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# WATER VAPOUR ANOMALY DURING THE 2003 EUROPEAN SUMMER

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*Гергана Герова.* ИЗСЛЕДВАНЕ НА ВОДНАТА ПАРА ПО ВРЕМЕ НА ТОПЛИННАТА ВЪЛНА ПРЕЗ 2003 ГОДИНА

Както климатичните модели, така и наблюденията, показват, че в световен мащаб водната пара се увеличава с около 7 % за всеки 1 °C увеличение на температурата. През лятото на 2003 г. средната температура от юни до август е средно 3 °C по-висока от 2001–2006 г. През юни 2003 г. средномесечната температура е 3 до 5 °C над тази през 2001-2006 г. и това води до увеличение на ИВП между 21 и 25 %, докато през август 2003 г. същата температурна аномалия води до увеличение между 6 и 10 %. Този слаб отговор на ИВП през август 2003 г. е вероятно свързан с дефицит на почвена влага, породена от липсата на валежи през пролетта на 2003 г. (-56 %).

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Both climate models and observations indicate that globally the column-integrated water vapor increases by about 7 % for every 1° C increase of temperature. During 2003 summer the temperature from June to August was on average 3° C higher than 2001-2006. In June 2003 the monthly mean temperature is on average 3 to 5° C above the 2001-2006 mean and the IWV increased by 21 to 25 %. While in August 2003 the same temperature anomaly resulted in 6 to 10 % increase of IWV. This weak response of IWV to radiative forcing in August 2003 is likely linked to the soil moisture deficit driven by a strong precipitation deficit in the 2003 spring (-56 %).

***Keywords:*** Global Navigation Satellite Systems (GNSS), GNSS meteorology, atmospheric water vapour, heat wave

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## 1. INTRODUCTION

Both climate models and observations indicate that the column-integrated atmospheric water vapor increases by about 7 % per 1° C increase of temperature [1–5]. This is in agreement with the Clausius-Clapeyron relation which predicts 6 to 7 % $K^{-1}$ increases in water vapor if relative humidity remains constant. As 86 % of the world's evaporation comes from the oceans [6], they control the global increase in water vapor. Large positive trends in atmospheric water vapor are reported over the North Atlantic [4] for the period 1988–2001. In contrast, no evident positive trend was found over Europe. This paper aims to investigate the temperature-water vapour feedback during the 2003 European summer.

According to [7], 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. [8] suggest that over 10 day long heat wave in August 2003 may be a manifestation of an exceptional northward extension of the Hadley Cell. In many regions the annual precipitation deficit was 50 % below the average [9]. The August 2003 heat wave represents a valuable benchmark case because regional climate model simulations [7] suggest that by 2100 every second summer could be as warm or warmer and as dry or dryer.

Switzerland comprises three basic topographical areas: the Swiss Alps, the Swiss plateau and the Jura mountains along the northwestern border with France. The Swiss plateau stretches from Lake Geneva on the French Border across central Switzerland to Lake Constance on the German and Austrian borders. The plateau has an average altitude of 580 m. The Swiss Alps form part of a chain of mountains that stretch across southern Europe and isolate Northern Europe from the Mediterranean Sea. The Swiss Alps have an average altitude of 1700 m and cover nearly two thirds of the surface area of Switzerland. The Swiss climate is generally temperate, but vary greatly between the localities, from glacial conditions on the mountaintops to Mediterranean climate at Switzerland's southern tip. In the Köppen-Geiger climate classification, the Swiss Plateau is classed as Maritime Temperate or Oceanic climate, temperate without dry season and with warm summer (Cfb), the Alps are classified as tundra climate (ET) and the climate of south of the Alps region is classified as temperate without dry season and with hot summer (Cfa) [10]. Thus, the water vapor feedback will be studied within those climatic zones.

## 2. DATA-SETS

Hourly Integrated Water vapour (IWV) observations were obtained from five stations of the Swiss ground-based GNSS network [11], operated by the Swiss Federal Office of Topography: two in the Swiss plateau, Payerne (PAYE) and

Neuchatel (NEUC); two in the Swiss Alps, Davos (DAVO) and Andermatt (ANDE); and one south of the Alps, Locarno Monti (LOMO) (see table 1). The GPS IWV is derived following [12] and [13] and is available through the STudies in Atmospheric Radiative Transfer and Water vapour Effects (STARTWAVE) database [14].

MeteoSwiss operates one radiosonding station in Payerne, which is collocated with the PAYE GNSS station. A balloon sonding is performed twice a day at 00 and 12 UTC measuring temperature, pressure, humidity and wind profiles. The sonde is type SRS 400 manufactured by MeteoLabor and is equipped with a fast response VIZ ACCU-LOK carbon hygristor sensor to measure relative humidity with an accuracy of 2 % rms [15].

**Table 1.** Column 1–3: station name, location and climatic zone type and altitude. The stations marked with a start the GNSS and meteorological stations are not collocated

| Instrument name | Location – climatic zone | Altitude [m] asl. |
|---|---|---|
| GNSS Payerne (PAYE) | Swiss Plateau – Cfb | 491 |
| GNSS Neuchatel (NEUC)* | Swiss Plateau – Cfb | 455 |
| GNSS Davos (DAVO) | Swiss Alps – ET | 1591 |
| GNSS Andermatt (ANDE)* | Swiss Alps – ET | 2284 |
| GNSS Locarno (LOMO) | South of Alps – Cfa | 380 |
| Radiosonde | Swiss Plateau – Cfb | 491 |

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. Temperature and precipitation observations from five stations: Payerne collocated with the PAYE GNSS station, Neuchatel within 2 km from NEUC GNSS station, Davos collocated with DAVO GNSS station, Andermatt within 2 km from ANDE GNSS station, and Locarno Monti collocated with LOMO GNSS station are used in this work. Note that at Andermatt there is a 33 m altitude difference between the GNSS and the surface data but no height correction was applied to the temperature reported in table 4.

## 3. WATER VAPOUR ANOMALY DURING 2003 SUMMER

Figure 1 presents the monthly mean IWV from the radiosonde measurements in Payerne during the 13 year period 1994–2006. When contrasted to the 13-year mean IWV data (dashed blue line), the following features stand out in 2003 (solid red line): i. IWV decrease in February 2003; ii. IWV increase in June 2003; and iii. IWV close to the average in July and August 2003. The same features are seen in



fig. 2 top left panel,
period 2001–2006.
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mm versus 15.0 mr
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fig. 2 top left panel, which shows the GNSS derived IWV at station Payerne for the period 2001–2006.

The 1994–2006 mean annual radiosonde IWV (column 2 in table 2) is 15.1 mm versus 15.0 mm in 2003 (column 3 in table 2). The mean 2003 GNSS IWV in Payerne (column 3 in table 3) reaches 15.6 mm versus 16.1 mm for the 6 year annual mean 2001–2006. The radiosonde IWV 2001–2006 mean is 15.4 mm. It is to be noted the difference between the radiosonde and GNSS is expected and reflects the different sampling frequency as well as the length of the time series. In 2003 both the radiosonde and the GNSS derived IWV show a small decrease in the range –3 to –1 % when compared to the 13 or 6 year mean. Note, however, that recorded in Payerne temperature increased by 0.5° C in 2003. 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 tables 2 and 3. During the 2003 winter, the IWV from GNSS measures a small increase of 0.2 mm (+2 %) compared to 6 year mean, while the radiosonde measures on average –0.4 mm (–9 %) compared to 13 year mean. The 6 year mean winter was –0.1° C colder than 2003. The 2003 spring IWV variation is in the range –2 to +3 % for the 6 and 13 year mean respectively. During the 2003 summer, consistent 1.4 mm (+6 %) increase in IWV is obtained with both technique. The 2003 summer temperature in Payerne increased by about 3° C compared to 6 year mean (table 4).

A similar IWV increase of 1.5 mm (+6 %) is seen in the JJA 2003 at Neuchatel (fig. 2 top right panel and table 3). Note that Neuchatel and Payerne are located in the Swiss plateau, i.e. in the climatic zone Cfb. The JJA 2003 water vapour increase is a result of an increase of surface temperature of close to 3° C at both locations as seen in table 4. The high alpine stations Davos and Andermatt, both above 1500 m, present another climatic zone to study the water vapour feedback. During the JJA 2003 period, the water vapour increased by 7 and 9 %, respectively, while the temperature was 2.4 and 3.1° C above the 2001–2006 summer mean. The GNSS station in Locarno Monti is in southern Switzerland in a region where the climate is influenced by the Mediterranean sea. Similarly, the 2003 summer was 3° C hotter compared with the 2001–2006 mean summers and the column integrated water vapour increased by about 9 %. Clearly, it can be concluded that across 3 climatic zones in central Europe the 2003 summer was consistently about 3° C hotter and between 6–7 % wetter when compared to the 2001–2006 mean summer.

The precipitation observations at the 5 locations are also examined. The last column in table 5 shows the 2003 summer precipitation. It can be seen that at all 5 locations it is 28 % below the 2001–2006 mean (column 9 in table 5). Further intercomparison in spring (MAM) shows that the precipitation decreased by more than 50 % in 2003, which is consistent for all 5 stations.

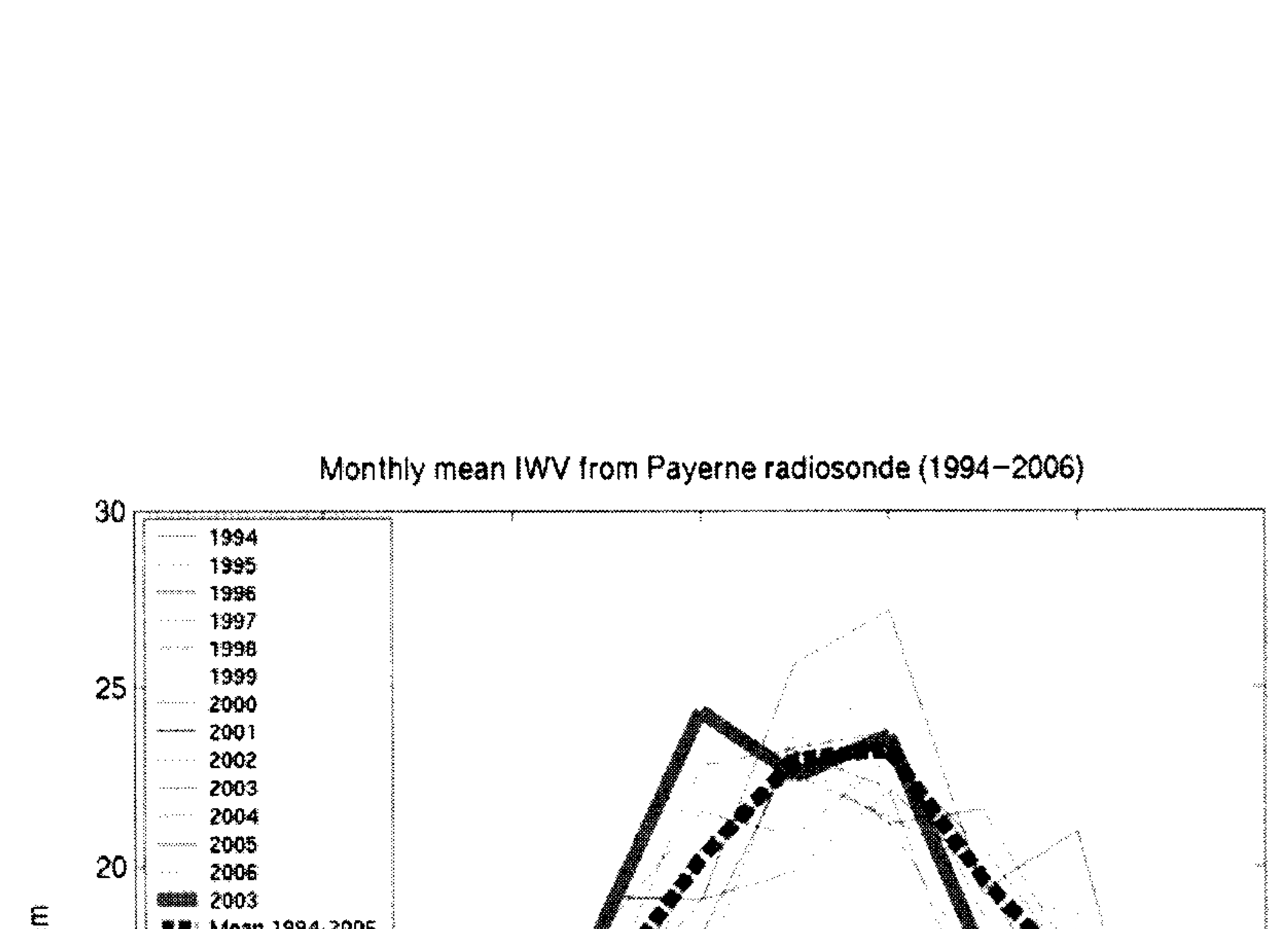


**Fig. 1.** Monthly mean IWV in [mm] from the radiosonde in Payerne, Switzerland. The thin lines are individual years from 1994 to 2006, the thick line is the 2003 mean and the dashed line is the 1994–2006 mean

A very robust finding in all climate models [16] is for an increase in potential evapotranspiration with global warming. In the absence of precipitation, the surface drying is enhanced, which leads 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 [17]. It is likely that this scenario is a crucial factor in the 2003 summer. The monthly mean IWV and surface temperature give a better picture of the processes during the 2003 summer. As mentioned water vapour peaked in June 2003 (fig. 2 all panels). In all 5 stations this represents an increase compared to 2001–2006 period in the range from 21 to 25 %. In June 2003, the monthly mean temperature in Payerne is about 5° C higher than the 2001–2006 mean. Thus it is to be concluded that in June 2003 the water vapour response to increase in surface temperature is consistent with the Clausius-Clapeyron equation. July 2003 has close to the mean 2001–2006 temperature and IWV. Interestingly, in August 2003 the monthly mean temperature in Payerne is again 5° C higher than the 2001–2006 monthly mean, but the IWV is only 6 % higher. At the remaining 4 stations the IWV increase in August 2003 is in the range 6 to 10 %. Thus it is to be concluded that the same increase in surface temperature resulted a factor of 2 to 3 weaker response of IWV in August 2003. The lack of substantial water vapor increases in August is probably a result of the soil moisture depletion driven by a large negative precipitation anomaly in spring 2003 (−56 %). Thus, it can be concluded that Clausius-Clapeyron equation is likely to hold in the early summer until the stored moisture in the soil is depleted then later in the summer the warming resulted in a heat-wave in August 2003.

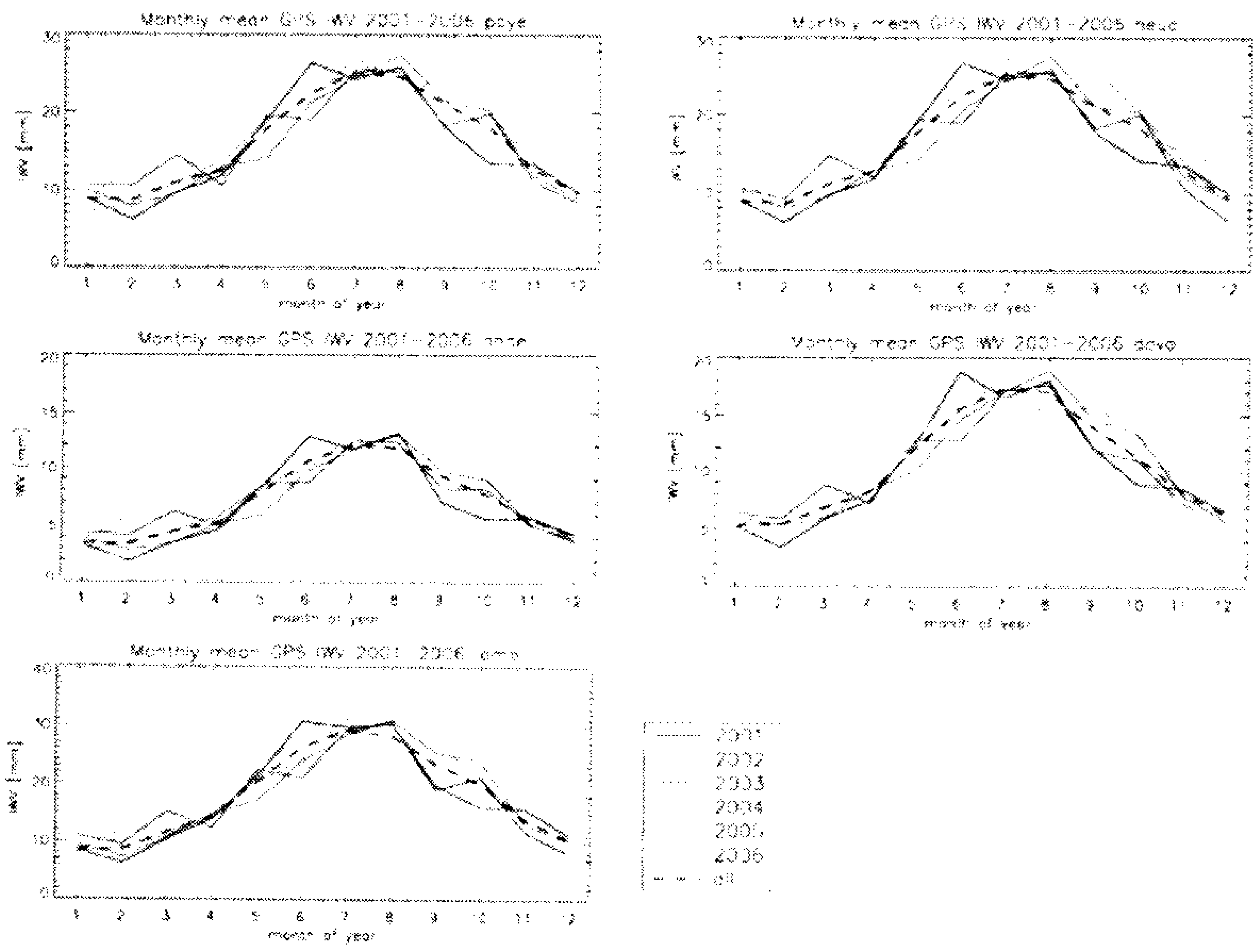

**Fig. 2.** Monthly mean IWV in [mm] from GNSS for 2001–2006. PAYE (top left panel), NEUC (top right panel), ANDE (middle left panel), DAVO (middle right panel) and LOMO (bottom left panel). The thick line is the 2003 mean and the dashed line is the 2001–2006 mean

**Table 2.** IWV in [mm] for the Payerne radiosonding. Column 1: station name; column 2–3: annual mean IWV for 1994–2006 period and 2003 accordingly; column 4–5: December, January and February (DJF) mean for 1994–2006 and 2003; column 6–7: March, April and May (MAM) mean for 1994–2006 and 2003; column 8–9: June, July and August (JJA) mean for 1994–2006 and 2003. The 2003 IWV departure from 1994–2006 mean is given in the last line. GNSS and meteorological stations coordinate

| Instrument name | 1994–2006 mm | 2003 mm | 1994–2006 DJF | 2003 DJF | 1994–2006 MAM | 2003 MAM | 1994–2006 JJA | 2003 JJA |
|---|---|---|---|---|---|---|---|---|
| Radiosonde | 15.1 | 15.0 | 9.3 | 8.5 | 12.9 | 13.3 | 22.1 | 23.5 |
| Changes | | −1 % | | −9 % | | +3 % | | +6 % |

**Table 3.** GNSS derived IWV in [mm] for five stations in Switzerland. Column 1: station name; column 2–3: annual mean IWV for 2001–2006 period 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 averaged IWV across all five stations is given in line 8. The 2003 IWV departure from 2001–2006 mean is given in the last line

| GNSS station name | 2001–2006 am | 2003 am | 2001–2006 DJF | 2003 DJF | 2001–2006 MAM | 2003 MAM | 2001–2006 JJA | 2003 JJA |
|---|---|---|---|---|---|---|---|---|
| Payerne (PAYE) | 16.1 | 15.6 | 9.1 | 9.3 | 13.8 | 13.5 | 24.1 | 25.5 |
| Neuchatel (NEUC) | 16.2 | 15.7 | 9.0 | 9.4 | 13.9 | 13.6 | 24.1 | 25.6 |
| Davos (DAVO) | 10.7 | 10.4 | 5.7 | 5.5 | 9.0 | 8.6 | 16.7 | 17.8 |
| Andermatt (ANDE) | 7.2 | 6.8 | 3.7 | 3.5 | 5.9 | 5.4 | 11.5 | 12.5 |
| Locarno (LOMO) | 18.0 | 17.8 | 9.2 | 9.4 | 15.5 | 15.2 | 27.8 | 30.2 |
| all stations | 13.6 | 13.3 | 7.3 | 7.4 | 11.6 | 11.3 | 20.8 | 22.3 |
| all stations | | -2 % | | +1 % | | -3 % | | +7 % |

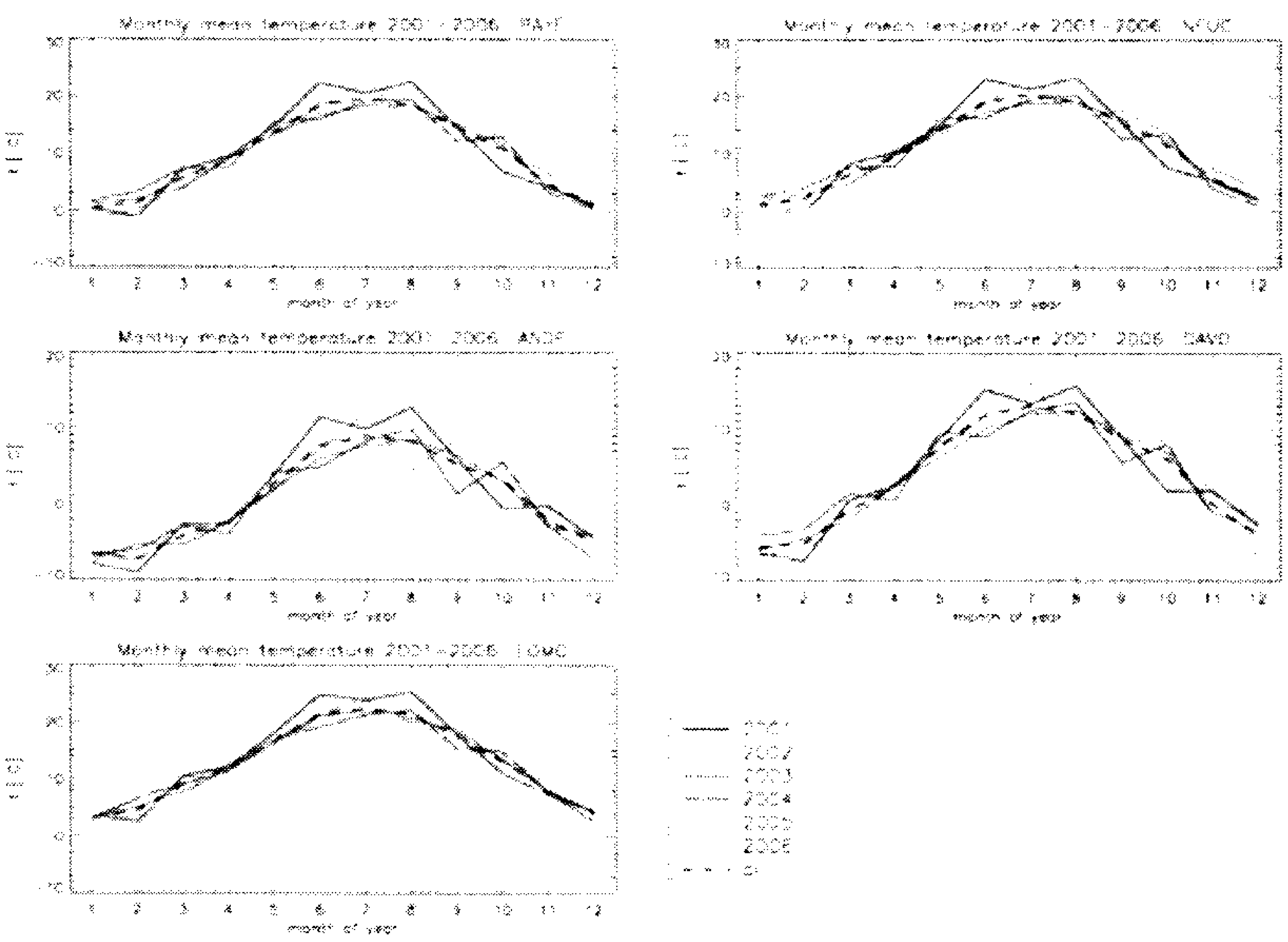

**Fig. 3.** Monthly mean surface temperature in [° C ] at PAYE (top left panel), NEUC (top right panel), ANDE (middle left panel), DAVO (middle right panel) and LOMO (bottom left panel). The thick line is the 2003 mean and the dashed line is the 2001–2006 mean

**Table 4.** Temperature in [°C] at five meteorological stations in Switzerland. Column 1: station name; column 2–3: annual mean temperature for 2001–2006 period 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 averaged temperature across all five stations is given in line 8. The 2003 departure from 2001–2006 mean is given in the last line

| GNSS station name | 2001–2006 am | 2003 am | 2001–2006 DJF | 2003 DJF | 2001–2006 MAM | 2003 MAM | 2001–2006 JJA | 2003 JJA |
|---|---|---|---|---|---|---|---|---|
| Payerne (PAYE) | 9.7 | 10.2 | 1.0 | 1.1 | 9.4 | 10.4 | 18.8 | 21.6 |
| Neuchatel (NEUC) | 10.6 | 11.0 | 1.8 | 1.7 | 10.1 | 11.2 | 19.5 | 22.6 |
| Davos (DAVO) | 3.9 | 4.4 | –4.9 | –5.3 | 3.2 | 4.0 | 12.3 | 14.7 |
| Andermatt (ANDE) | 0.8 | 1.4 | –6.1 | –6.8 | –1.3 | –0.5 | 8.3 | 11.4 |
| Locarno (LOMO) | 12.8 | 13.5 | 3.9 | 3.7 | 12.6 | 13.5 | 21.7 | 24.7 |
| all stations | 7.4 | 8.1 | –0.86 | –1.1 | 6.8 | 7.7 | 16.1 | 19.0 |
| all stations | | +0.7 | | –0.3 | | +0.9 | | +2.9 |

**Table 5.** Precipitation in [mm/month] at five meteorological stations in Switzerland. Column 1: station name; column 2–3: annual mean precipitation for 2001–2006 period 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 averaged precipitation across all five stations is given in line 8. The 2003 departure from 2001–2006 mean is given in the last line

| GNSS station name | 2001–2006 am | 2003 am | 2001–2006 DJF | 2003 DJF | 2001–2006 MAM | 2003 MAM | 2001–2006 JJA | 2003 JJA |
|---|---|---|---|---|---|---|---|---|
| Payerne (PAYE) | 71.6 | 49.1 | 45.6 | 36.6 | 81.3 | 40.9 | 78.4 | 57.2 |
| Neuchatel (NEUC) | 82.0 | 55.7 | 62.1 | 58.5 | 73.1 | 30.0 | 93.9 | 80.4 |
| Davos (DAVO) | 81.2 | 67.3 | 52.4 | 40.3 | 62.9 | 38.0 | 135.0 | 105.2 |
| Andermatt (ANDE) | 108.8 | 98.6 | 108.7 | 141.5 | 116.8 | 58.2 | 119.3 | 83.8 |
| Locarno (LOMO) | 136.5 | 88.8 | 72.7 | 30.8 | 127.0 | 37.6 | 175.7 | 107.2 |
| all stations | 96.0 | 71.9 | 68.3 | 61.5 | 92.2 | 40.9 | 120.4 | 86.8 |
| all stations | | –25 % | | –10 % | | –56 % | | –28 % |

## 4. CONCLUSIONS

During 2003 summer (June, July and August) a consistent 6–7 % increase of IWV was observed by two techniques and across 3 climatic zones in Switzerland. The 2003 summer is on average 3° C hotter than the 2001–2006 seasonal mean summer temperature. The monthly mean temperature in 2003 is shown to have double peak in June and August with on average 3 to 5° C above the 2001–2006 mean. In contrast in 2001–2006 the temperature peaks in the month of July. Corresponding to the June 2003 temperature anomaly the IWV increases by 21 to 25 %. While in August 2003 the same temperature anomaly results in a 6 to 10 % increase of IWV. This weak response of IWV to radiative forcing in August 2003 is likely linked to the soil moisture deficit driven by a strong precipitation deficit in the 2003 spring (–56 %). An increase in evapotranspiration in June 2003 facilitates the soil moisture depletion and further heating went into raising temperature hence the heat wave in August 2003. It can be concluded that the interplay between precipitation, soil moisture, water vapour and radiative heating contributed to the onset of the heat wave conditions in August 2003. This study suggests that over land the applicability of the Clausius-Clapeyron equation depends on the interplay between precipitation, soil moisture, water vapour and radiative heating. Further case studies for the 2007 heat wave in Southeast Europe will give an insight of the regional applicability of this work. The ongoing GNSS global reprocessing campaign will provide a consistent long term time series (over 15 year) well suited for water vapour trend analysis. The work is a contribution to working group three of the COST Action ES1206 "Advanced Global Navigation Satellite Systems tropospheric products for monitoring severe weather event and climate (GNSS4SWEC)" 2013–2017.

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