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Soil Moisture Deficits in South-Central Sweden

II – Trends and Fluctuations

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Soil moisture fluxes in forest and grassland soils were analyzed for a rather dry region in south-central Sweden in order to assess climatologically induced dryness variability. Time series were constructed, using a conceptual soil moisture model, optimised against neutron probe measurements. Data in a 105 yrs climatic record were used as driving variables. A method to deal with the inhomogeneity of the long precipitation record was developed. It was shown that large variations existed, not only between the median values, but even more for the range of the quartiles, depending on the choice of time period. The statistical distribution varied significantly even between the two 50 yrs series, where the latter showed larger fluctuations around the median caused by a trend towards increased amount of high summer soil moisture deficits. Estimates of the interannual variations of possible water deficit stress on vegetation were made. The only time (1883-1987) when there was a calculated risk for drought stress on the forest during four consecutive years was during 1973-1976. This might have increased the vulnerability to the threats of acidification. It was concluded that the use of standard- and return periods can hardly be justified as no sets of average conditions exists.

Introduction

The occurrence of extreme hydrologic events, like the severe drought over large parts of the US grain belt during 1988, has focused the interest on the possible effects of the much discussed global climatic change on the hydrological cycle. It is evident that what we actually experience and easily consider as indicators of lasting changes in one or another direction often are just temporal fluctuations. However, since increased fluctuations also are envisaged as a result of the climate change (J. Firor, cited by Palca 1988), even temporal extreme events may be due to other reasons than temporal natural fluctuations.

The soil moisture is a central part of the hydrological cycle, being the key to the interaction between atmosphere, soil and vegetation. Time series analysis of long records of soil moisture deficits is a way to detect the magnitude and directions of short and long time fluctuations in the cycling of water, caused by natural factors or human activities. The understanding of the dynamics of such long time fluctuations would be of crucial importance for the interpretation of the value of frequency analyses, which are often used in hydrology and which considers events as being randomly distributed over time.

Since there are no long time records of measured soil moisture deficits dryness fluctuations have commonly been described from rainfall records (Eriksson 1980). Precipitation is, however, only one although the most important factor deciding the water fluctuations in the soil moisture zone. Time series of long time variations of soil moisture deficits can be constructed by a model, which is only driven by variables that are available from long time climatic records. In this study, such a model (Andersson 1988; Andersson 1989) driven by a 105 yrs long climatic record from south-central Sweden (1883-1987) was used to investigate the magnitude of fluctuations soil moisture deficit fluctuations, the possible dependence between years and to detect if a trend towards drier or wetter soil moisture conditions could be found. This trend analysis was used to estimate the interannual variations of the risk for a water deficit stress on the vegetation.

The human hydrological memory was challenged by testing if recent summers, when soil moisture conditions had been characterized as extremely wet or dry, really were extremes in a longer time perspective.

Methods and Data

The Model

Soil moisture deficits in the upper metre of the soil profile were calculated from climatic data by a conceptual model (Andersson 1988; Andersson 1989). The model was optimised against neutron probe soil moisture measurements, representing the integrated moisture volume fraction over the upper metre of the soil profile from two forests and one grassland sites on till soils (sandy loam) at Sjöängen (Velen's representative basin), and one site with grassland on clayey soil at Källtorp (Norrköping). The structure of the model and the physical and biological interpretations of the obtained parameter values are discussed by Andersson (1989).

Driving Variables

Daily precipitation and mean temperature values from the province of Östergötland (south-central Sweden) were available from the climatic station at the Linköping fire-station for the period 1883 until 1977, when this station was shut down. For the period after 1977, data from Malmslätt, situated about five km from the fire station, were used. Monthly means values of potential evapotranspiration were calculated by the Penman equation (Penman 1948), using climatological data from 1931-1960 (Wallén 1966).

Inhomogeneity Problems

The precipitation record was assumed to include inhomogeneities caused by a number of movements and changes of measurement gauges. For long historical records, it is not possible to use standard techniques like double-mass curves to assess the timing and magnitude of inhomogeneity. Nearby stations with equally long records do seldom exist and even if they do, the effects of the alterations of the precipitation gauges would not be shown.

For this study, a method to detect inhomogeneities within a long precipitation record was developed. Daily rainfall, respectively snowfall amounts were grouped into classes (i): 0.1, 0.1-0.5, 0.6-1.0 ... 9.6-10.0 and > 10.0 mm/day. The basic principle was to test if the relative distribution of these classes for a certain time period was significantly different from the distribution during a reference period (Eq.(1)).

$$CF = \sum_{i=1}^{22} \frac{NEW_i \times NEW\mathrm{MEAN}_i}{OLD_i \times OLD\mathrm{MEAN}_i}$$

where

- CF – calculated correction factor
- $OLD\mathrm{MEAN}_i$ – mean of values in class i during the period for which the comparison is made
- $NEW\mathrm{MEAN}_i$ – mean of values in class i during the reference period
- OLD_i – share of all events (%) in period OLD that falls within class i
- NEW_i – share of all events (%) in period NEW that fall within class i

Calculations were made for 1882-1917 (10^{-3} m^2 zinc gauge, no wind shield), 1918-1945 (10^{-3} m^2 zinc gauge, wind shield) and for 1946-1960 (2×10^{-4} m^2 zinc gauge, wind shield), using 1961-1977 (2×10^{-4} m^2 aluminum gauge, wind shield) as the reference period. The calculated correction factors are shown in Table 1.

It was shown that the largest corrections had to be made for snow. Corrections of the rain measurements were only made on data from the period before 1946, using a correction factor of 1.1. The need for larger corrections for solid precipitation could be expected since aerodynamic errors are greater than for liquid precipitation. It is thus probable that the older types of precipitation gauges gave significant-

Table 1 – Calculated correction factors to make precipitation values comparative to the 1961-1977 values

	Snow	Rain
1882-1917	1.32	1.03
1918-1945	1.36	1.15
1946-1960	1.08	0.98

ly lower estimates of the solid precipitation than the rain gauges used today.

The influence on measured precipitation amounts caused by the change of climatic station (using the same type of rain gauge and wind shield) from Linköping to Malmslätt during the end of 1977 was probably rather small. Eriksson (1983) estimated that the station in Malmslätt, due to somewhat higher wind exposure, on average had a few (3-4) percentage lower measured precipitation than the one in Linköping. Therefore, the data for the period 1978-1987 were used without corrections.

It must be emphasized that the corrections were made to make precipitation records from different periods comparable and not in order to find the absolute correction values. To avoid overparameterization, no attempt was made to correct the modern precipitation records *e.g.* for aerodynamic losses. The used rainfall data are therefore systematically somewhat underestimated. However, since uncorrected precipitation data were used for optimization of the parameters in the soil moisture model, soil moisture deficits should not have been overestimated because of this.

The corrections of the precipitation records had a moderate influence on the simulated moisture dynamics (Fig. 1). The reason for this is that the largest corrections were made for snow. Snowmelt mainly occurs during periods when the soil is close to saturation and will thus not manifest itself in a proportional increase of soil moisture content.

When using this method for rainfall corrections, it is assumed that the difference of the relative frequency distribution between compared time periods is only attributed to the change of rain gauges. This is a simplification of natural conditions. However, since the classes with small precipitation amounts (a few mm/day) have the largest frequencies (Fig. 2), the effects of various frequencies of heavy rainstorms between different periods would probably just have marginal effects on the calculated correction factors.

Selection of Dryness Indicators

The aim of this paper is to analyze fluctuations and possible trends of soil moisture dynamics in a long term perspective, using a climatic record of 105 yrs. In any analysis of variability, the choice of indicator is of critical importance. It is usually necessary to make a compromise between data availability and relevance to the

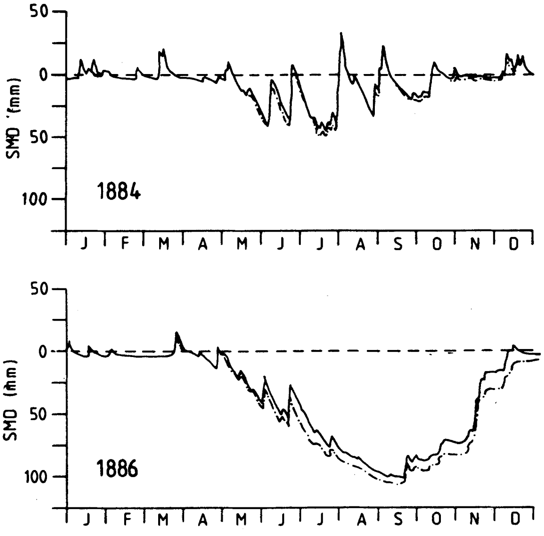

Fig. 1. Soil moisture deficit (SMD) simulations (Källtorp optimization) 1884 and 1886 with (solid) and without (dashed) precipitation corrections.

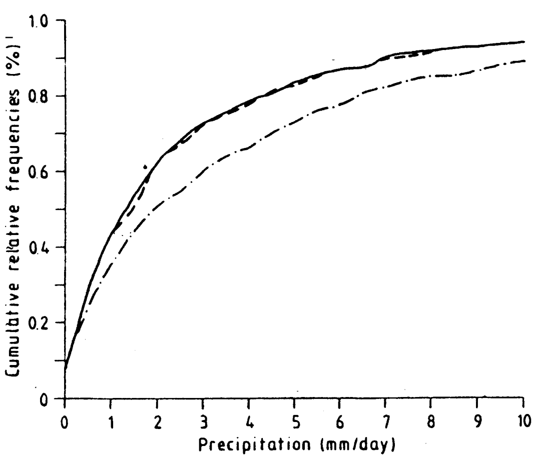

Fig. 2. Cumulative, relative frequencies of precipitation for snow (solid), rain September-April (dashed) and rain May-September (dash-dotted). Linköping 1961-1977.

studied phenomena. In the choice of dryness indicators, rainfall data is usually easier to achieve than information about soil moisture fluctuations. However, to which degree are different dryness indicators exchangeable?

In order to investigate this, a regression of nine time series (1883-1987) using different dryness indicators was made: I) Yearly sums of precipitation. II) Yearly means of soil moisture deficits. III) May-September sums of precipitation. IV)

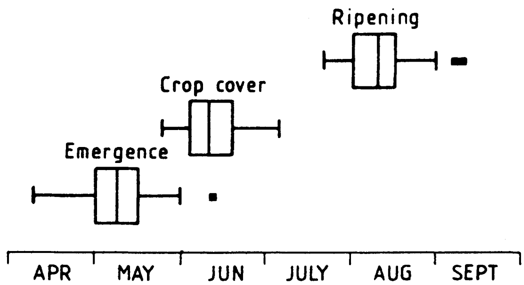

Fig. 3. Calculated duration of growth period for spring barley (1883-1987). The box-plot graphs shows the median, quartiles and the extent of the distribution. Extreme values are shown as separate points.

May-September means of soil moisture deficits. V) Yearly maximums of soil moisture deficits. VI) Emergence-crop cover sums of precipitation. VII) Emergence-crop cover means of soil moisture deficits. VIII) Crop cover-ripening sums of precipitation. IX) Crop cover-ripening means of soil moisture deficits.

The start and duration of the growth period are controlled by temperature in the humid temperate snow climate of the studied region. The time limits for the growth period were calculated for spring barley, using the sum of the daily mean temperatures recorded from the 1st of March (Aslyng and Hansen 1982) (Fig. 3). Emergence was calculated to take place at an accumulated temperature sum of 225°C., crop cover at 625 and full ripening at 1625°C.

The results of regressions between these time series, using the model optimization from grassland on clayey soil (Källtorp) for the soil moisture optimizations, are shown in Table 2.

Interception is very sensitive to the temporal distribution of rainfall amounts. However, the fits achieved from regressions of the precipitation time series against the forest series of soil moisture deficits were similar to those achieved when the precipitation records were compared with grassland series of soil moisture deficits.

Table 2 – Correlations (R^2) achieved after regression of different time series. The growth period is calculated for spring barley. High correlations are indicated by italics. Low correlations are put in parentheses.

	Yearly P	Yearly SMD	May-Sep P	May-Sep SMD	Max SMD
Yearly SMD	53.7				
May-Sep P	56.4	*75.5*			
May-Sep SMD	43.9	*93.4*	*73.5*		
Max SMD	28.2	*70.3*	50.4	*82.2*	
Emer-Cov P	(6.0)	(17.4)	(15.7)	(24.5)	(3.4)
Emer-Cov SMD	(2.1)	(10.4)	(8.4)	(13.3)	(0.6)
Cov-Ripe P	(13.8)	(18.2)	(26.5)	(20.2)	(14.8)
Cov-Ripe SMD	(24.3)	50.3	41.1	58.4	59.9

A regression of soil moisture deficit and rainfall time series calculated in different ways, for a south-central Swedish landscape, showed that time series were similar for yearly means of deficits and summer deficits (May-September). Summer rainfall series explained 75 % of the summer mean moisture deficit series. Yearly precipitation, however, only explained about 55 % of the summer mean deficits. This inconsistency is due to the time distribution of the rainfall and snowmelt events. Yearly maximums of deficits were even more sensitive to the distribution and therefore showed low correlations to total rainfall amounts. For specified intervals of the growth period of spring barley, more general drought indicators could be misleading. The importance of indicators that shows the degree of dryness for short time intervals, during which the presence or absence of water is critical might seem obvious. Nevertheless, this is not always considered in time series analyses of the interrelations between water availability and crop production.

Results

Water as a Limiting Factor for Vegetation

A firm relation exists between transpiration and net carbon dioxide assimilation. Growth is therefore limited when a reduced soil moisture reserve leads to decreased water uptake.

Estimates of interannual variations of the number of days during June-September when soil moisture deficit was estimated to act as a possible growth limiting factor were made, using time series of soil moisture simulations from 1883-1987.

The water uptake by roots can be limited not only by soil moisture deficits but also by low soil temperatures (*e.g.* Turner and Jarvis 1975). The influence of soil temperature on transpiration rates was considered in the model by accumulated air temperatures (Andersson 1988; Andersson 1989). For the studied period of 105 yrs, the calculations indicated a temperature effect on water uptake only during four years in June and never in July and August. The water stress will be reduced if high soil moisture deficits are combined with low atmospheric vapour pressure deficits. However, the atmospheric deficits are usually high during the main part of the prolonged dry spells which cause the high soil moisture deficits. Consequently, the distribution of years with different number of days with a influence of water deficits on growth should be well described by the moisture deficit based risk indicators.

For the forest sites, risk was defined to occur when the water deficit was greater than 50 % of the water content between the field capacity and the wilting point (Mohrmann and Kessler 1959). When using the model optimization made for the driest of the forest sites at Sjöängen, this limit was exceeded (once or for several days) during one year in June (1914) and during approximately a third of the years

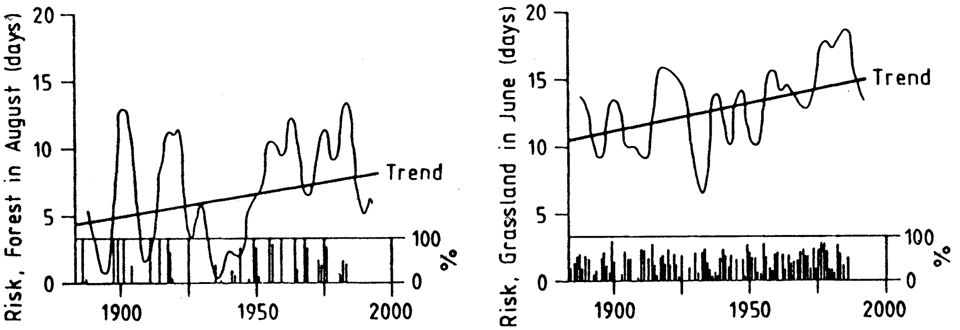

Fig. 4. The percentage of days/month during individual years (1883-1987) with a risk that soil moisture deficits would act as a stress factor for forests (optimised against the driest of the forest sites at Sjöängen) in August and for grassland (optimised against Källtorp) in June. Smoothed moving 5-years averages of the number of days/month and the calculated trend are also shown.

in July, August and September (Fig. 4). The only time during the 105 yrs period when four consecutive years could be characterized as having soil moisture deficits that could act as a stress factor, both in July, August and September was during 1973-1976.

When using the optimization made against soil moisture measurements from the wetter of the two forest sites at Sjöängen, the defined risk was only exceeded during one year in August (1914) and during five years in September (1886, 1914, 1955, 1969, 1983) (not shown in figure). These tubes were situated just a few metres from each other, with small variations of topography and soil texture. This demonstrates the importance of spatial variations, *e.g.* caused by macropores, root and canopy distribution.

A risk assessment was also made for less deeply rooted vegetation. This analysis was made from time series, made with a model optimization against measurements from grassland on a clayey soil (Källtorp). Two conditions had to coexist to fulfill the risk definition; the water content in the upper metre should be less than 75 % of the available water content at field capacity and a theoretical "upper transpiration zone" (Andersson 1989) of the soil profile, fed by rainfall and emptied by the calculated evapotranspiration, should be empty. The water content did often fall below the 75 % limit, which means that the recent rainfall conditions, expressed as water in the upper transpiration zone, were of major importance when calculating the number of days with a possible water stress for the shallowly rooted vegetation. Although the total soil profile (0-1 m) on average was driest in July, the calculated average number of drought sensitive days was therefore on average highest during June (13 days/month), when rainfall amounts often are smaller, than during July (12 days) and August (8 days).

This illustrates that shallowly rooted vegetation in south-central Sweden is most

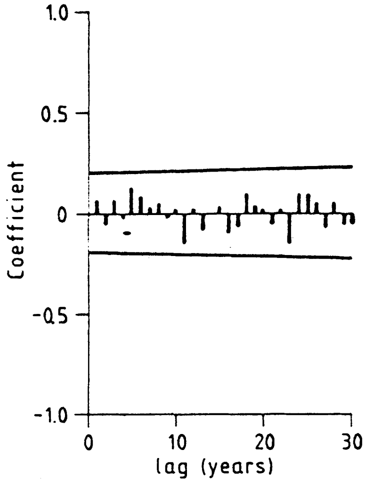

Fig. 5. Autocorrelation of mean summer soil moisture deficits (May-September) (1883-1987). Plus minus two standard deviations are shown. Model optimization from Källtorp (grassland on clayey soil).

sensitive to drought in the early parts of the summer, whereas deeply rooted vegetation becomes more sensitive in late summer when also deeper parts of the soil profile are depleted of water.

Dependence Between Years

The interannual dependence of mean summer soil moisture deficits (May-September) was tested by autocorrelation. No significant correlations, neither between adjacent years or between any other time steps could be found (Fig. 5). The correlation between mean soil moisture deficit during a certain summer and the surrounding 3 or 5 summers was in fact on average even smaller than the correlation between a single year and the mean of the whole period (1883-1987).

In spite of the large variation between adjacent years, a trend towards drier summer soil moisture conditions was, however, detected (Fig. 4). The soil moisture deficits are thus characterized not only by a large interannual variability, but also by a large degree of unpredictivity.

Choice of Standard Time Period

When discussing average conditions, a time interval of 30 yrs (1930-1960 is still the most commonly used) is generally accepted to be referred to as a standard period. However, sometimes even shorter records are used for calculations of average conditions.

From the time series analysis it was shown that large variations existed, not only between median values, but even more for the range of the quartiles (Fig. 6) depending on the choice of time period (when and how long). The statistical

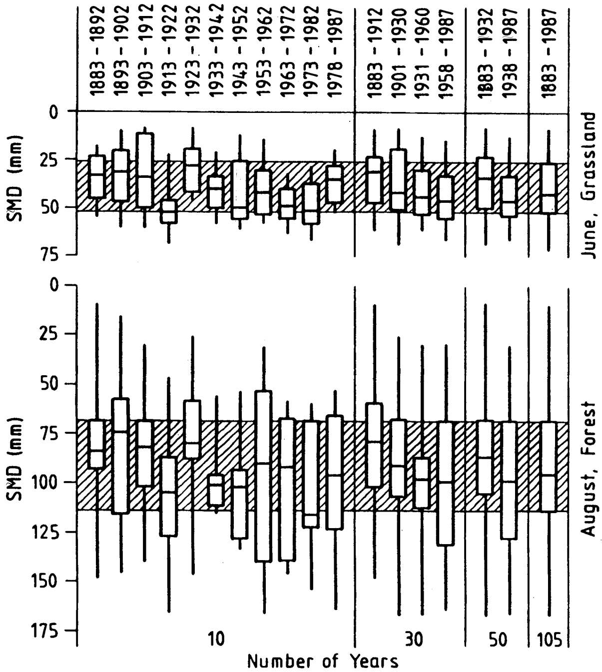

Fig. 6. Variability of 10, 30, and 50-year averages of soil moisture deficits for grassland in June (Källtorp optimization, upper graph) and forest in August (optimized against measurements from the driest site at Sjöängen, lower graph). The shadowed area shows the average distribution over the whole 105-year period.

distribution varied significantly even between the two 50 yrs series, where the later showed larger fluctuations around the median caused by an increased amount of dry events.

Ranking of Wet and Dry Years

Probability plots of maximum and minimum soil moisture deficit in Östergötland during June and August were constructed, using an average of the estimated deficits from four model runs with different optimizations, representing various soil and vegetation types (Fig. 7).

The human memory of earlier climatic conditions is usually short. Situations are often considered to be extreme although a comparison with a historical record gives another picture. For Östergötland, the summers of 1976 and 1983 were considered extremely dry and the summers of 1985 and 1987 extremely wet. From Fig. 7 it can be concluded that about 20 % of the summers of 1883-1987 had wetter soil moisture conditions than during the two recent wet summers. The two dry summers were, however, extremely dry even in the perspective of the latest 105 yrs.

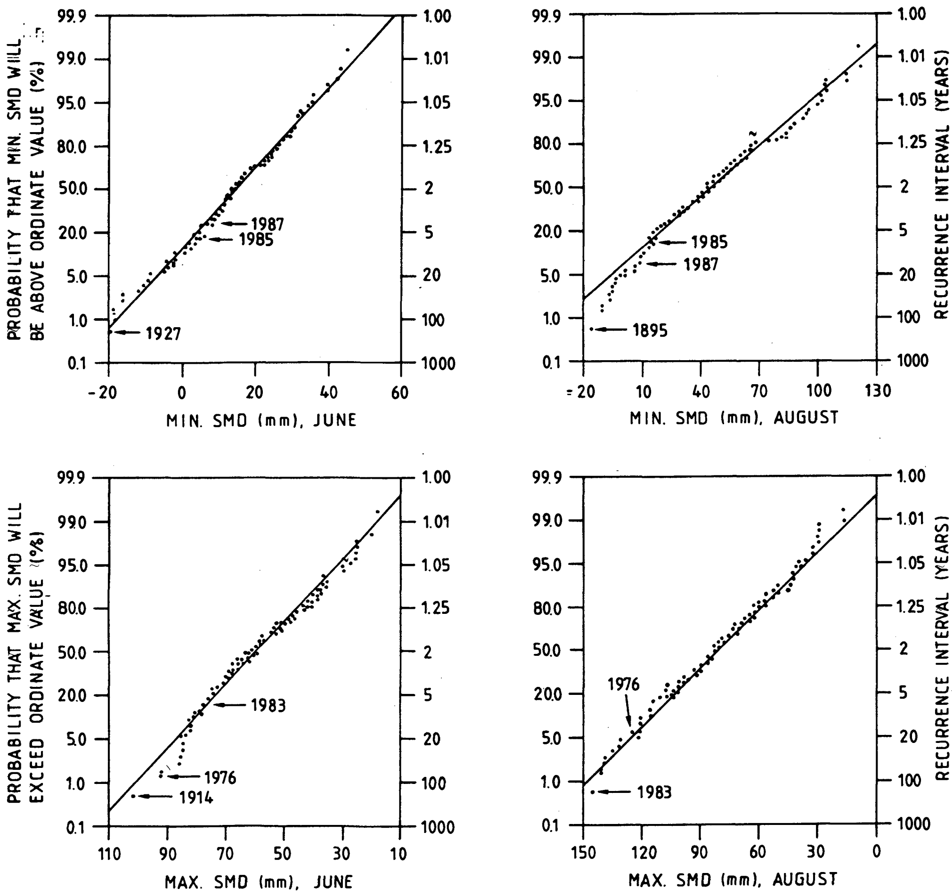

Fig. 7. Probability plots for monthly mean SMD, calculated as the weighted average of land use and soil types in Östergötland (1883-1987). The wet summers of 1985 and 1987, the dry summers of 1976 and 1983 and the summers with the highest, respectively lowest deficits are indicated.

Discussion and Concluding Remarks

Climatic Trends?

The climate is generated by a complicated physical system. Low volcanic activity causes temporal increase of the transparency of the atmosphere and the astronomic solar constant is unstable over time. This leads to temporal fluxes of the global air temperature (see *e.g.* Gilliand 1982). The much discussed global climatic change, predicted by climatologist as a consequence of increased concentrations of carbon dioxide and other greenhouse gases, superimposes a trend towards warmer conditions over these natural fluctuations. Changes of the global heat balance will also have effects on precipitation and evapotranspiration rates.

In this study, fluctuations of mean soil moisture deficits between various periods (Fig. 6) and a trend towards higher summer soil moisture deficits (Fig. 4) were detected. This detected nonstationarity might, however be due to natural fluctuations. Studies of rainfall records from central Sweden for the latest two centuries (Eriksson 1980) showed that marked tendencies towards drier or wetter climate have existed for time periods up to about 40 yrs. As earlier mentioned, the only time (1883-1987) when four consecutive years with prolonged periods of water stress occurred was between 1973 and 1976. It is possible that the accumulated effects from this long row of dry summers caused an increased vulnerability to the threat of forest injuries caused by acidification.

The trend towards drier summer soil moisture conditions, which was detected in this study (Figs. 4, 6), does only consider variations of the amount and distribution of rain and snowmelt penetrating into the soil. If the assumption that climatic change would have caused generally increased atmospheric water demands is correct, the trend would be enlarged. However, it must be emphasised that a trend, detected from soil moisture simulations, using a single climatic record, in itself gives no information about climatic change. One must be careful in citing single climatic records as evidences of climatic change (Van Hoyt 1981). On the other hand, comparisons with climatic records is the only way to validate the reliability of General Circulation Models (GCMs). The climatic scenarios simulated by GCMs are at present weak in simulating the hydrological cycle (*e.g.* Dickinson 1988), and predictions of the hydrological effects of climatic change, made with the help of different GCMs are sometimes contradictory. For the middle latitudes, rainfall is often predicted to be reduced during the summer whereas evapotranspiration is predicted to be increased (Bultot *et al.* 1988, Gleick 1987). South-central Sweden is situated in a transitional zone between middle and high latitudes. For this region, scenarios which envisage decreased summer soil moisture deficits are produced (Heino 1987). Other authors, however (*e.g.* Manabe *et al.* 1981) predict increased summer soil moisture deficits both for middle and high latitudes.

The Use of Frequency Analysis

Large variations of medians and the range of the quartiles, depending on the choice of analyzed time period, were detected even between the two 50 yrs series, where the later showed larger fluctuations around the median, mainly because of an increased amount of dry events (Fig. 6). The occurrence of such climatic fluctuations, which in addition might be superimposed by a trend (Fig. 4), makes it hard to justify the use of long term average values in the sense that there should exist normal conditions of climate related variables.

The idea that there exists a set of average conditions, with a certain statistical distribution, is the philosophy behind the use of frequency analysis in hydrology. From a physical point of view, an equal probability of extreme events in all time intervals is extremely improbable (Klêmes 1986). The fact that hydrological events are not random samples must be taken into consideration when determining the value of estimates built on concepts as standard or return periods. The results of such calculations will be critically dependent on the choice of the time period of the used hydrological record. As an example, a mean monthly summer deficit that was in the upper quartile, *i.e.* that was one of the 25 % driest years, during 1883-1912 would have been close to the median for the 1958-1987 period (Fig. 6).

The existence of a large variability within and between years, due to nonstationarity of physical conditions seems to be one of the most characteristic features of water availability. The fluctuations are largest in arid and semi-arid areas (*e.g.* Morales 1977), but also in humid areas "normal" is a concept that is of very little use when describing hydrological conditions.

Therefore, one should be careful to interpret the constructed probability plots of maximum and minimum soil moisture deficits (Fig. 7) as anything else but a description of the conditions during the studied time interval. As soon as the future gives us a few more unusually dry or wet years, the inclination of the probability line will be changed.

Acknowledgements

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