June 2012 at **(a)** 06:00 UTC, **(b)** 09:00 UTC, **(c)** 12:00 UTC and **(d)** 21:00 UTC. 2-D maps on 27 June 2012 at: 00:00 UTC **(e)** GNSS and **(f)** Meteosat, 06:00 UTC **(g)** GNSS and **(h)** Meteosat, 09:00 UTC **(i)** GNSS and **(j)** Meteosat and 15:00 UTC **(k)** GNSS and **(l)** Meteosat. The color maps of the Meteosat and GNSS-IWV are reversed.



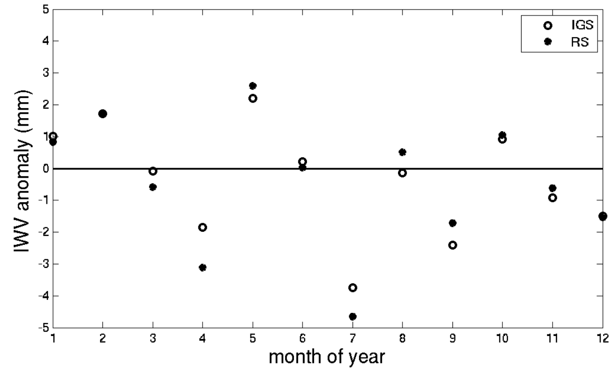


Fig. 7. Top figure: monthly mean IWV for SOFI, Bulgaria (thick line 2007, dashed line 2001–2010). Bottom figure: monthly anomaly (diffrence 2007 mean and 2001–2010 mean) from GNSS (open circles) and RadioSounde (filled circles).

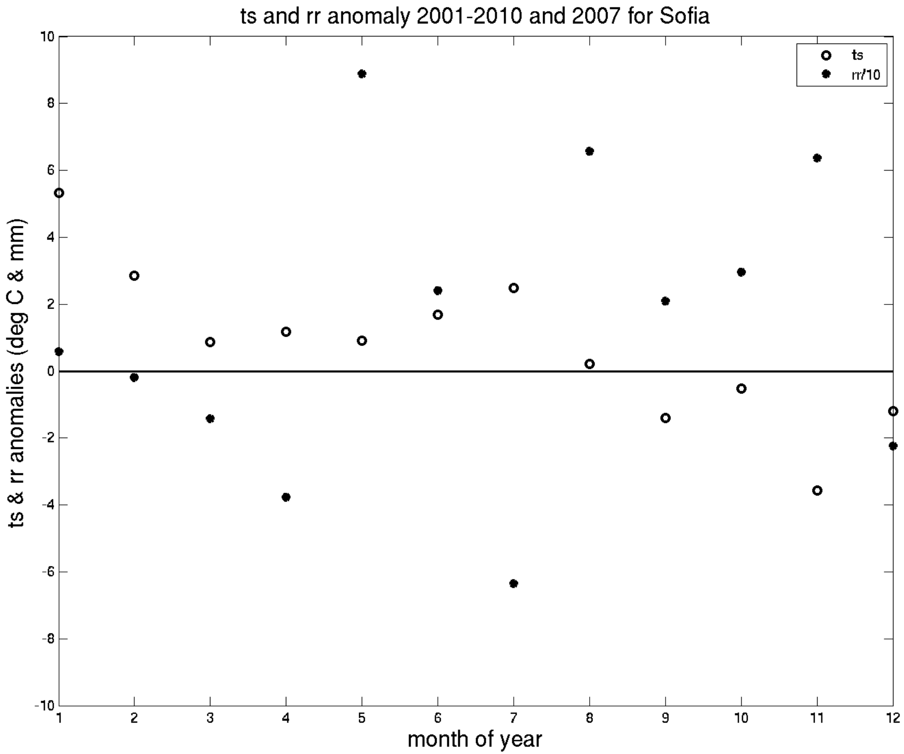


Fig. 8. Monthly anomaly of temperature (open circles) and precipitation (filled circles) for Sofia, Bulgaria.

AMTD
7, 2153–2185, 2014