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### ► To cite this version:

Crystèle Léauthaud, J. Demarty, B. Cappelaere, Manuela Grippa, L. Kergoat, et al.. Revisiting historical climatic signals to better explore the future: prospects of water cycle changes in Central Sahel. Proceedings of the International Association of Hydrological Sciences, 2015, 371, pp.195 - 201. 10.5194/PIAHS-371-195-2015 . hal-01828698

**HAL Id: hal-01828698**

**<https://hal.science/hal-01828698>**

Submitted on 6 Nov 2020

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## Revisiting historical climatic signals to better explore the future: prospects of water cycle changes in Central Sahel

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Received: 17 March 2015 – Accepted: 17 March 2015 – Published: 12 June 2015

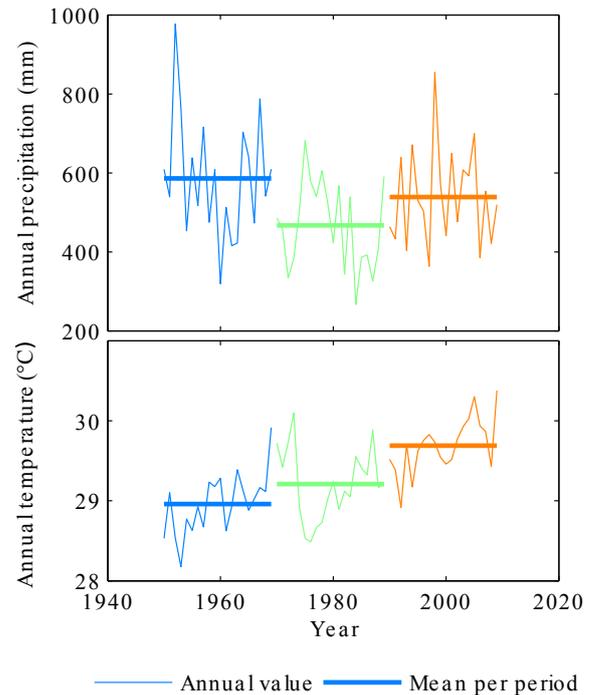
**Abstract.** Rainfall and climatic conditions are the main drivers of natural and cultivated vegetation productivity in the semiarid region of Central Sahel. In a context of decreasing cultivable area per capita, understanding and predicting changes in the water cycle are crucial. Yet, it remains challenging to project future climatic conditions in West Africa since there is no consensus on the sign of future precipitation changes in simulations coming from climate models.

The Sahel region has experienced severe climatic changes in the past 60 years that can provide a first basis to understand the response of the water cycle to non-stationary conditions in this part of the world. The objective of this study was to better understand the response of the water cycle to highly variable climatic regimes in Central Sahel using historical climate records and the coupling of a land surface energy and water model with a vegetation model that, when combined, simulated the Sahelian water, energy and vegetation cycles. To do so, we relied on a reconstructed long-term climate series in Niamey, Republic of Niger, in which three precipitation regimes can be distinguished with a relative deficit exceeding 25 % for the driest period compared to the wettest period. Two temperature scenarios (+2 and +4 °C) consistent with future warming scenarios were superimposed to this climatic signal to generate six virtual future 20-year climate time series. Simulations by the two coupled models forced by these virtual scenarios showed a strong response of the water budget and its components to temperature and precipitation changes, including decreases in transpiration, runoff and drainage for all scenarios but those with highest precipitation. Such climatic changes also strongly impacted soil temperature and moisture. This study illustrates the potential of using the strong climatic variations recorded in the past decades to better understand potential future climate variations.

## 1 Introduction

Climate research has now established clear linkages between anthropogenic activities and historical climate changes (IPCC, 2013). On a global scale, atmospheric carbon dioxide concentration increased by 40 % compared to pre-industrial times and temperature raised by 0.85 °C during the period 1880 to 2012 (IPCC, 2013). While tremendous modelling efforts are underway to understand the impact of these anthropogenic activities on past, current and future climate, current Global Climate Models (GCMs) still show large uncertainties in simulating climate at the regional scale. This suggests that they do not yet simulate some processes essential for regional climatology. In particular, representing the climatological features of the West African Monsoon (WAM) is a serious challenge (Biasutti, 2013; Roehrig et al., 2013). The Coupled Model Intercomparison Project Phase 5 (CMIP5) models capture, with varying degrees of accuracy, the south-north migration of rainfall, but they fail to reproduce the intermittence of precipitation over West Africa, its intraseasonal variability and its diurnal cycle. Prediction wise, spring and summer warming above global averages are noted, but the spread of model projections remains large for both air temperature and precipitation (Roehrig et al., 2013). These limits indicate that current GCMs may not yet be advanced enough to provide robust predictions on future climate trends in Western Africa. Yet, understanding potential future climatic changes in West Africa is vital, especially in the Sahelian belt. In this region where the surface water cycle is tightly linked to the vegetation cycle, strong changes in precipitation or temperature have had in the past and will most certainly in the future have a strong impact on vegetation productivity. With a largely rural population relying mostly on rainfed agriculture, this could lead to serious societal consequences as dramatically observed (e.g. Nicholson, 1980) and suggested for future climate (Sultan et al., 2013).

In the absence of agreement between climate models, alternative methods to explore potential future climate scenarios can be of great interest. In such a perspective, the climate of the last decades in Central Sahel shows an interesting feature: strong inter-decadal variability since the 1950s. Indeed, the Sahel experienced a severe drought in the 1970s and 1980s, followed by a somewhat partial recovery in rainfall relative to 1950–1969. Three 20-year climatologically distinct periods can hence be distinguished (Le Barbé et al., 2002; Lebel and Ali, 2009): abundant rainfall during the 1950s and 1960s, a severe drought during the following 20-year period, and finally moderate precipitation in the 1990s and 2000s compared to 1950–1969. Rainfall in the driest period showed a deficit of 25 % relative to the wettest period. Superimposed to this signal, mean decadal air temperature increased by approximately 1 °C in the past 60 years (Guichard et al., 2015, and Fig. 1). These are to be compared to the projections of most GCMs which indicate changes in temperature and precipitation for July–September in Central



**Figure 1.** Annual and 20-year mean precipitation and temperature at Niamey airport, Republic of Niger (1950–2009). The three climatologically distinct periods (1950–1969; 1970–1989; 1990–2009) are noted (respectively in blue, green and orange).

Sahel for the worst case scenario (Representative Concentration Pathway RCP8.5) in the order of  $4.5 \pm 1.5$  °C and 0–30 %, respectively. The extremely strong historical climatic signals can provide a first basis to understand the response of the water cycle to non-stationary conditions in this region of the world.

The objective of this study was to better understand the response of the surface water cycle to variable climatic regimes in Central Sahel. To do so, we took advantage of the historical climatic dataset recording strong inter-decadal variability and the use of a Soil-Vegetation-Atmosphere Transfer (SVAT) model and a dynamic vegetation model capable together of simulating the interactions between the water, energy and vegetation cycles. After a brief description of the dataset, simulated scenarios and coupling procedures in Sect. 2, results focus on analysing changes in the annual components of the water cycle, namely evaporation ( $E$ ), transpiration ( $T$ ), runoff ( $R$ ) and 4 m-deep drainage ( $D$ ) for a typical ecosystem in Central Sahel (grass/shrub savannah) as well as changes in surface and deep soil temperature ( $T_{s_{surf}}$  and  $T_{s_{250cm}}$ ) and moisture ( $W_{10cm}$  and  $W_{250cm}$ ). The method and results are discussed in a final section in regard of the potential for improving our modelling procedures and understanding of future climate and the consequences for the water cycle in Central Sahel.

## 2 Methodology

### 2.1 General approach

In the absence of reliable predictions for future precipitation trends, the strong historically observed inter-decadal rainfall signal of Central Sahel (1950–2009) was used to explore potential future changes in precipitation. Temperature increases of respectively +2 and +4 °C were superimposed to the precipitation signals, leading to six climatologically distinct virtual scenarios of 20 years each for the horizon 2100 (noted hereafter Sc1 to Sc6). A reference scenario was further obtained using the current 20-year climatic signal (denoted Sc0, 1990–2009). The response of the water budget to these scenarios was calculated by associating two surface models, capable in a coupled mode of simulating the tightly linked water-energy-vegetation cycles. Annual averages over the 20-year periods were estimated for the six virtual scenarios and the reference scenario (Sc0). A mean virtual scenario was also calculated, considering Sc1–Sc6 to be equiprobable, to better understand the mean response of the water cycle relative to the reference scenario. Finally, we analysed the differences in the components of the water cycle between climate projection scenarios and the reference scenario.

### 2.2 Dataset and simulated scenarios

Continuous and high temporal-resolution series of meteorological variables, namely precipitation ( $P$ , mm), air temperature ( $T_a$  at 2 m, °C), specific air humidity ( $g\ kg^{-1}$ , at 2 m), short- and long-wave down-welling radiation ( $W\ m^{-2}$ , at 2.88 m), wind speed ( $m\ s^{-1}$ , at 10 m) and surface air pressure (hPa) were necessary input variables for the models. As such datasets do not exist in Central Sahel, a time-series in which several gap-filling methods were used to obtain a coherent, continuous and high temporal resolution dataset for 1950–2009 was used (see Leauthaud et al., 2015 for more details). Developed for the location of Niamey airport (13.5° N–2.1° E), Republic of Niger, this dataset (denoted NAD) provided all the cited variables at a 30-min time-step compatible with model requirements. Local mean precipitation for the 1950–1969, 1970–1989 and 1990–2009 periods (Table 1, Fig. 1) were close to the regionally observed averages (1950–1969: mean precipitation of 576 mm over the region delimited by the 0–5° E and 11–17° N box; 1970–1989: 429 mm; 1990–2007: 478 mm, Lebel and Ali, 2009) and were used to simulate three precipitation scenarios. The superimposition of a uniformly distributed +2 and +4 °C increase in temperature led to six climate scenarios with precipitation and temperature means that differed from current climate (1990–2009) in the ranges of –15 to 8 % and +1.2 to 4 °C, respectively (Table 1). These differences span a large range of the uncertainty in future climate provided by current GCMs for both precipitation and temperature and were thus considered appropriate.

### 2.3 Modelling procedures

Due to the strong interactions between the vegetation, energy and water cycles in Central Sahel, it was necessary to simulate all three cycles to obtain a robust estimation of the surface water cycle. To do so, the hydrological/SVAT SiSPAT model (Braud et al., 1995) was used in association with the vegetation STEP model (Mougin et al., 1995) to represent a major land cover type of Central Sahel (grass/shrub savannah). This strategy combined the skills of each model in quite a simple coupling procedure. As a model with multiple soil layers in which water and heat transfers are described in detail, the SiSPAT model enabled the estimation of the surface water and energy cycles. It had been previously calibrated and validated in the Sahel for such purposes, notably on a similar land-cover type (fallow bush), so that in this study these calibrated soil and vegetation parameters were used (Velluet et al., 2014). The main biophysical information required to run the model was Leaf Area Index (LAI), which is a prognostic variable simulated by the vegetation model STEP. The latter was hence used to simulate the main growth processes of semi-arid grasslands (e.g. Pierre et al., 2012). STEP, in which the soil hydrology is calculated using a tipping bucket scheme, required a good estimation of hydrological processes, such as surface runoff, which is critical in Central Sahel where soils are prone to crusting. As this variable was a prognostic variable of the SiSPAT model, the two models were iteratively coupled to obtain good estimates of both LAI and runoff. Starting with a constant proportion of daily runoff (20 % of  $P$ ), STEP provided a first estimation of LAI. The latter was then used to run SiSPAT to estimate a new runoff. This procedure was iterated until convergence of LAI and  $R$ . Tests showed that two iterations led to the convergence of the exchanged variables. Initial soil temperature and humidity conditions necessary to run SiSPAT were taken from literature (Velluet et al., 2014) and a spin-up of one year, chosen randomly from the series, was added. Simulations therefore ran over 21 years for each scenario, although only 20 years were used for the analysis.

## 3 Results

### 3.1 Water cycle

Evaporation  $E$  represented the largest component for the water cycle (57 %) for Sc0, followed by Transpiration  $T$  (27 %), Runoff  $R$  (13 %) and Drainage  $D$  (2 %) (Table 2). Soil storage variation was negligible (< 1 %). This ranking remained identical for all simulated scenarios reflecting the general response of Sahelian ecosystems to precipitation: most precipitated water (> 80 %) returned to the atmosphere through evapotranspiration ( $ET = E + T$ ). Compared to Sc0, mean changes over all potential future climate scenarios showed an increase in proportion of  $E$  to the detriment of  $T$ ,  $R$  and  $D$  (Table 2). Four out of six scenarios showed an increase in

**Table 1.** Mean precipitation ( $P$ ) and temperature ( $T_a$ ) for the reference climate scenario (Sc0, 1990–2009) and six future climate scenarios (Sc1 to Sc6). Displayed are the mean  $\pm$  one standard deviation for  $T_a$  and  $P$ , as well as its increase compared to the historical period used for  $T_a$  (in parenthesis). Scenario names Sc1 to Sc6 are ordered from low to high  $P$  and  $T_a$ .  $\Delta P$  and  $\Delta T_a$  refer to differences relative to Sc0.

| Scenario | Historical period used | $T_a$ ( $^{\circ}\text{C}$ ) | Annual $P$ (mm) | $\Delta P$ (%) | $\Delta T_a$ ( $^{\circ}\text{C}$ ) |
|----------|------------------------|------------------------------|-----------------|----------------|-------------------------------------|
| Sc0      | 1990–2009              | $29.7 \pm 0.3$ (+0)          | $540 \pm 127$   | 0              | 0                                   |
| Sc1      | 1970–1989              | $31.2 \pm 0.4$ (+2)          | $460 \pm 110$   | –15            | 1.5                                 |
| Sc2      | 1970–1989              | $33.2 \pm 0.4$ (+4)          | $460 \pm 110$   | –15            | 3.5                                 |
| Sc3      | 1990–2009              | $31.7 \pm 0.3$ (+2)          | $540 \pm 127$   | 0              | 2                                   |
| Sc4      | 1990–2009              | $33.7 \pm 0.3$ (+4)          | $540 \pm 127$   | 0              | 4                                   |
| Sc5      | 1950–1969              | $30.9 \pm 0.3$ (+2)          | $585 \pm 157$   | 8              | 1.2                                 |
| Sc6      | 1950–1969              | $32.9 \pm 0.3$ (+4)          | $585 \pm 157$   | 8              | 3.2                                 |

**Table 2.** Mean annual values for the main components of the water cycle, namely evaporation ( $E$ ), transpiration ( $T$ ), runoff ( $R$ ) and deep drainage ( $D$ ), for the seven scenarios Sc0 to Sc6. Absolute values as well as maximum and minimum values (in brackets) are provided for Sc0. For all other scenarios, values are given as differences in means compared to Sc0. Extreme variations are shown in bold. The last line shows the mean difference ( $\Delta$ ) between the scenarios Sc1–Sc6 compared to Sc0

| Scenario | $P$ ( $\text{mm yr}^{-1}$ ) | $\Delta T_a$ ( $^{\circ}\text{C}$ ) | $E$ ( $\text{mm yr}^{-1}$ ) | $T$ ( $\text{mm yr}^{-1}$ ) | $R$ ( $\text{mm yr}^{-1}$ ) | $D$ ( $\text{mm yr}^{-1}$ ) |
|----------|-----------------------------|-------------------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| Sc0      | $540 \pm 127$               | $29.7 \pm 0.3$                      | 313 (387/253)               | 147 (222/88)                | 71 (182/15)                 | 9 (105/0)                   |
| Sc1      | $460 \pm 110$               | 1.5                                 | –28                         | –24                         | –19                         | –9                          |
| Sc2      | $460 \pm 110$               | 3.5                                 | –17                         | –35                         | –19                         | –9                          |
| Sc3      | $540 \pm 127$               | 2                                   | 8                           | –4                          | –1                          | –3                          |
| Sc4      | $540 \pm 127$               | 4                                   | 18                          | –13                         | –1                          | –4                          |
| Sc5      | $585 \pm 157$               | 1.2                                 | 23                          | <b>4</b>                    | 11                          | <b>8</b>                    |
| Sc6      | $585 \pm 157$               | 3.2                                 | <b>33</b>                   | –2                          | <b>11</b>                   | 4                           |
| $\Delta$ |                             |                                     | +6                          | –12                         | –3                          | –2                          |

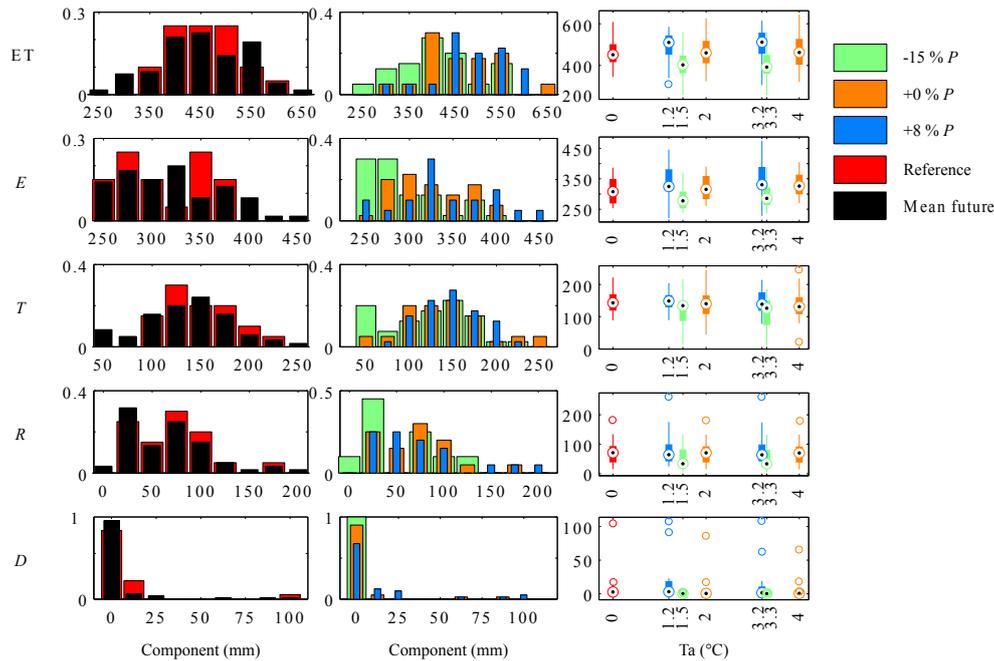
$E$ , as only strong decreases in  $P$  (–15 %) led to decreased  $E$ . On the contrary,  $T$  mostly decreased, by up to –23 % or only slightly increased (+3 %). Relative changes were highest for  $R$  and  $D$  (respectively within the ranges of –26 to +15 % and –100 to +88 %) compared to  $E$  and  $T$ , although absolute changes were small as these components only accounted for a small portion of precipitation. These components, especially  $D$ , seemed to act as an adjusting variable relative to changes in  $P$  and  $T_a$ .

Figure 2 (left column) shows the frequency histogram of evapotranspiration, its components  $E$  and  $T$ , as well as  $R$  and  $D$ , for the reference scenario and for the mean combination of all future scenarios studied. There was a general increase in the tail-end values of annual ET ( $< 350 \text{ mm yr}^{-1}$  or  $> 600 \text{ mm yr}^{-1}$ ) to the detriment of average values ( $> 350$  and  $< 550 \text{ mm yr}^{-1}$ ). Mean future values of  $R$  and  $D$  expressed a decrease in high values in favour of smaller annual total  $R$  and  $D$ . Scenario-averaged future values however hid the strong variability observed among Sc1 to Sc6 and the respective effects of  $P$  and  $T_a$  (Fig. 2 middle and right columns). Decreasing  $P$  seemed to shift ET from a positively skewed distribution for high  $P$  scenarios (+8 % relative to Sc0) to a less skewed distribution for low  $P$  scenarios

(–15 %). This was mainly due to a stronger response of  $E$  to decreasing  $P$  compared to  $T$ . Responses in  $R$  and  $D$  also had non-linear responses relative to changing  $P$ . It is noteworthy that a strong decrease in  $P$  (–15 %) led to the total disappearance of  $D$ . All components were thus highly sensitive to changes in  $P$ . On the contrary,  $R$  and  $D$  were not very sensitive to changes in  $T_a$  (Table 2 and Fig. 2). ET may respond to increased  $T_a$ , mainly through increased  $E$ .

### 3.2 Soil variables

Changes in future  $P$  and  $T_a$  also led to changes in soil states. In particular, soil temperature ( $T_s$ ) showed a strong response to simulated scenarios (Fig. 3). Estimated soil surface temperature ( $T_{s,\text{surf}}$ ) increased from  $31.8 \pm 0.4$  to  $33.4 \pm 0.8 \text{ }^{\circ}\text{C}$  from Sc0 to the mean future scenarios (Sc1 to Sc6) (Fig. 3).  $T_a$  had a strong effect on  $T_{s,\text{surf}}$  for all future scenarios. Precipitation only weakly modulated the increase of  $T_{s,\text{surf}}$ , which appeared to be predominantly driven by higher air temperature, and interestingly, this effect propagated to at least 250 cm within the soil with a more moderate increase, from  $32.3 \pm 0.2$  to  $32.9 \pm 0.3 \text{ }^{\circ}\text{C}$ . In all cases, the distribution of temperature became more positivity skewed. Soil water at



**Figure 2.** Simulation results for the annual components of the water cycle (Top to Down:  $ET$ ,  $E$ ,  $T$ ,  $R$  and  $D$ ). Left: frequency histograms for reference (Sc0) and scenario-averaged future climatic scenarios (Sc1–Sc6). Middle: frequency histograms for the three precipitation periods. Right: boxplots of annual components of the water cycle as a function of temperature scenarios. Water cycle components correspond to  $x$  axis in the left and middle columns, and to  $y$  axis in the right column.

both 10 and 250 cm also decreased (Fig. 3), with changes in  $P$  playing a major effect on this variable.

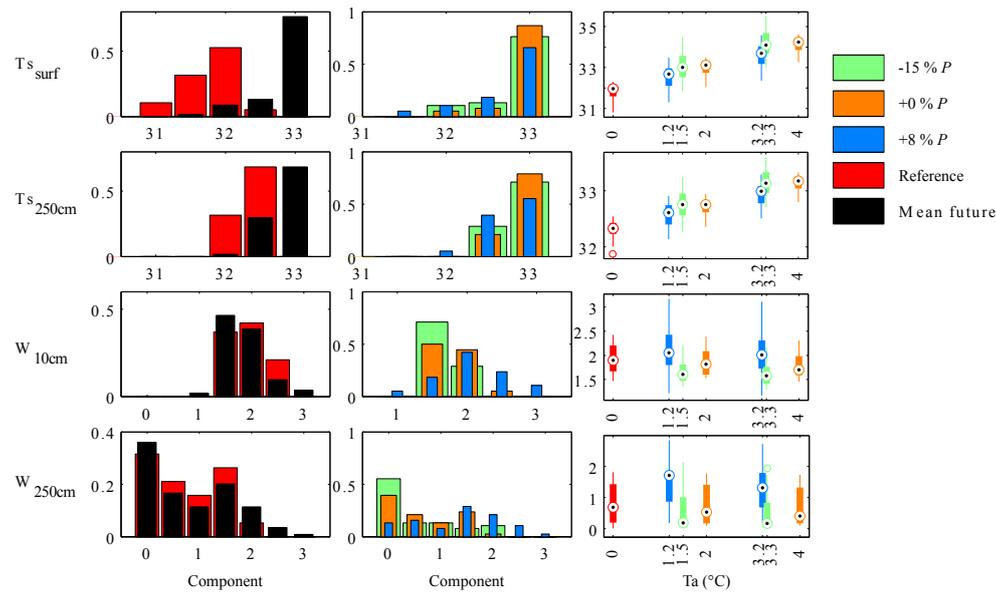
#### 4 Discussion

The interest of the Sahelian climate in the context of climate change studies resides in its distinct and very strong inter-decadal signal. In particular, the three historical periods used had very distinct rainfall and temperature seasonal cycles (Lubès-Niel, 2001; Lebel and Ali, 2009; Panthou et al., 2014; Guichard et al., 2015). For example, the driest period was characterised by an earlier occurrence of the seasonal rainfall maximum and a decrease in peak precipitation. Even though the inter-relationships between the water budget, seasonal rainfall and temperature variability were not investigated, the effects of these distinct characteristics were taken into account and propagated to the water budget. The historical precipitation signal has a range of variability higher than that predicted by GCMs for the future, which makes it relevant to use in order to investigate the impact of climate change on the water cycle in Central Sahel.

Although the scenarios explored in this study do not take into account all possible changing characteristics, some distinct features described here could be robust. First, evapotranspiration remained the main component of the water budget for all scenarios studied, suggesting that the recycling of a major part of precipitation to the atmosphere is a ro-

bust feature of Central Sahelian climate. Decomposition of  $ET$  into  $E$  and  $T$  was however variable between scenarios, suggesting in agreement with recent studies (Lohou et al., 2014), that the underlying processes responded differently to  $P$  and  $T_a$ . The variability in  $E$  and  $T$  obtained for the virtual scenarios highlights the need for more accurate projections. On the other hand,  $T_a$  had a negligible effect on runoff and deep drainage contrary to precipitation. In the advent of increased occurrence of extreme rainfall events, the latter's effect on runoff and drainage processes would need to be further explored. Finally, these results suggest a strong impact of changing precipitation and air temperature on soil state, with predicted increases in soil temperature for all future scenarios. This raises questions on the environmental effects of climate changes, with in particular, a potential effect on biological processes.

The proposed method presents some limits that would need to be addressed in future studies. First, on-going global warming suggests an intensification of the hydrological cycle with a slight rise in extreme rainfall occurrence (Panthou et al., 2014). The effect of differences in the structure of precipitation (e.g. changes in the frequency distribution such as occurrence of extreme events) beyond the observed domain is not documented here. Second, average air temperature increases in the past were not uniformly distributed throughout the seasons (Guichard et al., 2015). Similar seasonal tendencies could be expected in the future and it would be in-



**Figure 3.** Same as Fig. 2 for soil temperature at the surface and at 250 cm, and soil moisture at 10 and 250 cm.

interesting to have future climate scenarios that capture these seasonal differences. This raises a methodological question on how to distribute temperature increases throughout the year. Third, these temperature changes directly affect other climate variables, such as relative humidity. Future scenario runs could, as a first approximation, maintain constant relative humidity, so that specific humidity would also vary with temperature. This hypothesis, although debatable, is often used in climatological studies. Fourth, we did not simulate the effect of increased atmospheric  $CO_2$  concentration on vegetation productivity, partly because most species found in the Sahel have a C4 pathway of photosynthesis and are less sensitive to increases of atmospheric  $CO_2$ . This fertilisation effect could nevertheless affect plant growth processes. In a similar manner, the effect of increased air temperature on stomatal closure was not included in SiSPAT. Fifth, the STEP and SiSPAT models have been tested in various rainfall regimes but not in the range of temperature conditions used in this study. In the high tail-end temperature regimes, important processes may not be taken into account or parameter calibration may not be appropriate. An interesting venture would finally be to extend this study to millet crop, which is currently the main land cover type in Central Sahel and of major socio-economical relevance. The comparison of different climate scenarios using both grass/savannah and millet calibrations for the models would help to delineate the effects of land-use change and of climate change on the observed and potential future changes in the water cycle.

Beyond these methodological improvements, a better understanding of the underlying biological and physical processes is necessary. For example, our knowledge concerning the response of Sahelian vegetation to high temperatures is

very limited. Comparative studies along the climatic gradient found in the Sahel or the analysis of its temporal variability is a first step in identifying the major ecophysiological effects of high temperatures, but do not inform beyond the observed (temporal and spatial) range. Studies experimentally elevating  $T_a$  in the Sahel and analyzing its effect on vegetation have not yet been undertaken. In a similar way, important retroactions between the surface and the atmosphere – not taken into account in this off-line study – exist and directly affect the components of the water cycle, but are not yet well understood. It has been shown for example that the radiation budget and transpiration, which depend on vegetation development, can modify atmospheric circulations (Zeng et al., 1999), or that surface heterogeneities, which could be modified by high temperature increases, also affect atmospheric convection (Taylor et al., 2011). Studies focusing on the influence of surface processes on atmospheric circulation, such as undertaken in the ALMIP-2 project (Boone et al., 2009), will be important in improving our models to predict the future.

## 5 Conclusions

Understanding and predicting changes in the water cycle is vital in the Central Sahel region. Yet, complex non-linear relationships, lack of consensus on the sign of future precipitation changes and the difficulty of climate models to simulate the West African Monsoon make it challenging to extrapolate current models to future climatic conditions. The Sahel region experienced, in the past 60 years, one of the strongest climatic signals ever recorded. In this paper, we explored the possibility of using this strong inter decadal vari-

ability, in conjunction with different temperature scenarios, to analyse the response of the water cycle to non-stationary conditions. Preliminary results show a strong response of the water budget and its components to temperature and precipitation changes, including decreases in transpiration, runoff and drainage for all scenarios but those with strong precipitation increases. Climatic changes also strongly impacted soil temperature and humidity. Further studies that focus on other major characteristics, such as the effect of extreme rainfall occurrence on runoff and deep drainage, are now required. This study shows the potential of using the strong non-linear climatic signals of the past decades to better explore potential future climate variability.

**Acknowledgements.** This work was funded by the French National Research Agency (ANR) through the ESCAPE project (ANR-10-CEPL-005). Availability of raw data at Niamey airport station, through the AMMA and AMMA-CATCH databases, is gratefully acknowledged.

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