GNSS AND HEAT WAVES: CASE STUDIES FOR 2003 AND 2007

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ABSTRACT

Both climate models and observations indicate that globally the column-integrated atmospheric water vapour increases by about 7 % per 1°C increase of temperature. Over Europe however, no evident positive water vapour trend was found in the radiosonde record since 1988 despite the large positive trends over the North Atlantic.

The temperature/water vapour feedback is tested for the 2003 heat wave in Switzerland and the 2007 heat wave in Bulgaria. In August 2003, the column-integrated water vapour, derived from GNSS station Payerne Switzerland, increased by 7 % while the temperature was on averaged 5°C higher than the 2001-2006 mean. This weak response of water vapour on temperature forcing was found to be due to the significant precipitation deficit in the 2003 spring i.e. more than 50 % below the 2002-2006 mean. An increase of evapotranspiration observed in June 2003 facilitated soil moisture depletion and then the heating went in raising temperature hence the occurrence of heat wave in August 2003. The temperature/water vapour feedback is further tested for the 2007 heat wave in Bulgaria when the temperature was on average 1.6°C higher than 1961-90 mean. During the July heat wave in Southeast Europe, water vapour decreased by 18 %, while temperature was 3°C above the 2001-2006 mean.

Key words: GNSS, GNSS meteorology, heat waves.

1. INTRODUCTION

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 (Bono et al. 2004). They cause increased power consumption and power cuts, transport restrictions and a decreased agricultural production. The estimated economic losses exceed 13 billion euros during the 2003 heat wave in Western Europe and 2 billion euro during the 2007 heat wave in Southeast Europe. 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 (Matzarakis et al. 2007).

According to Schaer & Jendritzky (2004), the 2003 mean summer temperature in Switzerland was on average 3°C higher than the 1961 - 90 mean, corresponding to an excess of up to 5 standard deviations. The unusually high temperatures were associated with persistent anticyclonic blocking allowing African air mass to reach as far as UK as seen on figure 1a on August 10 2003. Beniston & Diaz (2004) suggest that this prolonged heat wave may be a manifestation of an exceptional northward extension of the Hadley Cell. In many regions of Europe the annual rainfall deficit was 50 % below the average (Ciais et al. 2005). The 2003 heat wave represents a valuable benchmark case, because regional climate model simulations (Schaer & Jendritzky 2004) suggest that by 2100 every second summer could be as warm or warmer and as dry or dryer.

Heat waves have become a common summer feature in the Southeast Europe (Matzarakis et al. 2007). During the 2007 summer, three heat waves are reported in the second half of June, July and August (Matzarakis et al. 2007). This works covers the heat wave in July 2007, which 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. On figure 1b is clearly seen a hot air tongue spreading over the Mediterranean sea and the Southeast Europe at 00 UTC on 23 July 2007.

The aim of this study is to investigate the behavior of atmospheric water vapour during the heat waves in August 2003 and July 2007. Monitoring water vapour during the heat waves is critical as the combination of high temperature and water vapour is lethal (Matzarakis et al. 2007).

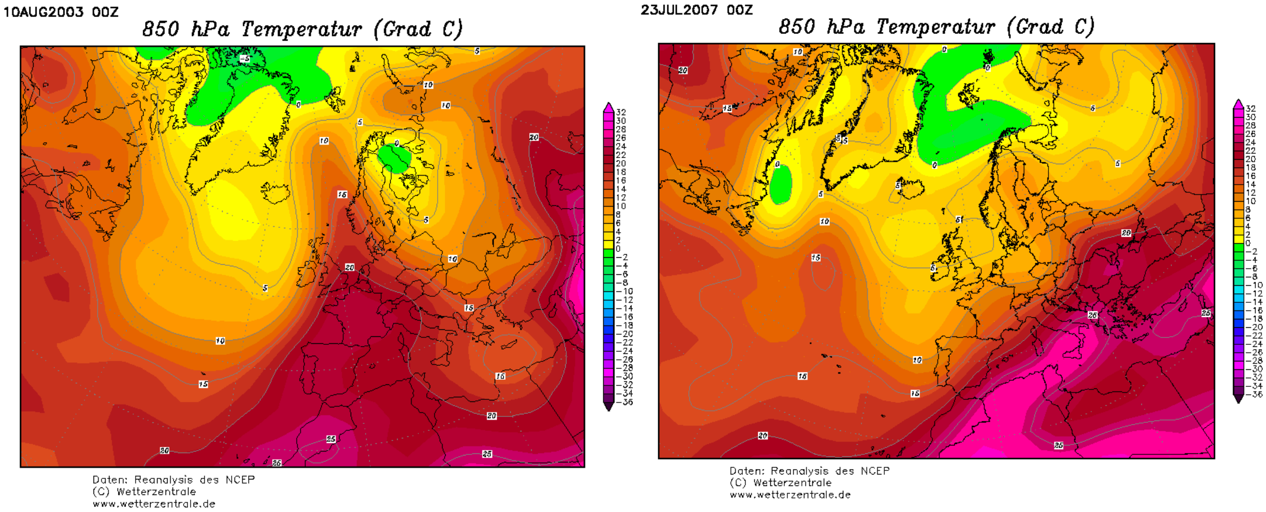

Figure 1. Temperature at 850 hPa (1.5 km asl.) on: a) 10 August 2003 00 UTC and b) 23 July 2007 00 UTC.

2. DATA-SETS

2.1. Global Navigation Satellite Systems data

Hourly Integrated Water Vapor (IWV) is calculated for the Global Navigation Satellite Systems (GNSS) station Payerne (PAYE) of the Swiss ground-based GNSS network (Brockmann et al. 2002), operated by the Swiss Federal Office of Topography. The IWV is derived following Bevis et al. (1992) and Emardson et al. (1998) and is available through the STudies in Atmospheric Radiative Transfer and Water vapour Effects (STARTWAVE) database (Morland et al. 2006).

In Bulgaria, there is one permanent European Reference Frame (EUREF) and International GNSS Service (IGS) station SOFI operating since 1997. The station is near the capital city of Sofia at elevation 1 120 m asl. In this work, we use the data from the reprocessed IGS tropospheric product (Byun & Bar-Sever 2009). The Zenith Total Delay and delay gradients are available every 5 min for the period 1997-2007. Due to lack of meteorological data with high temporal resolution the IWV is computed every 3 hours.

2.2. Meteo data

The automatic surface monitoring network of MeteoSwiss (ANETZ) covers all regions and altitudes of Switzerland. All instrument measurements are recorded automatically at 10 minute intervals. We use temperature and rainfall observations from station Payerne collocated with the PAYE GNSS station.

At station Sofia, of the surface monitoring network of the National Institute of Meteorology and Hydrology in Bulgaria, temperature and pressure are recorded on 3-hour interval and rainfall on 12-hour interval. The station is at elevation 590 m asl. For IWV computation the temperature and pressure are interpolated to the GNSS antenna height.

3. WATER VAPOUR ANOMALY

3.1. August 2003 heat wave

Figure 2a presents the monthly mean IWV from GNSS station Payerne for the period 2001-2006. When contrasted to 2001-2006 observations (dashed line), the following features stand out in 2003 (solid line): i.) IWV decrease in February, ii.) IWV increase in June and iii.) IWV close to the average in July and August. The 2001-2006 mean IWV (column 2 in table 1) is 16.2 mm versus 15.6 mm in 2003, which is an annual decrease of -4 %. The seasonal mean IWV for December to February (DJF), March to May (MAM) and June to August (JJA) are given in columns 4 to 9 of table 1. During the 2003 winter, the IWV from GNSS measures a small increase of 0.1 mm (+2 %). The 2001-2006 mean winter was -0.5°C colder that 2003. The 2003 spring IWV was +3 % higher than the 2001-2006 mean. During the 2003 summer, the IWV increased by 1.7 mm or by about +7 %, while the temperature increased by 3.5°C.

The rainfall observations at Payerne (last line in table 1) show that the 2003 summer is 27 % drier than the 2001-2006 mean (column 9 in table 1). Further intercomparison in spring (MAM) shows that the rainfall decreased by 50 % in 2003. The lack of rainfall during the 2003 spring and summer (fig. 4a) is a possible explanation for the factor of 2 difference between the observed 7 % increase of water vapour for 3.5°C increase of temperature instead of of 7 % for 1°C.

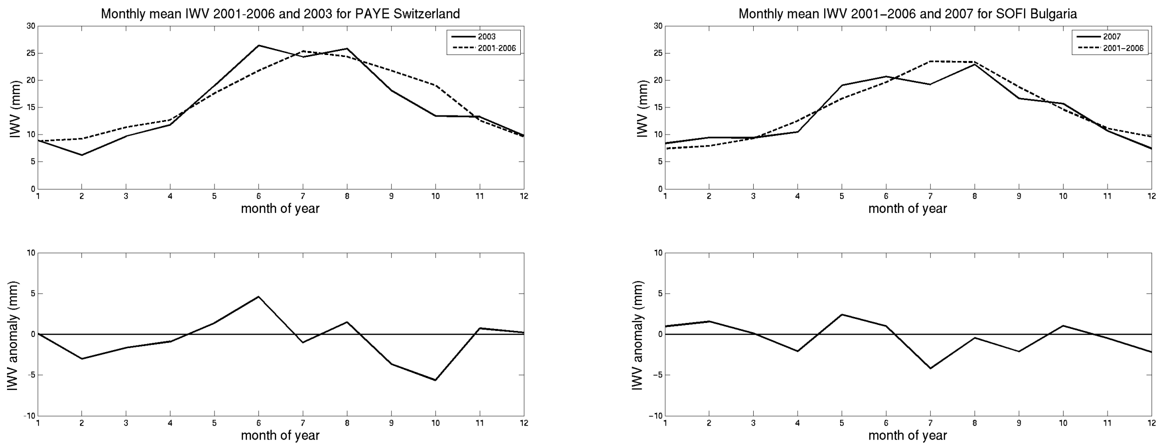

Figure 2. Monthly mean IWV (top) and anomaly (bottom) for : a) PAYE, Switzerland (thick line 2003, dashed line 2001-2006) and b) SOFI, Bulgaria (thick line 2007, dashed line 2001-2006).

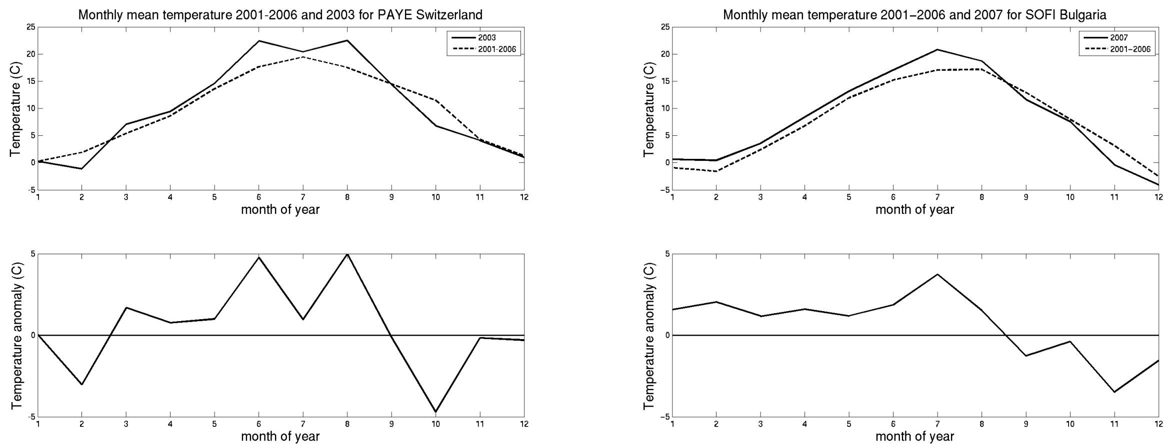

Figure 3. Monthly mean temperature (top) and anomaly (bottom) for: a) PAYE, Switzerland (thick line 2003, dashed line 2001-2006) and b) SOFI, Bulgaria (thick line 2007, dashed line 2001-2006).

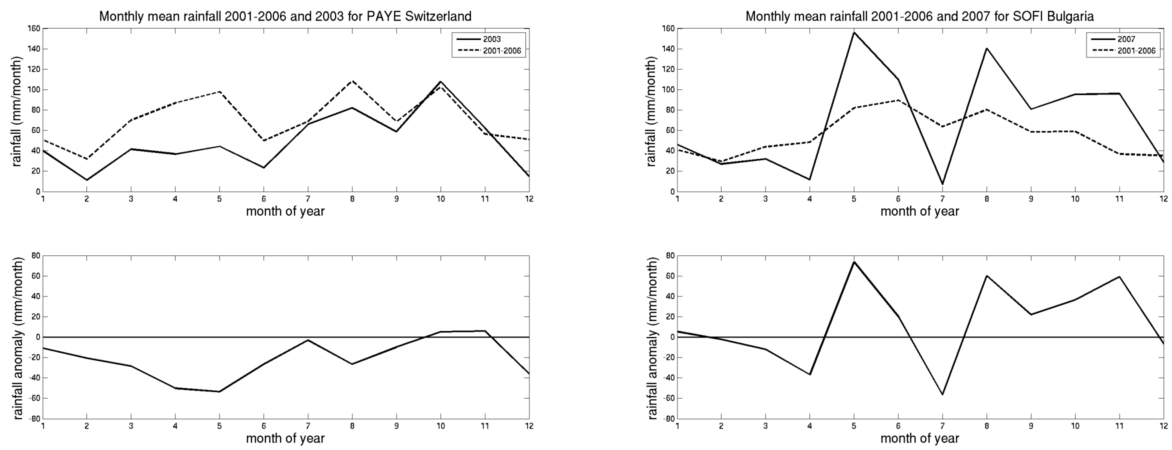

Figure 4. Monthly mean rainfall (top) and anomaly (bottom) for: a) PAYE, Switzerland (thick line 2003, dashed line 2001-2006) and b) SOFI, Bulgaria (thick line 2007, dashed line 2001-2006).

Met station	2001-2006	2003	2001-2006	2003	2001-2006	2003	2001-2006	2003
IWV	mm	mm	DJF	DJF	MAM	MAM	JJA	JJA
PAYE	16.2	15.6	9.2	9.3	13.9	13.5	23.8	25.5
Change		(-4 %)		(+2 %)		(-3 %)		(+7 %)
Temperature	[°C]	[°C]	DJF	DJF	MAM	MAM	JJA	JJA
PAYE	9.7	10.2	1.2	1.1	9.2	10.4	18.1	21.6
Change		(+5 %)		(-8 %)		(+13 %)		(+25 %)
Rainfall	mm/month	mm/month	DJF	DJF	MAM	MAM	JJA	JJA
PAYE	71.6	49.1	45.6	36.6	81.3	40.9	78.4	57.2
Change		(-31 %)		(-20 %)		(-50 %)		(-27 %)

Table 1. IWV & temperature & rainfall at station PAYE, Switzerland. Column 1-3: station name, annual mean for 2001-2006 and 2003 accordingly; column 4-5: December, January and February (DJF) mean for 2001-2006 and 2003; column 6-7: March, April and May (MAM) mean for 2001-2006 and 2003; column 8-9: June, July and August (JJA) mean for 2001-2006 and 2003. The 2003 departure from 2001-2006 mean is given in % in the brackets.

A very robust finding in all climate models (Houghton et al. 2001) is increase in potential evapotranspiration with global warming. In the absence of rainfall, the surface drying is enhanced, leading to increased risk of heat waves and wild fires because once the soil moisture is depleted all the heating goes into raising temperatures and wilting plants (Trenberth et al. 2003). It is likely that this scenario was a crucial factor in the 2003 heat wave and the lack of substantial water vapour increases in July and August is likely a result of the soil moisture depletion. Not surprisingly, the observed water vapour peaked in June 2003 (fig. 2a) not in August as 2001-2006. The 2003 temperature has a distinct double peak in June and August 2003 (see fig. 3a). Note, that in June 2003 the temperature increase of about 5°C resulted in an IWV increase of 21 %.

3.2. July 2007 heat wave

Monthly mean IWV from GNSS station SOFI is shown in figure 2b. When contrasted to 2001-2006 observations (dashed line), the following features stand out in 2007 (solid line): i.) IWV decrease in April, ii.) IWV increase in May and iii.) IWV decrease in July. The 2001-2006 mean IWV (column 2 in table 2) is 15.0 mm versus 14.2 mm in 2007, which is an annual decrease of -5 %. The seasonal mean IWV for December and February (DF), March to May (MAM) and June to August (JJA) are given in columns 4 to 9 of table 2. During the 2007 winter, the IWV decreased by -3 % (-0.3 mm). The 2001-2006 mean winter was -0.9°C colder that 2007 (fig. 3b). The 2007 spring IWV (fig. 2b bottom) overall is close to the 2001-2006 mean. In the 2007 summer, the IWV decreased by 1.3 mm or by about -6 %. The 2007 summer temperature at SOFI elevation (1 120 m asl) increased by 1.8°C compared to 2001-2006 mean. In particular, July 2007 was +3.7°C hotter and with -18 % less water vapour than the 2001-2006.

In 2007 the annual rainfall is 14 % above the 2001-2006 mean (column 3 in table 2). In spring (MAM) the rainfall decrease in March and April was followed by very large positive anomaly in May (+90 % fig. 4b bottom), thus resulting in an overall positive seasonal anomaly of +23 %. Later in the summer a large negative anomaly is registered in July.

4. DISCUSSION

The first common feature of the 2003 and 2007 heat wave is the northerly extension of subtropical jet stream allowing subtropical African air to reach West and Southeast Europe, respectively. The second common feature is a positive temperature anomaly (larger than 3°C) during the heat wave months August 2003 and July 2007. The third common feature is a weak response of IWV to the temperature forcing ranging between +6 % (2003) and -18 % (2007) suggesting that temperature alone could not explain the trend in water vapour. While the 2003 heat wave summer was preceded by very dry spring (negative rainfall anomaly 50 %) this feature was not characteristic for the 2007 spring with an exceptionally wet May (+90 %). Most likely, the difference between the rainfall pattern in 2003 and 2007 reflected the duration of the heat wave the 2003 lasting twice as long as 2007 i.e. two weeks in 2003 versus one week in 2007. Further more, low water vapour is to be expected as also a result of the adiabatic air subsidence (negative forcing from above) characteristic for an upper tropospheric ridge (Matzarakis et al. 2007).

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Met station	2001-2006	2007	2001-2006	2007	2001-2006	2007	2001-2006	2007
IWV	mm	mm	DF	DF	MAM	MAM	JJA	JJA
SOFI	15.0	14.2	8.8	8.5	12.9	13.0	22.2	20.9
Change		(-5 %)		(-3 %)		(+1 %)		(-6 %)
Temperature	[°C]	[°C]	DJF	DJF	MAM	MAM	JJA	JJA
SOFI	8.4	8.8	-2.2	-1.3	7.1	8.4	16.5	18.7
Change		(+5 %)		(+41 %)		(+18 %)		(+13 %)
Rainfall	mm/month	mm/month	DJF	DJF	MAM	MAM	JJA	JJA
Sofia	60.9	69.4	42.6	34.8	54.2	66.5	84.7	85.7
Change		(+14 %)		(-18 %)		(+23 %)		(+1 %)

Table 2. IWV & Temperature & rainfall at station SOFI, Bulgaria. Column 1-3: station name, annual mean for 2001-2006 period and 2007 accordingly; column 4-5: December and February (DF) mean for 2001-2006 and 2007; column 6-7: March, April and May (MAM) mean for 2001-2006 and 2007; column 8-9: June, July and August (JJA) mean for 2001-2006 and 2007. The 2007 departure from 2001-2006 mean is given in % in the brackets.

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