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Modelling soil temperature & soil water availability in semi-arid Sudan:

Validation and testing

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Modelling soil temperature & soil water availability in semi-arid Sudan:

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“The more you contemplate,
The more you realize that there are no simple answer.”

Winnie the Pooh

Abstract

The aim with this thesis was to investigate the land surface model used in DAYCENT. Through comparing the simulated soil moisture and soil temperature results with observed data, at the depth of 30 and 60 cm at the Demokeya site in semiarid Sudan, it was possible to evaluate the model. The ecosystem model uses soil texture data, land management information, and daily weather data to simulate plant growth, decomposition of dead plant material and soil organic matter, N cycling in soil, and trace gas exchanges between the soil and the atmosphere. The *Soil temperature sub model* and the *Available soil water sub model* were tested.

The DAYCENT model simulates soil temperature well (r = 0.79), but the accuracy decreases with soil depth. This is also the case in the available soil water sub model (r = 0.64), but it underestimates the soil water content. The user must, though, be observant to irregularities in annual and monthly rainfall while it might influence daily correlation and thereby affect gas fluxes. Parameters like soil texture, root fraction and crop has no significant impact on the model but exists more as a noise. Either an increase or decrease in air temperature generates a significant influence on the soil temperature and moisture, which makes accurate air temperature data by far the most important factor. It was also found that the estimation of biomass is crucial, while it is the governing parameter determining the simulation result of the two sub models. If DAYCENT will be used to estimate e.g. carbon sequestration in the Sahel, proper satellite images and climate data are needed.

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1. Introduction

Carbon (C) is a constituent of all organic compounds, many of which are essential to life on Earth. Plants convert atmospheric carbon dioxide (CO_2) to carbon-based compounds through photosynthesis. Once photosynthetic organisms have assimilated carbon, it is released again in the form of carbon dioxide as they respire. As an organism dies, the main part of the carbon is brought back to the air through bacterial decomposition and, occasionally, by fire. The rest is decomposed and constitutes the soil reservoir.

During the days of pre-industrialisation a balance between carbon in the atmosphere and the terrestrial system prevailed, the major reservoirs of carbon were the deep and shallow portions of the ocean; the soil, detritus, and biota of the land; and the atmosphere. The oceans were, and still are, the greatest reservoirs of carbon. In terrestrial environments, forests are the largest carbon reservoirs. Up to 80 percent of the aboveground carbon in terrestrial communities and about a third of belowground carbon are contained within forests. Large-scale deforestation in Russia and the Amazon basin are likely to have particularly significant effects on the global carbon storage and cycling (IPCC, 1995). Carbon is also released in immense amounts through burning of fossil fuels.

The considerable increase in atmospheric carbon dioxide from 280 ppmv in mid 19^{th} century to 365 ppmv by the beginning of 21st century has presumably come from the pedosphere as a result of intensive aquatic and land use change (IPCC, 1995). Former long-term sink ecosystems begin to act as sources for carbon dioxide; e.g. the Arctic tundra, with large amounts of carbon stored in its soils, has been a net sink for carbon dioxide during long periods of geologic time. The recent warming has accelerated the rate of soil decomposition, transforming Arctic areas into potential sources of atmospheric CO_2. Therefore, scientists and policy makers are interested in understanding the potential of the world soils to act as a sink for atmospheric CO_2. Understanding the extent of this potential requires a thorough knowledge of the magnitude and nature of soil carbon pools and their dynamics in different ecosystems.

Sequestration of carbon (C) in soil organic matter (SOM) has been suggested as means to compensate for greenhouse gas emissions (Bruce et al, 1999; Lal et al 1998). Observation show that some agricultural practices can deplete soils of C (Huggins et al, 1998) and that carbon depleted soils can sequester carbon upon change of management (Paustian et al., 1992). In addition to acting like a sink for atmospheric CO_2, increasing C in soil is positive for the soil fertility and water retention. Processes governing the dynamics of soil carbon pools differ among ecoregions and strongly interact with land use, i.e. farming systems and soil/crop management practices.

In 1992, 150 countries all over the world signed an agreement to reduce their greenhouse gas emissions with at least 5 % below the levels of 1990 in 2010. The decree from 1997, called The Kyoto Protocol, contained opportunities for developed countries to invest in sustainable development in undeveloped countries in order to reduce their own emissions. This soil reclamation scenario gives the receiving country e.g. potential benefits through change in land use, such as improved soil structure, moisture-retention capacity and soil fertility (Palumbo et al, 2004), but might also require a long-term strategy of managed rotations involving changes in amendment types and amounts over time, as well as succession in vegetation types (Palumbo et al, 2004). Management strategies promoting land reclamation and C sequestration include among others a change in land use (Ardö & Olsson, 2003), through the ecosystem model CENTURY (Metherell et al. 1993). A model with benefits like CENTURY it is quite easy to parameterise, is well known and widely used as well as gained good result compared to other ecosystem models such as e.g. CANDY, DAISY, ROTHC and SOMM (Smith et al, 1997). These benefits combined with that CENTURY is very flexible to management options, makes it the most favourable.

Developed ecosystem models can assist to determine the possibility to sequestrate carbon in different regions. To better estimate trace gas fluxes from different ecological units, the daily-based DAYCENT model was developed from CENTURY (Parton, 1998). DAYCENT uses the land surface sub model in conjunction with modified parameterisation of ecosystem processes to simulate actual evapotranspiration rates, plant production, nutrient cycling and trace gas fluxes (Parton, 1998). Through comparing simulated soil moisture and soil temperature results with observed data it is possible to evaluate the model.

The overall aim with this paper is to better understand the carbon cycle in semi-arid environments. This thesis will primarily focus on four issues: Quantify/estimate (a) soil moisture (water availability) (b) soil temperature on a daily basis in semi arid Sudan with the help of a model called DAYCENT (Parton et al 1993; 1994) and (c) through sensitivity analyses investigate how responsive sensitive parameters (for example soil texture and land use) are to changes. The model will be validated through comparison of model estimations to actual measurements (d) from Kordofan, Sudan.

2. Study Area

Data is often very hard to find, if even existing, or get from the Sahel countries. One exception though is the Sudan, in northeastern Africa, which has been studied since the days of the DECARP (1974) report in the early 1970's. This is the reason why there is some information available and the Northern Kordofan province in the Sudan was chosen to represent the Sahel.

2.1 Brief description of the Sudan

The climate of Sudan varies from continental in the northern parts, through savannah in the centre, to equatorial in its most southern parts. Rainfall varies from 20 mm/year in the north to some 1600 mm/year in the far south (FAO). Average annual rainfall is 436 mm. High temperature and high radiation load conspire to produce a large atmospheric demand for moisture; annual potential evapotranspiration gene-rally exceeds 2000 mm (Rockström, 1997). Water used in Sudan derives almost ex-clusively from surface water resources, as groundwater is used in only very limited areas, and mainly for domestic water supply. *Figure 1* gives a view of the Sudan and the location of the study area.

Figure 1. *The study area, Demokeya Forest Reserve, is located northeast of El Obeid (Al Ubayyid) in the Sudan and depicted in the picture as a star.*

2.1.1 Soils

Sahel soils are generally slightly acidic, and quite sandy, falling into the luvic arenosol category according to the Food and Agriculture Organisation (FAO) classification, with vertisols (black clay soils) often found in depressions. The soils are generally deficient in phosphorous and nitrogen, and organic matter content is usually less than 1% (Le Houerou, 1980). Arenosols cover millions of hectares of land in the semi-arid zones of the southern Sahara and southwest Africa, and are used mainly for grazing but dry farming is also possible especially on those rich in gypsum and calcareous materials. However, the high rates of infiltration make irrigation virtually impracticable (Adams et al, 1996).

Research on maintenance of soil fertility and productivity focuses on the preservation of top soils and their levels of organic matter and buffering capacities, as well as on the integration of the application of artificial chemical fertilizers into traditional crop-management systems (Mortimore, 1989). The need to minimize soil loss during cultivation has led to research into tillage methods, such as, for example, minimum tillage (Lal, 1974, 1980) and new cropping systems such as alley cropping, cover crops, mulching and supplementary irrigation techniques are being introduced not only to combat soil erosion but also to protect the soils against desiccation (Lal, 1974). Cultivation on mostly sandy and almost always nutrient-poor soils makes crop yield very sensitive to small changes in climate. Severe and heavy rainfalls cause the same devastation as the contradictory just as well as abnormally high temperatures leads to drought (Khogali, 1991).

2.2 The Kordofan province

The dominating soil types in the northern Kordofan Province are Xerosols, Arenosols and Vertisols (FAO, 1994). The Xerosols in the northern part of the area are generally fine textured with a clayey topsoil, comparatively rich in organic matter in spite of the low coarse textured soils with aeolian origin, locally named Qoz soils (Adams, 1967). The texture is characterized by 60-70% coarse sand, 20-30% fine sand and 5-10% clay (Mitchell, 1991). A small part in the south is covered by Vertisols, locally named Gardud soil, which is a non-cracking clay soil, mixed with aeolian sand. The region is representative in terms of soils, climate and vegetation type for a large region stretching from the Atlantic coast to the Ethiopian highlands (Olsson & Ardö, 2002).

In the southern parts of the province cultivation and livestock breeding is the major livelihood. Common crops are millet (*Pennisetum typhoideum*) and to a lesser extent sesame (*Sesamum indicum*), karkade (*Hibiscus sabdariffa*) as well as ground-nuts (*Arachis hypogaea*) but also production of gum arabic from the *Acacia senegal*. Cropland is generally burned annually prior to the planting in June or July. Observed fire return intervals in this and similar environments range from 1 to 12 years (Scholes & Walker, 1993; Parton et al., 1996; Sitch, 2000). From inter-views on location it is evident that the land-use practices have changed markedly from a rotation system with long fallow periods (15-20 yrs) interspread with short periods of cultivation over the last three to four decades (Olsson, K 1984). During the same period, the crop yields have decreased (Olsson, L., 1985). The decline has been said to be of the same magnitude as the reduction of fallow periods (Olsson, 1993) and in precipitation (Helldén, 1984, 1988; Olsson, 1983; Thomas, 1993).

2.3 Demokeya

The desert and semi-desert region of western Sudan is represented by El Obeid Research station where most of the research in area of reforestation, Arabic gum, desert crop, and carbon sequestration is preformed. The Research Farm is situated at Demokeya Forest Reserves, 37 km east of El Obeid. The *Acasia senegal* is the dominating tree species in the forest. The forest has been a reserve since the 1930s. An *A. senegal* plantation program is maintained since 1967. The meteorological station was installed in February 2002 (*fig. 2*). It collects meteorological data, which will help monitor changes on natural resource base, and impacts of the research interventions on soil carbon sequestration and other nutrient pools such as N, P, K etc. Data obtained are air temperature (mean, minimum & maximum), incoming radiation, relative humidity, vapour pressure, precipitation, wind speed and direction as well as soil water content and soil temperature at the depth of 30 and 60 cm.

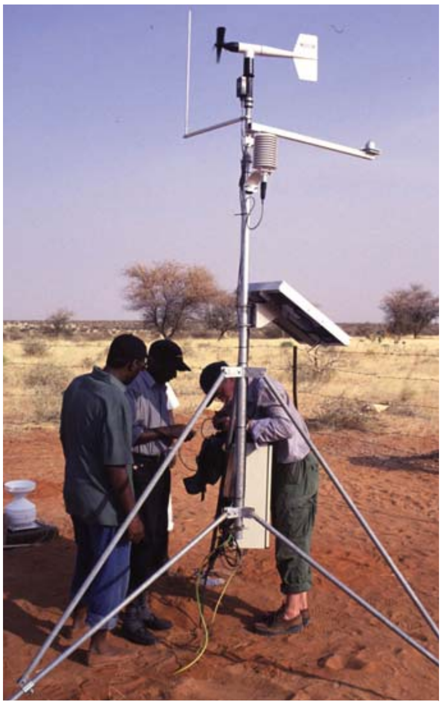


Figure 2 *The climate station in Demokeya Forest Reservetion. Note the vegetation cover and sparse distribution of trees (*Acacia senegal*) and bushes (Photo: J. Ardö).*

3. Theory

3.1 Soil water

Water is held in the soil by attraction of water molecules to each other and to soil particles by capillarity. The amount held changes over time, which affects the availability of water to plants and the potential movements of materials and nutrients. Saturation of a soil occurs when the soil pores are full of water. This condition is actually never reached because even saturated soil contains a very small amount of air. The drained upper limit, called the field capacity (FC), represents the amount of soil water retained by the soil against gravity. The lower limit is used as an index related to soil water available for plant utilization and is known as the wilting point. Plants cannot absorb soil water in an amount less than the value at the wilting point rapidly enough to meet their needs. At this point, the foliage of plants not adapted to drought, will wilt. As *fig. 3* shows, the wilting point depends on structure. The amount of water held in each state of availability depends on the soil structure. The organic content of a soil strongly affect its water-holding capacity (Burman & Pochop, 1994). The most important variable is the size of the soil particles and therefore the size of the pores between them. The Bulk density is used to calculate soil porosity, a crucial variable for climate and trace gas models (Mosier et al, 1996).

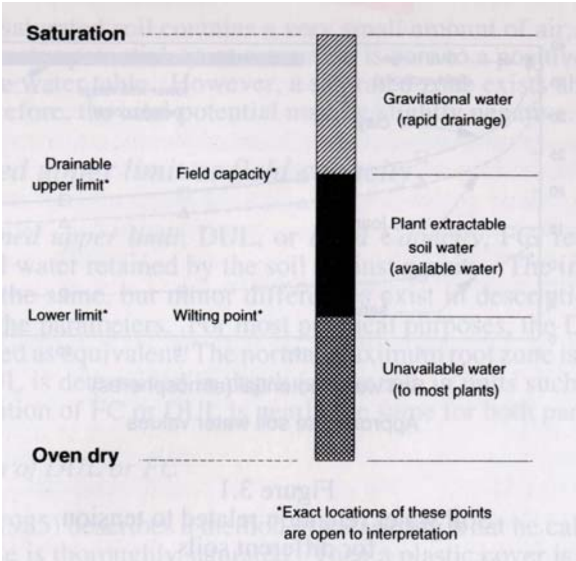


Figure 3. *Typical values for soil water availability in different soil textures (from Burman & Pochop, 1994).*

Soil provides structural support to plants, and, at the same time, provides stored soil water for growth and survival of plants. Soil water holding capacities of soils vary with soil texture and organic material among others. The water between field capacity and wilting point is termed plant extractable soil water or available water. It is also seen as the reservoir of water for evapotranspiration (Burman & Pochop, 1994). There are two ways to define evapotranspiration: a) actual evapotranspiration (E_a), which is the real rate of water vapour return to the atmosphere from the surface and b) potential evapotranspiration (E_p), representing the water vapour flux under an ideal set of conditions.

3.1.1 Evaporation and evapotranspiration

Between periods of rain, water held in the soil is gradually loosened by a twofold drying process. Firstly, immediate evaporation into the open air occurs at the soil surface and progresses downward. Ordinarily only the upper 30 cm of soil is dried by evaporation in a single dry season. In the prolonged drought of deserts, the dry condition extends to depths of many meters. Secondly, plants draw the soil water into their systems through vast networks of tiny rootlets. This water, after being carried upward trough the trunk and branches into the leaves, is discharged into the atmosphere through leaf stomata in the form of water vapour. The process is termed transpiration. Recent modelling investigates the impact of soil moisture recycling, evapotranspiration and surface roughness on rainfall patterns, generally shows that reductions in evapotranspiration and soil moisture through vegetation removal could indeed result in decreased rainfall at a number of different spatial scales by altering large scale patterns (Xue and Shukla, 1993; De Ridder, 1998).

3.1.2 Runoff and infiltration

There are two important factors affecting the infiltration of a soil. Firstly, the denser the plant cover and the root system are, the more infiltration. Secondly, the coarser the soil grain size, the more capacity the soil has for infiltration. In general, the coarse sands and gravel record high infiltration rates, while the fine particles record low infiltration rates. Regarding pedogeomorphical relationships, runoff is higher in fine textured or crusted surfaces. Simply put, the relationship of runoff to surface texture is inverse to that of infiltration (Osman, 1996). Considering soil moisture, the actual penetration of water into soils depends on the potential for infiltration, water holding capacity and permeability of the soil in relation to actual evaporation from both the soil and the plants. Nonetheless, the amount of moisture in the soil would depend upon the number of pores. The finer soil particles, the larger the soil water capacity (Scheroeder, 1984) that ranges from about 30% by volume for clay soil to less than 10% for sandy soils (Carson, 1969). Relative to climate and cover conditions, the threshold value of moisture tends to be high on days of potentially heavy withdrawal (dry, hot and sunny) and relatively low on days of smaller potential demand (Miller 1977).

In arid lands, Walter (1979) argues that clayey soils, sandy soils and stony soils retain 50%, 90% and 100% respectively of the infiltrated rainwater. Empirically (Gerrard, 1981) the gravely soil has 478 mm/h infiltration rate at the first 15 minutes, while silt loam has 0 mm/h rate value in the same period. Rapp et al. (1979) studied soil erosion and sedimentation in four catchments in semi-arid central Tanzania. They found that the ungrazed thicket, grass (or pasture), millet (or cultivated) and bare fallow lands lose 0.4%, 1.9%, 26% and 50.4% of rain water to runoff respectively. These figures exemplify how plants and different land use influence the partitioning of rainfall to runoff and infiltration.

3.2 Carbon sequestration in arid lands

Soil organic matter (SOM) accumulation is favoured by cool, wet conditions that slow decomposition and SOM turnover rates, while warm, moist conditions favour rapid decomposition and lower SOM (Tate, 1992). Therefore, SOM equilibrium levels tend to decrease from cool to warm environments. Climatic and vegetation factors, landscape features, and human activities that influence SOM are modified by soil properties that affect carbon inputs and decay rates such as particle size, pH, clay mineralogy, fertility, and internal drainage.

Grassland soils contain more soil carbon than forest soils and uncultivated soils more than cultivated soils. Soil texture is also an influencing factor, while soil carbon increases with increasing clay content (Batjes, 1996). Soil respiration is correlated with various factors including temperature, moisture and the nutrient content of the soil. Together with chemical and physical characteristics of the organic material, these parameters are considered to be the major factors controlling decomposition rates of soil organic matter (Swift et al, 1979). The oxygen availability, the type of microorganism present and faunal abundance and activity are also important factors (Lomander, 2002). Since the pool of soil carbon is twice as large as the pool of atmospheric C, relatively small changes in the former could have a significant impact on the CO_2 content of the atmosphere. The response of C mineralization rate to temperature is in many studies traditionally described by the Q10 relationship (the factor by which the activity increases when the temperature increases by 10°C), originally developed by Van't Hoff in 1898 (see review by Kirschbaum, 1995).

Soil organic carbon (SOC), is primarily determined from the balance between the assimilation of CO_2 via photosynthesis and C losses to the atmosphere through respiration. In addition to biologically driven processes, soil movement through wind and water erosion can redistribute carbon-enriched topsoil to different portions of the landscape or deliver sediment to surface waters (Huggins et al, 1998). Annual net primary production (ANPP) of grasslands is strongly related to precipitation and available soil moisture (Lauenroth, 1979; Sala et al., 1988). Net primary production of above- and below-ground biomass generally increases with greater growing season precipitation. Rotations with greater tillage intensity and soil incorporation of residues would be expected to increase decay rates; however, Huggins et al (1998) found that data indicated that treatment induced variations in SOC balance in the tall-grass prairie were mainly due to differences in carbon additions rather than SOC decay rates. Their analysis, however, did not consider possible treatment induced differences in soil erosion, soil bulk density, or SOC below the 20 cm sampling depth.

3.2.1 The Savannah zone

The significance of the savannah zone to the global environment is based on five factors (Scholes & Hall, 1996). a) The vast extent of the area (11.5% of the global land surface) makes it a significant component of global element budgets and gaseous fluxes. b) Seasonally dry climate permits extensive annual biomass burning. c) The proportion of trees and grass is inherently unstable, and small changes in climate or land use practice can lead to rapid changes in biomass and soil properties. d) It lies in mostly within the area of the developing world where the population pressure and land use changes will be greatest in the next decades. The agro-pastoral communities in savannahs are highly dependent on the natural vegetation, which is vulnerable to degradation and e) the biodiversity of plants and animals in these areas is greater than usually recognized.

Woodlands and savannahs are characterised by having an annual dry season of sufficient duration and intensity that most of the woody plants shed their leaves, and the grasses dry out. This accumulation of dry fuels permits fires every few years; and the fires help prevent complete domination of woody plants (Scholes & Walker 1993).

3.2.2 Primary production

Net primary production (NPP) is defined as the sum of net increases in total plant standing crop over a given period, including losses due to litter fall, root death and herbivory during the same period (Scholes & Hall, 1996). The three main factors controlling primary production in tropical woodlands, savannahs and grasslands are water and nutrient availability to the plants and the vegetation structure. The latter particularly regarding the tree-grass ratio, the plant density and cover, and the amount of standing dead material. Water availability is the relationship between water supply and water demand, seen from the plant point of view. Supply and demand have independent seasonal patterns and must be calculated using a model which takes into account precipitation, air temperature, radiation, humidity, wind, soil texture, rooting depth, vegetation attributes and landscape position (Scholes & Hall, 1996).

Precipitation occurs as short-duration, high-intensity convectional storms (Scholes & Hall, 1996). The climate is characterized by stable descending air masses for protracted periods of the year leading to highly seasonal rainfall, high continentality and very high solar radiation since the cloud cover is relatively low. These conditions result in generally low humidity and high daytime temperatures, and thus very high rates of evaporation. Annual potential evaporation substantially exceeds annual rainfall.

The overdriving control on the decomposition rate to plant residues in tropical grasslands and savannahs are water availability. The chemical composition of the litter, and to a lesser extent its physical structure, controls its decay rate during the moist periods. Grass litter decomposes faster than tree litter, due to the trees higher content of nitrogen, lignin and secondary compounds (Scholes & Walker, 1993), provided it is in contact with the soil surface; however grass litter frequently remains attached to the plant, where it decays gradually until burned, grazed or trampled (Scholes & Hall, 1996).

Fire effect on NPP

Even in annually burned savannahs, a surprisingly small fraction (<20%) of the NPP ends up being consumed by fire (Scholes & Walker, 1993). In triennially burned savannas, this fraction decreases to about 5% (Scholes & Hall, 1996). This is because a large part of the NPP is protected from fire, being underground or in the tree biomass, or having decayed in the interval between fires. About 40% of the total savannah area is to dry to accumulate substantial fuel loads except in high-rainfall years, or are to heavily graze to burn fiercely (Scholes & Hall, 1996).

In dry areas the total aboveground NPP in mixed tree-grass ecosystems is usually higher than in pure grasslands derived though the removal of woody plants, despite the large increase in grass production. Primary production by tropical grasses typically increases by about 20% in the season after a fire (Grossman et al., 1981).

3.3 Ecosystem models

Ecosystem models consider water, carbon and nitrogen flows between the plant and the terrestrial systems. Within this group of models, the plant compartments are highly aggregated and typically lump all green plant biomass into one compartment (Ryan et al, 1996). The objectives of the models are quite diverse; however, they generally include the ability to simulate ecosystem responses to changes in the abiotic driving variables (light intensity, soil water and soil temperature) and the interaction of dry matter production and nutrient cycling. The models CENTURY (Parton et al. 1987; Sanford et al. 1991) MBL-GEM (Rastetter et el., 1991), PnET-CN (Aber & Federer, 1992) and Q (Rolff & Ågren, 1996) will illustrate this model class. Two other classes of models (population models and regional models) exist, but they are more suited to different temporal and spatial scales than those in this study. Population models have been developed to simulate tree growth as affected by competition among individuals as well as climate. These consider birth or recruitment, growth of individuals; stand structure and spacing, and mortality as well as the effects of nutrient limitation on tree growth (Ryan, et al, 1996). An example of a physiologically based population model is HYBRID (Friend et al, 1993). Physiologically based models provide a framework integrating the many direct and indirect effects of elevated CO_2. Effects promoting growth include increased temperature (lengthening growing seasons and increasing photosynthesis in high light environments) and the beneficial direct effects of CO_2 enrichment on photosynthesis and water use efficiency (Ryan, et al, 1996). Effects reducing growth arising from greenhouse warming are increased water vapour saturation deficit and increased leaf area development, which may increase or decrease productivity. Where the objective is to asses the net effect of such opposing factors, physiologically based models are appropriate tools (Booth & McMutrie, 1988). Ecosystem models provide a framework for understanding the system level constraints for the response of productivity to elevated CO_2, and altered temperature and moisture (Ryan et al. 1996). Therefore, information about nutrition is necessary to assess longer-term interactions between the atmosphere and climate.

3.3.1 The DAYCENT Model

DAYCENT (Kelly et al, 1997; Parton et al, 1998) is a terrestrial ecosystem model used to simulate exchanges of C, N and trace gases among the atmosphere, soils and vegetation with a daily time step. DAYCENT is of intermediate complexity. The important processes are represented mechanistically, but the model makes use of empirically derived equations and the required input parameters are often available for many regions (Del Grosso et al, 2002). DAYCENT is the daily time step version of the CENTURY ecosystem model (Parton et al., 1994; Metherell, et al., 1993), which operate at a monthly time step while this degree of resolution is the best for simulation of medium to long term (10 - <100 years) changes in soil organic matter (SOM) and other ecosystem parameters in response to changes in soil water levels. Simulations of trace gas fluxes through soils require finer time scale resolution because a large proportion of total gas fluxes are often the result of short-term rainfall or irrigation events (Frolking et al., 1998). The processes often respond non-linearly to changes in soil water levels (Del Grosso et al., 2002).

DAYCENT includes sub models for plant productivity, decomposition of dead plant material and SOM, soil water and temperature dynamics and trace gas fluxes. Plant growth is limited by temperature, water and nutrient availability. Carbon and nutrients are allocated among leaf, wood and root biomass based on vegetation type. Transfer of C (*fig. 4*) and nutrients from dead plant material to the soil organic matter and available nutrients pools is controlled by the lignin concen-tration and the C:N ratio of the material, abiotic temperature/soil water decomposition and soil physical properties related to texture. Deterial material with low C:N ratios and low proportions of lignin (metabolic), for example, goes to the active SOM pool. A lower proportion of decomposing SOM is respired as CO_2 and more organic matter is retained in stable forms due to chemical and physical protection as soils become finer textured (Del Grosso et al. 2002) The available nutrient pool (NO_3^-, NH_4^+, P, S) is supplied by decom-position of SOM, biological N fixation and external nutrient additions such as fertilization and N deposition. The proportions of SOM in the respective pools and soil water, temperature and texture determine the rate of nutrients supply from decomposition. NO_3^- and NH_4^+ are available for both plant growth and for biochemical processes that result in N transformations (nitrification and de nitrification) and N gas emissions. Significant amounts of NO_3^- can be lost from soils via leaching when water flow through the soil profile is sufficiently high (Del Grosso et al, 2002). A daily time step is needed to represent trace gas fluxes since flux rates changes rapidly in response to changes in soil water and temperature. The current modelled and observed trace gas flux data suggests that land surface models need to use at least three soil layers in top 15 cm of the soil and have the ability to simulate above field capacity water contents following intense rainfalls (Mosier et al (1996); Parton et al, (1996a,b)).

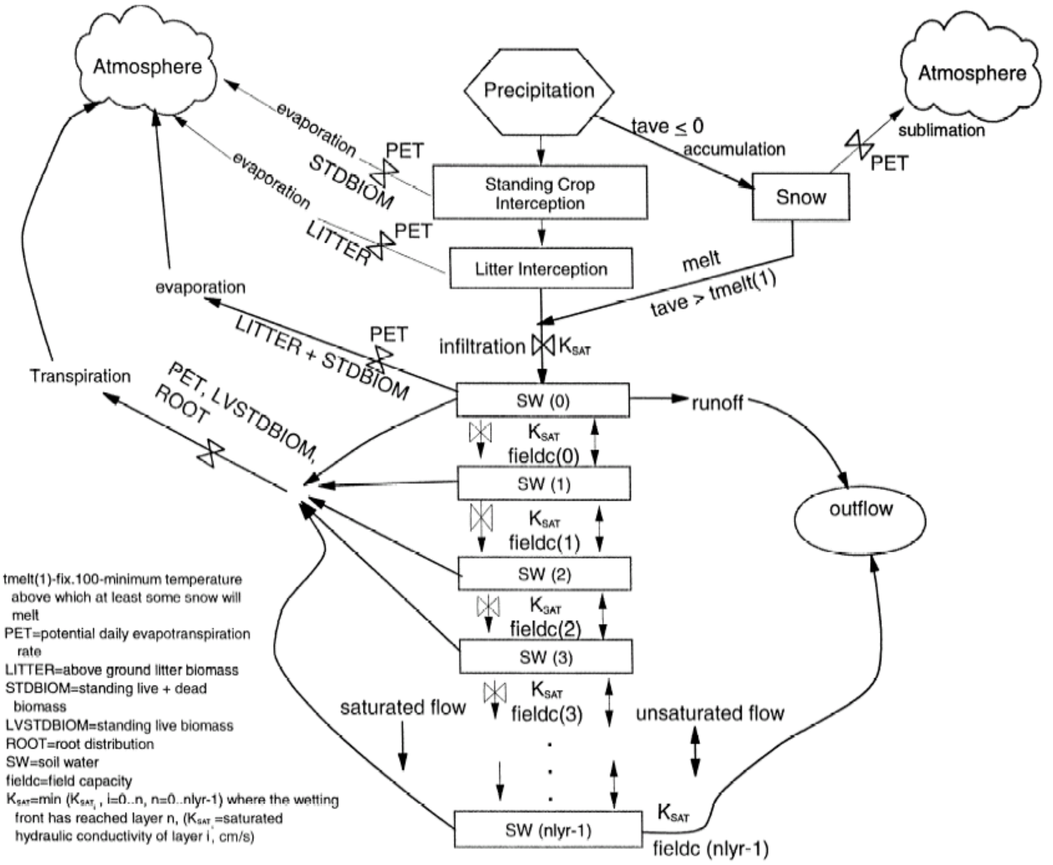


Figure 4. *This figure illustrates the carbon budget in grasslands (from Parton, 1998), but is also the principle on which DAYCENT is built.*

Biophysical submodels in DAYCENT includes a simplified water budget model which calculates monthly evaporation and transpiration water loss, water content of the soil layers, snow water content and saturated flow of water between soil layers. The potential evapotranspiration rate (PET) is calculated as a function of the average daily maximum and minimum air temperature using equations developed by Linacre (1977). Bare soil and interception water loss is a function of aboveground biomass, rainfall and PET. Transpiration water loss is a function of the live leaf biomass (exponential function of leaf biomass), rainfall and PET. The field capacity and wilting point for the different soil layers are calculated as a function of the bulk density, soil texture, and organic matter content using an equation developed by Gupta and Larson (1979).

3.3.3 Soil water content submodel

The water flow submodel simulates the daily flow of water through the plant canopy, litter, and soil layers. Rainfall is initially intercepted by the canopy, then by the surface litter and evaporated from these surfaces. Intercepted water evaporates at the potential evapotranspiration PET water loss rate and the amount of intercepted water is a function of the plant biomass and the rainfall amount (Parton, 1978). When there is water input, infiltration, runoff, and saturated flow are simulated first. Water is then evaporated and redistributed throughout the soil profile by an unsaturated flow algorithm modified from the work of Hillel (1977). This is followed by transpiration water loss using equations developed by Parton (1978). The PET water loss rate is calculated using the Penman equation. The maximum potential transpiration and bare soil evaporation water loss are calculated as a function of live leaf biomass (bare soil evaporation decrease and transpiration increase as live leaf biomass increase; Parton, 1978). The transpiration rate is reduced under low soil water conditions as a function of the soil water potential of the wettest soil layer in the top 30 cm or the weighted average soil water potential within the plant-rooting zone. Transpiration water loss from each soil layer is controlled by the soil water potential of the layer and root biomass (Parton, 1978). Infiltration and saturated flow of water through the soil profile are represented by a unidirectional downward flow. During infiltration the hydraulic conductivity of a layer equal's its saturated hydraulic conductivity (k_{sat}, cm/s).

Initially, the rate at which water enters the soil equalled the saturated hydraulic conductivity of the topsoil layer. As water input continues the rate at which the water enters the soil and percolates downward becomes the minimum of the hydraulic conductivities of the soil layers that is encountered by the wetting front. Water fills a layer to saturation before percolating to the next level. If water input intensity is greater than the rate at which water can enter the soil, the difference will go to runoff and is added to the outflow. Water is added to the profile until the set time of duration is over. Any layer that exceeds its field capacity is drained. Starting at the top of the soil profile and progressing downward, water in excess of field capacity is drained. If any water exits the bottom layer it is added to outflow. Unsaturated flow is represented by a bi-directional vertical flow (*fig. 4*). At each 2-h time step, the hydraulic potential and hydraulic conductivity of each soil layer were recalculated; from these, bi-directional water fluxes and net water flux to each soil layer were computed. Based on Darcy's law, the bidirectional water flux (cm/s) between two adjacent layers, *i-1* and *i*, was calculated as:

$$flux_i = \frac{dmp_{flux} * (h_{poti-1} - h_{poti}) * av_{condi}}{dist_i}, \quad i = 1 \ldots n_{lyr} - 1 \qquad eq.1$$

where where, dmp_{flux} is the damping multiplier, 0.000001; h_{poti} the hydraulic potential of layer *i* (cm), the sum of the matric potential and gravitational head, where $h_{poti} = m_{poti} - depth_i$; m_{poti} is the matric potential of layer *i* (cm); av_{condi} is the distance from the soil surface to the middle of layer *i* cm ; av is the average hydraulic conductivity of layer *i* (cm/s), a weighted average of $cond_{i-1}$, $cond_i$, and $cond_{i+1}$; $cond_i$ is the hydraulic conductivity of layer *i* (cm/s); $dist_i$ is the distance between the midpoints of two adjacent soil layers, *i*-1 and *i* (cm); n_{lyr} is the number of layers in the soil profile.

The bi-directional water flux (cm/s) between two adjacent layers is based on Darcy's law. The flux at the top of the soil profile is dependent on the potential soil evaporation rate (cm/s), the current soil water content of the top layer, and the minimum allowable water content in the top soil layer. The flux at the bottom of the soil profile is dependent on the hydraulic conductivity of the bottom soil layer. If flux is positive, water moves downward from layer to layer, if flux is negative, water move upward from layer to layer. Adjustments to the bi-directional fluxes and net fluxes are computed if the addition of the net flux would dry out a layer below its minimum allowable water content. If the addition of a net flux brought a soil layer above saturation, water in excess of saturation was added to outflow.

3.3.4 Soil temperature submodel

The soil temperature model calculates thermal diffusivity and predicts daily minimum and maximum soil temperatures at depth. Required inputs to the model is daily minimum and maximum air temperatures, plant biomass, soil moisture, soil texture, and average soil temperature at the bottom of the soil profile. Average daily soil temperature near soil surface is calculated using the equations developed by Parton (1984). A simple model was developed for calculating the daily maximum and minimum soil surface temperatures, given the maximum and minimum air temperature (2 m height) and the plant biomass. Maximum soil surface temperature (T_s^{max}, °C) is predicted as a function of the maximum air temperature (T_a^{max}, °C) and the plant biomass; minimum soil surface temperature is a function of minimum air temperature and plant biomass. The equation used for maximum soil surface temperature is:

$$T_a^{max} = T_s^{max} + ET * EB \qquad \textit{(eq. 2)}$$

Where ET is the elevation of maximum soil surface temperature over air temperature as a function of maximum air temperature, and EB is the effect of plant canopy (Parton, 1984). Parton (1984) showed that the elevation of maximum soil surface temperature increases with increasing air temperature up to 25 °C and then slowly approaches a constant value. Increasing plant biomass results in a decrease in elevation of T_s^{max} over T_a^{max}, and plant biomass levels above 400 g/m^2 cause the T_s^{max} to be lower than T_a^{max}. Plant biomass adsorbs and reflects solar radiation and thus reduces the amount of radiation incident of the soil surface. The parameter values of plant biomass effect on maximum soil surface temperature will probably vary for different plants; however, the general form of the equation is used (Parton, 1984). The results by Parton in 1984 showed that maximum air temperature and total daily solar radiation are the variables most correlated with maximum soil surface temperature. The minimum soil surface temperature (T_a^{min}, °C) is predicted as a function of minimum air temperature (T_a^{min}, °C) and plant biomass (Parton, 1984), using *eq. 3*.

$$T_a^{min} = T_s^{min} + 0.006B - 1.82 \qquad (eq.\ 3)$$

Where B is the plant biomass (g/m^2). The equation shows that minimum soil surface temperatures are higher with increased plant biomass and are a result of decreased long-wave radiation losses at night (Parton, 1984).

Maximum and minimum soil temperatures are simulated in the soil temperature model by using an equation for predicting the range of temperatures with depth. Both the range of temperature and the mean soil temperature models are based upon the Fourier heat transfer equation (Parton, 1984). The diurnal range of temperature with depth is given by a function of the diurnal temperature ranges at depth d and at the soil surface, respectively: the thermal diffusivity, and the period of oscillation (*eq. 4*).

$$R_d = R_s e^{\left[-d\left(\frac{\Pi}{\alpha p}\right)^{0.5}\right]} \qquad (eq.\ 4)$$

where R_d and R_s are the diurnal temperature ranges at depth *d* and at the soil surface, respectively, α is the thermal diffusivity, and *p* is the period of oscillation (84 600 s). This equation is developed with the assumptions that soil thermal diffusion is constant with the depth and that soil surface temperature follows a sine wave. The average daily soil temperature versus depth is calculated at 10 cm depth intervals to 170 cm, using the one-dimensional Fourier heat transfer equation (Parton, 1984). The average daily soil surface temperature is the upper boundary temperature, and the average daily temperature at the 180 cm depth is the lower boundary temperature. A finite difference scheme solves for the soil temperature in the top layer (10 cm depth) first, and then uses the new temperature in determining the next lower soil temperature (*eq. 5*).

$$\frac{T_i - T_i^1}{\Delta t} = \alpha K \frac{\left(T_i^{-1} - 2T_i^1 + T_{i+1}{}^1\right)}{\Delta x^2} \qquad (eq.\ 5)$$

where T_i and T_i^1 are average daily soil temperatures at point *i* (i = 2, 3, …,) at time *t* and t^1, respectively; Δx is the distance between profile points (10 cm); Δt is the time step (86400 s); and *K* is the time step correction coefficient. Deeper soil depths are sensitive to the set boundary conditions. It is, though, possible to put the minimum temperature for bottom soil layer for the year, the maximum temperature for bottom soil layer for the year, a time step, or damping, correction factor that relates to how fast the heat flows in to or out of the soil.

4. Methodology

4.1 Parameterisation

Most parameters used by DAYCENT are intended to remain constant in the majority of applications and is therefore fixed (Parton et al, 1993). Other parameters, which are particular to an individual site, are contained within site-specific files. Some of these site-specific parameters consist of the "minimum input" data required to run the DAYCENT model, which include soil texture (sand, silt and clay content), soil pH, soil depth for modelling water budget, plant type and weather data (daily precipitation and daily maximum and minimum temperatures). The remaining site-specific parameters relate mainly to plant physiological functions controlling growth, death, turnover and N inputs. Parameter values, reason and the base of estimation for each are presented below. If not mentioned otherwise all the parameters remained identical during the different runs. Abbreviations in parentheses give the parameter name in the model.

Observed data exist for soil temperature and soil water content at the depth of 30 and 60 cm. The soil moisture sensor at the depth of 30 cm was out of order during August until mid October 2003, which will be seen as a drop in the diagrams or explain why some of the observed data is missing. Though the uppermost layers (0-1, 1-4 & 4-15 cm) in the model are predetermined, a problem is caused: Should the actual data of 30 cm depth be compared to layer 4 (15-30 cm) or 5 (30-45), or perhaps to a mean of them both? Should the 60 cm observed data correlate to layer 6 (45-60) or layer 7 (60-75)? Statistical analyses, however, showed that best result was given through comparing with each layer separately. Therefore only result layer by layer will be reported.

4.1.1 Climate data

The DAYCENT model requires climate data like albedo, fraction of field capacity, and duration of rain event in hours as well as cloud cover. The albedo for savannah grassland was estimated to 0.25 (Liljequist, 1970). The fraction of field capacity, or the initial soil water content, is set to 0.6, the saturated hydraulic conductivity of deep storage layer to 0.0003 cm/s and the damping factor to 0.003 (Hillel, 1971; Chorley, 1969; Burman and Pochop, 1994). The cloud cover for each month was interpolated from Liljequist (1970) and a data set from the Tyndall Centre (2003). Cloud cover from November until February was set to 10%, March to 13%, April to 15%, May and October to 20%, June and July to 25%, August and September to 30%. After studying available climate data from the area, the duration of a rain was determined to approximately 4 hours and the min and max temperature for bottom soil layer to 23.0 and 40.0 °C. A weekly production time step, as well as the use of no extra weather drivers, was chosen.

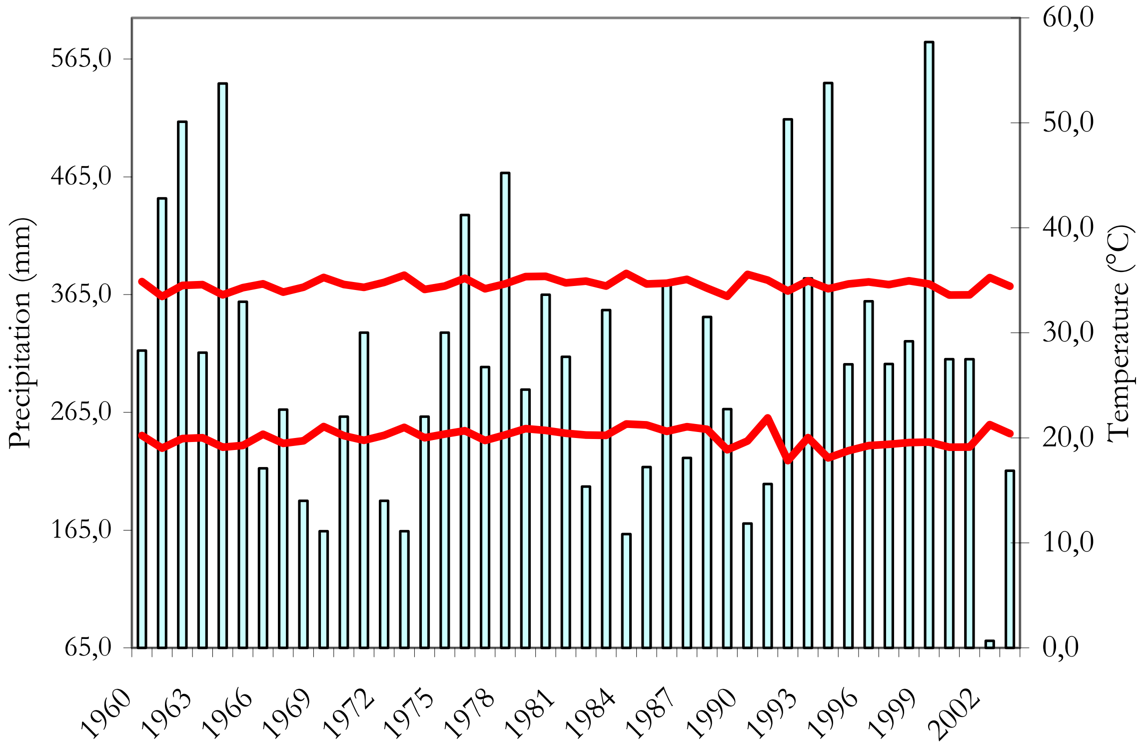


***Figure 5**. Precipitation and air temperature (minimum and maximum) during the last 40 years in El Obeid. Years with high precipitation are often connected to low mean annual temperatures and vice versa.*

Furthermore, daily minimum and maximum temperature (°C), and precipitation (cm) are required. It is possible to, on a daily basis, use extra weather drivers like solar radiation (langleys/day), relative humidity (%) and wind speed (miles/hour). Daily weather data from Demokeya only exists from Julian day number 39 in 2002 until Julian day no. 305 in 2003. To get daily data from the time before and after, weather generating was made based upon monthly rain as well as minimum and maximum air temperature data (1960 – 1999) from El Obeid, 30 km SW of Demokeya. The monthly minimum and maximum average was set as a daily min and max temperature for each month. Minimum amount to be observed with this method is 0.201 mm. This might cause that days with only small precipitation amount recorded is due to other particles than raindrops that has fallen into the bucket, and is thereby a possible source of error. During 2002-2003 the most days where recorded with precipitation below 4 mm, during 10 days between 4 mm – 8 mm and 3 days with precipitation >8 mm (in August). The total number of days with precipitation during the period was 205. The rain starts in June and last until October. The quantity, i.e. the span of only a short shower to a heavy rainfall, as well as the durability and number of events each month, was estimated from the daily data during 2002-2003 and randomly scattered over each month back to January 1985.

Climate variables

The DAYCENT model gives the opportunity to use some extra weather variables. In order to calculate PET from wind speed, incoming solar radiation and relative humidity, instead of only air temperature, it is necessary to have daily data from a weather station. With the intention to investigate the importance of, or the possibility not to, collecting such data in field the model was run. While only such data exist during the one and a half year, the weather file was built only upon one year, 2003, with the non-existing data replaced by records during the same time in 2002.

4.1.2 Soil

The model consists of 11 soil layers. Each soil layer was assigned unique properties including thickness, proportion of roots (*table 1*), field capacity, wilting point, bulk density, saturated hydraulic conductivity, minimum water content, (*table 2*) and pH. These values are based on observed data or estimates based on soil texture. The soil sample was analysed to a texture of 96.3% sand, 3.7% loam, pH to 6.2 and the organic matter content to 1.0 %. Note that the soil does not contain any clay.

Table 1. *The root dispersion of a plant differ between species and type of soil. The biomass of* Acacia Senegal *in Arenosoils in each soil layer used in this thesis is estimated from Adams (1967) and Lindquist (1998).*

Soil layer (cm)		Roots (%)
0.0	1.0	0.06
1.0	4.0	0.10
4.0	15.0	0.33
15.0	30.0	0.22
30.0	45.0	0.13
45.0	60.0	0.05
60.0	75.0	0.04
75.0	90.0	0.04
90.0	105.0	0.02
105.0	120.0	0.01
120.0	150.0	0.00

The physical parameters were calculated by the program Rosetta V1.0 (Schaap, 1999) and set to 1.70 g/cm^3 for bulk density and the volumetric values for field capacity and wilting point to 0.091 and 0.039 respectively. Physical values fit well with literature (Hillel, 1971; Campbell, 1985; Burman & Pochop, 1994). The evaporation coefficient is currently not being used as well as the pH (Del Grosso, 2003).

Table 2. *Physical properties of the different soil structures. K_{sat} stands for saturated hydraulic conductivity and θ_s for minimum volumetric soil water content. Sand, clay, field capacity and wilting point is given in %.*

Soil texture	Sand	Clay	Field capacity	Wilting point	k_{sat}	θ_s
Base statement	94.0	2.0	9.1	3.9	0.06	0.010
Sand (a)	93.7	2.66	9.1	3.3	2.81	0.053
Sand (b)	93.6	3.26	9.1	3.3	2.81	0.053
Loamy sand (a)	82.5	7.7	12.5	5.5	2.02	0.049
Loamy sand (b)	88.9	1.7	12.5	5.5	2.02	0.049

Documented data on root dispersion in soils is poor; Adams (1967) wrights about *Acacia Senegal* root spread in vertisols, Lindquist (1998) studied *Acacia mangium* fineroot biomass in an Orthic Acrisol soil in Indonesia. Nothing was found about Acacia roots in Arenosoils. Lindquist (1998) reported a deeper root penetration in sandy soils than in clayey soils. The parameter estimations were based on, and interpolated from, literature (Adams, 1967; Adams et al 1991, New, 1984; Lindquist, 1998). The percentage of roots in each soil layer was set to a concentration of roots in the upper 45 cm of the layer, with almost no roots below the depth of 1.0 m (*see tab. 1*).

4.1.3 Vegetation parameters

Grassland and tree parameters were taken from literature, referred to after each parameter, and, for those not interpolated or estimated, from the model originator default values for Acacias and different crops (NREL, 2003).

Crop parameters

The frequent crop was set as tropical C_4 grass. To calculate the potential aboveground monthly production for crops (g biomass/m^2/month) in the area the statement that plant growth take place during days with more than 1 mm rain (Olsson, 1985). Formula given by Olsson gives number of days with precipitation >1 mm times eight. That gives an approximate crop yield of 160 kg/ha or 1.33 g/m^2/month. Primary production and aboveground biomass parameter values are taken from (Scholes & Hall, 1996).

Acacia Senegal

Acacias are a commonly occurring tree or shrub on rangelands throughout the low-tree and shrub-savannah in East Africa. *Acacia senegal* grows on sandy soils in dry regions, between ca. 280 and 450 mm annual rainfall (Olsson, K 1984), and is commonly a part of the traditional rain-fed cultivation cycle. Annual consumption of dead plant material for firewood is about 870 kg/person and year (Olsson, K., 1985) in the Bara area in Northern Kordofan. The parameter controlling the ratio of sapwood to total stem wood (SAPK), expressed as grams per square meter, are estimated from Duke (1981) to 1600 g C/m^2. Olsson, K (1985) found that 7.2% of the total production each year becomes woody biomass. It comes into leaf towards the end of the dry season before the rains when the maximum temperature and the largest diurnal temperature ranges occur. The grass and herb layer beneath and between the bushes is usually poorly developed. In the clayey soils of east-central Sudan, a shallow but extensive root system radiates from the root crown, many of the roots extending 8-15 m parallel to the surface at a depth of 25 cm, enabling the plant to exploit soil moisture and nutrients in a large volume of soil (Adams et al, 1996). However, roots rarely penetrate deeper than a meter, which is the approximate depth of annual water penetration in vertisols, receiving about 400 mm rain per year. Lindquist found, when investigating *Acacia mangium* in an Indonesian rainforest, that the total fine root biomass was located down to a depth of 45 cm. The dispersion was 66 % in fine root biomass at the depth of 0-15 cm, 20 % in 15-30 cm the layer and 14% in the final layer. These numbers correlates well with numbers given by Adams, see above. The dispersion of root biomass of *Ac. Senegal* in Sudan was interpolated between the two and set as in tab. 2, while no data on root fractions of trees in the area, or in an arenosol soil, was found.

The dominant Acacias, in the drier parts of the savannah zone, have microphyllous pinnate leaves. The leaves are usually small and the total production of a year might occur within 2-3 weeks (Olsson, K., 1985). Scenescence starts in October. The large wood mass (KLAI) is calculated from Olsson, K (1985) to 292.11 g C/m^2 at which half of the theoretical maximum leaf area is achieved. The decomposition rate for the different tree compartments refers to investigations of savannahs and grasslands (Goudrian & Ketner 1984). The other tree parameters are derived from the Natural Resource Ecological laboratory (NREL), University of California, USA, acacia parameter file.

4.1.4 Fire

In the Sahel, there are three main types of biomass fires: those associated with land clearing for agriculture, burning of wood for domestic energy (either directly or after first converting it to charcoal); and fires in natural and semi-natural vegetation, which are not associated with changes in land cover or use. Fires in natural vegetation are not considered to be a net source or sink in the global carbon cycle because when integrated over large regions and over several years, CO_2 emitted by the fire is taken up again by vegetation re-growth (Desanker *et al.,* 1997).

Fire tolerance and spinescence of shrubs and trees are strongly developed in Africa. In a dry season fire may scorch the leaves and the ends of the branches, but will not reach the main stem (Adams et al, 1996). In post-mature forms, when the protective lower branches are lost, an inverted cone replaces the so typical hemispherical shape of the acacia and the grass and herb layer extends to the stem. *A. Mellifera* thickets thus become prone to fire damage and may be rapidly replaced by grassland (Adams, 1967). The parameters of the amount of each part of the plant that is removed by are estimated mainly from Adams et al (1991) and Olsson, K (1985). Approximation gives the following demolition; 80% of the live shoots, 70% of the surface litter, 100% of dead fine branches and 30% of the dead large wood.

4.2 Sensitivity analyses

The importance of a parameter is given by its impact of the result. A model that generates a result acceptably fitted to observed data, is interesting to use in different locations with similar but non-equal conditions. A small change in one parameter, and the others kept the same, makes it possible to investigate how sensitive the model is to driving variables. The sensitivity of the model is given when the results are compared to each other. If the original data are the same as those run by a new parameter, the influence of the latter is very small or insignificant. In the opposite condition, a significant difference is prevailed, which means, depending of the size of the difference, that the bigger dissimilarity the more important parameter. Tested parameter change is: root dispersion in soil layers, crop, soil texture, cloud cover, and an increase or decrease in air temperature as well as in precipitation.

4.2.1 Cloud cover

General about the Sudan, and major parts of the Sahel, is a very thin cloud cover during most of the year with a thickening during rain season in June until October. Mean annual cloud amount is approximately 10-30% (Liljequist, 1970; Tyndall Centre, 2003), declining with higher latitudes. No recorded data was available, so estimations are based upon global seasonal means. The model was set to run with a 10% increase and a 10% decrease in cloud cover.

4.2.2 Precipitation & Temperature

Climatic features differ a lot between locations and are sometimes quite cunningly. The model was run with all other parameters unchanged except for, in the first case, precipitation and in the second: temperature. Both factors were increased 5, 10 and 15%, and thereafter decreased with the same rates and run separately.

4.2.3 Root dispersion & Crops

One factor that might influence the final result is the dispersion of roots in the soil layers. To analyse how important it is to have correct measurements, the root fraction was changed to a more compressed and concentrated root mass. The biomass and root penetration in the first 4 cm as well as the fourth layer was kept, while the fifth layer was increased by 10%, 6:th and 7:th by 5%. Decrease in root biomass was set to 13% in the layer between 4 and 15 cm, thereby reducing all root biomass to zero below the depth of 75 cm.

The importance of knowing the crop in the area was measured through replacing the original parameters for tropical C_4 grass to barely sorgum harvest.

4.2.4 Soil texture

Something that can differ between locations is the soil texture. To analyse how responsive the model is to changes two soil samples, observed in field in 2002, at a radius of 100 km from the location. North of the Demokeya Forest Reserve, a sandy soil with 1.89% clay and 2.97% loam as well as two loamy sand samples (93.7%: 2.7% & 93.6%: 3.3 %) were collected. Further south the other sand sample (13.1% loam and 8.32% clay) was found. Loamy sand was taken from the soil textures are determined through the USDA textural classes. The model was run with the new cambic arenosol soil samples, and thereby changed physical parameters (tab. 2). The saturated hydraulic conductivity, K_s, is 2.808 and 2.022 cm/day respectively for the sand samples and for the loamy sand, while the minimum volumetric soil water content, θ_s, is 0.053 (cm^3/cm^3) for the former and 0.049 for the latter. The field capacity and wilting point (Burman & Pochop) was set, for sample number one to 9.1% and 3.3% respectively and for sample number two to 12.5% and 5.5%. θ_s and K_s was calculated by the software program Rosetta V1.0.

4.3 Model Validation

To test if the model is valid when applied to other databases, one needs to be assured that the results are correct. This is called validation or model verification. Through the use of correlation analysis it is possible to approximate the correctness of the model. The better the fit, the more accurate is the model. Three terms are used while determining the model accuracy: error, accuracy and precision.

$$\text{Error(absolute)} = \text{value(modelled)} - \text{value(measured or expected)} \qquad (eq.\ 6)$$

$$\text{Error (relative)} = \frac{\text{value (modelled)} - \text{value (measured or expected)}}{\text{Value (measured or expected)}} \qquad (eq.\ 7)$$

A value provided with e.g. four decimal places is very precise, but if it differs a lot from the expected value there is a large error. That means that a result can be very precise, even if it contains an error. The term accuracy is used as the complement of error, i.e. 95% accuracy implies a 5% error. If the model produces an unacceptably high error value, the model is a poor representation of the system of interest, and vice versa.

Another way to validate a system is to change only one parameter, and all other parameter kept constant. By altering parameters independently, and in conjunction, it is possible to see how sensitive the model is to variations. A sensitivity test may emphasize a weakness in the model as well as indicate the impact of a parameter.

5. Results

5.1 Soil temperature

5.1.1 Model evaluation

The soil temperature sub model was tested by comparing the simulated model results with observed data. The statistical results is accounted in table 1, appendix I. The correlation for soil temperature at the depth of 15-30 cm and 30-45 cm is r =0.79 and 0.47 respectively, at 45-60 cm and 60-75 cm is r = -0.13 and -0.70. In fig. 6 the observed data at the depth of 30 cm is plotted together with the simulated data at the depth of 15-30 cm and 30-45 cm, the result simulated at the former layer with the extra weather drivers; relative humidity, incoming radiation and wind speed. The simulated soil temperature at the 15–30 cm depth is similar to the observed (*fig. 6*), but smoothened, while the deeper layer has got a more general form; a trend that will increase with depth (see fig. 7 below). The simulated result at the depth of 30-45 cm is, however, not responsive at all to any temporal peak variation as those visual in the observed data (fig. 6). During the two-year period the model show signs of a one-week time lag. This leads to differences of up to 6°C during the rain period in 2003. Another large difference is noted during the turn of the year. An attempt to reduce the influence of the variations in the observed data was made through using a centred moving average, set to seven days.

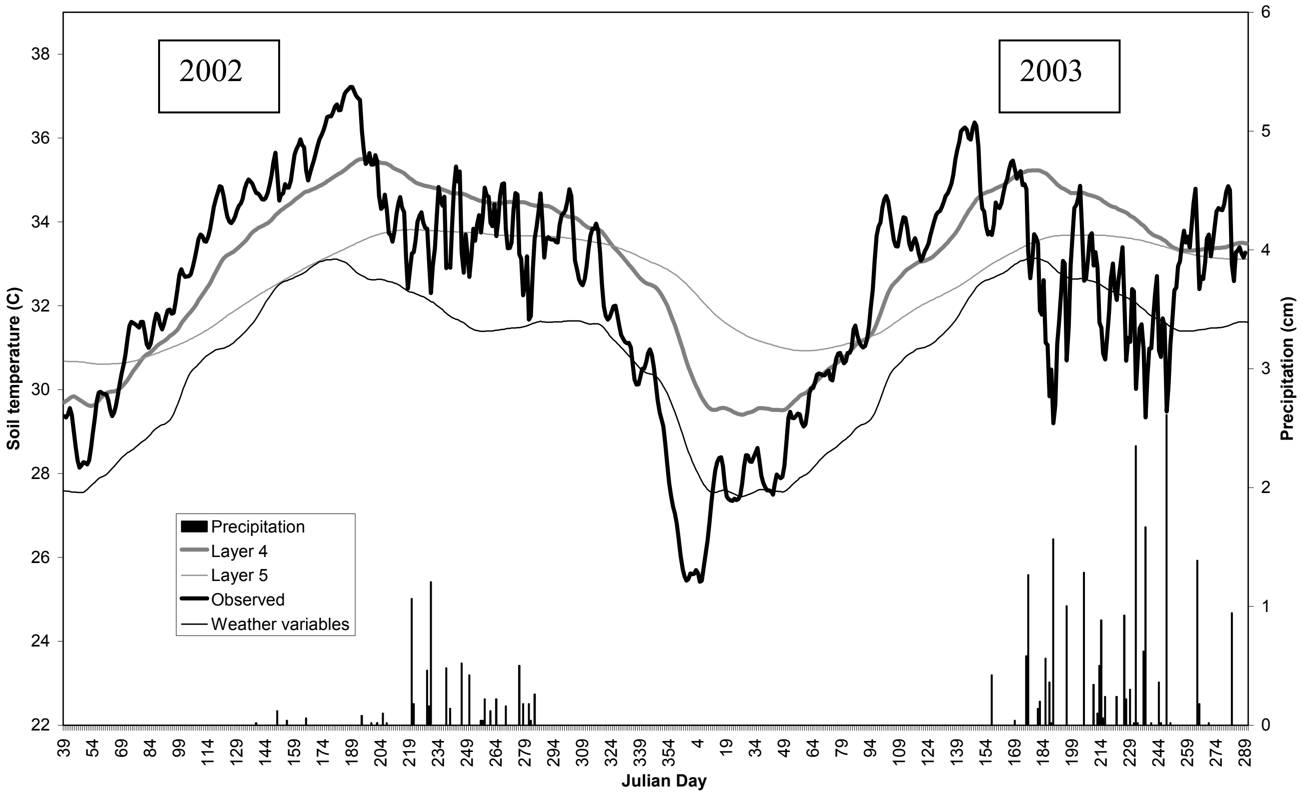


Figure 6*. The simulated soil temperature result of the base statement at the depth of 15-30 & 30-45 cm, the observed temperature at the depth of 30 cm and the simulation with the extra weather variables. In the latter simulation PET is calculated on wind speed, incoming radiation and relative humidity instead of air temperature.*

The correlation result by this operation was slightly higher than without (see table 3, appendix 1). As where the result when the correlation between the estimated, at each depth, and the observed for each year was made and also when the centred moving average of the observed data was set to 30, to get a more monthly-like and –based average. The latter investigation was made to see if there was a built-in positive seasonal influence, see correlation values in table 3, appendix 1.

The simulation for the extra weather variables is lower than the observed (*fig. 6*). A difference is taking place when the rain season starts in 2002. Even if not at all equally varied as the observed data, the estimated weather driver curve is more sensitive to climate variations than the estimated without. Nor seems the time lag to be present. The correlation of observed versus simulated with weather variables at the depth of 30 cm are r = 0.8 and r = 0.5 for the extra drivers vs. observed data (tab. 1, appendix I)).

The simulated results at the depth of 60 cm are even more general than the simulated result at the upper centimetres. Only for the 45-60 cm layer some kind of correct annual variation is predicted by the model (*fig. 7*), but with a time lag of 1.5 to 2 months. The simulated soil temperatures at the depth of 60-75 cm show an almost opposite picture of reality, with peaks during the year turn over and dips during summer time, as if rain season was equal to cold periods. The correlation coefficient for layer 45-60 cm is 0.13. For the 60 – 75 cm layer and with extra weather variables contra observed data *r* is –0.7 and –0.8 respectively.

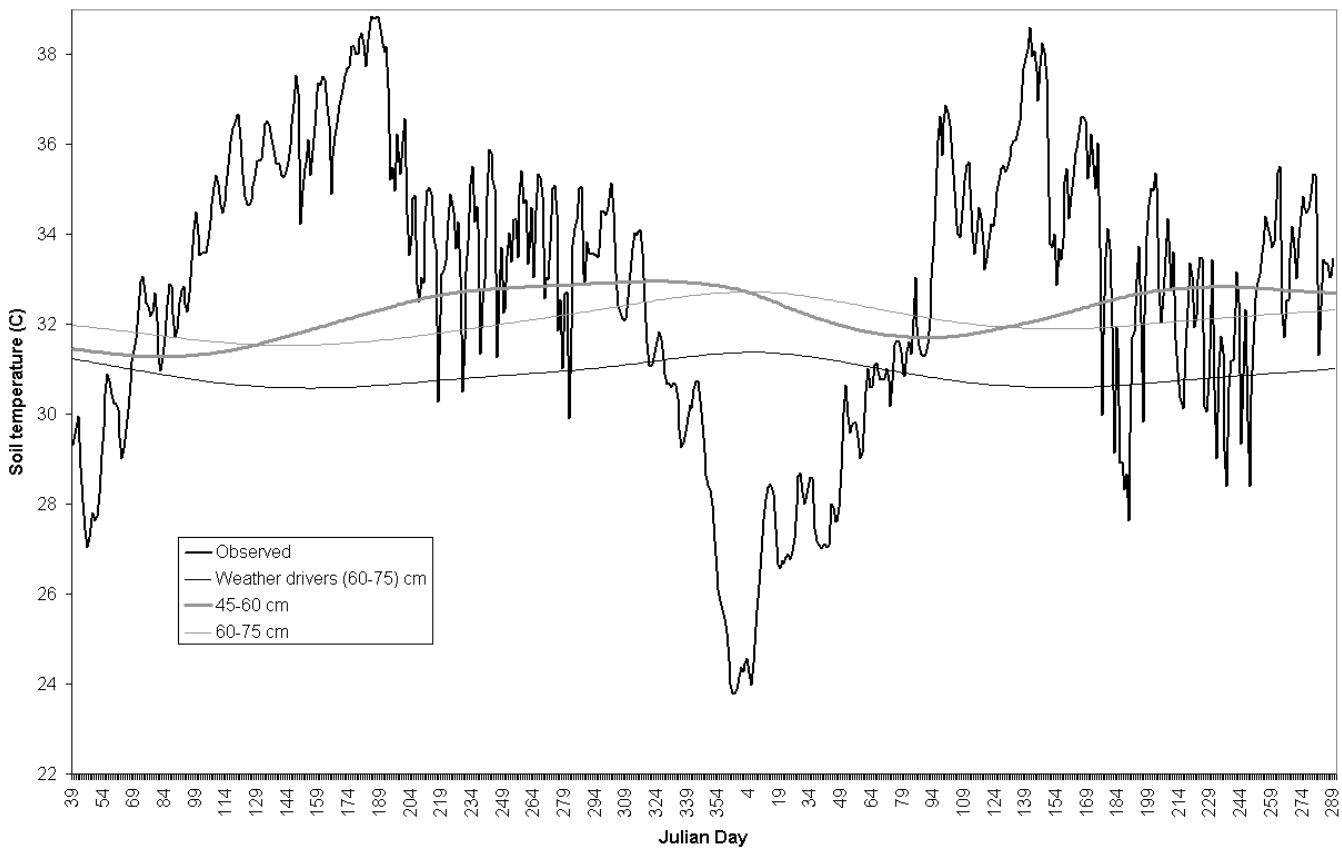


Figure 7. The simulated soil temperature result of the base statement at the depth of 45-60 & 60-75 cm, the observed temperature at the depth of 60 cm and the simulation with the extra weather variables. In the latter simulation PET is calculated on wind speed, incoming radiation and relative humidity instead of air temperature.

It is interesting to note that the simulated soil temperature result for the 4-15 cm layer (fig. 1, appendix 2) is quite similar and sometimes even equal, to the observed data at the depth of 30 cm, with the highest received correlation (0.95). Note that there is a striking temperature differences - up to 3 °C - between estimated and observed data until Julian day 312 in 2002 as well as during the rain season in 2003. The observed data at the depth of 30 cm drops at precipitation, which the estimated does not.

5.1.2 Sensitivity analyses

Looking at the influence of the different parameters in *fig. 8 - 10*, it can be noted that the simulations follow each other strictly, with only small variations of approx. 1 °C throughout the year. There is no significant difference present (table 2, appendix I). The crop sorgum simulates an approximately 3 °C lower temperature at the two depths just as the change in cloud cover simulates the same values as the altered root spread, see fig. 8 below for the 30 cm.

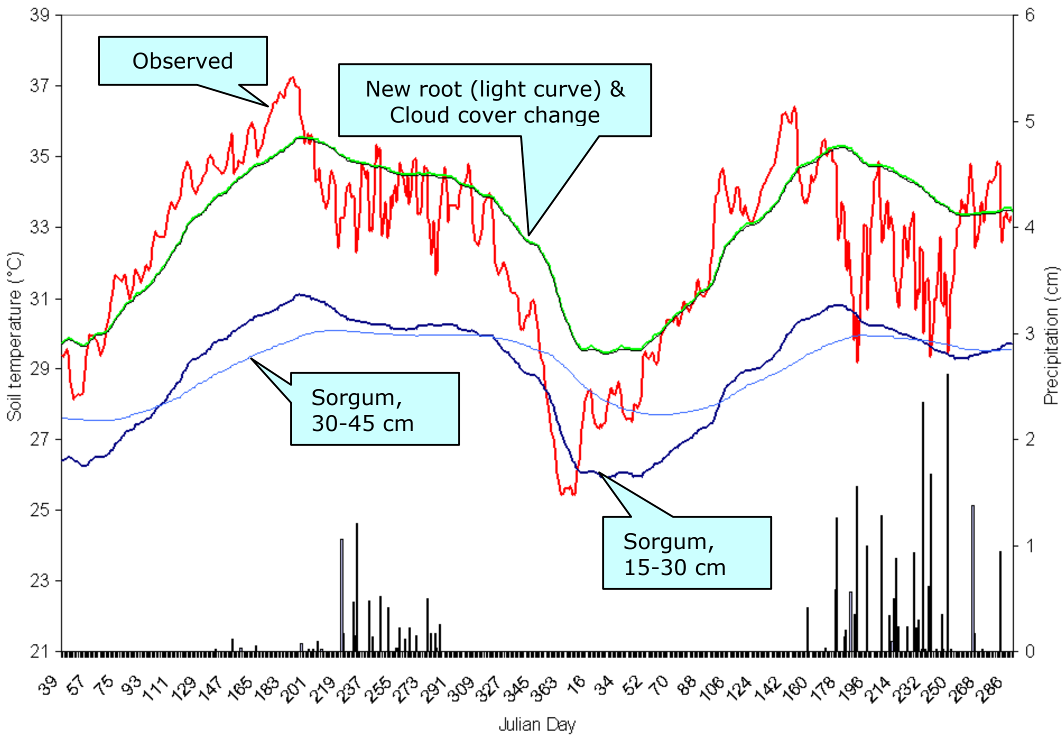


Figure 8. The annual precipitation and the simulated soil temperature change at the depth of 30 cm due to parameter change. A change in root dispersion and cloud cover (neither a positive nor negative) does not affect the soil temperature model, while a change from tropical C_4 grass does. The latter with 1 °C lower at best prediction but down to 4 °C at worst.

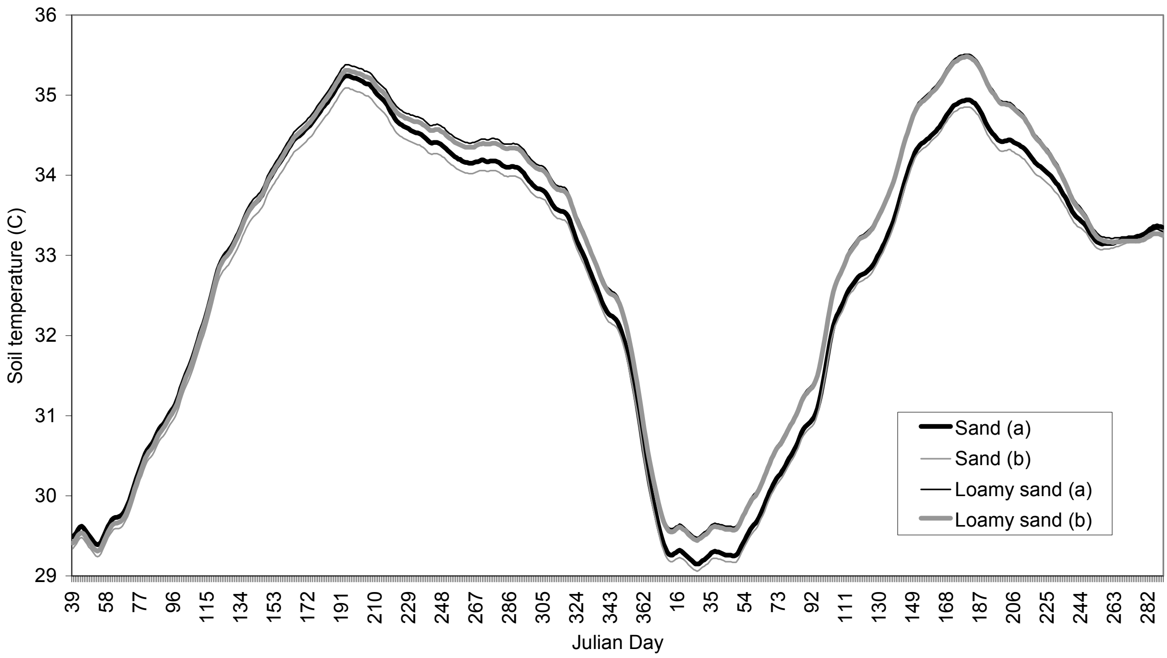


Figure 9. *The effect of four different soil samples with varying clay content to the soil temperature submodel was tested. The effect was very little, which also was the result at the 60 cm depth.*

The soil temperatures in the loamy sand sample at the depth of 30 cm (*fig. 9*), are in the beginning of 2002 lower than the simulated soil temperature in sand. This relationship finally turns as the rain season sets in, in the middle of May, a trend that will stay until the very end of 2003. The temperature in the loamy sand soils is generally slightly higher than in the sand soils. At the depth of 60 cm the latter is the highest simulated throughout the whole period. As shown in *figure 10*, a change in air temperature generates a stronger impact of the soil temperature then a difference in annual rainfall, no matter looking at the depth of 30 or 60 cm.

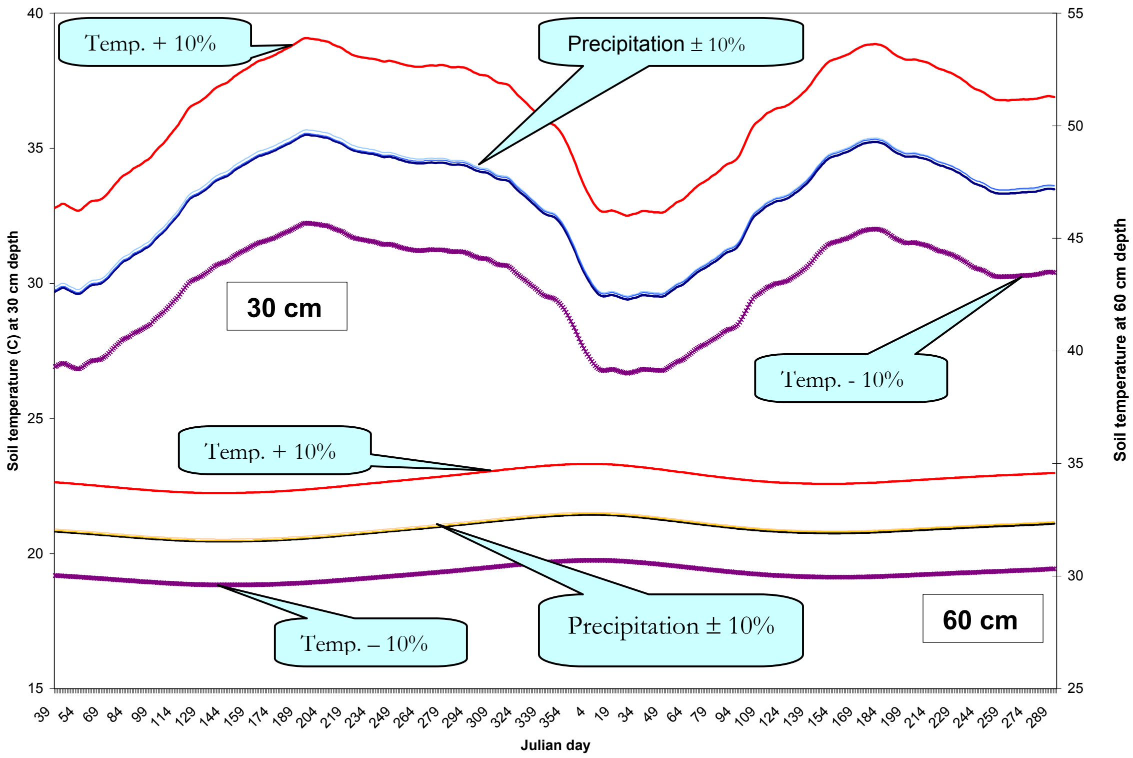


Figure 10*. The sensitivity of the soil temperature model to different climate variations is tested through change in precipitation and air temperature at the two different depths. A change in temperature truly generates an impact while the change in precipitation does not.*

5.2 Soil water content

The correlations regarding soil water content verses observed at the different depths are much lower then for the simulated soil temperature vs. observed for all simulations but one: the sand soil with 8.3% clay (r = 0.94), table 1, in app.1. General for all the soil water content simulations done is that the soil water deflects during precipitation; thereafter it is constant until the next rain event, while the observed data shows steady, but small, fluctuations.

5.2.1 Model evaluation

The constant water content simulated by the model differs from the observed variations. Precipitation makes a less impact on the observed data than in the estimated water volumetric content (*fig.11a-b & 12a-b*), especially in the depth of 15-30 cm. More than 10 mm rain is necessary to make a deflection in the estimated former depth, just as additional 7 mm is needed before a peak is noted in the depth of 30-45 cm during 2002, see *fig 11a.*. In the same diagram it is notable that the simulations, when the weather variables are used as in-put data, show upon much more variations in volumetric soil water content than the original estimations at the same depth does.

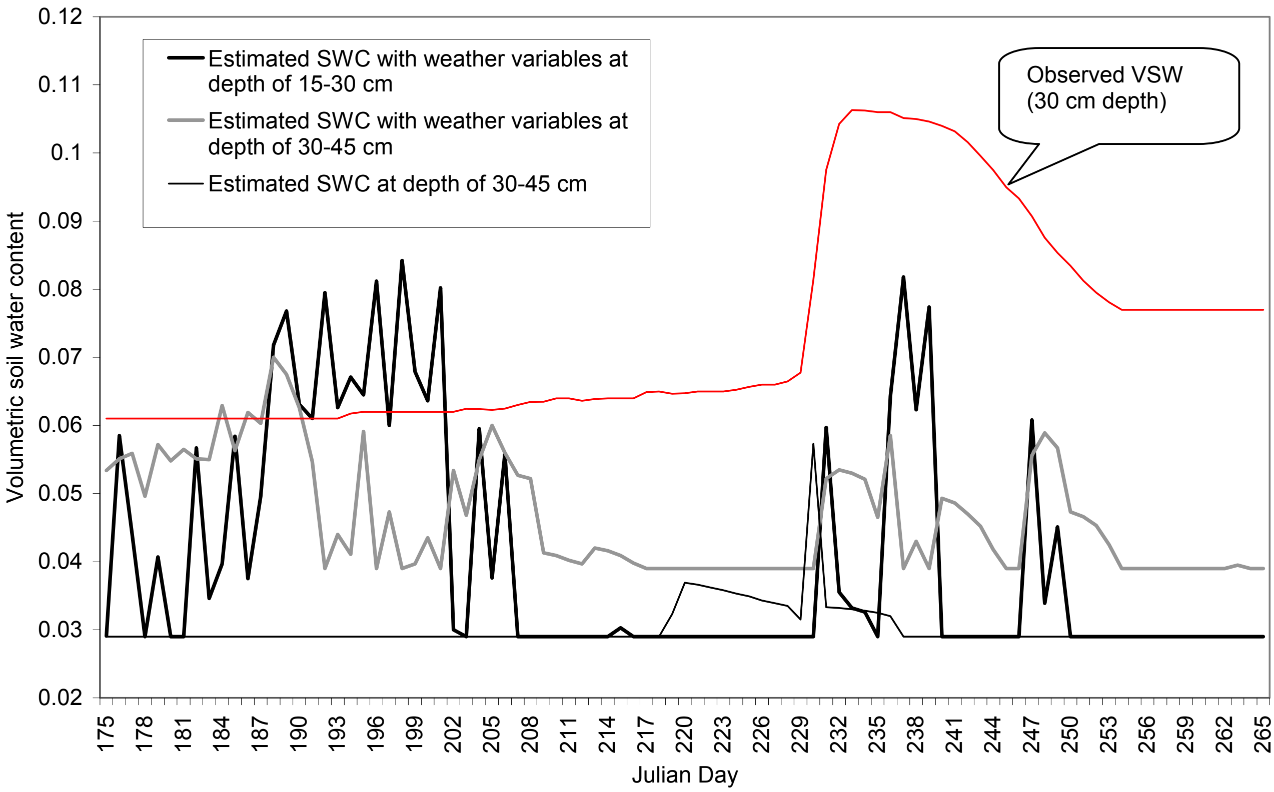


***Figure 11a**. The volumetric soil water content at the depth of 15-30 and 30-45 cm in 2002 is estimated by the Daycent, and plot in this diagram together with the observed soil moisture at the depth of 30 cm during the same period. The model estimates in general lower water content at the depth of 15-30 cm than in the layer below. The latter is, however, the first to react upon a rain event.*

There is no influence of precipitation on the simulated data after day 254, the same year, at all, despite that the rain period is not over. The highest discrepancy between observed and estimated data is 7.5%, in Julian day 189, 2003 (fig. 11b). This day observed volumetric soil water content is 13.6%, estimated at 15-30 cm is 5.8%, at 30-45 cm 5.9% and with the weather variables 7.5%; precipitation 15.7 mm. The rain during 2003 generates a large impact on the observed volumetric soil water content at the both depths, with a very steep increase during Julian day 194. There is no significant difference between the different simulations. The soil water content at the 60 cm depth is (fig. 12), just as all the other layers, only affected during periods of precipitation, which is why they all are visualised during this specific time only.

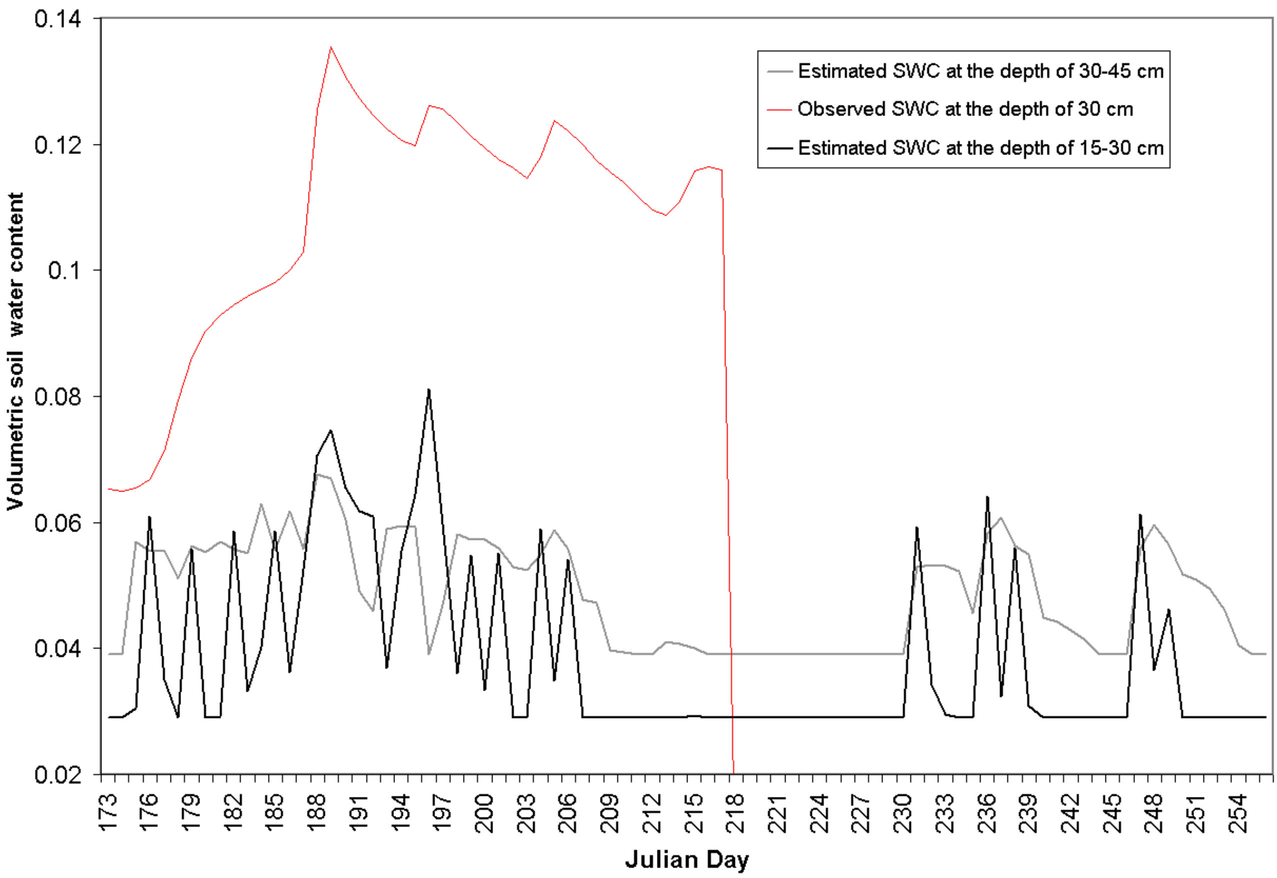


Figure 11b. *The estimated volumetric soil content at the depth of 15-30 and 30-45 cm during 2003 is systematically lower than the observed. The latter ends abruptly due to a problem with the sensor.*

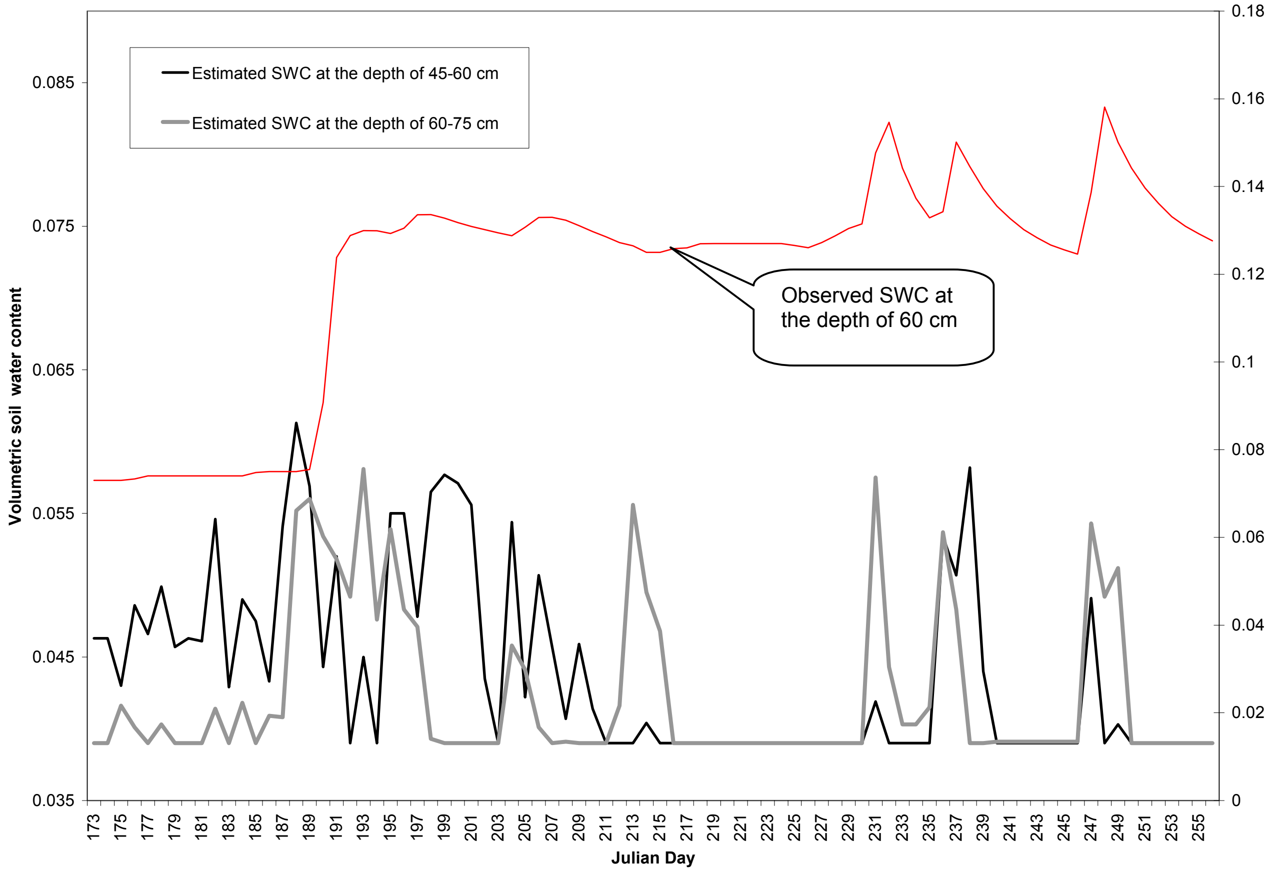
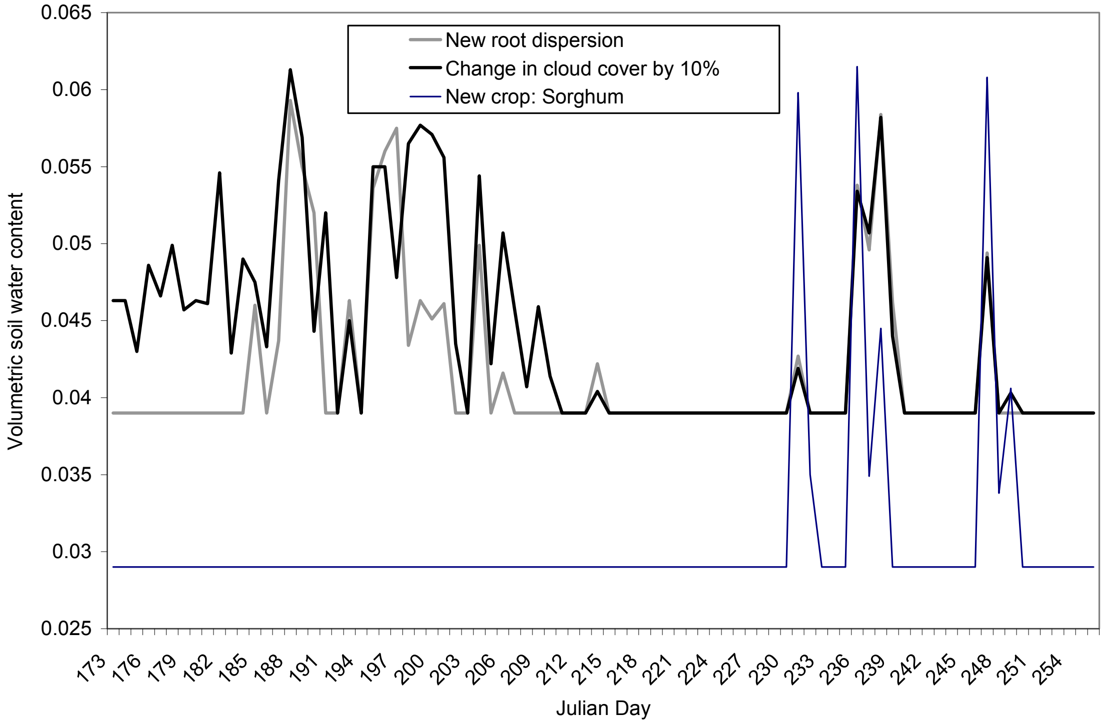


Figure 12. *The estimated soil water content at the depths around 60 cm is not only much lower than the estimated but also more varying and constant during 2003. The same goes for the year before. It can also be noted that the model seems to react on differences in soil moisture a little bit earlier and easier than what is observed in field.*

5.2.2 Sensitivity analyses

To analyse the impact of different parameters, the base scenario and simulated with new values are plotted together. At the depth of 30 cm, there is no achieved difference between the tropical C_4 grass and the crop sorgum in contrary to the greater depth *(fig 13)* were more water is stored. This is especially evident during the wet period in 2003. The root dispersion, on the other hand, generates more available soil water over all at the both depths. A 10% increase in cloud cover led to an increase in soil water at the depth of 15-30 cm but to no change at lower depths. A decrease of 10% had no effect at all.



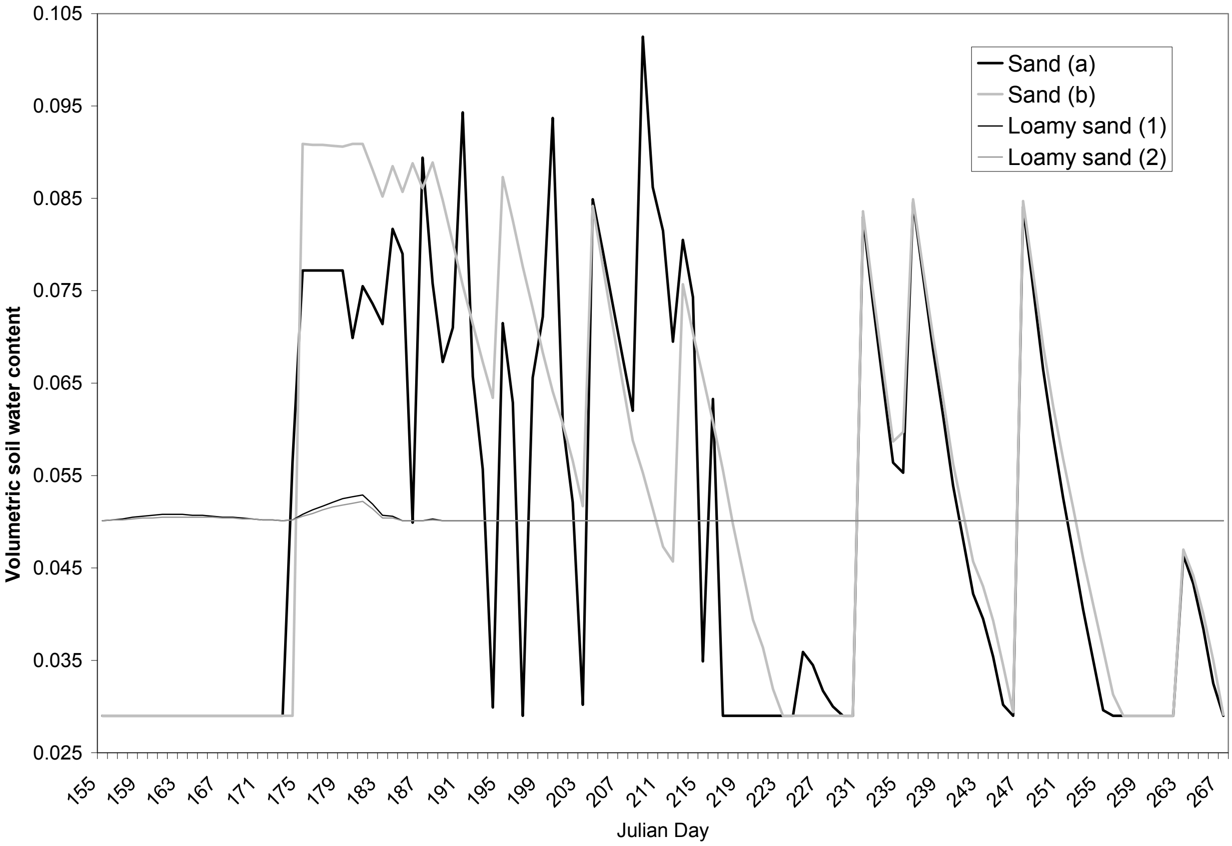


Figure 14. *The effects of different soil textures on VSWC at the depth of 30 cm during the year 2003. The variations in simulated soil water content at the depth of 30 cm is different due to the texture; the variations are much more in the sand soils than in the loamy sand, which shows upon almost no variation.*

The simulations with the two samples of loamy sand generate the same values in time and space at the both depths. The simulation with sand (8% clay) generates a higher percentage VSWC than the sand with 2% clay at the depth of 30 cm, but no one of the simulations achieves available soil water content as high as the observed (*fig 14*). At the depth of 60 cm the situation is different. The texture with 2% clay and 95% sand simulates a peak in August 2002 that does not exist in the observed data as well as it is more sensitive and reacts earlier to precipitation. The other sand texture curve is stair alike, simulates lower VSWC during observed rich times in winter time and higher soil moisture after the rain period in 2003. Air temperature has a significant impact on soil moisture of approx. 1.0%. A temperature decrease of 10% leads to larger difference in soil water content in the 30 cm depth than an increase of the same degree in the lower soil layer, *see fig. 15*.

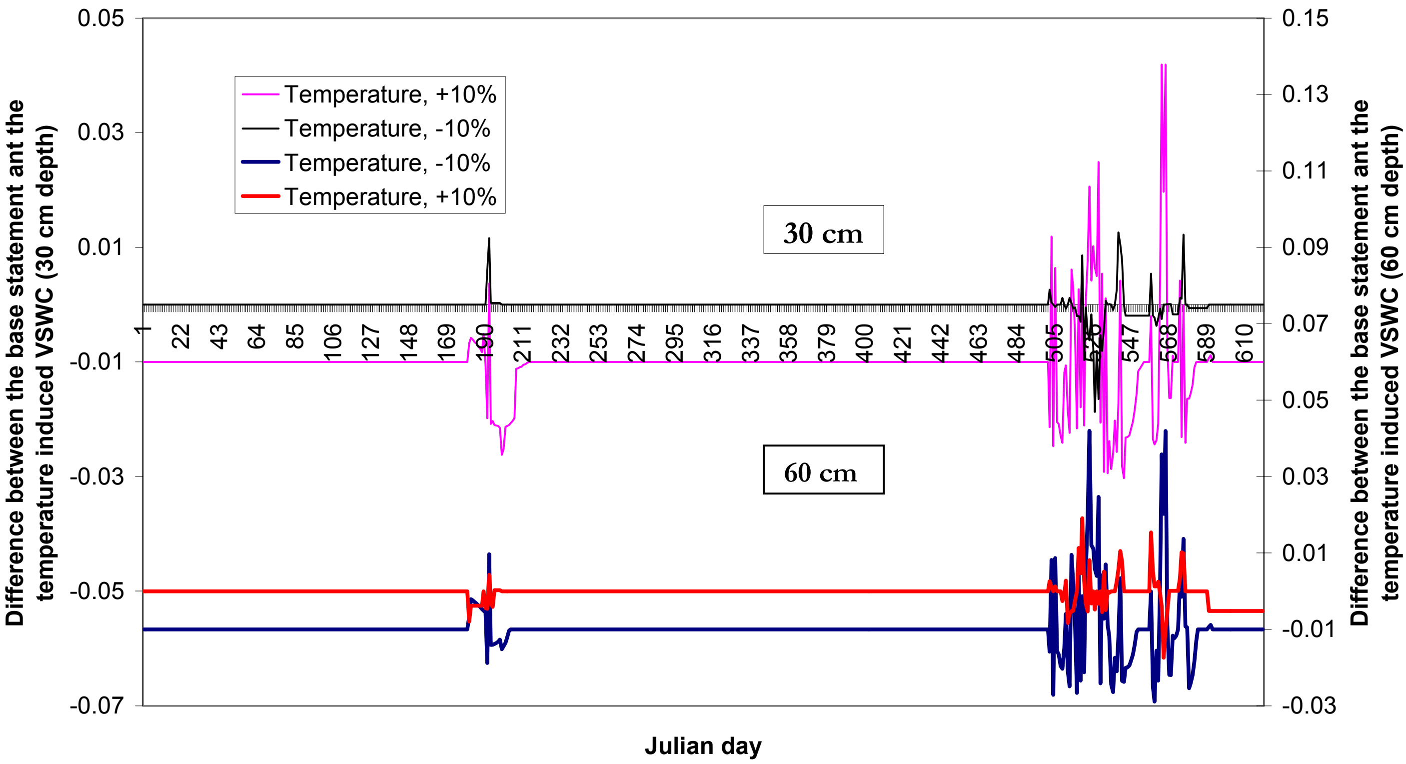


Figure 15. *The direct impact of increased air temperature at the depth of a) 30 cm and b) 60 cm. Visualized in the diagram is the difference between the simulated base statement and the simulations with a change in air temperature.*

5.3 Model validation

The result of the model validation is presented in table 2, appendix I. The *error (absolute)* at the depth of 30 cm is 0.547 & 0.122 for soil temperature and –0.045 & -0.035 for soil moisture. At the depth of 60 cm it is -0.444 & -0.655 for soil temperature and –0.042 & -0.046 for soil moisture. The *relative error* for soil temperature at the depth of 30 cm is 0.017 & 0.004 for soil temperature and –0.591 & -0.460 for soil moisture. At the depth of 60 cm it is -0.014 & -0.020 for soil temperature and –0.494 & -0.540 for soil moisture.

6. Discussion

Year 2002 was by far the driest period during the last 40 years in the El Obeid area (fig. 4). This makes an immense impact on the simulated result, where small variations in precipitation generate strong deflections in the simulated temperature and volumetric soil water content. It also influence the correlation of the observed verses the simulated soil temperature or volumetric soil water content, while the misfit between the observed and the base statement is evident during 2002, ending up with a low correlation coefficient. If the year 2002 was of the nature of a more general year, or the correlation coefficient was based on only 2003, it had been higher. The same peculiarity regarding precipitation has been noted in dry grasslands in Colorado, US (Parton et al, 1998). The major discrepancy found by Parton et al was a tendency of the model to overestimate the temperature during the winter months, probably due to spatial and temporal variability in snow cover. The sensitivity to annual precipitation below normal provides a foundation that the model is based on years with normally distributed climate conditions and that it is fairly sensitive to climate extremes. This must be kept in mind when using the model to simulate future carbon sequestration and gas fluxes, while Sudan is an area vulnerable to, and often influenced by, global weather patterns (IPCC, 2000; Klaar et al 1999) such as the ENSO related extreme events (drought, floods, changed patterns) but also to teleconnected feedbacks through global deforestation (Semazzi & Song, 2001). The smoothness of the result of the deeper soil depths may be due to the boundary conditions at the bottom of the soil profile (Keough, 2004). An adjustment of the boundary conditions for the soil could have generated a more accurate, and less general, simulation.

6.1 The effect of the climate

The two parameters that make the strongest impact on both sub models is the biomass and air temperature. The temperature is derived from equations and use observed data as input. Increasing air temperature generates higher T_s and less available soil water through increased evaporation. The maximum soil temperature equation used in the model is based on the result that maximum air temperature and total daily solar radiation were the variables most correlated with maximum soil surface temperature (Parton, 1984), with the supplement that not all sites will have the same correlations between maximum air temperature and solar radiation as found over the short-grass prairie in Colorado. Therefore an adjustment to the maximum soil temperature equation of the model, considering daily wind travel, total daily solar radiation, hourly solar radiation, soil water content, precipitation amounts, and time since the last precipitation event could result in better simulations. Parton (1981) expected that soil-water-related factors (i.e. soil water content, time since precipitation) would improve the prediction of T_s^{max}; however, his results from Colorado showed that the reduction and effect of precipitation was too low to be of interest, why it is not used in the model. Such factors should be taken into account while the different situation in the semi-arid Sudan, where precipitation is very sparse and rarely occurring, and is of such a crucial importance. It is also so, that since the finite difference scheme solves for the soil temperature in the top layer first, and then uses the new temperature in determining the next lower soil temperature, it follows that the result will have less and less variation in the temperature curve. This explains not only why the simulations at deeper layers show upon so few variations and low correlation, but also the extremely high *r* at the 4-15 cm soil depth.

6.1.1 General

A change in air temperature denotes a very clear and higher impact on the simulated VSWC, just as well as on the soil temperature, than a change in precipitation. The temperature is the variable which has the strongest effect upon total soil carbon; soil organic carbon decrease with increasing mean annual temperature (Burke et al, 1989). Moreover, the relationship between carbon in the soil and temperature has a quadratic term, and therefore the accumulation of carbon decreases sharply as a consequence of a small increase in temperature (Sala et al., 1996).

With extra weather variables the correlation of observed vs. simulated is higher than without, but the improvement is not worth the expenses that would follow with establishment of, or improved, climate stations. The use of the extra weather drivers do not impact the soil temperature model much, but lowers the mean temperature (Keough, 2004).

6.1.2 Soil temperature

The sensitivity to drought is most evident in the simulated 4-15 cm depth, while this is the simulated temperature curve with most variations and highest r-value (0.95). Here, the extra weather variables as well as the base statement, is very sensitive to, and disturbed by, the unexpectedly low rain fall. The difference between the observed data and the two simulated is fairly high and always present, while it during 2003 is an almost perfect fit. The same goes also for the 15-30, 30-45, 45-60 and 60-75 cm depths, but the variation decreases with depth making the simulated below 30 cm very smoothened and almost without variations. It is also to say that the less variations in the observed data, i. e. the higher amount of days used in the centered moving average, the higher r-value is received. The increase in correlation is so low, though, that this procedure is not useful. But it also implies that one-day extreme temperature events affect the correlation values. When finally evaluating the model as capable to use in the Sudan, it is also important to remember that the years with observed data, also is years with extreme weather conditions, which means that those is not capable of being representative of the normal climate in Sudan, and therefore neither the optimal to use as prevailing alone when determining the appropriation in using Daycent to determine the possibility to estimate carbon sequestration in arid soils.

6.1.3 Soil water content

The soil water sub model simulates the natural inertia inherent to the system. The upper levels react first to an input of precipitation but also to loss of water through evaporation. The lower depths, on the other hand, do not react to precipitation until the upper is saturated and is seldom affected by evaporation. This leads to higher and more stable observed water content at the 60 cm depth (*fig. 9 a & b*). The precipitation during 2002, only a third of what is normal, did not manage to penetrate down to the 60 cm level before it was evaporated or sucked up by plant roots. The simulated VSWC base statement at the both depths did not react until the rain amount received was 23 mm in the Julian day 176. The soil water model tended to underestimate the soil water content during the rain period, which proves that it is important to have good knowledge of the rain distribution and density as well as spatial and temporal variations. Increased cloud cover decreases the evaporation rate. Thereby more soil water is available.

6.2 The effect of vegetation

As mentioned in chapter 3.3 the required inputs are minimum and maximum air temperatures, plant biomass, soil moisture, soil texture and average soil temperature at the bottom of the soil profile. The air temperatures for year 2002-2003 are the observed data but there might be an earlier error caused by the weather generating process (se below). The estimation of plant biomass is based on what was available in literature and is therefore not always set correct. The DAYCENT model has underestimated the live biomass and thus AET rates (increasing live shoot biomass generally results in increasing AET rates) probably because of the inability of the model to simulate germination of forbs and annual grasses during an infrequent wet period (Kelly et al., 1997). The DAYCENT model is either not able to simulate year-to-year changes in species composition that can greatly alter biomass dynamics in certain years (Gilamnov et al, 1997 in Parton et al 1998). The vegetation cover and type of species also affect the amount of rain that actually reaches the soil. A dense vegetation piles up the droplets, from where it is later evaporated.

The misfit of the simulated curves during year 2002 is most likely due to the exceptionally low rainfall that year. Plant biomass will probably drop significantly during such a dry period, while the standard vegetation parameters given from NREL, that was used in the model, are based on mean values from a long time span.

6.2.1 Soil water content

The sensitivity analyses where the root dispersion was changed (*fig. 15 & 16*) shows upon an increase in VSWC during the dry periods, and a decrease during rain periods, leading to a totally less amount available water during the year. The available soil water diminish with depth until the 60-75 cm depth where it starts to increase, which can be explained by the base statements deeper root penetration. The root fraction used in the model was based upon the root spread of *Acacia senegal* and did not take into account the ability of the tropical C_4 grass to penetrate below the depth of the soil profile. An increase in root biomass generates more available water just as well as increased root penetration. An increase in the biomass can also make some influence on the soil structure. An underestimation in root biomass as input data might lead to a to low simulated VSWC. The new root fraction had got less biomass in the upper 4-15 cm while the 15-30 cm biomass was increased with 17%. A conclusion made of this is that the upper layers should have had a higher concentration of biomass, less in the deeper layers, then used in the model. Even an overestimation in live leaf biomass can result in too high actual evapotranspiration (AET) rates (Kelly et al. 1997).

The biomass is based on assumption and estimations. It should have been better if the model was coupled to a set of biomass data from, or a satellite image of, the area in question. A satellite image gives a more accurate estimation of the site while it possible to look straight at the area of interest instead of using estimations based on interpolation from books that might have, in best of cases, information from the same country but mostly from the same continent. Remote sensing is an assistant determining for example LAI; leaf area index (Seaquist, 2001). Another way to estimate the biomass correctly would be through fieldwork but this is both times demanding as well as expensive. Since both the bare soil evaporation water loss and the transpiration rate are based on functions containing biomass (above ground- and root biomass respectively) an under, or over, estimation could lead to major discrepancies.

6.3 The effect of changed crop

A change in crops from tropical C_4 grass to sorgum leads to no change in soil temperature but reduces the *r* for VSWC significantly at the depth of 60 cm. The simulated reduction in volumetric soil water content is 4,6% compared to the simulated C_4 grass. The fact that the latter generates more water available in the 60 cm depth than in the upper layers indicates that there is both a natural difference and a difference in harvesting between the two species. According to the parameters given by NREL sorgum is more sensitive to drought than the C_4 grass just as well as that the parameter determining the intercept for equation to predict lignin content fraction (based on annual rainfall for belowground material) is one fourth of the C_4 grass and that it has got a harvest index water stress factor that the grass does not. The biggest difference between the two species is, though, the level of aboveground C above which shading occurs and shoot senescence increase.

6.4 The effect of soil texture

The soil sample used was not taken from the same site as the soil temperature and soil moisture data, but from the same area, which might cause some small variations in the physical characteristics. The different structures are, however, not reflected in the temperature simulations. The VSWC increases as the sand fraction decreases for the different soil textures. The highest volumetric soil water content of all simulations is reached with the sand (8.3% clay) texture at the 60 cm depth. The problems with the two samples with loamy sand is due to the given physical values, such as k_{sat} and θ. Those are unfortunately not satisfactory calculated but only estimated from literature. The reason why the soil texture with the highest clay content is the one with most available water is due to the grain size and porosity of the soil, but an increase in clay content in the base statement would not be the solution to why so little VSWC is simulated.

6.5 The effect of soil moisture on soil temp.

All these parameters mentioned above are possible causes of poor simulations. The more probable cause is, however, the soil moisture factor. The soil moisture that was used to calculate the soil temperature at different depths is the soil moisture estimated by the model, and as it is seen in the VSWC simulations the model tends to underestimate it. This in turn influences the soil temperature according to the equations made by Parton (1984). Moisture limitations often increase with temperature on many seasonally dry sites, compared to constantly moist sites where increasing temperatures may not produce moisture limitations on soil respiration and root growth (Kirschbaum, 2000). Carbon dioxide-induced reductions in plant transpiration result in an increase in soil moisture (Niklaus et al., 2003). This might mean that as the CO_2 content of the air continues to climb ever higher, there is a good likelihood that the productivity of earth's grasslands, even in nutrient-poor areas, will steadily and consistently increase their productivity, even in areas that may experience slight decreases in precipitation Niklaus et al (2003). It is also stated that elevated CO_2 might increase the whole-plant dry weights of all three species and, in general, increase root growth more than shoot growth (Cotrufo et al., 1997; Niklaus et al., 2003). Derner et al (2001) states that C_4 grasses may have already experienced an augmentation in root growth, which is comparable to that experienced with a doubling of current CO_2 concentrations. As the atmospheric CO_2 concentration continues to rise, it will likely decrease water use in these grasses, due to CO_2-induced reductions in stomatal conductance, causing the indirect effects of greater soil moisture to further enhance their growth (Derner et al, 2001). Rising atmospheric CO_2 levels will stimulate photosynthesis under low soil nutrient conditions rather than limiting the photosynthetic response to elevated CO_2, limiting nutrient conditions could lead to the most significant stimulation in carbon acquisition (Davey et al., 1999). As the atmospheric CO_2 concentration increases, it is likely that this common C_4 grass will exhibit increased accumulation of biomass, even under conditions of water stress, which frequently occur within its tropical range

(Seneweera et al., 2001). This phenomenon should also lead to enhanced carbon sequestration within tropical grasslands as the CO_2 content of the atmosphere rises (Seneweera et al., 2001).

Ecosystem models need to simulate plant growth, nutrient uptake, nutrient mineralization, soil water and temperature dynamics well in order to simulate trace gas fluxes and an error in any one of these simulated processes can lead to errors in the trace gas prediction (Frolking et al 1998). Input data requirements, validation data, structure of the land surface model and resolution of the models are greatly impacted by the ecosystem processes represented in linked land surface-ecological models. Detailed process-oriented land surface models are required if trace gas fluxes are considered (Parton et al 1998). Parton et al (1996 a, b) showed that a detailed, near surface soil layer structure is needed to represent decomposition and nutrient cycling since most of the nutrient cycling and soil respiration occur in the top 15 cm of the soil. This makes DAYCENT excellent, regarding the high r-value of 0.95 at the depth of 4-15 cm (fig. 10) vs. the observed at the depth of 30 cm.

6.6 Final discussion

Since the time for the thesis is finite, there is an end to all possibilities, meaning that after a while there was no more time to try to modify the model parameters to get better simulations, why it in the discussion sometimes is mentioned as pure and known faults, e.g. the physical characteristics of the loamy sand. The bulk density is not known for the soil samples of sand and loamy sand, while the bulk density for the base statement has been used. This generates an error, especially for loamy sand (higher water holding capacity than sand), since the bulk density is specific to each soil sample and depending on its content of organic materials and water holding capacity.

Some parts of the simulations took more time than expected. It was for example a big problem to generate weather data while an accurate weather forecast is a very time-expensive process. The simplified forecast used in this thesis has a lot of errors, not at least while looking at the minimum and maximum temperatures. The maximum temperature for a month in the El Obeid dataset is actually the highest recorded temperature during that span of days. Generated in the weather file the same number gives a daily maximum value throughout the whole month, instead of being the highest value recorded. The same goes for the minimum temperature values. The problem was chosen to keep, while doing it otherwise would take to much time. It is also important to take into account that sudden very heavy rainfalls in the past could not be represented correct.

The model is very precise, but the simulated error increases with depth. The model predicts soil temperature best. The highest errors are achieved while simulating soil moisture, with the utmost disturbance at the change in air temperature. This, as well as the sensitivity analyses, show how important it is to have access to correct daily temperature and precipitation data if interested to use the DAYCENT model in Sahel conditions to model trace gas fluxes and carbon sequestration.

In a wider perspective the DAYCENT model, with the few adjustments mentioned above, can be fully adapted to GIS and remote sensing approaches to estimate green house gas fluxes and decompositions rates as well as the possibility of carbon sequestration. Finally, it can be said that it, in a way, was a happy coincidence that the period of observed data coincide with this abnormally weather period. In this way it was possible to see how sensitive the model is to abnormal precipitation conditions.

7. Conclusion

The DAYCENT model was tested through comparing observed soil temperature- and water content to what was estimated by the model. The model was validated through different operations including changes in crop, soil (content of clay and sand), root dispersion, as well as in precipitation and air temperature (± 5-15%). The following conclusions was made:

- The DAYCENT model underestimates the soil water content.

- The correlation of simulated soil temperature verses observed soil temperature data is higher when PET is calculated on wind speed, incoming radiation and relative humidity than on only air temperature.

- Soil texture, root fraction and sorgum make no significant impact on the DAYCENT model, but exist more as a noise.

- The DAYCENT model is precise, but the greater the depth – the less varied simulations of soil temperature and accurate prediction.

- The sand soil is more responsive to a change in precipitation, probably due to its higher porosity and permeability.

- The most important factor is - by far - to have accurate air temperature data when using the DAYCENT model. Either an increase or decrease in air temperature generates a significant influence on the soil temperature and soil moisture.

- The estimation of biomass is crucial, while it is determining the simulation result of the soil temperature model and soil water content model.

- The model must be adjusted to semiarid areas before frequently used in the Sahel area.

8. Nomenclature & Definitions

θ	volumetric soil water content
CO_2	carbon dioxide
DOM	dissolved organic matter
IPCC	Intergovermental Panel of Climate Change
NO_2	nitrogen dioxide
ppmv	parts per million by volume
SIC	soil inorganic carbon
SOC	soil organic carbon
SOM	soil organic matter
VSWC	volumetric soil water content (%)
WFPS	water filled pore space
Agroforestry	land management for the simultaneous production of food, crops, and trees
Desiccation	defined as a dry period that is extended to the point where it destroys natural or cultural communities.
Dry-land degradation	Reduction in the potential of land to produce crops (UNEP, 1992)
Field capacity	a soils capacity to hold water against the pull of gravity.
Storage capacity	the capacity of a soil to storage water
Grassland	defined as less than 10% tree cover.
Hashab	arabic for *Acacia senegal*
Sahel	Somalia, Ethiopia, Sudan, Chad, Niger, Mali, Burkina Faso, Mauritania and Senegal
Savannah	defined as 10-50% cover by woody plants, and in the unexploited state, a well-developed grass layer
Soil bulk density	the mass of dry soil per unit bulk volume
Volumetric	the amount of a substance determined by the volume that it occupies (%)
Wilting point	the soil wetness below which soil-water extraction by a given plant is insufficient to balance the transpiration rate demanded of it by the atmosphere, in a specific climatic environment (Hillel, 1971).

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Appendix I

Appendix I contain all statistical results and figures that are not presented in the report.

Table 1. *Correlation coefficient for the different simulations through the two submodels Soil temperature and Soil water availability of the daily-based ecosystem model DAYCENT.*

Soil temperature	*30 cm*		*60 cm*		*30 cm*		*60 cm*	
Measure	*Correlation (r)*		*Correlation (r)*		*r2*		*r2*	
Model validation	0.79	0.47	-0.13	-0.70	0.62	0.22	0.00	0.00
Climate variables*	0.80	0.52	0.12	-0.80				
Root fractions	0.79	0.47	-0.13	-0.70	0.62	0.22	0.00	0.00
Change in crop**	0.79	0.46	0.00	-0.75				
Sand	0.79	0.47	-0.13	-0.71	0.62	0.22	0.00	0.00
Sand II	0.79	0.47	-0.13	-0.71	0.62	0.22	0.00	0.00
Loamy Sand I	0.77	0.44	-0.14	-0.68	0.60	0.19	0.00	0.00
Loamy Sand II	0.77	0.44	-0.14	-0.67	0.59	0.19	0.00	0.00
Cloud cover +10%	0.79	0.47	-0.13	-0.70	0.62	0.22	0.00	0.00
Cloud cover -10%	0.79	0.47	-0.13	-0.70	0.62	0.22	0.00	0.00
Precipitation: +5%	0.79	0.47	-0.13	-0.70	0.62	0.22	0.00	0.00
10 %	0.79	0.47	-0.13	-0.70	0.63	0.22	0.00	0.00
15 %	0.79	0.47	-0.13	-0.70	0.63	0.22	0.00	0.00
-5 %	0.79	0.47	-0.13	0.70	0.62	0.22	0.00	0.00
-10 %	0.79	0.46	-0.13	-0.70	0.62	0.21	0.00	0.00
-15 %	0.79	0.46	-0.13	-0.70	0.62	0.21	0.00	0.00
Temperature: +5%	0.79	0.46	-0.13	-0.70	0.62	0.21	0.00	0.00
10 %	0.79	0.46	-0.14	-0.69	0.62	0.21	0.00	0.00
15 %	0.79	0.46	-0.14	-0.70	0.62	0.21	0.00	0.00
-5 %	0.79	0.47	-0.13	-0.71	0.63	0.22	0.00	0.00
-10 %	*0.79*	*0.47*	-0.12	-0.71	0.62	0.22	0.00	0.00
-15 %	*0.79*	*0.47*	-0.12	-0.72	0.62	0.22	0.00	0.00
Water content	*30 cm*		*60 cm*		*30 cm*		*60 cm*	
Measure	*Correlation (r)*		*Correlation (r)*		*r2*		*r2*	
Model validation	0.52	0.64	-0.02	0.34	0.27	0.41	0.00	0.12
Climate variables*	0.25	0.34	0.12	0.70				
Root fractions	0.48	0.64	0.21	0.31	0.23	0.41	0.04	0.10
Change in crop**	-0.02	0.25	0.22	0.15				
Sand	0.58	0.60	0.35	0.10	0.34	0.36	0.12	0.01
Sand II	0.57	0.74	0.72	0.94	0.33	0.54	0.52	0.87
Loamy Sand I	0.04	0.07	-0.65	*	0.00	0.01	0.00	*
Loamy Sand II	0.05	0.07	*	*	0.00	0.00	*	*
Cloud cover -10%	0.52	0.64	-0.02	0.34	0.27	0.41	0.00	0.12
Cloud cover +10%	0.52	0.64	-0.02	0.34	0.27	0.41	0.00	0.12
Precipitation: +5%	0.58	0.56	0.62	0.22	0.34	0.31	0.38	0.05
10 %	0.56	0.64	0.41	0.44	0.31	0.40	0.17	0.19
15 %	0.55	0.67	0.36	0.23	0.30	0.45	0.13	0.05
-5 %	0.52	0.60	0.24	0.35	0.27	0.36	0.06	0.12
-10 %	0.46	0.65	-0.43	0.48	0.21	0.43	0.00	0.23
-15 %	0.51	0.63	-0.59	0.36	0.26	0.40	0.00	0.13
Temperature: +5%	0.49	0.64	0.23	0.05	0.24	0.41	0.05	0.00
10 %	0.55	0.74	0.41	0.07	0.30	0.55	0.17	0.00
15 %	0.52	0.72	0.56	0.28	0.27	0.52	0.31	0.08
-5 %	0.55	0.65	0.35	0.43	0.30	0.42	0.12	0.19
-10 %	0.56	0.65	0.34	0.44	0.31	0.42	0.11	0.19
-15 %	0.57	0.59	0.57	0.29	0.32	0.35	0.33	0.08

Table 2. *Validation of the soil temperature model. The model was validated through calculating the* absolut *and* relative error *for every depth.*

	Error Absolut		*Error relative*		*Error Absolut*		*Error relative*	
	15-30	*30-45*	*15-30*	*30-45*	*45-60*	*60-75*	*45-60*	*60-75*
Model validation	0.547	0.122	0.017	0.004	-0.444	-0.655	-0.014	-0.020
Weather Drivers	-1.608	-1.681	-0.050	-0.052	-1.919	-1.840	-0.059	-0.056
Root fractions	0.591	0.160	0.018	0.005	-0.410	-0.627	-0.013	-0.019
Crop	-3.465	-3.374	-0.107	-0.104	-3.451	-3.195	-0.105	-0.098
Sand a) 1,9% clay	0.291	-0.101	0.009	-0.003	-0.631	-0.810	-0.019	-0.025
Sand b) 8,3% clay	0.180	-0.206	0.006	-0.006	-0.727	-0.894	-0.022	-0.027
Loamy sand a) 2.7% c	0.548	0.097	0.017	0.003	-0.483	-0.702	-0.015	-0.021
Loamy sand b) 3.3% c	0.497	0.049	0.015	0.002	-0.527	-0.740	-0.016	-0.023
Cloud Cover +10%	0.547	0.122	0.017	0.004	-0.444	-0.655	-0.014	-0.020
Cloud Cover -10%	0.547	0.122	0.017	0.004	-0.444	-0.655	-0.014	-0.020
Precipitation: +5%	0.632	0.198	0.019	0.006	-0.377	-0.598	-0.012	-0.018
+10%	0.697	0.258	0.021	0.008	-0.323	-0.553	-0.010	-0.017
+15%	0.693	0.254	0.021	0.008	-0.327	-0.555	-0.010	-0.017
-5%	0.632	0.191	0.019	0.006	-0.378	-0.600	-0.012	-0.018
-10%	0.633	0.192	0.020	0.006	-0.387	-0.609	-0.012	-0.019
-15%	-0.093	-0.315	-0.003	-0.010	-0.385	-0.606	-0.012	-0.019
Temperature: +5%	2.196	1.570	0.068	0.048	0.811	0.409	0.025	0.012
+10%	3.964	3.124	0.122	0.096	2.157	1.551	0.066	0.047
+15%	6.000	4.932	0.185	0.152	3.738	2.904	0.114	0.089
-5%	-0.903	-1.151	-0.028	-0.035	-1.546	-1.591	-0.047	-0.049
-10%	-2.509	-2.566	-0.077	-0.079	-2.774	-2.634	-0.085	-0.080
-15%	-4.056	-3.927	-0.125	-0.121	-3.954	-3.636	-0.121	-0.111

Table 3. *Validation of the soil water content model. The model was validated through calculating the absolut and relative error for each layer.*

	Error Absolut		*Error relative*		*Error Absolut*		*Error relative*	
	15-30	*30-45*	*15-30*	*30-45*	*45-60*	*60-75*	*45-60*	*60-75*
Model validation	-0.045	-0.035	-0.591	-0.460	-0.042	-0.046	-0.494	-0.540
Weather Drivers	-0.043	-0.034	-0.575	-0.451	-0.045	-0.044	-0.523	-0.509
Root fractions	-0.045	-0.035	-0.599	-0.459	-0.045	-0.046	-0.527	-0.538
Crop	-0.046	-0.036	-0.612	-0.479	-0.047	-0.046	-0.542	-0.540
Ny textur (1)	-0.042	-0.033	-0.550	-0.442	-0.024	-0.045	-0.280	-0.527
Ny textur 2	-0.041	-0.033	-0.538	-0.433	-0.022	-0.038	-0.257	-0.441
Loamy sand 1	-0.025	-0.025	-0.335	-0.336	-0.036	-0.036	-0.417	-0.417
Loamy sand (2)	-0.025	-0.025	-0.335	-0.336	-0.036	-0.036	-0.417	-0.417
Cloud Cover +10%	-0.045	-0.035	-0.591	-0.460	-0.042	-0.046	-0.494	-0.540
Cloud Cover -10%	-0.045	-0.035	-0.591	-0.460	-0.042	-0.046	-0.494	-0.540
Precipitation: +5%	-0.044	-0.035	-0.582	-0.462	-0.046	-0.044	-0.537	-0.516
+10%	-0.044	-0.034	-0.586	-0.455	-0.045	-0.046	-0.526	-0.535
+15%	-0.044	-0.034	-0.583	-0.450	-0.046	-0.041	-0.538	-0.473
-5%	-0.035	-0.036	-0.462	-0.478	-0.045	-0.045	-0.520	-0.520
-10%	-0.046	-0.035	-0.606	-0.464	-0.046	-0.056	-0.538	-0.647
-15%	-0.046	-0.035	-0.604	-0.465	-0.044	-0.046	-0.518	-0.540
Temperature: +5%	-0.044	-0.035	-0.586	-0.459	-0.046	-0.043	-0.535	-0.500
+10%	-0.045	-0.034	-0.594	-0.456	-0.046	-0.043	-0.537	-0.506
+15%	-0.044	-0.034	-0.586	-0.452	-0.046	-0.045	-0.532	-0.529
-5%	-0.044	-0.035	-0.588	-0.462	-0.045	-0.046	-0.521	-0.540
-10%	-0.044	-0.035	-0.587	-0.462	-0.044	-0.046	-0.518	-0.539
-15%	-0.038	-0.027	-0.501	-0.356	-0.036	-0.035	-0.423	-0.407

Table 4. *The correlation between the estimated daily temperature in the four different layers and a) the observed data, b) the 7 days, centred, moving average of the observed data and c) the 30 days, centred, moving average of the observed data. This was made to investigate the possibility of an existing influence by the season cycle.*

Year	Depth	Observed data	7 days	30 days
2002	15-30	0,80	0,79	0,80
	30-45	0,45	0,97	0,46
	45-60	-0,10	-0,12	-0,15
	60-75	-0,66	-0,66	-0,69
2003	15-30	0,77	0,77	0,81
	30-45	0,47	0,97	0,53
	45-60	-0,15	-0,16	0,07
	60-75	-0,79	-0,79	-0,93

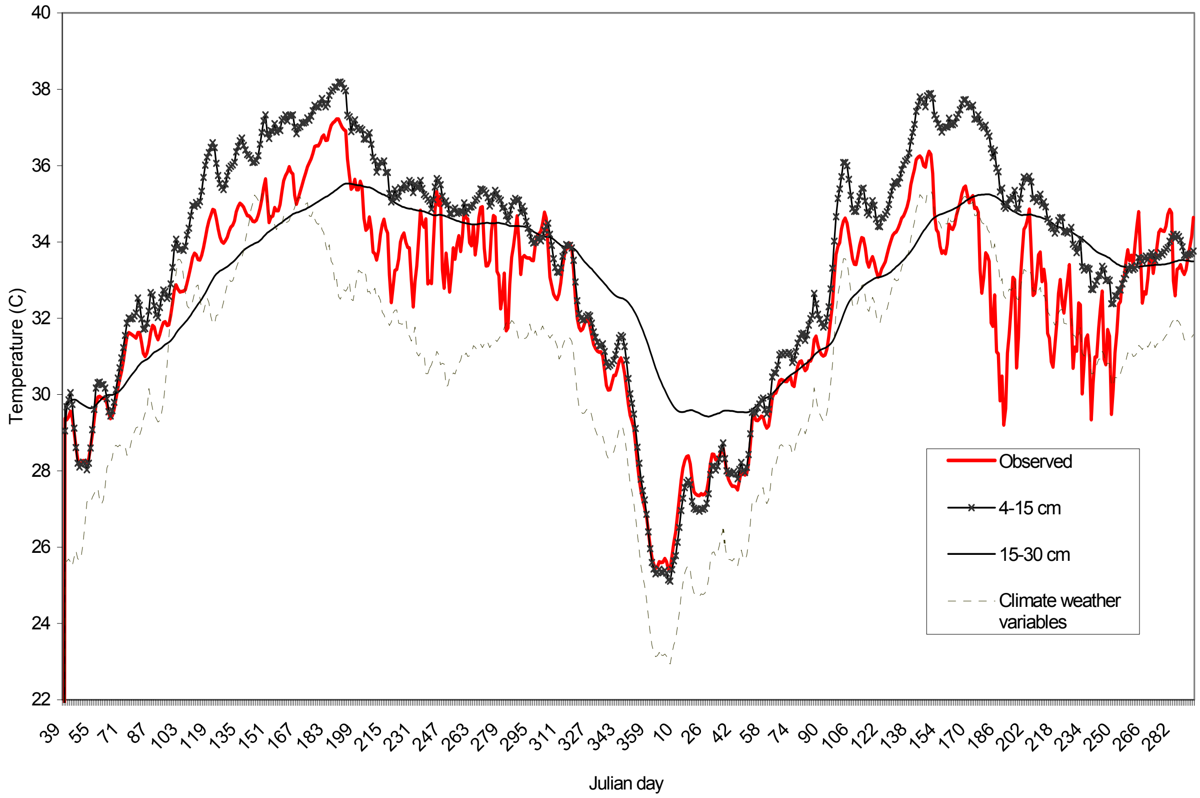

Figure 1. *The simulated soil temperature result of the base statement at the depth of 4- 15 cm, the observed temperature at the depth of 30 cm and the simulation with the extra weather variables. In the latter simulation PET is based on wind speed, incoming radiation and relative humidity instead of air temperature. The correlation for soil temp. at the 4-15 cm depth is r=0.95, tabl.1, appendix I.*

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