Feedback between soil moisture and spells of warm summer temperatures in Europe

Testing the link between soil moisture deficit and extreme temperatures for daily observed data for stations in the European Climate Assessment & Dataset

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MSc-thesis Meteorology and Air Quality (MAQ-80436)

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Abstract

Soil moisture is more and more recognized as an important factor in the occurrence of temperature extremes. As the climate is changing and Europe will very likely see increasing frequency of heat waves, low soil moisture is increasingly studied as a potential contributor to this feature. This report focuses on the potential link between soil moisture deficit and spells of extreme temperatures. The study is carried out with observed atmospheric data from across Europe, obtained from European Climate Assessment & Dataset. The soil moisture contents and the actual evapotranspiration are simulated with a simple two-layer water balance model that follows the method of Palmer, and are validated against measured data from Hupselse Beek. Several different methods are used in order to examine the presence of the link between soil moisture deficit and spells of extreme temperatures. The results indicate that the extreme summer of 2003 was extraordinary compared to other extreme years. There is observational evidence that the extreme temperatures and their duration are triggered by precipitation deficit in that year and thus, consequently, by soil moisture deficits.

Key words: soil moisture, extreme temperatures, heat wave, positive temperature feedback

Preface

This is my Master thesis finalizing the Master program Meteorology and Air Quality at the Wageningen University, The Netherlands.

Special thanks go to Gerard van der Schrier and Albert Klein Tank for the supervision and the requisite help at the KNMI, Royal Netherlands Meteorology Institute, where I have worked on this thesis. I also would like to thank Piet Warmerdam and Jaques Kole for the provision of data necessary to research the topic.

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Summary

Studies suggest that climatic change and more frequently occurring heat waves go hand in hand. The European summer of 2003 is a good example of a major heat wave. The consequences of the long spells of extreme temperatures in that year had large impact on society.

The above facts lead to the urgency for more and better knowledge of the mechanisms behind the occurrence of extreme temperatures. Many studies have already been done in order to extend the understanding of the phenomena and to enlarge the possibilities to predict these hazards. The main purpose of this study is to extend the understanding of the feedback mechanism between soil moisture and temperatures. Here, the observational data from European Climate Assessment & Dataset is central and it is carefully analyzed through different methods. A simple two-layer moisture balance model is used for the simulation of soil moisture and actual evapotranspiration. The simplicity of the approaches and the lack of complicated models make this study and the results obtained, highly robust.

The results of the validation and the sensitivity analyses of the models prove that the models used here are valid and robust, and justify their use in this study. The few parameters needed for input and the low level of complexity of the model make the moisture balance model used in this study even more powerful.

Five different approaches of data assessment are applied in order to study the existence of the link between soil moisture deficits and spells of extreme temperatures;

(1) comparison of hot summer years with ordinary years
(2) comparison of the year 2003 with a climatological mean
(3) precipitation pattern analysis
(4) comparison of the maximum temperatures of 2003 with virtual temperatures
(5) heat flux partitioning

All approaches are carried out for the station of Augsburg, due to its central position in Europe and an optimal completeness of the dataset.

The first approach resulted in the finding that hot summer years do indeed have lower soil moisture levels than ordinary years. Another finding was that the year 2003 seemed to have a slightly different situation from the other extreme year examined.

Therefore approach 2 was carried out. This resulted in the conclusion that soil moisture in 2003 dropped far below the long term average soil moisture and the temperatures also showed a significant difference compared to the 30-years average. The 2003 soil moisture shows a decrease prior the increase in the maximum temperature.

This fuels the hypothesis that soil moisture might have played a big role in the onset of the heat wave in 2003 in Europe. To give a possible justification for the hypothesis, precipitation pattern analysis was carried out. This analysis clarified that the precipitation deficits in 2003 were significantly larger than deficit in 1976. This supports the idea that 1976 was mainly driven by specific atmospheric circulation patterns, while a significant part of the drive in the year 2003 can be assigned to soil moisture.

Approach 4 made clear that not only soil moisture content is of importance, but also the memory of soil moisture plays a role. Even though both series, 2003 and the virtual series, encountered the same number of extremely hot days (30+°C), year 2003 knew more hot days (25+°C) and the spells of hot days were considerably longer. No spell of 10 days or more with temperatures of 25+°C can be found in the virtual series, whereas the series of 2003 knows three spells; two with temperatures of 25+°C and one with temperatures of 30+°C. Although the levels of soil moisture in the virtual series are almost as low as the soil moisture levels in 2003, the virtual series is a chain of single days of different year combined together into one series and not a continuous string of days as the 2003 series is.

The last approach, heat flux partitioning, consist of two methods, one is focused on the latent heat flux and the other on sensible heat flux. The section focused on the latent heat flux indicates the deviation of actual evapotranspiration in 2003. As actual evapotranspiration is linearly related to latent heat flux, a decrease in actual evapotranspiration denotes a decrease in the latent heat flux and thus a shift toward sensible heat flux resulting in a rise in temperature. This feedback can indeed be recognized in August 2003. This result can also be observed in the section focused on sensible heat flux. Here, the emphasis is set on the quantification of the increase of temperatures in 2003 due to the shift in the radiation balance superposed on the climatological mean values of temperature. According to this method, a large part of the temperature anomaly in August 2003 can be assigned to a rise in sensible heat flux.

All in all, the conclusion can be drawn that under circumstances as they were in 2003, there is more than just a link between soil moisture and extreme temperatures. Generally, soil moisture reacts on the increase in temperatures by decreasing, but in situations like in 2003, soil moisture seems to be the leading component in the soil moisture – temperature feedback due to large precipitation deficits. Moreover, this feedback seems to act on a local scale, as local soil moisture deficits have shown to have great impact on the surface heat balance.

1. Introduction

1.1. Background and problem description

The number of heat waves has seen an increase in the last couple of decades. The last decade, especially the summer of 2003 was extremely warm. In large parts of Europe the recorded temperatures during the heat wave in the summer of 2003 exceeded a 5°C deviation from the long term average (Figure 1).

Heat waves are not a sudden, high profile disaster, inflicting instantly recognizable damage. They are a silent disaster and are therefore often not recognized as a direct threat. This often leads to unprepardness which causes the impacts of the disaster to be even greater [*WDR, 2004*].

Between 22 thousand and 35 thousand people died due to the heat wave in August 2003. Especially elderly and marginalized people suffered because of the extreme conditions [*WDR, 2004*]. Also considering the environment the losses were enormous. Forest fires were stimulated, especially in the southern part of Europe, which caused a great destruction of large areas of land. In Portugal for example, 5.6% of the total forest area was destroyed, resulting in by far the worst forest fire season that the country had faced in the last two decades [*UNEP, 2003*]. Also the water ecosystems and glaciers were affected by the spells of extreme temperatures. In the Alps, the average loss in thickness of glaciers in 2003, about 3 meters water equivalent, was approximately five times larger than the average loss of 0.65 meters per year recorded during the exceptionally warm period 1980 – 2000 [*UNEP, 2003*]. The heat wave also caused power cuts and there were many transport limitations as well as a significant decrease in agricultural production [*UNEP, 2003*]. Economic losses totaled over 13 billion US dollars.

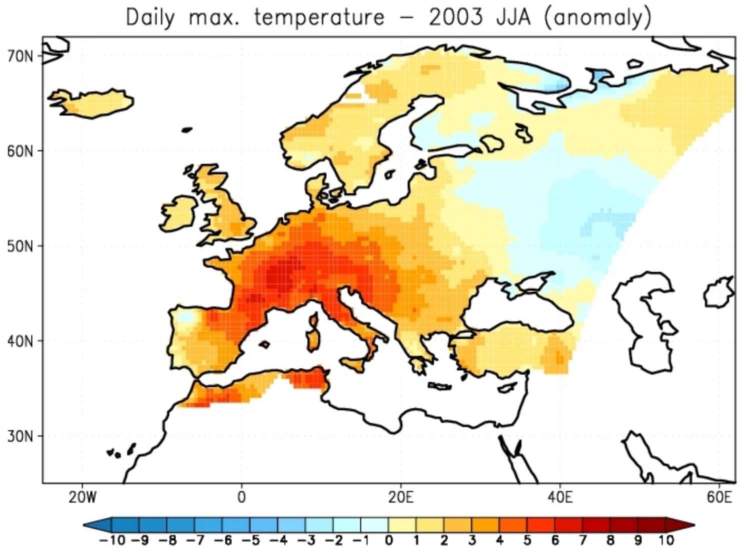

Figure 1: Anomaly of daily maximum temperature for summer months June, July and August. Year 2003 compared to climatological mean (1961-1990).

Global climate model simulations show that future heat waves will become more frequent, more intense and longer lasting with climate change on the rise. These predictions also concern the areas of Europe that already have been severely affected by heat waves in the past [*Meehl and Tebaldi, 2004*]. Many different factors can lead to high temperatures and the occurrence of heat waves is a very complex feature. Generally, heat waves are linked to specific atmospheric circulation patterns. These patterns are represented by semi-stationary 500-hPa positive height anomalies that dynamically produce subsidence of air, clear skies, light winds, warm-air advection, and prolonged hot conditions at the surface [*Meehl & Tebaldi, 2004*]

Nevertheless, the role of soil moisture in these future projections is being more and more acknowledged. According to predictions the increasing concentrations of CO_2 in the atmosphere lead to higher temperatures [*IPCC, 2007*]. Higher temperatures are coupled to a rise in evaporative demand. The hypothesis is that this increase will outweigh the predicted increase in precipitation [*Robock et al., 2005*]. Furthermore, as the hydrological cycle is predicted to intensify, with an associated increase in the frequency and/or magnitude of heavy precipitation [*Fowler & Hennessy, 1995*], the runoff will probably increase as well. As a result, the levels of soil moisture are likely to descend.

This change in the hydrological cycle could lead to a change in the radiation balance and to a positive feedback on temperature. As the levels of soil moisture are hypothesized to decrease under global warming, the latent heat flux will decrease due to limited soil moisture reserves available for evaporation. The closing of the balance requires then an increase in sensible heat flux and thus a further increase in temperatures and consequently a further decrease in soil moisture.

1.2. Objective of the research

This research focuses on the research questions:

Are low levels of soil moisture linked, through a feedback mechanism, to spells of extreme temperatures for the stations in the ECA dataset?

Central in this study is a simple two-layer 1-D soil moisture model. This model is validated against measurements for one station in the Netherlands. Soil moisture levels for a selection of stations in Europe are calculated using this simple soil moisture model. Input for this model is meteorological data from European Climate Assessment & Dataset project, ECA&D [*Klein Tank et al., 2002*]. Moreover, the relation between the obtained soil moisture and meteorological data is examined in order to draw conclusions on the occurrence of a feedback between low levels of soil moisture and experienced heat waves.

Due to the lack of sufficient data and for the sake of simplicity, assumptions are made in this research. The assumptions that are made without further study of their legitimacy are summarized here below. Other assumptions made, are tested and discussed further throughout the report.

- As we are interested in the time changes and variability of the variables and not in their magnitude, absolute quantities are of lower importance. This justifies the use of a simple water balance model.
- Homogeneity of the area is assumed, as one single value for water holding capacity is entered. This assumption concerns the soil type as well as the vegetation growing on the land regarded.

1.3. Literature review

Soil moisture is more and more recognized as an important contributor to climate extremes. Hence, an increasing amount of research has appeared to investigate the influence of soil moisture and factors influencing it.

Brabson et al. [2005] examined how the periods of extreme temperatures, as predicted for the end of the 21st century, are related to low soil moisture. They investigated, with a use o a general circulation model, the occurrence of extreme temperatures and specifically the three aspects of it; the movement of extremes, the changes in symmetry and the increases in persistence, all three particularly with respect to their relationship with soil moisture. The general finding of that research is that longer periods with extreme temperatures are stimulated both by the prolonged spells of low soil moisture and by the increases in the mean and standard deviation. Fischer[1] at al. [2007] investigated the role of soil moisture-atmosphere interactions as a key feedback mechanism for the heat wave in the summer of 2003. This was done with the help of monitoring data and simulations, the latter using a regional climate model. They concluded that soil moisture deficit was one of the most important factors that led to the temperature record-breaking summer of 2003. The dry conditions began with a precipitation deficit early that year. Early vegetation activation accelerated the loss of soil moisture. Moreover, clear sky conditions led to persistent excess of short wave radiation that amplified the soil drying further through an increased evapotranspiration. All these factors led to an early strong reduction of soil moisture. Without the extraordinary soil moisture deficit, the summer of 2003 would still be warm, but not as extreme and devastating as it was. Vautard et al. [2007] analyzed the influence of wintertime Mediterranean rainfall deficit on heat waves and drought in summertime in Europe. Looking at the European daily maximum temperature and precipitation records from the Mediterranean region, both over 58 years, they found a relationship between these two. They concluded that a southern European drought was one of the constraining factors for the development of extreme high temperatures in Europe. A different approach is applied by Seneviratne et al. [2006] in order to determine the influence of land-atmosphere feedbacks on the variability of summer temperatures in Europe. They used regional model simulations of present and future climatic conditions, both with and without land-atmosphere coupling. Comparison of the outcomes indicates that the feedback explains a significant part of the predicted future variability in summer temperatures and thus that changes in atmospheric circulation alone are not sufficient. Meehl and Tebaldi [2004] found that the areas that are nowadays most vulnerable to heat waves, will experience the largest increase in heat wave severity in the future. But also other areas, areas that are currently not as susceptible, will experience an increase according to this study. Not only the amount of heat waves will increase, the duration will increase as well.

1.4. Structure of the report

The next section gives an overview of the materials used in this study. The models, as well as data are discussed, and the models are tested for their validity and robustness. Chapter 3 describes the methods used to assess the existence of the feedback between soil moisture and spells of warm summer temperatures. Chapter 4 presents the obtained results, and a short interpretation and discussion accompany each finding. The conclusions in chapter 5 end this report.

2. Materials

For this study two models are used, a moisture balance model (MB-model) to model the soil moisture and a potential evapotranspiration model (PET-model) to model the potential evapotranspiration that is needed as an input variable for the MB-model. In this section these two models are described and observational data that serves as input for the models is discussed. In order to assure that the models are appropriate for this study, validation and sensitivity tests are applied.

2.1. Models

2.1.1. Description of the MB-model

The MB-model used in this project to simulate soil moisture content is based on the theory of Palmer (model algorithm can be found in the Appendix 1) and is a modified version of the program in use at the National Climatic Data Center. The core of the program has been obtained from NCDC.

In 1965 Wayne Palmer introduced the Palmer Drought Severity Index (PDSI). This index uses temperature and precipitation as input and it is based on a simple water balance approach [*NOAA, 2008*].

Water balance approach to climatic study allows calculating a realistic image of the time distribution of moisture surplus and shortage. Water balance shows the in- and out flows of water in a system. A simplified general equation describing a water balance is:

$$P = Q + E + \Delta S \tag{1}$$

Where:

P = precipitation

Q = runoff

E = evapotranspiration

ΔS = change in storage

Obviously, water balance can be presented in more sophisticated way than in eq. 1. This, however, requires larger detail of input data. For the sake of simplicity, the simplified general water balance equation is used as presented in eq. 1. All terms of this equation have an influence on the water content in the soil. They can act either as a gain terms or as loss terms with respect to soil moisture. Precipitation acts as a gain term, runoff and evapotranspiration as loss terms, and change in storage represents water content change in the soil and can either increase (positive ΔS value) or decrease (negative ΔS value).

The input of the MB-model is potential evapotranspiration, precipitation and soil water holding capacity and the output is soil moisture (either total or only upper/lower layer), actual

evapotranspiration, recharge, runoff and residual moisture. The model is a simple two layer 1-D model. In this empirical method the soil is divided into two horizontal layers. The thickness of the upper soil layer is fixed; at field capacity, the layer is assumed to contain 2.5 centimeters of available moisture. Onto this layer the rain falls and from this layer the evaporation takes place. It is assumed that moisture evaporates at the potential rate from this layer until all the available moisture has been removed. Once all the available moisture from the upper layer is removed, moisture can be removed from the underlying layer. Likewise, it is assumed that the lower layer can not be moisturized until the upper layer has reached 2.5 cm of available moisture. Further it is assumed that there is no runoff until both layers are brought to field capacity *[Palmer, 1965]*.
Figure 2 shows the course of the soil moisture as a function of evapotranspiration for this model.

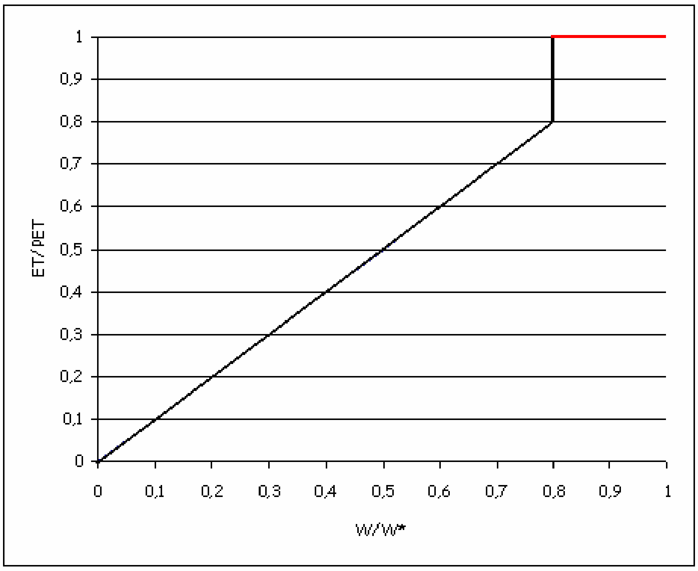

Figure 2: ET/PET (daily actual evapotranspiration/daily potential evapotranspiration) as a function of the soil wetness W/W* (root zone moisture/root zone storage capacity) after *Mintz and Walker [1993]*.

The red horizontal line reaching from (0.8,0.8) to (1,1) represents a situation where moisture is available in the upper soil layer. As mentioned, in this situation the model sets the actual evapotranspiration to be equal to the potential evapotranspiration. Once all the water from the top layer is evaporated, the actual evapotranspiration is lower than the potential evapotranspiration. Actual evapotranspiration is from that point on linearly related to the fraction of available root zone moisture.

A possible shortcoming of the model is the fact that the uptake of water by plant roots is not simulated realistically. In reality, in water limited environments, roots can penetrate soils to a great depth, in extreme cases even to several tens of meters depth [*Lubczynski, 2008*]. The

MB-model does not account for this phenomenon. This possibly means that in case of a very dry period, this approach underestimates the dryness of the soil.

2.1.2. Description of the PET-model

The model to estimate potential evapotranspiration used in this study follows the Penman-Monteith method. The choice to use the Penman-Monteith method is made for the sake of consistency as this method is also used in the Hupsel database used in this study (described later).

Penman-Monteith (P-M) equation is a combination equation combining energy balance and an aerodynamic formula. John Monteith developed an equation for computing water evaporation from vegetated surfaces [Monteith, 1965]. This was build upon a derivation of Howard Penman [Penman, 1948]. The formula for P-M combination equation is *[FAO, 1998]*:

$$\lambda ET = \frac{\Delta(R_n - G) + \rho_a c_p \dfrac{(e_s - e_a)}{r_a}}{\Delta + \gamma\left(1 + \dfrac{r_s}{r_a}\right)} \tag{2}$$

Where:

R_n = net radiation

G = soil heat flux

$(e_s - e_a)$ = vapor pressure deficit of the air

ρ_a = mean air density at constant pressure

c_p = specific heat of the air

Δ = slope of the saturation vapor pressure temperature relationship

γ = psychrometric constant

r_s = (bulk) surface resistance

r_a = aerodynamic resistance

The software used in this study, WaSim ET, is designed at Cranfield University [*Hess, 2001*].

2.2. Observational data

In this study, the observational data is used for two different purposes: (i) for the processing of the models; and (ii) for the validation of the MB-model.

2.2.1. Data for processing of the MB-model

As mentioned previously, the MB-model requires three input variables; potential evapotranspiration (mm/day), precipitation (mm/day) and soil water holding capacity (mm). The availability of this data is discussed below.

PET input data

Potential evapotranspiration (PET) is one of the three required data inputs for the MB-model. Here the PET is calculated with P-M method and the required input data is temperature (either mean or maximum and minimum), mean relative humidity, sunshine duration and wind speed. The first three variables come from daily blended observed meteorological database ECA&D [*ECA&D, 2008*].

The selection of stations from the ECA database used in this project is based on three criteria; (i) the station selected must be in Europe and (ii) must contain the full list of meteorological variables needed. Furthermore, (iii) he selected stations must be scattered throughout Europe, and thus not concentrate in one single place. The stations selected in this project are listed in the table 1 and their position is shown on the map in figure 3.

Table 1: List of stations studied in this project

Station name	Number*	Coordinates	Height [m]	Usable Data – range
Augsburg (DE)	1	48:26 N, 10:56 E	463	1961-2004
Beograd (BA)	2	44:48 N, 20:28 E	132	1961-2004
De Bilt (NL)	3	52:06 N, 05:11 E	2	1961-2004
Geneve (CH)	4	46:15 N, 06:08 E	420	1961-2004
Görlitz (DE)	5	51:10 N, 14:57 E	238	1961-2004
Hannover (DE)	6	52:28 N, 09:41 E	56	1961-2004
Hupsel (NL)	7	52:07 N, 06:65 E	29	1977-1982
Hurbanovo (SK)	8	47:52 N, 18:12 E	115	2002-2005
Kaunas (LT)	9	54:53 N, 23:50 E	75	1976-2004
Leeuwarden (NL)	10	53:13 N, 05:45 E	2	1962-2004
Lugano (CH)	11	46:00 N, 08:58 E	273	1961-2004
Madrid (ES)	12	40:25 N, 03:39 W	667	1961-2005**
Ni (BA)	13	43:20 N, 21:54 E	202	1961-2004
Verona (IT)	14	45:23 N, 10:52 E	68	1999-2005
Zagreb (HR)	15	45:49 N, 15:58 E	156	1961-2004**

* This number is not the official station number. It is added for convenience and is equivalent to the station number indicated on the map (Figure 3).

** The series contains many missing values and therefore it becomes unusable.

Figure 3: Map of stations studied. The red squares represent the ECA&D stations selected and the brown square represents the station of Hupsel provided by Hydrology and Water Quality chair group of Wageningen University. The numbers correspond to the number listed in table 1.

For the last variable needed, wind speed, hourly potential wind data is used originating from Hydra project [*HYDRA, 2008*].

Rain input data

The second required input for the MB-model is precipitation data. The data used in this research is also daily blended observed data and it originates from the ECA database as well. The stations chosen are the same as used for the PET-model input.

WHC input data

The third input variable, the water holding capacity (WHC) of the soil, needs to be defined manually. As this depends on field capacity (FC) and root zone thickness (D);

$$WHC = FC \cdot D \tag{3}$$

and field capacity depends on soil type and root zone thickness, and the root zone depends in turn on vegetation type (this can change drastically over time), the WHC is difficult to quantify. In this project, the WHC for Hupsel is estimated to 230 cm [approximated from Noble, 2008 and Mintz and Walker, 1993].

2.2.2. Data for validation of the MB-model

The MB-model is validated with field acquired soil moisture data. Due to the data availability constrains, such validation was carried out only for the Hupsel dataset provided by the Hydrology and Water Quality chair group of Wageningen University [www.hwm.wur.nl]. The data set consists of soil moisture measurements from around Hupselse Beek (52.1N, 6.7E) measured over twelve different depths; 0.15, 0.25, 0.35, 0.45, 0.65, 0.85, 1.05, 1.25, 1.45, 1.65, 1.85 and 2.05 m. In this paper, data from Assink Meteo is used.

The soil moisture data applied in this study was measured on average two to three times a month and expressed in percentages. The measurements were done by gravimetric sampling i.e., the soil samples were weighted and placed in a kiln to dry and after drying they were again weighted. The difference in the weight represents the amount of moisture in the soil. The measured Hupsel soil moisture data, applied for validation of the MB-model is available in the period 1976 – 1984 and corresponds with micrometeorological data of the same location also provided by the Hydrology and Water Quality chair group of Wageningen University.

2.3. Testing the models

2.3.1. Validation of the MB-model

Validation with soil moisture data

The validity of the MB-model is tested with a simple correlation test by calculating a correlation coefficient between simulated and measured soil moisture and actual evapotranspiration variables. The higher the correlation coefficient, the more reliable, and thus valid, the model is.

As soil moisture was measured twice or three times a month, no continuous data series was available. In order to validate the model, i.e. to compare the measured data with the model output, only days corresponding to the available measured days were correlated with the model output. Second difficulty in validating the MB-model was the fact that the soil moisture was measured in percentages and the model output was in millimeters. To solve that problem, the measured data was multiplied with the depth of the soil between the lower measurement and the measurement above it.

Figure 4 represents the measurements and the model output for the years 1977 until 1984. As spells of heat waves in Europe occur exclusively in the summer month, only these are plotted in figure 4.

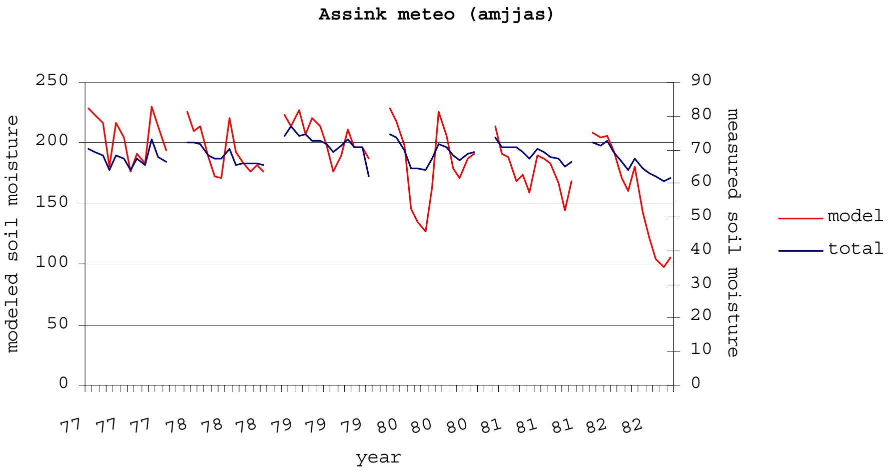

Figure 4: Soil moisture based validation of the MB-model. Only extended summers are presented (April, May, June, July, August and September) for the period 1977-1982. The red line represents the modeled output and the blue line represents the measurements.

As can be seen in figure 4, the simulated soil moisture matches the pattern of the measured soil moisture reasonably well. The correlation coefficient for this validation is 0.80. Unfortunately, due to the scarcity of soil moisture data across Europe, no alternative dataset is available to validate the model.

The figure also shows that the magnitude of soil moisture is not well modeled. Average bias is in the order of 120 cm. However, the course is simulated reasonably well and as the main interest in this study goes to time changes and variability, the simulation of the course of soil moisture is of primer importance.

Validation with actual evapotranspiration data

For the validation with actual evapotranspiration (ET_A), ET_A modeled and ET_A measured is used. The ET_A measured was calculated indirectly by means of the energy budget at the ground surface - air interface, based on one hour measurements. In the energy budget the sensible heat flux was calculated from the mean temperature profile and wind speed [*Stricker & Brutsaert, 1978*]. The temperature profile consisted of temperature measurements from four different heights; ground level, 0.1, 1.5 and 3 meters. This daily sensible heat flux, leads to derivation of the daily rate of evapotranspiration [*Stricker & Brutsaert, 1978*]. This experiment was performed between 1977 and 1982 and took only place in the summer month. Therefore no valid data is available for the winter months and thus the validation of the MB-model for ET_A will only be carried out for the summer period.

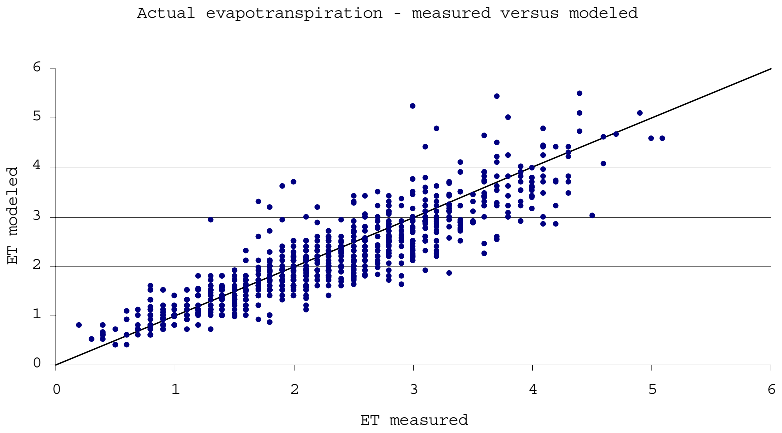

Figure 5: Comparison of a measured series of ET_A from Hupselse Beek with a modeled series, 1977-1982.

Figure 5 shows the result of the validation. The correlation coefficient for the two data series is very high at 0.93. The high correlation coefficient and the high level of overlapping indicate high validity of the modeled data. Furthermore, the absolute values are similar as well.

The validation of the MB-model for ET_A is carried out with two continuous data series with equal initial units. The fact that the comparison of the outcomes for these two series results in similar absolute values raises the hypothesis that the bias in the previous validation test, where soil moisture series were compared, is due to the difference in initial units and to the fact that the modeled series is continuous series and the measured series is discrete.

2.3.2. Model sensitivity tests

In order to find out how robust the models are, sensitivity tests are applied. The PET-model sensitivity is tested in two ways; (i) through comparison of series obtained with limited input data with series created with extended input data and (ii) through comparison of different series, all with different wind input. The sensitivity of MB-model is tested with different WHC inputs.

These outcomes of these three sensitivity tests are fundamental for this study, as the variables that are used in these tests are either limited or need to be approximated.

Limited input data vs. extended input data

The PET-model is tested for its robustness for limiting the amount of input data. In order to find out what the impact is of limiting the input data, two PET series are compared. One series is created with a limited input; *temperature (maximum and minimum), mean relative humidity, wind speed and sunshine*, and the second series is created with an extended input; *limited input + solar radiation, net radiation and soil heat flux*. Thereupon, both outputs are used as input for the MB-model in order to find out what the influence of the limitation of a dataset is on the simulated soil moisture content.

Figure 8 shows two outcomes for PET for the year 1981 for the Hupselse Beek; the green line is obtained with limited input data and the purple line is obtained with extended input data. The year 1981 is one of a few years that had almost no data missing. For this reason, the year 1981 is chosen for this test. The seasonal cycle (SC) is subtracted from the results in order to exclude the possible seasonal correlation. In order to create a SC, daily data is averaged day by day for the whole dataset available. For instance, in a dataset existing of 20 years, all twenty 1st of Januaries are averaged etc. Thereby a series of average year values is created.

As can be seen in the figure, the model is not very sensitive to a decrease in the variables used for input when the course is considered. The correlation between these series obtained with limited input data and series created with extended input data equals 0.94, over a period of one year (1981).

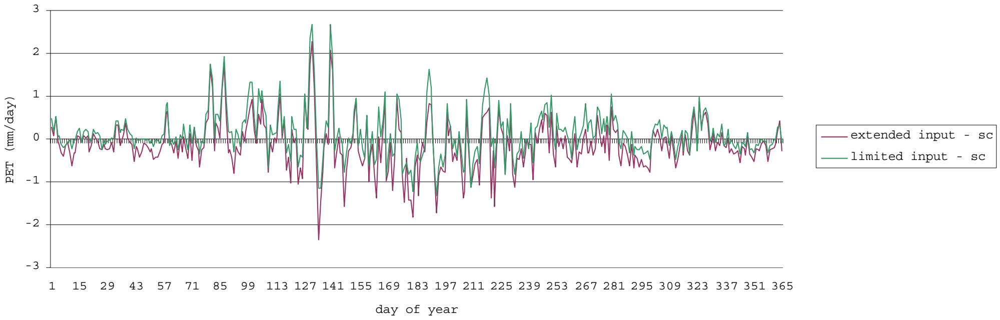

Figure 8: Sensitivity analysis of the PET model. Two different series, both with the seasonal cycle subtracted, are compared; a series with an extended input (purple line) and series with limited input (green line), 1981.

When looking at the magnitudes, the run with the limited input overestimates the PET compared to the run with extended input. However, as can be seen in figure 9 this small overestimation has a minor impact on the time changes and variability of the output of MB-model and as these are of primer interest in this study, this overestimation is not critical for the validity of the model.

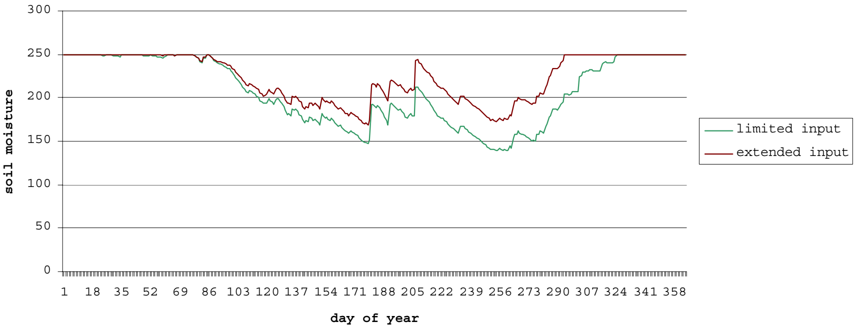

Figure 9: Simulations of soil moisture content for the year 1981 for Hupselse Beek. The green line shows the content when limited input is used to calculate PET, and the brown line represents soil moisture content when extended input is used to calculate PET.

Wind data dependency

One problem attached to the PET-model used in this project, is the fact that wind data is required. This variable is not included in the ECA dataset. For the Netherlands however, the wind data can be found on the Hydra project site [*HYDRA, 2008*] as potential wind data. To determine the importance of the wind data for the calculations of PET, and thus the magnitude of the problem, a sensitivity test is carried out. The PET-model is run three times with daily meteorological data from Augsburg acquired from ECA dataset. The only difference between the runs is that for every run the wind data is taken from a different place; for one run the wind data is from Augsburg (for Augsburg wind data is available from the site of Deutsche Wetter Dienst (DWD, 2008)), for one run it is taken from De Bilt and one run is simulated with a constant daily wind speed (2 ms^{-1}). Remaining required input variables for the three runs are all equal and originating from Augsburg. The outputs of the three runs are compared in order to quantify the importance of the wind data. Figure 10 shows the result of this sensitivity test.

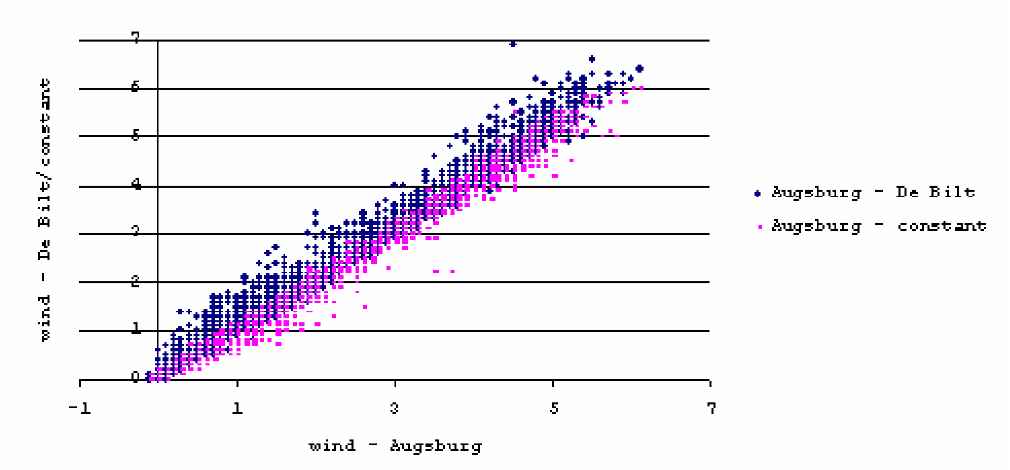

Figure 10: Sensitivity test for change in wind data. Blue dots represent a run with wind data from De Bilt as a function of a run with wind data from Augsburg. Pink stripes represent a run with a constant wind speed (2 ms^{-1}) as a function of a run with wind data from Augsburg. Other required input variables remained unchanged throughout all runs and originate from Augsburg.

As can be seen in figure 10, the model is insensitive to different wind data inputs. The outcomes position practically on the line x=y. Even a constant wind speed gives highly accurate results of PET simulation.

Based on this sensitivity analysis, conclusion can be drawn that the wind data is of minor importance for the outcome of the PET-model. It must be noted however, that considering European scale, the distances across the Netherlands and the distance from De Bilt to Augsburg are relatively small. Therefore, the conclusion given above cannot be expected to straightforwardly hold true for the rest of Europe, as the conditions elsewhere might differ drastically from the conditions in the examples studied above. On the other hand, with the constant value of wind speed as input, the PET is simulated very well (correlation coefficient equals 0.996). Therefore, and due to lack other wind data sources, the conclusion drawn above will be considered as true and potential wind data from the Netherlands, and specifically from De Bilt, will be used for all stations selected (with exception for Augsburg in subsection 4.5). The reason behind the choice for De Bilt rather then Augsburg is the fact that wind data from Augsburg cover merely the period between 1991 and 2008, where data from De Bilt cover the period between 1961 and 2008.

WHC input sensitivity

WHC is a variable that is difficult to define due to its complex composition and the variability of the components (see eq. 3). As WHC is one of the three input variables needed for the MB-model, it is crucial for this study.

In order to examine how sensitive the MB-model is to the value of WHC, the soil moisture content (sp) is examined for different WHC inputs. For this purpose four model simulations are carried out. All four runs have the same PET- and precipitation input, but they differ in the WHC input. The WHC in the first run equals 150 cm, in the second run 200 cm, in the third one 250 cm and in the fourth run 300 cm, see figure 11.

Fortunately for this study, the sensitivity analysis shows that the WHC variability affects mainly the absolute magnitude of soil moisture, not its temporal behavior. Here, the main interest is set on the temporal changes of soil moisture, and the results of this sensitivity study motivate to settle for an approximation of WHC.

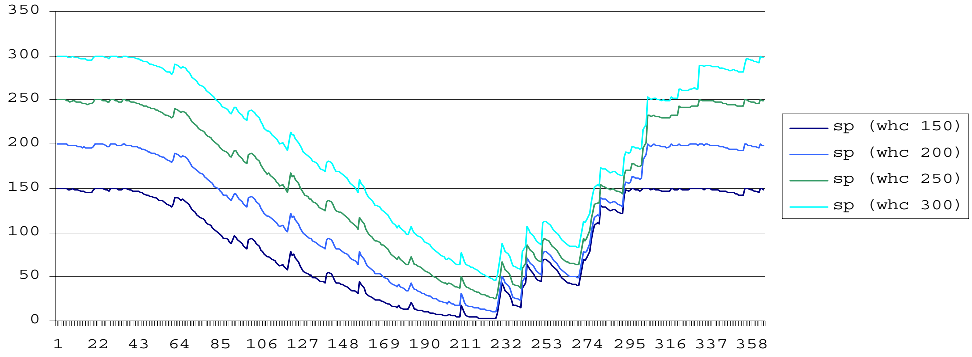

Figure 11: The course of the soil moisture content (sp) in four different scenarios; each scenario has a different value for water holding capacity. All other input remains unchanged and thus equal in all four cases. The test is carried out for Geneva, year 2003.

3. Methods

The data assessment with respect to the feedback between soil moisture and spells of extreme temperatures is approached in five different ways. Here, the applied methods by approach are discussed. Augsburg is chosen as the representative station, due to the completeness of data and its central position in Europe.

1. *Comparison of hot summer years with ordinary years*

For the comparison of hot summer years with ordinary years the daily soil moisture and maximum daily temperature (T_{MAX}) data of a hot summer year are compared to data of an ordinary year in order to draw conclusions about the differences between ordinary years and hot summer years. This analysis is based on visual differences, no statistical tests are applied. The hot summer years are represented by 1976 and 2003 and the ordinary years are represented by years that precede the warm summer years by two years, so 1974 and 2001.

2. *Comparison of the year 2003 with a climatological mean*

For the comparison of the year 2003 with a climatological mean the daily soil moisture and the daily T_{MAX} data of the year 2003 are compared with a climatological data series. Climatological data series is an average of 30 years, dating from 1961 to 1990. Over a period of 30 years, daily soil moisture as well as daily T_{MAX} is averaged by calendar days, in order to create two series, one for daily soil moisture and the other for daily T_{MAX}, which can function as a long term average series for both variables.

3. *Precipitation pattern analysis*

The precipitation patterns of the year 2003 are analyzed by calculating the cumulative difference between 2003 precipitation and a climatological precipitation. This approach is also carried out for the year 1976 in order to be able to make a comparison between both years.

4. *Comparison of the maximum temperatures of 2003 with virtual temperatures*

For the year 2003 a comparison is made with a “virtual” year series. For the creation of the virtual series, soil moisture levels from the year 2003 are compared day by day with soil moisture levels from the years 1961 until 2004 (obviously, the year 2003 was left out). The series is created by selecting calendar days from other years in the series with soil moisture levels that have the best resemblance with the soil moisture values at each calendar day of 2003. This selection takes place out of all available years. In this manner, a new series is developed, that contains soil moisture values as similar as possible to that of 2003. The corresponding T_{MAX} values form a new series that is treated here as a virtual series. Moreover, the high temperature days in both, the series of 2003 and the virtual series, are counted. Two thresholds for high temperatures are applied; ≥ 25°C and ≥ 30°C. Also the duration of the spells of high temperatures is determined, in order to help draw conclusions about the soil moisture - temperature feedback.

5. *Heat flux partitioning*

Firstly, in order to estimate the role of 2003 soil moisture on the surface heat balance, the 2003 ET_A and the 2003 T_{MAX} are compared to the climatological average series of these two variables.

A simplified equation for surface heat budget is as follow (upward terms are positive) [Stull, 1950]:

$$-Q_S = Q_H + Q_E - Q_G \tag{6}$$

Where:

Q_S = net radiation at the surface

Q_H = sensible heat flux

Q_E = latent heat flux

Q_G = soil heat flux

Actual evapotranspiration serves as a representative for latent heat flux:

$$Q_E = L_v ET \tag{4}$$

Where L_v is the latent heat of vaporization of water (J kg^{-1}) *[Stull, 1950]*:

$$L_v \cong (2.501 - 0.00237 \cdot T(°C)) \cdot 10^6 \tag{5}$$

For a daytime situation (Figure 12), when the sun begins to warm the surface, a sensible heat flux develops in order to remove some of the excess heat from the ground surface to the air. If the ground is moist, the latent heat flux stored in water vapor will also remove heat, through evaporation. Some heat will also be conducted into the ground through the molecular heat flux, but as the magnitude of this flux is negligible compared to the magnitude of the sensible and the latent heat flux, it will be neglected here.

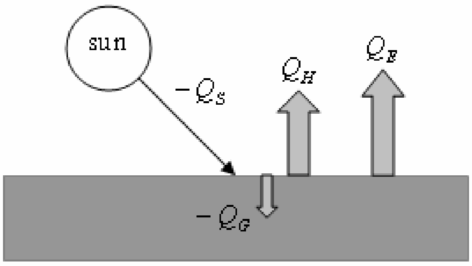

Figure 12: Terms of the surface energy balance for a daytime situation over land. Arrow length indicates relative magnitude (except for the radiation arrow) [Stull, 1950]

The magnitude of the latent heat flux depends on the moisture available in the soil. A decrease in soil moisture means a decreased availability of moisture for evaporation and thus a decrease in latent heat flux. This decrease is compensated by an increase in sensible heat flux. Increase in sensible heat flux directly means an increase in surface air temperature. As higher temperatures cause higher evaporative demand, this positive feedback has apparent influence on the length and severity of dry spells and spells of extreme temperatures.

Secondly, heat flux partitioning is applied in order to estimate the temperature rise related to a shift in the surface heat balance, a shift from latent heat flux to sensible heat flux.
The physics behind the feed back is that the evaporative cooling is curbed when soil moisture levels are low. The incoming short wave radiation should be balanced by the sum of the latent heat and the sensible heat flux. When the first is reduced, the latter should increase, which can only occur when surface temperatures rise.
Assuming that the incoming short wave radiation is approximately constant for the summers (this ignores changes in cloud cover):

$$Q_S^{2003} \approx Q_S^{ave} \qquad (7)$$

we have for the 2003 summer and an 'average' summer:

$$\frac{-Q_S{}^{2003} = Q_H{}^{2003} + Q_E{}^{2003}}{-Q_S{}^{ave} = Q_H{}^{ave} + Q_E{}^{ave}} \qquad (8)$$

Or:

$$1 \sim 1 + \frac{\Delta Q_H + \Delta Q_E}{Q_H{}^{ave} + Q_E{}^{ave}} \qquad (9)$$

The 'average' summer is represented by a climatological mean value over 30 years, dating from 1961 till 1990.
In the above equations ΔQ_H and ΔQ_E are the changes in sensible and latent heat flux, respectively, for the 2003 summer compared to the 'average' summer.
This leads to:

$$\Delta Q_E \approx -\Delta Q_H \qquad (10)$$

which is simply stating that the change in latent heat flux is compensated by the change in sensible heat flux.

The change latent heat flux is proportionate to the change in evapotranspiration (recalling eq. 4):

$$\Delta Q_E = L_v \Delta ET \tag{11}$$

Where ΔET is the difference between the 2003 evapotranspiration and the climatological mean value of evapotranspiration. Here $2.453 \cdot 10^6$ is used as a constant value for L_v.
Following Gill [*Gill, 1980*], the sensible heat flux can be written as follow:

$$Q_H = \rho_a \cdot c_p \cdot c_H \cdot u \cdot (T_s - T_a) \tag{12}$$

Where ρ_a is the density of air (1.188 kgm^{-2}), c_p is the heat capacity of air at constant pressure (1010 J kg^{-1} K^{-1}), c_H is the Stanton number and gives a measure for the rate of turbulent exchange of fluxes ($1.10 \cdot 10^{-3}$ for unstable conditions, $0.83 \cdot 10^{-3}$ for stable conditions), u is the wind speed, T_s is the temperature of the upper layer of the soils and T_a is the temperature at standard height.
For the 2003 summer, the relationship is used in order to calculate the increase in (T_s -T_a) based on the (modeled) reduction in evaporation:

$$\Delta(T_s - T_a) = \frac{L_v \Delta E}{-\rho_a c_p c_H u} \tag{13}$$

For wind speeds the *maximum* wind speed is used rather than the daily average since this would relate better to the unstable conditions which must have been present during the times of day with the highest temperatures. Values for the wind strength for Augsburg can be found at the site of the Deutsche Wetter Dienst [*DWD, 2008*].

4. Results and discussion

This section presents the results of the approaches applied to determine the role of soil moisture in the occurrence and the duration of spells of warm summer temperatures.
A simple and straightforward approach of correlating T_{MAX} with soil moisture content is presented figure 13.

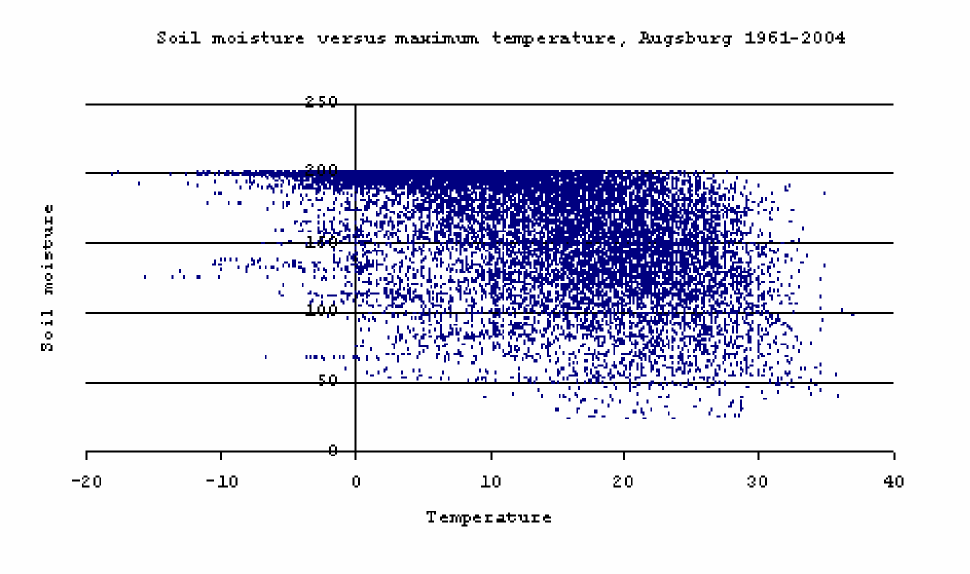

Figure 13: Correlation of T_{MAX} and soil moisture content, Augsburg 1961-2004

As can be seen this simple approach presents a slight indication that high temperatures are coupled to low levels of soil moisture, and/or the other way around. Analyses of other stations give similar results. However, the results are not very forceful. A lot of scattering can be seen in the figure, which denotes a high level of spreading. Therefore five different approaches of data assessment are applied:

(1) Comparison of hot summer years with ordinary years
(2) Comparison of the year 2003 with a climatological mean
(3) Precipitation pattern analysis
(4) Comparison of the maximum temperatures of 2003 with virtual temperatures
(5) Heat flux partitioning

4.1. Hot summer years versus ordinary years

The two figures on the next page represent the courses of the total modeled soil moisture content and of observed T_{MAX}, with the length of one year each. In all two figures two years are included, one of the two years is a hot summer year and the other one is an average year, preceding two years before the hot summer year. The time span of two years is chosen arbitrary. The hot summer years represented in the two figures are 1976 and 2003 [based on criteria from *Vautard et al, 2007*].

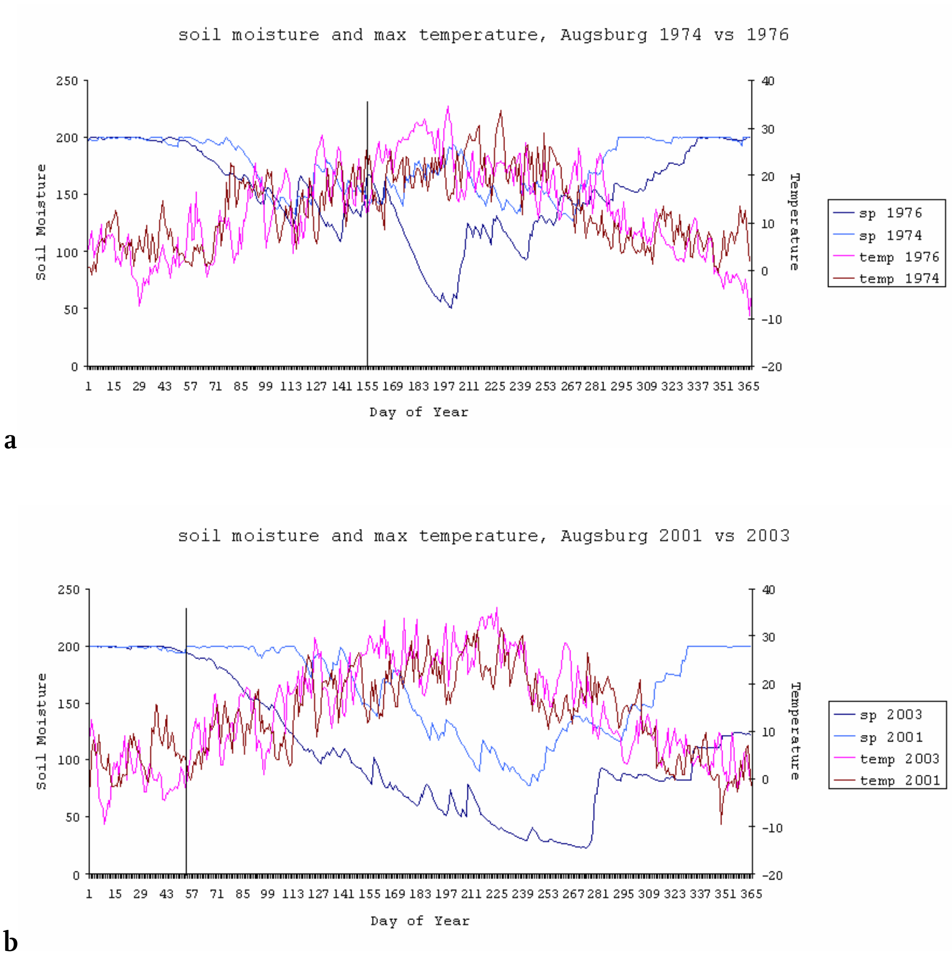

Figure 14: Representation of the two hot summer years (a: 1976 and b: 2003) in comparison to two "ordinary" years - the years preceeding the hot summer years by two years (so a: 1974 and b: 2001), for Augsburg. The dark blue lines show the daily soil moisture content in the hot summer year, blue lines are the daily soil moisture content in an ordinary year, pink lines represents the T_{MAX} profile for the hot summer year and the brown lines show the T_{MAX} profile for the ordinary year.

As can be seen in the figures presented above, the situation of 2003 is different from the situation of 1976. Both figures show disparity between the warm summer year and ordinary year, but the disparity in figure 14a is not as significant and constant as the disparity between the years 2001 and 2003 (Figure 14b) and it is also of significantly shorter duration. The 2003 soil moisture not only drops far below the soil moisture in the ordinary year, but it is also much lower than the soil moisture content in 1976. Also T_{MAX} in 2003 jump more often above the threshold of 30°C then it does in 1976.

In 1976 it also seems as if the soil moisture decline follows the rise in temperatures and not precedes it. Main drops in the soil moisture level seem to be accompanied by jumps in temperature few days before. A good example is the jump around day 155 (indicated in the figure with a vertical black line). From then on, T_{MAX} remain overall high, and this rise is followed by a drop in soil moisture, with a time lag of around one week. Therefore, it is reasonable to state that the soil moisture content declined because of the rise in the temperature. When temperatures rise, the evaporative demand rises as well. In order to meet this increased demand, more soil moisture will evaporate. Thus the rise in temperature seems to be the cause and the decline in soil moisture the consequence.

The situation of 2003 seems to be slightly different; the soil moisture content drops before the temperatures rise to extremes. This can best be seen around day 55 (indicated in the figure with a vertical black line); the soil moisture starts to decline around that day, even though this is not preceded by any major increase in temperature. This finding likely indicates the existence of a soil moisture feedback.

4.2. Year 2003 versus climatological mean

As the disparities in soil moisture content between the hot summer year 1976 and the corresponding two years predecessor is overall not very large, and in case it is large, it is of a relatively short duration, it is plausible to state that no evidence is found of soil moisture feedback in that particular year.

The case of 2003 seems to be a slightly different story. In the beginning of 2003, the levels of soil moisture are as high as the levels in 2001. Around mid February (± day 43) the level of soil moisture starts to decline. However, the temperatures are still on the low side compared to 2001. Once the soil moisture declines significantly, the temperatures start showing a trend of average higher values than in 2001.

In order to investigate the year 2003 more thoroughly and in order to exclude the coincidence possibly attached to the arbitrary choice of the year 2001, the values of soil moisture and T_{MAX} are compared to a 30-years average, ranging from 1961 till 1990 as presented in figure 15.

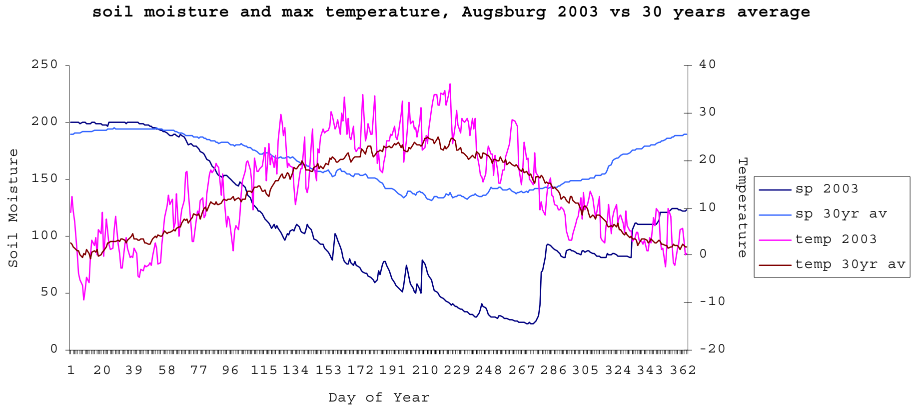

Figure 15: The T_{MAX} for the year 2003 (pink line) and the climatological (1961-1990) T_{MAX} for Augsburg station. The blue lines show the course of soil moisture: the dark blue line represents the 2003 value and the light blue line represents the climatological value.

As can be seen in the figure 15, around day 55, the 2003 soil moisture starts to drop far below the long term average soil moisture and the temperatures also show a large difference compared to the 30-years average. With a confidence interval of the difference of 98%, the significance value equals 0.00. As this value is lower then 0.02, it indicates that there is a significant difference between the two series (see Table 2 in Appendix 2).

The 2003 soil moisture shows a decrease prior the increase in T_{MAX}. This raises a hypothesis that soil moisture might have played a great role in the onset of the heat wave in the summer of 2003 in Europe. This holds also true for all station analyzed that had sufficient data to apply this approach (figures in Appendix 3). In order to look into the reason for the anomalously low soil moisture levels, the precipitation patterns for the year 2003 will be examined next. Also a comparison with the year 1976 is included.

4.3. Precipitation patterns analysis

Recalling eq. 1, it is evident that the amount of precipitation has a direct influence on the soil moisture content. Thus, one of the possibilities for the soil moisture of 2003 to be below its average value might be an anomalously low precipitation. Figure 16 shows the cumulative sum of the difference between the precipitation amount in year 2003 (and 1976) and climatological average precipitation.

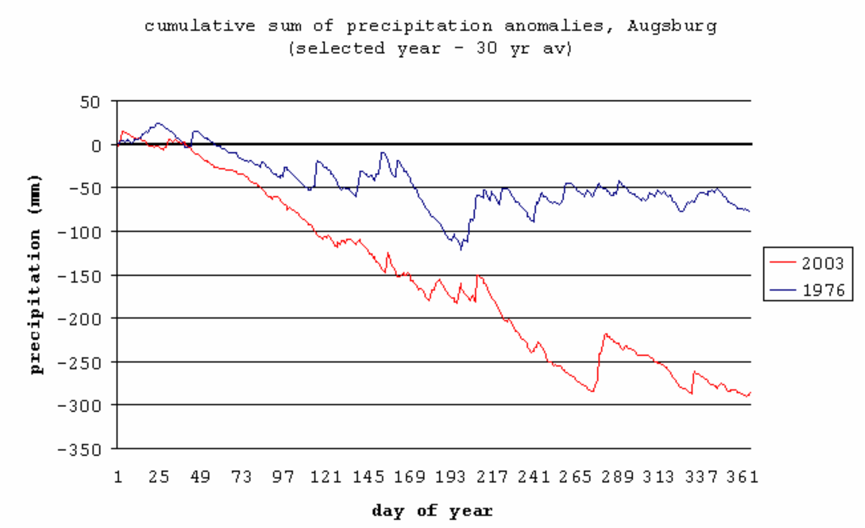

Figure 16: The cumulative sum of the difference between the precipitation in a selected year (1976 or 2003) and the climatological (1961-1990) precipitation, Augsburg

As can be seen in figure 16, both years started with a slight rain excess with respect to the climatological precipitation, but shifted to a negative value in February and remained negative on the cumulative scale. Remarkable is the difference between the two years. Both years show a predominantly negative course, but where 1976 compensates periodically with an increase in the precipitation, 2003 remains decreasing and ends at a value approximately three times lower then 1976. This indicates that both years had a precipitation deficit compared to a climatological series. Thereupon, the year 2003 experienced an enormous deficit in precipitation and can be seen as an anomalously dry year. Therefore it is likely that a significant part of the drive of the heat wave in the year 2003 can be assigned to low soil moisture.

4.4. 2003 versus “virtual” year

In order to distinguish the effect of long term soil moisture deficiency on T_{MAX}, a “virtual” T_{MAX} series for the year 2003 is created. By comparing the real 2003 situation with a virtual series, insight is gained in the effect that memory of soil moisture has on T_{MAX}, as the series of 2003 is a continuous series and the virtual series is a chain of single days of different year combined together into one series. By combining single days together, a part of the memory is erased, as the conditions of a certain day in this virtual series have no influence on the conditions of the next day in this series. This does not hold true for all data points, as some days in a row with best soil moisture resemblance with 2003 could be found in one single year. Therefore, the memory is not completely erased in the virtual series.

The result of this approach is presented in figure 17.

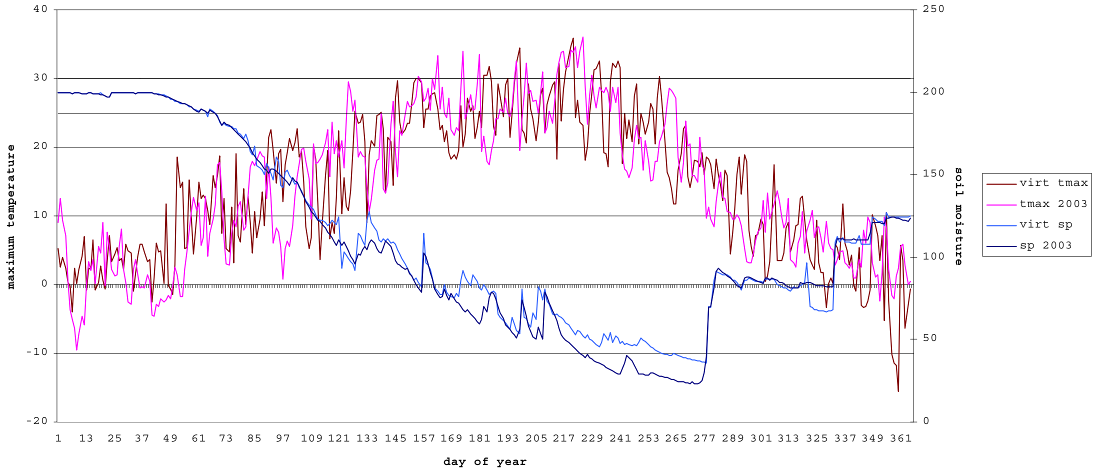

Figure 17: T_{MAX} for 2003 (pink line) and virtual T_{MAX} (brown line) for Augsburg station. The dark blue line represents the values for soil moisture content in 2003 and the bright blue line represents the virtual soil moisture content values.

During a certain period of time in 2003, soil moisture levels were lower than the levels of any year between 1961 and 2004, most prominently between 1st of August (day 213) and 5th of October (day 278). The average T_{MAX} in the summer months June, July and August (days 152 till 243 in the graph), was over 1°C higher in 2003 than in the corresponding summer average of the virtual series. When looking at the extreme values, both series have the same amount of days with T_{MAX} higher than 30°C, namely 21 days. However, days with T_{MAX} higher than 25°C, are more frequent in 2003; the virtual series count 63 days and the series of 2003 count 80 days. Moreover, when looking at the spells of extreme temperatures instead of single days, one more dissimilarity is found. The virtual series contain no spells of ten days or more in a row with T_{MAX} higher than 25°C, whereas the series of 2003 even contain a spell of twelve days with T_{MAX} higher than 30°C. Furthermore, two more spells with T_{MAX} higher than 25°C can be found in the 2003 series, one of 17 days and one of 13 days. Apparently a persistent deficit of soil moisture contributes to the establishment of spells of extreme temperatures. Although the levels of soil moisture in the virtual series are almost as low as the soil moisture levels in 2003 (with exception of the period between days 213 and 278, as mentioned previously), the virtual series is not a continuous series with an ongoing memory. This is in line with the findings of Fischer[1,2] et al. [2007]. They demonstrated that soil moisture may strongly amplify European temperature anomalies in an extreme summer as the one in 2003. They state that in absence of the soil moisture feedback, the summer of 2003 would still be warm, but it would not have been as disastrous as it turned out to be. This is in line with the findings by Black et al [2004]. They found that the latent heat flux anomaly was initially positive, but became, due to a ongoing drying of the earth, gradually more and more negative. Conversely, the sensible heat flux anomaly remained positive and increasing, causing the surface air temperatures to increase more and more.

4.5. Heat flux partitioning

In order to estimate the role of 2003 soil moisture on the surface heat balance, the 2003 ET_A and the 2003 T_{MAX} are compared to the climatological average series of these two variables. Figure 18 shows the anomaly in T_{MAX} (ΔT_{MAX}) (red dots) and in T_{MAX} (ΔET_A) (blue dots) of 2003 from the climatological means (1961-1990). The continuous red line represents the moving average for ΔT_{MAX} and the blue line represents the moving average for ΔET_A. The moving average is in both cases over a period of 7 days. The length of the period is long enough to exclude the noise and short enough to still be relevant for this study as this study focuses on short term relationships.

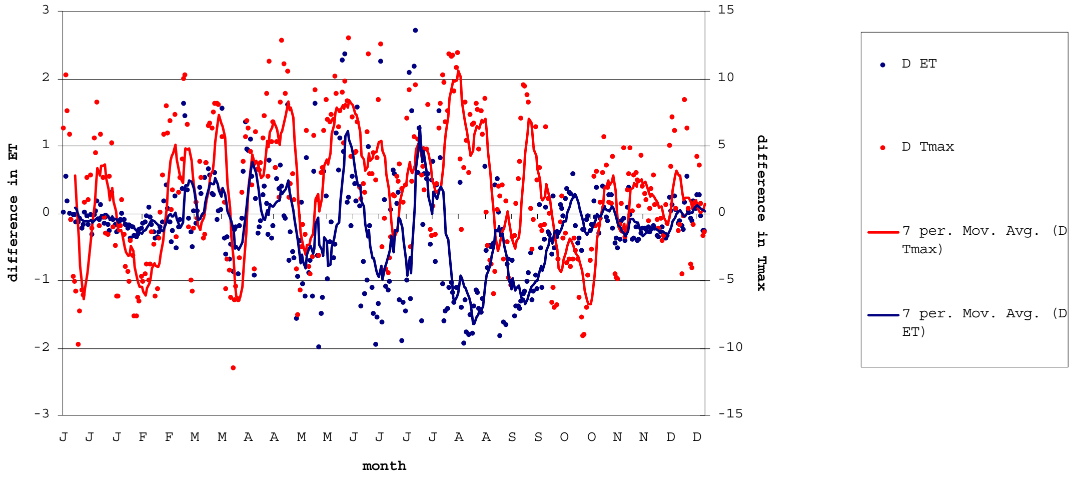

Figure 18: ΔT_{MAX} (red dots) and ΔET_A (blue dots) of 2003 from climatological mean. Red line represents 7 period moving average of ΔT_{MAX} and blue line represents 7 period moving average of ΔET_A, all for the station of Augsburg.

A negative ΔET_A value in the figure above indicates that the ET_A of that particular day in 2003 was lower then the corresponding climatological mean value. As ET_A is proportional to latent heat flux and thus disproportional to sensible heat flux (see chapter 3), a negative ΔET_A

value in the figure denotes that the heat flux balance was shifted toward sensible heat flux with respect to the climatological mean.

Overall, the course of ΔET_A is proportional to the course of ΔT_{MAX}. This likely indicates the absence of the soil moisture feedback and makes it plausible to state that the rise in temperature can be assigned to circulation patterns.

However, in August the jump in ΔT_{MAX} is accompanied by a large drop in ΔET_A. As a drop in ΔET_A denotes a decreased evaporation with respect to average value, and a decrease in evaporation means a decrease in latent heat flux, sensible heat flux must increase in order to close the surface heat balance. The increase in ΔT_{MAX} shows that this increase indeed took place.

In order to estimate the temperature rise related to a shift in the surface heat balance, heat flux partitioning is applied. Figure 20 is the result of this approach for Augsburg for the 2003 summer. The shift compounds of $\Delta(T_s - T_a)$ (which is proportional to a sensible heat flux anomaly, see eq. 13) superposed on the climatological mean temperature series.

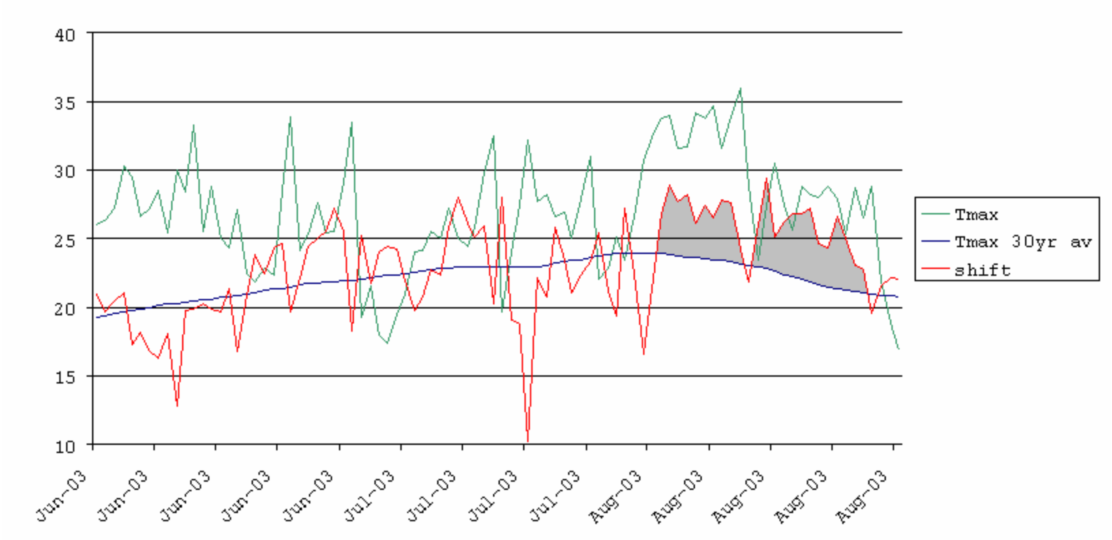

Figure 19: The climatological (1961-1990) T_{MAX} values (blue, smoothed with a 31-day weighted running mean) and the measured T_{MAX} values (green) for the 2003 summer in Augsburg. The red line denotes the increase of temperatures due to the shift in the radiation balance superposed on the climatological mean values.

Here, analogous with figure 18, August 2003 stands out when the shift in the surface heat balance is considered. As can be seen in figure 19, the high temperatures in August are accompanied by a rise in $\Delta(T_s - T_a)$ and thus a rise in the sensible heat flux. The gray shaded area in the figure indicates the part of the temperature rise that can be assigned to the shift in the surface heat balance towards sensible heat flux.

These findings likely indicate the presence of the soil moisture feedback and make it plausible to state that a significant part of the rise in temperature in August 2003 can be assigned to this feedback.

5. Conclusions

- Model validation and sensitivity tests convince that the models used in this study are valid and robust
- As expected, hot summer years (1976 and 2003) have lower soil moisture contents then ordinary years
- For the station of Augsburg, the year 2003 was drier then 1976:
  - Duration of the period with low soil moisture levels is considerably longer in 2003 then in 1976
  - Anomalous precipitation deficit in 2003 is significantly larger than in year 1976
- The year 2003 is significantly warmer and drier then the climatological mean value:
  - Soil moisture drops and remains far below the long term average soil moisture
  - 2003 maximum temperatures show a significant difference compared to the climatological mean values of maximum temperatures
- Beside the levels of soil moisture, also the memory of soil moisture plays an important role in the occurrence and persistence of extreme temperatures, as is evident from the comparison of 2003 maximum temperature series with the virtual maximum temperature series
- August 2003 experienced a major shift from latent towards sensible heat flux. Large part of the temperature anomaly in that month can be assigned to an increase in sensible heat flux. This shift indicates the presence of the feedback between soil moisture and temperatures
- Considering all findings, it is credible to state that the anomalously low soil moisture content indeed had a great influence on the onset and persistence of extreme conditions in the summer of 2003, at least for the stations selected in this study. Of course many different factors might have played a role, but a deficit in soil moisture was certainly one of them
- The regularity and consistency in the findings strongly indicate the robustness of the results

Recalling the research question "**Are low levels of soil moisture linked, through a feedback mechanism, to spells of extreme temperatures for the stations in the ECA dataset?**", a general conclusion can be drawn that; *"yes, considering all findings it is credible to state that low levels of soil moisture are linked to spells of extreme temperatures through a feedback mechanism. This at least holds true for a situation similar to Augsburg in August of 2003".*

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Appendix 1

```
      implicit none
      integer   fyear,lyear

      call readarg()

      call readPE(fyear,lyear)

      call readprecip(fyear,lyear)

      call palmer(fyear,lyear)

      call output(fyear,lyear)

      end
      implicit none

      integer     bcaly,ecaly,begyr,endyr
      real        absent,absen
      parameter   (bcaly=1931,ecaly=1980,begyr=1900,endyr=2010)

      integer     kd,kstn,iend,i,j,k,fyear,lyear,length
      real*8      whc,precip
      real*8      wctop,wcbot,ss,su,wctot,et,p,sl,ul,tl,ro
      real*8      ssu,sss,r,rs,ru,pe,pl,sp,pr
      real*8      xPE(begyr:endyr,12,31)
      real*8      xprecip(begyr:endyr,12,31)
      real*8      xprecipnorm(12,31),xPEnorm(12,31)
      real*8      spdat(begyr:endyr,12,31),
     +    pldat(begyr:endyr,12,31), prdat(begyr:endyr,12,31),
     +    rdat(begyr:endyr,12,31), tldat(begyr:endyr,12,31),
     +    etdat(begyr:endyr,12,31), rodat(begyr:endyr,12,31),
     +    sssdat(begyr:endyr,12,31), ssudat(begyr:endyr,12,31)


      character*15  outfile,PEfile,precipfile

      common /inputpar/ PEfile,precipfile,outfile
      common /data1 /xPE,xprecip
      common /soilpar/ whc
      common /outdata/spdat,pldat,prdat,rdat,tldat,etdat,rodat,
     +           sssdat,ssudat

      absent = -99.9
      absen = -99.0

      call calcNormals(xPEnorm,xprecipnorm)

      wctop = 25.0
```

```
call mm2inch(wctop)
wcbot = whc

call mm2inch(wcbot)

if(whc.lt.1.0) then
  wcbot = 0.0
else
  wcbot = wcbot - wctop
endif

ss = wctop
su = wcbot
wctot = wcbot

kd=0
kstn=0
iend=0

do i=fyear,lyear
  do j=1,12
    call lengthofmonth(i,j,length)
    do k=1,length
      pe = xPE(i,j,k)
      if(pe.lt.absen) pe = xPEnorm(j,k)
      sp = ss + su
      pr = wcbot + wctop - sp
      p = xprecip(i,j,k)
      if(p.lt.absen) p = xprecipnorm(j,k)
      call mm2inch(p)
      if (ss.ge.pe) then
        pl  = pe
      else
        pl   = ((pe - ss) * su) / (wcbot + wctop) + ss
        pl   = amin1(pl,sp)
      endif
      if (p.ge.pe) then
        et = pe
        tl = 0.0
        if ((p - pe).gt.(wctop - ss)) then
          rs = wctop - ss
          sss = wctop
          if ((p - pe -rs).lt.(wcbot - su)) then
            ru = p - pe - rs
            ro = 0.0
          else
            ru = wcbot - su
            ro = p - pe - rs - ru
          endif
          ssu = su + ru
          r   = rs + ru
        else
```

```
           r   = p - pe
           sss = ss + p - pe
           ssu = su
           ro  = 0.0
          endif
         else
          r = 0.0
          if (ss.ge.(pe - p)) then
           sl = pe - p
           sss = ss - sl
           ul = 0.0
           ssu = su
          else
           sl  = ss
           sss = 0.0
           ul  = (pe - p - sl) * su / (wctot + 1.0)
           ul  = amin1(ul,su)
           ssu = su - ul
          endif
          tl  = sl + ul
          ro  = 0.0
          et  = p  + sl + ul
         endif
         spdat(i,j,k)=sp
         pldat(i,j,k)=pl
         prdat(i,j,k)=pr
         rdat(i,j,k)=r
         tldat(i,j,k)=tl
         etdat(i,j,k)=et
         rodat(i,j,k)=ro
         sssdat(i,j,k)=sss
         ssudat(i,j,k)=ssu

         su = ssu
         ss = sss
        enddo
       enddo
      enddo

40    format(9f7.2)
      return
      end
      subroutine readarg
      implicit none

      integer       numdat
      real*8        whc,finput
      character*15  outfile,PEfile,precipfile
      character*128 ainput

      common /inputpar/ PEfile,precipfile,outfile
```

```
      common /soilpar/ whc

      call inputt(5,numdat)

      whc    = finput()
      PEfile = ainput()
      precipfile = ainput()
      outfile = ainput()

      write(6,11) whc,PEfile,precipfile,outfile

11    format('Water Holding Capacity : ',f12.5,/,
     ,       'Pot. Evaporation file  : ',a15,/,
     ,       'Precipitation file     : ',a15,/,
     ,       'Output file            : ',a15)

      return
      end

      subroutine mm2inch(p)
      implicit none

      real        p

      p = p/25.4

      return
      end
      subroutine C2F(t)
      implicit none

      real        t

      t = (9.0/5.0)*t + 32.0

      return
      end

      subroutine readPE(fyear,lyear)
      implicit none
      integer      begyr,endyr,fyear,lyear
      parameter    (begyr=1900,endyr=2010)
      integer      year,month,day
      real*8       xPE(begyr:endyr,12,31)
      real*8       xprecip(begyr:endyr,12,31)
      real*8       pe,fdum
      character    clong*10

      character*15  outfile,PEfile,precipfile

      common /inputpar/ PEfile,precipfile,outfile
      common/data1 /xPE,xprecip
```

```
      call initialize(xPE)

      fyear = endyr
      lyear = begyr
      open(1,file=PEfile,status='old')
      read(1,*) clong
20    read(1,*,end=200) month,day,year,fdum,pe

      if(year.lt.fyear) fyear = year
      if(year.gt.lyear) lyear = year

      xPE(year,month,day) = pe
      goto 20

200   close(1)
      write(6,*) 'Potential Evaporation file read'

110   format(3I4,2f8.2)
111   format(A10,f6.1,f5.1)
112   format(I4,2I3,f6.2)

      return
      end
      subroutine readprecip(fyear,lyear)
      implicit none
      integer      begyr,endyr
      parameter    (begyr=1900,endyr=2010)
      integer      year,month,day,fyear,fyearprecip,lyear,lyearprecip
      real*8       xPE(begyr:endyr,12,31)
      real*8       xprecip(begyr:endyr,12,31)
      real*8       precip

      character*15  outfile,PEfile,precipfile

      common /inputpar/ PEfile,precipfile,outfile
      common/data1 /xPE,xprecip

      call initialize(xprecip)

      fyearprecip = endyr
      lyearprecip = begyr

      open(1,file=precipfile,status='old')
20    read(1,110,end=200) year,month,day,precip

      if(year.lt.fyearprecip) fyearprecip = year
      if(year.gt.lyearprecip) lyearprecip = year

      xprecip(year,month,day) = precip
      goto 20
```

```
200  close(1)
     write(6,*) 'Precipitation file read'

     fyear = max(fyear,fyearprecip)
     lyear = min(lyear,lyearprecip)

110  format(I6,2I4,f8.2)
112  format(I4,2I3,f6.2)

     return
     end

     subroutine initialize(array)
     implicit none
     integer      begyr,endyr
     parameter    (begyr=1900,endyr=2010)
     integer      i,j,k
     real*8       array(begyr:endyr,12,31)
     real*8       absent

     absent = -99.9
     do i=begyr,endyr
       do j=1,12
         do k=1,31
           array(i,j,k) = absent
         enddo
       enddo
     enddo

     return
     end
     subroutine output(fyear,lyear)
     implicit none

     integer      begyr,endyr
     real         absent,absen
     parameter    (begyr=1900,endyr=2010)

     integer      kd,kstn,iend,i,j,k,fyear,lyear,length
     real*8       spdat(begyr:endyr,12,31),
    +     pldat(begyr:endyr,12,31), prdat(begyr:endyr,12,31),
    +     rdat(begyr:endyr,12,31), tldat(begyr:endyr,12,31),
    +     etdat(begyr:endyr,12,31), rodat(begyr:endyr,12,31),
    +     sssdat(begyr:endyr,12,31), ssudat(begyr:endyr,12,31)
     character*15  outfile,PEfile,precipfile


     common /inputpar/ PEfile,precipfile,outfile
     common /outdata/spdat,pldat,prdat,rdat,tldat,etdat,rodat,
    +            sssdat,ssudat

     absent = -99.9
```

```
      open(1,file=outfile)
      do i=fyear,lyear
        do j=1,12
              call lengthofmonth(i,j,length)
          do k=1,length
            write(1,200) i,j,k,etdat(i,j,k)
          enddo
        enddo
      enddo

200   format(3I4,f8.2)

      return
      end
      subroutine calcNormals()

      implicit none

      integer      bnory,enory,begyr,endyr
      real         absent,absen
      parameter    (bnory=1961,enory=1990,begyr=1900,endyr=2010)

      integer      i,j,k,length,npres
      real*8       xdum
      real*8       xPE(begyr:endyr,12,31)
      real*8       xprecip(begyr:endyr,12,31)
      real*8       xprecipnorm(12,31),xPEnorm(12,31)

      absent = -99.9
      absen = -99.0

      do j=1,12
        call lengthofmonth(1973,j,length)
        do k=1,length
          npres = 0
          xdum = 0.0d0
          do i=bnory,enory
            if(xPE(i,j,k).gt.absen) then
              npres = npres + 1
              xdum = xdum + xPE(i,j,k)
            endif
          enddo
          if(npres.gt.0) then
            xPEnorm(j,k) = xdum/dble(npres)
          else
            write(6,*) 'not enough data to calculate climatology'
            stop
          endif
        enddo
      enddo
```

```
do j=1,12
  call lengthofmonth(1973,j,length)
  do k=1,length
    npres = 0
    xdum = 0.0d0
    do i=bnory,enory
      if(xprecip(i,j,k).gt.absen) then
        npres = npres + 1
        xdum = xdum + xprecip(i,j,k)
      endif
    enddo
    if(npres.gt.0) then
      xprecipnorm(j,k) = xdum/dble(npres)
    else
      write(6,*) 'not enough data to calculate climatology'
      stop
    endif
  enddo
enddo
return
end

subroutine lengthofmonth(iyear,imonth,length)
implicit none
integer         iyear,imonth,length
logical         leap

if(imonth.le.6) then
  if(imonth.eq.1) then
    length = 31
  elseif(imonth.eq.2) then
    call leapyr(iyear,leap)
    if(leap) then
      length = 29
    else
      length = 28
    endif
  elseif(imonth.eq.3) then
    length = 31
  elseif(imonth.eq.4) then
    length = 30
  elseif(imonth.eq.5) then
    length = 31
  else
    length = 30
  endif
else
  if(imonth.eq.7) then
    length = 31
  elseif(imonth.eq.8) then
    length = 31
  elseif(imonth.eq.9) then
```

```
    length = 30
  elseif(imonth.eq.10) then
    length = 31
  elseif(imonth.eq.11) then
    length = 30
  else
    length = 31
  endif
endif
return
end

subroutine leapyr(iyear,leap)
implicit none

integer          iyear
logical          leap
if(mod(iyear,4).eq.0) then
  leap = .true.
else
  leap = .false.
endif
if((iyear.eq.1800).or.(iyear.eq.2000)) leap = .false.

return
end
```

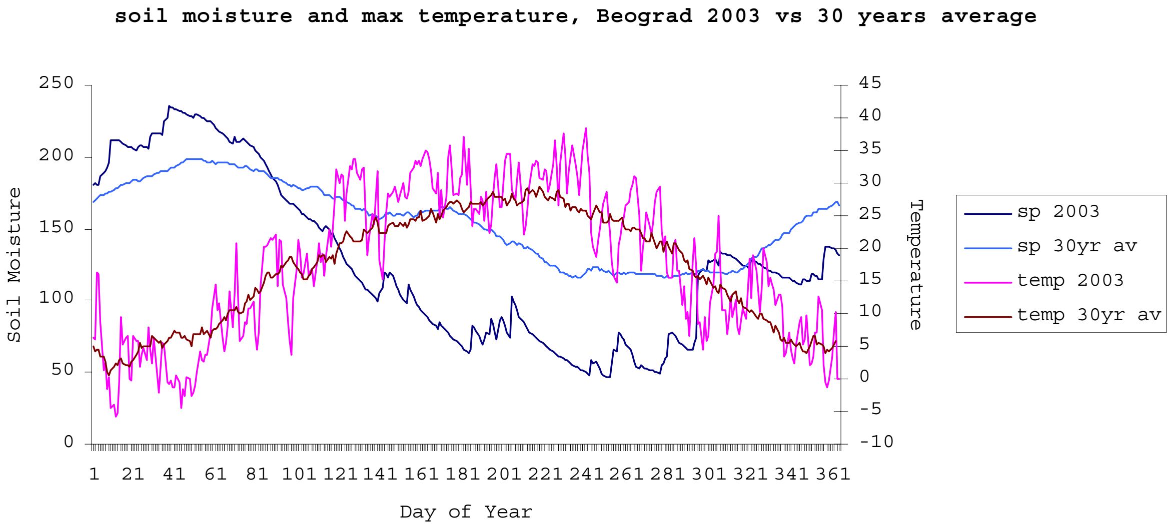
Appendix 2

Table 2: Paired-samples T-test for the 2003 (real) and virtual series with a confidence interval of 98%.

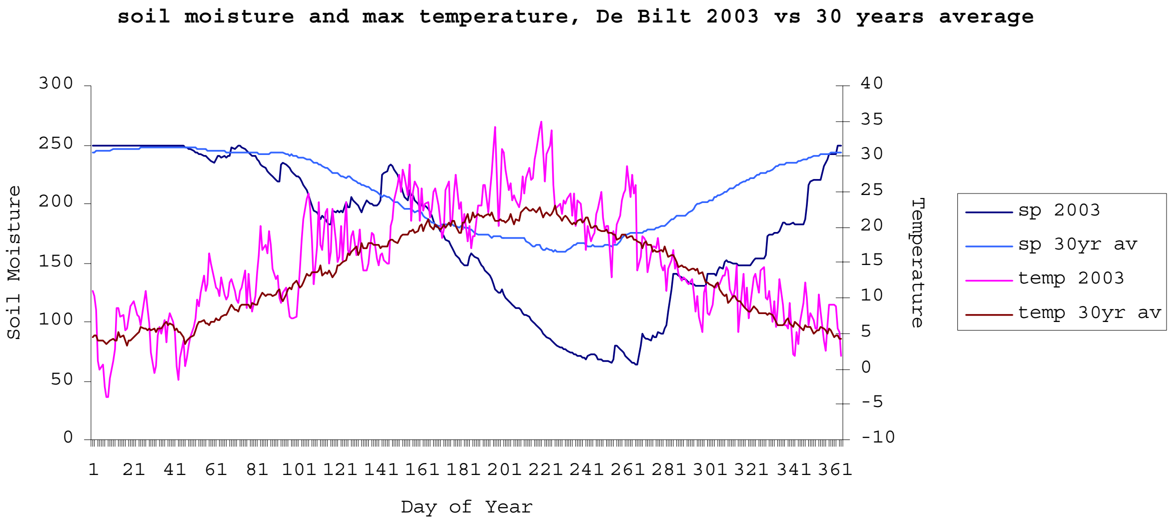
		Paired Differences					t	df	Sig. (2-tailed)
					98% Confidence Interval of the Difference				
		Mean	Std. Deviation	Std. Error Mean	Lower	Upper			
Pair 1	real - virtual	1,63106	5,01329	,26241	1,01791	2,24421	6,216	364	,000

Appendix 3

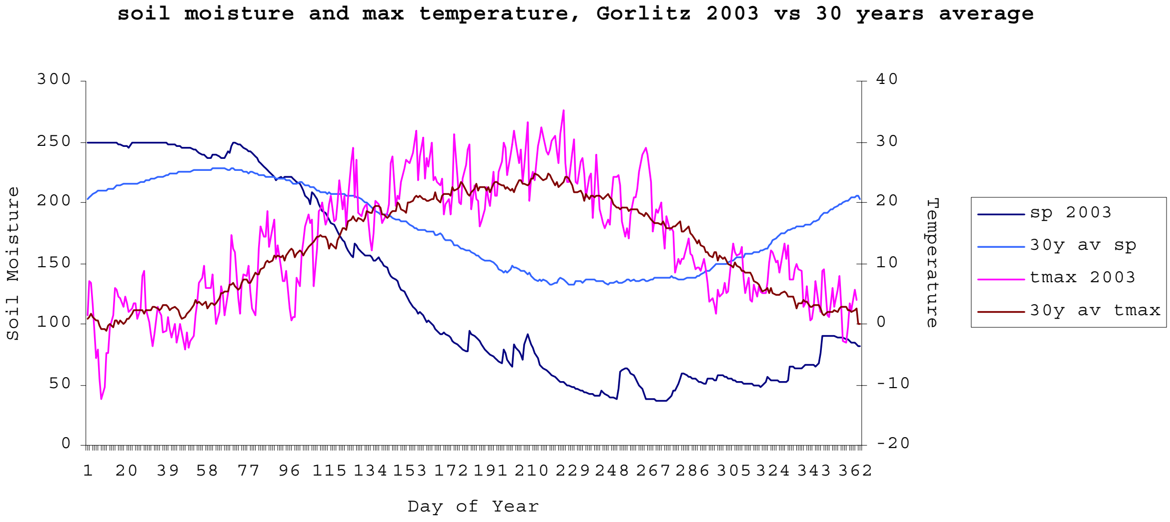
Station of Beograd:



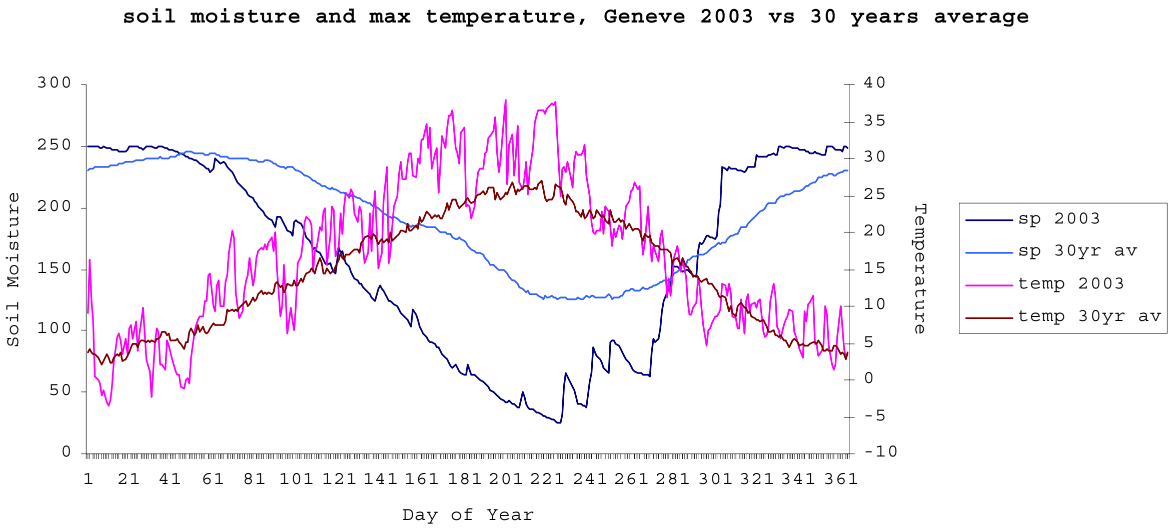
Station of De Bilt:



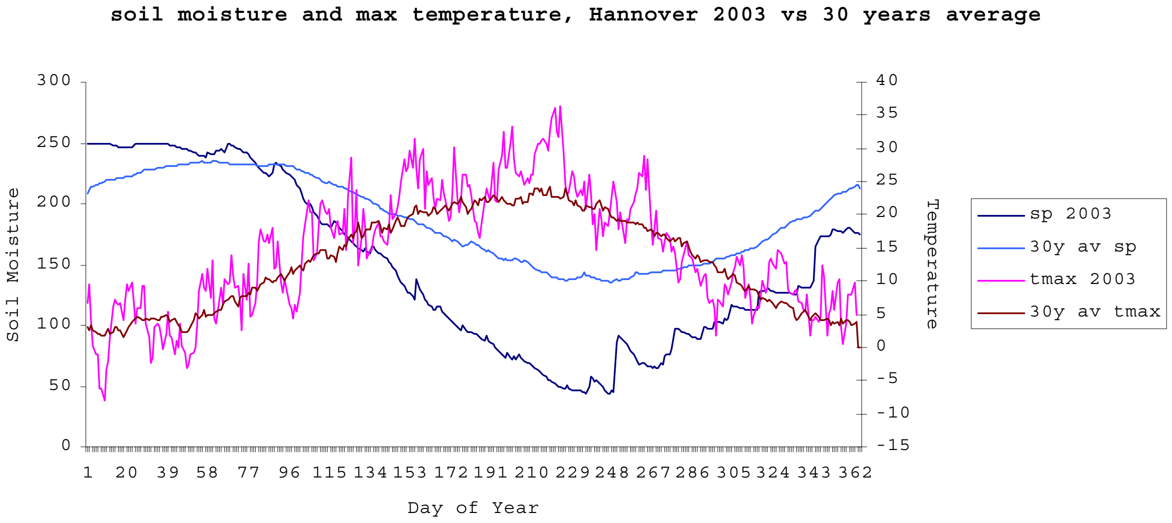
Station of Geneve:



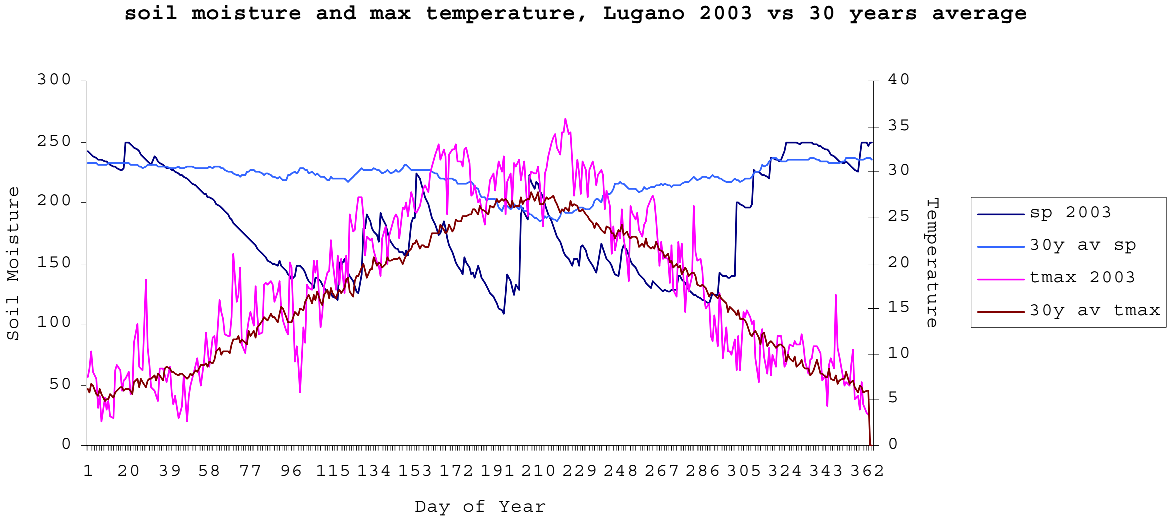
Station of Görlitz:



Station of Hannover:



Station of Lugano:



Station of Ni: