engineering proceedings

MDPI

Proceeding Paper

On the Role of Leaf Area Index Parameterization in Simulating the Terrestrial Carbon Fluxes of Africa Using a Regional Coupled Climate–Vegetation Model †

Samy A. Anwar [1,*] and Yeonjoo Kim [2]

1 Egyptian Meteorological Authority, Qobry EL-Kobba, Cairo P.O. Box 11784, Egypt
2 Department of Civil and Environmental Engineering, Yonsei University, Seoul 03722, Republic of Korea
* Correspondence: ratebsamy@yahoo.com

† Presented at the 3rd International Electronic Conference on Applied Sciences, 1–15 December 2022; Available online: https://asec2022.sciforum.net/.

Abstract: In this study, the Regional Climate Model version 4 (RegCM4) coupled with the Community Land Model version 4.5 (CLM45) including a module of carbon–nitrogen cycling (CN) (RegCM4-CLM45-CN) was used to examine the sensitivity of the terrestrial carbon fluxes of Africa to leaf area index (LAI) parameterization. Two LAI formulas were implemented in CLM45-CN. The new LAI formula is based on a modified BioGeochemical Cycles ecosystem model. The two simulations were designated as LAIorg and LAImod, respectively, they both shared the same initial and lateral boundary conditions, and they were evaluated concerning reanalysis products and FLUXNET measurements. In LAIorg, the above-ground terrestrial carbon fluxes were overestimated to the reanalysis products, which were also noted for the below-ground terrestrial fluxes. On the other hand, in LAImod, terrestrial carbon fluxes were notably decreased relative to LAIorg, and the model bias was reduced. In the in situ observation, LAImod was better matched to the observation than LAIorg, although both were limited in capturing the observed magnitude and seasonality of gross primary production (GPP) to some extent. In conclusion, switching between the two formulas has a substantial effect on the simulated terrestrial carbon fluxes. Despite noted biases, the regional coupled RegCM4-CLM4-CN-LAImod model can be recommended for future studies to investigate the influence of climate change on the terrestrial carbon fluxes of Africa.

Keywords: Africa; community land model; leaf area index; regional climate model; terrestrial carbon fluxes

Citation: Anwar, S.A.; Kim, Y. On the Role of Leaf Area Index Parameterization in Simulating the Terrestrial Carbon Fluxes of Africa Using a Regional Coupled Climate–Vegetation Model. *Eng. Proc.* **2023**, *31*, 9. https://doi.org/10.3390/ASEC2022-13839

Academic Editor: Nunzio Cennamo

Published: 9 December 2022

1. Introduction

The complexity of the carbon cycle arises from combining various carbon reservoirs in the Earth system (e.g., atmospheric carbon dioxide (CO_2) in the atmosphere, soil organic carbon and vegetation), including fluxes and feedbacks which regulate the dynamics of these reservoirs [1]. Photosynthetic and respiration processes regulate the CO_2 net flux at the surface, affecting atmospheric CO_2 concentrations, surface energy balance and the hydrological cycle [2]. Mainly, Africa plays an essential role in the carbon cycle in the 21st century as it has large areas of moist tropical forest, seasonal and semi-arid woodland, savannah, grassland and desert.

The performance of the offline land surface or regional coupled regional climate–vegetation models (for simulating LAI and GPP) has been evaluated over Africa (e.g., [3]). For instance, ref [4] showed that a coupled climate–dynamic vegetation model overestimates both GPP and LAI concerning the Machine Tree Ensemble (MTE; [5]).

Ref. [6] examined the role of LAI parameterization in controlling the surface energy balance and climate of Africa with RegCM4 coupled with Community Land Model version 4.5 (CLM45), including a module of carbon–nitrogen cycling (CN) (RegCM4-CLM45-CN).

They reported that when the modified LAI formula is used, the model performance is improved relative to the original LAI formula, and it shows a similar performance relative to the static vegetation case. Additionally, the LAI parameterization notably influences the total evapotranspiration and surface energy balance budgets. This study aims to examine the role of LAI parameterization in simulating the terrestrial carbon fluxes in Africa using a regional coupled climate–vegetation model (RegCM4-CLM45-CN). Section 2 describes the study area, data and experiment design; Section 3 discusses the results of simulations over the African domain. Finally, Section 4 shows the summary and conclusion.

2. Materials and Methods

2.1. Model Description and Experiment Design

Version 4.5 of the International Center for Theoretical Physics (ICTP) regional climate model (i.e., RegCM4) was used in this study. In addition, the community land model version 4.5 (CLM45) was used because it offers substantial improvements such as reducing the excessive tropical GPP, a revised canopy radiation scheme, and the canopy scaling of leaf processes [7]. The CLM45-CN land model adapts the formula of [8] to simulate LAI using knowledge of the leaf carbon content (C_L; in gC m^{-2}) and the specific leaf area at the top of the vegetation canopy (SLA_o; in m^2 gC^{-1}).

Ref. [9] reported that LAI is overestimated concerning MODIS. To overcome such overestimation, ref [6] proposed a new LAI formula based on the BIOME-BGC model. Because of the empirical nature of the BIOME-BGC model, it was calibrated with respect to the MODIS (as the observational based dataset), ensuring reasonable bias compared to a study conducted by [9]. Additional details of the new BIOME-BGC over Africa can be found in [6]. While [6] investigated the role of LAI parameterization on the surface energy balance and climate, this study examines the potential role of LAI parameterizations in simulating the terrestrial carbon fluxes of Africa. Figure 1 shows the topography (in meters) over the domain, including three focus areas [10].

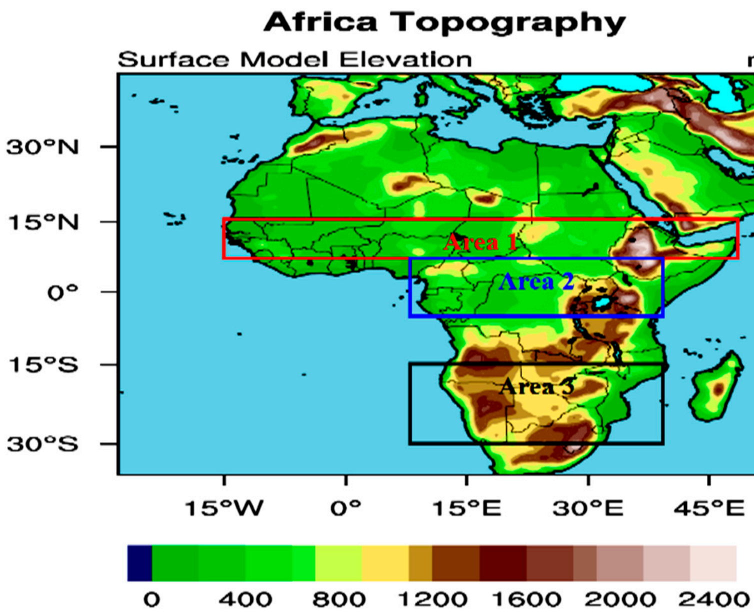

Figure 1. The figure shows the model domain and topography elevation (unit: meters).

The simulations shared the same initial and lateral boundary condition from the National Centre for Environmental Prediction/National Centre for Atmospheric Reanalysis version 2 (NCEP/NCAR2, [11]), which was used as the lateral boundary conditions, and ERA-Interim data were used as the sea surface temperature (SST; [12]). The RegCM4 model simulations adopted the physical configuration of [10]. Initializing the coupled RegCM4-CLM4-CN-LAIorg/RegCM4-CLM4-CN-LAImod model requires a long-term spinning up of the CN (which is provided by the NCAR) to ensure that the vegetation carbon and NEE are in equilibrium, as recommended by [3,4].

2.2. Validation Data

This study used the CARbon DAta MOdel fraMework version 1.0 dataset (CARDAMOM; [13]) and Fluxnet tower datasets ([14]). For the present study, the CARDAMOM product was bilinearly interpolated on the RegCM4-CLM45-CN curvilinear horizontal grid with the bi-linear interpolation method. To further evaluate the two simulations, FLUXNET datasets at three sites in Africa, which were Demokeya (SD-Dem; [15]), Mongu (ZM-Mon; [16]) and Tchizalamou (CG-Tch; [16]), were used to evaluate the simulated GPP on a monthly time scale. Following [14], data were quality controlled and processed using uniform methods to ensure consistency and intercomparability. Among eight available sites in Africa (namely, Demokeya, Skukuza, Nxarag, Guma, Mongu, Tchizalamou, Ankasa and Dahra), three sites of SD-Dem, ZM-Mon and CG-Tch (Table 1) were selected, because data from other sites are limited with missing records.

Table 1. The table shows a list and description of FLUXNET sites used in this study as well as statistical metrics for the model evaluations. Additionally, it shows mean bias (MB), standard deviation ratio (SD) and Pearson correlation coefficient (CORR) to quantitatively evaluate the performance of LAIorg and LAImod with respect to FLUXNET observations.

Station	Latitude	Longitude	Vegetation Species	MB		SD		CORR	
				LAIorg	LAImod	LAIorg	LAImod	LAIorg	LAImod
Demokeya (SD-DEM)	13.2829	30.4783	Savanna	5.7	4.16	2.5	2.47	0.46	0.44
Mongu (ZM-Mon)	−15.4391	23.2525	Deciduous forest	1.21	0.75	1.29	1.22	0.41	0.67
Tchizalamou (CG-Tch)	−4.2892	11.6564	Savanna	5.48	2.38	0.91	1.11	0.01	0.14

3. Results

3.1. Ecological Indicators and Terrestrial Carbon Fluxes

To illustrate the potential role of LAI parameterization in simulating the simulated terrestrial carbon fluxes, the following ecological indicators were analyzed: solar radiation absorbed by the vegetation (SABV; in W m^{-2}), photosynthesis rate (FPSN; in µmol$m^{-2}s^{-1}$), leaf carbon (LEAFC; in gC m^{-2}) and soil temperature of depth 10 cm (ST10; in K) for 2001 to 2010 (Figure 2). From Figure 2a–c, it can be observed that LAImod has a lower SABV than the LAIorg by 40–80 W m^{-2} over the Savanna of the Northern and Southern hemispheres, while over the evergreen forest (Congo basin region), the change is approximately 20 approaching 40 W m^{-2}. Such behavior can be explained by the fact that LAIorg severely overestimates the Total Leaf Area Index (TLAI; sum of sunlit and shaded leaves) relative to the MODIS, while LAImod alleviates this overestimation, particularly over the Savanna. Because of the noted behavior of the SABV, LAIorg reduces the FPSN by 2–4 µmol $m^{-2}s^{-1}$ approaching 8 µmol.m^{-2}.sec^{-1} over the Savanna of the Northern hemisphere, by 2–6 over the Savanna of the Southern hemisphere and it is ±1 µmol $m^{-2}s^{-1}$ over the Congo basin (Figure 2d–f). Therefore, LAImod reduces the total carbon stored in the leaf (LEAFC) by 80–200 gC m^{-2} over the Savanna of the Northern and Southern hemispheres and by ±40 gC m^{-2} over the Congo basin (Figure 2g–i). From Figure 2j–l, it can be noted that LAImod has a higher ST than LAIorg over the Savanna regions by 6–9 K and by 1–3 K over the Congo basin. Such behavior can be explained by the fact that LAIorg allows a low rate of incoming solar radiation because of high LAI. In contrast, LAImod allows a high rate of the incoming solar radiation [6].

Figure 3 shows the comparisons for GPP (defined as the total photosynthesis yield at the ecosystem scale). In general, RegCM4 is able to reproduce the spatial pattern of the GPP in comparison with the CARDAMOM in all seasons (Figure 3a–c,g–i,m–o,s–u), yet varying with the season as well as the region. For brevity in the analysis, only the spring (March–April–May; MAM) is considered for discussion. In the MAM season, it can be noted that LAIorg overestimates the GPP over the Savanna of the Southern hemisphere by 2–5 gC m^{-2} day^{-1} and underestimates the GPP by 2–4 gC m^{-2} day^{-1} over the Congo basin and the coastal region of West Africa (Figure 3d). On the other hand, LAImod overestimates the GPP over the Savanna of the Southern hemisphere by 1–2.5 gC m^{-2} day^{-1} and underestimates the GPP over the Congo basin and West Africa by 3–4 gC m^{-2} day^{-1} (Figure 3e). LAImod has a lower GPP than the LAIorg by 1–3 gC m^{-2} day^{-1} overall in tropical Africa (Figure 3f). As such, LAImod reduces the GPP bias over the southern region of tropical Africa but slightly increases the GPP negative bias over the Congo basin and West Africa. Such behavior can be attributed to the fact that LAImod notably reduces the SABV, FPSN and LEAFC over the Savanna regions. In contrast, it slightly reduces over the Congo basin and West Africa. Additionally, the increase in ST10 by LAImod contributes to decreasing the GPP relative to the LAIorg.

NEE is an essential component of Earth system modeling since it quantifies the net emission of CO_2 and the atmosphere's net uptake. As presented in Figure 4, RegCM4 shows a good ability to capture the spatial pattern of NEE (either sink or source; negative/positive CO_2) (Figure 4a–c,g–i,m–o,s–u). For instance, in MAM, LAIorg overestimates the NEE by 2–3 gC m^{-2} day^{-1} (i.e., LAIorg shows more CO_2 emissions) over the northern Savanna and underestimates over the southern Savanna by the same order of magnitude (Figure 4d). On the other hand, LAImod also overestimates the NEE over the northern Savanna by 3 gC m^{-2} day^{-1} but reduces the underestimated NEE over the southern Savanna to be 0.5–2 gC m^{-2} day^{-1} (Figure 4e). Strictly speaking, LAImod reduces the NEE by 1.2–1.8 gC m^{-2} day^{-1} but increases the NEE by 1.4–1.8 gC m^{-2} day^{-1} over the southern Savanna relative to LAIorg (Figure 4f).

3.2. Site Evaluations

Monthly GPP is evaluated in three locations, as shown in Figure 5 and Table 1. In SD-DEM, LAIorg and LAImod show two peaks of GPP in May and January, while FLUXNET only shows one peak of GPP in August. In addition, both LAIorg and LAImod overestimate the GPP with respect to the FLUXNET observation with the mean bias (MB) of 5.7 and 4.16 gC m^{-2} day^{-1}, respectively. Yet, LAImod is closer to the FLUXNET than the LAIorg. At ZM-MON, both LAIorg and LAImod capture the monthly variability with respect to the observation. Furthermore, LAImod shows improved performance compared with the LAIorg, as LAIorg has an MB of 1.2 gC m^{-2} day^{-1}, while LAImod shows an MB of 0.75 gC m^{-2} day^{-1}. In particular, the Pearson correlation coefficient (CORR) is improved from 0.41 of LAIorg to 0.67 of LAImod. Finally, at CG-TCH, the models show a poor ability to capture the monthly variability in the GPP compared to FLUXNET. However, LAImod still outperforms LAIorg, because LAImod has an MB of 2.38 gC m^{-2} day^{-1}, while the MB of LAIorg is 5.48 gC m^{-2} day^{-1}. As mentioned already, the mismatch in spatial representation between the model results and Fluxnet data should be noted, yet it still provides qualitative insights into the model performance to some extent.

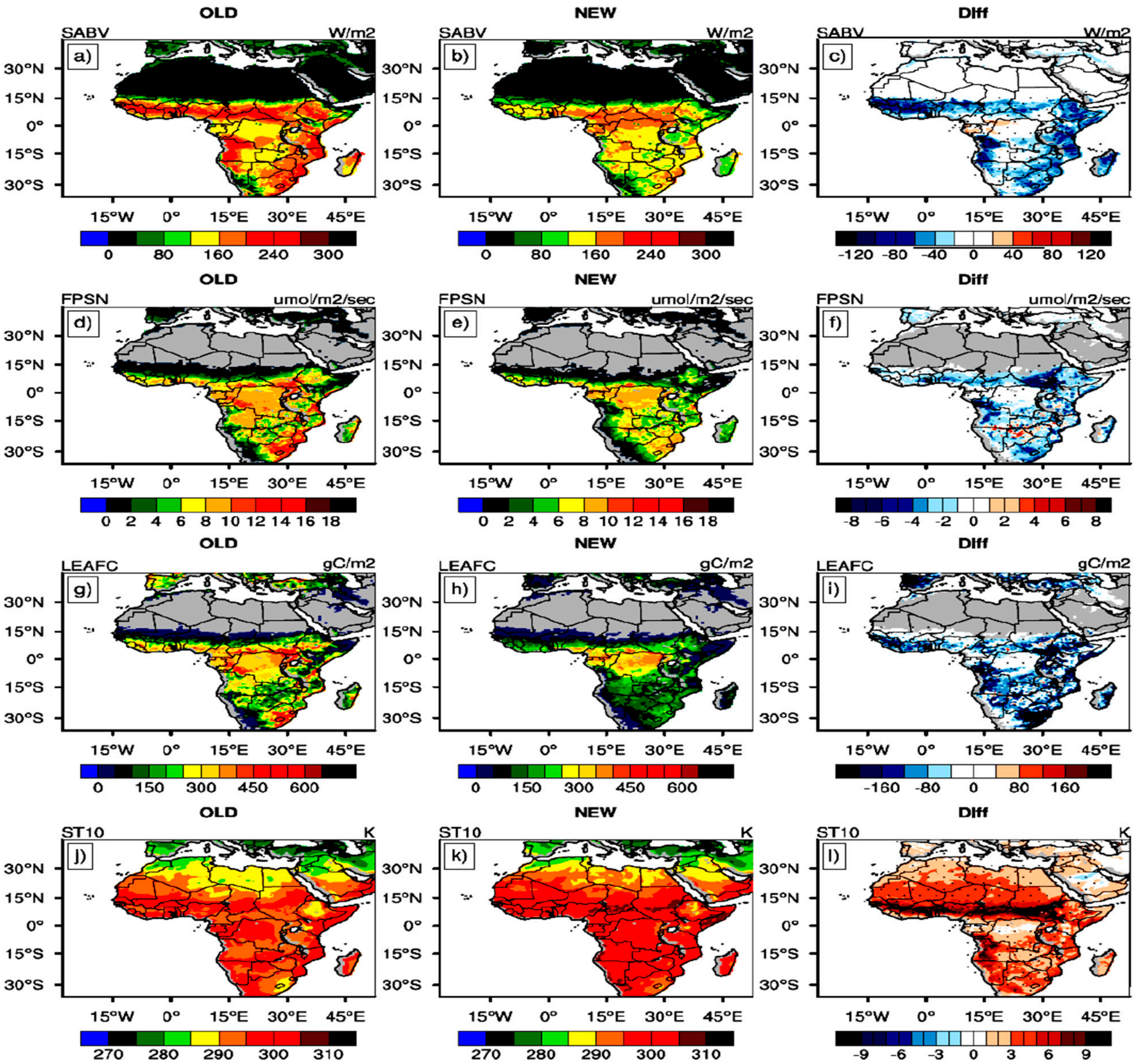

Figure 2. The figure shows the spatial pattern of the solar radiation absorbed by the vegetation (SABV; in W m^{-2}; (**a**–**c**)), photosynthesis rate (FPSN; in μmol m^{-2} s^{-1}; (**d**–**f**)), leaf carbon (LEAFC; in gC m^{-2}; (**g**–**i**)) and soil temperature of depth 10 cm (ST10; in K; (**j**–**l**)) over the period of 2001–2010 for the LAIorg (OLD) and LAImod (NEW) simulations and the significant difference (Diff) between the two simulations. The significant difference was calculated using Student's *t*-test with $\alpha = 0.05$.

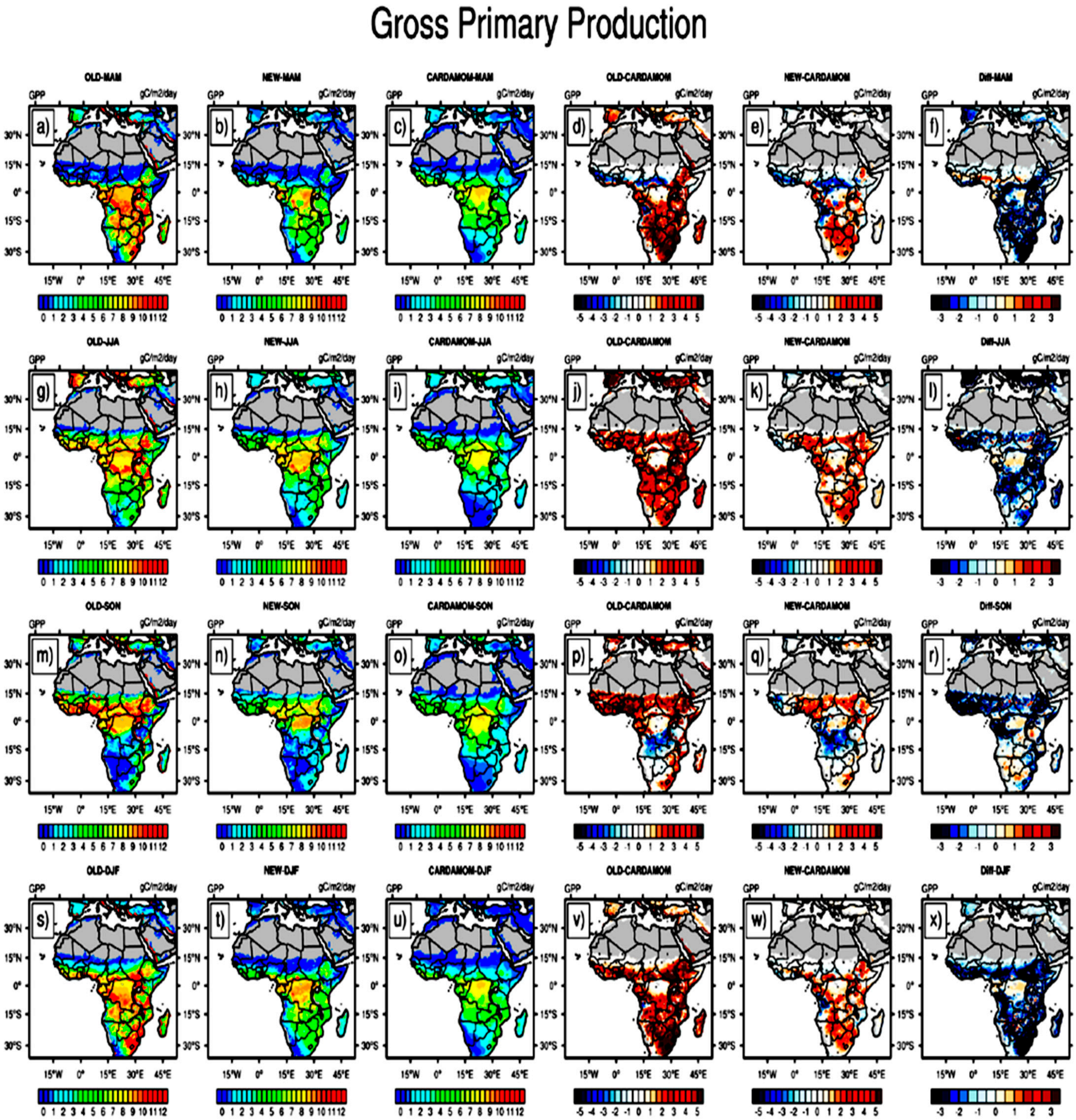

Figure 3. The figure shows the gross primary production (GPP) over the period of 2001–2010 (in gC m^{-2} day^{-1}) for: MAM season in the first row (**a**–**f**); JJA in the second (**g**–**l**); SON in the third (**m**–**r**), DJF in the fourth (**s**–**x**). For each row, LAIorg (OLD) is on the left, followed by LAImod (NEW); CARDAMOM is in the third from left, OLD minus CARDAMOM, NEW minus CARDAMOM and the difference between NEW and OLD. Significant model bias is indicated in black dots using Student's *t*-test with $\alpha = 0.05$.

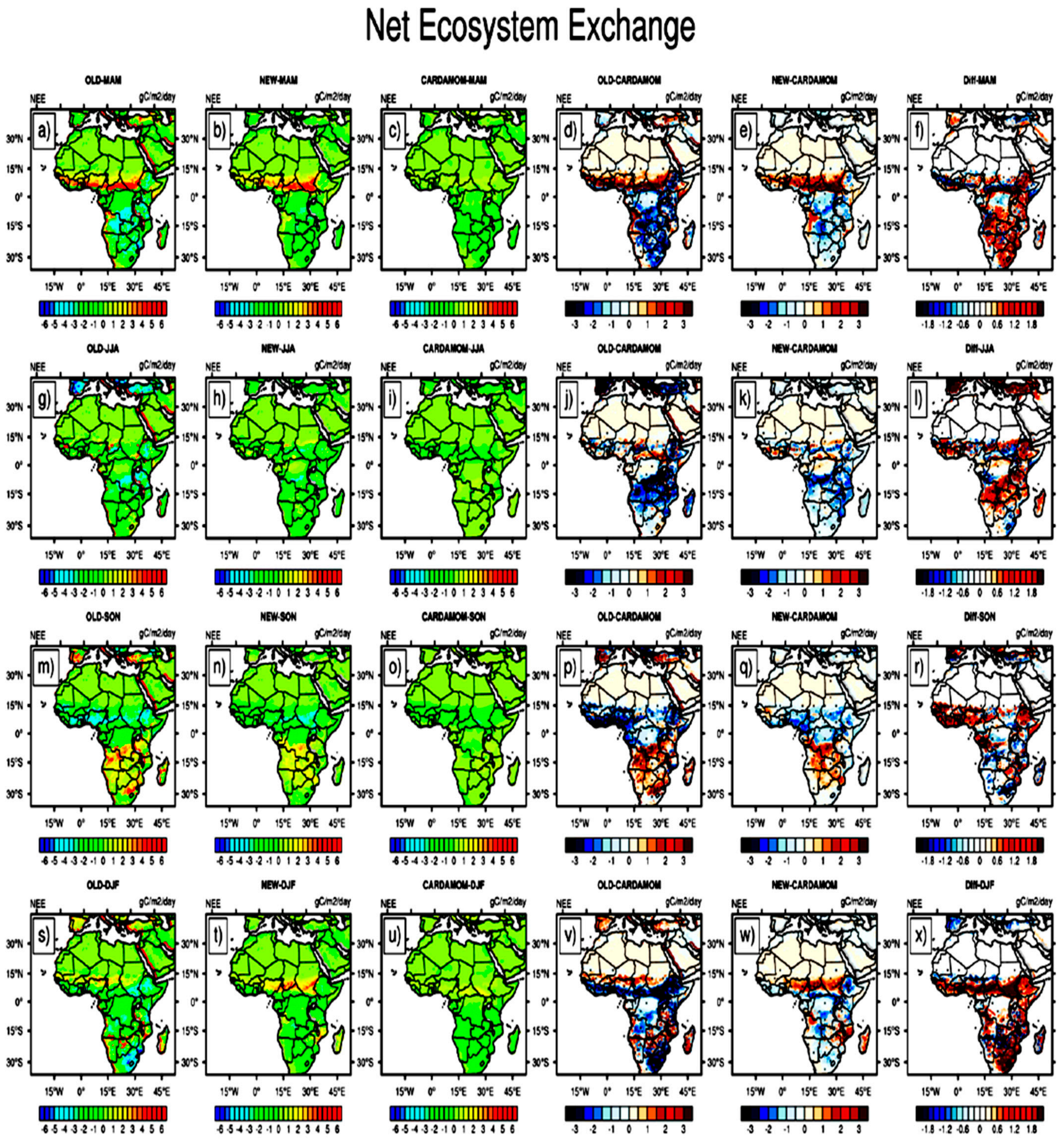

Figure 4. The figure shows the Net Ecosystem Exchange (NEE) over the period of 2001–2010 (in gC m^{-2} day^{-1}) for: MAM season in the first row (**a**–**f**); JJA in the second (**g**–**l**); SON in the third (**m**–**r**), DJF in the fourth (**s**–**x**). For each row, LAIorg (OLD) is on the left, followed by LAImod (NEW); CARDAMOM is in the third from left, OLD minus CARDAMOM, NEW minus CARDAMOM and the difference between NEW and OLD. Significant model bias is indicated in black dots using Student's *t*-test with α = 0.05.

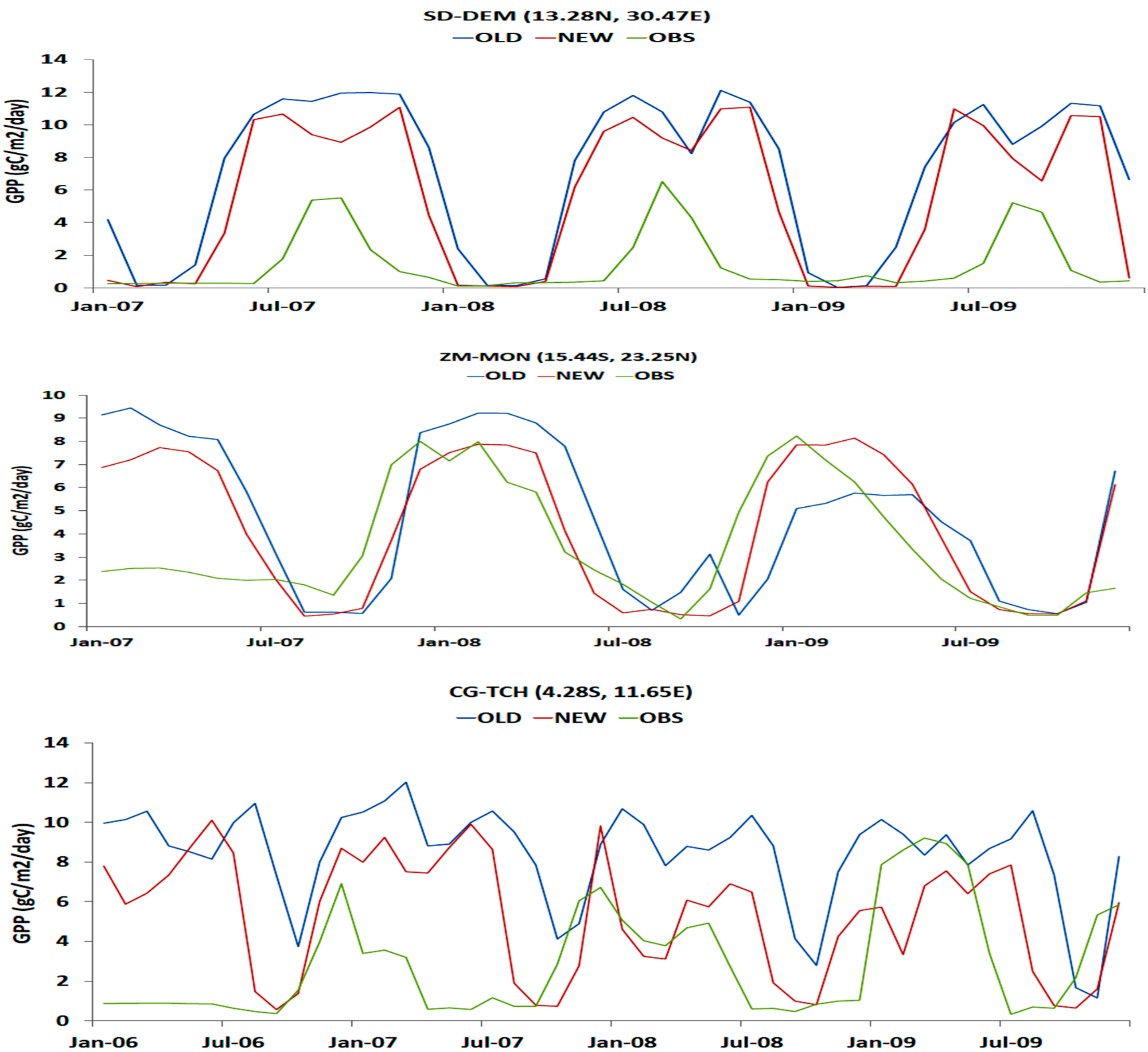

Figure 5. The figure shows the monthly mean GPP (in gC m^{-2} day^{-1}) for the LAIorg (OLD; in blue), LAImod (NEW; in red) and Fluxnet observation (in green) for the locations: SD-DEM (**first row**), ZM-MON (**second row**) and CG-TCH (**third row**).

4. Discussion

Vegetation cover changes (as represented by LAI) play an essential role in simulating Africa's regional surface climate and the terrestrial carbon cycle. Regarding the surface climate, this role has been extensively covered in previous studies (e.g., [3,4,6]) using a coupled regional climate–vegetation model. Concerning the terrestrial carbon fluxes, ref. [4] also used a regional coupled climate–dynamic vegetation model to examine the influence of the modified GPP parameterization on the simulated GPP with respect to MTE using different physical configurations. In addition, ref. [17] examined the role of vegetation cover and soil moisture changes in simulating GPP and observed that GPP is more sensitive to vegetation–soil-moisture-coupled systems than when only vegetation cover changes are considered.

Moreover, ref. [6] reported that the LAImod improves the simulated surface energy balance and surface climate compared to the LAIorg formula against reanalysis products. Recently, RegCM4 has been upgraded to work as an Earth system model ([18]). Therefore, optimizing the RegCM4 performance concerning the terrestrial carbon fluxes is important. In the present study, the influence of LAI parameterization on the terrestrial carbon fluxes of Africa was examined by conducting two 13-year simulations using the RegCM4 model. The results are summarized in the following points:

1. Compared with the MODIS, LAImod succeeds in alleviating the LAI bias relative to the LAIorg, particularly in JJA and SON.
2. LAImod reduces the SABV, FPSN and LEAFC and increases ST10 relative to LAIorg.
3. LAImod improves the simulated GPP and NEE bias concerning the CARDAMOM product. Additionally, LAImod improves the simulated HR with respect to the CARDAMOM product over the Savanna regions but not over the Congo basin.
4. Concerning the Fluxnet observation, the RegCM4 model performance varies with respect to the location. Yet, LAImod shows better performance than LAIorg.

5. Conclusions

In the present study, a new LAI formula (based on the BIOME-BGC ecosystem model) was implemented in the RegCM4 model. Then, two 13-year simulations (LAIorg and LAImod) were conducted to examine the potential influence of the vegetation cover changes (represented by LAI) on the terrestrial carbon fluxes of Africa. The results were compared with a reanalysis product and Fluxnet measurements. The results showed that switching between the two LAI formulas led to a notable influence on the ecological indicators as well as the terrestrial carbon fluxes. Furthermore, LAImod outperforms the LAIorg in simulating the LAI and terrestrial carbon fluxes with respect to observational-based datasets. Compared with the results reported by [3,4], LAImod reduces the LAI and GPP bias concerning reanalysis/satellite products. Additionally, ref. [19] tested the new modifications (implemented in the CLM45 land surface model) on LAI, GPP, Evapotranspiration (ET) and biomass. However, the influence on the other terrestrial carbon fluxes was not discussed.

The present study gives a first insight into the simulated LAI and the terrestrial carbon fluxes with respect to reanalysis/satellite products and Fluxnet measurements. Moreover, it can be noted that LAI parameterization has a notable influence on the ecological indicators which can explain the documented biases of the terrestrial carbon fluxes. In addition, the RegCM4 source bias can be attributed to the following reasons: (1) RegCM4 physical parameterization, (2) uncertainty associated with the lateral and initial boundary condition, (3) uncertainty associated with the CARDAMOM reanalysis product ([20]) and Fluxnet measurements ([14]) and (4) the representation of LAI and terrestrial carbon fluxes in the CN module. Nevertheless, the LAImod shows the improved performance of the RegCM4 compared to the CARDAMOM reanalysis product and Fluxnet measurements. A future study will consider the following points:

1. Using a nitrogen plant model of [19] to simulate the GPP and other terrestrial carbon fluxes realistically.
2. Examining the influence of various environmental factors affecting the simulated terrestrial carbon fluxes as in [17].
3. Using the Variable Infiltration Capacity (VIC) as a land–surface hydrology scheme and dynamic vegetation (DV) with the new LAI parameterization [6].
4. Addressing the RegCM4 sensitivity to climate forcing as in [10].

Author Contributions: Conceptualization, S.A.A.; methodology S.A.A.; software, S.A.A.; validation, S.A.A.; formal analysis, S.A.A. and Y.K.; investigation, S.A.A.; resources, S.A.A.; data curation, S.A.A.; writing—original draft preparation, S.A.A. and Y.K.; writing—review and editing, S.A.A. and Y.K. All authors have read and agreed to the published version of the manuscript.

Funding: No fund received for this study.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The OFID-ICTP is acknowledged for supporting the funding of the STEP program in the ICTP institute. Additionally, the ESP team climate group is acknowledged for providing the RegCM model code, computational facilities and input data to run the model. An-thony Bloom and Jean-François Exbrayat are recognized for providing the CARDA-MOM dataset. The National Center for Atmospheric Research institute is acknowledged for providing the spin-up file. Fluxnet tower data of the monthly GPP were retrieved from (https://fluxnet.org/data/fluxnet2015-dataset; accessed on 1 March 2023). We would like to thank Shabnam Pourshirazi (Gorgan University of Agricultural Sciences & Natural Resources Gorgan; Iran) for improving the manuscript quality.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Shao, P.; Zeng, X.; Sakaguchi, K.; Monson, R.K.; Zeng, X. Terrestrial carbon cycle: Climate relations in eight CMIP5 earth system models. *J. Clim.* **2013**, *26*, 8744–8764. [CrossRef]
2. Stuart, S.F.; Matson, P.A.; Mooney, H.A. *Principles of Terrestrial Ecosystem Ecology*; QH541.C3595 © Springer-Verlag LAImod York, Inc.: New York, NY, USA, 2002.
3. Erfanian, A.; Wang, G.; Yu, M.; Anyah, R. Multi model ensemble simulations of present and future climates over West Africa: Impacts of vegetation dynamics. *J. Adv. Model. Earth Syst.* **2016**, *8*, 1411–1431. [CrossRef]
4. Wang, G.; Yu, M.; Pal, J.S.; Mei, R.; Bonan, G.B.; Levis, S.; Thornton, P.E. On the development of a coupled regional climate–vegetation model RCM–CLM–CN–DV and its validation in Tropical Africa. *Clim. Dyn.* **2016**, *46*, 515–539. [CrossRef]
5. Jung, M.; Reichstein, M.; Margolis, H.A.; Cescatti, A.; Richardson, A.D.; Arain, M.A.; Arneth, A.; Bernhofer, C.; Bonal, D.; Chen, J.; et al. Global patterns of land-atmosphere fluxes of carbon dioxide, latent heat, and sensible heat derived from eddy covariance, satellite, and meteorological observations. *J. Geophys. Res.* **2010**, *116*, G00J07. [CrossRef]
6. Anwar, S.A.; Diallo, I. Modelling the Tropical African Climate using a state-of-the-art coupled regional climate-vegetation model. *Clim. Dyn.* **2022**, *58*, 97–113. [CrossRef]
7. Bonan, G.B.; Lawrence, P.J.; Oleson, K.W.; Levis, S.; Jung, M.; Reichstein, M.; Lawrence, D.M.; Swenson, S.C. Improving canopy processes in the Community Land Model (CLM4) using global flux fields empirically inferred from FLUXNET data. *J. Geophys. Res.* **2011**, *116*, G02014. [CrossRef]
8. Thornton, P.E.; Zimmermann, N.E. An Improved Canopy Integration Scheme for a Land Surface Model with Prognostic Canopy Structure. *J. Clim.* **2007**, *20*, 3902–3923. [CrossRef]
9. Yu, M.; Wang, G.; Pal, J.S. Effects of vegetation feedback on future climate change over West Africa. *Clim. Dyn.* **2016**, *46*, 3669–3688. [CrossRef]
10. Anwar, S.A.; Mamadou, O.; Diallo, I.; Sylla, M.B. On the Influence of Vegetation Cover Changes and Vegetation-Runoff Systems on the Simulated Summer Potential Evapotranspiration of Tropical Africa Using RegCM4. *Earth Syst. Environ.* **2021**, *5*, 883–897. [CrossRef]
11. Kanamitsu, M.; Ebisuzaki, W.; Woollen, J.; Yang, S.K.; Hnilo, J.J.; Fiorino, M.; Potter, G.L. NCEP-DOE AMIP-II Reanalysis (R-2). *Bull. Am. Meteorol. Soc.* **2002**, *83*, 1631–1643. [CrossRef]
12. Dee, D.P.; Uppala, S.M.; Simmons, A.J.; Berrisford, P.; Poli, P.; Kobayashi, S.; Andrae, U.; Balmaseda, M.A.; Balsamo, G.; Bauer, D.P.; et al. The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Q.J.R. Meteorol. Soc.* **2011**, *137*, 553–597. [CrossRef]
13. Bloom, A.A.; Exbrayat, J.F.; Ivar, R.; Feng, L.; Williams, M. The decadal state of the terrestrial carbon cycle: Global retrievals of terrestrial carbon allocation, pools and residence times. *Proc. Natl. Acad. Sci. USA* **2016**, *113*, 1285–1290. [CrossRef] [PubMed]
14. Pastorello, G.; Trotta, C.; Canfora, E.; Chu, H.; Christianson, D.; Cheah, Y.W.; Poindexter, C.; Chen, J.; Elbashandy, A.; Humphrey, M.; et al. The FLUXNET2015 dataset and the ONE Flux processing pipeline for eddy covariance data. *Sci. Data* **2020**, *7*, 225. [CrossRef] [PubMed]
15. Ardö, J.; Mölder, M.; El-Tahir, B.A.; Elkhidir, H.A.M. Seasonal variation of carbon fluxes in a sparse savanna in semi arid Sudan. *Carbon Balance Manag.* **2008**, *3*, 7. [CrossRef] [PubMed]
16. Merbold, L.; Ardö, J.; Arneth, A.; Scholes, R.J.; Nouvellon, Y.; De Grandcourt, A.; Archibald, S.; Bonnefond, J.M.; Boulain, N.; Brueggemann, N.; et al. Precipitation as driver of carbon fluxes in 11 African ecosystems. *Biogeosciences* **2009**, *6*, 1027–1041. [CrossRef]
17. Anwar, S.A.; Diallo, I. A RCM investigation of the influence of vegetation status and runoff scheme on the summer Gross Primary Production of Tropical Africa. *Theor. Appl. Climatol.* **2021**, *145*, 1407–1420. [CrossRef]
18. Reale, M.; Giorgi, F.; Solidoro, C.; Di Biagio, V.; Di Sante, F.; Mariotti, L.; Farneti, R.; Sannino, G. The regional Earth system Model RegCM-ES: Evaluation of the Mediterranean climate and marine biogeochemistry. *J. Adv. Model. Earth. Syst.* **2020**, *12*, e2019MS001812. [CrossRef]

19. Ghimire, B.; Riley, W.J.; Koven, C.D.; Mu, M.; Randerson, J.T. Representing leaf and root physiological traits in CLM improves global carbon and nitrogen cycling predictions. *J. Adv. Model. Earth Syst.* **2016**, *8*, 598–613. [CrossRef]
20. Green, J.K.; Konings, A.G.; Alemohammad, S.H.; Berry, J.; Entekhabi, D.; Kolassa, J.; Lee, J.E.; Gentine, P. Regionally strong feedbacks between the atmosphere and terrestrial biosphere. *Nat. Geosci.* **2017**, *10*, 410–414. [CrossRef] [PubMed]