Soil Water Retention and Gross Primary Productivity in the Zábrod area in the Šumava Mts.

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Abstract: The synergy between the hydrologic extremes, plant transpiration, gross primary productivity, and soil water retention was studied in the experimental area Zábrod – Meadow in the Šumava Mts. (Bohemian Forest) during the vegetative seasons of 1983–2000. The heat balance, potential and actual transpiration, entropy production and gross primary productivity were evaluated. It was found that the global radiation, precipitation amount, and soil water retention are the crucial factors determining the hydrologic pattern and gross primary productivity. Insufficient soil water retention leads to low entropy production by evaporation and low gross primary productivity, which results in the extremalisation of the hydrologic cycle. On the other hand, in the case of sufficient soil water retention, high entropy production by transpiration and high gross primary productivity lead to the stability of the hydrologic cycle.

Keywords: hydrologic cycle; evapotranspiration; gross primary productivity; entropy production; soil water retention

A significant role of the soil water in the hydrologic cycle was pointed out in the textbook of Kutílek (1978). The author called attention to the fact that the soil cover forms a huge water reservoir. Its retention capacity is one order greater than the capacity of all artificial and natural water reservoirs in the Czech Republic and Slovakia. The soil water is monitored in the long-term in the hydrologic research in the Šumava Mts., Krkonoše Mts., Jizerské hory Mts., Orlické hory Mts., Bohemo-Moravian Highland, Beskydy Mts., and Jeseníky Mts. in the Czech Republic (e.g. Chlebek & Jařabáč 1994; Šír *et al.* 2004b; Tesař *et al.* 2006; Doležal *et al.* 2004).

The analysis of the relationships between the transpiration and vegetation temperatures, precipitation, soil water retention and runoff (Chlebek & Jařabáč 1994; Tesař *et al.* 2001; Šír *et al.* 2004b; Tesař *et al.* 2006) led to the finding that

Supported by the Academy of Sciences of the Czech Republic, Institutional Research Plan AV0Z20600510 and Project No. 1QS200420562, by the Czech Science Foundation, Project Nos. 205/05/2312 and 205/06/0375, by the Ministry of Environment of the Czech Republic, Project No. SP/1a6/151/07, by the Ministry of Education, Health and Youth of the Czech Republic, Project No. 2B06132, and by the Scientific Grant Agency VEGA, Project No. 2/6003/26.

two factors maintain the regular character of the hydrologic cycle in mountainous conditions:

(1) Sufficient retention and infiltration capacity of the soil cover: the soil operates as a reservoir which compensates for the differences between the irregular inflow of rainwater and the generally regular water uptake for the plant transpiration in the vegetative season. The greater the soil retention capacity, the more reliable the compensation for differences between water inflow and uptake. As a result, a sufficient amount of water circulates in the hydrologic cycle and, simultaneously, no extreme runoff is generated and the plant transpiration is not limited by water shortage.

(2) Sufficient area of the landscape covered by fully transpiring plants during the whole growing season: during the growing season, transpiration causes sufficient cooling of the landscape, thus rather small temperature differences originate in diverse segments of the landscape from the solar heating. As a result, heavy rains, whose formation is catalysed by great differences in temperatures, are not generated, and the prevailing rains of rather small intensities are reliably stored in the soil.

The above-mentioned analysis gave no answers to the questions relating to the reasons for the observed homeostatic tendency in the case of the plant cover being changed by human activity (Chlebek & Jařabáč 1988) or the properties of the atmosphere being changed by volcanic eruptions (Šír *et al.* 2004a). When the fundamental cause of homeostasis was found in plant transpiration (Pokorný 2001), the analysis of the entropy production by evaporation was shown to be a promising way to solve this problem (Kleidon 2006, 2008; Tesař *et al.* 2007).

The aim of this study is the analysis of synergy between meteorological quantities (precipitation, income of solar heat), plant transpiration, gross primary productivity, and soil water retention in the experimental area Zábrod – Meadow in the Šumava Mts. (Bohemian Forest) during the growing seasons (1. 6.–30. 9.) 1983–2000.

Experimental catchment

The Zábrod – Meadow experimental area is situated in the mountainous and submontane regions of the Šumava Mts. This locality lies in the Vimperk Highlands, which are a part of the Moldanubicum metamorphic complex. It is formed mainly of metamorphosed rocks, paragneiss with smaller injected localities in the northern part of the region. In the valley bottoms, the whole bedrock is covered by non-calcareous (acid) sediments, and in depressions and the middle parts of slopes also by quaternary sediments.

The experimental area is located in the southwestern part of the Vimperk Highlands in the basin of the Zdíkov brook that flows through the wider meadow depression. In its upper part, the brook is placed on the northerly oriented forest slopes. The experimental area is situated below these forested slopes and exploited as a permanent meadow. In 1976, the locality was drained by pipe drainage. The soil type is the acid slightly gleyic Eutric Cambisol (WRB 1998). Some soil hydrophysical properties are shown in Table 1. The soil water retention capacity reaches about 90 mm (Lichner *et al.* 2004). The coordinates are 13°41'45"E and 49°04'15"N, and the elevation is 788 m a.s.l. The mean annual air temperature is 6.3°C, and the mean annual precipitation amount is 825 mm.

The experimental area is equipped with an automatic monitoring station for the continuous measurement of the air and soil temperatures, tensiometric pressure in the soil, soil moisture, and precipitation amount and intensity.

METHODS

The heat balance, primary productivity, and entropy production by evaporation are evaluated for each day from 5 a.m. till 8 p.m. In this daily period, other long-wave heat fluxes and the associated entropy production on the Earth's surface (e.g.

Table 1. Soil hydrophysical properties in the Zábrod – Meadow locality

Horizon	Thickness (cm)	Residual moisture content (% vol.)	Saturated moisture content (% vol.)	Saturated hydraulic conductivity (m/s)
A	0–17	22	43	2×10^{-5}
B	17–60	18	38	1.5×10^{-5}
C	60–100	16	32	6.5×10^{-5}

heating up of the soil covered by dense vegetation) are negligible compared with the solar radiation, latent and sensible heat. It means that the heat balance can be obtained by Eq. (1).

$$\alpha\, G = H + L \qquad (1)$$

where:
G – flux of global radiation (W/m^2)
H – flux of sensible heat
L – flux of latent heat
α – effective absorptivity

The entropy production is evaluated in a simplified model of the abiotic/biotic surface (Tesař *et al.* 2007). The core of this model is the theory of plant transpiration, based on the finding that plants protect themselves against overheating (caused mainly by absorption of the solar radiation) by transpiration – i.e. by the heat uptake for water vaporisation. This theory is based on the experimental evidence that the surface temperature of leaves or needles does not surpass a certain temperature T_o, even if the income of the solar radiation is high. It means that transpiration can be interpreted as the response of the plant to the need for water to keep the temperature from exceeding a certain optimum value.

The regulative mechanism governing the supply of the transpiration water into the transpiratory organs is attributed to the plant. The following regulation rules are considered sufficient: (1) in the case that the plant is sufficiently cooled by the ambient air, no transpiration takes place; (2) if cooling by air is not sufficiently effective, i.e. if the optimum temperature T_o is exceeded, transpiration sets in; (3) as soon as the temperature of the plant falls below the optimum value T_o, transpiration stops. The physical background of this theory, including appropriate equations, is described in articles by Pražák *et al.* (1994, 1996).

From the view of plant physiology, the temperature T_o = 25°C can be regarded as optimum for plant growth. This value is an effective compromise between the optimum temperature for plant respiration (about 30–35°C) and the optimum temperature for type-C3 photosynthesis (about 18–22°C), where a good solubility of CO_2 in water is necessary (Larcher 2003). It was found that "the need for water to keep the optimum temperature T_o" (1) corresponds very well to the diurnal course of the plant transpiration evaluated on the basis of conventional techniques (Dekker *et al.* 2000), and (2) brings good estimates of the daily sums of stand transpiration (Pražák *et al.* 1994; Tesař *et al.* 2001).

According to the model of the abiotic/biotic surface (Tesař *et al.* 2007), the relation between the plant temperature T (K), transpiration flux ET (kg/s/m^2), and the entropy production by evaporation e_L (W/m^2/K) is given by Eqs. (2) and (3):

$$\text{If } T \neq T_o \text{ then } L = 0 \text{ and } e_L = 0 \qquad (2)$$

$$\text{If } T = T_o \text{ then } L = \lambda\, ET \text{ and } e_L = \lambda\, ET/T_o \qquad (3)$$

where:
λ – specific latent heat of vaporisation (J/kg)
L – latent heat flux (W/m^2)
T_o – optimum temperature of the plant cover (K)

The gross primary productivity is supposed to be proportional to the time t_o at which the vegetation temperature is equal to the optimum value T_o = 25°C (Körner 2003; Larcher 2003). It means that the gross primary productivity in Eq. (4) can be expressed in relative time units as P_t (s/s).

$$P_t \approx t_o \qquad (4)$$

Considering Eq. (3) and the well-known fact that the phytomass productivity is proportional to transpiration (Spiecker 1995), the gross primary productivity can be quantified in the entropy flux units as P_e (W/m^2/K) using Eq. (5):

$$P_e \approx e_L \qquad (5)$$

It should be mentioned that the relation between P_t and P_e quantities is not a trivial equality because at each time interval t_o a very different amount of the latent heat can be used to maintain the optimum temperature T_o.

The potential transpiration PET, actual transpiration ET, plant temperature T, latent heat flux L, and sensible heat flux H were calculated using the model published by Pražák *et al.* (1994). In this model, the potential transpiration PET is calculated as the amount of water necessary for cooling the plants to their optimum temperature T_o. In this theory, the actual transpiration ET is equal to the potential transpiration PET if the tensiometric pressure of the soil water contained in the root horizon is higher than the limit value (meaning that the plant transpiration is not limited by the soil water shortage), and to zero if the tensiometric pressure falls below the limit value. This means that the plant transpiration is strongly limited by the soil water shortage (Novák & Havrila 2006).

The calculations using Eqs. (1) to (5) are parameterised by the values of optimum temperature T_o = 25°C, effective absorptivity α = 0.75, effective thickness l = 0.001 m of the plant surface (leaf), and the limiting value (equal to –60 kPa) of tensiometric pressure in the root zone of soil below which the water uptake for transpiration is impossible. The model input data are the time courses of the air temperature, global radiation flux, and tensiometric pressure in the root zone of the soil. The model outputs are the temporal course of the potential transpiration *PET* (kg/s/m²), actual transpiration *ET* (kg/s/m²), latent heat flux *L* (W/m²) used for transpiration, sensible heat flux *H* (W/m²) emitted from the plant cover into the atmosphere, and the time course of the surface temperature *T* (°C) for the plant surface from which the gross primary productivity and entropy production by evaporation are derived.

The relation between P_t and P_e quantities was tested using linear regression in the double mass curve of Σt_o and Σe_L in the form given by Eq. (6).

$$\Sigma e_L = C\, \Sigma t_o \qquad (6)$$

where:

C – empirical constant

Σe_L – denotes the successive addition of yearly sums of e_L

Σt_o – denotes the successive addition of yearly sums of t_o

RESULTS

The values of global radiation, air temperature, and tensiometric pressures in the root zone of the plant cover (water availability for plant tran-

Table 2. Evaluation of solar heat income and precipitation in the Zábrod – Meadow locality during the growing seasons (1. 6.–30. 9.) 1983–2000

Season	α *G* (MJ/m²)	*P* (mm)	*ET* (mm)	*PET* (mm)	*ET*/*PET* (%)	Surplus of solar heat	Lack of solar heat	Lack of precipitation	Lack of soil water retention
1983	*1557*	272	209	306	68	++			
1984	1342	319	171	171	100		+		
1985	1517	302	210	211	100				
1986	1413	236	206	206	100				
1987	1295	281	173	173	100		++		
1988	1400	301	166	203	82				+
1989	1284	421	158	158	100		++		
1990	1414	281	140	207	68				+
1991	1359	299	197	197	100				
1992	*1567*	*185*	138	299	46	++		++	
1993	1464	358	200	210	95				+
1994	*1562*	321	221	286	77	++			
1995	1329	485	172	199	86		+		+
1996	1332	370	151	158	95		+		+
1997	1422	286	171	171	100				
1998	1384	290	196	212	92		+		+
1999	1391	355	150	183	82				+
2000	1495	*188*	163	240	67			++	
Frequency						3 ×	6 ×	2 ×	7 ×

α *G* – absorbed solar radiation, *P* – precipitation amount, *ET* – actual transpiration, *PET* – potential transpiration

spiration), measured during the growing seasons (1. 6.–30. 9.) of 1983–2000, were used for the calculation of the model outputs by Eqs. (1) to (6). The hourly sums of global radiation and hourly air temperature were measured at the meteorological station Churáňov located near the experimental area. The tensiometric pressures in the root zone of the plant cover were measured in the experimental area every morning.

Table 2 shows the seasonal sums of the absorbed solar radiation α *G*, precipitation amount *P*, actual transpiration *ET*, potential transpiration *PET*, and the *ET/PET* ratio. The relation between the absorbed heat and the precipitation was categorised (surplus of solar heat, lack of solar heat, lack of precipitation, lack of soil water retention) and evaluated (+ means occurrence of a factor, ++ means extreme value of a factor). Table 3 presents the seasonal sums of the sensible heat *H*, entropy production by evaporation e_L, gross primary productivity which is proportional to the duration of the optimum temperature, duration of temperature below optimum in hours, and duration of temperature above optimum in hours. The factors determining the loss of the gross primary productivity are pointed out: overheating and undercooling. The column marked undercooling gives in brackets the value lowered by 1089, which is the duration of undercooling in the season of 1992. Table 4 demonstrates the duration of overheating in hours, entropy production by evaporation e_L, and categorises the cause of the loss of the gross primary productivity: surplus of solar heat, lack of soil water retention, and absolute lack of precipitation.

Constant *C* in Eq. (6), obtained by linear regression in the double mass curve Σt_o and Σe_L (Eq. 6), had the value $C = 2.74$. The regression coefficient was greater than 0.99. This testifies to a very narrow link of both quantities as demonstrated in Figures 1 and 2.

DISCUSSION

The following findings concerning the relation between the precipitation amount and the heat income during vegetative seasons can be derived from Table 2.

The greatest income of solar radiation, greater than 1550 MJ/m^2, was recorded in seasons 1983, 1992, and 1994. The extreme sums of solar radiation are marked in column α *G* (Table 2).

The smallest income of solar radiation, smaller than 1360–1380 MJ/m^2, was recorded in seasons 1984, 1986, 1987, 1989, 1995, 1996, and 1998. Simultaneously, the precipitation amount was greater than *PET*.

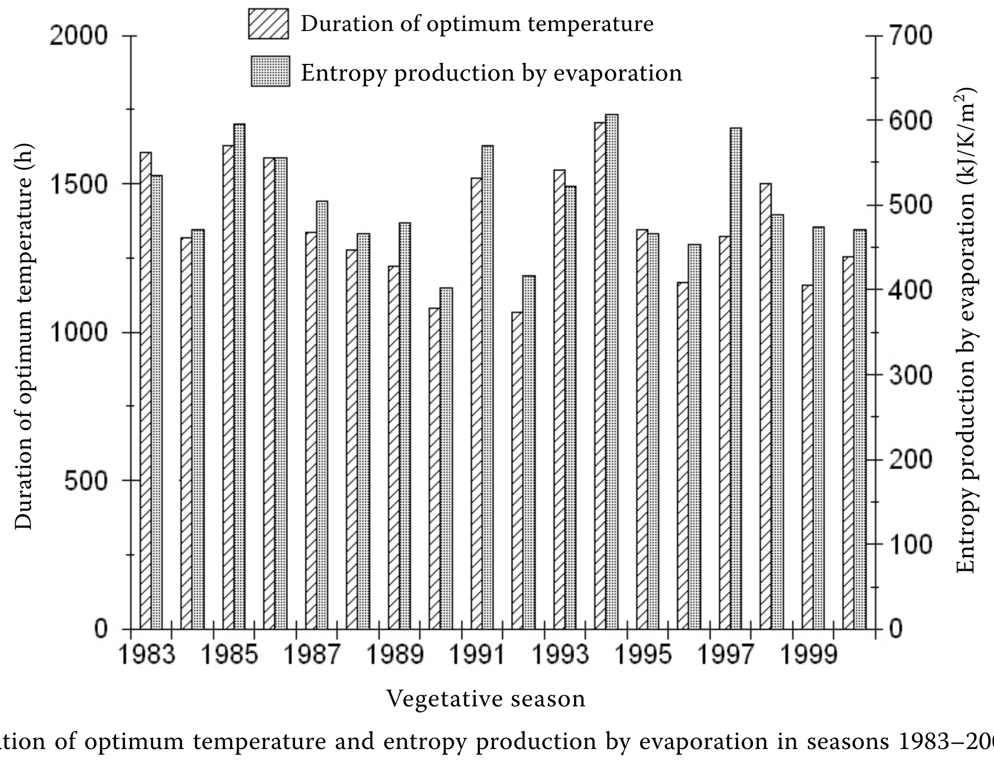

Figure 1. Duration of optimum temperature and entropy production by evaporation in seasons 1983–2000 in the experimental area Zábrod – Meadow

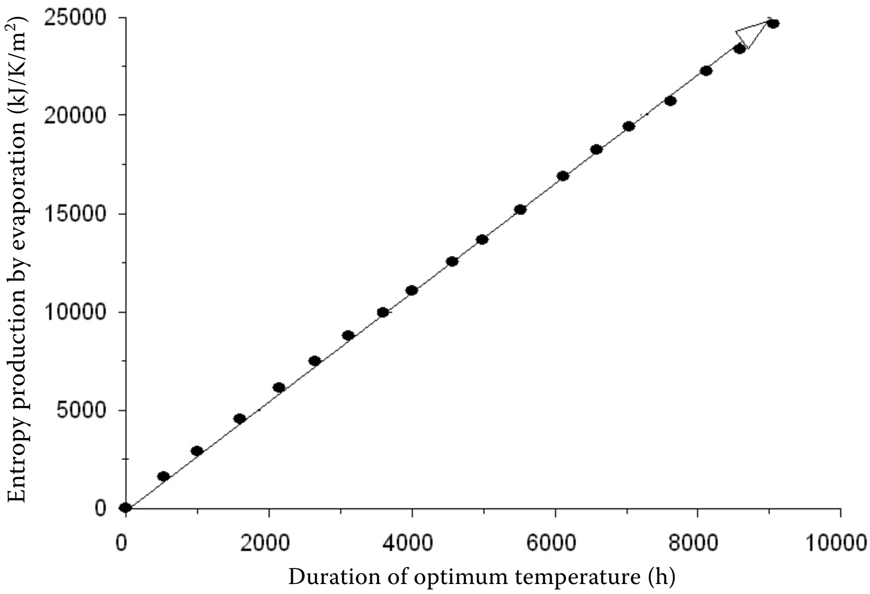

Figure 2. Double mass curve in coordinates duration of optimum temperature and entropy production by evaporation in seasons 1983–2000 in the experimental area Zábrod – Meadow; the arrow indicates the linear regression

Table 3. Evaluation of factors causing the loss of gross primary productivity in the Zábrod – Meadow locality during the growing seasons (1. 6.–30. 9.) 1983–2000

Season	H (MJ/m^2)	e_L (kJ/K/m^2)	Gross primary productivity (h)	Undercooling (h)	Overheating (h)	Cause of productivity loss
1983	1076	1607	534	1097 (8)	199	overheating
1984	955	1319	470	1359 (280)	0	undercooling
1985	1040	1626	595	1235 (146)	0	
1986	946	1588	555	1274 (185)	0	
1987	903	1337	504	1326 (237)	0	undercooling
1988	1021	1279	466	1282 (193)	82	overheating
1989	926	1221	479	1350 (261)	0	undercooling
1990	1091	1083	402	1286 (197)	141	overheating
1991	913	1519	571	1259 (170)	0	
1992	1242	1068	416	1089 (0)	325	overheating
1993	1009	1545	522	1286 (197)	22	overheating
1994	1056	1705	606	1101 (12)	122	overheating
1995	938	1325	448	1327 (238)	55	undercooling
1996	990	1166	454	1357 (268)	19	undercooling
1997	1035	1322	590	1240 (151)	0	
1998	938	1501	488	1297 (208)	45	overheating
1999	1046	1160	473	1255 (165)	101	overheating
2000	1120	1253	471	1202 (113)	158	overheating
AVG	1013	1368	503	1257 (168)	71	
SD	84.2	191.9	59.5	83.3	87.6	

H – sensible heat, e_L – entropy production, SD – standard deviation, AVG – average

Table 4. Entropy production e_L and the cause of overheating in the locality Zábrod – Meadow during the growing seasons (1. 6.–30. 9.) 1983–2000

Season	Overheating (h)	e_L (kJ/K/m^2)	Cause of overheating
1983	199	1607	great heat income
1990	141	1083	insufficient soil water retention
1992	325	1068	great heat income, absolute scarcity of precipitation
1994	122	1705	great heat income
1999	101	1160	insufficient soil water retention
2000	158	1253	absolute scarcity of precipitation

Absolute scarcity of precipitation, less than 190 mm, was recorded in seasons 1992 and 2000. The precipitation amount (and consequently *ET*) was much lower than *PET*. The precipitation extremes are marked in column *P* (Table 2).

Insufficient soil water retention was demonstrated in seasons 1988, 1990, 1993, 1995, 1996, 1998, and 1999. Although the precipitation amounts were greater than *PET*, the rains were too extreme to be fully intercepted in the soil. This caused water scarcity and a limitation to plant transpiration. As a consequence, *ET* was smaller than *PET*.

Seasons 1985, 1986, 1991, and 1997 were characterised by a well-balanced combination of precipitation and solar heat income. The actual transpiration (*ET*) was equal to the potential one (*PET*) and, simultaneously, no extreme in the solar heat income or in the precipitation took place.

Table 3 shows the influence of the solar heat and rainwater income on the gross primary productivity. The productivity is lowered by the overheating and undercooling of plants.

Plant overheating is caused by insufficient transpiration as a consequence of the soil water scarcity. Two reasons can be suggested (a) absolute precipitation scarcity in relation to the income of solar heat: *PET* is much greater than the precipitation amount, thus the income of rainwater is not sufficient for transpiration cooling and, consequently, *ET* is smaller than *PET*; (b) an insufficient retention capacity of the soil in relation to unsteady rains: the seasonal precipitation amount is sufficient but, in some rain events, water is not stored in the soil and flows out of the soil cover and therefore *ET* is smaller than *PET*.

Plant undercooling is caused by low air temperatures in combination with insufficient solar radiation in mornings and evenings. In these periods, the solar radiation is not capable of warming plants up to the optimum temperature. Table 3 shows that, in the climatic conditions studied, the minimum duration of undercooling was 1089 hours per season (the warm season of 1992). In a cold period, in which the rainwater is not used for transpiration cooling, undercooling is a typical cause of the productivity loss.

Table 3 gives the findings concerning the relations between the gross phytomass productivity, absorbed solar heat, and precipitation.

Maximum productivity, measured by the duration of the optimum temperature or entropy production by evaporation, was recorded in seasons 1983, *1985*, *1986*, *1991*, 1994, and *1997*. The seasons marked with *italics* were characterised by a well-balanced combination of precipitation and solar heat income. A substantial productivity loss caused by undercooling, more than 230 hours in comparison with the season of 1992, was registered in seasons 1984, 1987, 1989, 1995, and 1996.

In seasons 1983 and 1994, the maximum productivity was also reached. However, it could have been even greater, had no overheating limited the productivity. As a consequence of a huge solar heat income (Table 2), the productivity loss caused by overheating was compensated for by the productivity increment resulting from the shorter duration of undercooling (Table 3).

The loss of productivity as a consequence of overheating was registered in 11 cases during the 18 seasons tested.

A substantial loss of productivity as a consequence of overheating, more than 100 hours per season, was recorded in 6 cases during 18 seasons. The causes of the productivity loss are analysed in Table 4.

If water was available for transpiration (1983, 1994), the hydrologic cycle in the experimental area responded to the great solar heat income by a high entropy production (Table 3). It means that the transpiration sufficiently cooled the vegetation cover (the entropy production by evaporation is equal to the fraction of the latent heat and the temperature of the surface from which water is evaporated, see Eq. (3)). The scarcity of water for transpiration (1990, 1992, 1999, and 2000) caused the loss of the entropy production by evaporation. This means that transpiration was strongly restricted and, therefore, the total solar radiation absorbed warmed up the plants and this energy was irradiated back into the atmosphere in the form of sensible heat. Consequently, the atmospheric boundary layer was warmed up. This is demonstrated in Table 3 by a long duration of the overheating of plants.

The great income of solar heat in 1983, 1992, and 1994 was caused by a climatic anomaly as a consequence of the El Chichon eruption in 1982 and the Mount Pinatubo eruption in 1991 (Šír *et al.* 2004a). These climatic perturbances were caused by significant external phenomena from the point of view of the hydrologic cycle, whereas the rainfall extremes in 1990 and 1999 and the absolute rain scarcity in 2000 were manifestations of the internal variations in the hydrologic cycle, and may have been reinforced by climatic extremalisation in Europe (Moberg *et al.* 2006).

Self-organised dissipative structures, like whirlwinds and windstorms, can be created in the overheated atmospheric boundary layer. They may cause extreme rains. Actually, if the overheated area is large, the inhibition of the atmosphere movement occurs on a large scale . This inhibition disabled the movement of the moist air from the Atlantic Ocean into Central Europe in the summer of 2000. A very small precipitation amount and a huge income of solar radiation testifies to the absence of clouds (Table 2).

Non-equilibrium thermomechanics states that, in the case of an open system, the decrease of internal entropy is proportional to the entropy outflow from the system caused by energy exchanges between the system and its surroundings (e.g. Kleidon & Lorenz 2005). In the case of the productive Earth's surface (Tesař *et al.* 2007), the system is created by the photosynthesising plants, water, soil, and atmosphere. Solar energy in the form of photons (high frequency) flows into the system and heat (low frequency) flows out of the system. In this situation, the decrease of the system entropy (i.e. the production of low-entropy phytomass by photosynthesis measured by the gross primary productivity P_t) is proportional to the entropy production e_L (i.e. P_e, according to Eq. (5)). This gives the reasons for the very narrow link between the seasonal sums ΣP_t and ΣP_e, as depicted in Figure 1. The question of why the link between P_t and P_e is significant only in the cold climatic conditions tested is answered in the article by Bonan (1993). He stated that the empirical observations, gathered from a variety of climatic regions, show that the net primary productivity increases with warmer mean air temperature and annual precipitation. It means that this narrow link can be expected in various climatic conditions. Hence, the gross (or net) primary productivity can be measured by the entropy production by evaporation or by the duration of the optimum plant temperature.

CONCLUSIONS

The global radiation, the precipitation amount, and the soil water retention are the crucial factors determining the hydrologic pattern and gross primary productivity in the experimental area Zábrod – Meadow during the period 1983–2000. Insufficient soil water retention leads to a small entropy production by evaporation and a small gross primary productivity, which results in the extremalisation of the hydrologic cycle. On the other hand, in the case of sufficient soil water content, the high entropy production by transpiration and the high gross primary productivity leads to the stability of the hydrologic cycle.

Under the conditions of a sufficient retention capacity of a catchment (mainly the soil) and the area covered by transpiring vegetation, the hydrologic cycle was resistant to the great climatic perturbances in the growing seasons of 1983, 1992, and 1994.

The gross (or net) primary productivity can be measured by the entropy production by evaporation or by the duration of optimum plant temperature.

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