



Projected Hydroclimate Changes over Senegal (West Africa)

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Abstract. Understanding and assessing hydroclimate changes is essential to provide reliable information in developing countries such as Senegal in order to guide adaptation strategies. In this work, we have examined the projected changes in temperature and precipitation over the six eco-geographical zones in Senegal. Furthermore, we have assessed the river flow changes in the three major river basins (Casamance, Gambia, Senegal). Climate simulations from the Coupled Model Intercomparison Project Phase 6 (CMIP6) were analyzed. The ensemble mean of the climate models projects a continued increase in mean, minimum and maximum temperatures across Senegal (up to more than 4 °C in the long term under the SSP5-8.5 scenario). The projected warming is greater in eastern Senegal and the Sylvo-pastoral zone. As for rainfall, it is characterized by very high interannual variability; the projections show decreasing trend from 2015 to 2100. The groundnut basin is the most area affected by the decrease in rainfall (24%). However, slight humidity conditions are projected for the near future (2021–2040). The downward trend of rainfall is much more pronounced around 2045 to 2100. In addition, we found a slight increase in extreme wet events that are more marked in the near future. This could increase the risk of flooding in urban and peri-urban areas. Moreover, future flows are strongly impacted by climate change. Thus, the stations of Kolda (Casamance River), Gouloumbou (Gambia River) and Kidira (Senegal River) could experience a slight increase in flow rates (up to 20%) by 2030; while by 2060 and 2100, a decline of about 40% is projected. Our findings can help the water managers and decision-makers to better plan their adaptation measures.

Keywords: Climate change impacts · Senegal · rainfall · temperature · river flow

1 Introduction

Today, the issue of climate change in Sub-Saharan Africa (SSA) is no longer in doubt. Indeed, even if progress remains to be made both in terms of the production of knowledge and its availability, as well as the ability to implement it in order to reverse the current trend, efforts are being carried out for better consideration of the said changes with regard to their serious economic implications on the entire development process, but also on the daily lives of the populations. It is commonly accepted that, due to its low adaptive capacity, Africa remains very vulnerable to climate change (Nicholson 2013; Engelbrecht et al. 2015; Niang et al. 2014; IPCC 2014). Indeed, not only does it remain the continent whose warming is faster than average, but climate projections show a rise of 3 to 4 °C over the course of the century. This will necessarily lead to or even exacerbate existing challenges, whether economic and financial, scientific and technological, etc. Senegal is one of the most vulnerable countries to climate change. The State of Senegal is not only a signatory of international conventions in the field of environment and climate, but it is resolutely committed to taking better account of climate change in development policies and plans. Thus, this contributes to strengthening the country's adaptation and resilience capacities. It is in this context that the government of Senegal submitted its updated version of the NDC to the UNFCCC secretariat in December 2020, with a mitigation target of 36% (including an unconditional target of 7% and a conditional target of 29%) by 2030, relative to the reference scenario. In the same vein, Senegal has been engaged since 2015 in the process of carrying out its National Adaptation Plan (NAP). Today, studies are being carried out in certain agro-ecological zones or in progress. Thus, it is urgent that Senegal, like other signatory countries of the Paris Agreement (PA) on climate, be more ambitious by developing long-term strategies with an inclusive economy with low greenhouse gas emissions 2050 and beyond. The strategy carried by a visionary program, a political certainty, will be around the scaling up of agriculture that sustainably increases productivity and resilience (adaptation), reduces/eliminates GHGs (mitigation) in a possible way and enhances the achievement of food security and development goals for sustainable economic transformation. In all agro-ecological zones of the country, climate change is already dramatically affecting the natural ecosystems on which poor rural communities, and in particular women, depend to develop their production systems and, in short, their survival. In addition, major environmental problems are emerging and have repercussions both on animal and plant biodiversity, and both on agricultural production, water resources, economy and food security of populations are threatened, even weakened, and this situation continues to exacerbate. The overall objective of this work is to investigate the hydroclimate changes using the new SSP (Shared Socio economic Pathways) scenarios over the century.

2 Study Area

Six eco-geographical zones of Senegal, namely Niayes, Casamance, Ferlo (Sylvo-pastoral zone), River Valley, Groundnut Basin and Eastern Senegal are marked by specific pedo-climatic, human and agricultural conditions (Fig. 1). They hosted a high ecosystem diversity with the presence of forest ecosystems, agroforestry ecosystems,

fluvio-lacustrine ecosystems and finally coastal marine ecosystems thanks to the existence of a coast of more than 700 km. The country is located in three climatic domains at the same time (Sahelian in the north, Sudanian in the center and sub-Guinean in the south).

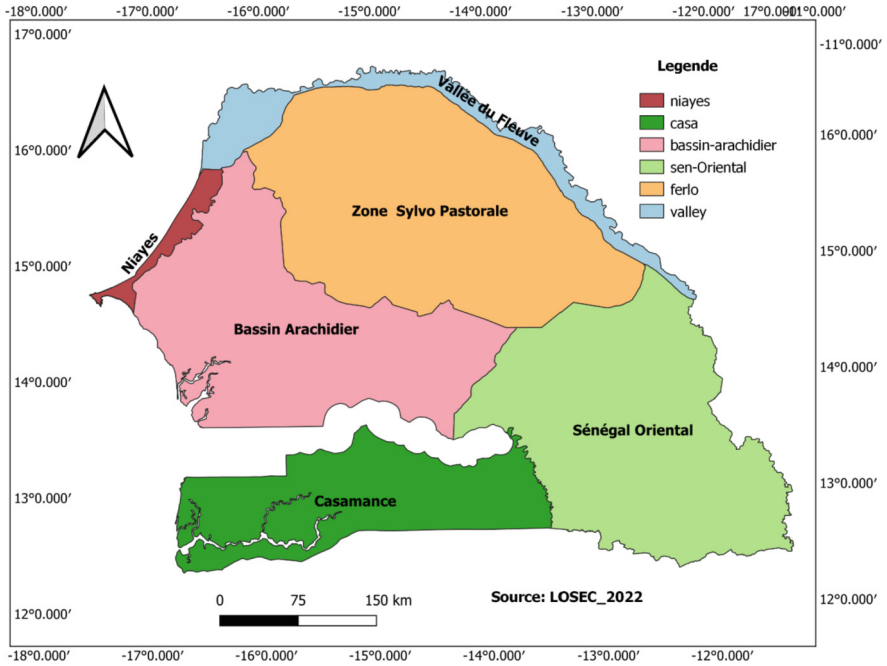


Fig. 1. Eco-geographical Zones in Senegal

3 Data and Methods

Climate change affects many climate variables including precipitation and temperature. At the international level, many countries have committed to the Paris Agreement to hold the global temperature increases to “well below 2 °C” and to pursue efforts to limit warming to 1.5 °C above pre-industrial levels. Meeting this target implies a drastic reduction in greenhouse gas (GHG) emissions and drastic social, political and economic transformations. The extent and exact nature of this transition to a low-carbon economy will depend on the actions that our societies will implement, and therefore cannot be perfectly known in advance. This transition induces risks and opportunities for economic actors that they must anticipate in order to build their strategy in a context of uncertainty. In this regards, the scientific community has developed scenarios called SSP (Shared Socio-Economic Pathways). These SSPs are narratives of socioeconomic development exploring plausible developments in the world in the absence of additional policies and measures to limit global warming (Riahi et al. 2017). These scenarios were defined by

the scientific community to build a common framework and to facilitate analysis of climate change impacts, mitigation and adaptation options, and their costs. These five scenarios (SSP1, SSP2, SSP3, SSP4 and SSP5) describe the possible social, economic, political and technological evolutions by the end of the 21st century.

In this work, we will study three of the five scenarios, namely SSP126, SSP245 and SSP585. Each scenario was translated into quantitative data, including economic growth, population, urbanization (O'Neill et al. 2017). These assumptions were used as model inputs to obtain reference scenarios for each SSP (i.e., not taking into account a climate target). These data were previously used over Africa by Almazroui et al. (2020). Moreover, we compute hydroclimate changes for heavy rainfall, accumulated rainfall over 5 days interval, the coefficient of variation, the annual rainfall, the rainy days, temperatures, and river discharge. These indices were successfully evaluated in West African regions (Agyekum et al. 2022; Faye and Akinsanola 2022; etc.). We took the ensemble mean of the models because it is well documented that the models average gives better performance in reproducing climate features and indices. This reduces the natural variability and systematic biases present in individual models (Akinsanola and Zhou 2019). We consider the period: 1981–2010: reference period, 2021–2040: near future. 2041–2070: mid future and 2071–2100: far future.

4 Results

4.1 Rainfall and Temperature Changes

In the following section, we diagnose the expected changes in extremes rainfall over the six considered domains under the three scenarios. Figure 2 presents the interannual changes of heavy rainfall. Results show that there will be a strong fluctuation of this index during the future marked by an alternation between years for which the heavy rainfall will decrease or increase over the six areas of the country for all scenarios. This decrease of heavy precipitation will be more pronounced during the far future (2071–2100) for all SSPs in particular under the SSP585 scenario.

Furthermore, our results are in line with those of Saley and Salack 2023 who found showed significant changes toward higher values in the probability distribution function of the future heavy rainfall events in West Africa, which may likely trigger more floods in the region. Mbaye et al. (2019) have also found a slight increase in heavy rainfall over Senegal in the coming decades. Figure 3 present the changes in the interannual 5-days precipitation accumulations in the six zones of Senegal under the three scenarios. The 5-days rainfall cumulative are known to be favorable to flooding and therefore they are a major concern for local populations. During the future, there would be an alternation between years for which the 5-days cumulative rainfall will decrease or increase in the six areas of Senegal under the three scenarios. The magnitude of these changes will be much pronounced under the SSP585 scenario over the river valley, the Niayes area, the groundnut basin and the Sylvo-pastoral area compare to the SSP126 and SSP245 scenarios. Strong peaks of changes of the 5-days cumulative rainfall will be recorded in 2055 and 2075 in the groundnut basin and the Niayes area under the SSP585 scenario.

The interannual changes of the coefficient of variation of precipitation as well as the interannual changes of mean rainfall are presented respectively in Fig. 4 and 5.

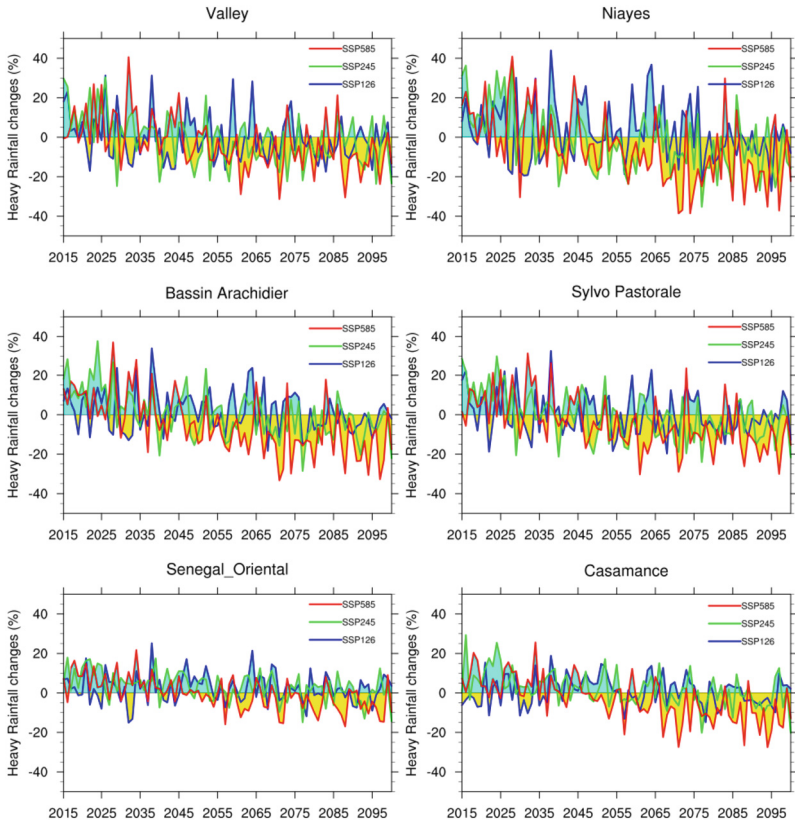


Fig. 2. Interannual changes in heavy precipitation under the three scenarios and the six areas of the country. Blue, green and red lines depict SSP126, SSP245 and SSP585, respectively. (Color figure online)

The coefficient of variation of precipitation will remain below 20% in the present-day and medium term (2015–2040) with a strong interannual fluctuation in the six zones of the country under the three scenarios (Fig. 4). This high variability could be explained by the changes in Sea Surface Temperature (SST) as stated by Mohino et al. (2011). From 2055 onwards, there will be many years for which the coefficient of variation of precipitation will be above 20% with weak interannual fluctuation. When considering the interannual changes of the mean rainfall (Fig. 5), there will be a strong interannual fluctuation marked by a succession of years for which the mean rainfall will decrease or increase in the six zones of the country in the present-day and medium term (2015–2050) under the three scenarios. From 2066 onwards, there will be a general decrease of the mean rainfall in the six zones of the country under the three scenarios. This decrease will be more pronounced under the SSP585 scenario and less under the SSP126.

Figure 6 presents the changes in the number of rainy days (in percentage) in the near, mid and far future over Senegal under three different scenarios. In the near future (2021–2040), the results project a slight increase in the number of rainy days in the northeast

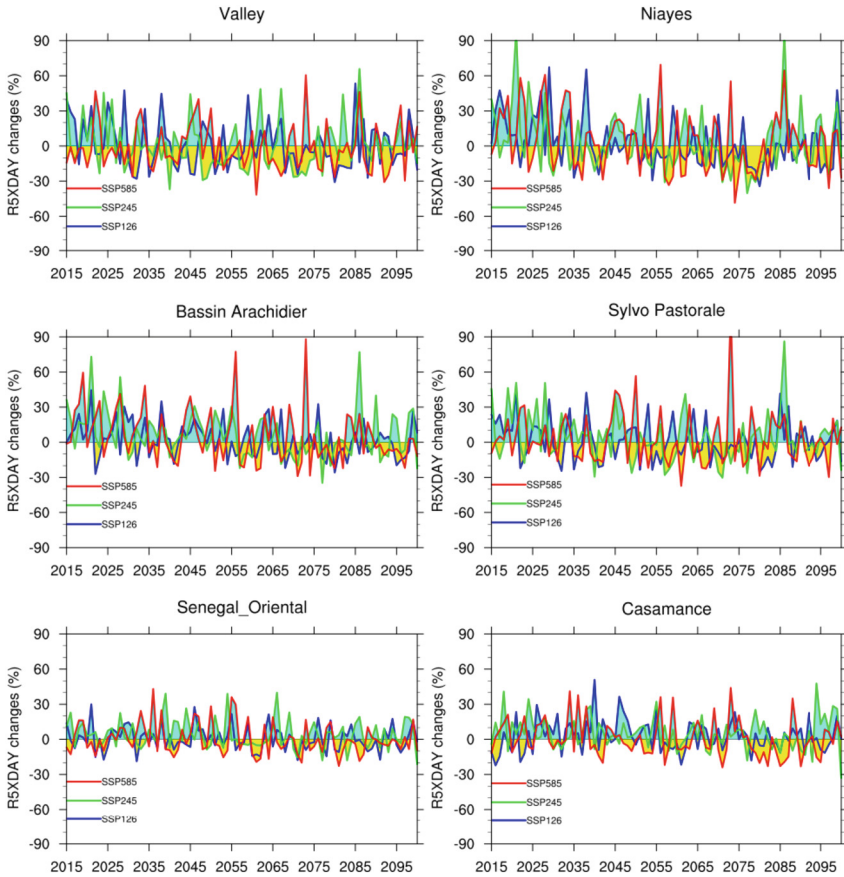


Fig. 3. Year-to-year changes in total 5-day rainfall under the three scenarios and the six areas of the country. Blue, green and red lines depict SSP126, SSP245 and SSP585, respectively. (Color figure online)

and southwest of the country under the scenarios SSP2-4.5 and SSP5.8.5. This slight increase of rainfall was also observed in previous study in the near future by Mbaye et al. (2020a). The results also show that the number of rainy days decreases over some regions of Senegal during the near future (2021–2040) under the SSP1-2.6 scenario. In the medium (2041–2070) and the far future (2071–2100), there will be a decrease in the number of rainy days throughout Senegal under the scenarios SSP2-4.5 and SSP5.8.5.

This decline will be much greater in the centre and north of the country and will have negative consequences on pastoralism, which is one of the pillars of the country's economy.

These dry conditions in mid and far futures were also observed in the past by Mbaye et al. (2021) over Sub-Saharan countries.

Figure 7, shows the temporal variations of the mean temperature in the future with respect to the historical period. The results show that all six areas of the country have

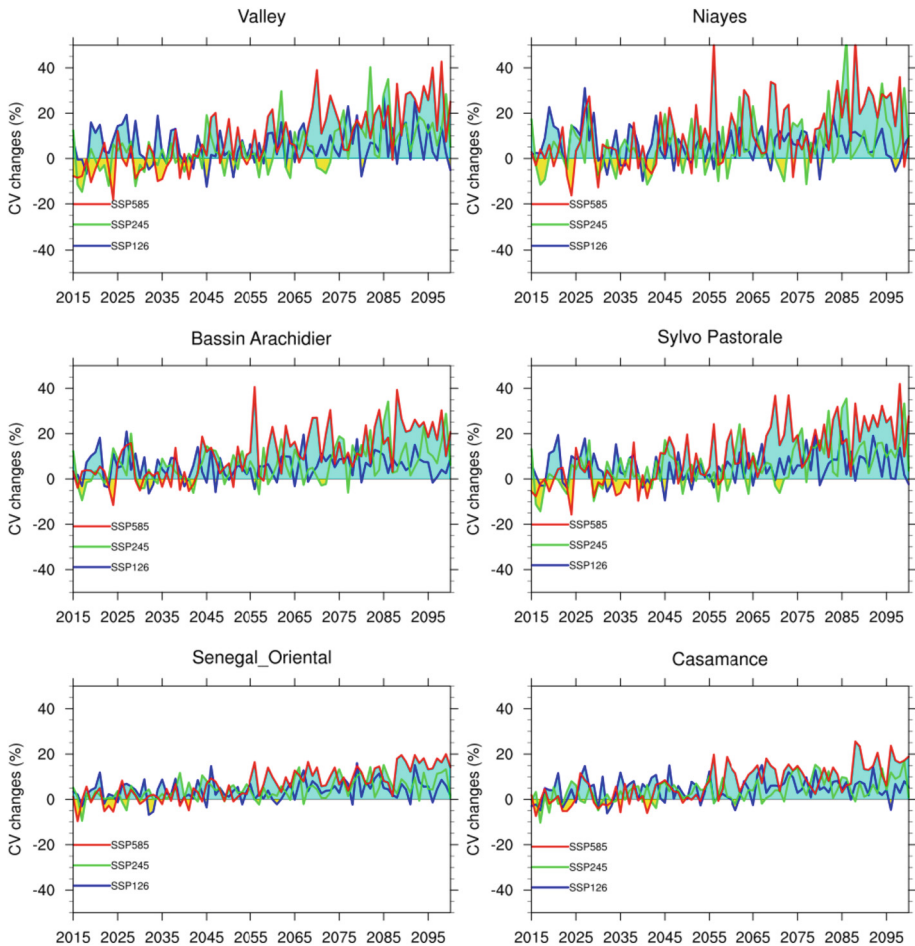


Fig. 4. Interannual changes in the coefficient of variation of precipitation and the six areas of the country. Blue, green and red lines depict SSP126, SSP245 and SSP585, respectively. (Color figure online)

experienced a weak warming during the historical period 2015–2020. The temperatures will increase in all six areas of the country under the three scenarios which highest magnitude for the SSP585. The warming trend will increase by 2050s under the SSP245 scenario (Fig. 8). In addition, agriculture, which is an important source of income for the country’s farmers, is the most sensitive sector to temperature changes. Indeed, a strong increases of temperature could inhibit the growth of some plants (Salack et al. 2015; Basak et al. 2013) or reduce their growing cycle which could lead to yield losses. For example, some crops yields such as wheat, rice, maize, or peanuts could be significantly impacted by extremely high temperatures. These temperature increases can also have negative impacts on human health as shown by Hass et al. (2016) and Garland et al. (2015). This increase could be linked to some factors such as the warming of the Sahara,

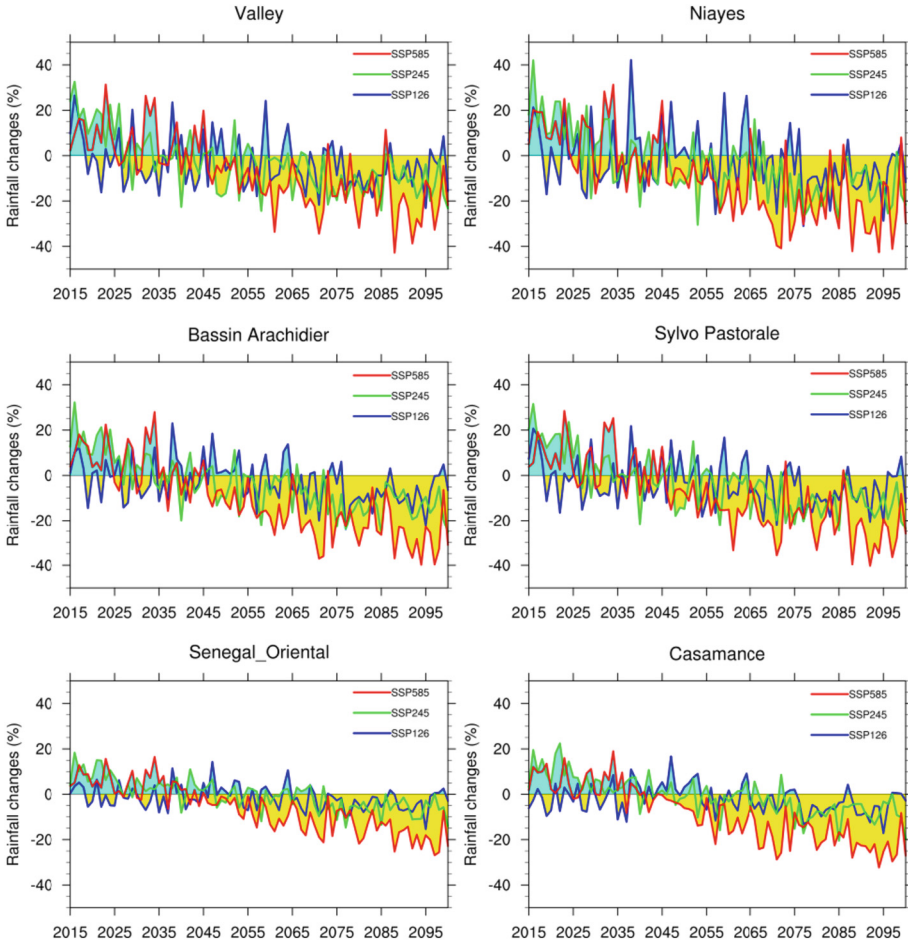


Fig. 5. Interannual changes in mean precipitation and the six areas of the country. Blue, green and red lines depict SSP126, SSP245 and SSP585, respectively. (Color figure online)

the increasing concentration of aerosols and greenhouse gases in the atmosphere (in Saley and Salack 2023).

Generally, temperatures could reach more than 3 °C under the scenario SSP245 at the end of the century. Eastern Senegal shows the highest warming while the river valley shows the lowest increase. The shift in warming between the different zones appears around 2050; this could be explained by the dominance of internal climate variability over projections at near horizons, while anthropogenic forcing have much more influence over the long term in climate simulations.

Figure 9 presents the spatial patterns of annual mean temperature change over Senegal during the future under the SSP126, SSP245 and SSP585. The results show that the whole country will undergo warming under the three scenarios during the near future (2021–2040), the medium (2041–2070) and the far future (2071–2100). This warming

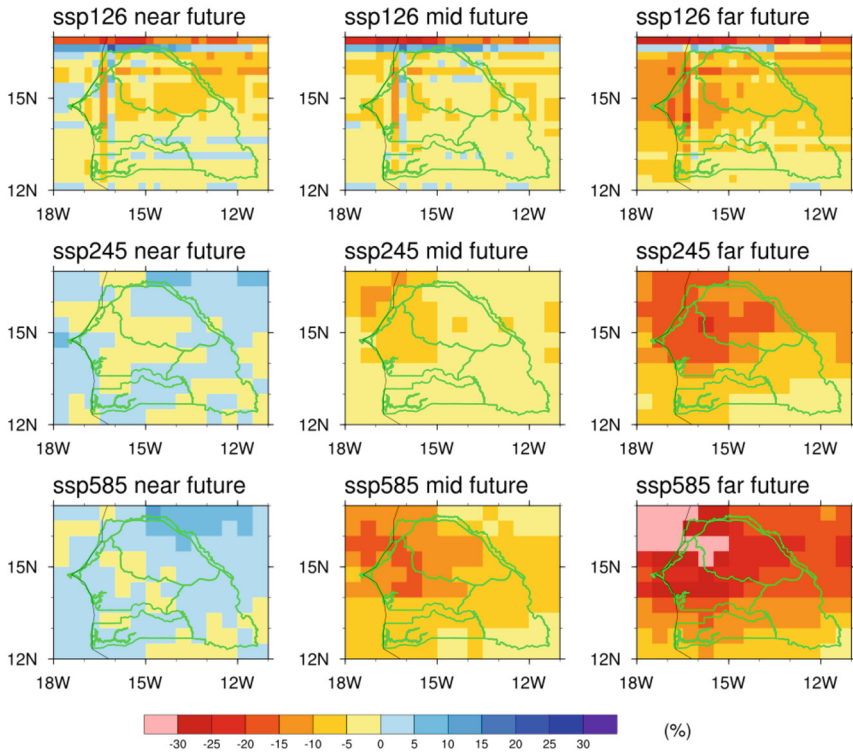


Fig. 6. Rainy days changes for the SSP126, SSP245 and SSP585 in the near (2021–2040), mid (2041–2070) and far future (2071–2100) over Senegal.

will increase at the end of the century under the three scenarios. During the near future (period 2021–2040), the warming will be more pronounced under the SSP126 scenario. There will be no large differences between the SSP245 and SSP585 scenarios during the near future. The warming will increase considerably in the eastern part of the country during the medium and far future under the SSP585 scenario. This area could face a situation of thermal discomfort of populations and livestock.

The increase of temperatures should lead to an intensification of the hydrological cycle. Todzo et al. (2020) have underlined that this intensification is expected to increase over the Sahel as a result of increasing rainfall intensity and lengthening of dry spells. Moreover, the increasing temperatures could favor an increase in the rainfall intensity through the Clausius–Clapeyron (CC) relation. In addition, extreme rainfall are projected to intensify with increasing moisture under global warming following the Clausius–Clapeyron (CC) relationship (Martinez and Neelin 2023).

Figure 10 summarizes the changes in mean temperature and precipitation in each eco-geographic zone over the near, middle and far future. Thus, for the near future, the rates of change do not exceed 1.5 °C whatever the scenario considered. In generally, the warming is around 1 °C with small increases (>5%) in precipitation under the SSP245 and SSP585 scenarios. Relatively normal conditions for precipitation accompanied by

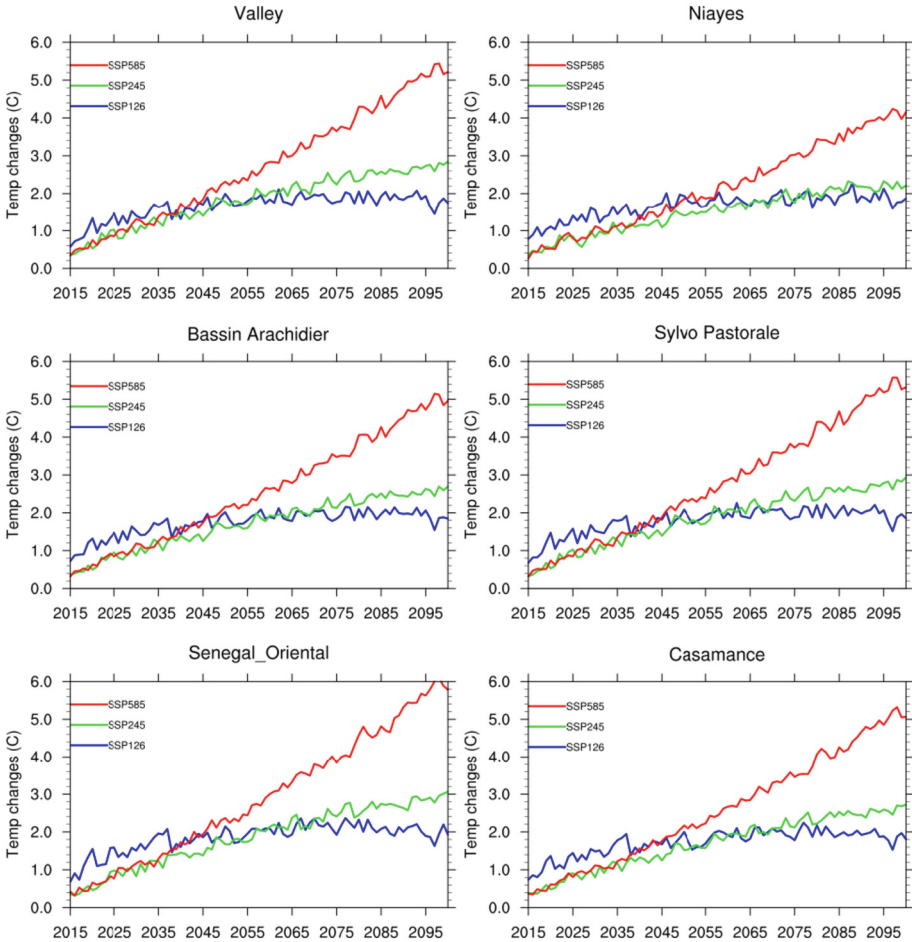


Fig. 7. Interannual changes in average temperatures for six different areas of the country. Blue, green and red lines show SSP126, SSP245 and SSP585, respectively. (Color figure online)

a warming of around $2\text{ }^{\circ}\text{C}$ are found at medium term under the low scenario SSP126. In addition, the warming is accentuated with the highest scenario SSP585 (increase of 2 to $3\text{ }^{\circ}\text{C}$). The decrease in rainfall is much more marked in the groundnut basin, while for temperatures warming are more pronounced in eastern Senegal. At the end of century, the decrease in precipitation varies from -5% (eastern Senegal) to -25% (groundnut basin), while the increase in average temperature varies from $3.5\text{ }^{\circ}\text{C}$ (in the Niayes area) to $4.85\text{ }^{\circ}\text{C}$ (in eastern Senegal).

The decrease of rainfall is in line with the work of Cook et al. (2022) who found a drier western Sahel. In general, the rates of change are greater under the SSP585 scenario for both temperature and precipitation in the far future. The increase in temperatures will lead to more water losses through evapotranspiration because the increases in PET (potential evapotranspiration) would have a larger drying effect on the surface layer (Zhao and

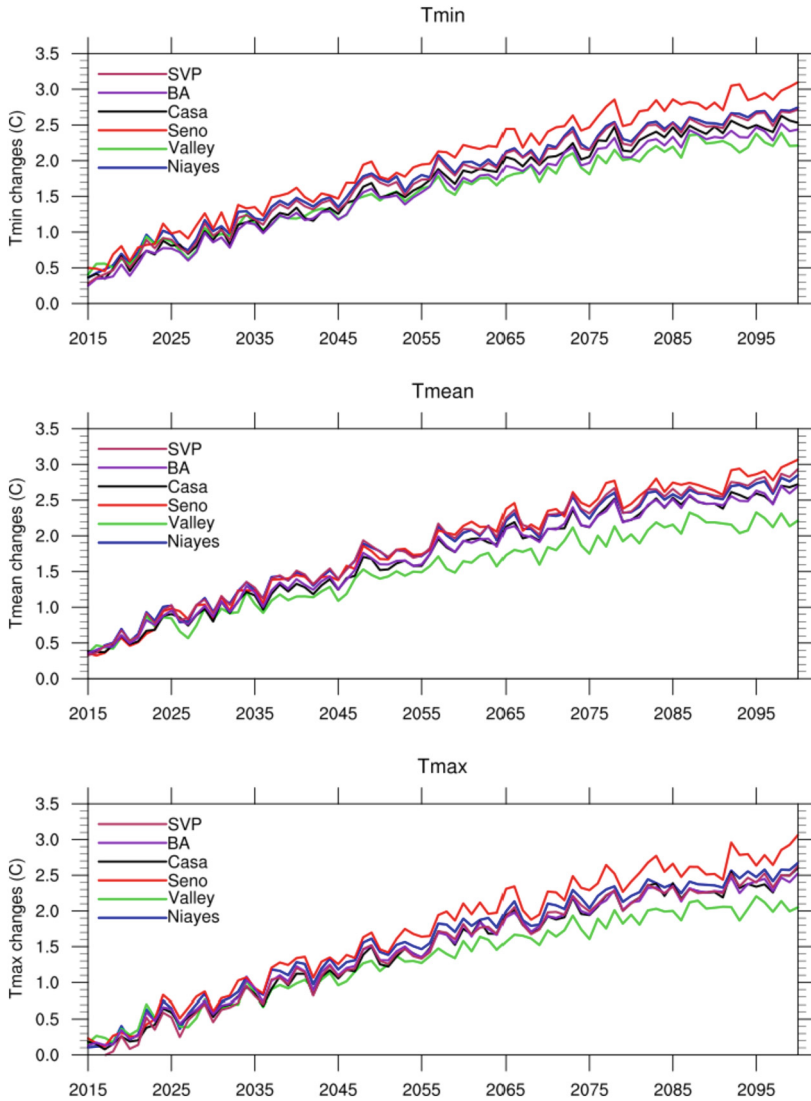


Fig. 8. Absolute change in temperature under the SSP 245 scenario. SVP: sylvopastoral, BA: groundnut basin, casa: Casamance, seno: eastern Senegal. The minimum temperature (top row), the mean temperature (medium row) and the maximum temperature (bottom row) were considered.

Dai 2022). In addition, this decrease of rainfall was revealed by Todzo et al. (2020) who found that mean precipitation decreases with the increase of temperature over the Sahel. The changes are more pronounced under the extreme scenario (SSP585); this means that more there will be warming, more the impacts will be great. Osima et al. (2018) have underlined the higher effect of global warming under 2 °C level compared to the 1.5 °C warming level over the Greater Horn of Africa. This warming will most likely

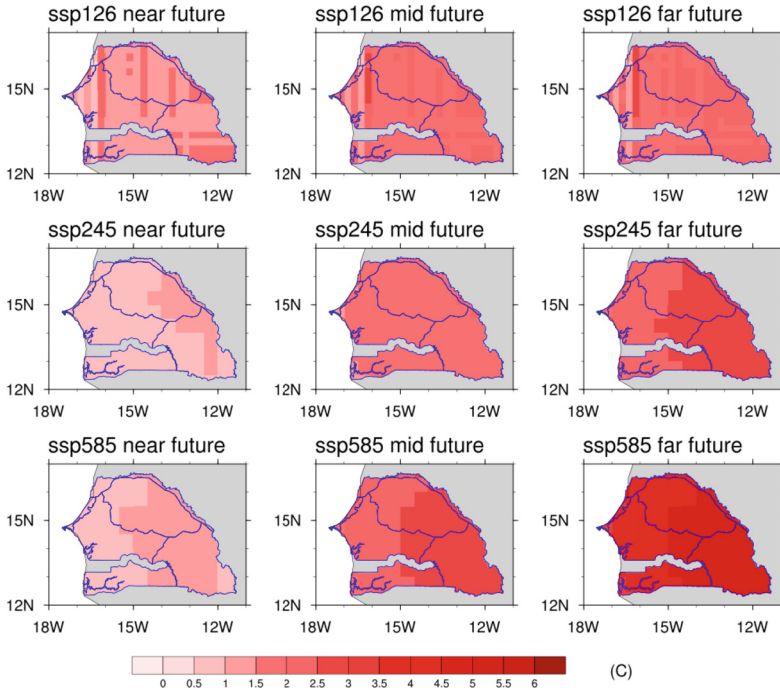


Fig. 9. Annual change in mean temperature for the SSP126, SSP245 and SSP585 in the near (2021–2040), mid (2041–2070) and far future (2071–2100) over Senegal.

lead to an increase in evapotranspiration and heat waves particularly in the eastern and south-eastern regions. Furthermore, Myhre et al. (2019) found that for a 2 K global mean surface warming, the extreme events frequency would double or triple in the future.

4.2 River Discharge Changes

In this section, we have used the hydrological simulations carried out in West Africa within the framework of the AMMA-2050 project by Rameshwaran et al. (2022). The analyses were carried out on three major watersheds, namely: the Casamance River basin (Fig. 11), the Gambia River (Fig. 12), and the Senegal River watershed (Fig. 13).

We considered only hydrometric stations located in Senegal for transboundary basins. The inter-annual change rates were calculated relative to the baseline period 1985–2014. Strong interannual variations are observed in all the stations studied in all the watersheds areas. From 2015 to 2045, the watersheds could experience slight increases in flows (20%) as shown in Figs. 11, 12 and 13. All the watersheds will face a considerable drop in flows up to 40% towards the end of the century with the SSP585 scenario. In the Casamance River basin, the Medina Namou station recorded the most significant changes of up to -50%. The stations of Simenti and Gouloumbou would be much more affected by the hydrometric deficit than those of Kédougou and Mako in the Gambia River basin.

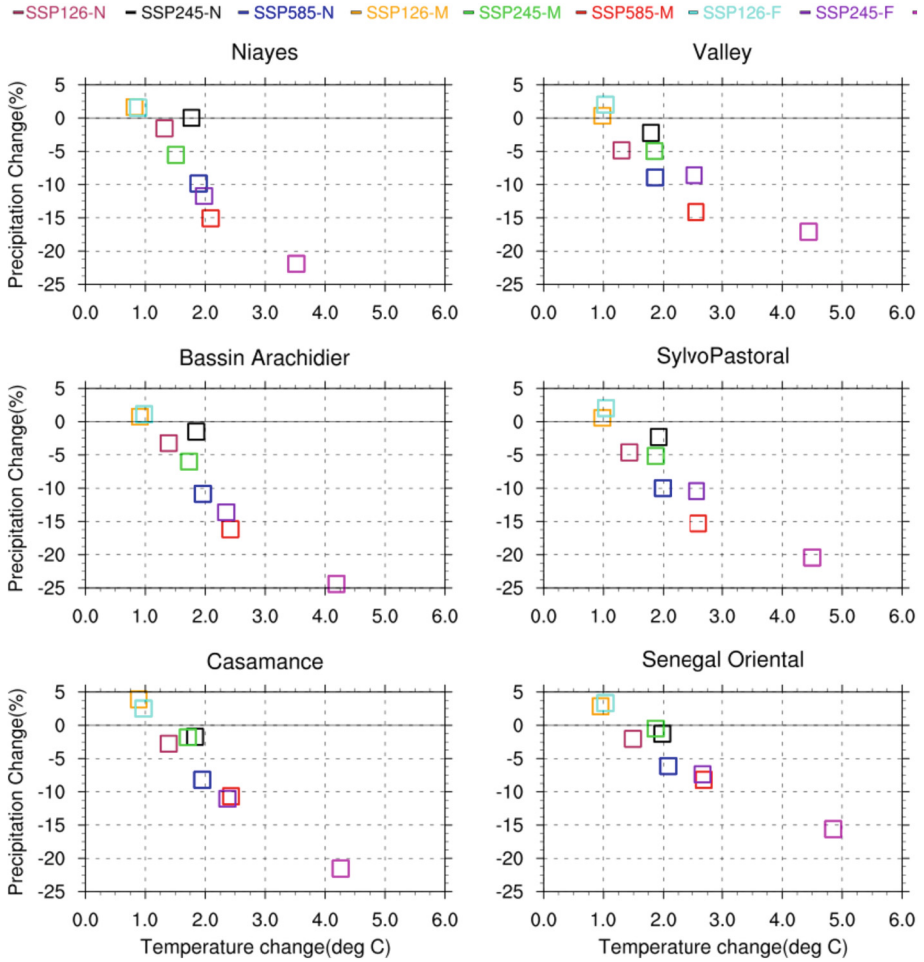


Fig. 10. Relation between absolute change in mean temperature and relative change in precipitation under the SSP126, SSP245 and SSP585 scenarios for the near, mid and far future. SVP: sylvopastoral, basin A: groundnut basin, Casa: Casamance, Seno: eastern Senegal).

For the watershed of the Senegal River, the stations of Podor, Matam and Bakel show similar trends; while the hydrometric station of Kidira would experience the most pronounced changes. This was revealed by Mbaye et al. (2020b) in the Faleme Basin where a downward trend in annual and monthly average flows is expected. These hydrological conditions could negatively impact water uses (human water consumption, agriculture, livestock, fishing, mines, industries, etc.). In addition to these, the salinization of soils, the degradation of vegetation, the disappearance of native animal and plant species, diseases over the Senegal River valley and the estuary (Taibi et al. 2023) may increase the vulnerability of the basin and the people.

This decline of river discharge was also suggested by Dembélé et al. (2022) in a West African basin (Volta River Basin) decrease under RCP2.6 and RCP4.5 scenarios. Hence,

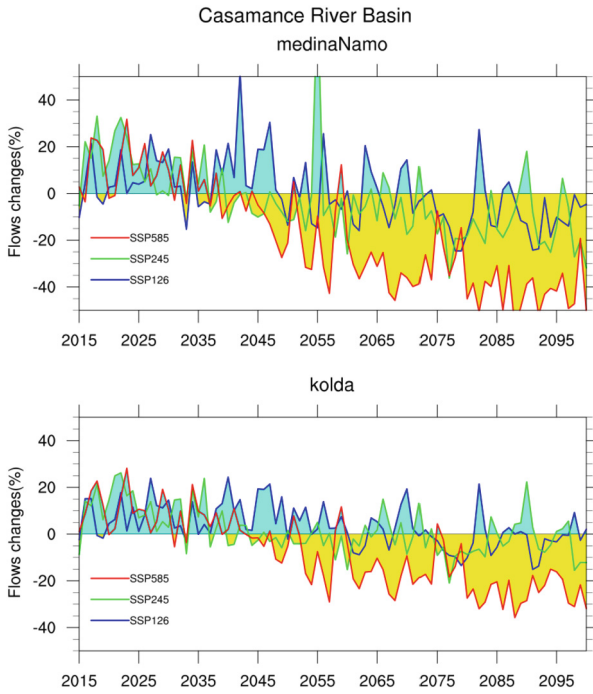


Fig. 11. Interannual changes in discharge for Médina Namó and Kolda stations in the Casamance River basin. Blue, green and red lines show SSP126, SSP245 and SSP585 respectively. (Color figure online)

the increase of temperature combined with decreased of rainfall and stream flow would have drastic consequences for the future availability of water resources for agricultural purposes and hydropower (NASAC 2015).

The Gambia River Basin

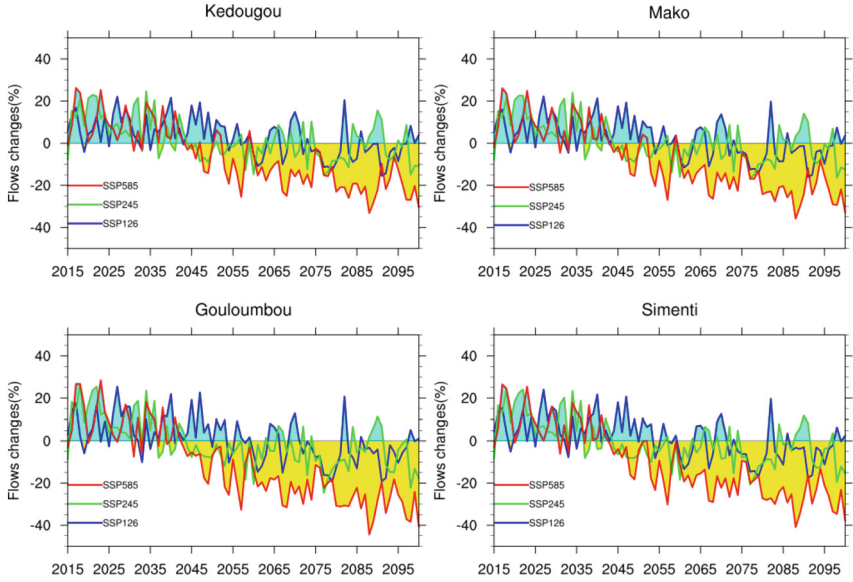


Fig. 12. Interannual changes in discharge for Kédougou, Mako, Simenti and Gouloumbou stations in the Gambia River basin. Blue, green and red lines show SSP126, SSP245 and SSP585 respectively. (Color figure online)

Senegal River Basin

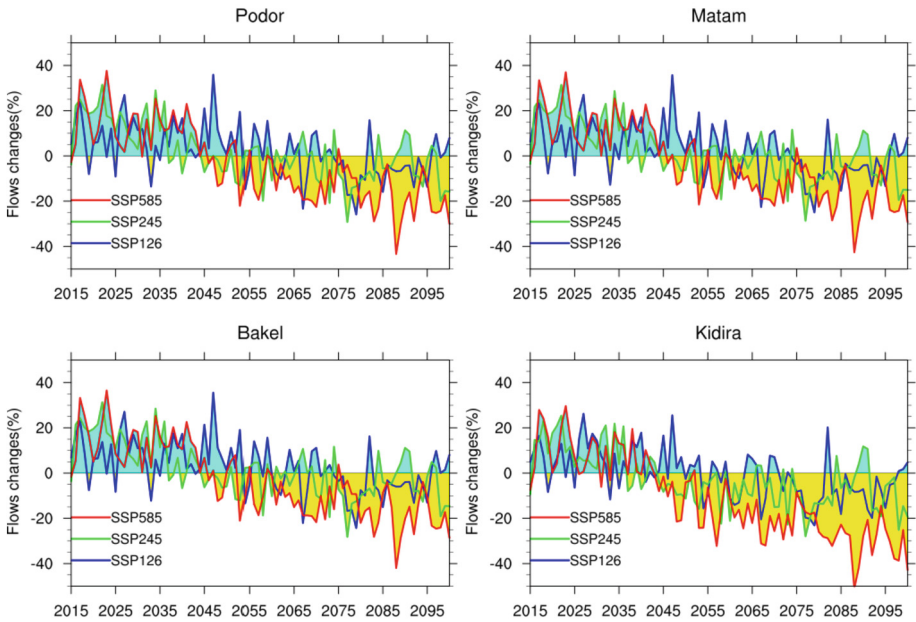


Fig. 13. Interannual changes in discharge for Podor, Matam, Kidira and Bakel stations in the Senegal River basin. Blue, green and red lines show SSP126, SSP245 and SSP585 respectively. (Color figure online)

5 Conclusion

This study assessed the hydroclimate changes over Senegal and its major river basins. The new climate change scenarios SSPs (Shared Socioeconomic Pathways) from CMIP6 models were used under different time slices. The first part of this work was focused to the changes in rainfall and temperatures over six eco-geographical zones in Senegal; the hydrological changes were assessed over the three major river basins in Senegal, in the second part. In the first part, the results show that Rainfall is likely to decrease over almost the whole Senegal in the far future under SSP126, SSP245 and SSP585 scenarios. The results also show that the number of rainy days decreases over almost all of Senegal during the near future (2021–2040) under the SSP1-2.6 scenario. In the medium term (2041–2070) and the far future (2071–2100), there will be a decrease in the number of rainy days throughout Senegal under the scenarios SSP2-4.5 and SSP5.8.5. This decline will be much greater in the center and north of the country and will have negative consequences on pastoralism, which is one of the pillars of the country's economy. Moreover, the decrease in heavy rainfall will be much more felt in the far future (2071–2100) over the six areas of the country under scenario SSP5.8.5. The decrease in rainfall is much more marked in the groundnut basin, while temperatures are warming up more in eastern Senegal. As for the far future, the decrease in precipitation varies from -5% (eastern Senegal) to -25% (groundnut basin). As for the average temperature, it will rise from 3.5 C (in the Niayes area) to 4.85 C (in eastern Senegal). This decrease in rainfall will have negative consequences on agriculture. In terms of temperature, a general increase is noted under these three scenarios. Much of the country could experience much larger temperature increases than the 1.5 °C and 2.0 °C levels set by the 2015 Paris Agreement for all scenarios. The increase in temperature in the future could lead to increased energy consumption for food and food preservation in rural areas and for cooling and air conditioning in urban areas. In addition, extreme wet events are also characterized by high variability and a slight increase more marked in the near future. The risk of flooding in urban and peri-urban areas would be exacerbated with the increase in extreme wet events. Future flows are strongly impacted by climate change. Thus, the stations of Kolda (Casamance River), Gouloumbou (Gambia River) and Kidira (Senegal River) could experience a slight increase in flow rates by 2030; while by 2060 and 2100, a decline is projected. Furthermore, future studies should be oriented in the understanding of the dynamics of hydrological extremes which cause several damages over the basins.

Acknowledgements. We would like to thank the Staff of the Laboratoire d'Océanographie, des Sciences de l'Environnement et du Climat (LOSEC) at the University Assane Seck of Ziguinchor where this work has been done. We thank also the DGPRES (Direction de la Gestion et de la Planification des Ressources en Eau) for providing the river discharge data.

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