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TOPIC

**Assessment of Current Climate Services for Energy Resilience
in West Africa: the Case of Senegal**

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DECLARATION

I, hereby declare that this thesis and the work presented within are entirely my original work. This thesis has not been submitted in whole or in part for any other degree or qualification at any other university or institution.

I further declare that all sources used and referenced in this thesis have been duly acknowledged. Any assistance received from individuals, organizations, or literature sources has been appropriately acknowledged and credited.

I affirm that any data, figures, or other materials presented in this thesis are accurate to the best of my knowledge.

A handwritten signature in blue ink, consisting of a stylized 'A' followed by a series of loops and a long horizontal stroke extending to the right.

Aissatou Ndiaye

05/02/2024

DEDICATION

This thesis is dedicated to my wonderful Mum Khodia Gueye and the loving memory of my late Dad Ousmane Ndiaye. Their sacrifices made for my education have been the driving force behind my academic achievements.

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Abstract

The rapid growth of renewable energy deployment in West Africa, coupled with the anticipated impacts of climate change on the energy sector, highlights the need to evaluate the effectiveness of climate services in enhancing energy resilience. Climate services (CS) play a crucial role in providing valuable information and insights to support decision-making and contribute to the resilience of the energy sector in the face of climate change impacts. This thesis investigated the performance of CS in the energy sector over West Africa with a focus on Senegal towards an improved resilience and sustainability of the energy sector to climate variability and change. A mixed-methods approach is employed which combines qualitative and quantitative analyses. The qualitative approach used is a semi-structured interview with key stakeholders in the energy and meteorological sectors to acquire a deeper understanding of how climate services are accessed and utilized. The quantitative analysis employs a dual approach which includes using data from regional climate models driven by global climate models to project the future climate change impacts on solar PV and wind energy potential in West Africa and Senegal, under RCP2.6 and RCP8.5. The other approach is to assess the impacts of different shortwave radiation schemes (Dudhia and RRTMG) in the WRF-Solar model for Global Horizontal Irradiance (GHI) forecasting in two solar plants in Senegal (Diass and Ten Merina). Two simulations were conducted for the RRTMG scheme, one without aerosol optical depth (AOD) and one with AOD (RRTMG_AOD). The results and outcomes respectively show limited collaboration between the energy and meteorological sectors, resulting in challenges in accessing essential climate-related information for decision-making processes. Projections from regional climate models show a general decline in solar PV potential by approximately -2% in the near future and -4% in the far future across the region. The wind power density (WPD) is anticipated to increase by around 20% in the near future and 40% in the far future. Furthermore, the findings reveal that the RRTMG_AERO scheme outperforms the Dudhia and RRTMG schemes in both solar plants. The RRTMG_AERO scheme demonstrates superior performance across clear sky, cloudy sky, and all-sky conditions, despite notable biases, particularly in cloudy sky conditions. This study offers valuable insights for policymakers, energy sector stakeholders, and meteorological agencies.

Keywords: renewable energy, climate service, climate change, West Africa, Senegal, WRF-Solar.

Résumé

La croissance rapide du déploiement des énergies renouvelables en Afrique de l'Ouest, associée aux impacts du changement climatique sur le secteur de l'énergie, met en évidence l'importance d'évaluer l'efficacité des services climatiques pour renforcer la résilience énergétique. Les services climatiques jouent un rôle crucial en fournissant des informations précieuses pour soutenir la prise de décision et contribuer à la résilience du secteur de l'énergie face aux impacts du changement climatique. Cette thèse vise à étudier la performance des services climatiques dans le secteur de l'énergie en Afrique de l'Ouest avec un accent sur le Sénégal vers une meilleure résilience et durabilité du secteur de l'énergie face à la variabilité et au changement climatique. Une approche à méthodes mixtes qui combine des analyses qualitatives et quantitatives est employée. L'approche qualitative utilisée est un entretien semi-structuré avec les principales parties prenantes des secteurs de l'énergie et de la météorologie pour recueillir des informations sur l'accessibilité et l'utilisation des services climatiques. L'analyse quantitative utilise une double approche qui comprend l'utilisation de données provenant de modèles climatiques régionaux pilotés par des modèles climatiques globaux pour projeter les impacts futurs du changement climatique sur le potentiel de l'énergie solaire photovoltaïque et éolienne en Afrique de l'Ouest et au Sénégal, dans le cadre des scénarios RCP2.6 et RCP8.5. L'autre approche consiste à évaluer les impacts de différents schémas de rayonnement à ondes courtes (Dudhia et RRTMG) dans le modèle WRF-Solar pour la prévision de l'irradiance horizontale globale dans deux centrales solaires au Sénégal (Diass et Ten Merina). Deux simulations sont réalisées pour le schéma RRTMG, une sans aérosol (AOD) et une avec aérosol (RRTMG_AOD). Les résultats montrent respectivement une collaboration limitée entre les secteurs de l'énergie et de la météorologie, ce qui entraîne des difficultés à accéder aux informations climatiques essentielles pour les processus décisionnels. Les projections des modèles climatiques régionaux montrent une baisse générale du potentiel solaire photovoltaïque d'environ 2 % dans un futur proche et de 4 % dans un futur lointain dans toute la région. Le potentiel éolien devrait augmenter d'environ 20 % dans un futur proche et de 40 % dans un futur lointain. De plus, les résultats révèlent que le schéma RRTMG_AERO surpasse les schémas Dudhia et RRTMG dans les deux centrales solaires. Le schéma RRTMG_AERO démontre des performances supérieures dans des conditions de ciel clair, de ciel nuageux et de ciel total, malgré des biais notables, en particulier dans des conditions de ciel nuageux. Cette étude

offre des informations précieuses aux décideurs politiques, aux acteurs du secteur de l'énergie et du secteur de la météorologie.

Mots clés: énergies renouvelables, service climatique, changement climatique, Afrique de l'Ouest, Sénégal, WRF-Solar.

Extended abstract

Renewable energy deployment is experiencing rapid growth and is anticipated to further expand in the coming decades across West Africa, serving as a vital response to meeting the region's power requirements and addressing the imperative of mitigating climate change. Conducting research on the future effects of climate change on the energy sector, particularly on renewable energy sources (RES) such as solar PV and wind, is imperative. There is a need to identify and develop strategies for adapting to and mitigating the potential impacts on these RES. CS are essential inputs for decision-makers in the energy industry, enhancing the resilience of the energy system to weather and climate variability and change. The impacts of climate change on the energy system have been discussed over the past decades, appropriate CS will help minimize the impacts by strengthening adaptive and resilience capacity in the energy sector. However, the accessibility of climate services to the energy sector in the West Africa region is limited. The energy industry often faces challenges in accessing the necessary climate-related information and services that are crucial for decision-making processes. This thesis aims to investigate the performance of the CS in the energy sector over West Africa with a focus on Senegal towards an improved resilience and sustainability of the energy sector to climate variability and change. An assessment of the current state of climate services for the energy sector in Senegal based on semi-structured interviews with actors was undertaken. The information is collected through a face-to-face interview which allows direct interaction with the experts. A total number of sixteen experts participated in this exercise and they are all working in the energy (thermal, solar, wind) and meteorological sectors. The study also explored the anticipated future effects of climate change on solar PV and wind energy potential across West Africa. This was accomplished using an ensemble of three regional climate models (RCMs), each driven by three global climate models (GCMs) from the new coordinated high-resolution output for regional evaluations (CORDEX-CORE) under the RCP2.6 and RCP8.5 scenarios. The study considered two projection periods: the near future (2021–2050) and the far future (2071–2100). To assess the models, reanalysis data from ERA5 and satellite-based climate data (SARAH-2) were used. Along the same line, the future of renewable energy production (mainly solar) in Senegal was investigated on the horizon of 2050. The RegCM4, model, driven by GCMs (NorESM1-M, MPI-ESM-MR, and HadGEM2-ES) from CORDEX-CORE simulation

data was used for the projection of energy production. The simulation period spanned from 1975 to 2050, with the reference period being 1975 to 2004 and the future period extending from 2005 to 2050 under the RCP8.5 scenario. In addition, the study investigated the impacts of two different shortwave radiation schemes (Dudhia and the Rapid Radiative Transfer Model for GCM (RRTMG)) in the Weather and Research Forecasting for solar energy applications (WRF-Solar) model for GHI forecasting in two solar plants in Senegal (Diass and Ten Merina). For the RRTMG scheme, two simulations were carried out: one without aerosol optical depth (AOD) and one with AOD (RRTMG_AOD). ERA5 reanalysis data was used as the initial and lateral boundary conditions. The modelling approach used, involved implementing a one-way two nested domain, with the outer domain over West Africa (D1) having a spatial resolution of 15 km, while the inner domain (D2) focusing on Senegal had a higher resolution of 3 km. The study period spans the entire year of 2020.

The following results were obtained:

- i. The interview exposes a lack of collaboration between the sectors. Experts interviewed unanimously expressed concerns regarding limited access to climate data and the underutilization of climate services in decision-making processes. A need for exchange between the meteorological office on the one hand and the energy sector on the other hand is identified. It also emerged from the interview, the willingness of most of the participants from the energy sector to receive tailored climate services from the meteorological office.
- ii. Moreover, the findings show that the models and their ensemble mean demonstrate acceptable performance in simulating the solar PV potential, wind power density (WPD), and related variables with some biases. The ensemble mean predicts a general decline in the solar PV potential across the region, approximately -2% in the near future and -4% in the far future. These changes appear to be consistent although the intensity varies depending on the specific RCM used. WPD is projected to increase by around 20% in the near future and 40% in the far future. However, there are disparities among the RCMs in terms of both intensity and direction.
- iii. The projection of the solar energy production of the solar plants in Senegal shows a slight decrease on the horizon of 2050 with Malicounda, Sakal, and Mekhe experiencing the highest decrease.

- iv. The results also highlight that the RRTMG_AERO performs well in both solar plants compared to Dudhia and RRTMG schemes. The RRTMG_AERO scheme demonstrates superior performance under the clear sky, cloudy sky, and all-sky conditions even though there are significant biases, particularly under cloudy sky conditions. While the RRTMG_AERO scheme demonstrates superior performance overall, there is still room for improvement in accurately capturing irradiance under cloudy conditions including the improvement of aerosol-cloud-radiation feedback. Also, the findings suggest that the inclusion of a shallow convection scheme in the simulations does not have a significant impact on the estimation of GHI in Senegal across the different shortwave radiation schemes used under clear skies and all skies. However, there are some differences under cloudy skies in Ten Merina. Considering the specific location of Senegal, it is advisable to deactivate the shallow convection scheme and instead run the model in convective permitting mode.

These findings provide valuable insights for policymakers and decision-makers in the energy sector, offering guidance for future renewable energy projects and the development and accessibility of climate services tailored to the sector's needs. They also underscore the performance and limitations of WRF-Solar in estimating GHI for solar energy applications in Senegal. Implementing these recommendations, including strengthening collaboration and adopting appropriate modelling approaches, can contribute to the sustainable growth of renewable energy and enhance climate resilience in West Africa.

Keywords: renewable energy, climate service, climate change, West Africa, Senegal, WRF-Solar.

Résumé étendu

Le déploiement des énergies renouvelables connaît une croissance rapide et devrait se développer au cours des prochaines décennies en Afrique de l'Ouest, servant de réponse vitale pour répondre aux besoins énergétiques de la région et répondre à l'impératif d'atténuation du changement climatique. Il est impératif de mener des recherches sur les effets futurs du changement climatique sur le secteur de l'énergie, en particulier sur les sources d'énergies renouvelables comme le solaire photovoltaïque et l'éolien. Il est nécessaire d'identifier et de développer des stratégies d'adaptation et d'atténuation des impacts potentiels sur ces sources d'énergie renouvelable. Les services climatiques sont des intrants essentiels pour les décideurs du secteur de l'énergie afin d'améliorer la résilience du système énergétique face aux conditions météorologiques et à la variabilité et au changement climatiques. Les impacts du changement climatique sur le système énergétique ont été discutés au cours des dernières décennies, des services climatiques appropriés aideront à minimiser les impacts en renforçant la capacité d'adaptation et de résilience dans le secteur de l'énergie. Cependant, l'accessibilité des services climatiques au secteur de l'énergie dans notre région d'Afrique de l'Ouest est limitée. Le secteur de l'énergie est souvent confronté à des difficultés pour accéder aux informations et services climatiques nécessaires qui sont cruciaux pour les processus de prise de décision. Cette thèse vise à étudier la performance des services climatiques dans le secteur de l'énergie en Afrique de l'Ouest avec un accent sur le Sénégal vers une meilleure résilience et durabilité du secteur de l'énergie face à la variabilité et au changement climatique. Une évaluation de l'état actuel des services climatiques pour le secteur de l'énergie au Sénégal sur la base d'entretiens semi-structurés est réalisée. Les informations sont recueillies par le biais d'un entretien en face à face qui permet une interaction directe avec les experts. Au total, seize (16) experts ont participé, travaillant tous dans les secteurs de l'énergie (thermique, solaire, éolien) et de la météorologie. L'étude examine également les impacts futurs attendus du changement climatique sur le potentiel de l'énergie solaire photovoltaïque et éolienne en Afrique de l'Ouest en utilisant un ensemble de trois modèles climatiques régionaux (MCR). Chaque MCR est guidée par trois modèles climatiques globaux (MCG) issus de la nouvelle sortie à haute résolution pour les évaluations régionales (CORDEX-CORE) dans le cadre des scénarios RCP2.6 et RCP8.5. Deux périodes de projection sont utilisées : le futur proche (2021-2050) et le futur lointain (2071-2100). Pour l'évaluation du modèle, les données de réanalyse de ERA5 et les

données climatiques satellitaires (SARAH-2) sont utilisées. Dans le même ordre d'idées, l'avenir de la production d'énergie renouvelable (principalement solaire) au Sénégal est étudié à l'horizon 2050. Les données de simulation CORDEX-CORE ont été utilisées pour la projection de la production d'énergie. RegCM4, piloté par des MCGs (NorESM1-M, MPI-ESM-MR et HadGEM2-ES) à partir des données de simulation CORDEX-CORE est utilisé pour la projection. La période de simulation s'étend de 1975 à 2050, dont la période 1975-2004 est prise comme référence et 2005-2050 comme le futur et sous le scénario RCP8.5. En outre, l'étude examine les impacts de deux différents schémas de rayonnement à ondes courtes (Dudhia et RRTMG) dans le modèle WRF-Solar pour la prévision de l'irradiance horizontale globale dans deux centrales solaires au Sénégal (Diass et Ten Merina). Pour le schéma RRTMG, deux simulations sont réalisées : une sans aérosol (AOD) et une avec aérosols (RRTMG_AOD). Les données de réanalyse ERA5 sont utilisées comme conditions initiales. Notre approche de modélisation a impliqué la mise en œuvre d'un domaine unidirectionnel à deux imbrications, où le domaine extérieur (D1) a une résolution spatiale de 15 km, tandis que le domaine intérieur (D2) centré sur le Sénégal a une résolution plus élevée de 3 km. La période d'étude comprend toute l'année 2020. Les résultats suivants ont été obtenus :

- i. Les résultats de l'entretien révèlent un manque de collaboration entre les secteurs. Les experts interrogés ont exprimé à l'unanimité leurs préoccupations concernant l'accès limité aux données climatiques et la sous-utilisation des services climatiques dans les processus décisionnels. Un besoin d'échange entre le bureau de la météorologie d'une part et le secteur de l'énergie d'autre part est identifié. Il est également ressorti de l'entretien la volonté de la plupart des participants du secteur de l'énergie de recevoir des services climatiques sur mesure de la part du service de la météorologie.
- ii. De plus, les résultats montrent que les modèles et leur moyenne d'ensemble présentent des performances acceptables pour les simulations du potentiel solaire PV, de la densité de puissance éolienne et des variables associées avec certains biais. La moyenne d'ensemble prédit une diminution générale du potentiel solaire PV sur la région d'environ -2 % dans un futur proche et de -4 % dans un futur lointain. La densité de l'énergie éolienne devrait augmenter d'environ 20 % dans un futur proche et de 40 % dans un futur lointain. Les changements pour le potentiel solaire photovoltaïque semblent cohérents, bien que l'intensité diffère selon le modèle régional utilisé. En ce qui concerne la densité de l'énergie

éolienne, il y a des divergences entre les modèles sur le plan de l'intensité et de l'orientation. La projection de la production d'énergie solaire des centrales solaires au Sénégal montre une légère baisse à l'horizon 2050 avec Malicounda, Sakal et Mekhe connaissant la plus forte baisse.

- iii. Les résultats soulignent également que le RRTMG_AERO a des performances meilleures dans les deux centrales solaires par rapport aux schémas Dudhia et RRTMG. Le schéma RRTMG_AERO démontre une performance supérieure dans des conditions de ciel clair, nuageux et tout-ciel, bien qu'il y ait des biais importants, en particulier dans des conditions de ciel nuageux. Bien que le schéma RRTMG_AERO démontre des performances globales supérieures, il est encore possible d'améliorer la précision de la prédiction de l'irradiance dans des conditions nuageuses, notamment l'amélioration de la rétroaction aérosol-nuage-rayonnement. De plus, nos résultats suggèrent que l'inclusion d'un schéma de convection peu profonde (shallow convection) dans les simulations n'a pas d'impact significatif sur l'estimation de l'irradiance solaire au Sénégal à travers les différents schémas de rayonnement à ondes courtes utilisés sous ciel clair et sous toutes les conditions du ciel. Cependant, il y a quelques différences sous un ciel nuageux à Ten Merina. Compte tenu de l'emplacement spécifique du Sénégal, il est conseillé de désactiver le schéma de convection peu profonde et d'exécuter plutôt le modèle en mode convectif. Cette recommandation repose sur le fait qu'avec une résolution de 3 km, le schéma microphysique du modèle peut simuler explicitement la convection sur la grille du modèle.

Ces résultats fournissent des informations précieuses aux responsables politiques et aux décideurs du secteur de l'énergie, offrant des orientations pour les futurs projets d'énergie renouvelable et le développement et l'accessibilité de services climatiques adaptés aux besoins du secteur. Ils soulignent également les performances et les limites de WRF-Solar dans l'estimation de l'irradiation solaire global pour les applications d'énergie solaire au Sénégal. La mise en œuvre de ces recommandations, y compris le renforcement de la collaboration et l'adoption d'approches de modélisation appropriées, peut contribuer à la croissance durable des énergies renouvelables et améliorer la résilience climatique en Afrique de l'Ouest.

Mots clés: énergies renouvelables, service climatique, changement climatique, Afrique de l'Ouest, Sénégal, WRF-Solar.

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List of Acronyms

AMS	American Meteorological Society
ANACIM	National Agency for Civil Aviation and Meteorology
ANER	National Agency for Renewable Energy
AOD	aerosol optical depth
ASER	Agency for Rural Electrification
BSRN	Baseline Surface Radiation Network
CAMS	Copernicus Atmosphere Monitoring Service datasets
CAQDAS	Computer Assisted Qualitative Data Analysis Software
CMIP5	Coupled Model Intercomparison Project 5
COGIC	Operational Center for Inter-ministerial Crisis Management
COMRECC	Regional Committee on Climate Change
CORDEX	Coordinated Regional Climate Downscaling experiment
CORE	Coordinated Output for Regional Evaluations
COSMO	Consortium for Small-scale Modelling
Covid-19	Coronavirus disease 2019
CS	climate service
CSP	Concentrating Solar Power
CWP	cloud water path
DIF	diffuse horizontal irradiance
DJF	December January February
DNI	direct normal irradiance
DPC	directorate of civil protection
EIA	Energy Information Administration
ECMWF	European Centre for Medium-Range Weather Forecasts
ERA5	Fifth major global reanalysis produced by ECMWF
EOT	equation of time
EWS	Early Warning System
FARMS	Fast All-sky Radiation Model for Solar Applications

FPAR	Fraction of Photosynthetically Active Radiation
GCM	global climate model
GERICS	Climate Service Center Germany
GFCS	Global Framework for Climate Services
GHG	greenhouse gases
GHI	Global Horizontal Irradiance
GTP	Multidisciplinary Working Group
ICTP	Abdus Salam International Centre for Theoretical Physics
IEA	International Energy Agency
ILBC	initial and lateral boundary conditions
IOA	index of agreement
IPCC	Intergovernmental Panel on Climate Change
IPP	Independent Power Producers
IRENA	International Renewable Energy Agency
ITCZ	Intertropical Convergence Zone
JJA	June July August
Kt	clearness index
LSM	Land Surface Model
MAE	mean absolute error
MAM	March April May
MVIRI	Meteosat Visible and InfraRed Imager
MYNN	Mellor-Yamada-Nakanishi-Niino
NAP	national adaptation plan
NCAR	National Center for Atmospheric Research
NDC	Nationally Determined Contribution
NFCS	National Frameworks for Climate Services
NMHS	National Meteorological and Hydrological Services
NOCT	nominal operating cell temperature
NWP	Numerical Weather Prediction
PBL	Planetary Boundary Layer
PV	photovoltaic

PVGIS	Photovoltaic Geographical Information System
RCM	regional climate model
RCP	Representative Concentration Pathway
RES	Renewable Energy Sources
RMSE	root mean square error
RRTMG	Rapid Radiative Transfer Model for GCM
SARAH-2	Surface Solar Radiation Data Set – Heliosat Edition 2
SENELEC	Senegal National Electricity Company
SEVIRI	Spinning Enhanced Visible and Infrared Imager
SMS	short message service
SON	September October November
SSA	Sub-Saharan Africa
STC	Standard Test Conditions
SZA	Solar Zenith Angle
UTC	Universal Time Coordinated
WCC	World Climate Conference
WCRP	World Climate Research Program
WEMC	World Energy & Meteorology Council
WEO	World Energy Outlook 2022
WMO	World Meteorological Organization
WPD	wind power density
WPS	WRF preprocessing system
WRF-Solar	Weather and Research Forecasting for solar energy applications

Chapter 1: Introduction

1.1 Background

In an era marked by pressing environmental concerns and the need for sustainable development, the global community has embarked on a monumental journey toward a clean energy transition. Renewable energy technologies, electrification, and energy efficiency stand as the primary pillars of the energy transition (IRENA, 2021). In 2050, over 90% of the solutions involve renewable energy, encompassing direct supply, electrification, energy efficiency, green hydrogen, and bioenergy with carbon capture and storage (IRENA, 2021). The rapid decline in costs and increasing competitiveness, notably in solar photovoltaics (PV) and wind power, has resulted in significant additions to the installed capacity of renewable energy. *Figure 1.1* is a perfect illustration of the increase in global renewable energy capacity. The levelized cost of electricity from solar PV has experienced a 73% reduction between 2010 and 2017, while electricity from onshore wind has seen a 23% decrease (Gielen et al., 2019). In 2017, a quarter of global electricity was generated from renewable energy (RE). Nevertheless, to achieve energy sector decarbonization, the proportion of renewables in power generation would need to rise significantly from approximately one-quarter in 2015 to about 60% by 2030 and 85% by 2050 (Gielen et al., 2019).

This transition not only promises a healthier planet but also holds significant implications for regional energy security and economic prosperity. According to the African Union Agenda 2063, the expansion of Africa's energy systems should rely on renewable and clean energy sources, to guarantee energy security and promote decarbonization. In 2021, approximately 43% of the population in Africa, equivalent to around 600 million people, still lacked access to electricity. The majority, around 590 million were in sub-Saharan Africa (IEA, 2022). Zooming in on the dynamic landscape of West Africa, one can witness a region ready to seize the vast potential of clean energy. The region already made significant steps in RE development. Senegal, for instance, has made significant progress in renewable energy development. The country's renewable energy capacity has increased with the construction of several solar plants, such as Ten Merina, Mekhe, Sakal, Kahone, Malicounda, Bokhol, etc., and a wind farm (*Figure 1.2*). The government has also implemented policies and incentives to attract investment in renewable energy. These projects have contributed to expanding energy production and improving access to electricity.

However, the transition to renewable energy also involves a more dependent energy sector on weather and climate. Atmospheric variability has a substantial impact on the energy sector, given that both energy demand and supply depend on atmospheric conditions across various time scales. This ranges from small-scale fluctuations to day-ahead weather predictions and seasonal anomalies and extends to the broader impacts of climate change (Dubus et al., 2018). Seasonal or multiannual climate oscillations, along with long-term trends, significantly impact the generation of renewable energy from solar and wind power installations (Lledó et al., 2018). To effectively plan and manage the transition to high shares of renewable energy generation, it is crucial to gain a comprehensive understanding of this variability and its impacts on the power system (Staffell and Pfenninger, 2018). It is critical to consider the potential impacts of climate change and develop strategies to enhance its resilience and sustainability. Understanding the risks and vulnerabilities associated with climate change is a key factor in enhancing the resilience and sustainability of the energy sector. Many studies have addressed the impacts of climate change on the energy sector (e.g., Pryor and Barthelmie, 2010; Gaetani et al., 2014; Fant et al., 2016; Huber et al., 2016; Troccoli, 2018; Müller et al., 2019; Soares et al., 2019; Sawadogo et al., 2021; Ogunjobi et al., 2022; Danso et al., 2022; Ndiaye et al., 2022). Considering the range of weather and climate conditions that affect both wind and solar power generation is crucial (Staffell and Pfenninger, 2018). The efficient planning, management, and operation of energy services across diverse spatial and temporal scales require the use of weather and climate services.

Over the last decade, efforts to produce and disseminate climate services have grown in terms of scale, diversity, complexity, and spread. Climate services have expanded in scale, with more regions and countries recognizing the importance of climate information for decision-making (Webber, 2019). National meteorological offices and climate agencies, research institutions, and international organizations have been actively involved in producing and disseminating climate services. The services encompass a wide range of sectors, including agriculture, water resources, disaster risk reduction, health, and energy. Nevertheless, in Senegal, the effectiveness of these services in meeting the needs of the energy sector is not well-known. The current climate services for the energy sector in Senegal may not be adequately tailored or optimized to address the weather and climate-related risks, highlighting a need for performance assessment and improvement.

On the other hand, these services are not always accessible to the users in our region. This is the case in many places around the world, including the majority of African countries. The

collection of climate data has been inadequate, and even when available, accessibility remains a significant challenge (Dinku, 2019). Many African countries face challenges due to a lack of access to climate information and services contextually relevant (Vogel et al., 2019). There is a need for concerted efforts to enhance the provision of climate information and services, along with the integration of climate considerations into development practices (Dinku, 2019). By providing relevant information, climate services contribute to building resilience, enhancing adaptive capacity, and supporting sustainable development in various sectors including the energy sector. Numerical Weather Prediction (NWP) models such as The Weather Research and Forecasting for solar energy applications (WRF-Solar) model can contribute to certain aspects of climate services, particularly in terms of providing short-term weather forecasts and data for specific locations, especially for solar energy. WRF-Solar facilitates the generation of high-frequency irradiance output and provides diagnostic information on radiation-related variables crucial for the solar industry. These include Global Horizontal Irradiance (GHI), Direct Normal Irradiance (DNI), and Diffuse Horizontal Irradiance (DIF) (Liu et al., 2022).

Thus, this thesis can provide insights into the current status and effectiveness of climate services in Senegal, which is essential for improving the resilience and sustainability of the energy sector. In addition, it will examine the risks of climate change to the energy sector in West Africa and Senegal and evaluate the effectiveness of the WRF-solar model in providing solar irradiance forecasting as a climate service for the energy sector in Senegal.

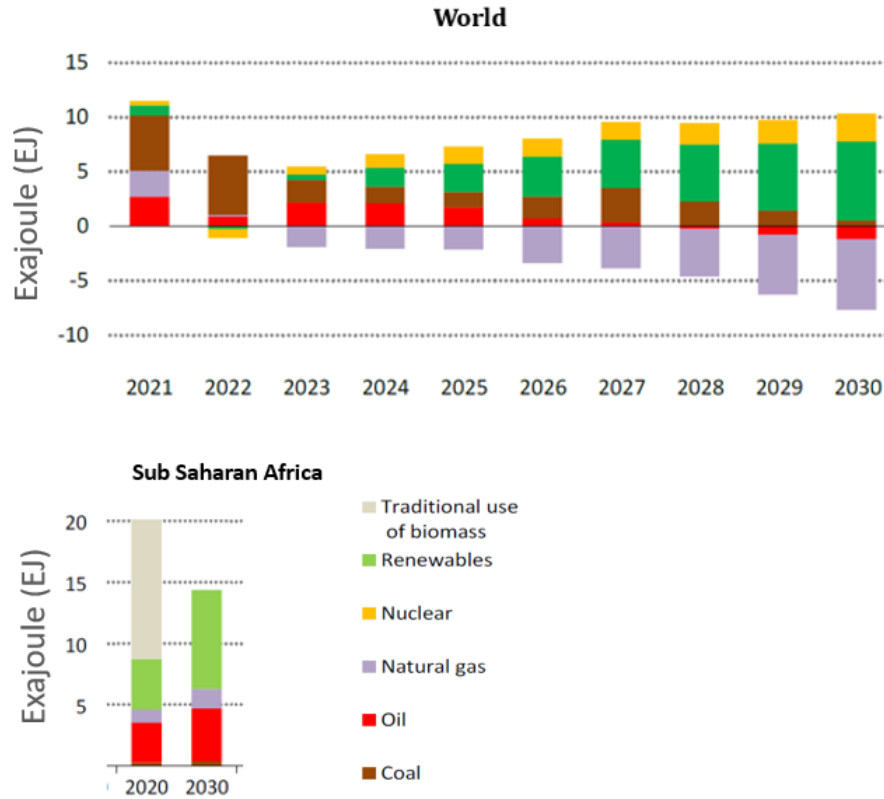


Figure 1.1 Total primary energy supply by fuel. Notes: Positive numbers in the world figure indicate total energy supply is higher in the World Energy Outlook 2022 (WEO) than in the WEO-2021 (IEA, 2022).

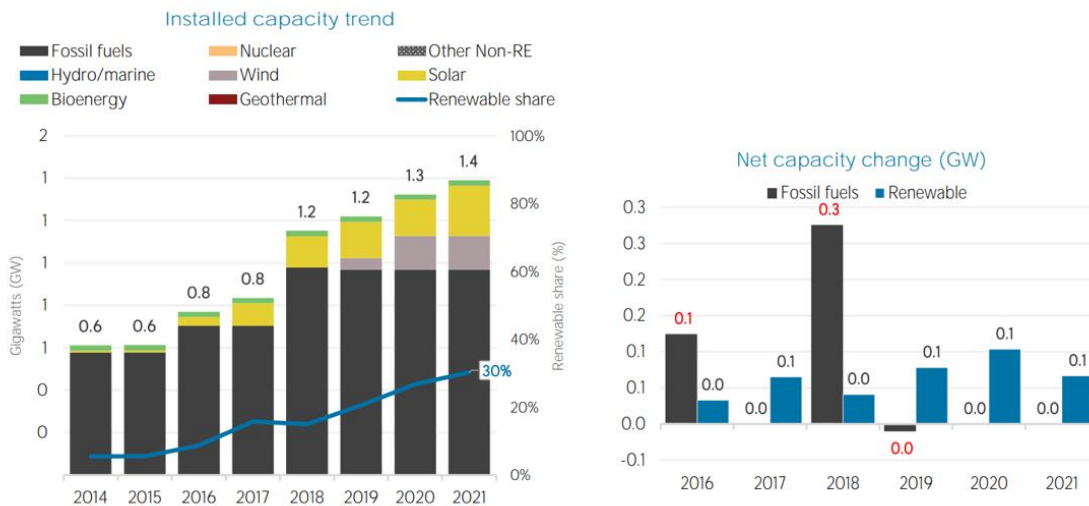


Figure 1.2 Senegal's installed capacity trend (2014-2021) and net capacity change (2016-2021) between the fossils and the renewables (IRENA, 2021).

1.1.1 What are climate services?

With the impacts of climate variability and change coupled with climate-related extreme events recurring frequently nowadays, the need for climate adaptation is apparent. Climate services are developed to reduce climate impacts and help adapt to climate change by addressing user needs (Figure 1.3). There are many definitions of climate services. Besides the definition of Tall et al. (2018) mentioned earlier, the American Meteorological Society (AMS) defines it as “scientifically based information and products that enhance user’s knowledge and understanding about the impacts of climate on their decisions and actions. These services are made most effective through collaboration between providers and users.” It encompasses the generation, delivery, and contextualization of information and knowledge derived from climate research, tailored for decision-making at various levels of society. The definition of climate services as given by the World Meteorological Organization (WMO) is “providing climate information in a way that assists decision-making by individuals and organizations”. The goal of climate services is to provide individuals and organizations with timely and customized climate-related knowledge and information, empowering them to mitigate climate-related losses (Vaughan and Dessai, 2014). A thorough comprehension of the users and their climate information requirements is crucial for developing climate science that is both useful and usable. In a broader context, this understanding is vital for the development of effective climate services that cater to real-world decision-making. (Bruno et al., 2017).

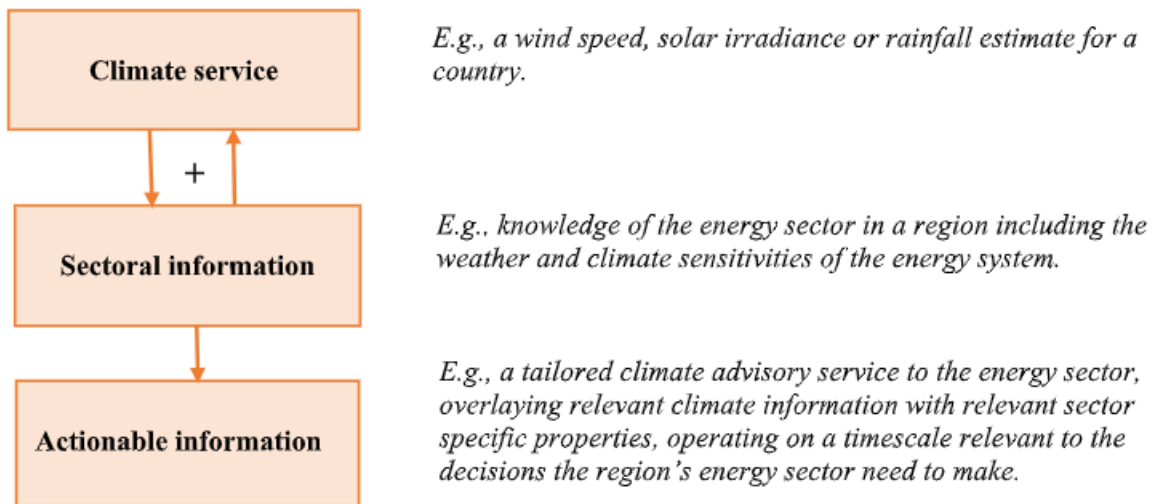


Figure 1.3 Climate service definition (David Brayshaw, 2021)

1.1.2 What are the Global Framework for Climate Services and the National Framework for Climate Services?

In 2009, the Third World Climate Conference (WCC 3) endorsed the concept of a Global Framework for Climate Services (GFCS). This initiative aimed to enhance the production, availability, delivery, and application of science-based climate predictions and services, with a particular focus on supporting developing countries. In the years following WCC-3 and following its implementation in 2012, the governments committed to establishing National Frameworks for Climate Services at the country level (Vaughan and Dessai, 2014). GFCS refers to the structures and systems in place to provide accurate and relevant information about the climate to decision-makers and the public. This can include weather forecasting, monitoring of climate data, and the development of climate models. The goal of GFCS is to support the sustainable development and adaptive capacity of communities and economies by providing them with the information they need to respond to the impacts of climate change.

GFCS is an international initiative spearheaded by the WMO. Its objective is to bolster countries and their National Meteorological and Hydrological Services (NMHS) by improving their capacity to generate, customize, communicate, and use improved weather, climate, water, and related environmental information, predictions, and advisory products and services to support effective climate risk management, including the development of adaptation strategies, decision-making, and actionable measures (Request for Project Mapping Data from GFCS Partners, 2016). It has five priority areas and is made of five pillars, namely, the user interface platform, observation and monitoring, capacity building, climate services information system and research, modelling, and prediction (*Figure 1.4*). The priority areas are health, agriculture and food security, water resources, disaster risk reduction, and energy.

The regional approach is complemented by national initiatives to develop climate-responsive solutions at the national level to address national needs and implement National Frameworks for Climate Services (NFCS), strengthening the capability of NHMSs to service sectorial user needs (Request for Project Mapping Data from GFCS Partners, 2016). While some countries have successfully implemented effective climate services, the majority of governments, communities, and business sectors worldwide, especially in 70 of the most vulnerable and least-developed countries, still lack access to climate information and forecasts that are both scientifically credible and usable (WMO-GFCS, 2016).

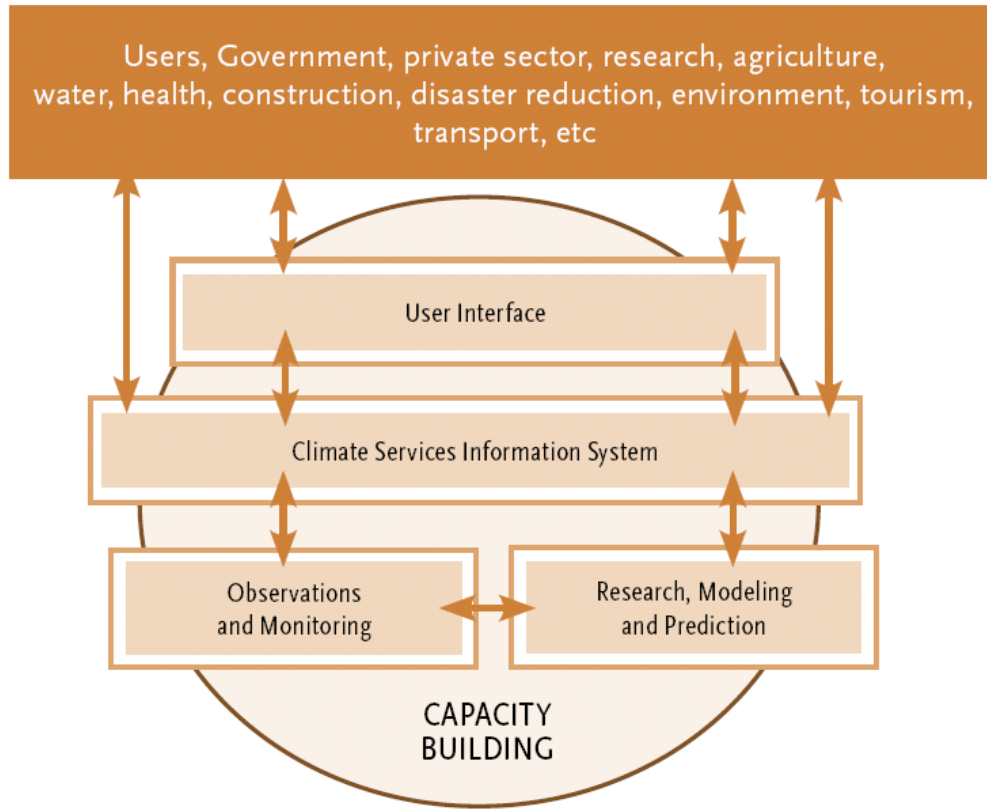


Figure 1.4 The five pillars of the GFCS (WMO-GFCS, 2016)

1.2 Problem statement and objectives

The Intergovernmental Panel on Climate Change (IPCC) has identified Africa as one of the most vulnerable continents to climate change. This vulnerability is attributed to the continent's high exposure to climate stress and its comparatively low adaptive capacity (IPCC, 2014). In the latter half of the 20th century, most of Sub-Saharan Africa (SSA) witnessed upward trends in annual mean, maximum, and minimum temperatures across extensive areas of the sub-region. The most significant warming occurred during the last two decades of that period (Dinku et al., 2018). The changes are likely to affect the energy sector, especially the renewables, which are weather and climate dependent. The components of the energy system are impacted by climate change through long-term alterations in climate parameters, variability, and the occurrence of extreme weather events (Field et al., 2014). There is an increasing acknowledgment that substantial investments in weather and climate services are imperative to strengthen adaptive capacity and effectively manage climate-related risks (Hansen and al., 2014; WMO, 2014). A service necessitates appropriate engagement, coupled with an effective access mechanism, and must

address user needs.

With the management of climate change impacts, adaptation, and resilience, climate services have received much more attention in recent years. The interest in climate services has increased, especially with the increased attention to and improved quality of available information about the climate system (Giannini et al., 2016; Vaughan and Dessai, 2014; Visbeck, 2008; Vaughan et al., 2016). Over the last decade, there has been a rapid growth in interest in developing climate services for various users, driven by improved forecasting capabilities since the 1997/98 El Nino event (Vaughan and Dessai, 2014). While there is increasing recognition that climate services play a crucial role in the climate adaptation agenda, there has been limited progress in providing evidence regarding the value added by tailored climate information in the hands of users. This is particularly relevant for the energy sector, where the impacts of climate change can have significant consequences.

In West Africa, especially in Senegal, there is little information about the nature of the relationship between climate services providers and users in the energy sector and the types of services that are being exchanged.

Nonetheless, the monitoring and evaluation of the value of specific services continue to be a significant challenge (Tall et al., 2018). Studies on the value of climate information and services have mainly focused on agriculture/farming in the past (Vasikalos, 2019).

This thesis aims to investigate the performance of the climate services in the energy sector over West Africa with a focus on Senegal towards an improved resilience and sustainability of the energy sector to climate variability and change. The specific objectives are the following: To

- 1) assess the level of performance/penetration of the current climate services for the energy sector in Senegal and explore possible improvement options;
- 2) address climate vulnerability for the energy sector resilience and sustainability:
 - a) assess the risks of climate change to the energy sector in West Africa and Senegal
- 3) evaluate the WRF-solar model for solar irradiance forecasting in Senegal.

1.3 Research Questions

The overarching research question is: How do climate services currently perform in providing information to the energy sector in Senegal, and how can this information be used to improve the resilience and sustainability of the energy sector in the face of climate variability and change?

Some specific research questions are:

- What is the current level of performance of climate services for the energy sector in Senegal, and what are the possible options for improving the effectiveness of these services to enhance the resilience and sustainability of the energy sector in the face of climate variability and change?
- How can climate vulnerability be effectively addressed? What are the specific risks and potential impacts of climate change on the energy sector especially the renewable in West Africa and Senegal, and how can these risks be mitigated to ensure the resilience and sustainability of the sector?
- How effective is the WRF-solar model for forecasting solar irradiance in Senegal, and how can this model be used as a climate service tool to enhance the performance and sustainability of the energy sector in the face of climate variability and change?

1.4 Significance and potential contributions of the study

The thesis can provide insights into the current status and effectiveness of climate services in Senegal, which is essential for improving the resilience and sustainability of the energy sector. It can also help identify the current gaps and opportunities for improvement in climate services for the energy sector. Another significance of this study is that it can help identify the key vulnerabilities and risks associated with climate change impacts on the energy sector in West Africa and Senegal, which is also essential for building resilience and sustainability in the face of these impacts. Also, this thesis has the potential to reveal significant insights regarding the potential of the WRF-solar model as a climate service tool for solar irradiance forecasting in Senegal, which is critical for the effective management and utilization of solar energy resources in the country.

The thesis can contribute to the development of strategies and policies that enhance the performance of climate services and the adaptive capacity and resilience of the energy sector in Senegal and West Africa. The study can make a valuable contribution to the development of tailored climate services and solutions that address the specific needs and challenges of the energy sector in Senegal, particularly in the context of climate change impacts. Overall, the results of this thesis can aid in developing customized and efficient climate services and solutions for Senegal's energy sector, with a specific focus on climate change effects.

1.5 Overview of the Structure of the Thesis

The thesis is organized into five main chapters. Chapter 1 provides an overview of the research problem, the objectives, the research questions, and the significance of the study. Chapter 2 uses qualitative research methods to provide an in-depth analysis of the current climate services available for the energy sector in Senegal. In Chapter 3, the potential impacts of climate change on renewable energy resources in West Africa and Senegal are analyzed. Chapter 4 centers on evaluating the efficacy of the WRF-solar model for forecasting solar irradiance in Senegal, analyzes the results of the evaluation and draws conclusions regarding the model's effectiveness. Chapter 5 is dedicated to presenting the conclusions drawn from the research findings and summarizing the main outcomes of the study and their implications for the energy sector in Senegal. It also highlights the limitations of the study and provides recommendations for future research.

Chapter 2: Qualitative assessment of the state of current climate services for the energy sector in Senegal

2.1 Introduction

The primary factors contributing to the surge in global energy demand are population and income growth. According to the 2019 report from the US Energy Information Administration (EIA), there is a projected 50% increase in worldwide energy consumption from 2018 to 2050. Besides that, weather and climate variability and change impact the energy system from production to supply and use.

Figure 2.1 below is an illustration of the impacts. Several studies have demonstrated the influence of climate change on energy at a broad level (Mideksa and Kallbekken, 2010; Schaeffer et al., 2012; Dowling, 2013; Troccoli, 2018), and renewable energy in particular (Fant et al., 2016; Sawadogo et al., 2020; Pryor and Barthelmie, 2010; Gaetani et al., 2014; Huber et al., 2016). In their study, Schaeffer et al. (2012) have shown a variety of impacts of climate change on the energy system. The study showed the impacts on resource endowments, energy supply and utilization, transmission and distribution, and infrastructure siting. Some impacts on the demand and supply side include changes to the balance of heating and cooling resulting from increasing temperatures. Additionally, changes in the averages and variability of wind and solar, as well as the efficiency of PV panels, thermo-electric power plants, and transmission lines, are attributed to rising temperatures (Ebinger and Vergara, 2011). The potential for enhancing these energy operations becomes evident when utilizing high-quality weather and climate information (Troccoli, 2010).

Efficient planning, management, and operation of energy services across diverse spatial and temporal scales require essential weather and climate information. Consequently, such information is crucial, especially considering the anticipated rise in global energy demand and consumption in the forthcoming decades, along with the interdependence of weather, climate, and energy production and use. (Gunasekera, 2018).

The energy sector is known to be very vulnerable to climate variability and change. Thus, appropriate climate services are needed to help minimize the impacts in the sector.

Climate services can be defined as decision-making support tools developed based on a process of transforming climate information into relevant advisory services that assist decision-making by individuals and organizations of a society (Tall et al., 2018). Climate services aim to provide

individuals and organizations with timely, customized knowledge and information related to climate, enabling them to mitigate climate-related losses and maximize benefits (Vaughan and Dessai, 2014). Having access to reliable weather and climate information holds the potential to enhance our ability to adapt and build resilience in the face of climate variability and change (Christel et al., 2018). Access to valuable and practical climate information constitutes a crucial stride toward constructing climate-resilient societies. In such societies, the threats arising from climate variability and change are not only anticipated and mitigated but also potential opportunities are maximized (Goddard, 2016; Soares et al. 2017).

The energy sector is weather and climate-dependent. Although the energy sector stands out as one of the most advanced users of weather and climate information, its rapid evolution consistently generates new requirements. This necessitates a new paradigm for a more efficient exchange of information between meteorologists and users in the energy sector (Dubus et al., 2018). Scientific advancements alone are insufficient to enhance the value of weather forecasts. The improvement of decision-making processes and, consequently, the value of meteorology, necessitates enhanced communication and mutual understanding between professionals in the energy and meteorology sectors (Dubus et al., 2018). The global energy sector is experiencing an increasing demand for weather and climate information across various regions. The effective delivery of such information entails consistent interactions with users throughout the energy supply chain (Gunasekera, 2018).

In recent years, climate services have evolved with advanced progress in terms of research. In Europe, as noted by Soares et al. (2017), there is a scarcity of studies that specifically examine climate services providers, the climate information and tools generated (examples include Mániez and Zölch, 2014; Banos de Ghisasola, 2014), or the climate information requirements of end-users (as seen in studies such as Dessai and Soares, 2015; Turnpenny et al., 2004). In Africa, climate services research mainly focuses on the agricultural sector (Carr et al. 2015; Roudier et al. 2011; Dayamba et al. 2018; Bayala et al., 2017; Clarkson et al., 2017; Mabe et al. 2014; Zongo et al. 2014; Tall et al. 2018; etc.). However, studies to assess the impact of climate services, to determine the value of these services for the energy sector are very few if not nonexistent in Africa and most of the studies are concentrated on the agricultural sector.

This chapter aims to qualitatively assess how well the climate services are provided and disseminated in the energy sector in Senegal, to identify the needs and the potential gaps between

the producers of the information (i. e. meteorological service) and the energy sector users. The energy sector refers here to the electric energy or power sector which is a mix of thermal and renewable energy (solar, wind, and hydro). In this study, we will only consider the thermal, wind, and solar power plants.

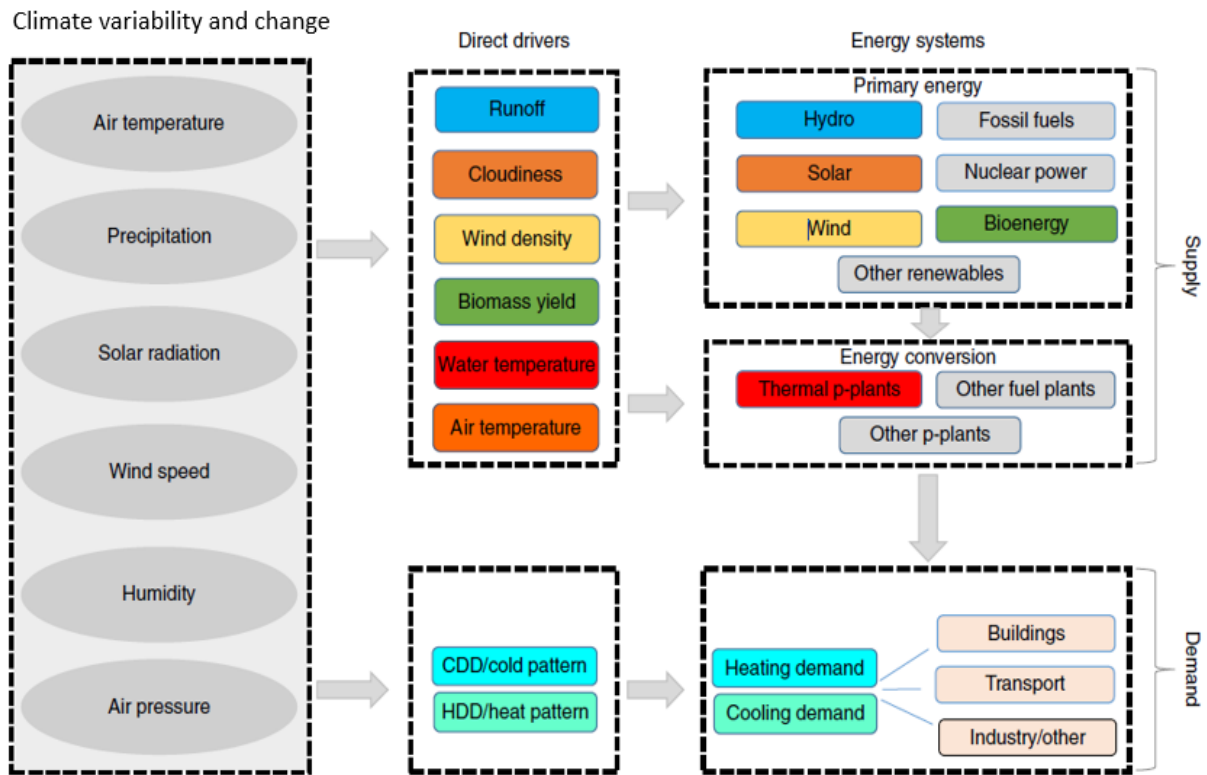


Figure 2.1 Climate variability and change impact on the energy system (Yalew et al., 2020)

2.2 Objective of the interview

In recent years (from 2015 onwards), the penetration of renewable energy (solar and wind) into the energy mix of Senegal has become important with the deployment of many solar plants and a large wind farm. Since 2015, the Senegalese government has actively been encouraging the development and expansion of renewable energy within the country. The National Energy Plan of 2014-2035 states that 40% of the total installed capacity should be from renewable sources by 2035. To this end, the government has implemented numerous solar PV projects such as Bokhol, Malicounda, Ten Merina, Sakal, Mekhe, etc., and the largest wind farm in West Africa (Taiba

Ndiaye).

The above measures have helped to increase the share of renewable energy in the Senegalese energy mix. According to the International Renewable Energy Agency (IRENA), Senegal has witnessed a growth in the proportion of renewable energy in its overall installed capacity, rising from 6.3% in 2015 to 13.1% in 2019. Climate services benefits to the energy sector especially the renewables are well documented in recent years. The objective of conducting this semi-structured interview with the energy and meteorological experts is to qualitatively assess the state of current climate services for the energy sector in Senegal. Some further objectives include:

- To acquire a comprehensive understanding of the topic through the expert’s knowledge and experience.
- To know the energy expert’s needs and how the current climate services received (if they exist) could be improved.
- To explore the expert’s perspective and opinions on current issues and controversies in the field.
- To explore the expert’s perspective and opinions on the collaboration (if it exists) between the sectors.
- Finally, explore the state of the NFCS to see if the implementation of the framework has facilitated the collaboration of the sectors.

2.3 Choice of the interview type

The data used in this chapter is collected through a semi-structured interview. Various interview types are employed in qualitative research, including structured interviews, semi-structured interviews, unstructured interviews, and focus group interviews. *Table 2.1* below displays the advantages and disadvantages of these types of interviews (Stuckey, 2013; Alsaawi, 2014; de la Croix et al., 2018; George, 2022).

Table 2.1 Types of Interviews

Type of interview	Advantages	Disadvantages
Structured interview	<ul style="list-style-type: none"> • Comparisons of data are feasible. • Ensures high reliability and validity. 	<ul style="list-style-type: none"> • Pre-planned interviews are specifically focused on the given topic.

Type of interview	Advantages	Disadvantages
	<ul style="list-style-type: none"> • Offers time effective for both the interviewer and the respondent. • The interview process is simplified through the standardization provided by structured interviews. • Allows for collective analysis of the obtained answers. 	<ul style="list-style-type: none"> • The researcher is restricted from asking additional questions for further clarification or nuance. • Respondents are compelled to choose from predetermined answer options. • These interviews may lack richness, as the variation among responses is constrained. • There is a limited scope, and there's a potential to miss out on capturing interesting data. • There is a risk of response bias associated with this approach.
Semi-structured interview	<ul style="list-style-type: none"> • Ensures the provision of reliable and comparable qualitative data. • Interviewees are allowed to elaborate and explain specific issues, allowing flexibility to follow their line of thought. • Enables the inclusion of spontaneous questions during the interview. • Researchers have the freedom to express interview questions in their preferred format, in contrast to the structured interview. 	<ul style="list-style-type: none"> • Effective conversational skills are essential to extract valuable information during the interview. • Preparation for interviews can be time-intensive. • There's a potential for bias in the interview process. • Asking spontaneous questions to some participants and not others may be perceived as unfair. • Answers obtained may be challenging to quantify and analyze systematically.

Type of interview	Advantages	Disadvantages
	<ul style="list-style-type: none"> • Represents the most prevalent type of interview utilized in qualitative research. 	
Unstructured interview	<ul style="list-style-type: none"> • Respondents may feel more comfortable and at ease. • Rich and qualitative data can be collected through this approach. • Useful when there is limited prior knowledge about the topic. • There are no rigidly predetermined questions, increasing the flexibility of the entire research process. 	<ul style="list-style-type: none"> • Interviewees have the freedom to elaborate, potentially leading the conversation in unpredictable directions. • Due to the lack of structure, unstructured interviews may take more time to conduct. • The absence of a standardized set of questions and guidelines raises concerns about the reliability of unstructured interviews. • Unstructured interviews may exhibit low reliability and validity. • Effective conversational skills are crucial to maintaining the flow of the interview.
Focus group interview	<ul style="list-style-type: none"> • Interviewees can challenge, argue, and debate with each other, potentially yielding in-depth and rich data. • Efficient method as multiple people are interviewed simultaneously. • Respondents often feel more at ease in a group setting. 	<ul style="list-style-type: none"> • Challenging to transcribe. • Limited questions due to time constraints in group interviews. • Requires strong conversational and leadership skills. • Higher risk of observer bias when handling group interactions. • Confidentiality and other ethical considerations become harder to

Type of interview	Advantages	Disadvantages
	<ul style="list-style-type: none"> • Provides a conducive environment to discuss difficult or sensitive topics more easily. 	guarantee with multiple participants present.

A semi-structured interview provides the interviewer with flexibility while remaining focused on a predetermined set of topics. It allows the interviewer to pursue topics of interest while still obtaining the desired information. The interviewer has the freedom to ask follow-up questions and explore the participant’s responses more deeply. This type of interview also helps to build rapport between the interviewer and the participant, as it is less formal than a structured interview. Based on this, the semi-structured interview was chosen for our study.

2.4 Data and Methodology

2.4.1 Energy profile of Senegal

In Senegal, the energy sector is constituted mainly of The National Electricity Company (SENELEC) which is in charge of the production, distribution, and commercialization of electricity in the urban areas. The National Agency for Renewable Energy (ANER) is a governmental agency with the mission of promoting the utilization of renewable energies, including bioenergy, across all sectors of activity. Additionally, ANER is tasked with identifying, assessing, and harnessing the economically viable potential of renewable energy resources in various regions of the country. The Senegalese Agency for Rural Electrification (ASER) is an autonomous service unit of the Ministry of Energy, responsible for promoting rural electrification through support for initiatives at the national and international level, in particular, to develop electrification programs decided based on the electrification plan defined by the Minister of Energy. Besides this, Senegal to date has about nine (9) operational Independent Power Producers (IPPs) in renewable energy. The nine comprises eight (8) solar plants with each having an installed capacity greater or equal to 20 MW and one wind farm with an installed capacity of 158 MW. The solar IPPs are located at Bokhol, Sakal, Malicounda, Ten Merina, Santiou Mekhe, Kahone, and Touba. The wind farm is located at Taiba Ndiaye. All the IPPs are on grid, they are directly connected to the SENELEC network which buys the electricity produced.

2.4.2 Data collection

The data are collected through semi-structured interviews with experts in both the energy and the meteorological sectors of Senegal. The steps required in an interview process are shown in *Figure 2.2*.

A total number of sixteen (16) experts were interviewed: twelve (12) were face to face, two (2) via email, and two (2) were online Zoom meetings because of the Covid-19 situation. The experts are distributed by institutions: three (3) at the Meteorological office, two (2) at SENELEC, two (2) at ANER, and the remaining are one per IPP. A total of seven solar plants are interviewed out of eight. One expert from the regional office of the Global Framework for Climate Services (GFCS) is interviewed to know the current state of the National Framework for Climate Services (NFCS). The profile of the respondents can be found in *Table 2.2*.

A semi-structured interview was used to allow open-ended responses to have much more information about the questions. Semi-structured interviews prove to be a valuable method for data collection when the researcher aims to: (1) gather qualitative, open-ended data, and (2) delve into participants' thoughts, feelings, and beliefs regarding a specific topic (Brown, 2021). It allows an interaction between the interviewer and the respondents where the latter most likely opens up and provides information beyond the question asked. A semi-structured guide of about forty questions was developed based on the research questions. All the questions revolve around the same subject, namely: an introductory part, the communication framework, the type of climate services received at the power sector side (produced at the meteorological side), the early warning system, and legislation (see APPENDIX). In the introductory part, questions asked are about the experts and their expertise, the role and responsibilities of the institutions, and the installed capacity of the plants, among others. The interview took roughly thirty (30) minutes to one hour. Notes were taken and audio recordings were made with the consent of the respondents. The national language of Senegal being French, all the transcriptions were translated into English by taking into account the accuracy of the words used. Efforts were made as much as possible to conserve the meaning of the original words.

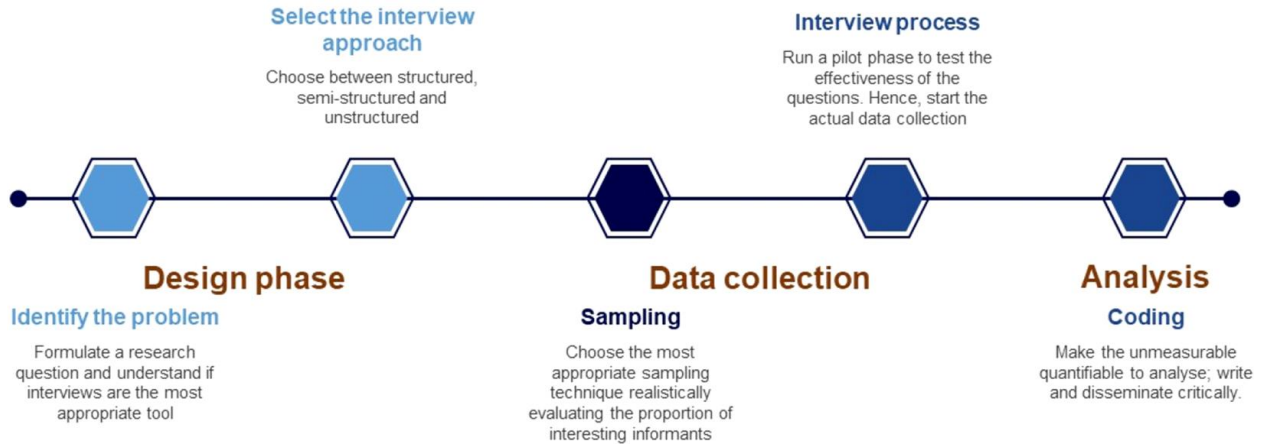


Figure 2.2 The key steps of an interview process (Larosa and Mysiak, 2020)

Table 2.2 Profile of the Respondents

Type of occupation	Institutions	Number
Technical Advisor to the Director General of ANER	ANER	1
Engineer, Projects, and Programs Department	ANER	1
Director of Meteorological Operations	ANACIM	1
Head of the meteorological information system, Department of Meteorological Operations.	ANACIM	1
Head of the climatology and climate services, Research and development department.	ANACIM	1
Site manager and plant operations manager	Bokhol	1
Plant Operations Manager	Kahone1/Energy Ressources	1
Plant Engineer	Malicounda	1
Regional expert of the Global Framework for Climate Services	GFCS	1
Business Manager of the plant	Ten Merina	1
Business Manager of the plant	Kael	1
Business Manager of the plant	Kahone2/Solarsen	1
Plant Manager	Taiba Ndiaye	1

Type of occupation	Institutions	Number
Business Manager	Mekhe	1
Forecasting Expert, Electrical System Operation	SENELEC	1
Head of Research and Demand Management	SENELEC	1

2.4.3 Data analysis

A semi-structured interview is used and the answers of the respondent are not straightforward to analyze. Therefore, it is necessary to perform data analysis (thematic analysis) to identify patterns (themes) within the data (Braun and Clarke, 2006). Thematic analysis is a methodology employed to identify, analyze, and report patterns within data, facilitating the exploration and interpretation of recurring themes or patterns present in qualitative information. It involves several steps such as data compilation, data organization, data reduction, and interpretation. During the data compilation step, the interviews are transcribed and all the data is collected. In the data organization step, the data is then organized into meaningful categories and themes. In the data reduction step, the data is further reduced by discarding redundant information and focusing on the important themes. Finally, in the interpretation step, the data is analyzed to identify patterns and gain insights into the data. By performing a thematic analysis, it is possible to gain useful insights. This information can then be used to inform decision-makers and understand the thoughts and opinions of respondents. Thematic analysis, with its theoretical flexibility, serves as a valuable research tool. It has the potential to offer a comprehensive and intricate account of data, allowing for a rich and detailed exploration of themes (Braun and Clarke, 2006). This analysis method was chosen because of its flexibility. We use an inductive approach which is a data-driven approach to code the data and identify themes focusing on the semantic content of the data (Braun and Clarke, 2006; Frith and Gleeson, 2004). A theme captures a key aspect of the data in relation to the research question and represents some level of patterned response or meaning within the data set.

NVIVO version 20.5.0.935, which is a form of Computer Assisted Qualitative Data Analysis Software (CAQDAS) is used to help analyze the data which consisted of transcripts and recording. It has been used in many qualitative studies (Ozkan, 2004; Siccama and Penna, 2008; Zamawe, 2015; Houghton et al., 2017). The detailed approach and the step-by-step analysis method can be found in *Table 2.3*.

Table 2.3 Phases of Thematic Analysis (Braun and Clarke, 2006).

Phase	Description of the process
1. Getting familiarized with your data:	Transcribing data, going through the data multiple times, and noting down initial thoughts.
2. Creating initial codes:	Systematically coding noteworthy features of the data across the entire dataset and compiling data associated with each code.
3. Identifying themes:	Organizing codes into potential themes and assembling all data pertinent to each potential theme.
4. Reviewing themes:	Evaluating the coherence of themes concerning the coded extracts (Level 1) and the entire dataset (Level 2).
5. Establishing and labeling themes:	Continual analysis to fine-tune the details of each theme and the overarching narrative of the analysis; creating precise definitions and names for each theme.
6. Generating the report:	The concluding phase of analysis involves selecting vivid and compelling extract examples, conducting a final analysis of these chosen extracts, connecting the analysis back to the research question and existing literature, and ultimately producing a scholarly report summarizing the analysis.

2.5 Results

As mentioned earlier, this study aims to assess the current state of the climate services for the energy sector in Senegal. Nine themes and sixteen subthemes were identified from the analysis of the 16 transcripts. *Table 2.4* and *Figure 2.3* present the thematic framework and the word cloud that emerged from the data, respectively.

Table 2.4 Thematic Framework of the Interview

Theme	Files (how many participants discussed the theme)	References (how many times the theme was discussed)
ADAPTATION AND RESILIENCE OF THE SECTOR	12	56
Adaptation to climate extremes	9	9
Resilience to the extremes	12	47
BENEFITS AND OPPORTUNITIES	12	29
Climate data and services benefits	12	22
Climate impact on the sector	6	7
CHALLENGES AND BARRIERS	14	29
Lack of collaboration	11	17
Weak communication framework	7	12
CLIMATE SERVICE NEEDS	13	57
Climate data or service needs	13	46
EWS needs	11	11
COMMUNICATION CHANNELS	10	16
Format and Channels used	10	16
EXISTING ACTION ON CLIMATE SERVICES	12	63
Current climate service provided	7	17
Frequency of the services	5	12
Tailoring of the services	12	34
LEGISLATION, STRATEGY AND PLAN	2	7
Legislation, Strategy and Plan	2	7
PRIVATE PROVIDERS	7	11

Theme	Files (how many participants discussed the theme)	References (how many times the theme was discussed)
Private providers and limitations	7	11
GFCS	3	20
GFCS definition and role	2	8
NFCS challenges and plans	2	12



Figure 2.3 Word cloud emerging from the interview

2.5.1 Legislation, Strategy and Plan

In terms of legislation and mandate, there is a decree that governs how ANACIM provides data and even specifies the cost of each data and each service. In Senegal, all climate and meteorological services ranging from weather forecasting to seasonal forecasts are managed by ANACIM which provides them. However, the legislative capacity for climate service is weak. The main existing legislation concerns working groups such as the Multidisciplinary Working Group (GTP) which meets every 10 days during the rainy season mainly for the agricultural sector.

There is the National Framework for Climate Services (NFCS) which is led by ANACIM and where a strategy is defined. There is also the internal weather strategy and a monitoring and evaluation document with objectives that are set and evaluated each year. ANACIM promotes the incorporation of climate change elements into planning processes, such as the national adaptation plan (NAP) which is planned to train decision makers (national assembly, territorial administration, etc.) so that they can integrate climate change issues into decisions. Training programs are scheduled at the local level as part of the Regional Committee on Climate Change (COMRECC) and NAP framework.

2.5.2 The Global and National Framework for Climate Services (GFCS, NFCS)

This theme was discussed mainly by the met office, ANER, and the regional office of the framework. From their responses, it emerges that the GFCS was one of the needs of the countries within the scope of climate change to organize around climate services and define a framework for countries to work together to mitigate the negative impacts of climate change in all priority sectors. The framework was born to support all the countries worldwide, particularly the developing countries. The NFCS is a strategic framework that brings together all actors in all sectors of activity including politicians and scientists at the national level to consult and define a plan to combat climate change and in particular define appropriate climate services for priority sectors. At this moment, each country must define the most important sectors and in relation to this the GFCS has identified its five priority sectors. The NFCS is a framework for consultation at the national level to define a strategic plan and an action plan to combat climate change and define indicators for appropriate climate services in relation to priority sectors of socio-economic development. Senegal ratified its Action Plan in 2016 with a decree from the prime minister's office to define how the NFCS should be conducted in the country. Senegal has identified in relation to these six priority sectors: water resources, energy, agriculture, disaster risk reduction, health, and tourism. The strategic plan is led by the meteorological office (ANACIM), which organizes and coordinates all activities at the national level. Agriculture and fisheries are the most dynamic sectors of the framework because they have been able to benefit from a good number of activities: capacity-building workshops, bulletins, etc. For example, the Multidisciplinary Working Group (GTP) is a group that is generally active during the rainy season to support the agricultural sector. The GFCS has some plans and projects, however, there are a number of

challenges raised by the respondents:

“There are sectors that have benefited, such as agriculture, fisheries, health, etc. There are other sectors where it is slow to materialize. For the energy sector, I don't think it has any activities so far”

“Currently, to speak frankly, it is slow to make it real on the ground and it is due to a lack of funding. If we take the case of Senegal, although we have the decree of the prime minister's office which is signed to validate the CNSC, Senegal no longer has a prime minister's office. Now we are working on how to reactivate this decree with ANACIM”.

“There has been no real progress with the GFCS. We had budgeted but after the budget receipts had their realities, we were not able to finalize this project”.

“There are projects underway but it is slow to materialize on the ground because there has been a lot of upheaval at the administrative level which makes it a bit difficult”.

In these extracts, the participants revealed some challenges of the framework. They also stated some of the plans and projects “Now what the NFCS is trying to do with all the other sectors is to define groups of activities for each sector to carry out the services and identify indicators and develop bulletins. Currently, efforts are being made to seek funding to implement the activities of the framework”. According to the meteorological office, efforts are being made on how to expand the GTP to all sectors so that in these meetings they can all give complementary information regarding the sectors, to exchange so that the system is more coordinated. It is necessary to define these sector activities to implement bulletins, capacity building, organize consultation workshops, etc., so that, they work in relation to a common coordinator as ANACIM is the lead of the activities of the framework. A consultation framework with the energy sector would be a good starting point to see the needs in terms of capacity building in the context of climate services and concerning budgetary considerations. For a more detailed discussion about the meteorological office and the energy sector, see the following sections.

2.5.3 Benefits and opportunities

All participants were unanimous about the impact of climate on the energy sector and they emphasized more on the production part and its use. From the interview, several examples were given about these impacts:

“Most of the climate parameters like temperature, wind, and rainfall, etc. can influence the energy sector and that is why we need weather and climate information”

“We receive information about wind and it has of course an impact on the production; no wind no production. During the hot season, we have a very weak production because of lack of wind”.

“Where it is really hot like the northern part, we can have some impact of the temperature on the solar panel efficiency”

These are some extracts that the participants used to highlight some climate impacts. Climate has an impact on the energy sector in general mainly on the renewable energy part which accounts in Senegal for about 400 MW (solar and wind) out of the overall installed capacity (1478 MW) of the national electricity company (SENELEC) with 245 MW from solar and 158 MW from wind. All the experts accepted that climate information has become a need for the energy sector. *“It is a need, it is an input, people are more and more in agreement with this fact”*. The different benefits of climate data and services highlighted by the experts are given in *Figure 2.4* below. Nevertheless, they also mentioned a number of challenges in getting this information.

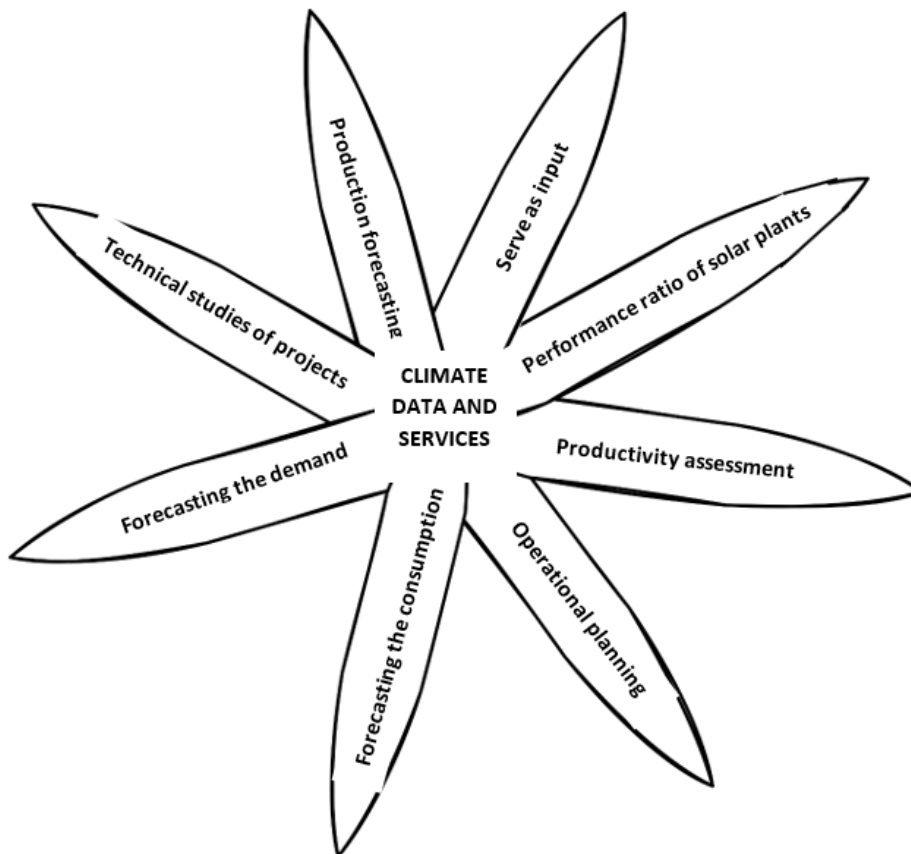


Figure 2.4 Benefits of climate services according to the participants

2.5.4 Challenges and barriers

As noted in the previous section, there are several challenges raised by the energy sector experts in getting climate services in Senegal. The main challenge raised is the lack of convention and a weak communication framework with the government institutions namely SENELEC, ANER, and ANACIM. Formally, these institutions are connected through the NFCS. The framework is the first mechanism of dialogue between the institutions. The participants expressed that the exchange must be further developed. *“There is an official NFCS communication framework but we would like to go much further and perhaps have bilateral collaboration for the needs of the energy sector and renewable energies in particular”*.

Also, a need for a sector-specific exchange framework was raised by the energy experts because, according to them, the sector has very specific needs. The energy sector is interested in having information currently produced but wants a specific framework that governs all their needs. The extracts below show clearly how the challenges were expressed:

“Formally we are connected to the energy sector through this framework, we have been working with SENELEC for quite some time and we have been in discussions for the signing of a memorandum of understanding (MoU) because they need us to provide them with climate information on a regular basis”.

“Would be important to make a convention between the two agencies. We have to try to work together between government departments so that we can have access to this information. I think the convention can allow us to have access to some data and information without all the time writing and asking”.

“Discussions are underway to partner with ANACIM for the provision of climate data on a regular basis”.

For the IPPs, there is a lack of collaboration with the meteorological office. Eight IPPs, seven solar plants out of eight, and one wind farm all said that they have no collaboration with ANACIM, they work with private providers. *“However, we did not try to approach ANACIM we just use the platforms listed above”*.

One of the IPPs has signed a contract with a foreign institution for the provision of a daily forecast of climate parameters. Some of them express their interest in collaborating for multiple purposes. They listed some benefits of having the services from the meteorological office:

“We clean the panels once a month but sometimes it happens that just after the cleaning there

is a sandstorm and we will be forced to clean again otherwise we will not be optimizing production. So, we need this collaboration with ANACIM to avoid this. We wouldn't have cleaned up if we knew there was going to be a sandstorm. This is an additional burden on operating costs”.

“It would be interesting to exchange with ANACIM because they are the ones who have the most accurate data”.

“At the plant, we have local stations but sometimes it is necessary to collaborate with ANACIM in order to make a comparison study with the data because especially the precipitation part, sometimes our forecasts are very different from those of ANACIM”.

2.5.5 Existing action on climate services

Although there are some challenges in getting climate services in Senegal for the energy sector, there is a certain number of exchanges of information between government institutions. It is said from the interview that this information is given under request. So, not on a regular basis.

“In the past, we had to work with some institutions such as ANER and SENELEC, which always make requests, and for the moment we are responding on an ad hoc basis in relation to these requests but we have not yet considered in relation to the routine thinking about new products. These products are supplied according to demand”.

“We do not receive climate information on a daily or monthly basis, there is no fixed frequency”

Most of the services that the energy sector demands from ANACIM are alerts, forecasts, predictions, and projections on climate parameters mainly temperature, humidity, wind, and rainfall. This information is considered to be very informative and the participants declared to be generally satisfied but wish to strengthen the link in order to have the services on a regular basis.

There is a lot of information produced at ANACIM that the energy sector would benefit from. There is a seasonal forecast (one, two, or three months) on rainfall and temperature. There are also weather forecasts (24h, 48h, 72h) on rainfall and temperature but also wind and insolation. This would allow the energy sector to have a view of the evolution of the weather, first, in terms of forecasting and in a posteriori way to give them information on past events. ANACIM also makes projections in terms of temperature increase which can be done as impact studies in certain localities on the horizon of 2030, for example, to see if there will be an increase in temperature or rainfall. Forecasts of climate extremes also exist especially heavy rains during the rainy season,

heat waves during periods of extended high temperatures, drought during the dry season or periods of less rainfall, etc. ANACIM provides an Early Warning System (EWS) on heat waves, cold waves, and everything that alerts on dangerous weather phenomena such as heavy rain, wind gusts, etc. The frequency of the delivery is on an ad hoc basis because it depends on the existence of the products. There is not yet a mechanism to coordinate all the EWSs maybe the EWSs for flood risks, agriculture, and fishing but recently with the Operational Center for Inter-ministerial Crisis Management (COGIC) which is piloted by the Directorate of Civil Protection (DPC), there is a mechanism which is being established and it is going to be a national EWS. One should note that the EWSs are very developed for the sectors of agriculture and fishing where they are provided in SMS and the local language. The energy sector as a whole (SENELEC, ANER, and the IPPs) said that they receive these alerts only via TV broadcasting of ANACIM. Channels of communication are required for the exchange of information and this is discussed in the next section.

2.5.6 Communication Channels

The government institutions that receive some climate services and the meteorological office itself said that the main channel used is email. The type of services varies, it can be a report or raw data. The extract below mentions it:

“We do periodic reports but it depends on the type of request we receive. Some requests require raw data so we provide them in Excel format and some requests just require a report and, in this case, we provide these reports”.

However, ANACIM provides an EWS mainly for agriculture and fishing in the form of bulletins, vigilance maps, or SMS alerts, and as mentioned earlier, the energy sector receives these alerts through national TV. ANACIM uses multiple channels to disseminate climate information according to its experts. There is a Geoportal, the national framework portal, the ANACIM website, social networks, radios, and televisions. They have a long-standing collaboration with the “union des radios communautaires”, which includes more than 120 community radio stations. They also use the public-private partnership and work with start-ups to develop the digital communication component. From the interview, we identified certain requirements for climate services that the energy experts mentioned, which we will discuss in the following section.

2.5.7 The identified needs in climate services

Several needs in terms of data and climate services came up from the energy experts from both the government institutions and the IPPs. *Table 2.5* summarizes the different needs and their frequencies. Reasons given for the use of the services differ mainly from renewable (IPPs, ANER) and conventional (SENELEC).

In addition to the different benefits stated earlier, the IPP experts explained in the extracts below how the EWS could help them know the best time to clean up the panels and the best time to schedule for maintenance of the plants so that their weekly tasks will not be disrupted. Also, according to one expert, when there is heavy rain or strong wind, the staff stay home for their safety. So, knowing the EWS (forecast) in advance would also help in this regard. The EWS would also permit them to know one way or another the production curve of a wind farm:

“Our biggest concern is the extreme wind speeds. The turbine stops automatically at 21m/s (for mechanical safety)”

“For example, if we know in advance that tomorrow there will not be much sun (low irradiation), it is better for us to use this day to do maintenance instead of taking a day where there is a lot of sunshine. Also, we can decide to clean the panels but if it rains, we will no longer need to do this cleaning. If we know in advance that there will be rainfall during the week, we can take this into account so as not to disrupt our schedule for the week”.

“If we can get personalized services with ANACIM which can give us the information a week or two weeks in advance, it will be good. We’ll know the best time to clean up the panels. Because with the announcements that pass on TV the time is usually very short, the information usually passes the day before”.

Table 2.5 Identified needs

Needs	Frequency
Cloud duration	Daily, weekly, seasonal
Aerosol intensity, duration, and concentration	Daily, weekly, seasonal, yearly
Alerts on extreme climatic situations	Daily, weekly, monthly, quarterly
Heavy precipitation alert	A week before
Strong wind alert	A week before
Sandstorms	One or two weeks before
Sun radiation forecast	A week before

Forecast of wind speed	Hourly
Provision of forecasts (Temperature, Humidity, Rainfall)	Daily, weekly, seasonal

2.5.8 Private providers

As stated above, almost all IPPs use free online platforms and software for their climate service needs. There is also an IPP that is under contract with a European institution that provides daily forecasts. In addition to what is provided to the government institutions under request, these institutions also use some online platforms for a daily forecast of climate parameters, especially temperature. Some of the platforms and software used are Meteo Matics, PVGIS, wunderground.com, weatherchannel.com, weather2umbrella.com, etc. These tools are often used for pre-feasibility studies, weather prediction, production forecasts, etc. *“In addition, for production forecasts, the website is consulted to find out if there will be clear skies in the coming days and what will be the temperature and wind speed. Depending on that, we can have the irradiation to know roughly how much we will produce during this period”*.

Most of the IPPs declared to be satisfied with the platform as shown in this extract: *“It’s ok, the forecasts are pretty good since we’ve been using the platform”*.

However, about four IPPs wish to have better and raised some limitations of the platforms. One expert said that he usually goes to the ANACIM website for complementary information. These IPPs are ready for collaboration with the meteorological office. The following extracts illustrate this.

“Usually, I go to the ANACIM website to get information about the forecasts”

“It is satellite data therefore not 100% reliable but since we have no other alternatives, we are obliged to use them. We wish to have better if possible”

2.5.9 Adaptation and Resilience of the Sector

Climate change is a threat to the development sectors including the energy sector. So, it is important to have some action plan for adaptation and resilience. All the participants agreed that they have plans in place to help them remain resilient and adapt to extreme climate conditions. Some institutions especially government institutions make a yearly assessment of their projects. *“For example, in our first projects, we used lead batteries for solar storage but now we use lithium batteries. We try to improve every year to have better production. With extreme temperatures, you*

can have a low production of PV panels. That's why we always try to use the best panels on the market". The evaluation will assess the positive outcomes and achievements of the completed projects, as well as identify ways to prevent similar issues from occurring in future projects. They also said that it would be necessary to have an endowment in human and technical resources but also in terms of tools and models to consider the impacts of extreme events on the sector.

The IPPs mentioned unanimously that the plants are well-sized. Climatic factors were taken into account during the study phase. Studies were carried out on soil resistivity, even the material aspect of the panels. They have taken into account heavy precipitation, strong variations in the sunshine, strong winds, etc. So, the plants are ready to face climatic extremes even though there was one accident at a solar plant raised by an expert. The latter explained that, at the start of the operational phase, they observed the solar panels being lifted by the strong wind; however, they were able to fix the issue afterward. Another climate impact raised is from the wind farm. The expert said that they witnessed heavy rain which kept them from doing some maintenance. The extracts below summarize their opinion about the resilience of the plants.

“We had heavy rains that damaged the roads but the production was not affected”

“This is well taken into account because these are plants that are suited to the conditions. Usually, for the weather forecast part, we take into account the hottest months with extremes of irradiation”.

“Yes, we are resistant to winds such as hurricanes which have not yet happened to us”.

“Yes, we are resistant as a whole. So far, we have had only one problem with the structure of the panels. An incident which caused the lifting of some panels of a production table following a strong wind was recorded two (2) years ago”.

One needs to note that there is no defined resilience plan in all the plants but most of them have multiple actions in order to be resilient. Preventive maintenance is taken into account in the monitoring of devices and the proposal of new technologies adapted for various disturbance phenomena in the future. Also, when there is so much heat or extreme temperature variations, the lifespan of the PV panels is considerably reduced due to the degradation of the cells, hence the need to have a stock of spare parts that can be modulated according to these climatic variations is taken into account. Some plants are equipped with sensors that detect when extreme temperatures occur, causing the machines to stay at a standstill, i.e., at normal operating temperatures.

The energy sector participants provided some suggestions for good resilience of the sector.

All the points are extracted from the respondents.

- Integrate more of the energy mix, to have many types of power plants to diversify the energy sources (thermal, renewable, and storage);
- SENELEC alone has a great responsibility, so it would be beneficial to have a sector specifically for production, another for transport and distribution, and a third for commercialization;
- For the existing SENELEC network, it is essential to identify and address issues to achieve the desired level of efficiency. Strategies must be put in place to minimize losses and optimize performance;
- We need a stable technology with less disturbance which takes into account the aspect of load balance. The IPPs need to have more control over their productive load aspects, this will allow SENELEC to manage its network well in a stable manner;
- A fairly robust, flexible, and stable transportation system;
- Production units meeting demand;
- A synergy of actions of the different stakeholders;
- Climate services should be accessible to the sector on a regular basis.

2.6 Conclusion

This chapter assesses the current state of the climate services for the energy sector in Senegal. A total number of sixteen experts were interviewed.

The study found that the current climate services for Senegal's energy sector are not adequate. The majority of the experts interviewed felt that there is insufficient access to climate data and that climate services are not extensively used in the decision-making process. This is mainly due to a lack of convention and a weak communication framework but also a lack of collaboration between the meteorological office and the IPPs. Enhancing communication and coordination among the stakeholders engaged in the development and provision of climate services and the energy sector is imperative. This should be addressed in order to foster a more efficient and effective climate services delivery in the energy sector.

The study also identified a number of potential opportunities for improving the existing climate services for the energy sector in Senegal. These include the need to strengthen the capacity and resources available supporting the utilization of climate services, to build capacity in utilizing

climate data and services, and to promote the use of climate services in decision-making. The interview also revealed that there is a lack of resources and capacity for climate services development.

Overall, the study concluded that there is a need to strengthen the current climate services for the energy sector in Senegal to ensure that energy sector decision-makers have access to reliable and accurate climate services.

The next chapter discusses the importance of climate service to the energy sector especially renewable by showing the climate impacts on the sector at the regional and country level.

Chapter 3: The Risks of Climate Change to Renewable Energy Resources in West Africa and Senegal

A- West Africa

3.1 Introduction

Global energy demand is increasing driven by income and population growth. Currently, fossil fuels remain the dominant source, 80% of energy demand is met by fossil fuels, and the energy system is the source of approximately two-thirds of global CO₂ emissions (Foster and Elzinga, 2015). These fuels are associated with the degradation of the environment by releasing greenhouse gases (GHG) into the atmosphere through their combustion. The increase in the concentration of GHG changes the radiative balance of the atmosphere and is considered to be the main driver of the observed changes in hot and cold extremes on the global scale and most continents (IPCC-AR6, 2021).

However, many African countries are promoting renewable energy in the framework of climate change mitigation. Renewable Energy Sources (RES) play a role in providing energy services in a sustainable manner and in mitigating climate change (Moomaw et al., 2012). RES derive their energy directly from the Sun or the heat in the Earth's interior and are thus constantly being renewed. Among the RES currently used for electricity generation, solar and wind energy are the most promising and widely used (IEA, 2019).

Global renewable power capacity is set to expand by 50% between 2019 and 2024, led by solar photovoltaic (PV) (IEA, 2019). Based on this projection, solar PV represents nearly 60% and onshore wind a quarter. The sub-Saharan Africa region is forecasted to add 22 GW of renewable energy capacity during the period 2019-2024 (IEA, 2019). For example, Senegal has implemented more than eight solar plants since 2016 and has the largest wind farm in West Africa with a capacity of 158.7 MW. Nevertheless, the energy sector, especially renewable, is highly dependent on weather and climate conditions which affect energy supply and use, energy demand, transport, distribution, and energy markets. Some of the key environmental effects of climate change are an increase in global surface temperature, changes in hydrological cycles, a rise in mean sea level, and a higher incidence of extreme weather events. The disruption to the generation and supply of electricity is likely to be considerable due to these environmental changes (Chandramowli and Felder, 2014). For this reason, it is important to assess and quantify the magnitude of changes in climate variables that will affect future energy

systems, both from a climate and energy perspective, especially in the renewable energy sector (Troccoli et al., 2018).

To date, studies on the potential impacts of climate change on solar and wind energy resources are various and the results depend on the region and many other issues. A review of possible mechanisms by which global climate variability and change may influence the wind energy resource and operating conditions showed changes in wind shear, intensity, and duration (Pryor and Barthelmie, 2010). Studies for Europe using an ensemble of Regional Climate Models (Tobin et al., 2015), showed that changes in wind power potential will remain within ± 15 and $\pm 20\%$ over most European countries by the mid and late centuries, respectively. Using CMIP5 projections for solar PV, Müller et al. (2019) observed positive impacts for most European countries with only minor negative impacts in northern countries. In the United States, Breslow and Sailor (2002) and Crook et al. (2011) projected a reduction in wind speed of up to 5% by 2050 and 2100 and a decrease of the PV output over the Western USA ($\sim 3\%$) by the end of the century, respectively. In recent years, studies on Africa on the same topic have become more numerous. Sawadogo et al. (2020) and Soares et al. (2019) projected respectively an increase in wind power density in the near and mid-century under RCP2.5 and RCP8.5 over Africa and an increase in wind energy density in the northern regions ($< +10\%$) and a decrease ($> -10\%$) in the southern region of Africa. Studies over West Africa found an increase in monsoon wind speed and wind power density (Sawadogo et al., 2019), while Ogunjobi et al. (2022) found a potential decrease in energy produced by up to 12% in the period 2021–2050 and a possible increase (about 24–30%) in power production in the far future (2071–2100). On the other hand, using different climate models to assess future solar resources, a general decrease with different magnitudes of PV potential was found over West Africa (Huber et al., 2016; Bazyomo et al., 2016; Sawadogo et al., 2021; Danso et al., 2022).

In the mid-2010s, the CORDEX-CORE initiative was launched (Gutowski et al., 2016) to better address the problem of heterogeneity in the size and simulation setup (e.g., choice of driving global climate model, GCM) of the projections in different CORDEX domains. The CORDEX-CORE simulations provide a homogeneous set of projections for all CORDEX domains using a core set of RCMs driven by a common set of GCMs. The model horizontal grid spacing is 25 km x 25 km, i.e., a resolution of four folded compared to the previous CORDEX simulations (Giorgi et al., 2021). Studies on the subject of this investigation over West Africa using an ensemble of RCMs from CORDEX-CORE are very few if not non-existent to our knowledge. The existing CORDEX-CORE studies for the African region mainly

dealt with other variables and processes (eg., Olusegun et al., 2022, Dosio et al., 2021, Torres-Alavez et al., 2021, Coppola et al., 2021).

The objective of this chapter is therefore to investigate the expected future impacts of climate change on solar and wind energy potential over West Africa using the high-resolution RCM simulations from CORDEX-CORE under the RCP2.6 and RCP8.5 scenarios. As stated above, the projected changes in wind power potential over West Africa are still uncertain, with widely diverging results. We use an ensemble of GCM-RCM combinations to better explore the inherent uncertainties of climate projections and to provide more robust estimates for the target variables of this study. As stated by Tebaldi and Knutti (2007), the ensemble mean of a multi-model approach in climate modelling often presents less biases compared to the individual models, especially for first-order statistics. Moreover, the new high-resolution (25 km) CORDEX-CORE Climate Models could provide significant added value in terms of spatial resolution as compared to the standard simulations of the CORDEX initiative, which were done in 50 km resolution. The study is complemented by a detailed model evaluation of the RCMs for the target variables using state-of-the-art global datasets as reference products.

3.2 Material and Method

3.2.1 Study domain

The study region ranges from 0°N to 25°N, and -20°W to 20°E and includes all West African countries (*Figure 3.1*). The region is endowed with renewable energy potential with a high solar energy resources availability (IRENA, 2014). The climate of West Africa is strongly determined by the different atmospheric processes of the West African Monsoon system (Nicholson, 2013). Continental dry air masses originating from the high-pressure system north of the Sahara Desert give rise to dusty Harmattan winds over most of West Africa from November to February. In the main monsoon period (June to August), humid air masses originating from the Atlantic Ocean bring monsoon rains over most parts of the study region (Nicholson, 2013). Both temperature and rainfall and their annual cycle depend on the way in which dry and moist air masses interact over the year (Lewis and Buontempo., 2016). In this study, we consider three different climatic zones of the region namely the Guinea zone (18°W to 18°E, 4°N to 8°N), the Savannah zone (18°W to 18°E, 8°N to 12°N), and the Sahel zone (18°W to 18°E, 12°N to 16°N) adopted from Abiodun et al. (2012). Similar domains were used by many other RCM studies for this region (e.g., Heinzeller et al., 2018; Dieng et al., 2018; Sawadogo et al., 2019). The Guinea zone is characterized by a sub-humid climate with average

annual rainfall usually between 1250 mm and 3000 mm, the Savannah is a semiarid zone with average annual rainfall between 750 mm and 1250 mm (Akinsanola et al., 2015). Most of the rainfall in the Sahel zone falls in the boreal summer months (June to September) with an annual mean rainfall amount from roughly 750 mm in the south to less than 200 mm in the north (Biasutti, 2019).

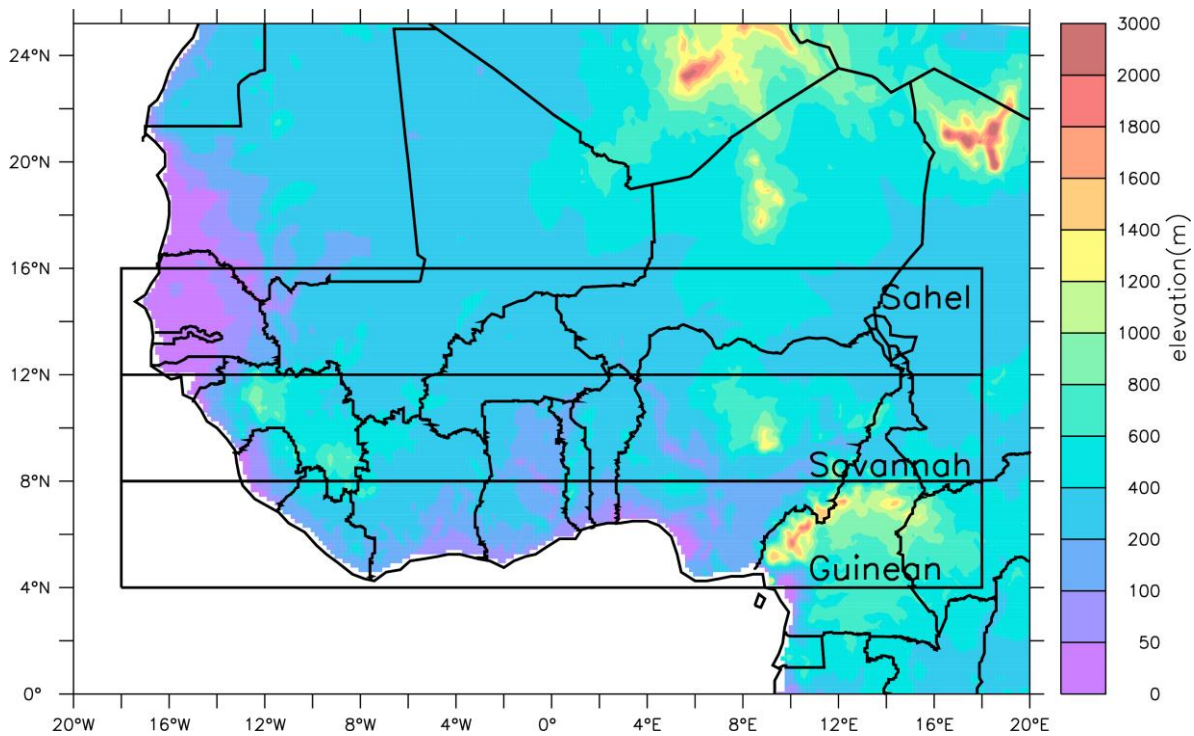


Figure 3.1 Study area with the three climatic zones (Guinea, Savannah, and Sahel) and the topography in meters (m) in West Africa.

3.2.2 RCMs and reference datasets

The data used in this study are the current CORDEX-CORE simulations from the World Climate Research Program (WCRP), the atmospheric reanalysis dataset ERA5 (Hersbach et al., 2020), developed by the European Centre for Medium-Range Weather Forecasts (ECMWF), as well as a satellite-based climate dataset (SARAH-2, Pfeifroth et al., 2017).

The CORDEX-CORE simulation data used in this study is based on three RCMs namely: RegCM4, REMO, and CCLM, each driven by three GCMs (NorESM1-M, MPI-ESM-MR, and HadGEM2-ES) from the Coupled Model Intercomparison Project 5 (CMIP5, Taylor et al., 2012; Giorgi et al., 2021). According to Giorgi et al. (2021), these GCMs are among the best-performing models over Africa in the CORDEX domains within the CMIP5 ensemble (e.g., Elguindi et al., 2014; McSweeney et al., 2015). They roughly span the range of global climate

sensitivity of the CMIP5 ensemble, with HadGEM2-ES having high sensitivity, MPI-ESM-MR, and NorESM1-M having medium and low sensitivity, respectively, in terms of increase in global mean temperature compared to the pre-industrial level. RegCM4 is the fourth-generation version of the RegCM regional modelling system (Giorgi et al., 2012) developed at the Abdus Salam International Centre for Theoretical Physics (ICTP). REMO is a hydrostatic atmospheric model using hybrid vertical coordinates (Jacob et al., 2012; Remedio et al., 2019) developed at the Climate Service Center Germany (GERICS). CCLM is a non-hydrostatic model developed by the Consortium for Small-scale Modelling (COSMO) community. In addition, RCMs participating in CORDEX-CORE offer only two RCPs: RCP2.6 and RCP8.5 scenarios (Giorgi et al., 2022). All three RCMs have been frequently used for climate simulations in West Africa. Examples are shown by Sawadogo et al. (2021) and Kouassi et al. (2022) for RegCM, Paeth et al. (2011) and Paxian et al. (2016) for REMO and by Dosio and Panitz (2016) and Dieng et al. (2017) for CCLM. To study the future potential in terms of solar PV and wind energy, the climate variables taken from the CORDEX-CORE simulations via the ESGF nodes (<https://esgf-data.dkrz.de/search/cordex-dkrz/>) are monthly surface downwelling shortwave radiation (RSDS), near-surface air temperature (Tas) and near-surface wind speed at ten meters above ground level (WSPD).

To validate the RCM simulations, monthly surface wind speed (10m above the ground level) and the ambient air temperature were taken from the ERA5 dataset which is the fifth generation ECMWF reanalysis for the global climate and weather produced by the Copernicus Climate Change Service at ECMWF. The ERA5 dataset provides estimates of atmospheric variables at a resolution of approximately 31 km worldwide. The monthly shortwave solar radiation was received from the second version of the Surface Solar Radiation Dataset - Heliosat (SARAH-2). SARAH-2 is a satellite-based climate data record of the solar irradiance, the direct irradiance, the sunshine duration, spectral information, and the effective cloud albedo derived from satellite observations of the visible channels of the MVIRI and the SEVIRI instruments onboard the geostationary Meteosat satellites (Pfeifroth et al., 2017). Details about the quality of this dataset have been demonstrated in many studies including Mueller et al. (2015) and Pfeifroth et al. (2018). The SARAH and the ERA5 data cover the period from 1985-2014. More details about the data used in this study and the model configurations are given in *Table 3.1*.

Table 3.1 Configuration of the RCMs used in this study in the CORDEX-CORE simulation.

	RegCM	REMO	CCLM
Institution	Abdus Salam International Center for Theoretical Physics (ITCP)	Climate Service Centre Germany (GERICS)	Consortium for Small-Scale Modelling (COSMO) community, the German Weather Service (DWD)
Microphysics	SUBEX (Pal et al. 2000)	Lohmann and Roeckner (1996)	Doms et al. (2007)
Cumulus convection	Tiedtke and Kain-Fritsch (Tiedtke, 1989; Kain-Fritsch, 1990)	Tiedtke (1989) Nordeng (1994) Pfeifer (2006)	Tiedtke (1989) being modified by D. Mironow (DWD)
Planetary boundary layer	Holtzlag (Holtzlag et al. 1990)	Monin-Obukhov similarity theory (Louis, 1979)	Herzog et al. (2002)
Radiation scheme	(Kiehl et al. 1996)	Morcrette et al. (1986); Giorgetta and Wild (1995)	Ritter and Geleyn (1992)
Interactive aerosols	Organic and black carbon, SO ₄ (Solmon et al. 2006) ; Dust (Zakey et al. 2006) ; Sea salt (Zakey et al. 2008)	No aerosol module included. The information about aerosols, for example in the radiation scheme is based on the climatology from Tanre et al. (1984)	No aerosol module included.

SUBEX=Subgrid explicit moisture scheme

3.2.3 Methods

Figure 3.2 indicates the conceptual framework of the study with the two state-of-the-science global datasets used for RCM evaluation (left side) and the different RCM/GCM combinations of the CORDEX-CORE ensemble (right side). To estimate the solar PV and wind energy potential, the PV potential (PVP) and the wind power density (WPD) are calculated from the respective RCMs and reference datasets. In addition, further variables such as wind speed at 100 m and cell temperature (T_{cell}) are calculated from the datasets, which are needed for the estimation of the main target variables. Afterward, a model evaluation of the RCMs of CORDEX-CORE is performed for 30 years based on the ensemble mean using the reference datasets. In addition, the projected changes of PVP and WPD are calculated from the CORDEX-CORE ensemble for future periods.

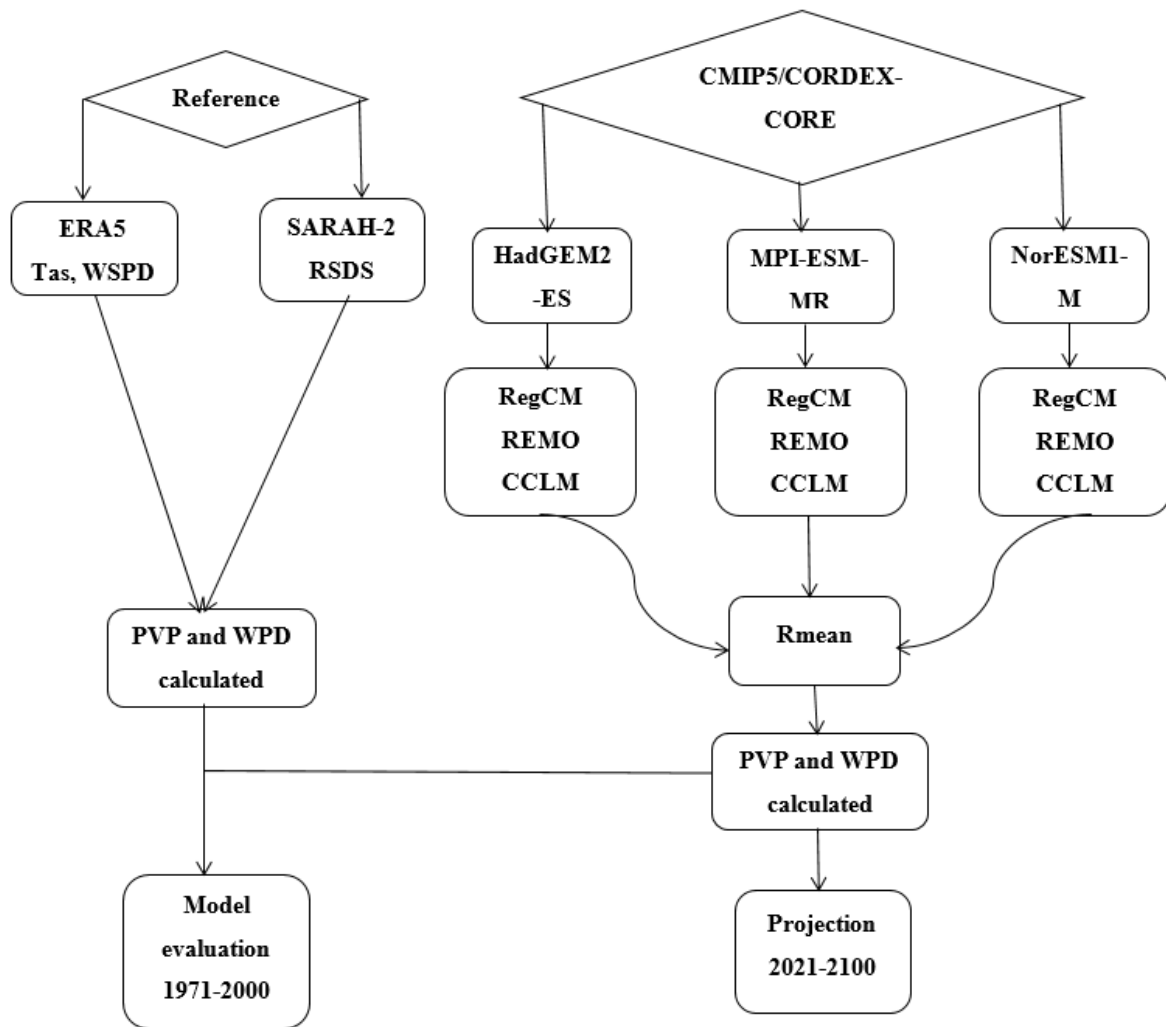


Figure 3.2 Conceptual framework of the methodology including the main target variables (e.g., PVP and WPD), the chosen RCMs/GCM combinations of CORDEX-CORE for providing climate projections, and the reference datasets used for model evaluation.

3.2.3.1 Solar PV potential estimation (PVP)

Photovoltaic potential (PVP) is a value for the expected average electricity production (in kilowatt-hours per kWh) of grid-connected photovoltaic systems without batteries under standard test conditions. The PVP is a function of the performance ratio (Pr) and the RSDS. Pr measures the performance of a PV system and considers environmental factors such as temperature, irradiance, humidity, wind speed, and other meteorological variables. In this study, the PVP is computed following the formula of Mavromatakis et al. (2010). It accounts for the performance of the PV cells with respect to their nominal power capacity according to the actual ambient conditions. This formula has been adopted by many studies (Jerez et al., 2015; Sawadogo et al., 2019; Bichet et al., 2019; Feron et al., 2020; Poddar et al., 2021). It can

be expressed by the equation (3.1):

$$PVP = Pr * RSDS \quad (3.1)$$

Where RSDS is the shortwave solar radiation at the location ($W m^{-2}$) and Pr is the performance ratio, which refers to the changes in PV cell efficiency due to the effect of the cell temperature (T_{Cell}). According to Jerez et al. (2015), it can be estimated by using the equation (3.2):

$$P_R = 1 + \gamma (T_{cell} - T_{STC}) \quad (3.2)$$

Where T_{cell} is the PV cell temperature and T_{STC} is the temperature of the cell under standard test conditions ($25\text{ }^{\circ}C$). γ is the power thermal coefficient and is equal to $0.005\text{ }^{\circ}C^{-1}$ for mono-crystalline silicon cells (Tonui and Yiannis., 2008). According to Chenni et al. (2007), T_{cell} is usually calculated based on multiple linear regression considering the effects of the temperature, solar radiation, and wind speed as follows:

$$T_{cell} = C_1 + C_2 * T_{as} + C_3 * RSDS + C_4 * WSPD \quad (3.3)$$

where T_{as} is the ambient temperature around the cells ($^{\circ}C$), RSDS is the downward solar radiation ($W m^{-2}$), WSPD is the wind speed ($m s^{-1}$) and C_1 , C_2 , C_3 and C_4 are coefficients that depend on the PV material properties. From recent studies, it has been shown that the wind speed effect on the PVP can be negligible in the West Africa region (Sawadogo et al., 2021). We use only the effect of the temperature and the shortwave solar radiation to calculate the T_{cell} . Equation 3.3 can be reduced as follows:

$$T_{cell} = C_1 + C_2 * T_{as} + C_3 * RSDS \quad (3.4)$$

In this study, we assume that the PVP is generated from a mono-crystalline silicon plant as they are commonly used in West Africa. For this category of material, the coefficients of equation (4) are $C_1 = 3.75\text{ }^{\circ}C$, $C_2 = 1.14$ and $C_3 = 0.0175\text{ }^{\circ}C m^2 W^{-1}$ based on Crook et al. (2011).

3.2.3.2 Wind power density estimation

The wind power density (WPD) is an important indicator for assessing the potential of wind energy at a site (Emeis, 2013). Following Zahid et al. (2017) and Sawadogo et al. (2019), the WPD expressed in $W m^{-2}$ is calculated using the following equation:

$$WPD = \frac{1}{2} \rho (WSPD_z)^3 \quad (3.5)$$

where $WSPD_z$ is the wind speed at 100 m above ground level and the air density ρ . In this study, the 100 m wind speed is calculated by extrapolating the 10 m wind speed (Emeis, 2005), using the power law equation:

$$WSPD_z = WSPD_{zr} \left(\frac{z}{zr} \right)^\alpha \quad (3.6)$$

where z is the turbine hub height (100 m), zr is the reference height (10 m), and $WSPD_{zr}$ is the wind speed at the reference height. We assume that $\alpha = 0.143$ for open land surfaces (Sawadogo et al., 2019).

The air density is estimated following Custódio (2009):

$$\rho = \frac{353.4 \left(1 - \frac{z}{45271} \right)^{5.2624}}{273.15 + T} \quad (3.7)$$

T is the temperature at 100 m height. It is calculated by considering a dry adiabatic lapse rate of about 1°C per 100 m.

3.2.3.3 RCMs evaluation and impact analysis

The analysis of the CORDEX-CORE ensemble is done for a simulation period ranging from 1971 to 2100 from which the period 1971-2000 was taken as reference, 2021-2050 for the near future simulation and 2071-2100 for the far future and under the RCP2.6 and RCP8.5 scenarios. The RCP2.6 is the most optimistic scenario, predicting a global temperature increase of only 1 °C, whereas the RCP8.5 is the most pessimistic, with a global temperature rise of up to 4 °C by the end of the century. The RCP2.6 scenario is considered to be one of the most ambitious of the RCPs, as it requires the most significant reduction in GHG emissions. The RCP8.5 scenario illustrates a somewhat conservative situation of business as usual with low income, high population, and high energy demand. It uses the 90th percentile of the baseline scenario without explicit climate policy and represents the highest RCP scenario in terms of greenhouse gas (GHG) emissions. The choice of these scenarios was based on the fact that the RCMs participating in CORDEX-CORE offer only these two scenarios (Giorgi et al., 2022). The future period is divided into two-time slots; 2021-2050 for the near future and 2071-2100 for the far future. Monthly data are used for all variables calculated from the model and reference datasets. The annual means are obtained by averaging the monthly values and the ensemble mean (hereafter Mean) is obtained by averaging over the three RCMs, which are also averaged over the 3 GCMs. The model evaluation of the RCM is done for target variables (Tcell, PVP, and WPD) and further variables (WSPD, Tas, and RSDS) relevant for the calculation of the target variables using common performance metrics like the root mean square error (RMSE), the mean absolute error (MAE) and the correlation coefficient r using the equation 3.8, 3.9 and 3.10 respectively.

$$RMSE = \sqrt{\sum_{i=1}^n \frac{(P_i - O_i)^2}{n}} \quad (3.8)$$

$$MAE = \frac{1}{n} \sum_{i=1}^n (|P_i - O_i|) \quad (3.9)$$

$$r = \frac{\sum_{i=1}^n (O_i - \underline{O})(P_i - \underline{P})}{\sqrt{\sum_{i=1}^n (O_i - \underline{O})^2 \sum_{i=1}^n (P_i - \underline{P})^2}} \quad (3.10)$$

where P is the RCM data, O the reference data at timestep i , and n the number of data points. \underline{O} and \underline{P} the mean value of the reference and RCM data, respectively.

The validation of the model output focuses on important climate features (e. g. annual patterns and cycle) in addition to temporal statistics using diagnostic tools like the Taylor-Diagram. Relative to the reference period, the changes in future PVP and WPD over the region are analyzed and no bias adjustments were applied. Indeed, bias requires reference data that reflect the true weather of the location (Ehret et al., 2012). The reference datasets used in this study are subject to some biases that have been pointed out in previous studies (Neher et al., 2020; Tall et al., 2019). A recent study by Dieng et al. (2022) showed that the change signals of wind speed and solar irradiance are largely preserved after bias correction over West Africa. The projected changes in temperature are estimated as the difference between the future and reference periods (absolute change). For the other variables, the changes are estimated in terms of percentage (relative change). A statistical t-test is also done to indicate the significance of the projected changes at a 95% confidence level. According to Seaby et al. (2013), it could be useful to evaluate climate models for statistically significant changes over the 21st century for purposes of model comparison and selection for impact modelling. The t-test is among the most common test used in climate science to estimate the significance of modelled changes (Tebaldi et al. 2011). Finally, the model agreement for the projected changes is assessed, as agreement across models has become an important tool for evaluating the robustness of model outputs. When multiple independent models agree, their shared conclusion is more likely to be true (Pirtle et al., 2010). In this study, the agreement of the RCMs is designated by the colored areas, and the disagreement by uncolored or white areas.

3.3 Results and discussion

3.3.1 Evaluation and validation of the model

3.3.1.1 Annual patterns of the climate variables in the reference period

For the validation of the models, a comparison of the model outputs and the reference

datasets (ERA5 and SARA-2) is done. *Figure 3.3* and *Figure 3.4* show the simulated and observed spatial patterns of the annual means for all the variables of this investigation, for the reference period (1971-2000). The RCMs and the ensemble mean show a relatively good representation of the spatial distribution of the different variables. All spatial correlations are greater than 0.8. Despite this performance of the RCMs, there are some pronounced biases. A high bias of PVP and WPD is noticed for all the single RCMs and especially for the Sahel zone. A bias ranging between -300 to 150 kWh.m^{-2} for PVP and 50 to 150 W.m^{-2} for WPD with CCLM having a strong underestimation of -300 kWh.m^{-2} of PVP in the Guinea sub-region. The RCMs present less bias for the other variables. RegCM shows an overestimation of all the climate variables, especially in the Sahel. CCLM presents an underestimation of RSDS over Guinea and Savannah and Tcell and Tas over West Africa as a whole. In opposite to RegCM and CCLM, REMO underestimates RSDS and PVP in the Sahel zone but overestimates WSPD and WPD like the other two RCMs. However, the ensemble mean shows a better representation in terms of RMSE, MAE, and correlation and presents less biases as compared to the single RCMs. Similar biases of RSDS and Tas are shown in Sawadogo et al. (2019) who used an ensemble of 14 RCMs from the Coordinated Regional Climate Downscaling Experiment simulations to investigate the impact of climate change on photovoltaic power generation potential over West Africa. However, for WSPD, while we find an overestimation of about 2 m.s^{-1} over West Africa, results from the studies of Sawadogo et al. (2019) and Ogunjobi et al. (2021) present a similar overestimation but only for Guinea and Savannah and an underestimation for the Sahel. Model biases can be related to many factors. These biases might result from both the driving GCM and the RCM, but differences between the GCMs are typically larger than those between the RCMs except for coastal areas and regions with complex topography (Moemken et al., 2018). This study used the CORDEX-CORE datasets which provide high-resolution regional climate information. Some comparison studies between the global climate models (CMIP5, CMIP6) and regional climate models (CORDEX, CORDEX-CORE) showed a better performance of the CORDEX-CORE in simulating drought and rainfall indices over the region (Dosio et al., 2021; Coppola et al., 2021).

Regardless of these biases, The RCMs are able to reproduce the spatial pattern of the different climate variables. The highest values of RSDS and Tas are in the Sahel zone and the lowest in the Guinea zone. The same observation is indicated for Tcell and PVP. This could be explained by a lack of vegetation in the Sahel, a very low amount of precipitation during a short period of time, and a long dry season compared to the Guinea zone which has a long rainy season. The highest wind speed and wind power density are in the northern coastal area, mainly

the northern coast of Senegal, Mauritania, and the Sahel zone. The lowest are in the Guinea zone.

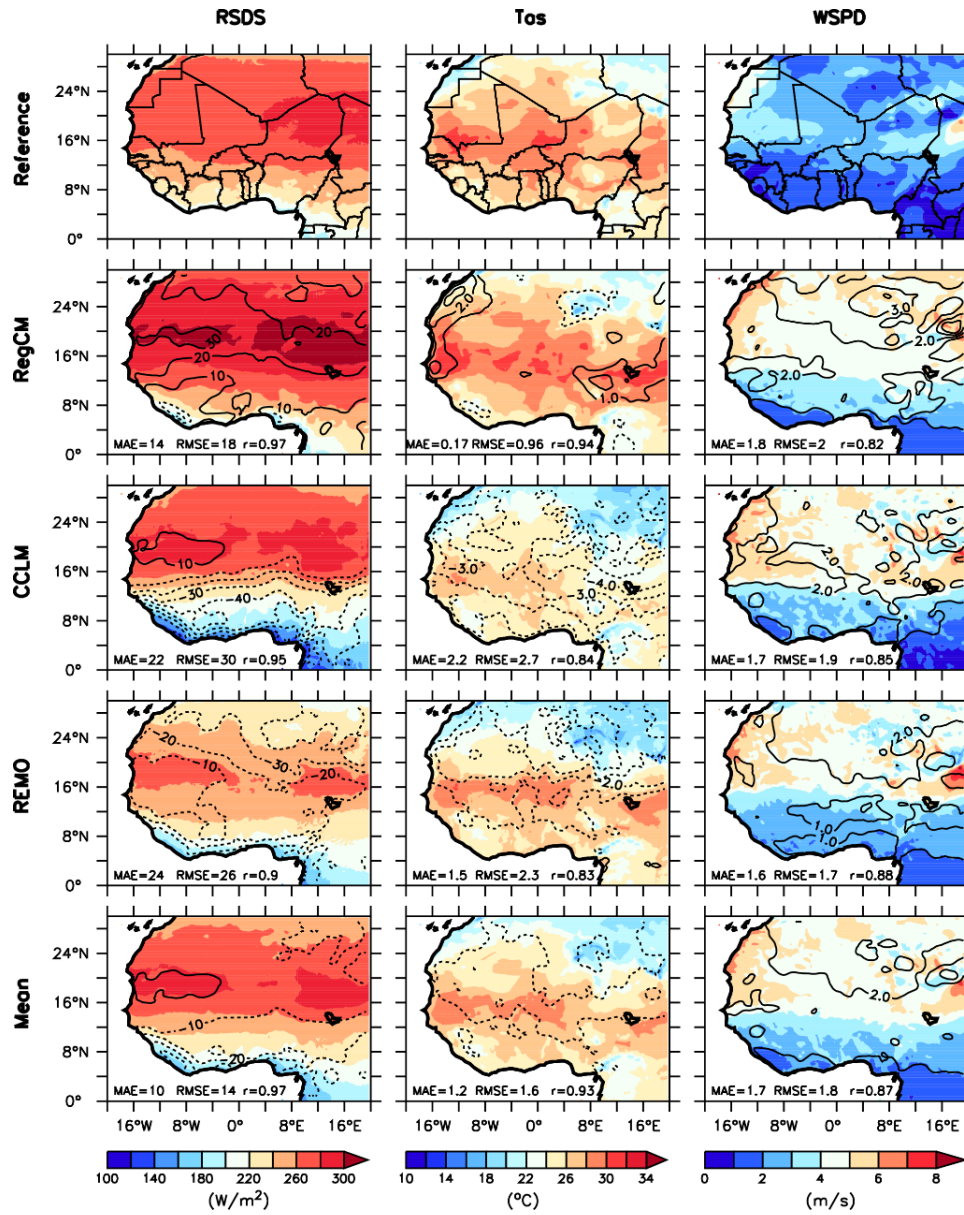


Figure 3.3 Spatial distribution of the annual averages of observed and simulated solar irradiance (RSDS), ambient air temperature (Tas), and surface wind speed (WSPD) over West Africa.

The bias is plotted in contours, and the correlation (r), mean absolute error (MAE), and root mean square error (RMSE) between the observation and the model were also indicated.

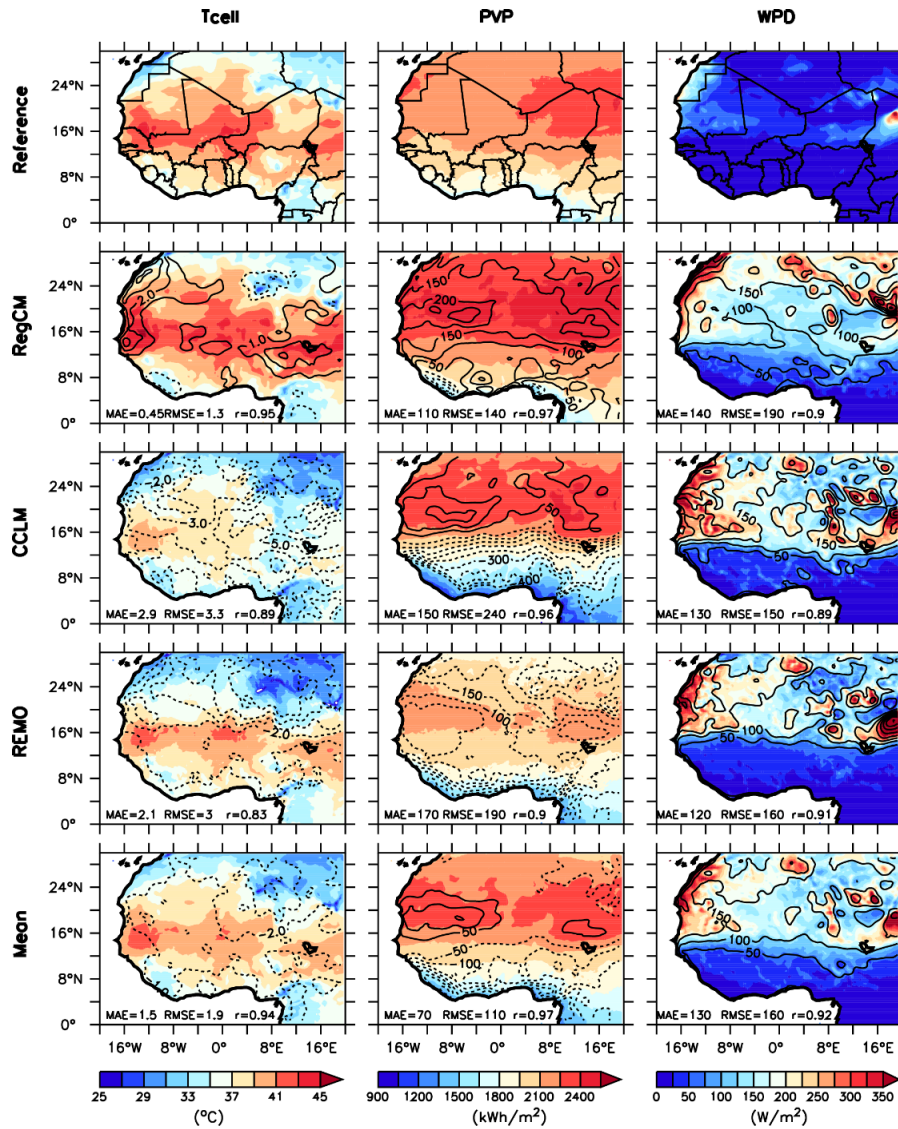


Figure 3.4 Spatial distribution of the cell temperature (T_{cell}), the solar and wind potential (PVP and WPD respectively), and over West Africa.

The bias is plotted in contours, and the correlation (r), Mean Absolute Error (MAE), and Root Mean Square Error (RMSE) between the observation and the model are also indicated.

3.3.1.2 Annual cycle of the climate variables in the reference period

For the same variables, the mean annual cycle of the three selected climatic zones of West Africa is represented, namely Sahel, Savannah, and Guinea (*Figure 3.5* and *Figure 3.6*). The RCMs capture the pattern of the variables in all regions, although strong overestimations are present, especially for the wind variables. Comparing the model's performance, the temperature variables (T_{as} and T_{cell}) are better simulated by the RCMs which capture not only the pattern but also the amplitude in the three areas of the region apart from a slight underestimation of the CCLM model.

The WSPD and the WPD are strongly overestimated by all the RCMs and the ensemble mean and in all climatic zones with higher biases observed for the WSPD than the WPD and the Sahel zone. Nevertheless, the RCMs agree well with the pattern of these variables with REMO showing better amplitudes and less bias compared to the other RCMs. The highest values of WSPD and WPD are in the Sahel with two peaks, in February and in July with WSPD reaching almost $4 \text{ m}\cdot\text{s}^{-1}$ in the Harmattan period (DJF). RSDS and PVP exhibit the same pattern according to the region. The RCMs and the ensemble mean underestimate the RSDS and PVP from March to November with RegCM presenting a better representation in the different areas.

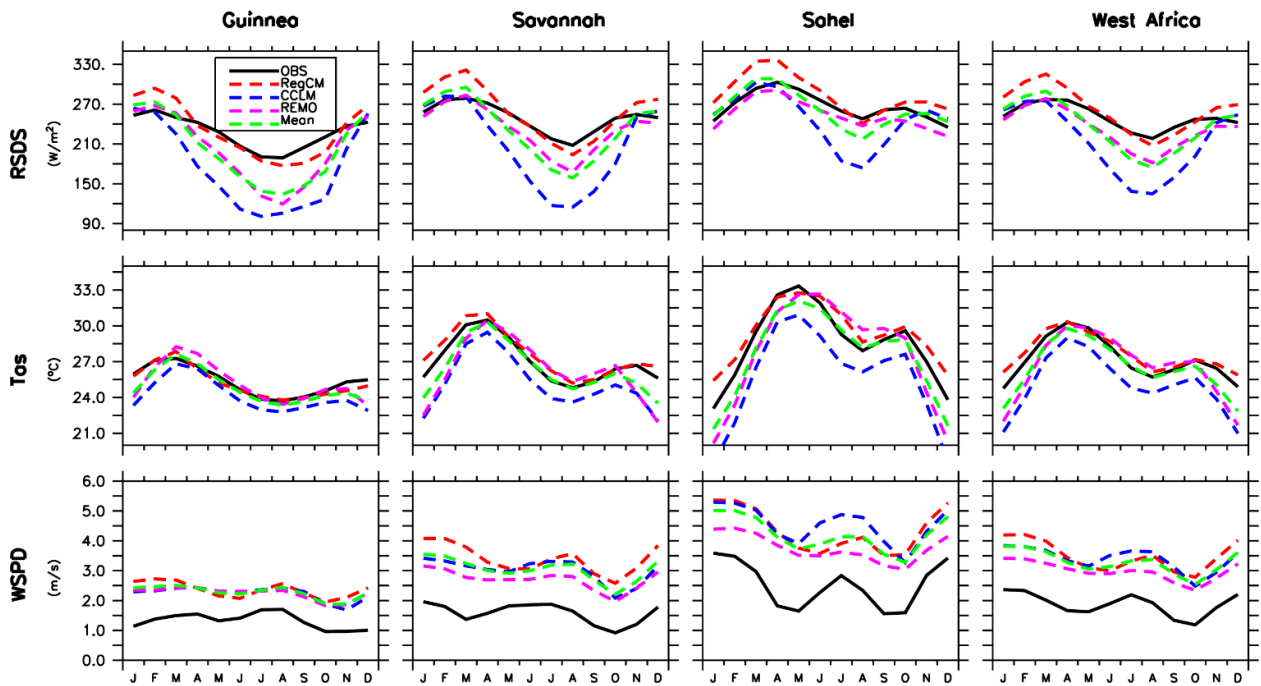


Figure 3.5 Annual cycle of observed and simulated solar irradiance (RSDS), ambient air temperature (Tas) and surface wind speed (WSPD) over the three climatic zones of West Africa.

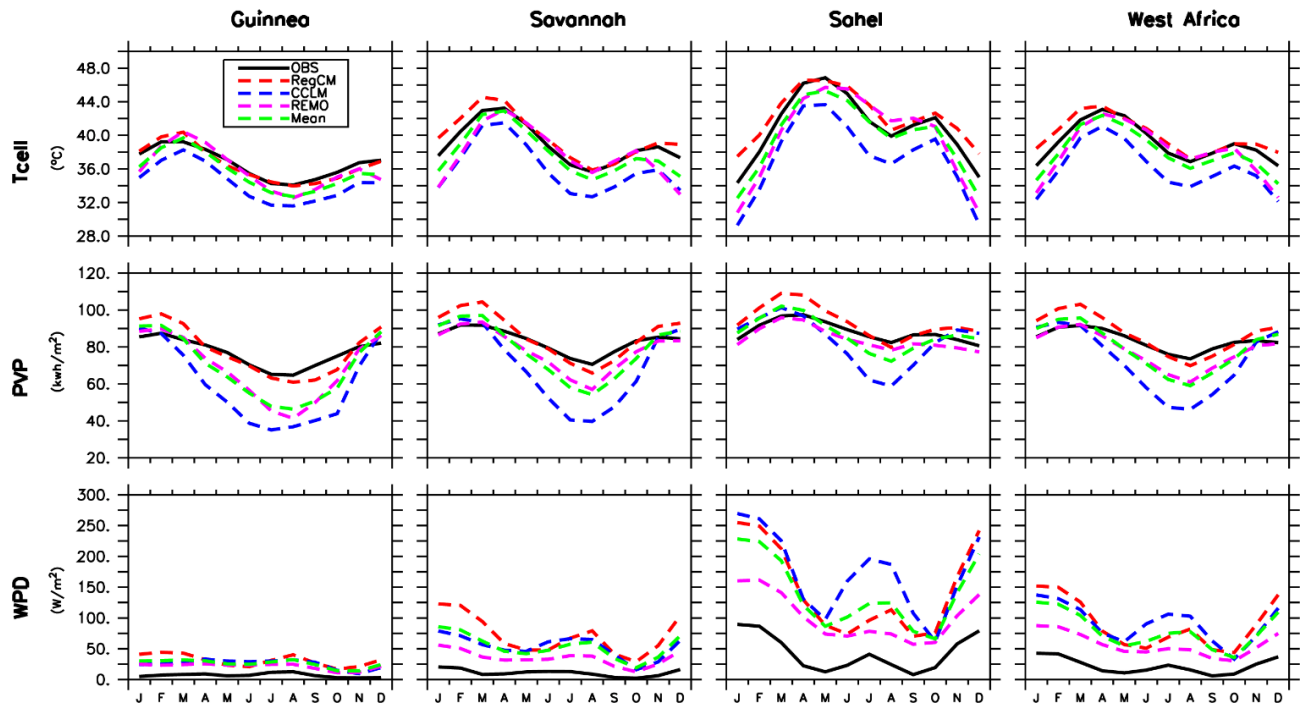


Figure 3.6 Annual cycle of observed and simulated cell temperature (T_{cell}), solar, and wind potential (PVP and WPD respectively) over the three climatic zones of West Africa.

3.3.1.3 Seasonal cycle of the climate variables in the reference period

Figure 3.7, Figure 3.8, and Figure 3.9 present the seasonal cycle of the observed and simulated solar irradiance (RSDS), ambient air temperature (T_{as}), and surface wind speed (WSPD) for the reference period (1971-2000). Over West Africa, solar irradiance and ambient air temperature are much higher during March-April-May (MAM) and June-July-August (JJA). During these months, solar irradiance is highest in the northern parts of West Africa due to their proximity to the Sahel. The southern parts of West Africa tend to have lesser solar irradiance and lower temperatures during these months. December-January-February (DJF) and September-October-November (SON) have lower solar irradiance levels and temperatures as compared to the other months. In addition, the highest wind speed occurs in DJF and is located above 12°N .

The RCMs capture the profile of the variables in the region, although there is some bias. A better simulation of RSDS in DJF, MAM, and SON is observed. In JJA, an underestimation of the solar irradiance by the RCMs in the southern parts of the region is noticed. RegCM overestimates RSDS across West Africa and all the seasons while REMO underestimates it. The wind speed in the region is overestimated by all the RCMs and in all the seasons.

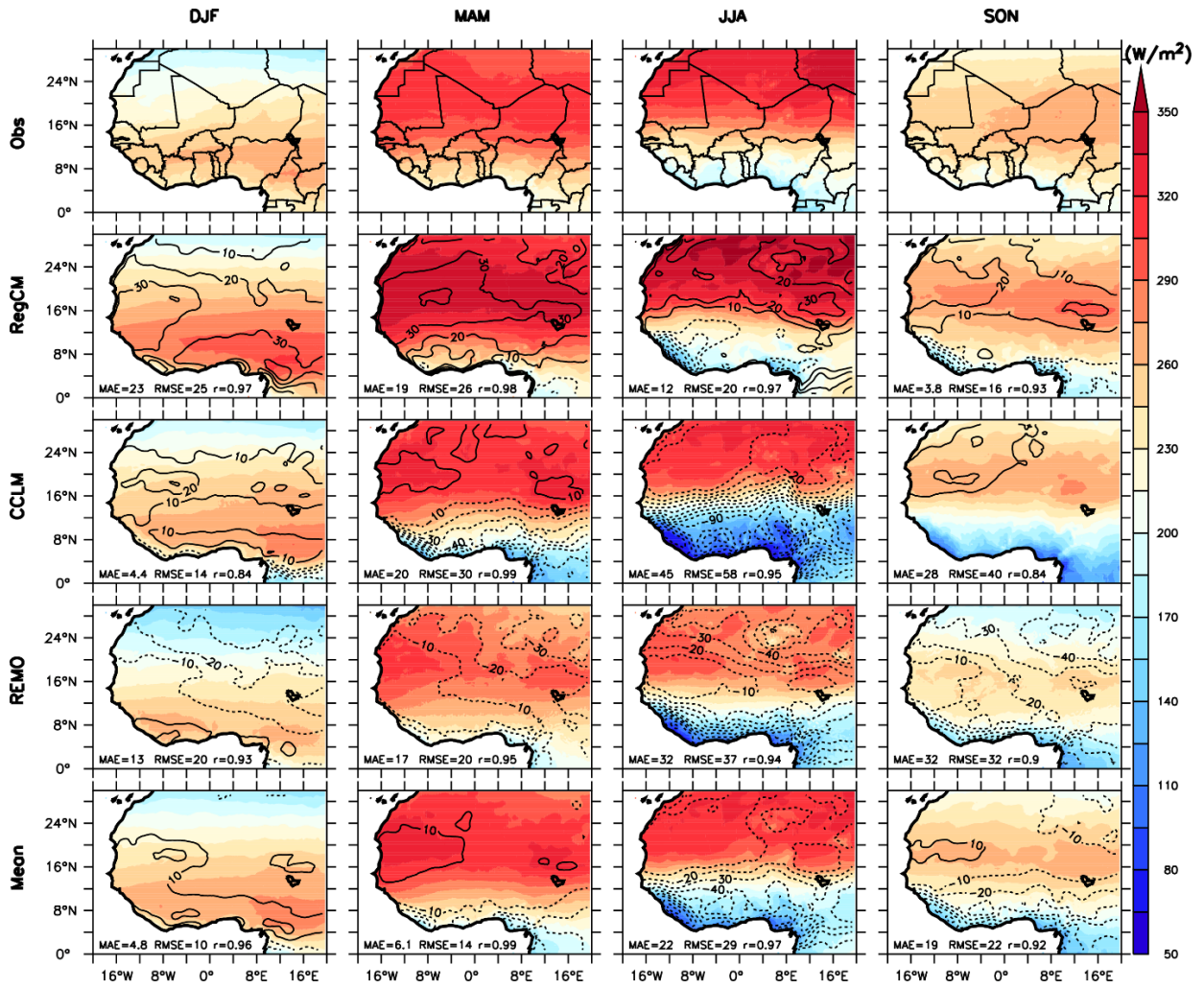


Figure 3.7 Seasonal cycle of the observed and simulated solar irradiance (RSDS) for the reference period (1971-2000).

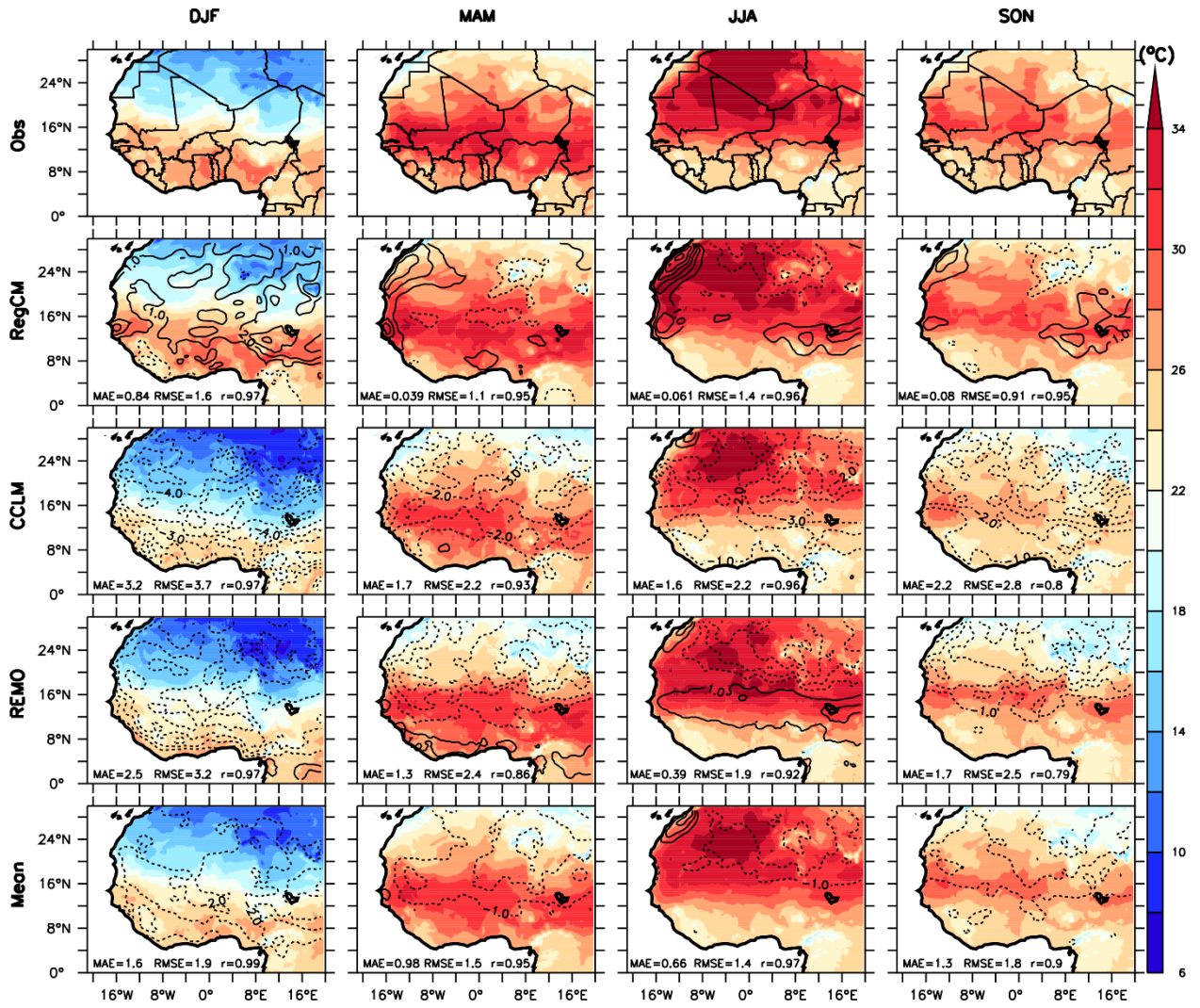


Figure 3.8 Seasonal cycle of the observed and simulated ambient air temperature (T_{as}) for the reference period (1971-2000).

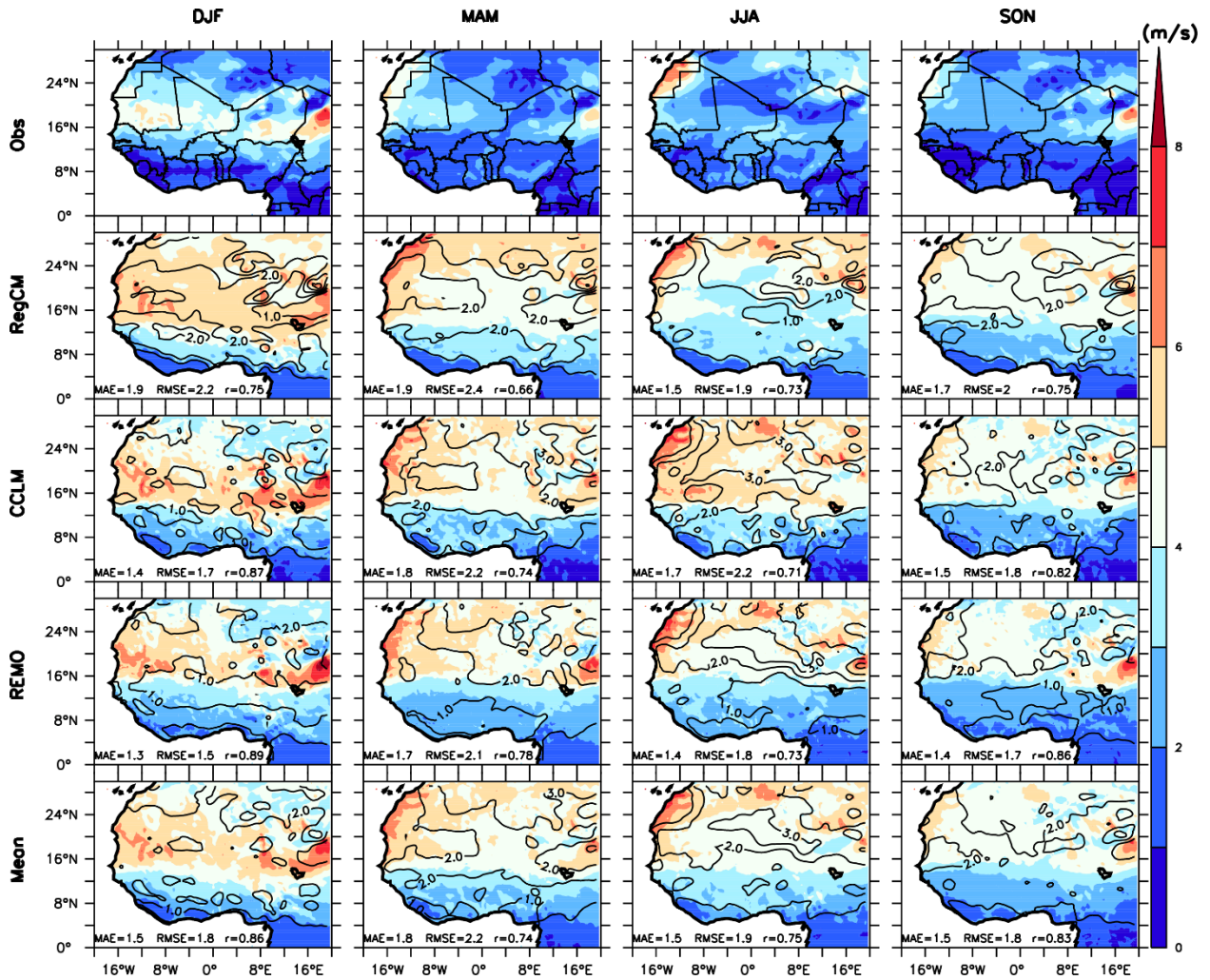


Figure 3.9 Seasonal cycle of the observed and simulated surface wind speed (WSPD) for the reference period (1971-2000).

3.3.1.4 Model performance in the reference period

To evaluate the accuracy and other quality attributes (e.g., correlation and standard deviation) of the model simulations, a statistical analysis is also performed using a Taylor diagram (Figure 3.10). The Taylor diagram is an analysis of the monthly average of the variables over each climatic zone. The black dot indicates data perfect model simulation, while the other colored dots indicate that of the different RCMs simulations. The ensemble mean and RegCM perform best in most cases for the radiation variables (RSDS and PVP) with better results for Guinea and Savannah compared to the Sahel zone. CCLM is the least efficient model for RSDS and PVP simulations. In the case of the wind variables, REMO is the best model among the RCMs for representing WSPD and WPD in the sub-regions and West Africa confirming therefore the findings of the previous section. The simulations of Tcell and Tas present smaller differences in the normalized standard deviation for the RCMs than the wind

and radiation variables. CCLM shows better performance in the Tas and Tcell simulations compared to other parameters. Nevertheless, there is more consistency between the observation and simulation in the other zones than in the Sahel.

Basically, the models show a high disparity for the WSPD and WPD simulations and for all the sub-regions. The same disparities in the simulation of all the climate variables and for the Sahel zone are noticed. Across the individual RCMs and the individual climate variables, the model RegCM is the best in simulating the RSDS and PVP in the sub-regions. For the WSPD and WPD simulations, REMO best fit the observation in the different zones. Both REMO and RegCM perform well for the simulations of the temperature variables.

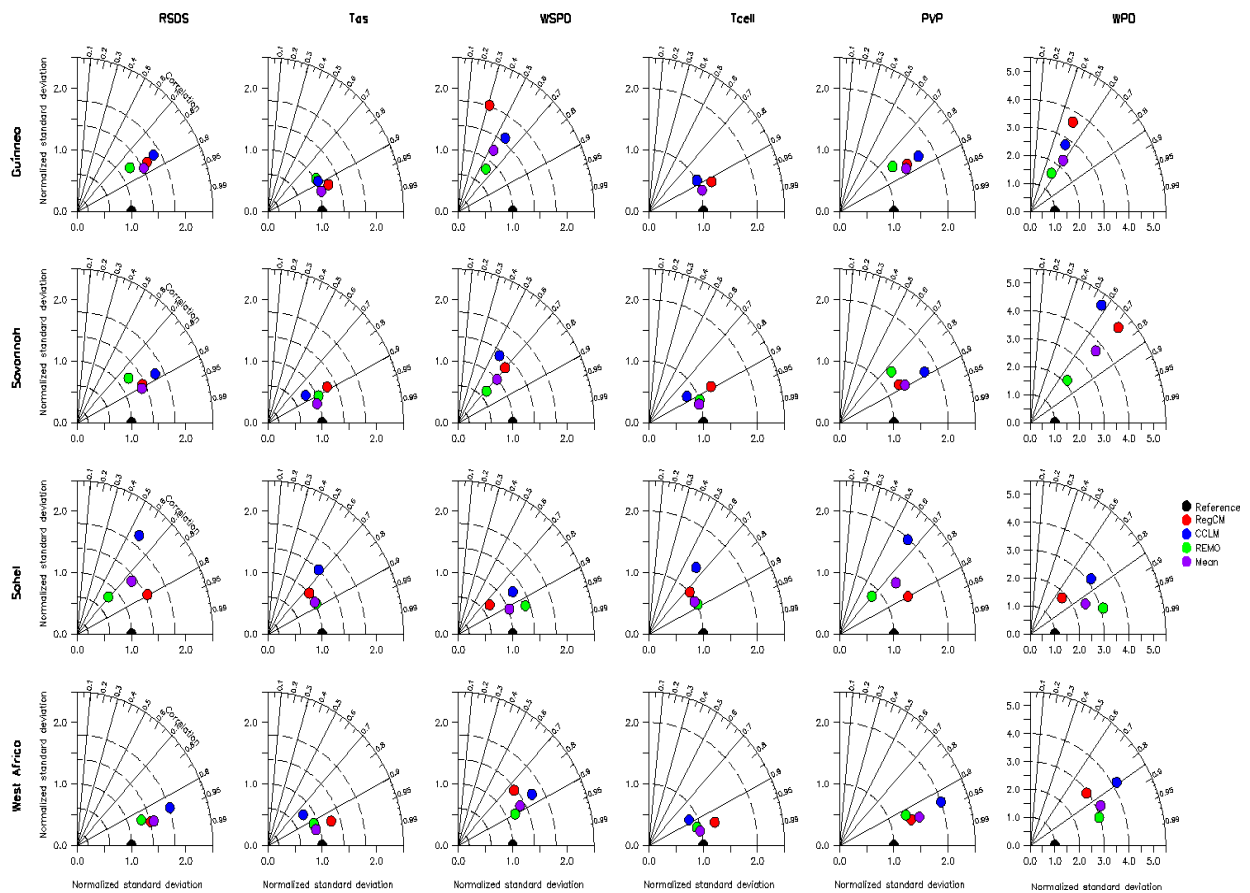


Figure 3.10 Taylor diagram of the observed and simulated solar irradiance (RSDS), ambient air temperature (Tas), surface wind speed (WSPD), cell temperature (Tcell), photovoltaic potential (PVP), and wind power density (WPD) in the reference period and over the three sub-regions of West Africa.

3.3.2 Projected climate changes

3.3.2.1 Future temperature, shortwave solar radiation, and wind speed changes under RCP2.6

Figure 3.11 and *Figure 3.12* show the projected changes of RSDS, Tas, and WSPD under the RCP2.6 scenario. In both future periods, the projection of the variables shows a slight change. The projection of the temperature by the RCMs shows a slight increase across the region in both the near and far future. An increase ranging between 1 °C and 1.5 °C is expected in the near future and far future. CCLM and REMO project lower values of temperature located at the northern coast, southern Niger, and some parts of Nigeria. The highest temperatures are located in the northern part of the region, mainly Niger, Mali, and north of 12°N and 16°N, respectively for RegCM and REMO.

The RCMs expect a slight decrease and a slight increase respectively in solar radiation and surface wind speed, in both periods. A non-significant decrease of about -1% in solar radiation is expected in almost all the regions by the RCMs. CCLM and REMO project a significant decrease in Niger, Guinea, and Savannah zones, respectively. In addition, CCLM is the only RCM expecting an increase in the north of West Africa (Guinea, Savannah, and part of Sahel). For the surface wind speed, a general increase is noticed which is more pronounced with CCLM projection. The increase is significant across the region and ranges between 2 and 4%.

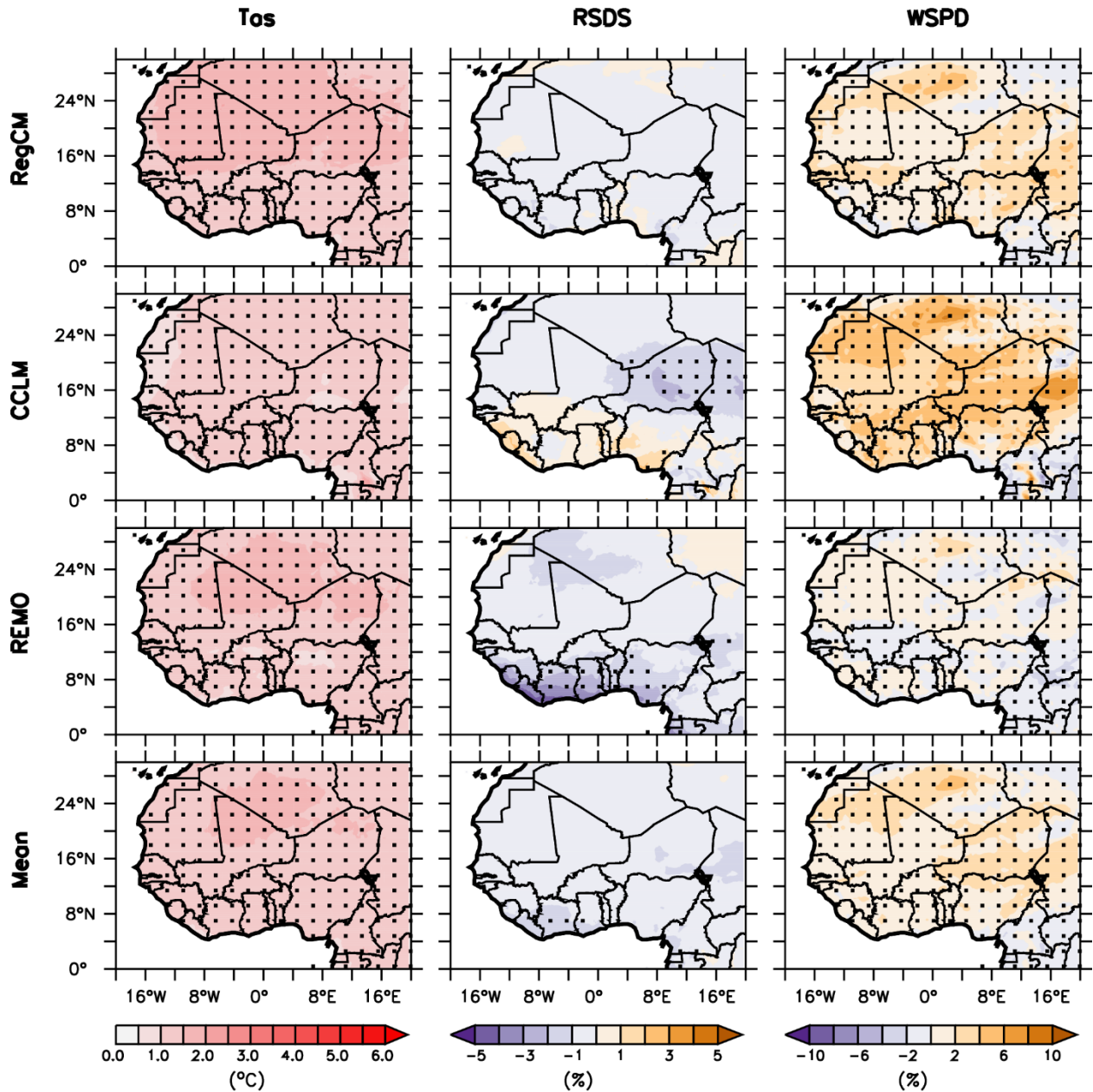


Figure 3.11 Projected changes in the annual average of solar irradiance (RSDS), ambient air temperature (Tas), and surface wind speed (WSPD) over West Africa for the near future (2021–2050) and under the RCP2.6 scenario.

Statistically significant areas are indicated with black dots.

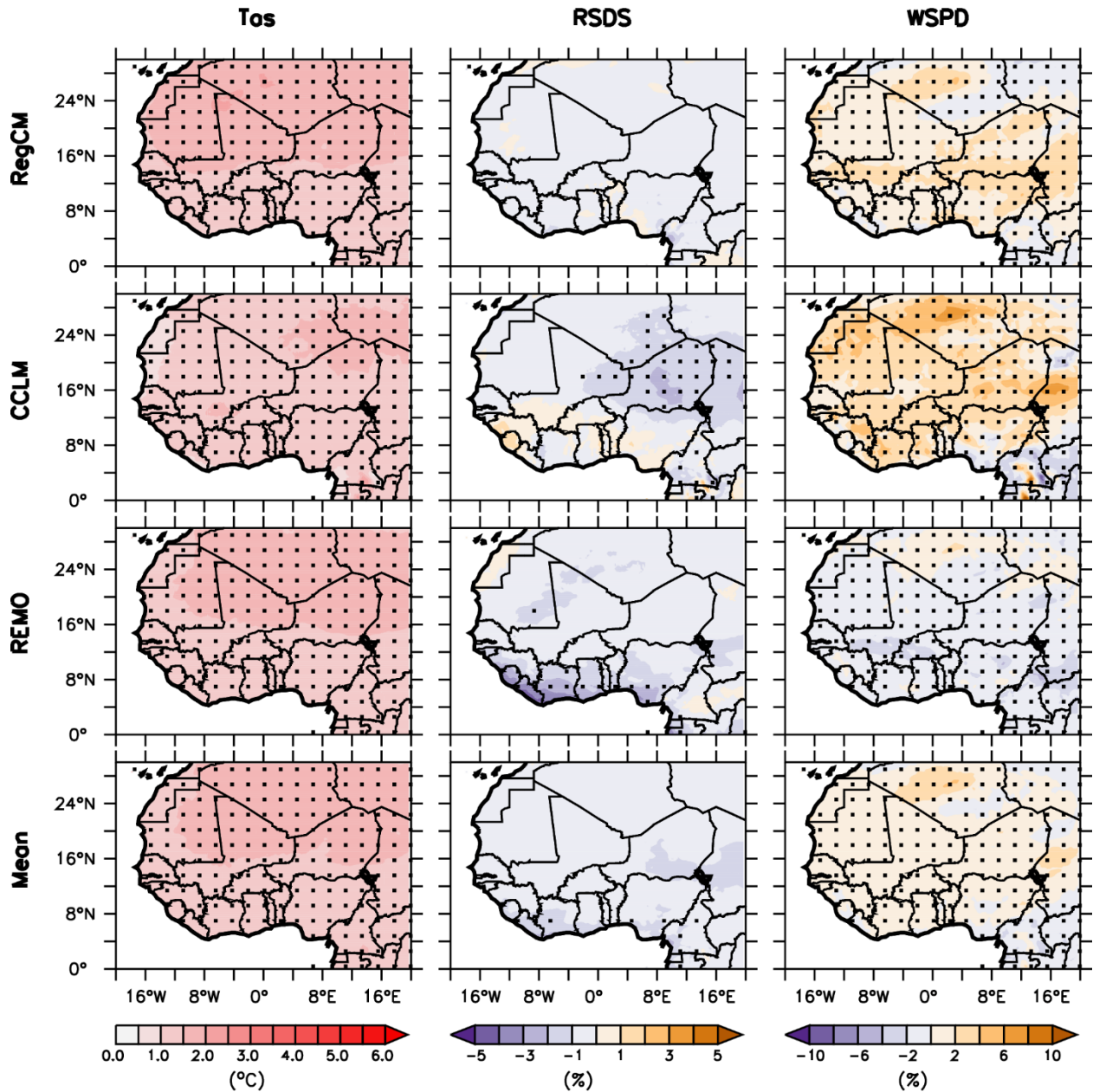


Figure 3.12 Projected changes in the annual average of solar irradiance (RSDS), ambient air temperature (Tas) and surface wind speed (WSPD) over West Africa for the far future (2071–2100) and under the RCP2.6 scenario.

Statistically significant areas are indicated with black dots.

3.3.2.2 Changes in cell temperature, PV potential, and wind power density under RCP 2.6

As noticed in the projection of RSDS, Tas, and WSPD, the projections of Tcell, PVP, and WPD show no major changes (Figure 3.13 and Figure 3.14). In both future periods, the projected increase in Tcell is about 1.5 °C across West Africa and reaches 2 °C in the Sahel and above 16°N. The projections of the PV potential show an average decrease of -1.2 %, in

the near and far future. The projections of Tas and PVP are fairly uniform as compared to WPD. The WPD is expected to have a major increase of less than 20% in some regions and RCPs and less than 10% in others, in both periods. REMO projects that WPD may increase in some regions in the near future and decrease in the far future.

As a result, the projections of the variables under RCP2.6 indicate minor changes in the near and far future.

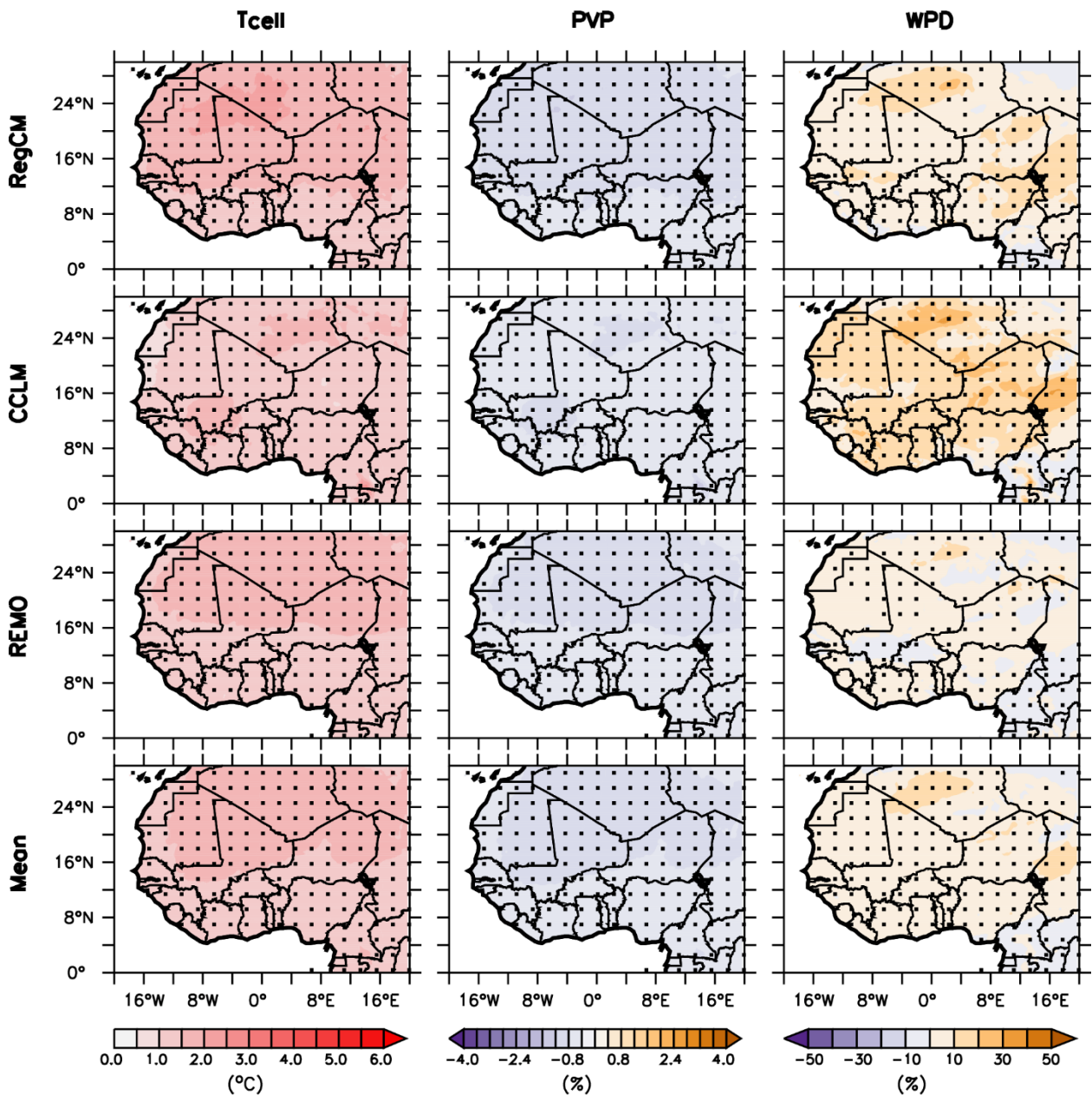


Figure 3.13 Projected changes in the annual average of the cell temperature (T_{cell}), photovoltaic potential (PVP) and wind power density (WPD) over West Africa for the near future (2021–2050) and under the RCP2.6 scenario.

Statistically significant areas are indicated with black dots.

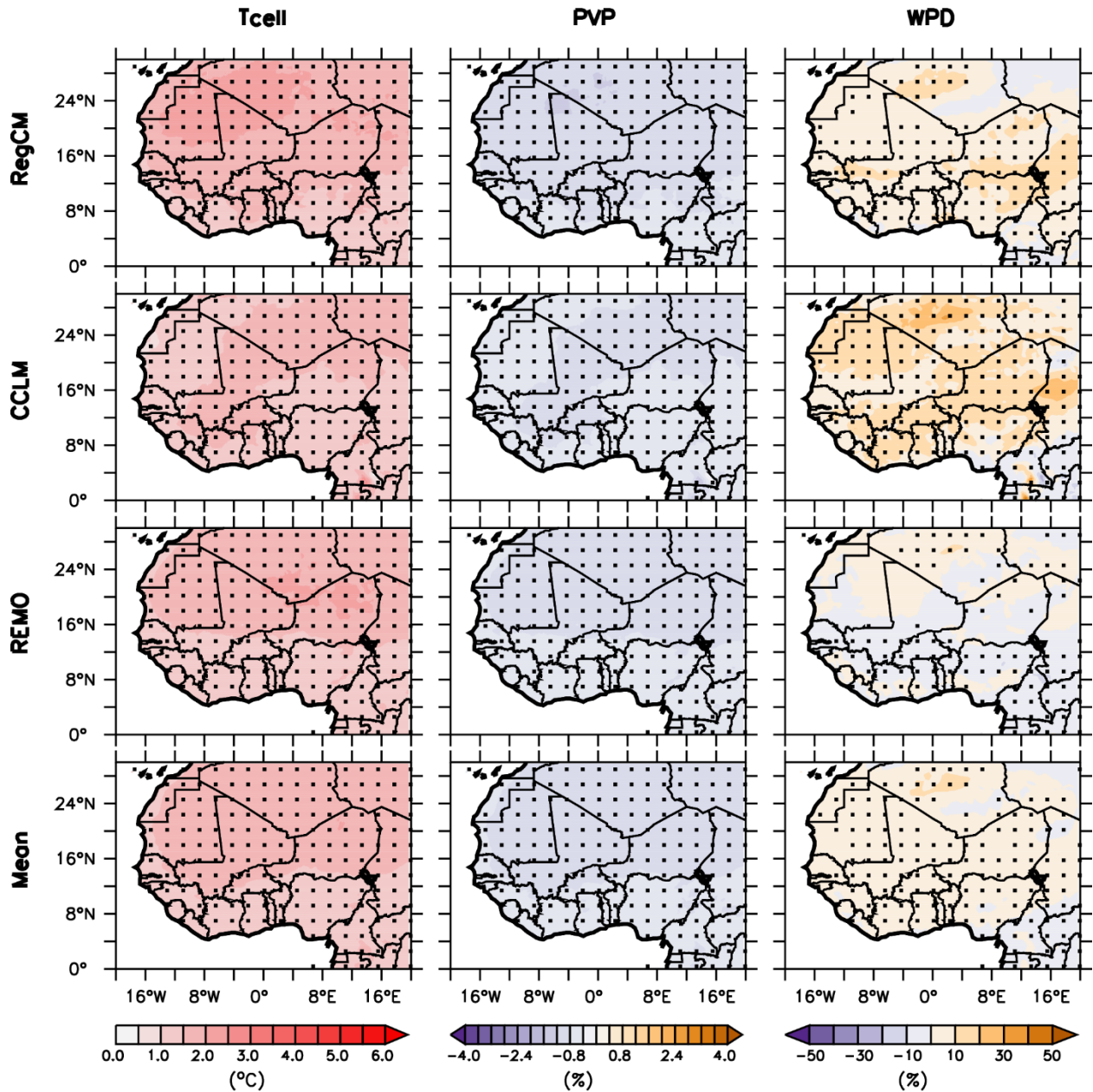


Figure 3.14 Projected changes in the annual average of the cell temperature (Tcell), photovoltaic potential (PVP), and wind power density (WPD) over West Africa for the far future (2071–2100) and under the RCP2.6 scenario.

Statistically significant areas are indicated with black dots.

3.3.2.3 Future temperature, shortwave solar radiation, and wind speed changes under RCP8.5

Compared to the RCP2.6 scenario, the changes in the variables are most pronounced in the RCP8.5 scenario over the region. This is because the RCP8.5 scenario is the most extreme scenario and is more closely aligned with the current global trends in climate change than the RCP2.6 scenario. In the RCP8.5 scenario, temperatures increase significantly more than in RCP2.6.

All three RCMs agree that there will be significant warming over West Africa (*Figure 3.15* and *Figure 3.16*). This increase in temperature is more pronounced in the far future than in the near future. However, the magnitude of the changes varies according to the RCM in both periods. For instance, where RegCM, REMO, and the ensemble mean project an increase of around 2.5 to 3 °C, CCLM projects lower temperatures (~2 °C) for the northern coast of Senegal and around Mauritania. For the near future, the highest temperatures are north of 16 °N for RegCM while for REMO, they are in the northern part of Mali and Niger. The ensemble mean shows an increase of 2.5 °C over the Savannah and Sahel zones, while in Guinea, it projects lower values of around 1.5 °C. This uncertainty in the degree of warming is also discussed by Deme et al. (2017) who found differences in the warming trend in the north of 15 °N (where 3.5 °C is reached) and south of 15 °N (2 °C) over the period 2041-2070 with more moderate warming across the Guinean coast under the RCP8.5 scenario.

In contrast to the temperature projection, a much more diverse picture is shown for RSDS and WSPD projections. A general decrease in RSDS is projected by RegCM, REMO and the ensemble mean for the near and far future. For the near future, RegCM projects a slight decrease (-1 %) which is not significant in most parts of the region, and a slight increase (~1 %) over Senegal and Mauritania. For the far future, a significant decrease is projected in Niger, Mali and the Guinea zone (~- 3 %). The REMO model indicates a significant decrease in almost all West African countries for both periods. A decrease of ~-3 % and ~-2 % for the Guinea and Sahel areas, respectively in the near future and ~- 5 % and ~- 3 % in the far future. These results are consistent with those of Huber et al. (2016) who projected that solar irradiance is likely to decrease mainly in southern and western Africa. In addition, Sawadogo et al. (2019) projected a general decrease in RSDS over West Africa. Only CCLM projected a significant increase (~2 %) over Savannah and a significant decrease (~3 %) over northern Mali and Niger, for the near future. A significant increase of up to 5 % is projected over Guinea, Savannah, and Sahel for the far future.

The projected decrease in RSDS could be explained by an increase in aerosol and cloud cover. Future changes in the cloud and aerosol properties will drive the projected changes in surface irradiance (Danso et al., 2022). In their study, Danso et al., (2022) investigated the relationship between the change in the cloud water path (CWP), aerosol optical depth (AOD) at 550 nm, and the change in surface irradiance, using multiple linear regression. The results showed negative coefficients between CWP and AOD changes and the surface irradiance. They concluded that a unit increase in either CWP or AOD will lead to a reduction of surface irradiance.

There are also discrepancies between the models in the wind speed projection. In both future periods, RegCM, CCLM, and the ensemble mean show a dominant increase in WSPD (up to 10 % for the far future) which is also statistically significant over the region. Whereas REMO shows a decrease in most parts of the region and for both periods.

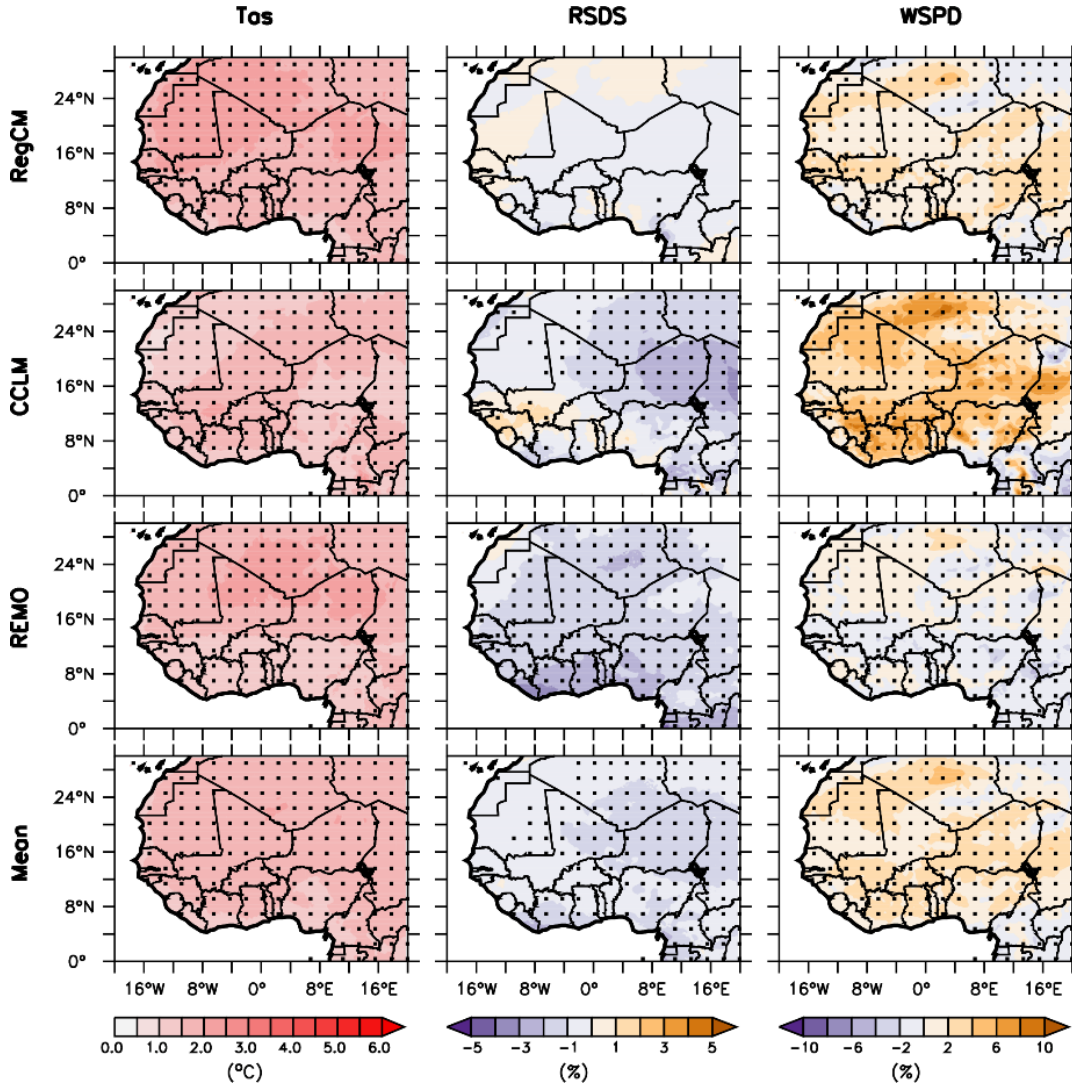


Figure 3.15 Projected changes in the annual average of solar irradiance (RSDS), ambient air temperature (Tas) and surface wind speed (WSPD) over West Africa for the near future (2021–2050) and under the RCP8.5 scenario.

Statistically significant areas are indicated with black dots.

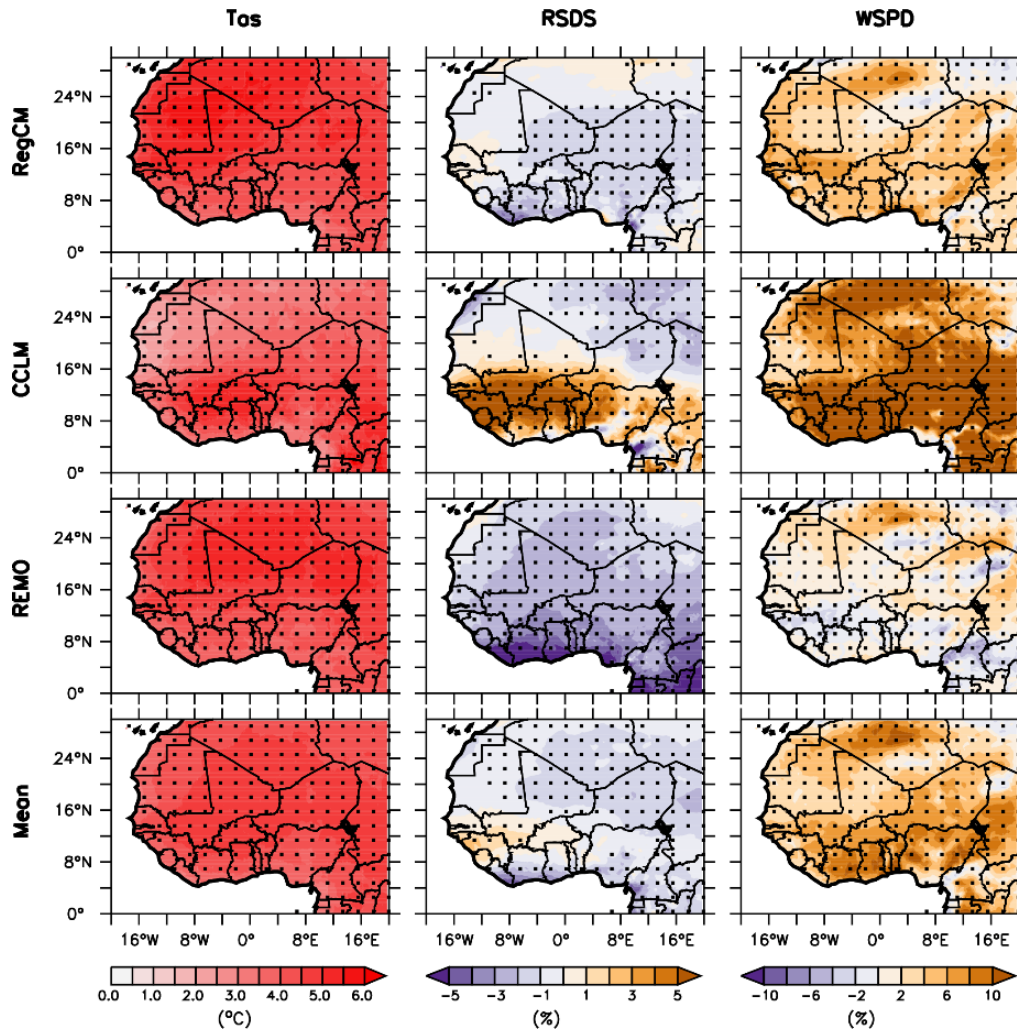


Figure 3.16 Projected changes in the annual average of solar irradiance (RSDS), ambient air temperature (Tas), and surface wind speed (WSPD) over West Africa for the far future (2071–2100) and under the RCP8.5 scenario.

Statistically significant areas are indicated with black dots.

3.3.2.4 Changes in cell temperature, PV potential, and wind power density under RCP8.5

The projection of these variables is similar to that of Tas, RSDS, and WSPD. The formulae presented in the methodology show the dependence of the variables. As noted in the previous section on Tas, the projection of Tcell shows an increase across the region which is higher and more accentuated in the far future. In the near future, the lower values of Tcell are in the Guinea zone for RegCM, REMO, and the ensemble mean (~2 °C), while for CCLM, they are on the northern coast of Senegal and around Mauritania. In the far future, a general increase of about 4 °C to 6 °C is projected by the RCMs and Mean. As shown in Equation 4, Tcell depends only on air temperature and solar radiation. Since the radiation changes are marginal, the increase

in Tcell can be explained by the relatively strong increase in air temperature.

A general decrease in PVP is projected over the region (*Figure 3.17* and *Figure 3.18*). The ensemble mean shows a decrease of -2% in the near future and more than -3 % in the far future. All RCMs agree on the magnitude of the changes in the far future (>-2.4 %) except CCLM which projects lower values ranging between -0.8 and -1.6% in the north of Senegal, Mali, Mauritania, north of Niger, and Algeria. The RegCM model indicates that the Sahel area will experience a higher decrease in PVP than the Guinea and Savannah areas in the near future, while REMO projects a higher decrease in the north of Mali, Niger, and a part of Algeria. The spatial variation of PVP in the region could be explained by the spatial variation of Tcell and RSDS. The PVP is sensitive to Tcell which can induce its reduction. According to Mavromatakis et al. (2010), one of the major factors leading to the reduction of the power produced by a PV system is the increase in its temperature. Another factor is solar irradiance since it is the dominant variable for PVP calculation. For instance, Sawadogo et al. (2019) found a strong positive correlation between RSDS and PVP ($r > 0.93$). The decrease in PVP in West Africa has been shown by several studies (Sawadogo et al., (2019); Danso et al., (2022); Huber et al., (2016); Bazyomo et al., (2016)). As shown in the previous section, RCM simulations suffer from biases and other limitations, but the future decrease of the PVP over West Africa seems evident even though the magnitude of the decrease varies among the RCMs.

Conversely, the projection of WPD is subject to some uncertainties (*Figure 3.17* and *Figure 3.18*). The models RegCM and CCLM, as well as the ensemble mean project a dominant increase of up to 20% in the near future, but more pronounced in the far future (~ 40 %). REMO is more likely to project a dominant decrease of about -10 % in most parts of the region in both future scenarios. The results of the studies of wind power potential over West Africa are quite diverse. The uncertainties in the projection of wind energy potential are larger than those of solar PV potential over West Africa. This could be due to the consistency of the models in simulating the temperature and solar radiation compared to the representation of the wind speed.

The results of this study are in line with those of Sawadogo et al. (2020) who projected an increase in the WPD when using the RegCM4 CORDEX-CORE ensemble. However, they are in contradiction with the study of Ogunjobi et al. (2022) who found a decline in the wind production in Guinea and Savannah in the near future (2021-2050) before increasing towards the end of the century under RCP4.5 and RCP8.5 scenarios. It is noted that results obtained at lower resolution (CORDEX, CMIP6) showed a decrease in wind power density over the Sahel

(Akinsanola et al., 2021) and over Guinea and Savannah (Ogunjobi et al., 2022) where an increase is projected in our study.

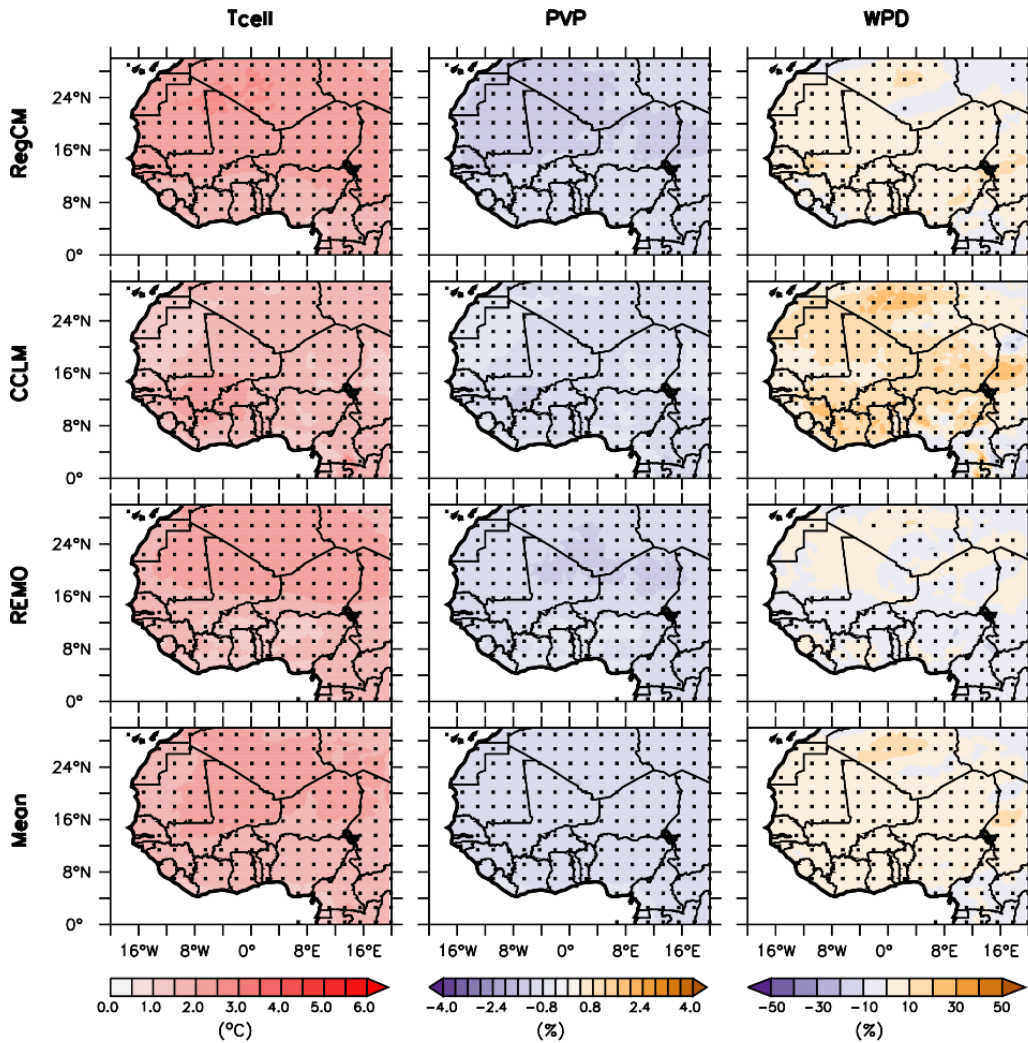


Figure 3.17 Projected changes in the annual average of the cell temperature (*T_{cell}*), photovoltaic potential (*PVP*) and wind power density (*WPD*) over West Africa for the near future (2021–2050) and under the RCP8.5 scenario.

Statistically significant areas are indicated with black dots.

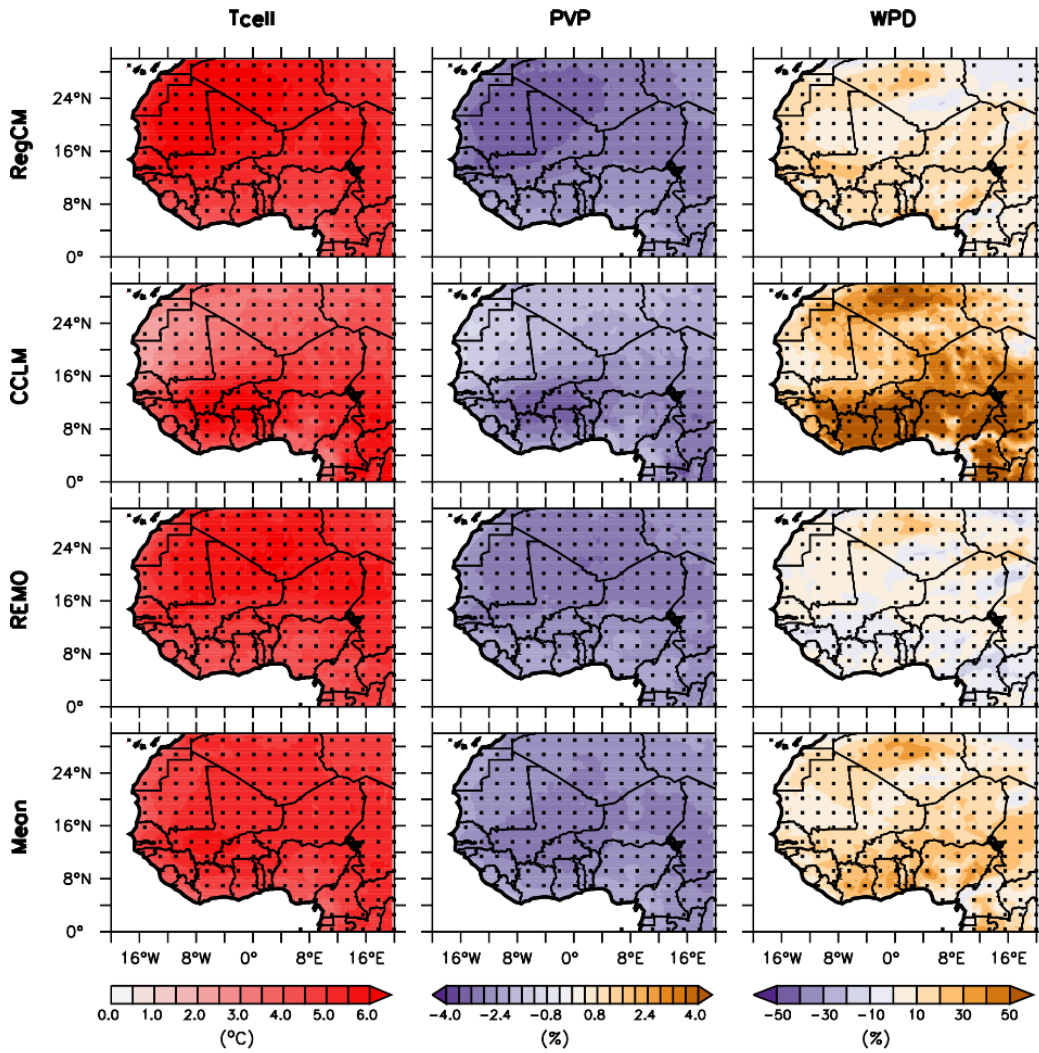


Figure 3.18 Projected changes in the annual average of the cell temperature (*T_{cell}*), photovoltaic potential (*PVP*) and wind power density (*WPD*) over West Africa for the far future (2071–2100) and under the RCP8.5 scenario.

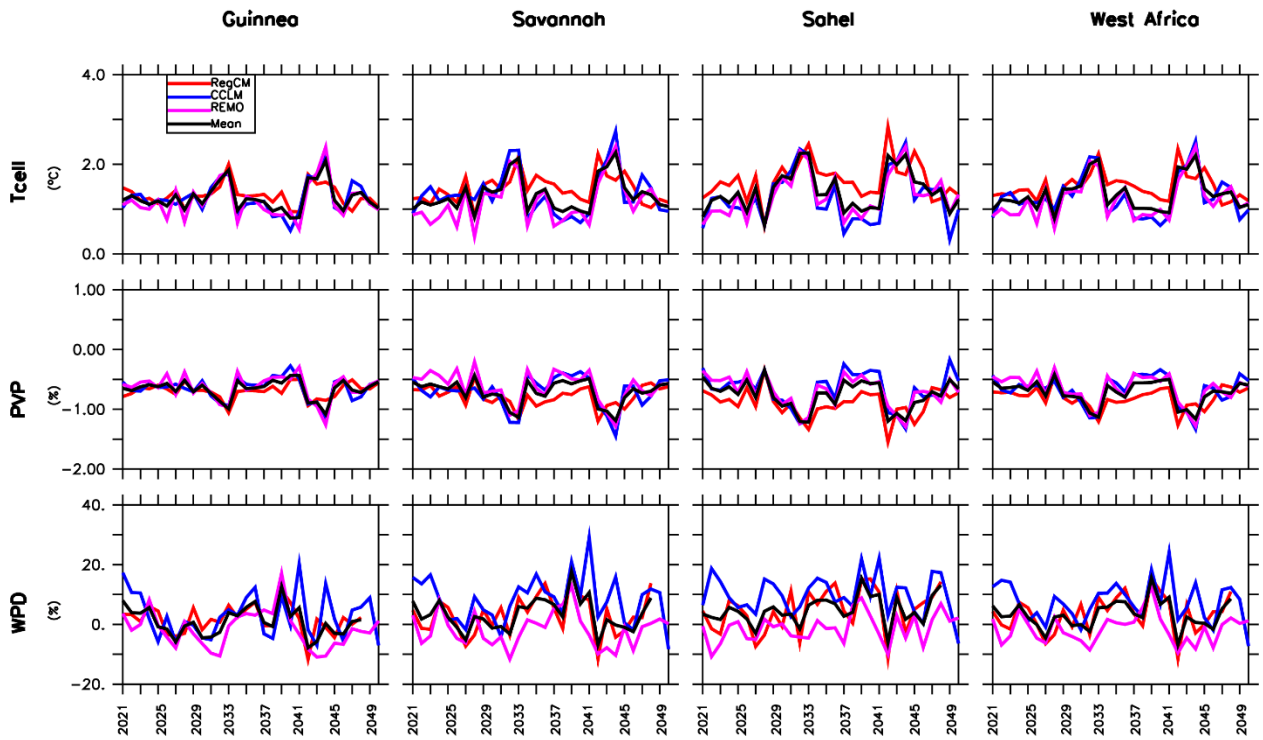
Statistically significant areas are indicated with black dots.

3.3.3 Inter-annual variability under RCP2.6

The interannual variability under the RCP2.6 scenario for the cell temperature, the PV potential, and WPD is shown in *Figure 3.19*. The models are consistent with the trend and magnitude of *T_{cell}* and *PVP*. For both future scenarios, the models show an increase in *T_{cell}* which is less than 2 °C in all sub-regions. The same for the PV potential with a decrease of about -1%. The results of the interannual variability of *WPD* indicate a slight increase in all sub-regions and periods. The models are more in agreement with the direction, with some models projecting a higher magnitude of changes in some regions. Overall, the models project a future with increased *T_{cell}* and *WPD*, and a decrease in PV potential in all sub-regions. The

degree of change varies between models and regions, mostly in the case of WPD.

(a)



(b)

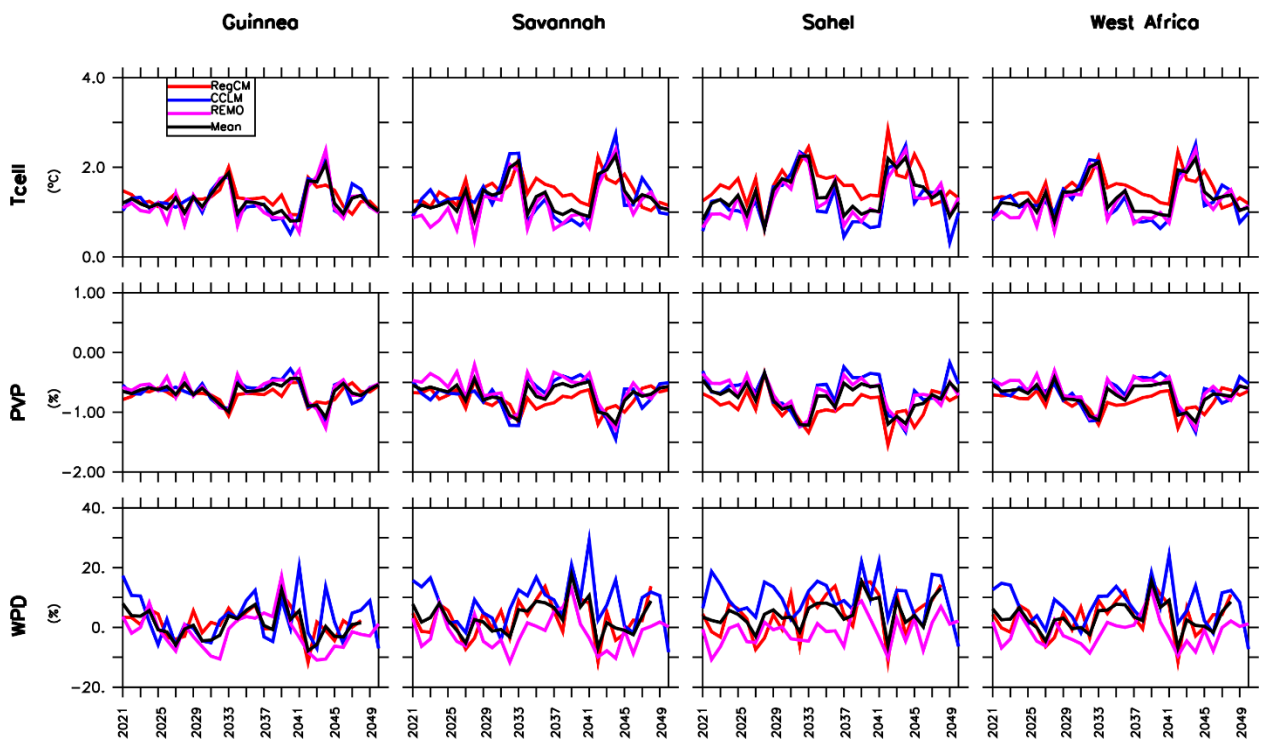


Figure 3.19 Inter-annual variability of the projected changes of the cell temperature (Tcell) and the solar and wind potential (PVP and WPD respectively) over the climatic zones of West Africa for the near future (a) (2021–2050) and far future (b) (2071-2100) and under RCP2.6 scenario.

3.3.4 Inter-annual variability under RCP8.5

Figure 3.20 shows the inter-annual variability of Tcell, PVP, and WPD under the RCP8.5 scenario and for the mid and late centuries. As seen in scenario RCP2.6, the models broadly agree on the pattern and magnitude of Tcell and PVP projections as compared to WPD in all the sub-regions. For both future scenarios, the RCMs indicate a progressive increment in Tcell and a decrease in PVP. In the near future, for all sub-regions, a rapid increase in Tcell of about 3 °C for the Sahel and Savannah, 2.4 °C for Guinea, and about 2.7 °C for West Africa were found for the period 2021-2050. By the end of the century, about 6 °C and 5 °C for Sahel-Savannah and Guinea, respectively. For the same period 2021-2050, the decrease in PVP is slightly stronger (-2%) in the Sahel-Savannah than in Guinea, (~-1.4%) and becomes more pronounced in the far future where the values for Sahel-Savannah and Guinea reach -3.5% and -3%, respectively.

The inter-annual variability of WPD shows more divergence between the models compared to RCP2.6. CCLM predicts a higher magnitude in the projected WPD in both periods and for all the climatic zones. In the mid-century, CCLM and REMO project a slight increase and a slight decrease in WPD over the region, respectively. In comparison, CCLM expects a sharp increase for the period 2071-2100, which in terms of intensity at the end of the century is about 60% for the Guinea zone, about 65% for the Savannah, and 40% for the Sahel. On the other hand, REMO expects a slight decrease in WPD of about -3 to 5% for Guinea, Savannah, and the whole region of West Africa and no major change for the Sahel. RegCM and the ensemble mean tend to show no major variations in the near future and an increase between 10 and 20% in the far future.

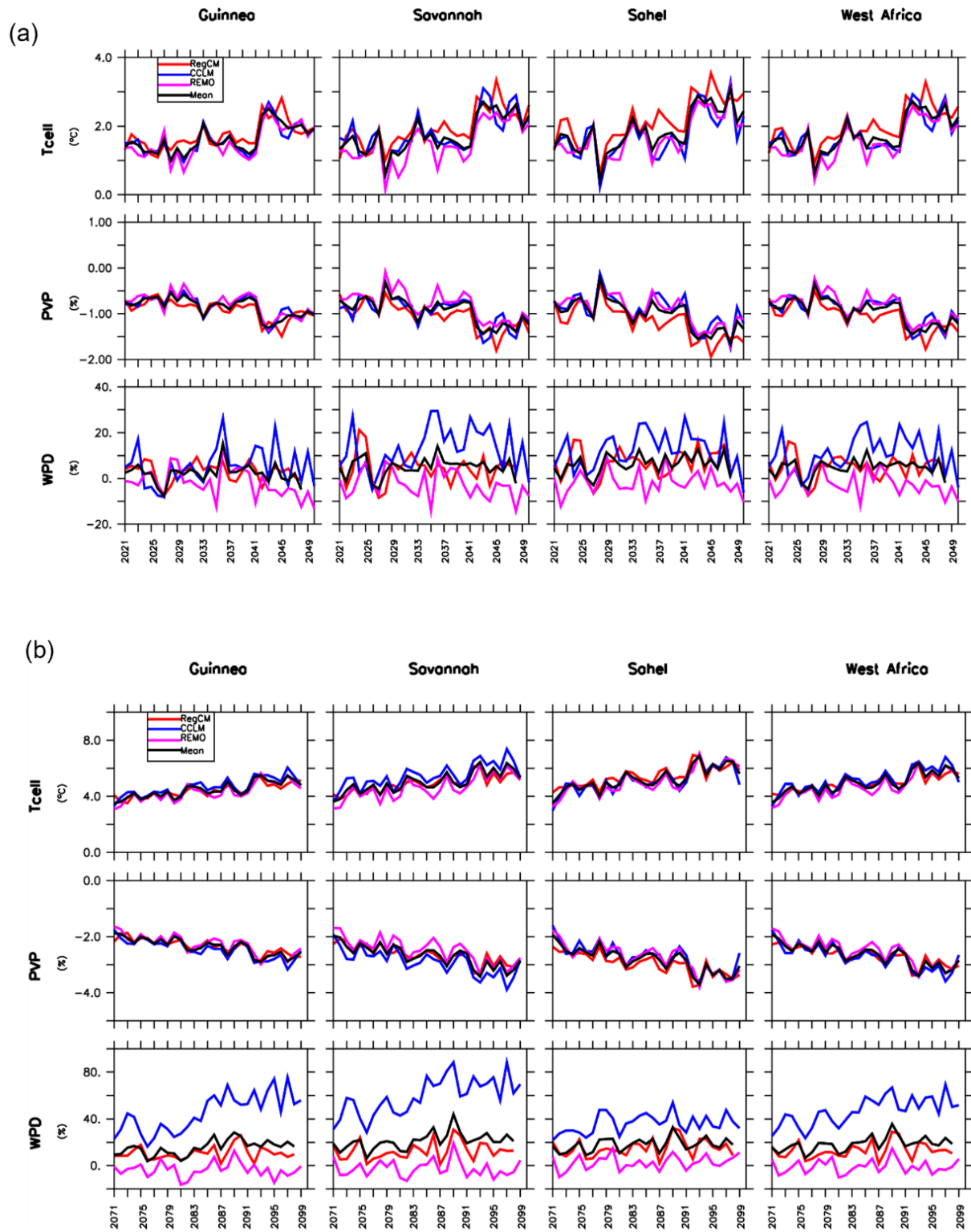


Figure 3.20 Inter-annual variability of the projected changes of the cell temperature (T_{cell}) and the solar and wind potential (PVP and WPD respectively) over the climatic zones of West Africa for the near future (a) (2021–2050) and far future (b) (2071-2100) and under RCP8.5 scenario.

3.3.5 Models' agreement on the projected changes under the RCP8.5 scenario

The representation of the agreement between the models for the projections of the variables (*Figure 3.21*) shows a general agreement across the region for Tas (near and far future) and Tcell (near future). This shows a robust projected change for the temperature variables. The RCMs agree on warming and project a 1°C increase in the air temperature in the near future and between 3.5°C and 4 °C in the far future with Mali, Burkina, and Niger experiencing the highest temperatures at the end of the century. The models also expect an increase in Tcell of 1°C to 1.5 °C in the near future. In the far future, an increment of 3.5 °C to 5 °C is expected in the northern part of the region, mainly the Sahel zone, in some parts of Savannah and north of 16°N. This is also valid for the other variables like WSPD, PVP, and WPD, where the RCMs show consistent agreement results in the same zones.

For the decrease in PVP, the models disagree in most parts of Guinea and Savannah and for both future periods. A general decrease ranges between -0.8 and - 2.4 % and more than - 2.4 % over the Sahel area and north of 16 °N, respectively in the near and far future is projected. A similar agreement is noticed for WSPD and WPD for both periods. Unlike PVP, the disagreement in WPD is spread over the region in both periods, it is not just limited to one area. The RCMs agree majorly in Niger, the north of Mali and Nigeria, but also around Mauritania and Algeria, for the far future. In these areas, an increase in WPD ranges between 10 to 20 % is expected. The projection of the temperature variables and PVP show more consistent agreement as compared to RSDS, WSPD, and WPD. In summary, most parameters show inconsistency in the sign of future changes in some areas, which could be related to the internal variability of the model, the initial conditions, or the configurations of the different GCMs (Giorgi and Francisco, 2000). A lack of agreement therefore implies lower reliability of projected change of these variables over the considered period.

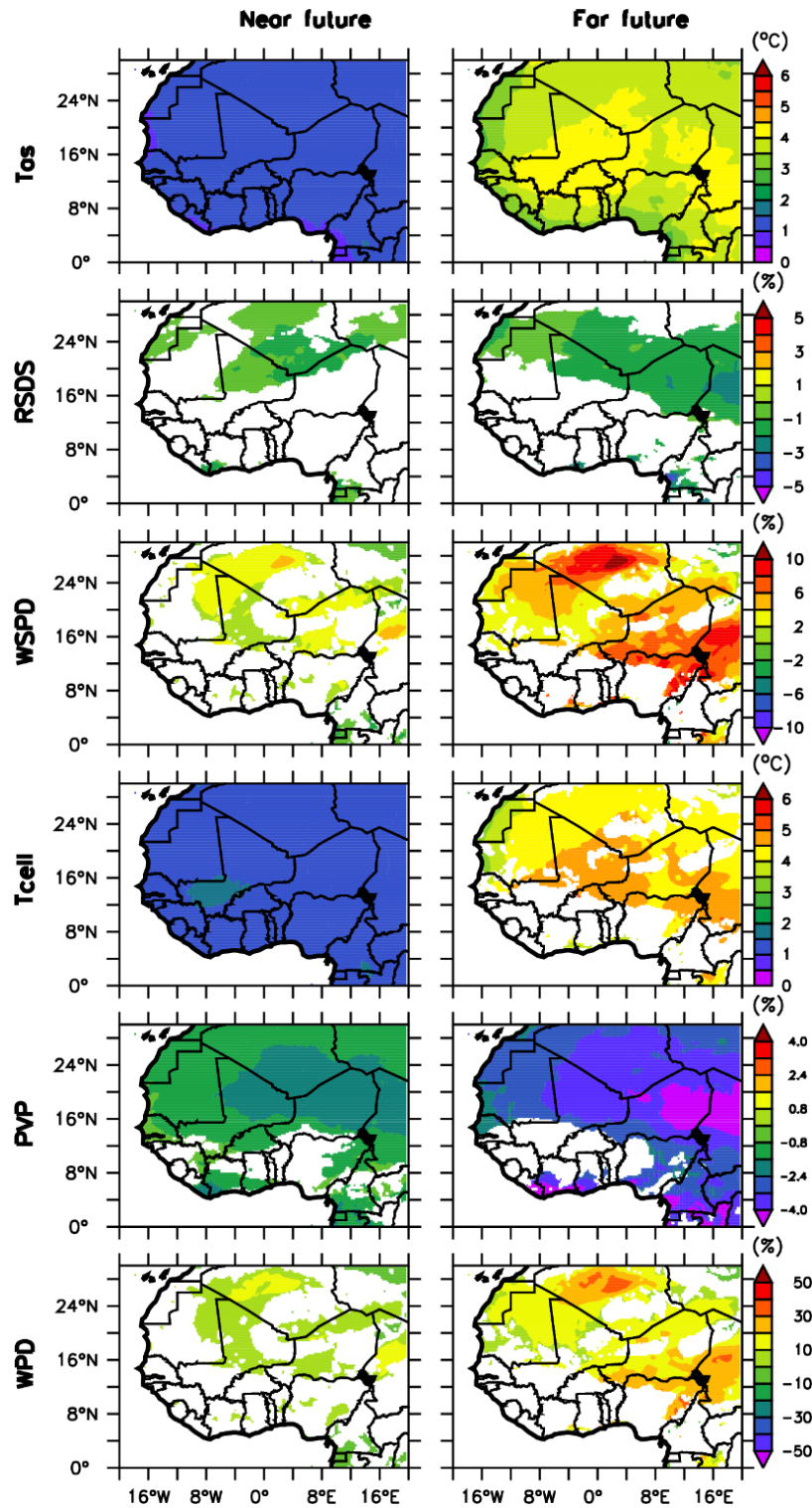


Figure 3.21 Models agreement: Projected changes in the annual average of solar irradiance (RSDS), temperature (Tas), surface wind speed (WSPD), cell temperature (Tcell), photovoltaic potential (PVP) and wind power density (WPD) over West Africa for the near (2021–2050) and far future (2071–2100) under the RCP8.5 scenario.

The white color indicates areas where the models disagree.

B- SENEGAL

The goal of this section is to examine the outlook for future renewable energy production, particularly solar, in Senegal. Since 2016, the government of Senegal has been investing in renewable energy with more emphasis on solar. About ten solar plants and a large wind farm are implemented in the country. Renewable energy sources are becoming more important in Senegal as the country strives to achieve its goals of energy security and access. The country has committed to increasing its energy production from renewables to 15% by 2025 and 25% by 2030. The goal of this section is to examine how solar energy production from the existing solar plants in the country will evolve in the horizon of 2050. We look at the current trends in solar energy production, the expected growth over the next 30 years, as well as the potential effects of climate change on energy production in the country.

3.4 Climate change's impact on solar production

3.4.1 Methodology

3.4.1.1 Study Area and Data

The study focuses on the existing solar plants of Senegal more specifically on Ten Merina. Senegal is a coastal West African country that has a population of approximately 17 million people. Ten Merina is located in the department of Tivaoune, the region of Thies. The plant is an on-grid independent power producer with an installed capacity of 23 MW. The energy produced is directly injected into the SENELEC network which buys it. Ten Merina has been operational since early 2018. The plant comprises 92160 polycrystalline panels over an area of 44 ha.

The plant has meteorological stations that measure data on solar irradiance, cell and ambient temperature, humidity, wind speed, pressure, etc. We collected one-year hourly data (2020) on solar irradiance and cell temperature. The monthly and yearly mean used in this study are calculated from the hourly data. We also collected daily production data for the plant for 2020 and yearly for 2018, 2019, and 2021.

In this study, CORDEX-CORE simulation data were employed for the projection of energy production. The regional climate model (RCM) RegCM4, driven by three Global Climate Models (GCMs) (NorESM1-M, MPI-ESM-MR, and HadGEM2-ES) from the fifth version of the Coupled Model Intercomparison Project (CMIP5) were used. Ndiaye et al. (2022) found that RegCM4 is the most effective model for simulating solar irradiance in West Africa in comparison to REMO and CCLM, and it is also capable of accurately predicting air

temperature. Therefore, RegCM4 was chosen for this study. Monthly shortwave solar radiation and air temperature are used. The model was validated with ERA5 data. In this study, we work with yearly mean which is calculated from the monthly and daily data respectively of CORDEX and ERA5. The simulation spans from 1975 to 2050, with the reference period being 1975–2004 and the future period being 2005–2050 under the RCP8.5 scenario. The ERA5 data ranges from 1979-2021. The locations of the Ten Merina plant, as well as the other operational solar plants in Senegal, are shown in *Figure 3.22*.

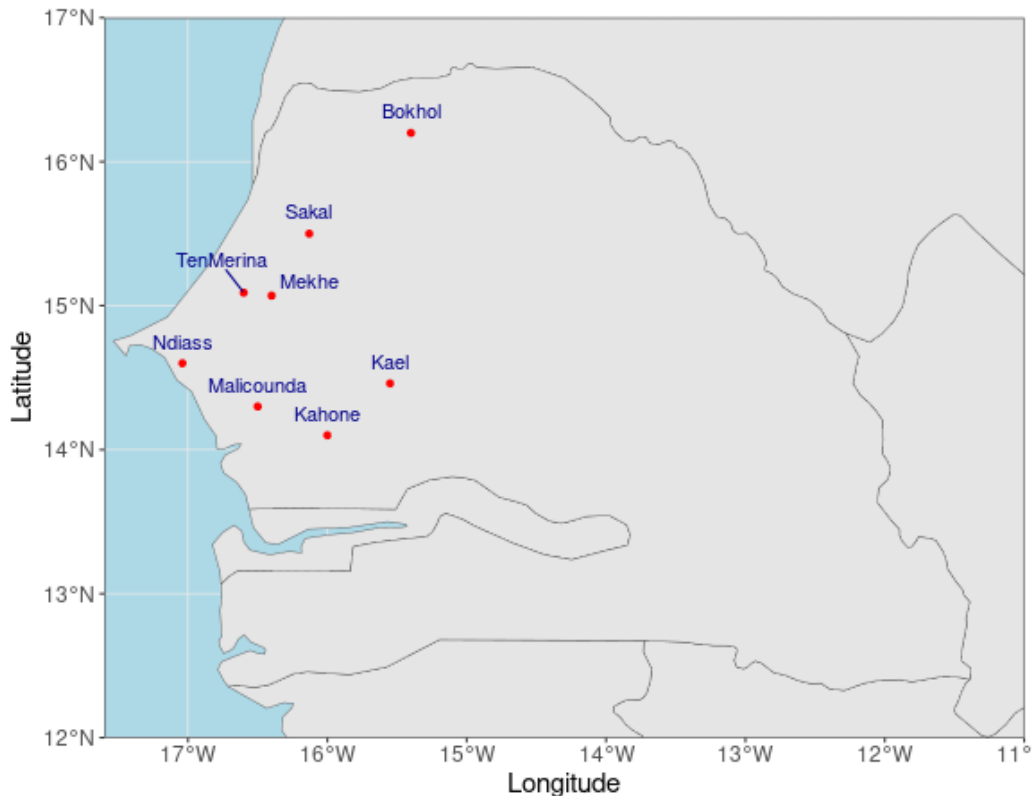


Figure 3.22 Study area showing the operational solar plants in Senegal.

3.4.1.2 Methods

3.4.1.2.1 Solar Plant production estimation (Estimating Solar Plant output)

To estimate the production P of the Ten Merina solar plant, we applied the formula introduced by Mavromatakis et al. (2010). This method involves estimating solar plant production by considering the performance of PV cells in real-world environmental conditions. The formula from Mavromatakis et al. (2010) was utilized in Section 3.1, and in this section, we incorporate the contribution of nominal power. The production can be represented by Equation 3.11:

$$P = P_p * P_r \frac{G}{G_{stc}} \quad (3.11)$$

In the provided equation, P_p represents the nominal power of the PV module given by the manufacturer at STC conditions. G is the solar irradiance at the plane of the module, G_{STC} represents the solar irradiance of 1000 W/m^2 , and P_r denotes the performance ratio of a PV system, which accounts for various environmental factors.

To have the energy produced by the plant, we multiply P by the time (t).

$$P \text{ (KWh)} = P_p * P_r \frac{G}{G_{stc}} * t \quad (3.12)$$

The performance ratio P_r is estimated following Jerez et al. (2015):

$$P_r = 1 + \gamma(T_{cell} - T_{stc}) \quad (3.13)$$

where T_{cell} denotes the PV cell temperature and T_{stc} represents the temperature of the cell under standard test conditions ($25 \text{ }^\circ\text{C}$). The parameter γ is the temperature coefficient of the maximum power and is equal to $0.0035 \text{ }^\circ\text{C}^{-1}$ for poly-crystalline silicon cells (Fuentes et al., 2007). According to Skoplaki (2008) and Sun et al. (2020), T_{cell} is computed based on the NOCT (nominal operating cell temperature) coefficient:

$$T_{cell} = T_a + \left(\frac{NOCT-20}{800} \right) * G \quad (3.14)$$

The NOCT is generally given by the manufacturer and is around $45 \pm 2^\circ\text{C}$ for both monocrystalline and polycrystalline PVs (Sun et al., 2020). T_a is the ambient air temperature.

3.4.1.2.2 Bias correction

To reduce the overestimation of the production calculated with the CORDEX-CORE data and to improve the accuracy of the model's projection, a bias correction was performed. Bias correction enhances the accuracy of the model by adjusting the estimated parameters to compensate for any bias. This adjustment can be done by using a variety of methods. In this study, we use the method of Hawkins et al. (2013):

$$P_{BC}(t) = \overline{O_{ref}} + \frac{\sigma_{o,ref}}{\sigma_{T,ref}} (T_{raw}(t) - \overline{T_{ref}}) \quad (3.15)$$

Where $P_{BC}(t)$ is the bias-corrected production calculated with Cordex data, O_{ref} and T_{ref} are ERA5 and CORDEX production in the historical reference period, respectively. T_{raw} is raw CORDEX production for the historical or future period $\sigma_{T,ref}$ and $\sigma_{o,ref}$ represent the standard deviation in the reference period of the CORDEX production and ERA5, respectively.

3.4.2 Results

3.4.2.1 Validation of the production formula

Figure 3.23 illustrates the monthly mean of the energy production of the Ten Merina plant for the year 2020. The black curve represents the observed production collected from the plant,

the blue curve is the calculated (reconstructed) production using Equation 3.12, and the red curve is the solar irradiance. The production level is higher during the dry season (January-May and October-December) as compared to the rainy season (June-September). The highest production is recorded in March, April, and October when the country receives abundant irradiation. Conversely, during the rainy season, the presence of cloud cover diminishes the amount of solar radiation reaching the Earth's surface. This indicates the dependence of solar energy on weather conditions. Besides, the figure shows that the calculated output (in blue) closely follows the actual output (in black) over the period of time. This indicates that the formula is accurate and can be used to predict the production of a solar plant.

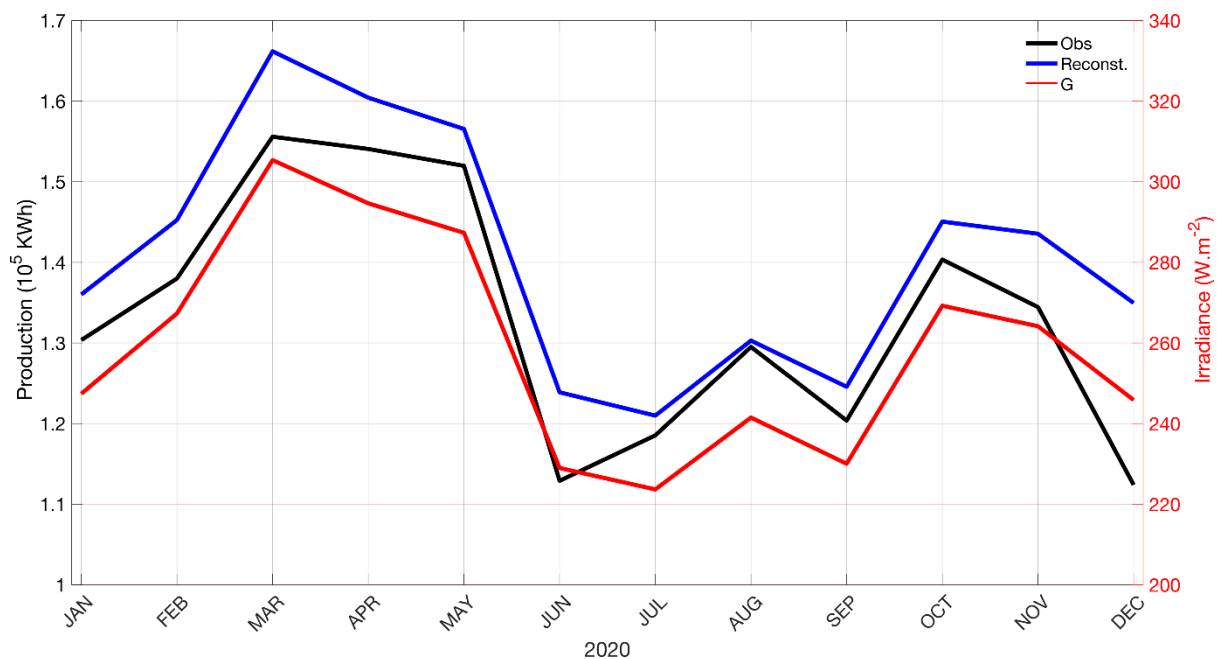


Figure 3.23 Reconstruction of the solar energy production of Ten Merina for the year 2020.

3.4.2.2 Evaluation and validation of ERA5

Figure 3.24 depicts the reconstruction of the energy production of Ten Merina using ERA5 data from 1979 to 2021. In order to use ERA5 for the validation of CORDEX, we validate the production of ERA5 by comparing it with the observed production for the years 2018-2021 in which production data were available (Table 3.2). This comparison determines the accuracy of ERA5 in simulating the climate variables such as temperature and irradiation used to calculate the production. As shown in Table 3.2, ERA5 captures the temporal pattern of the production and its intensity from 2018 to 2021 with a slight overestimation ranging from 2540 kWh to 7322 kWh.

The ERA5-simulated mean production is slightly higher than the observed mean production with a lower coefficient of variation. Overall, ERA5 is able to accurately capture

the temporal pattern and intensity of the observed production from 2018 to 2021 and can be used to validate CORDEX.

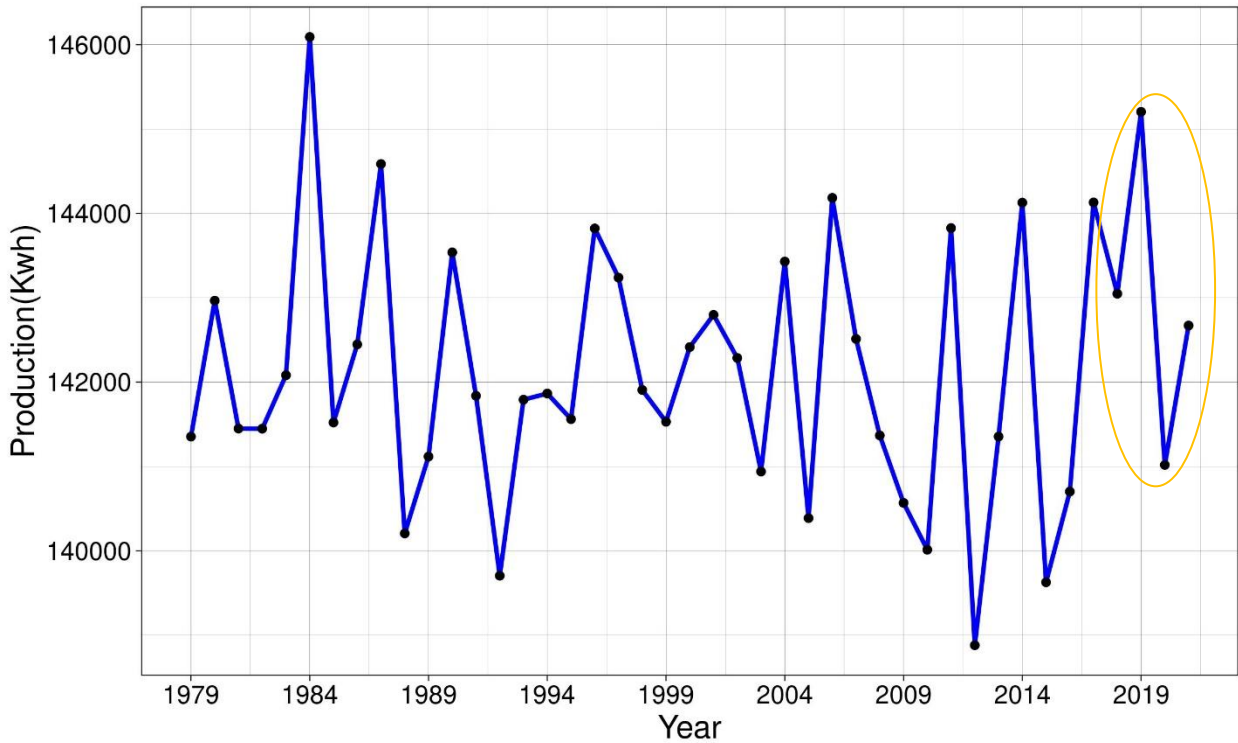


Figure 3.24 Reconstruction of the yearly energy production of Ten Merina using ERA5 data from 1979 to 2021.

Table 3.2 ERA5 production vs observed production for the years 2018-2021

	2018	2019	2020	2021
Observed production (KWh)	134.862	139.357	133.626	132.267
Reconst_ERA5	139.923	141.897	137.909	139.589

3.4.2.3 Model evaluation

To validate the models, a comparison between the model outputs and ERA5 data is conducted. *Figure 3.25* and *Figure 3.26* show the simulated (CORDEX-CORE) and observed (ERA5) time series of the annual mean production of Ten Merina for the reference period and the spatial distribution of the annual mean solar production over Senegal, respectively. *Figure 3.25* indicates an overestimation of the production of the plant even though the annual variability is captured. An overestimation of about 10000 KWh by the GCMs is noticed. This could be caused by various reasons such as the resolution, changes in the local climate, modelling parameters, etc. The GCMs are often unable to capture local-scale effects such as

topography, land-use changes, and aerosol effects. The models may also be subject to biases in their assumptions and parameterizations.

We performed a bias correction using the method outlined in *section 3.4.1.2.2*. The bias of 10000 KWh is corrected and the plant production by CORDEX-CORE is more accurate (*Figure 3.25 (b)*). This correction will help to have a better projection of future production and provide more reliable estimates to the stakeholders.

Overall, the figure indicates that the models are not accurately predicting energy production and need to be corrected. The results suggest that the model can accurately predict the annual mean production of the solar plant with bias correction.

In *Figure 3.26*, the spatial distribution of the annual mean solar production over Senegal is presented. The GCMs demonstrate satisfactory accuracy in their spatial representation with some biases. They generally provide a good pattern representation of the mean production. However, the accuracy of the GCMs can vary across different zones of the country. The northern part of Senegal is better represented as compared to the centre and southern parts where the production is overestimated by all the models.

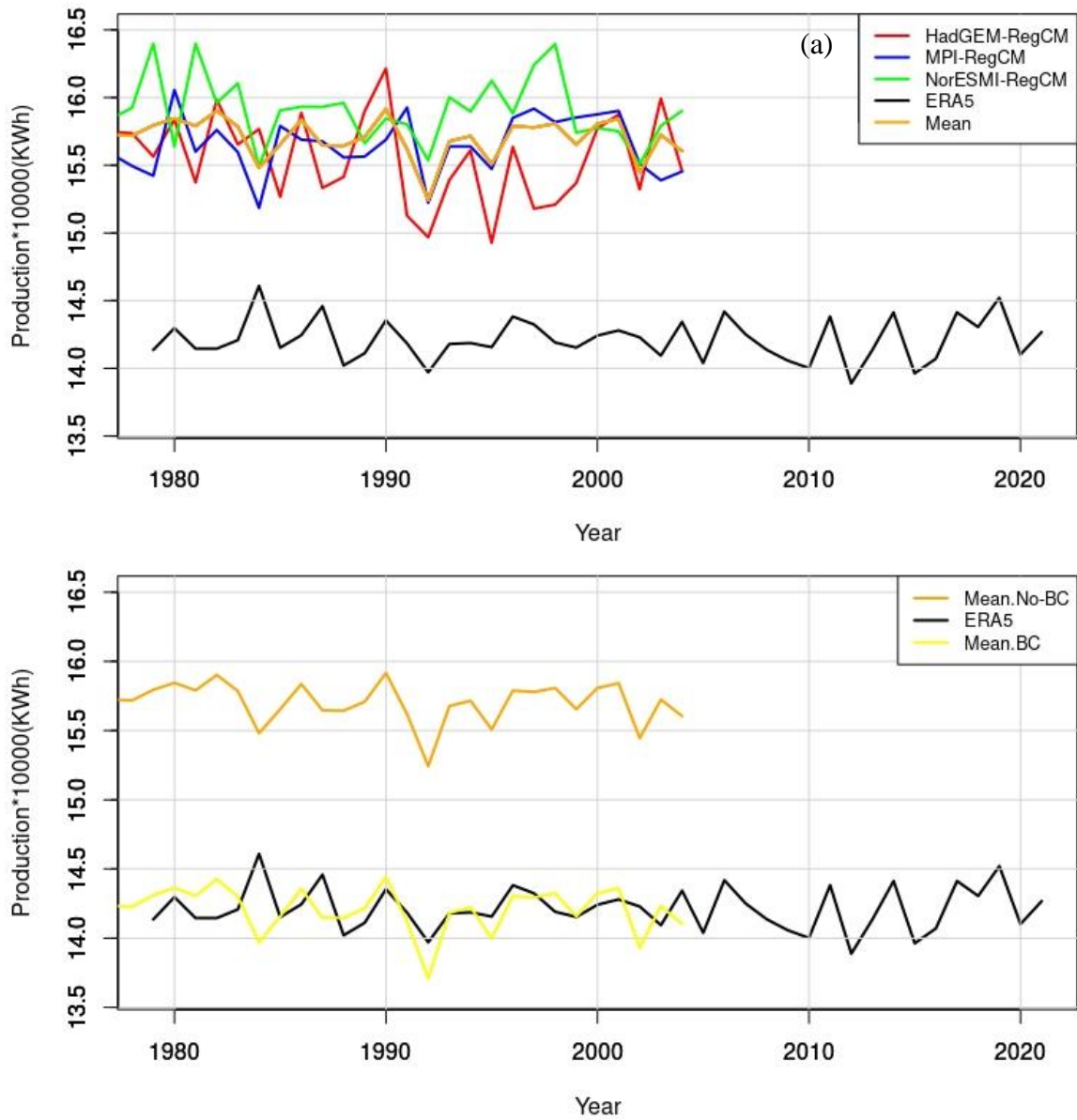


Figure 3.25 Time series of the annual mean production of Ten Merina using RegCM4 of CORDEX-CORE (1975-2004) and ERA5 (1979-2021).

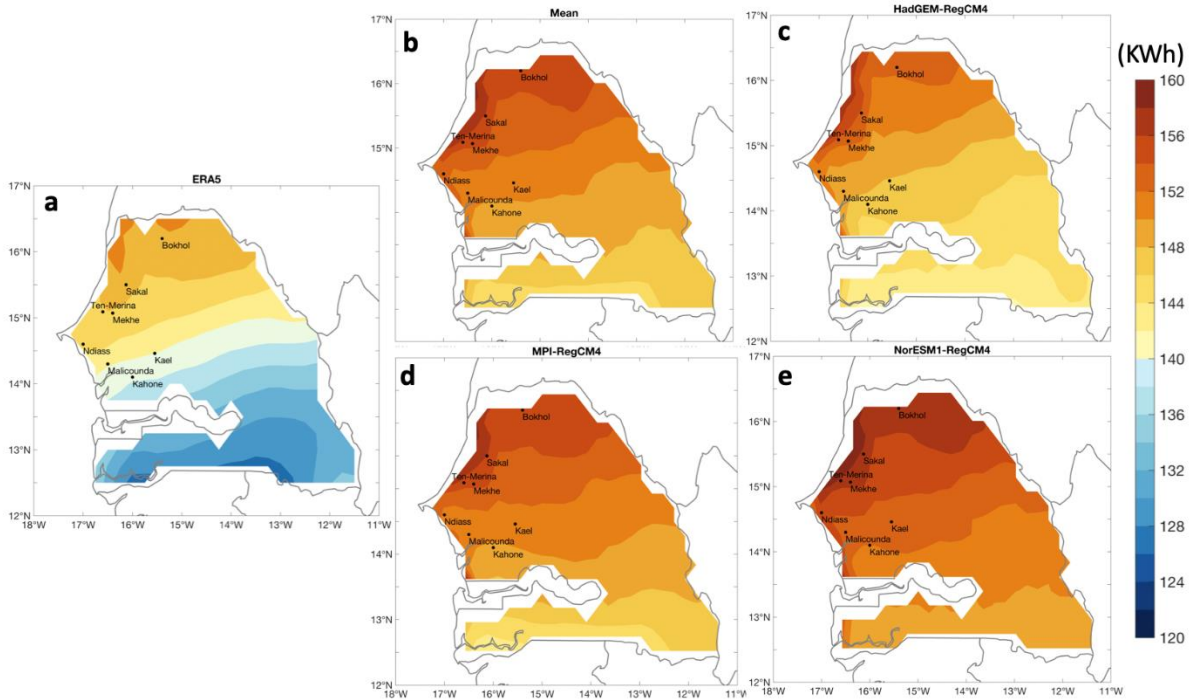


Figure 3.26 Spatial distribution of the annual mean solar production using RegCM4 of CORDEX-CORE (1975-2004) and ERA5 (1979-2021).

3.4.2.3.1 Projected production in Ten Merina and other solar plants

The projection of Ten Merina production at Horizon 2050 as well as the future production of other operational solar plants in Senegal are shown in *Figure 3.27*. The GCMs tend to overestimate production by approximately 10,000 kWh. To account for this, a bias correction was applied using ERA5 production data from 2005 to 2021, where available, resulting in the corrected production projection. Only the corrected trend of the GCMs was considered, as it provides a more accurate estimation compared to the non-corrected trend.

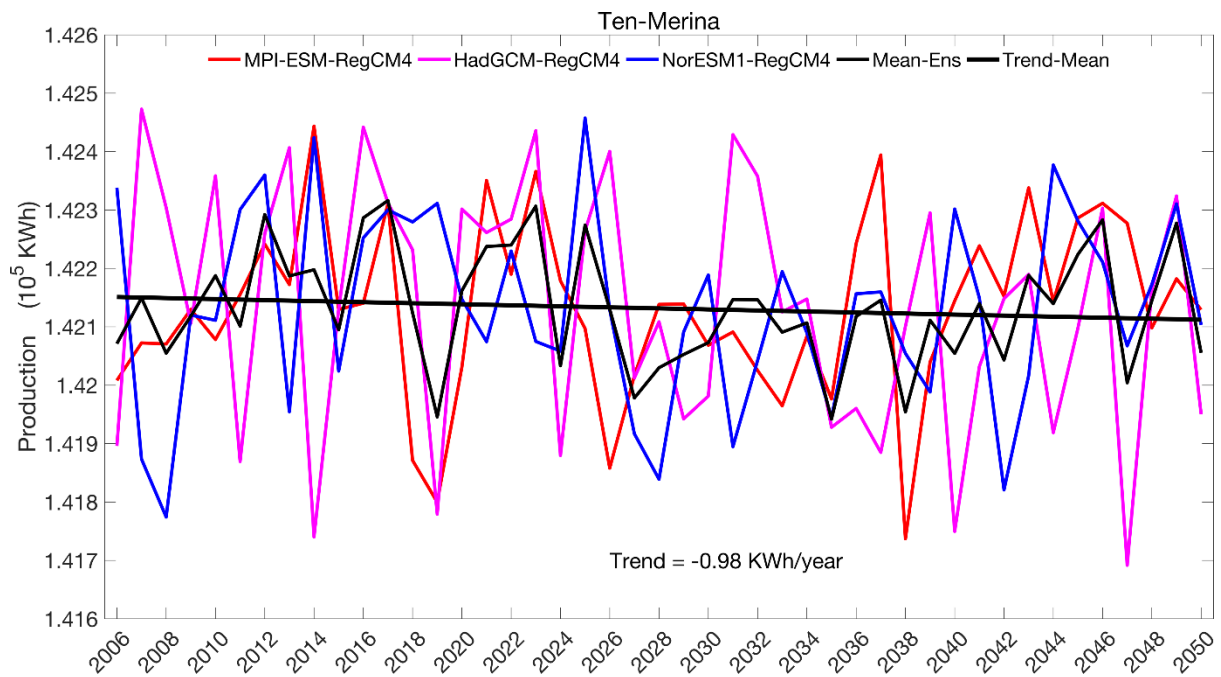
The time series graphs reveal a slight decrease in production for the various plants over the modeling period. However, the magnitude of the decrease in kWh differs between the plants. The plants experiencing the greatest decrease in production are Malicounda and Sakal, followed by Mekhe (*Table 3.3*). The remaining plants, including Ten Merina, exhibit decreases of less than 1 kWh per year. This observation suggests that Malicounda and Sakal are most affected by factors contributing to the decline in production, resulting in a more significant decrease compared to the other plants. Nevertheless, these plants, as well as the other plants that are less affected, are all located in the part of the country where less trend is observed indicating less decline in future production. The southeastern part and central parts of the country will experience more decline as compared to the western part when considering the projection of the ensemble mean of the GCMs (*Figure 3.28*).

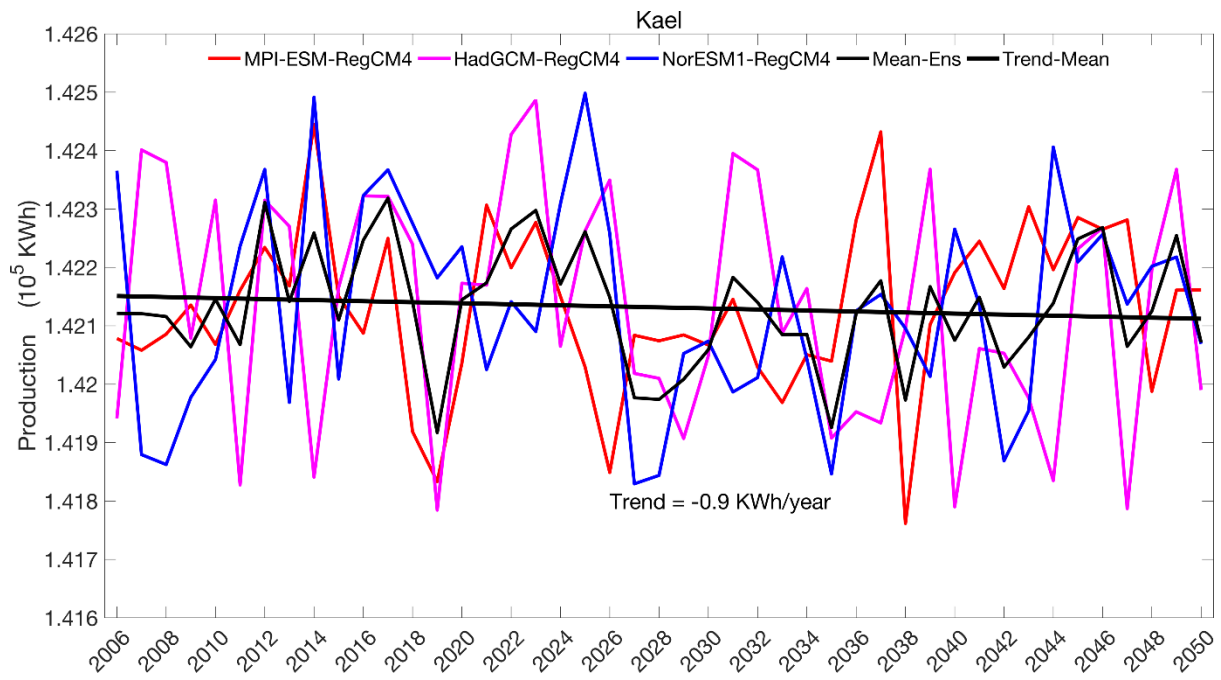
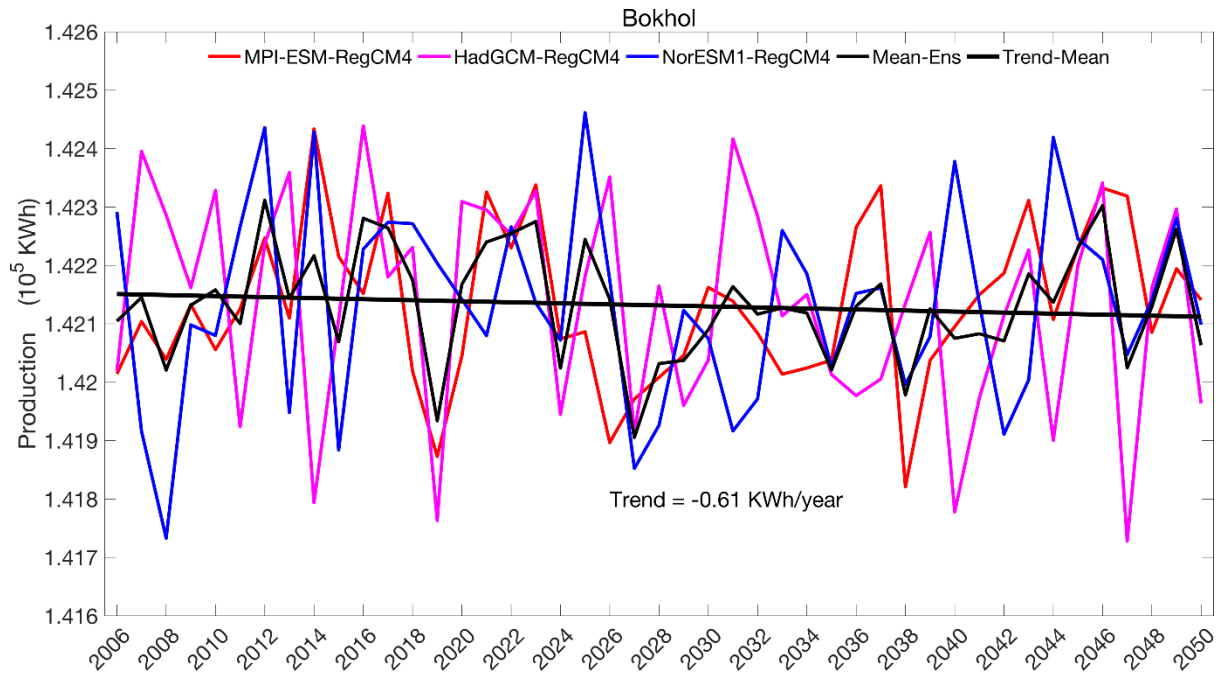
Table 3.3 presents the overall trend divided into two distinct periods. The period from 2006 to 2025 reflects an upward trend in all plant productions, while the period from 2025 to 2050 shows a decline. As an illustration, in the case of Ten Merina for example, the production trend shifts from 4.62 to 2.61, indicating that the overall decrease in production between 2005 and 2050 can be attributed to the decline observed specifically from 2025 to 2050.

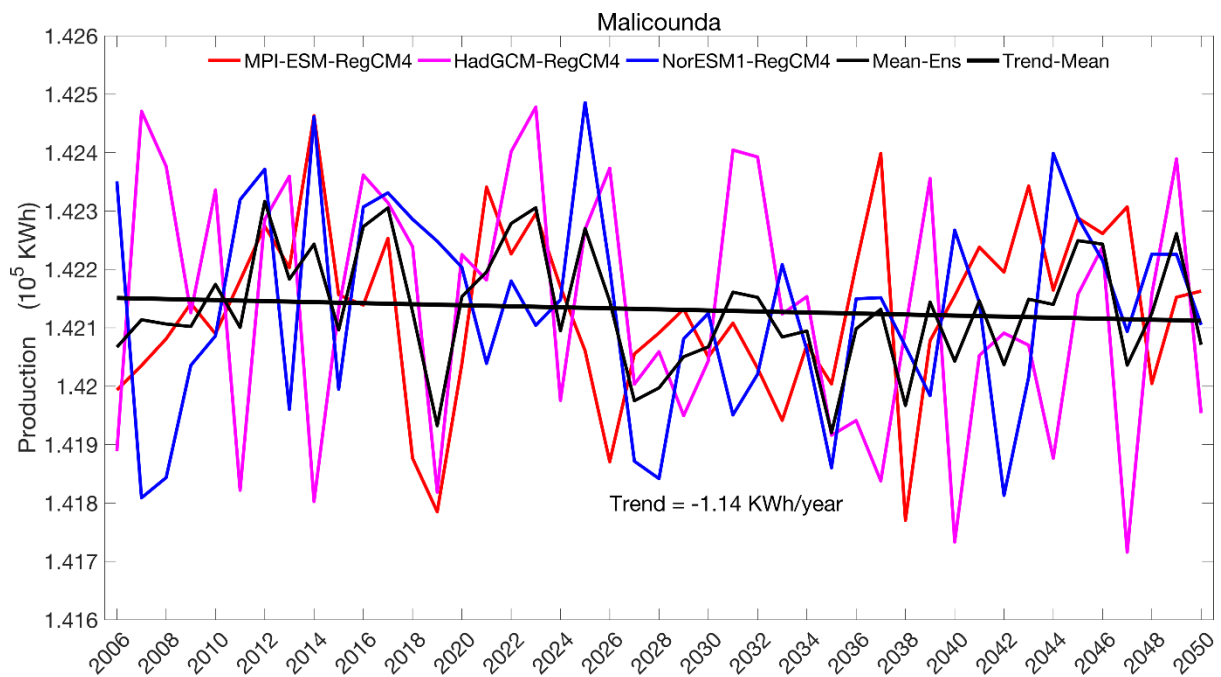
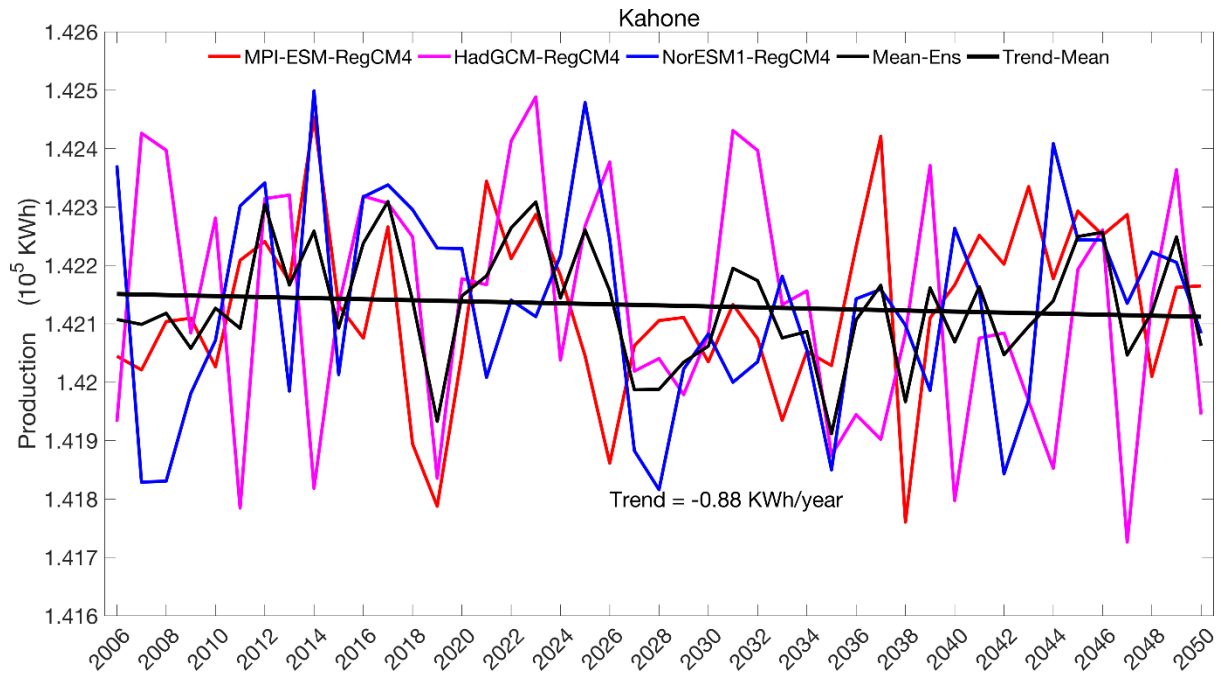
The decrease in production can be attributed to various factors. Environmental changes play a significant role, as alterations in environmental conditions can impact solar power generation. For instance, the projected reduction in solar irradiance and the anticipated rise in air temperature across West Africa, as illustrated in *section 3.1*, could contribute to this decline. Numerous studies have explored the relationship between meteorological factors and PV performance and found a strong relationship between solar radiation, temperature, and PV performance (Mavromatakis et al., 2010; Sawadogo et al., 2019; Casula et al., 2020). In addition, in their study, Jong Yoo et al. (2018) found a positive correlation between plant power generation and solar radiation, as well as temperature. They concluded that solar radiation has a more significant influence on solar power generation, but both factors must be taken into account for an accurate prediction of solar power generation. However, in practice, another potential reason for the decrease is the aging or degradation of solar panels over time. Various environmental factors have contributed to the deterioration or aging of PV panels (Santhakumari and Sagar., 2019; Ameur et al., 2022; Damo et al., 2023). Various factors, including exposure to severe weather conditions, accumulation of dust, and material degradation, can detrimentally impact the performance of solar panels. The accumulation of dirt, dust, and other pollutants on the surface of a photovoltaic PV module can significantly affect its performance and aging. The main reason for this is that it diminishes the amount of sunlight reaching the module's surface, resulting in a decrease in power output and an elevation in operating temperature (Rahman et al., 2023). Regular inspection, cleaning, and maintenance of the solar plant's components are vital to ensure optimal performance.

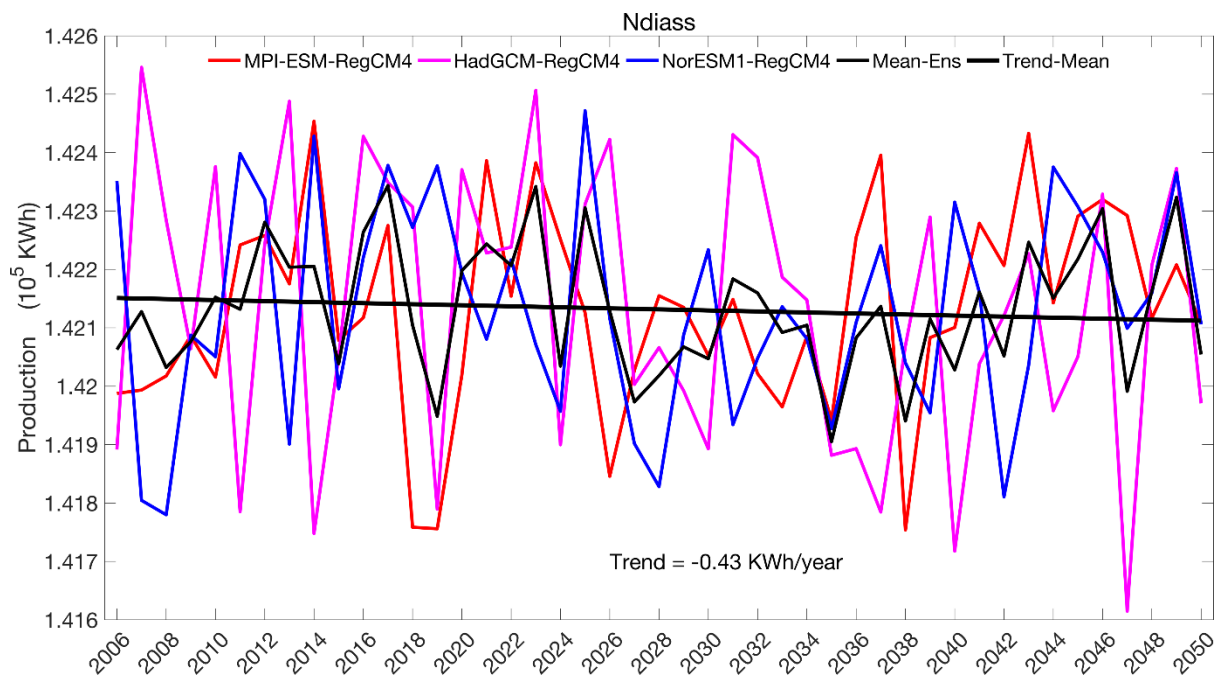
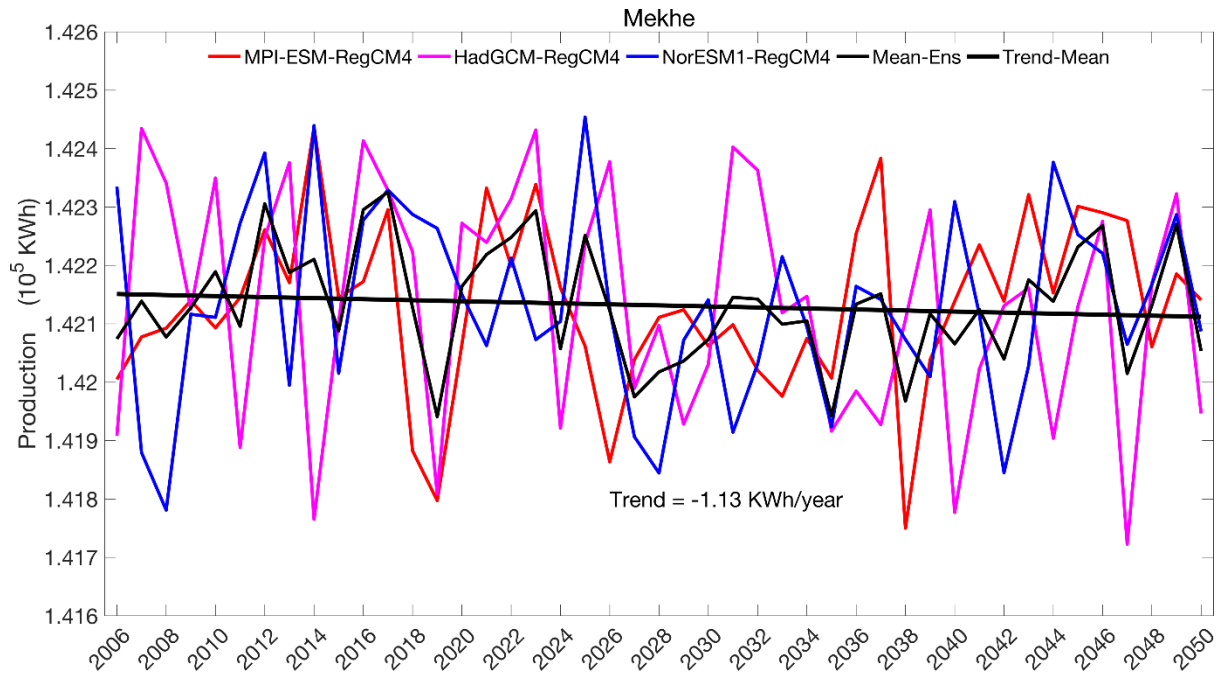
In summary, the projected production of Ten Merina and other solar plants in Senegal indicates a decreasing trend, highlighting the importance of proper maintenance and adaptation to changing conditions. To achieve the energy access targets set by the country, it is crucial to optimize the performance and output of these solar plants. This is just a first attempt trying to see the future of the plants in Senegal. Further analysis and investigation are necessary to identify the specific factors causing the production decline in each plant and develop suitable mitigation strategies. By understanding the unique circumstances of each plant, appropriate

measures can be implemented to address the underlying issues and optimize power generation. Additionally, considering other sources of renewable energy might be a worthwhile consideration for the government. Diversifying the energy mix by exploring alternative renewable energy sources, such as wind, and hydro, could provide additional options for sustainable and reliable energy generation. After establishing the only existing wind farm (Taiba Ndiaye), the government can multiply the number of wind farms in the country, leveraging the favorable conditions and expanding the renewable energy infrastructure as the coast has a high wind potential. By maximizing the potential of various renewable energy technologies, the country can achieve long-term energy security while facilitating its transition towards a cleaner and more sustainable energy future. Embracing a diverse mix of renewable energy sources allows for a resilient energy system that is less reliant on fossil fuels.









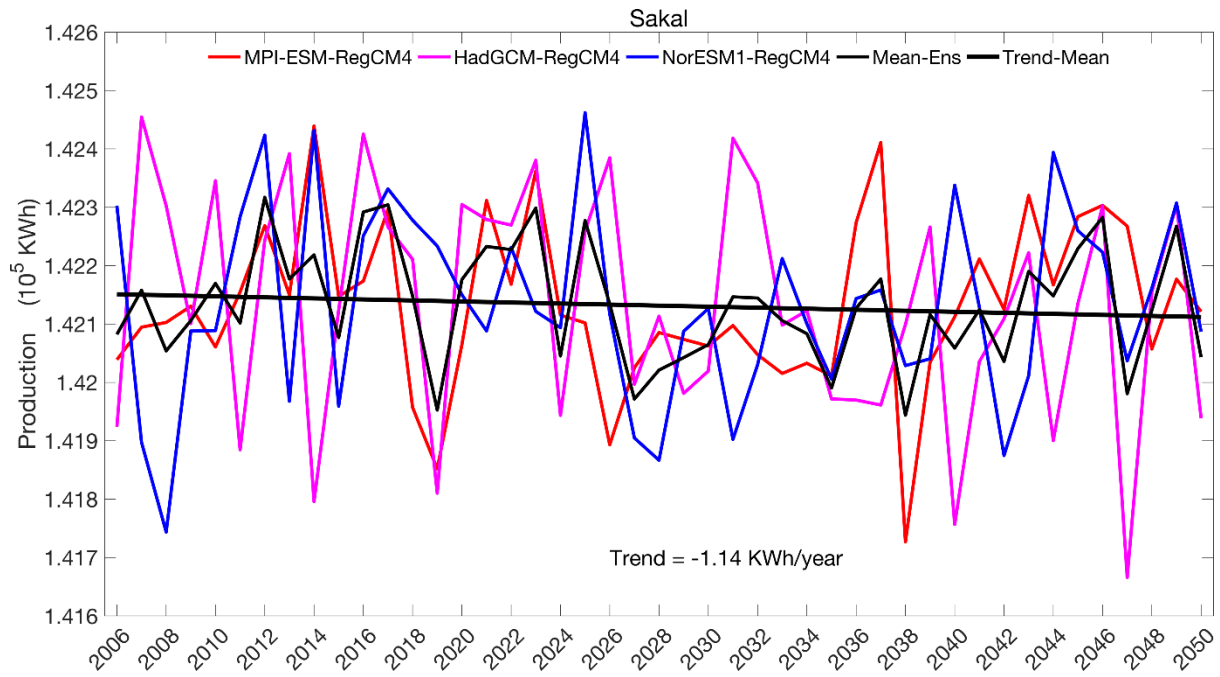


Figure 3.27 Time series of the projected annual mean production of Ten Merina and other solar plants in Senegal using RegCM4 of CORDEX-CORE (2005-2050).

Table 3.3 The trend of the solar plants

N°	Stations	Total Trend (2006-250) (KWh/year)	Trend (2006-2025) (KWh/year)	Trend (2025-2050) (KWh/year)
1	Ndiass	-0.43	6.60	3.19
2	Bokhol	-0.61	4.05	3.16
3	Kahone	-0.88	5.93	2.43
4	Kael	-0.90	5.78	3.14
5	Ten Merina	-0.98	4.62	2.61
6	Mekhe	-1.13	4.08	2.82
7	Malicounda	-1.14	5.21	2.66
8	Sakal	-1.14	4.65	2.20

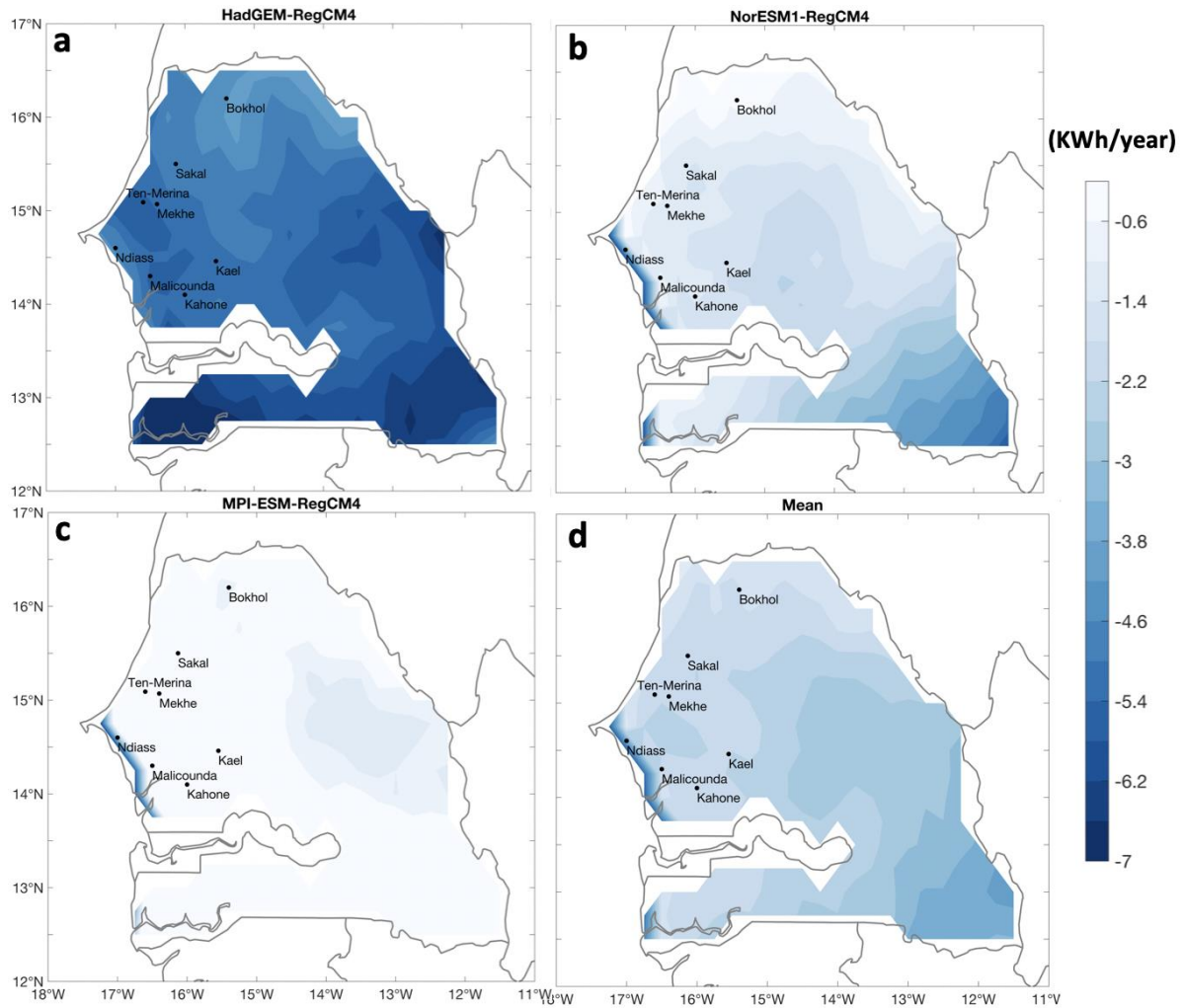


Figure 3.28 Spatial plot of the projected trend over Senegal using RegCM4 of CORDEX-CORE (2005-2050).

3.5 Climate change impact on wind production

The wind farm considered in this study is the only existing on-grid farm in Senegal (Taiba Ndiaye). The farm is located in the region of Thies with an installed capacity of 158 MW with 46 turbines. The farm has been operational since December 2019. We collected 10-minute interval data on the wind speed for three months (April-May-June) and for the year 2021. We also collected one-year production data for 2021. Regrettably, access to data for this institution is very limited. We were only able to collect three months of data and this proved insufficient for conducting advanced analysis in this study.

3.5.1 Methods

3.5.1.1 Wind production estimation

To estimate the production of the wind farm, the formula proposed by Masters (2004) was utilized. The production can be expressed using Equation 3.16.

$$E = \frac{1}{2} \rho A V^3 C F \Delta t \quad (3.16)$$

ρ is the air density (kg/m^3); A is the cross-sectional area through which the wind passes (m^2); V is the wind speed; CF is the capacity factor and Δt is the time.

$$A = \frac{\pi}{4} D^2 \quad D \text{ is the blade diameter} \quad (3.17)$$

$$CF = \frac{\text{Actual Energy Delivered}}{\text{Rated Power}} \quad (3.18)$$

The anomaly of the production was calculated following Equation 3.19.

$$Anom = P - \bar{P} \quad (3.19)$$

P is the actual value of daily average production and \bar{P} is the average production over the year.

3.5.2 Results

3.5.2.1 Seasonal cycle of the production

Figure 3.29 depicts the seasonal cycle of the Taiba Ndiaye's production for the year 2021, along with the production anomaly. The graph reveals that the production is notably higher in January and April compared to other months. This suggests that the country experiences its highest wind speeds during these periods, as indicated by the seasonal cycle of wind speed (*Figure 3.30*). Furthermore, during the rainy season spanning from June to October, the production shows a relative decrease, with the figure indicating approximately 400 MWh of energy generated compared to the approximately 2000 MWh produced in January and April. This observation highlights the influence of weather conditions on wind energy generation. Wind energy production is heavily reliant on wind speeds, and the variation in wind speeds throughout different seasons directly impacts the overall energy output.

The findings emphasize the significance of weather and climate information for renewable energy systems, particularly wind and solar energy. By considering the weather and climate data, stakeholders can make informed decisions regarding energy management and grid stability, ultimately enhancing the overall efficiency and reliability of renewable energy systems.

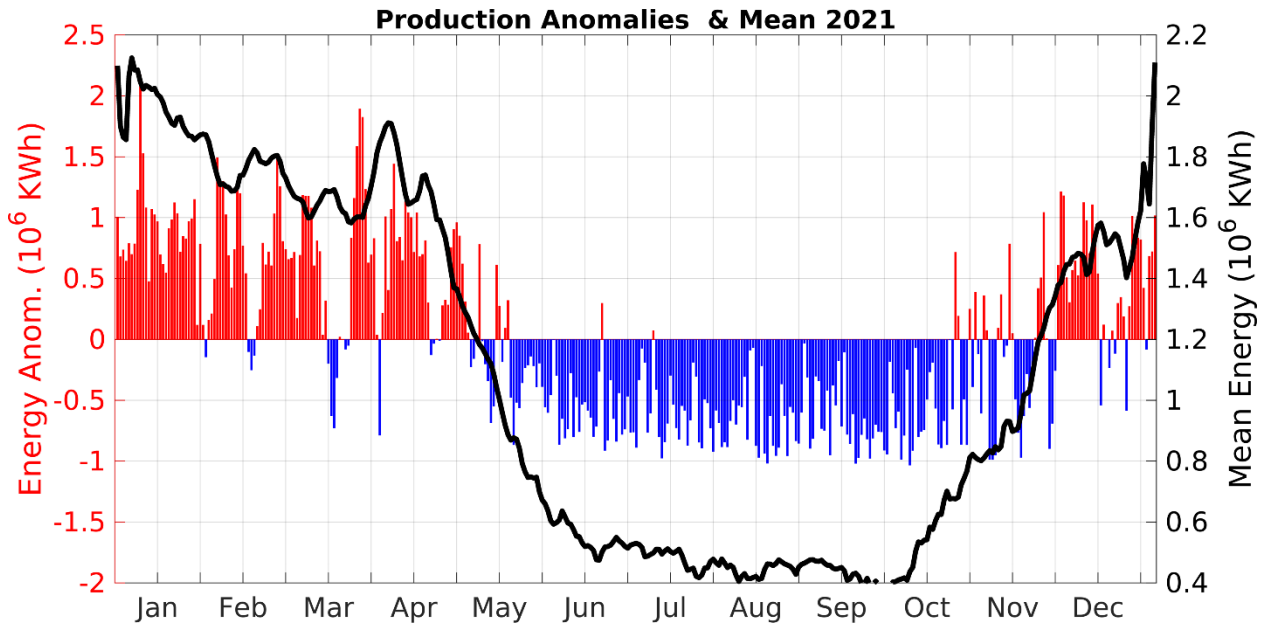


Figure 3.29 Seasonal cycle of the production of Taiba Ndiaye wind farm in 2021

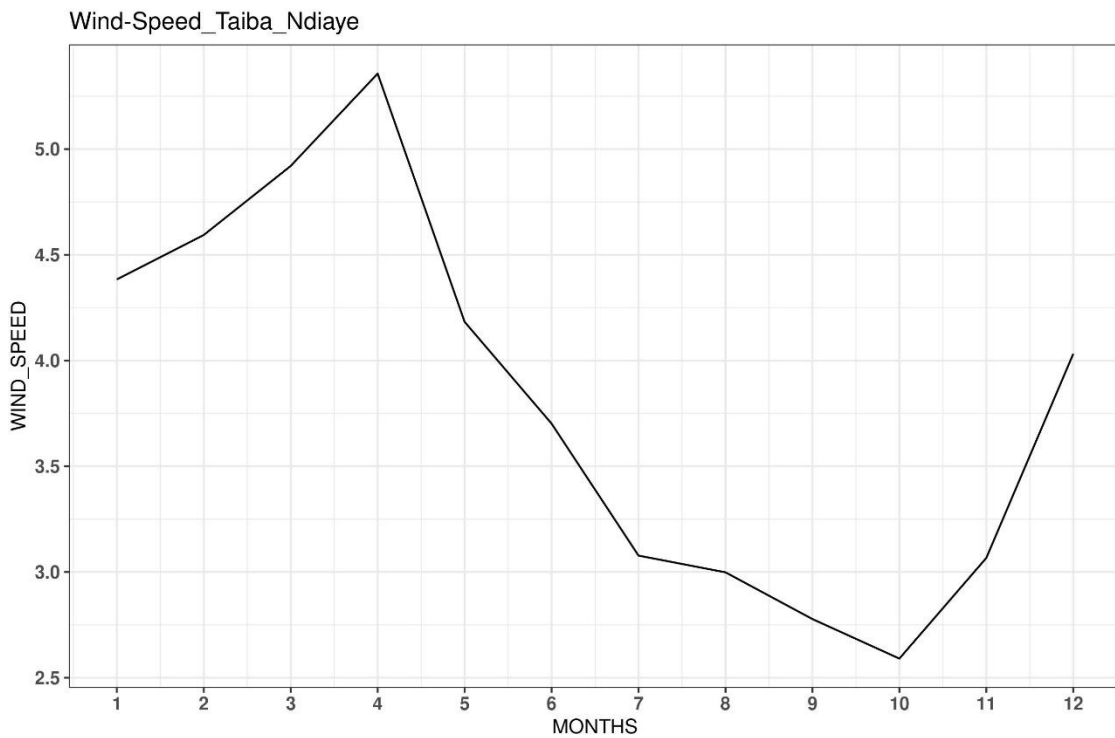


Figure 3.30 Seasonal cycle of the wind speed of Taiba Ndiaye in 2021 from ERA5.

3.5.2.2 Validation of the wind production formula

Unlike solar data, where we had access to one year of irradiance and cell temperature data, we only had three months of data available for wind. However, using Equation 3.16, we were able to reconstruct the production of the Taiba Ndiaye wind farm for those three months.

Remarkably, the calculated (reconstructed) production, represented by the red curve, aligns well with the actual production (black curve) of the farm (*Figure 3.31*). The formula captures the underlying factors and dynamics that influence wind energy generation at the Taiba Ndiaye wind farm. This agreement suggests that the formula is accurate and can effectively predict the production of a wind farm.

As previously mentioned, the limited availability of data for wind production and wind speed is a potential limitation that may impact the accuracy and reliability of the findings. With only three months of data, it becomes challenging to conduct a more extensive analysis and draw robust conclusions.

Ideally, having production data for a period of about three to five years would have provided a more extensive dataset to evaluate the ability of ERA5 to reconstruct the yearly production of the farm. This longer timeframe would enable a more thorough assessment and validation of the performance of the ERA5 dataset before using it to validate CORDEX-CORE. Additionally, having one year of wind speed data would have been beneficial in observing the reconstruction of production patterns over the entire year. It's important to highlight the limitations imposed by data availability and recognize the potential impact it can have on the accuracy and reliability of the findings. Obtaining access to a more extensive and representative dataset would be beneficial for conducting a more robust and thorough analysis in the future.

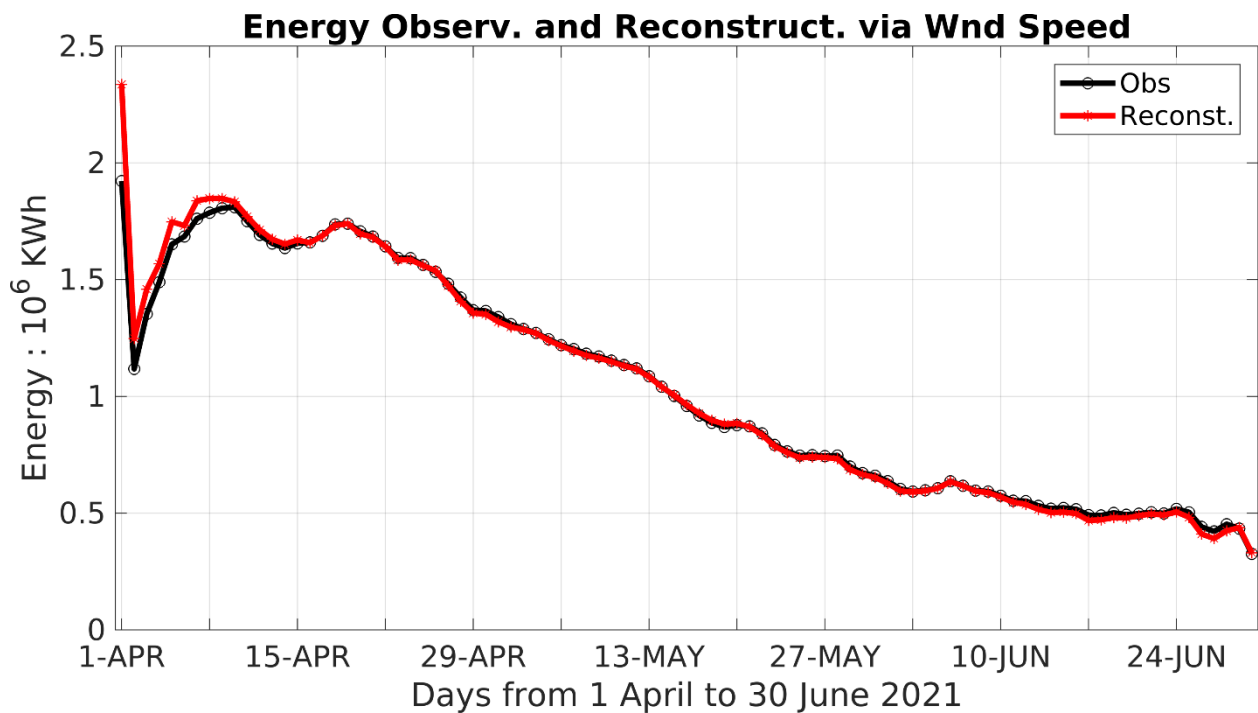


Figure 3.31 Reconstruction of the wind energy production of Taiba Ndiaye, Apr-May-Jun 2021.

3.6 Summary and Conclusions

This section presents the projected changes in solar PV and wind energy potential over West Africa using CORDEX-CORE ensemble simulations. Three regional climate models (RCMs), driven by three different GCMs, namely NorESM1-M, MPI-ESM-MR, and HadGEM2-ES from the CMIP5, were used. The expected changes in solar PV and wind potential over the region, as well as related variables such as air temperature, solar radiation, and wind speed, were analysed. The results of our investigation can be summarized as follows:

- The model evaluation shows a relatively good representation of selected annual and monthly patterns of the simulated solar PV potential, the wind power density, and related variables, with high spatial correlations ranging between 0.82 and 0.97. However, we also identified strong under and overestimations of the RCM simulations, especially for the wind variables.
- RegCM is the best model among the RCMs for the simulations of the solar irradiance and the solar PV potential in the sub-regions.
- REMO is the best model for wind speed and wind power density simulation over the region.
- For the air temperature, both REMO and RegCM had a good performance. CCLM was the least efficient model for this simulation.
- A better simulation of these variables with less biases is noted when using the ensemble mean of the Regional Climate Models.
- The projection under the RCP8.5 scenario indicates a decrease in solar irradiance and solar PV potential. The solar PV potential is expected to have a significant decrease for all the RCMs and their ensemble mean, as well as for the near (2021–2051) and far future (2071–2100), and under the RCP8.5 scenario. The decrease concerns the whole of West Africa and varies from ~ -2 to about -4% in the considered period. This is mainly due to the increase in cell temperature and the decrease in solar radiation over the region.
- The wind power projection shows a predominant increase over West Africa, with a projection of about 20 to 40% by the ensemble mean and for the two future periods. The RCMs convey more consistency in the projection of the other climate variables than the wind speed and the wind power density. The latter is subject to some divergences, with REMO expecting a decrease, RegCM and the ensemble mean an increase, and CCLM a high increase.

- In Senegal, the projection of the solar energy production of the solar plants shows a slight decrease on the horizon of 2050 with Malicounda, Sakal, and Mekhe projected to have the highest decrease.

The CORDEX-CORE provides, in a consistent manner, a high-resolution dataset of RCM projections for West Africa. However, the current projections are only based on three RCMs, as they are the only modelling groups that participated in the CORE initiative (to date). Therefore, a relatively small ensemble of RCM projections is used to determine the inherent uncertainty of climate projections. To reduce the uncertainties in the climate projections, more simulations should be available from the CORDEX-CORE, similar to the CORDEX data (~50 km). The study shows useful results, which are an important contribution to research on the future changes in solar PV and wind energy potential over West Africa and Senegal. The results can help governments and policymakers in targeting RES for future projects as part of the energy transition for climate change mitigation by considering the impacts of climate change on these resources.

After investigating the vulnerability of the energy sector to climate variability and change, the next chapter evaluates the WRF-solar model for solar irradiance forecasting in Senegal to contribute to certain aspects of climate services, particularly in terms of providing short-term weather forecasts, especially for solar energy.

Chapter 4: Evaluation of the WRF-solar model for solar irradiance forecasting in Senegal

4.1 Introduction

With respect to the Paris Agreement and the cost reduction of renewable technologies, many countries are increasing their renewable energy share in the energy mix in the framework of climate change mitigation. In 2022, 183 Parties had included renewable energy components in their Nationally Determined Contributions (NDC), of which 108 had defined targets for renewables in the power sector (IRENA, 2022). As part of Senegal's strategic initiatives, there is a plan to add a total of 300 MW of additional renewable energy capacity by 2030. This includes 100 MW from solar, 100 MW from wind, 50 MW from biomass, and 50 MW from Concentrated Solar Power (CSP) (CDN Senegal, 2020).

Renewable energy sources are efficient in reducing CO₂ emissions due to their low carbon intensity, with emissions per unit of energy output usually ranging from 1 to 10% of that produced by fossil fuels (Moomaw et al., 2011). In recent years (2010-2020), renewable energy deployments have grown, with a 7% increase in renewables-based generation capacity on the continent of which solar energy had the largest additions (IRENA and AfDB, 2022). To date, about 10 solar energy projects have been implemented in Senegal since 2016. However, solar energy like other renewable energy is heavily dependent on weather and climate conditions. Some climate information like solar irradiance is needed to assess or predict the production of a solar plant. A recent interview done with renewable energy (solar and wind) power producers in Senegal revealed that climate information is not accessible to these power producers and that they mostly use online platforms for their climate data needs. The use of climate data and information products has been very limited in Africa due to a lack of relevant information or difficulties in accessing existing data (Dinku, 2019). In Africa, although the National Meteorological and Hydrological Services (NMHSs) are mandated to provide and share national data, data sharing with other institutions, within or outside the country is quite limited and often includes the cost for provision when available (Dinku, 2019; Overpeck et al., 2011). Solar energy forecasting is essential for utilities that rely on solar power generation to ensure a dependable and economically efficient supply of electricity to their customers. Accurate solar energy forecasting helps utilities plan and schedule their power generation more efficiently. Numerical weather prediction (NWP) could be an alternative and is an essential tool for forecasting solar irradiance more than a few hours in the future and it is useful for the day ahead

forecasts applicable to the scheduling of solar-power plants (Larson, 2013). NWP models use atmospheric reanalyses as initial and lateral boundary conditions and provide forecasts for various parameters like temperature, relative humidity, and wind speed (Lara-Fanego et al., 2012).

The Weather and Research Forecasting model for solar energy applications (hereafter WRF-solar) is a NWP model which has been used in many studies for global horizontal irradiance (GHI) forecasts (eg., Lara-Fanego et al., 2012; Diagne et al., 2014; Lee et al., 2017; Verbois et al., 2018; Gueymard and Jimenez, 2019; Prasad and Kay, 2020; Sawadogo et al., 2023). WRF-Solar stands out as the first NWP model explicitly designed for solar energy applications (Jimenez et al., 2016). It is an augmented version of the WRF model developed to address the increasing need for specialized numerical forecast products tailored for solar energy applications (Jimenez et al., 2016). The WRF model has been improved and adjusted to better model the interaction of aerosols, clouds, and radiation which helps to decrease the prediction uncertainty of GHI (Haupt et al., 2016). WRF and WRF-solar have been used in numerous studies around the world. In Spain, Arbizu-Barrena et al. (2017) used a novel approach known as Cloud Index Advection and Diffusion (CIADCast) for short-term solar radiation forecasting. This method combines the precision of satellite cloud representation with the modeling capabilities of the WRF to simulate atmospheric dynamics. In Australia, Mukkavilli et al. (2018) compared different physical parameterization schemes for predicting hourly direct normal irradiance under varying aerosol conditions. Studies for the USA, Gamarro et al. (2019) and Lee et al. (2017) combined the WRF-Solar modifications with a multilayer energy model to create a harmonized WRF forecasting systems called urban WRF-Solar and evaluated WRF-solar alongside four different nowcasting models for GHI forecast in California, respectively. Many studies have been done in Africa and in particular over West Africa and they mainly dealt with several variables and processes such as precipitation, temperature, cloud, solar and wind resources, etc. (Abdallah et al., 2015; Nooni et al., 2022; Diaz et al., 2015; Arnault et al., 2016; Klein et al., 2015; D'Isidoro et al., 2020; Zhao et al., 2011). Nonetheless, Sawadogo et al. (2023) evaluated the performance of various shortwave radiation schemes within the WRF-Solar model for simulating GHI in West Africa, specifically focusing on Ghana and the southern region of Burkina Faso. Some studies for Senegal mainly looked at dust concentration (PM_{2.5}, PM₁₀) for air quality and respiratory health (Toure et al., 2019; Diokhane et al., 2016; Jenkins et al., 2022). In another study, two modeling mesoscale systems, namely MM5 and WRF, were employed to simulate instances of high-impact heavy precipitation and low-temperature scenarios in Senegal, particularly focusing on heavy off-season rains (Fall et al.,

2007). So, there is a lack of information on the performance of the WRF-Solar model in Senegal for solar energy applications.

The objective of this chapter is to assess WRF-solar for solar irradiance forecasting in Senegal for solar energy applications. The impacts of two different shortwave radiation schemes (Dudhia and RRTMG) are investigated in the WRF-Solar model for two solar plants in Senegal (Diass and Ten Merina). For the RRTMG scheme, two simulations are carried out: one without aerosol optical depth (AOD) and one with AOD (RRTMG_AOD). Different from the study by Sawadogo et al. (2023) who did not look at the aspect of shallow convection, we examine the impacts of shallow convection on the three simulations. WRF-Solar is evaluated with hourly instantaneous values of GHI for the year 2020 from the two solar plants.

4.2 Material and methods

4.2.1 Study area and observation data

The study focuses on the two solar plants in Senegal. Senegal is a West African country located at a latitude of 12° N to 17° N and a longitude of 11° W to 17° W (*Figure 4.1*). The country spans an area of approximately 196,700 km² and has a coastline of more than 500 km. The climate is tropical regulated by the Intertropical Convergence Zone (ITCZ) with a long dry season from October to May (Sarr et al., 2014). During the rainy season (June-September), the ITCZ moves northwards, and rainfall amount is more abundant in the south compared to the northern part. The country is endowed with high solar energy resources with about 3000 hours of sunshine per year and the average solar energy received is estimated to be around 2000 kWh/m²/year (Youm et al., 2000).

Ground-based GHI data are used for the evaluation of the WRF-Solar model. The ground based GHI data were collected from two solar plants, all located in the region of Thies (*Figure 4.1*). Thies is about 50 km from the capital city of Dakar and is characterized by an annual rainfall between 500 and 650 mm, a semi-arid climate, and a mean annual temperature of 26.7° C (Senghor et al., 2011).

The solar plants are dotted with meteorological stations including pyranometers which take measurements of the GHI. There are no criteria based on the choice of these plants and the test year of 2020. Among the solar plants in Senegal, these were selected based on data availability.

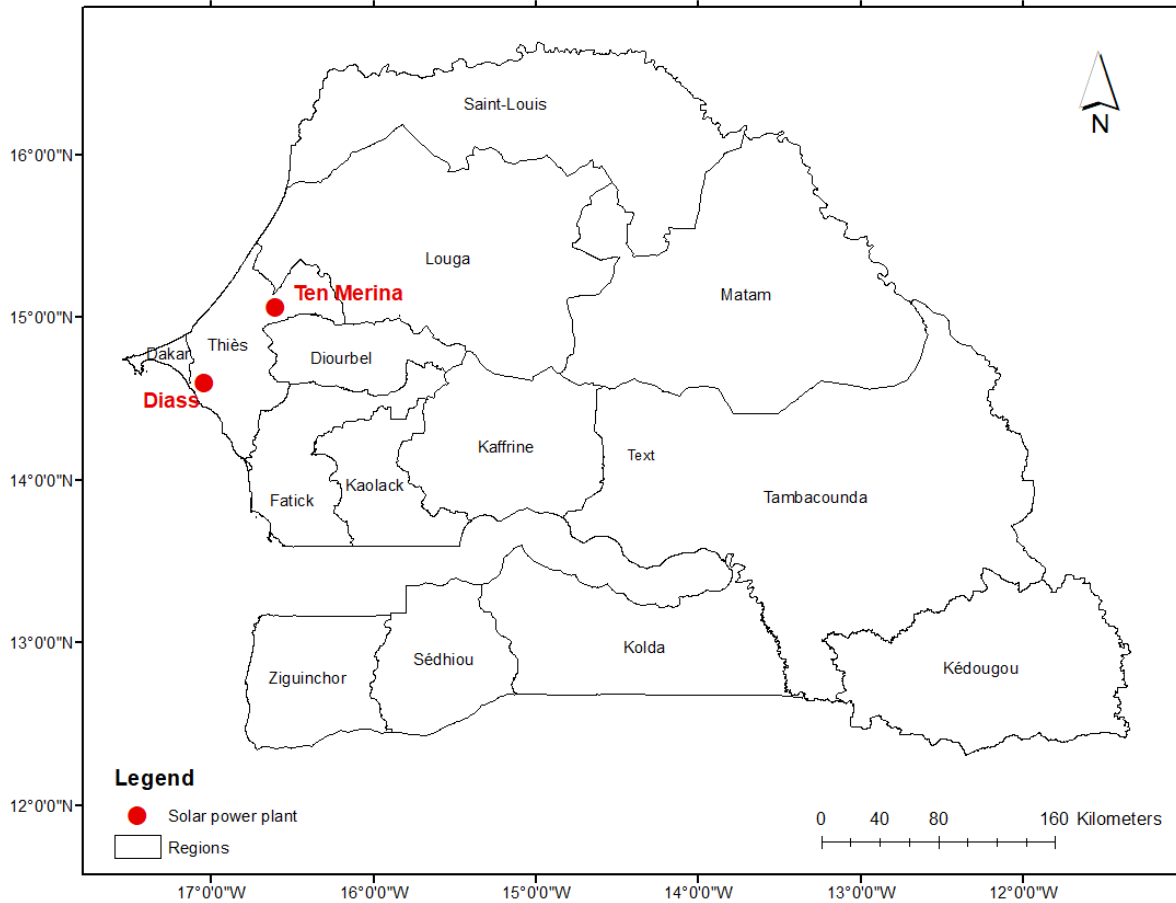


Figure 4.1 Study area showing the location of the two solar plants.

4.2.2 Model data

4.2.2.1 ERA5 data

ERA5 reanalysis data serve as the initial and lateral boundary conditions (ILBC) for the WRF-Solar model. This reanalysis data is produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) (Hersbach et al., 2020). The ERA5 dataset represents the fifth-generation ECMWF reanalysis for global climate and weather. It features enhanced resolution in both the horizontal and vertical dimensions and is produced by the Copernicus Climate Change Service. This dataset offers estimates of atmospheric variables at a worldwide resolution of approximately 31 km. The reanalysis datasets downloaded are hourly surface and atmospheric pressure data from 01 December 2019 to 31 December 2020.

4.2.2.2 Copernicus Atmosphere Monitoring Service datasets (CAMS)

The aerosols data AOD 550 nm in this study were obtained from the Copernicus Atmosphere Monitoring Service datasets (CAMS). CAMS, implemented by the ECMWF, utilizes the operational infrastructure and modeling tools of ECMWF to generate near-real-

time global analyses and forecasts of atmospheric composition (Peuch et al., 2022). The analyses, forecasts, and reanalyses of the global atmospheric composition of CAMS are based on the ECMWF integrated prediction system and exploit more than 90 different satellite data streams (Peuch et al., 2022). In the operational configuration of CAMS, simulations are conducted at a horizontal spectral resolution equivalent to a grid size of approximately 40 km and a vertical resolution comprised of 137 levels (0.01 to 1013 hPa) (Garrigues et al., 2022). The Angstrom exponent (α) used in this study is estimated from the linear regression of Equation 4.1 (Reid et al., 1999; Knobelspiesse et al., 2004, Schuster et al., 2006), at a different wavelength of 469, and 865 nm. The AOD at 469, 550, and 865 nm data are 3-hourly data and cover the period of 01-December 2019 to 31-December 2020.

The Angstrom exponent is estimated using Equation 4.1 (Knobelspiesse et al., 2004).

$$\alpha = - \frac{\ln \frac{\tau_{\lambda_1}}{\tau_{\lambda_2}}}{\ln \frac{\lambda_1}{\lambda_2}} \quad (4.1)$$

τ_{λ_1} and τ_{λ_2} are the total AOD with wavelengths of λ_1 and λ_2 , respectively.

4.2.3 WRF-Solar model

4.2.3.1 WRF-Solar description

WRF-Solar is a numerical weather prediction model specifically designed for solar energy applications. It is an extension of the Weather Research and Forecasting (WRF) model, a widely used mesoscale numerical weather prediction system. It incorporates detailed atmospheric physics and solar radiation processes to generate high-resolution forecasts for GHI and related variables. The augmentation of the WRF model involves the incorporation of a fully coupled model with aerosol properties, aiming to improve the representation of radiation scattering and absorption by aerosols. It also includes enhanced feedback systems between clouds, aerosols, and radiation to account for both direct and indirect aerosol effects (Gamaro et al., 2019). These parameters are crucial for predicting the amount of solar radiation reaching the Earth's surface at a given location and time. The model has been extensively tested and validated against observational data and has been shown to accurately predict GHI at high spatiotemporal resolution. Jimenez et al. (2016) reported a significant improvement in irradiance compared to the standard WRF. They demonstrated that WRF-Solar improves GHI, DNI, and DIF in clear sky predictions compared to the standard WRF. On average, GHI sees an improvement of 46%, DNI by 60%, and DIF by 70%. This makes WRF-Solar a valuable tool with diverse applications, encompassing solar energy forecasting, solar resource

assessment, and the integration of solar energy into the grid. WRF-Solar is an open-source model and is freely available for download from the National Center for Atmospheric Research (NCAR) website (<https://ral.ucar.edu/solutions/products/wrf-solar>).

The output from WRF-Solar can be used by energy companies, utilities, and other organizations to optimize solar energy production, forecast energy demand, and manage renewable energy resources. The model can also be used for research purposes, such as studying the impact of climate change on solar energy resources. *Table 4.1* highlights the difference between WRF-Solar and the standard WRF model.

Table 4.1 Comparison of WRF and WRF-Solar (Jimenez et al., 2016)

	WRF-Solar	WRF
Solar energy applications	Output DNI and DIF	-
	High-frequency output of surface irradiance	-
	Solar position algorithm includes EOT	EOT is not included
Aerosol–radiation feedback	Observed/model climatology or time-varying aerosols	Model climatology
Cloud–aerosol feedback	Aerosol indirect effect represented	-
Cloud–radiation feedback	Cloud particles consistent in radiation and microphysics	-
	Shallow cumulus feedback to radiation	-
	Fully coupled aerosol–cloud–radiation system	Uncoupled

EOT=equation of time

4.2.3.2 WRF configuration and setup

To assess the model for solar irradiance forecasting in Senegal, the WRF-solar version 4.2.2 was used. In this study, we used one-way two nested domains: an outer domain (D1= 15 km) which covers the whole of West Africa, and an inner domain (D2= 3 km) set over Senegal (*Figure 4.2*). The simulation was done for the whole year 2020 at 15 km spatial resolution (lower resolution) and 3 km (higher resolution), respectively for D1 and D2. The two domains have grid points of 200x220 and 401x301, respectively. ERA5 hourly data was used for the specification of the ILBC which delineates the state of the atmosphere. We integrated the land use index and land use fraction derived from the 21-class Moderate Resolution Imaging Spectroradiometer (MODIS), along with the green vegetation index from the Fraction of Photosynthetically Active Radiation (FPAR), into the WRF Preprocessing System (WPS).

Additionally, the land use in the model was initialized using GEODATA TOPO 10M from the topography data of the United States Geological Survey (USGS).

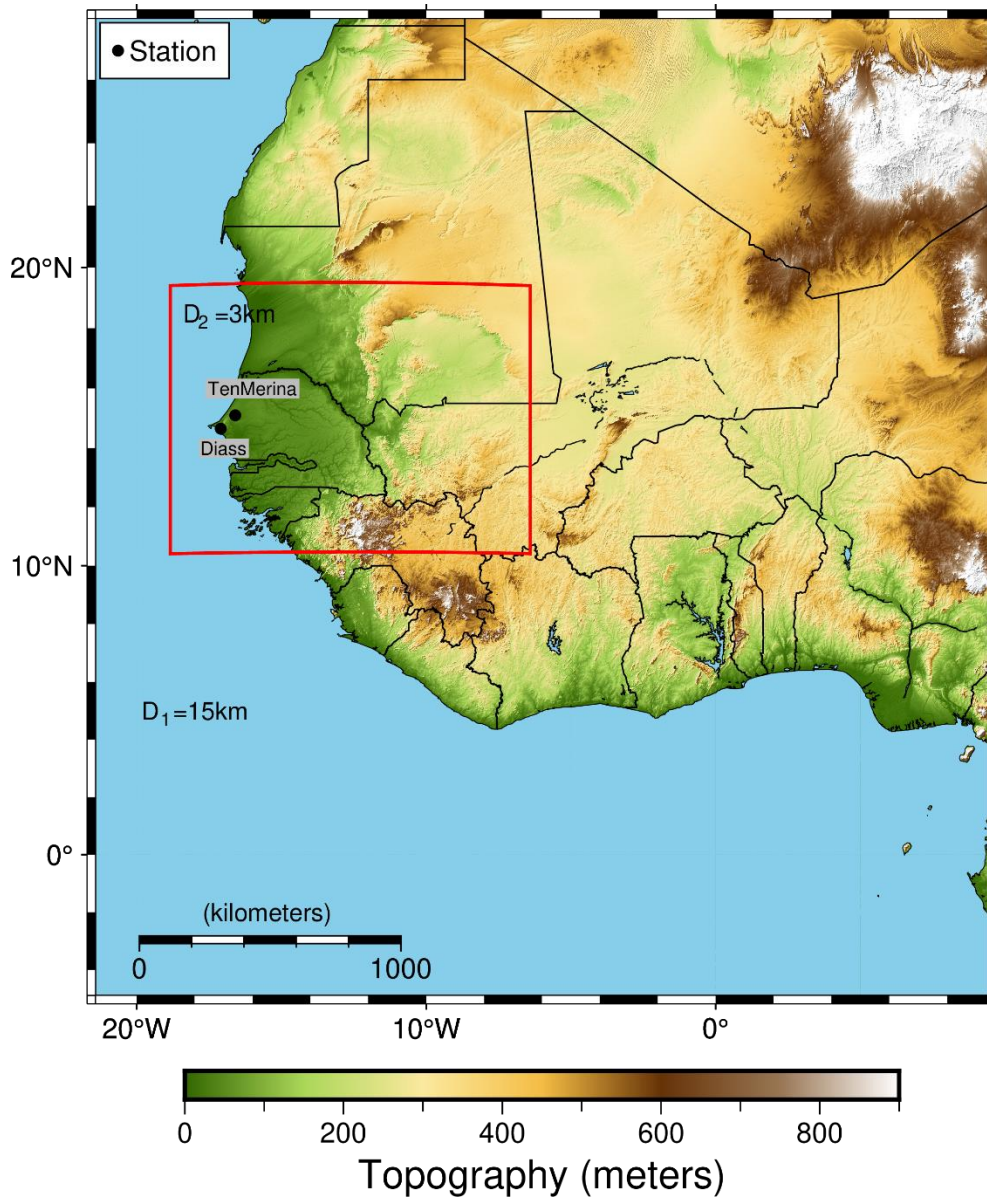


Figure 4.2 WRF domains showing the two domains: the outer domain (D_1) with a resolution of 15 km and the inner domain (D_2) with a resolution of 3 km.

4.2.3.3 WRF Experiment

The performance of the different parametrizations implemented in WRF-Solar for solar irradiance forecasting was assessed with a series of experiments. Many factors were considered in formulating the physical parameters of the model, including cloud cover, aerosol optical depth, and solar radiation. It is important to select the best combination of physical parameterization options in the WRF model for the chosen region for any given simulation

(Patil and Kumar, 2016). The appropriate selection ensures a realistic representation of the physical processes in the simulation. According to Dudhia (2014), the WRF schemes are interrelated. *Figure 4.3* illustrates the relationship between the schemes. The WRF model provides several options for the microphysics scheme. This scheme is used to describe the processes of cloud formation, precipitation, and other microphysical processes in the atmosphere. In this study, we have applied the Thompson microphysics scheme which is a good scheme for cloud properties simulations (Otkin and Greenwald, 2008; Jimenez et al., 2016; Yang et al., 2021). Cumulus and microphysics are responsible for convective and non-convective rain, respectively (Aryaputera, 2015). The Cumulus scheme is used to represent the effects of deep convection that occur on a scale too small to be resolved by the model. However, the cumulus scheme has been found to misrepresent the sub-grid scale clouds. To improve the simulations of clouds, the WRF-Solar model incorporates a shallow convection scheme. We use Deng's shallow cumulus parametrization scheme to account for the effect of unresolved clouds. Deng's scheme is a mass-flux-based approach that incorporates a cloud entraining/detraining model to represent updrafts. Its activation is determined by factors such as planetary boundary layer depth and turbulent kinetic energy, as outlined by Jimenez et al. (2016). The scheme has demonstrated the ability to generate reasonable cloud fractions and reduce surface temperature biases (Deng et al., 2014). However, at high resolution (3 km), microphysics, and convection schemes, can be explicitly simulated on the model grid, making cumulus or shallow convection schemes unnecessary. Nonetheless, a study conducted by Jiménez et al. (2022) has recently demonstrated that incorporating Deng's shallow cumulus parametrization can enhance solar irradiance forecasts even at high resolution in the CONUS domain, particularly when the model is operated in convection-permitting mode. To assess this claim in Senegal, the effects of enabling and disabling the shallow convection scheme are examined at a 3 km resolution.

Other physics parametrizations chosen in this study include the Fast All-sky Radiation Model for Solar applications (FARMS), the Mellor-Yamada-Nakanishi-Niino (MYNN) planetary boundary layer (PBL) scheme, and the Noah Land surface model (Niu et al., 2011). FARMS holds significant importance in the WRF-Solar model as it facilitates the computation of surface shortwave irradiance at each model time step, offering a realistic representation of the variability in solar irradiance (Gueymard and Jimenez 2019). It is designed to be computationally efficient while still providing accurate results, making it suitable for use in weather and climate simulations. The WRF model provides many options for the PBL and Land Surface Model (LSM) schemes. The MYNN scheme parameterizes boundary layer

clouds, generating both the cloud mixing ratio and the cloud fraction of boundary layer clouds (Yang et al., 2021). The LSM is used to represent the exchanges of heat, moisture, and momentum between the land surface and the atmosphere (Chen and Dudhia 2001).

A number of experiments were done to investigate the impacts of two different shortwave radiation schemes (Dudhia and RRTMG) in the WRF-Solar model in two solar plants in Senegal (Diass and Ten Merina). For the RRTMG scheme, two simulations were carried out: one without aerosol optical depth (AOD) and one with AOD (RRTMG_AOD). Aerosols have complicated radiative, microphysical, and dynamic effects in the atmosphere. The presence of aerosols can significantly reduce the amount of GHI reaching photovoltaic systems (Jimenez et al., 2016). For the RRTMG_AOD simulation, the Thompson and Eidhammer (2014) scheme was applied to enable cloud–aerosol feedback. Besides this, the same schemes have been applied to all the simulations and all the experiments were done under no shallow and shallow schemes.

Hourly instantaneous values of GHI are provided from the simulation period spanning from December 1, 2019, to December 31, 2020, where the month of December 2019 was exclusively utilized for the spin-up process.

Table 4.2 Parameterization schemes used for the model configurations.

Physics		Dudhia	RRTMG	RRTMG_AERO	References
Radiation	Shortwave	Dudhia	RRTMG	RRTMG + aerosols	Dudhia (1989); Iacono et al. (2008)
	Longwave	RRTMG	RRTMG	RRTMG	
Land surface		Noah land surface model			Niu et al. (2011)
Microphysics		Thompson		Thompson and Eidhammer (2014)	Thompson et al. (2016)
PBL		Mellor–Yamada–Nakanishi–Niino (MYNN)			Yang et al. (2021)
Shallow cumulus		Deng cumulus			Deng et al. (2014)
FARMS		Activated			Gueymard and Jimenez, (2019)

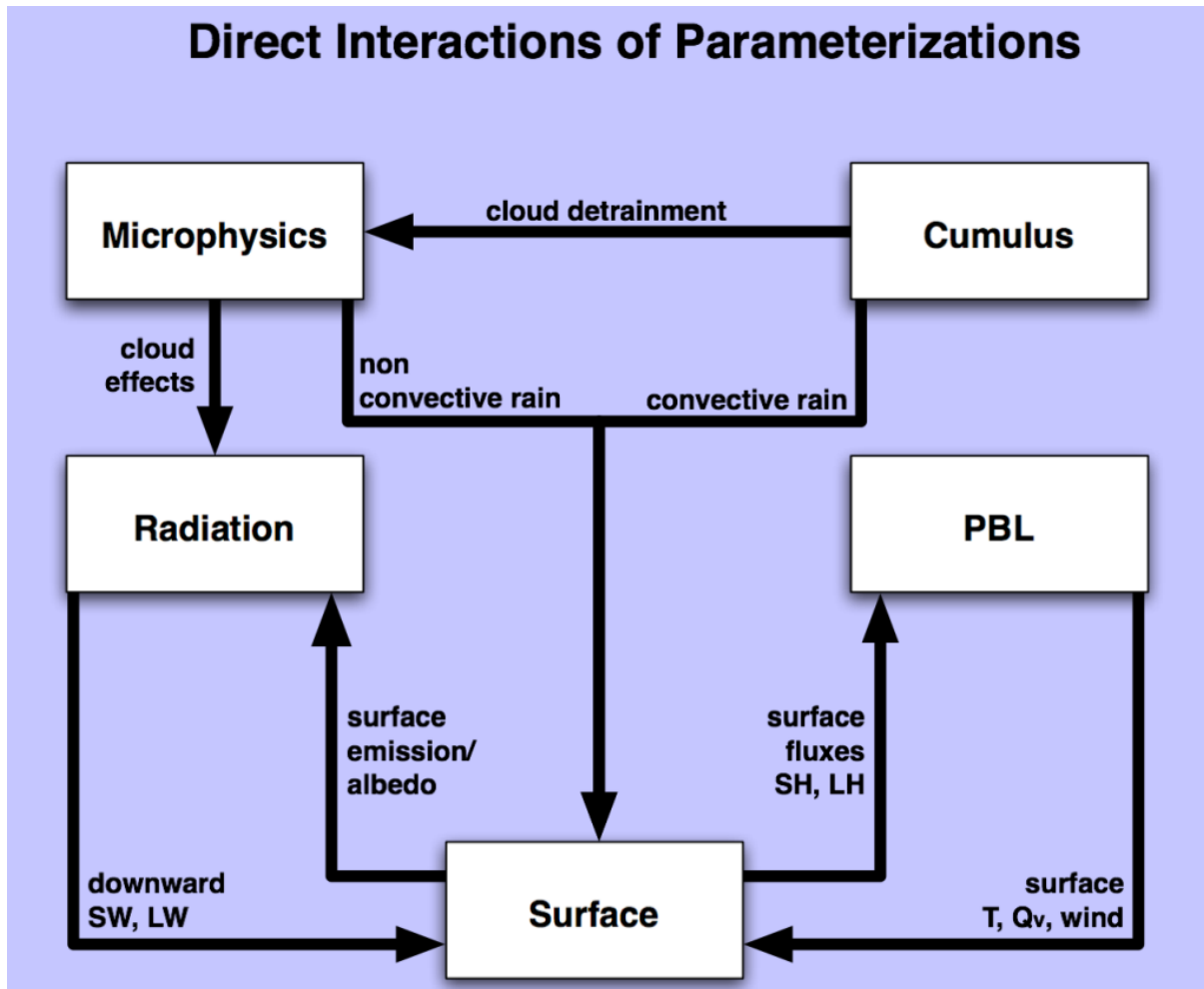


Figure 4.3 Interactions of WRF parameterizations (Dudhia, 2014)

4.2.4 Method

4.2.4.1 Quality control procedures for the observation data

The data quality control involves visualizing the hourly GHI throughout the year and removing any missing data and suspicious GHI values. Initially, the raw data consisted of sub-hourly measurements, and the GHI values for each hour were extracted. In the event of any missing values occurring between 20:00 and 5:00 in the raw data, a value of 0 was assigned to them. Nevertheless, if there are any missing values outside of this time window, we considered the GHI values for the next three time steps ($t+1$ to $t+3$). Otherwise, the value was set to NaN. *Figure 4.4* illustrates the time series of instantaneous hourly GHI for both Diass and Ten Merina stations. These two stations exhibit a similar pattern of hourly GHI throughout the year. The availability of solar resources is highest during the dry season, while the GHI values slightly decrease during the rainy season. Both stations accurately reflect the GHI pattern in the region. However, there were some missing data points in Diass (4) and Ten Merina (54),

which were excluded from the analysis. Finally, in order to identify and exclude recorded data that may be suspicious due to sensor calibration issues or faults, the BSRN (Baseline Surface Radiation Network) tests have been applied. The tests identify GHI values that deviate from the normal range. The BSRN guidelines (BSRN, 2021) provide the physically possible limit (Equation 4.2) and the extremely rare limit (Equation 4.3) for GHI measurements:

$$-4 \text{ W/m}^2 < GHI < I_0 * 1.5 * \cos(SZA)^{1.2} + 100 \text{ W/m}^2 \quad (4.2)$$

$$-2 \text{ W/m}^2 < GHI < I_0 * 1.5 * \cos(SZA)^{1.2} + 50 \text{ W/m}^2 \quad (4.3)$$

where I_0 the solar constant and SZA is the solar zenith angle

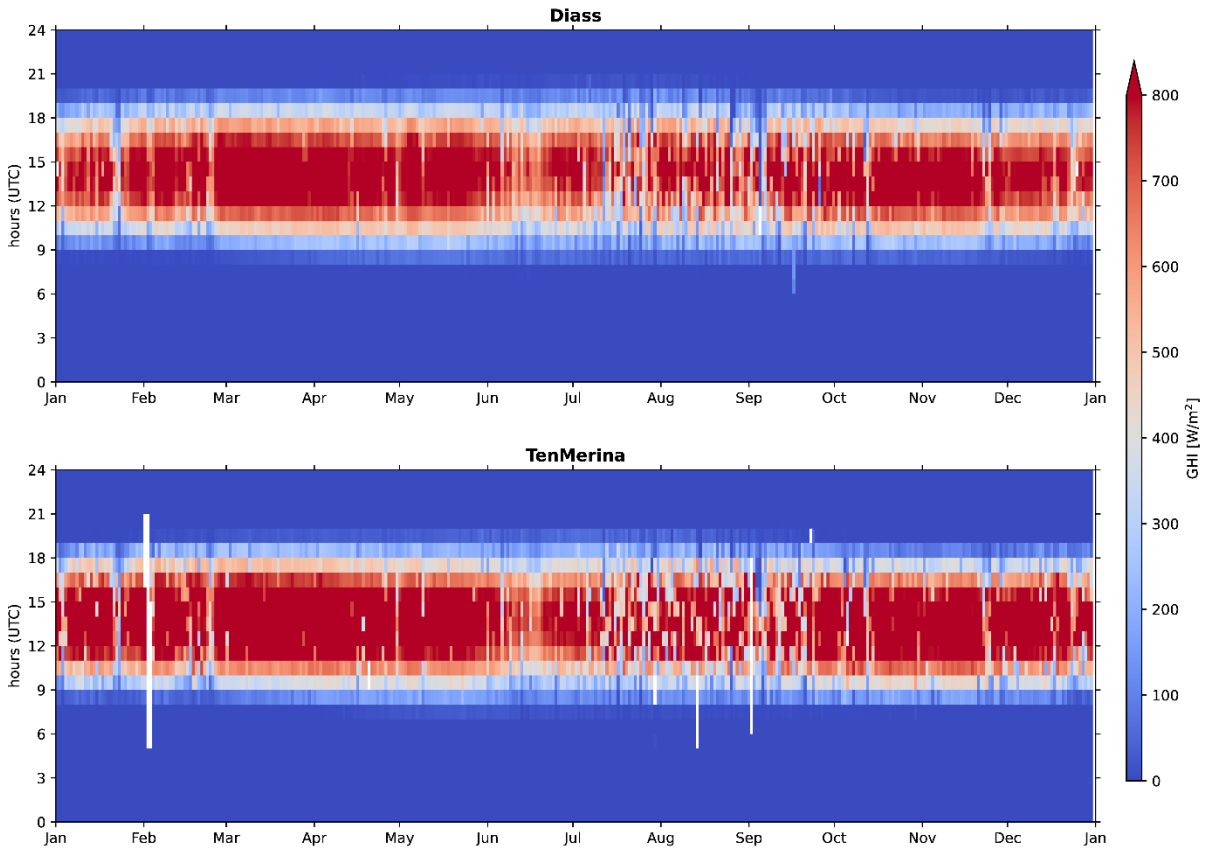


Figure 4.4 Time series of instantaneous hourly GHI showing the data quality for the two stations. The white bands represent missing data.

4.2.4.2 Evaluation of the Model

The evaluation of the model involves comparing its output with observations to assess its accuracy and reliability in predicting hourly GHI values. To identify and extract the corresponding locations in the simulation results that match the geographical coordinates of the station, a nearest-neighbour interpolation technique was used. When evaluating the performance of different simulations in relation to observations, the focus was solely on GHI values derived from observations when the solar zenith angle (SZA) is below 85 degrees. This

selection criterion was implemented to prevent potential GHI errors caused by measurement uncertainties during early morning and late evening periods, as well as the seasonal effects of sunrise and sunset (Sawadogo et al., 2023). For the study region, SZA values less than 85 degrees correspond to a Universal Time Coordinated (UTC) period between 8:00 and 18:00, during which the diurnal variation of GHI was analyzed. Our analysis comprised three types of scenarios, namely cloudy sky, clear-sky, and all-sky conditions. In the cloudy and clear-sky analyses, the observational data were categorized based on the clearness index (Kt) to identify composite days with cloudy and clear-sky conditions.

$$Kt = \frac{GHI}{G_0} \quad (4.4)$$

Where GHI represents the global solar irradiance measured at ground level, and G_0 represents the solar irradiance at the top of the atmosphere.

The clearness index is a measure of the amount of direct solar radiation that reaches the earth's surface. Therefore, the clearness index values used to define cloudy and clear skies can change depending on the location. In this study, clear and cloudy sky conditions are defined as Kt values $Kt \geq 0.65$ for clear skies and $Kt \leq 0.4$ for cloudy skies.

The daily extra-terrestrial radiation G_0 ($\text{MJ m}^{-2} \text{day}^{-1}$) is obtained using the following Equation (Allen et al., 1998):

$$G_0 = \frac{24(60)}{\pi} G_{SC} d_r [\omega_s \sin(\varphi) \sin(\delta) + \cos(\varphi) \cos(\delta) \sin(\omega_s)] \quad (4.5)$$

where:

G_{SC} represents the solar constant and is equal to $0.0820 \text{ MJ m}^{-2} \text{ min}^{-1}$

d_r denotes the inverse relative distance Earth-Sun [rad]

ω_s is the sunset hour angle [rad]

φ is the latitude of the location [rad]

δ represents the solar declination [rad]

The daily mean GHI was calculated by taking the average of the instantaneous GHI values for days without any missing GHI data. An algorithm was developed to identify both cloudy and clear-sky days for the stations and aggregate the data to generate an average diurnal cycle of GHI. The same procedure was applied to determine the sky conditions for the different experiments, based on the identified dates at various locations.

4.2.4.3 Performance measures

To assess the accuracy of the WRF-Solar model, a range of performance metrics have been used, including the root mean square error (RMSE), mean absolute error (MAE), and correlation coefficient (r). These metrics were utilized to assess the accuracy of the model's

predictions. The normalized values of the MAE and RMSE were also calculated as nMAE and nRMSE, respectively. Additionally, we calculated the index of agreement to further evaluate the model's performance. The index of agreement (IOA) measures the degree of agreement between the predicted and observed values, considering both the magnitude and timing of the errors.

$$MAE = \frac{1}{n} \sum_{i=1}^n (|P_i - O_i|) \quad (4.6)$$

$$nMAE = \left[\frac{MAE}{\max(O) - \min(O)} \right] * 100 \quad (4.7)$$

$$RMSE = \sqrt{\sum_{i=1}^n \frac{(P_i - O_i)^2}{n}} \quad (4.8)$$

$$nRMSE = \left[\frac{RMSE}{\max(O) - \min(O)} \right] * 100 \quad (4.9)$$

$$R = \frac{\sum_{i=1}^n (O_i - \underline{O})(P_i - \underline{P})}{\sqrt{\sum_{i=1}^n (O_i - \underline{O})^2 \sum_{i=1}^n (P_i - \underline{P})^2}} \quad (4.10)$$

$$IOA = 1 - \frac{\sum_{i=1}^n (P_i - O_i)}{\sum_{i=1}^n (|P_i - \underline{O}| + |O_i - \underline{O}|)^2} \quad (4.11)$$

Here P represents the simulation value, O the observation data at timestep i , and n the number of data points used for comparison. $\max(O)$ and $\min(O)$ refer to the maximum and minimum values of the observation. \underline{O} and \underline{P} are the mean values of the observation and simulation, respectively.

4.3 Results

4.3.1 Evaluation of the WRF-Solar simulations

4.3.1.1 Scatter plot of the GHI simulations

GHI forecasting plays a pivotal role in optimizing solar energy production, resource planning, and grid integration. It enables stakeholders to make informed decisions, improve operational efficiency, and harness the maximum potential of solar energy resources. The scatter plot analysis for GHI is presented in *Figure 4.5*, which compares the performance of different WRF shortwave radiation schemes, including shallow and no shallow schemes, for the study locations and the entire dataset. In general, the estimated GHI shows minimal or no differences between simulations run with or without the shallow convection scheme under all-sky conditions. For instance, the Dudhia_shallow experiment shows a RMSE = 198 W/m² (15%), MAE 146 W/m² (11%), while the Dudhia_no_shallow indicates a RMSE = 199 W/m² (15%) and MAE = 146 W/m² (11%). These results suggest that the inclusion or exclusion of the shallow convection scheme in the WRF-Solar model has little impact on the estimation of

GHI at 3 km within the region under all-sky conditions.

The RRTMG_AERO experiment scheme exhibits the best forecasting performance for GHI at the two stations. The RRTMG_AERO_shallow experiment achieves the highest correlation coefficient of 0.85 and IOA of 0.84 with the lowest values of RMSE (160 W/m²) and MAE (110 W/m²), indicating a strong positive correlation between the predicted and observed values. Similar performance has been observed for the no shallow scheme as well with both a correlation coefficient and IOA of 0.85, RMSE (158 W/m²), and MAE (110 W/m²). The Dudhia scheme follows the RRTMG_AERO scheme in terms of performance, while the RRTMG scheme exhibits the least performance among the evaluated experiments. The analysis has revealed a substantial difference in the metrics between the RRTMG and RRTMG_AERO schemes. The inclusion of aerosol effects improves the accuracy of the modelled GHI. Aerosols can absorb and scatter incoming solar radiation, leading to changes in the amount and distribution of radiation that reaches the Earth's surface. By accounting for these effects, the coupled WRF-Solar model with aerosol input can provide a more accurate estimate of GHI over a given region. Therefore, incorporating aerosol effects into solar radiation forecasting models can significantly enhance their performance, particularly in regions where aerosol concentrations are significant. This aligns with the findings of Verbois et al. (2018) who demonstrated that the Dudhia scheme performs better than the RRTMG for solar irradiance forecasting, and Jimenez et al. (2016) demonstrated that the fully coupled WRF-Solar model with time-varying aerosol data improved the estimated GHI.

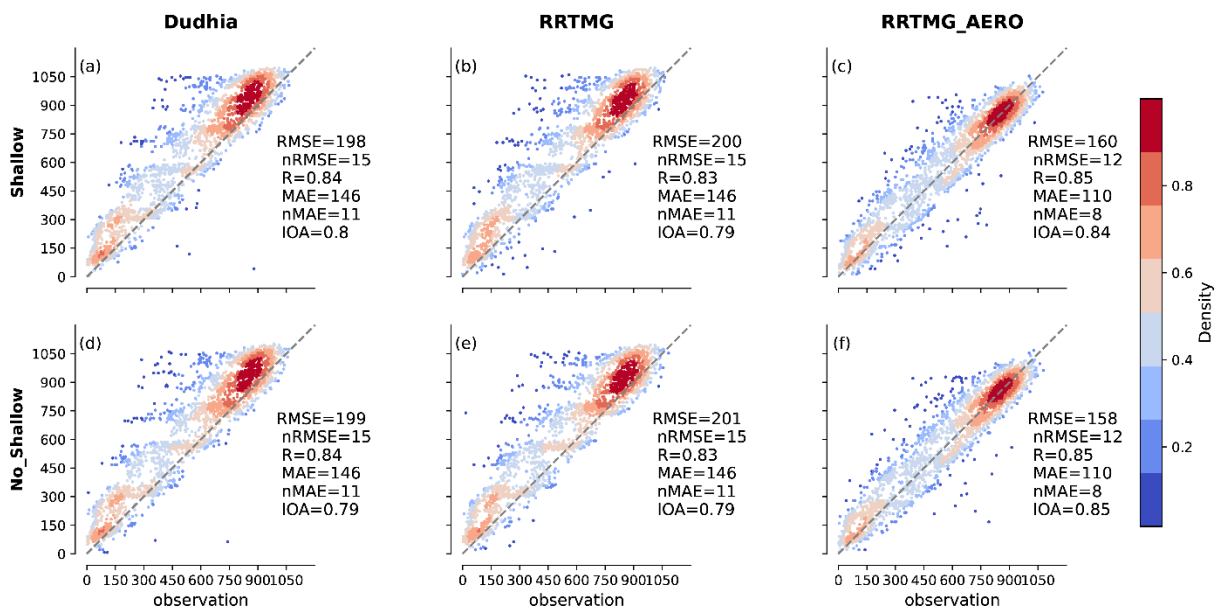


Figure 4.5 Scatter plot of the hourly values of GHI from different WRF-Solar simulations and observation for the two stations.

4.3.1.2 Seasonal performance of the GHI simulations

Figure 4.6 presents the comparison of the seasonal performance between ground measurements and the WRF-Solar model estimates of GHI. RRTMG_AERO performs best in all seasons for both shallow and no-shallow schemes. The simulations using both the Dudhia and RRTMG schemes show similar performance across all seasons, with only a small difference. However, in December-January-February (DJF), March-April-May (MAM), and September-October-November (SON) seasons, the Dudhia scheme, both shallow and no shallow, displays slightly better performance as compared to RRTMG, this is indicated by the relatively lower nRMSE and nMAE values. During DJF and MAM seasons, the values of nRMSE and nMAE are relatively low as compared to the other seasons indicating good performance in these seasons. In June-July-August (JJA), which is considered the rainy season, the simulations show high values of nRMSE, accompanied by significantly high nMAE values. The large bias in GHI may be attributed to the difficulty of the WRF-Solar model in estimating cloud properties. This limitation of WRF Solar to properly forecast cloud conditions is also discussed by Lara-Fanego et al. (2012) who found a high value of RMSE under cloudy conditions (50%). According to Tapakis and Charalambides (2013), the amount of irradiance reaching the Earth's surface is largely affected by the presence of clouds in the sky, which is considered one of the major unpredictable factors. The results of the study align with the observations made by Sawadogo et al. (2023), who have demonstrated a notable deviation in the hourly estimated GHI during the JJA season compared to other seasons.

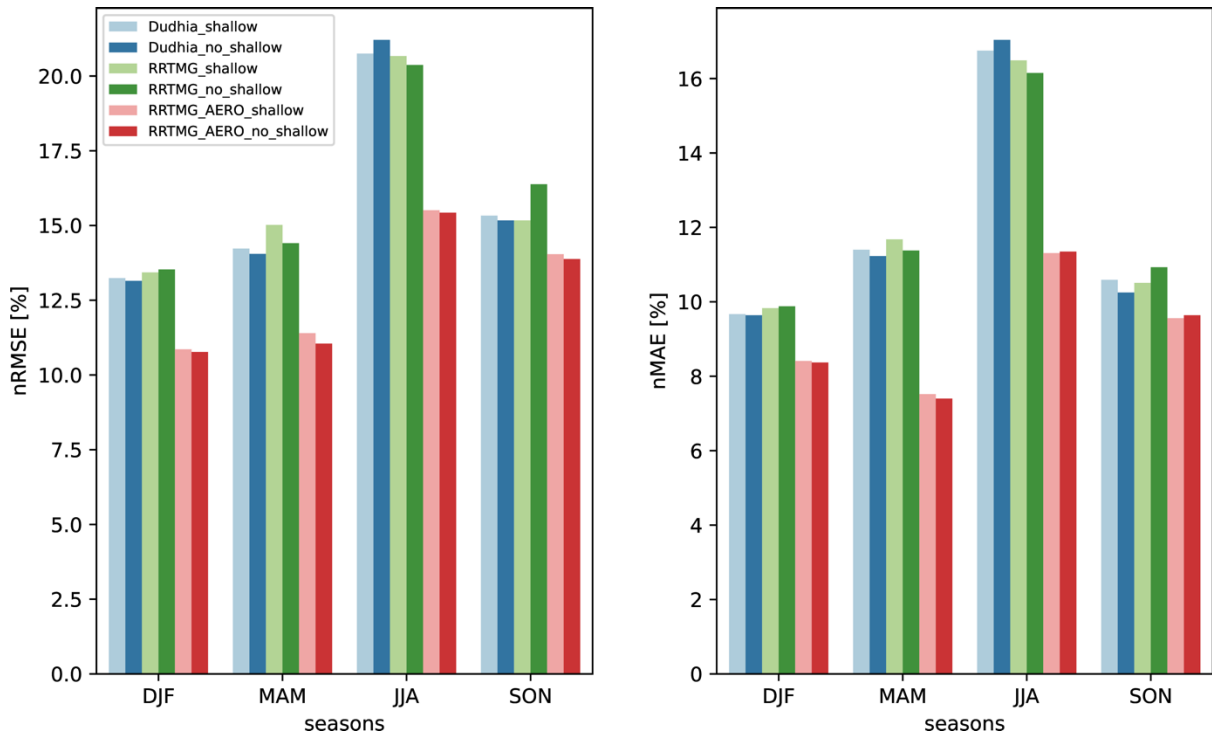


Figure 4.6 Seasonal performance (measured by $nRMSE$, $nMAE$) of the simulated GHI for the different WRF-Solar configurations and the two stations.

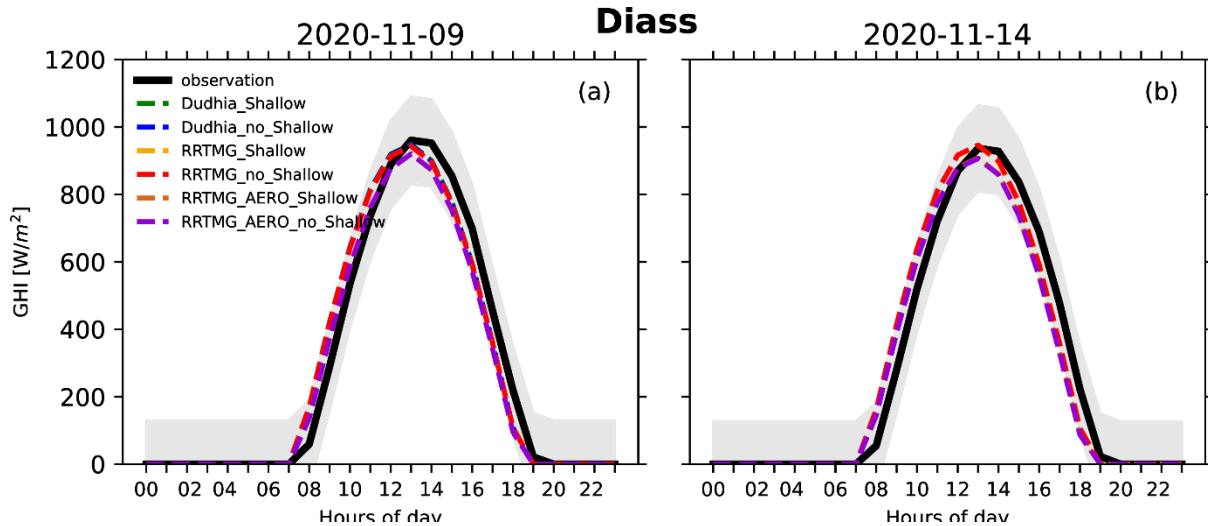
4.3.1.3 Diurnal cycle performance of the GHI simulations

In this part, our focus is on assessing the model's performance in the diurnal cycle (clear sky, cloudy sky, and high AOD). Evaluating the model's performance during clear sky is essential because clear sky conditions often serve as a baseline for estimating solar energy potential. The cloudy sky conditions help determine the model's ability to simulate cloud cover accurately and estimate the associated reduction in solar radiation. The high AOD conditions help assess its capability to account for aerosol effects and predict the resulting reduction in GHI. This is particularly important in regions with significant aerosol pollution. This evaluation helps identify potential biases, strengths, and limitations of the model that could enable improvements in its parameterizations or input data.

4.3.1.3.1 Performance of the model for clear sky

The daily pattern of the GHI for the different experiments and observations at Diass and Ten Merina under clear sky conditions is shown in *Figure 4.7*. The plot provides a visual comparison of the accuracy of different WRF-Solar configurations considered in this study in reproducing the observed diurnal variation of GHI at the two stations. The dates selected for comparison correspond to the 99th percentile of clear sky dates recorded at each station. The number of clear sky day composites is higher in Ten Merina than in Diass. The difference in

the number of clear days could be due to many factors such as topography (Lee et al., 2019), urbanization (Ouyang et al., 2022), and proximity to the coast as maritime influences such as sea breezes and fog could reduce the number of clear days (Garau and Gelabert, 2022). The performance of various experiments exhibits variability across the two stations. In Diass, the various experiments exhibit a better performance as they do not only capture the diurnal variation but also the amplitude of the GHI. On the other hand, Ten Merina exhibits an underestimation of GHI on clear days, although the pattern of all experiments falls within the 95% confidence interval of the observed data. Our findings indicate that the WRF-Solar model fails to accurately capture the peak GHI values during periods of high AOD since the station has a high AOD concentration compared to Diass (*Figure 4.8*). This could be related to the bias in the CAMS aerosol data since the WRF-Solar model incorporates the aerosol data directly into the radiative transfer routine, without parametrization (Ruiz-Arias et al., 2014). Additionally, the relatively poor performance of most experiments in Ten Merina can be attributed to the prevalence of high AOD on those days compared to Diass. Nonetheless, both stations exhibit consistent diurnal patterns across all experiments, demonstrating the ability of WRF-Solar to estimate GHI on clear sky days.



TenMerina

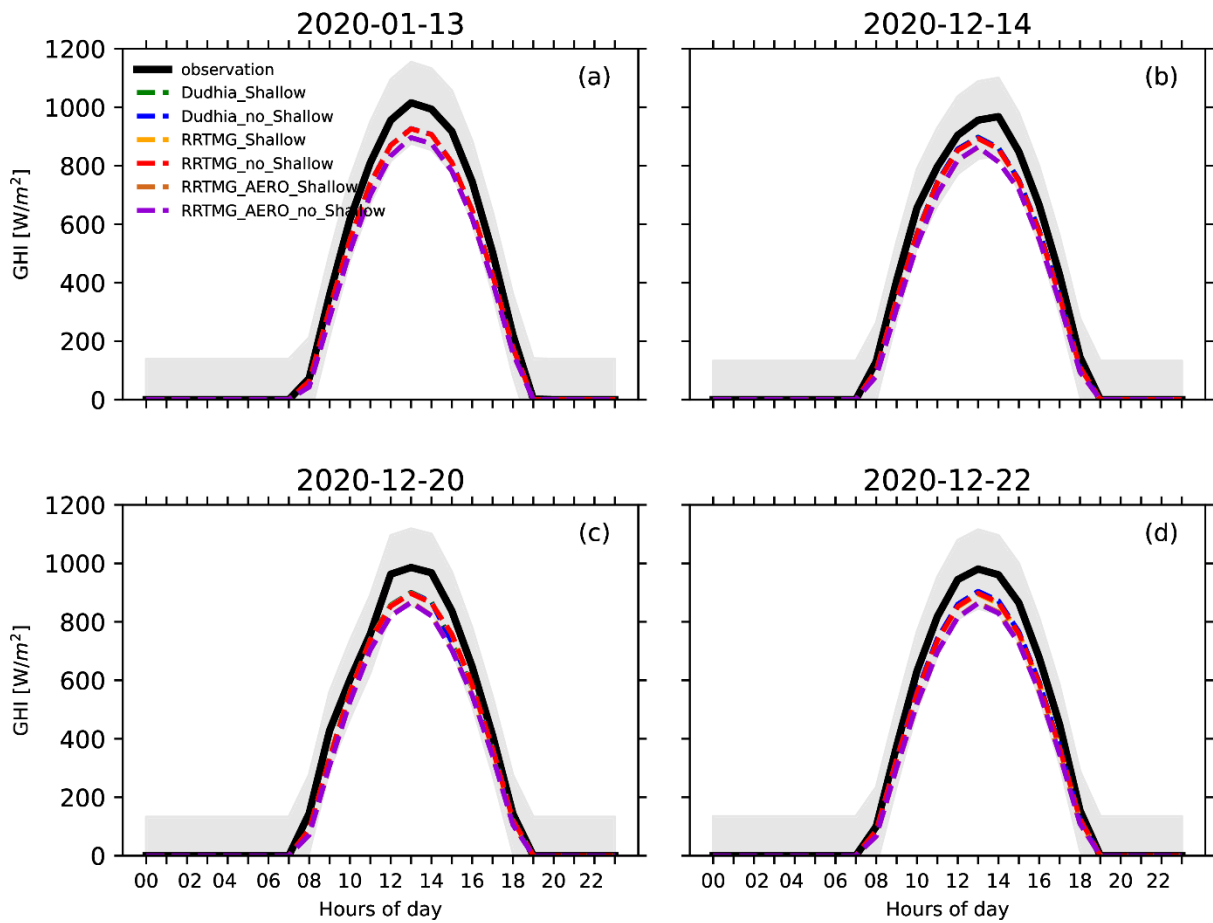


Figure 4.7 Diurnal variation of different WRF-Solar configurations and observation of the GHI at the two stations under clear conditions.

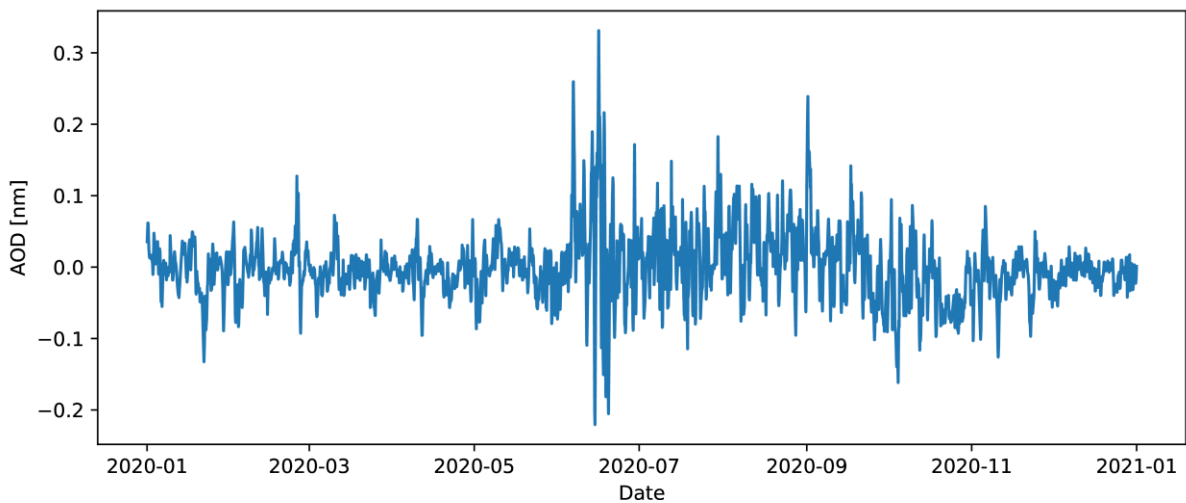


Figure 4.8 Hourly difference between AOD at Ten Merina and AOD in Diass for the year 2020.

4.3.1.3.2 Performance of the model for cloudy sky

Figure 4.9 displays the average daily variation of GHI, calculated from a composite of cloudy days across the stations. It is important to note that Diass experiences fewer clear sky days and more cloudy days, as indicated in the preceding section. In comparison to the performance of the WRF-Solar experiments on clear sky days, it is noteworthy that the model's performance is significantly lower under cloudy sky conditions at both stations. The different experiments fail to capture not only the diurnal variation but also the magnitude of the GHI. Moreover, there is an overestimation of GHI in both stations. One potential explanation for the lower performance of the WRF-Solar model under cloudy sky conditions could be an underestimation of cloud properties in the model. This could lead to an incorrect representation of GHI reaching the Earth's surface, as the presence of clouds tends to diminish the amount of solar radiation reaching the surface. The performance of the WRF model is influenced by the choice of different physical parameterizations and numerical configurations. Studies have indicated that although the WRF-Solar models have effectively reduced biases in GHI in comparison to the original WRF model, there are still considerable uncertainties associated with initial and lateral boundary conditions, physical parameterizations, and model parameters (Jimenez et al., 2016; Yang et al., 2021). Liu et al. (2022) found that three cloud parameters accounted for more than 90% of the total variance in solar irradiance under cloudy conditions. Uncertainties could also be related to aerosols. GHI is highly sensitive to uncertainties in albedo, aerosol, and cloud properties in the cloudy sky (Yang et al., 2021). The aerosol-aware Thompson-Eidhammer microphysics scheme used in this study explicitly accounts for direct aerosol effects for WRF-Solar. While there have been improvements in aerosol treatment within WRF-Solar, uncertainties persist due to internal model parameters associated with aerosol processes, as well as external factors (Liu et al., 2022). Nevertheless, the RRTMG_AERO shallow and no shallow schemes seem to have better performance in Ten Merina (a, b) and Diass (a, b, and c).

Diass

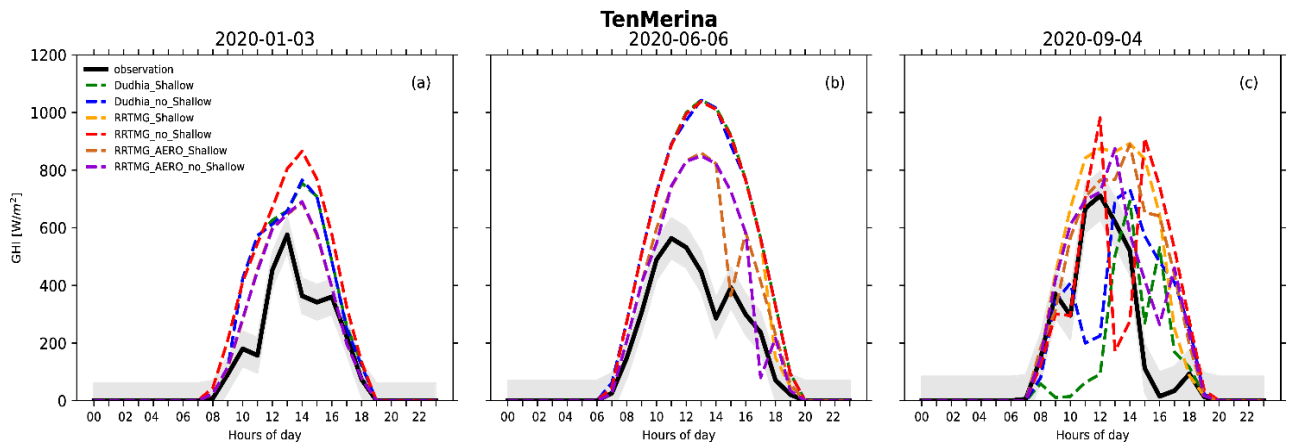
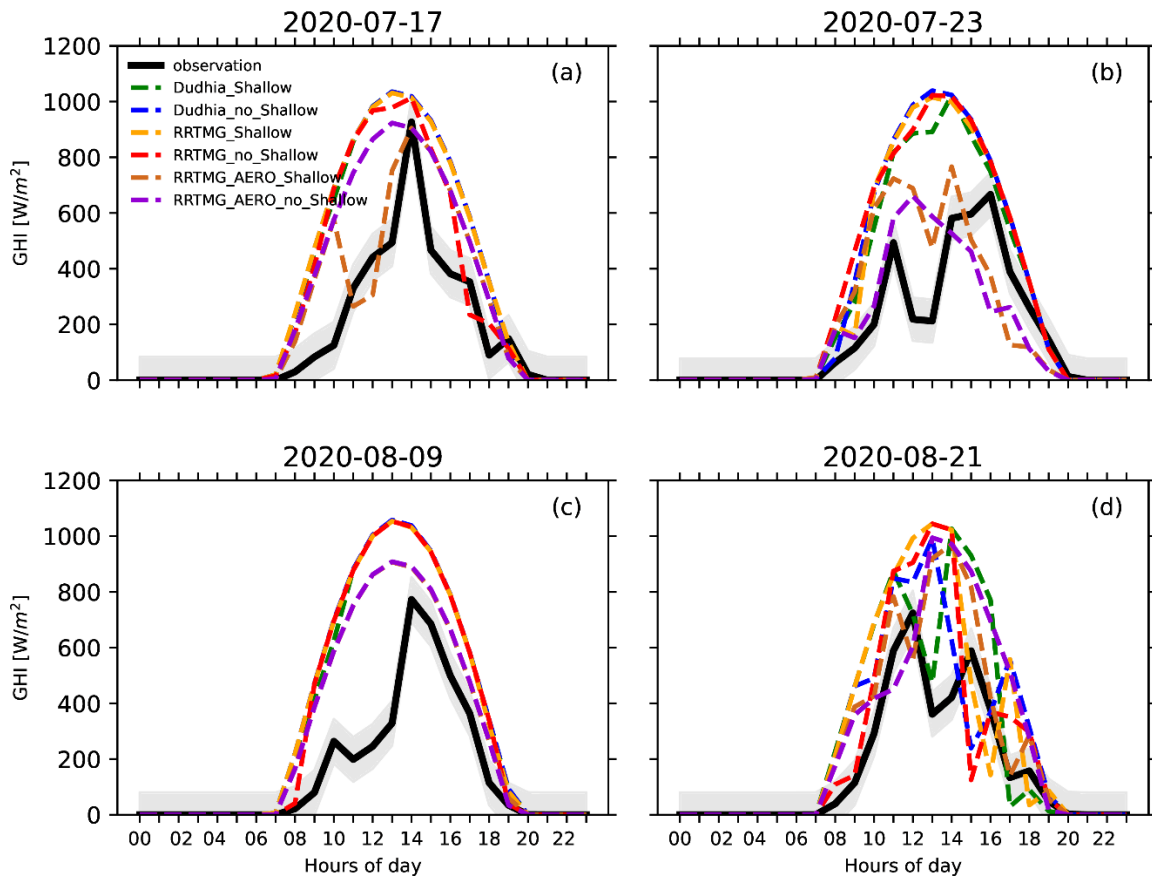


Figure 4.9 Diurnal variation of different WRF-Solar configurations and observation of the GHI at the two stations under cloudy conditions.

4.3.1.3.3 Performance of the model for high AOD

Figure 4.10 shows the average daily variation of GHI, computed from a composite of days characterized by high AOD across the stations. The WRF experiments exhibit improved performance on days characterized by low AOD values of 0.1 at both stations. During such conditions, the model effectively captures the amplitude and variations of GHI, albeit with a slight underestimation at the Ten Merina station. In comparison, the RRTMG and Dudhia radiation schemes, whether considering a shallow convection scheme or not, slightly demonstrate a closer approximation to the observed GHI amplitude than the RRTMG_AERO scheme.

Conversely, on days characterized by high AOD (2.2 and 2.3), respectively at Ten Merina and Diass, the RRTMG_AERO scheme, including both shallow and non-shallow configurations, demonstrates better performance in representing GHI with a closer amplitude to the observed GHI. In these situations, the RRTMG_AERO proves to be more effective in capturing the variations and magnitude of GHI when compared to other schemes. The inclusion of aerosol effects in the RRTMG_AERO scheme contributes to a more accurate representation of GHI under such high AOD conditions. Nonetheless, despite efforts to account for aerosol effects in the RRTMG_AERO scheme, it is important to acknowledge that uncertainties remain. This is consistent with the results found in the diurnal pattern of GHI in Ten Merina under clear skies when the experiments are not able to capture the maximum of the observed due to high AOD.

Therefore, further research and improvements in the assimilation of aerosol processes are necessary to enhance the accuracy of GHI predictions in the WRF-Solar model. Overall, the inclusion of a shallow convection scheme appears to have a minimal contribution to the representation of the GHI under high AOD.

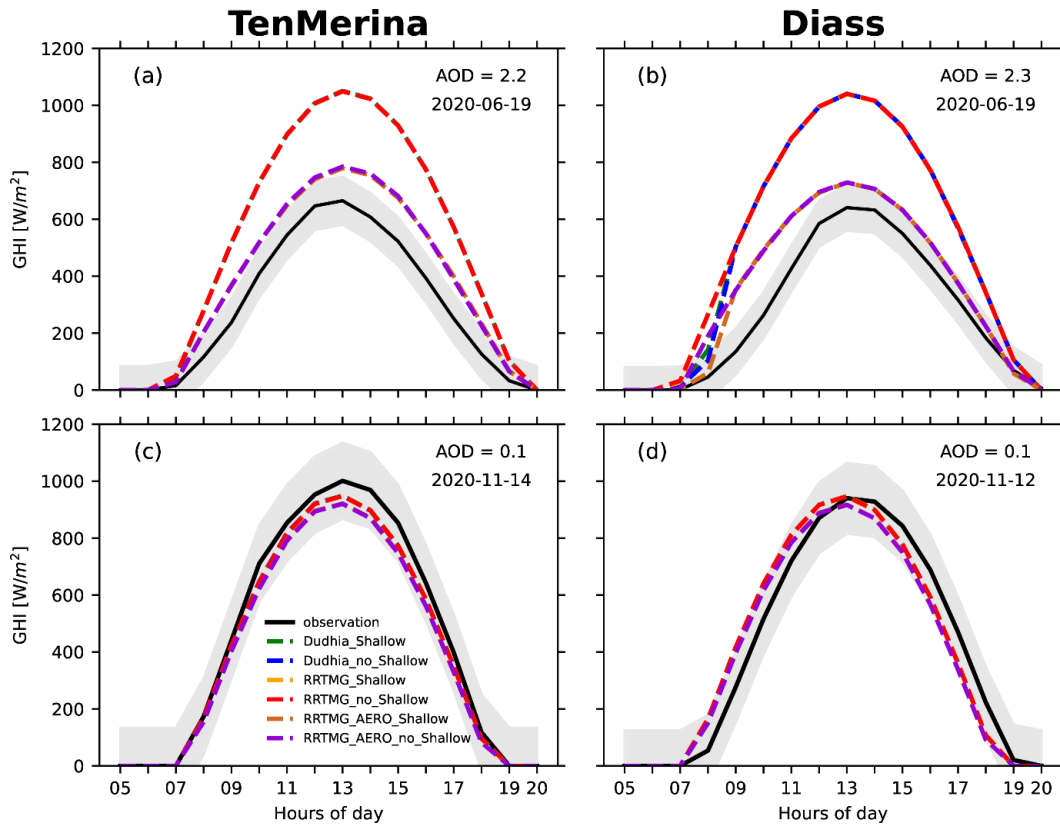


Figure 4.10 Diurnal variation of different WRF-Solar configurations and observation of the GHI at the two stations under high AOD conditions.

4.3.1.4 Overall performance

Table 4.3 summarizes the performance of the different simulations for the two stations under clear and cloudy sky conditions. The statistical results from the metrics indicate that the WRF-Solar model performs quite well in estimating GHI, at both locations. The model's simulations exhibit higher accuracy under clear sky conditions compared to cloudy skies. For Diass, under clear sky conditions, the average correlation coefficient (R) is found to be 0.91, with an RMSE of 135 W/m^2 and a MAE of 108 W/m^2 . On the other hand, under cloudy conditions, the R-value drops to 0.6, and the corresponding RMSE and MAE values increase to 341 W/m^2 and 281 W/m^2 , respectively. At the Ten Merina station, under clear sky conditions, the model shows even better performance with an R-value of 0.93, an RMSE of 114.1 W/m^2 , and a MAE of 77.9 W/m^2 . Conversely, under cloudy sky conditions, the R-value decreases to 0.58, and the RMSE and MAE values increase to 324.5 W/m^2 and 258.7 W/m^2 , respectively. These results highlight that the WRF-Solar model's forecasting accuracy for GHI highly depends on sky conditions at both locations.

Additionally, the results indicate that under clear sky conditions in Diass, the RRTMG_AERO experiment, both with and without considering a shallow convection scheme,

demonstrates better performance in estimating GHI. Following that, the Dudhia scheme also shows relatively good performance as well. Similarly, in Ten Merina, RRTMG_AERO and the Dudhia experiments exhibit the best performance in GHI estimating. However, when considering the MAE, the RRTMG_AERO scheme performs best. This is in line with the study of Sawadogo et al. (2023) who found that RRTMG_AERO and Dudhia schemes have the best performance in estimating GHI for 18 stations in West Africa. Under cloudy conditions in both stations, all experiments show a large uncertainty in GHI estimation in both stations. This is consistent with previous studies (Liu et al., 2022; Yang et al., 2021) showing that the WRF-Solar model has uncertainties in GHI estimation during cloudy days. Nonetheless, the RRTMG_AERO experiment remains the best-performing scheme for forecasting GHI. This experiment consistently outperforms other schemes in accurately capturing GHI. This indicates the experiment's effectiveness in accounting for aerosol effects and its ability to provide reliable GHI predictions even though some improvements are required.

These findings suggest that in both locations, the RRTMG_AERO scheme, with its inclusion of aerosol effects, shows favorable performance in capturing GHI under clear and cloudy skies. The Dudhia scheme also demonstrates good performance, although the RRTMG_AERO scheme outperforms it when considering MAE.

Additionally, the inclusion or exclusion of a shallow convection scheme in the WRF-Solar model has minimal effect on the estimated GHI at both stations under clear skies. This is evident in *Figure 4.11*, where during the dry season, which consists predominantly of clear-sky days, there is little difference in the total cloudiness between the two experiments. However, during the rainy season, which is characterized by a higher incidence of cloudy days, there are some differences in total cloud cover between the shallow and no-shallow experiments. Both stations show a similar pattern of total cloud cover. However, in TenMerina, the difference in terms of RMSE between the shallow and no_shallow experiment is higher with the RRTMG_AERO experiment (16 W/m^2) as compared to Diass (5 W/m^2). This discrepancy could be due to the higher average bias between the two experiments in TenMerina compared to Diass, especially during the peak of the rainy season (August), as shown in *Figure 4.11*. Furthermore, the relatively better performance of the RRTMG_AERO experiment in Diass compared to TenMerina could be related to the cloud-aerosol-radiation interaction, as TenMerina has a high concentration of aerosols during the rainy season (*Figure 4.8*). This means that the shallow convection scheme contributes to uncertainties in the estimation of GHI when clouds and high aerosol concentrations are involved in radiation interactions under

cloudy skies. So, the choice of using shallow convection or not in the WRF-Solar depends on the location, i.e., the AOD concentration.

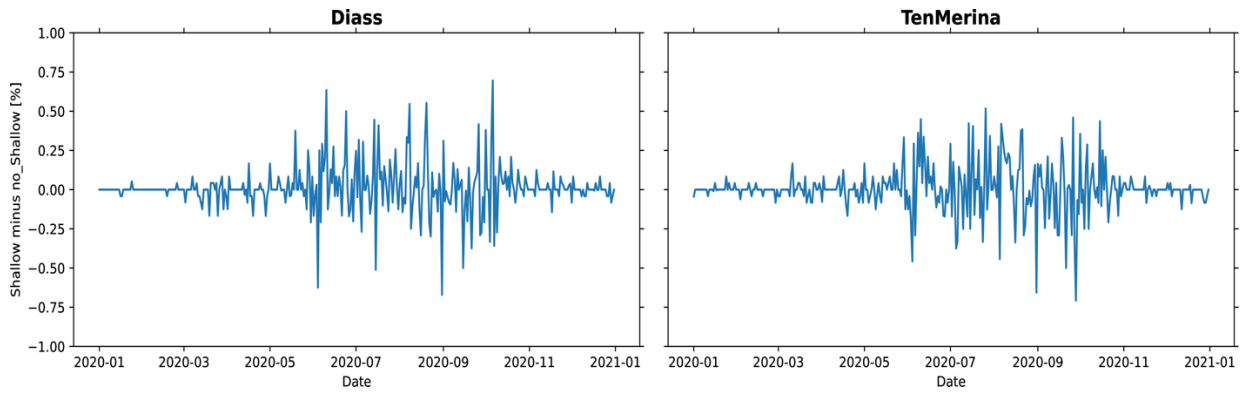


Figure 4.11 Difference of daily total cloud cover between shallow and no_shallow with the RRTMG_AERO experiment in Diass and Ten Merina for the year 2020

Table 4.3 Error values for GHI forecasts categorized according to the prevailing sky conditions.

Cloud conditions	Station	RMSE	nRMSE	R	MAE	nMAE	IAO	Experiment
Cloudy sky	Diass	382	41.32	0.66	323.73	35.01	0.47	Dudhia_Shallow
	Diass	374	40.45	0.68	309.09	33.43	0.48	RRTMG_Shallow
	Diass	263	28.45	0.55	209.13	22.62	0.6	RRTMG_AERO_Shallow
	Diass	373	40.34	0.61	307.66	33.28	0.47	Dudhia_no_Shallow
	Diass	386	41.75	0.55	316.98	34.28	0.46	RRTMG_no_Shallow
	Diass	268	28.99	0.57	219.33	23.72	0.59	RRTMG_AERO_no_Shallow
	TenMerina	367	42.29	0.54	295.9	34.09	0.48	Dudhia_Shallow
	TenMerina	367	42.29	0.64	297.88	34.32	0.47	RRTMG_Shallow
	TenMerina	245	28.23	0.46	182.13	20.99	0.6	RRTMG_AERO_Shallow
	TenMerina	359	41.36	0.57	285.1	32.85	0.49	Dudhia_no_Shallow
	TenMerina	380	43.78	0.7	317.25	36.55	0.46	RRTMG_no_Shallow
	TenMerina	229	26.39	0.56	174.24	20.08	0.64	RRTMG_AERO_no_Shallow
Clear-sky	Diass	138	14.01	0.93	114.17	11.59	0.87	Dudhia_Shallow
	Diass	142	14.41	0.91	115.8	11.75	0.87	RRTMG_Shallow
	Diass	122	12.38	0.9	93.48	9.49	0.89	RRTMG_AERO_Shallow
	Diass	141	14.31	0.92	115.62	11.73	0.87	Dudhia_no_Shallow
	Diass	145	14.72	0.9	116.86	11.86	0.86	RRTMG_no_Shallow

Cloud conditions	Station	RMSE	nRMSE	R	MAE	nMAE	IAO	Experiment
	Diass	122	12.38	0.9	93.37	9.48	0.89	RRTMG_AERO_no_Shallow
	TenMerina	113	9.22	0.94	81.12	6.62	0.91	Dudhia_Shallow
	TenMerina	119	9.71	0.93	82.62	6.74	0.91	RRTMG_Shallow
	TenMerina	114	9.3	0.93	72.02	5.88	0.91	RRTMG_AERO_Shallow
	TenMerina	112	9.14	0.94	79.63	6.5	0.91	Dudhia_no_Shallow
	TenMerina	115	9.38	0.93	80.35	6.56	0.91	RRTMG_no_Shallow
	TenMerina	112	9.14	0.93	72.18	5.89	0.91	RRTMG_AERO_no_Shallow

4.4 Conclusion

This chapter focused on investigating the effects of two shortwave radiation schemes, Dudhia and RRTMG, within the WRF-Solar model for two solar power plants located in Senegal: Diass and Ten Merina. The RRTMG scheme was examined in two simulations, one without considering AOD and one incorporating AOD (RRTMG_AOD). Additionally, the study explored the influence of shallow convection on all three simulations.

The performance evaluation of the model was conducted using hourly instantaneous measurements of GHI obtained from the two solar plants for 2020. The evaluation process involved examining the performance of the WRF-Solar model under different sky conditions, including all-sky, clear-sky, and cloudy conditions. By considering GHI measurements from these diverse sky conditions, a comprehensive assessment of the model's performance and its ability to capture the variations in solar irradiance under different atmospheric conditions was achieved. The simulations were conducted using a one-way two-nested domain, with a spatial resolution of 15 km for the outer domain and 3 km for the inner domain but focused on the latter domain. The main results can be summarized as follows:

- For the seasonal evaluation of the WRF-Solar model, it is observed that the values of nRMSE and nMAE are relatively low for DJF and MAM as compared to the other seasons indicating good performance in these seasons. However, the JJA season showed the lowest performance of the experiments, characterized by high values of nRMSE and nMAE.
- Under clear sky situations, the simulations of the model successfully replicate the average diurnal variation and magnitude of the observations at the stations, even though there is a slight underestimation at Ten Merina. In contrast, the model's performance is noticeably diminished under cloudy sky conditions at both stations as cloud cover poses challenges in accurately predicting irradiance.
- Under high AOD conditions, the WRF experiments are observed to be better on days characterized by low AOD values rather than high values.
- Overall, the RRTMG_AERO scheme, regardless of the consideration of the shallow convection scheme, exhibits superior performance in forecasting GHI at these stations. This is followed by the Dudhia scheme, which also shows relatively good performance under clear, cloudy, and all-sky conditions.

- The results suggest that the impact of including shallow clouds in the model does not significantly improve the model's ability to forecast GHI at the studied stations under clear skies and all skies. However, there are some differences under cloudy skies in Ten Merina.

These findings highlight the performance of various radiation schemes in the WRF-Solar model for forecasting GHI at the Diass and Ten Merina solar plants in Senegal. The results indicate that the RRTMG_AERO scheme demonstrates superior performance compared to other schemes. This holds under clear, cloudy, and all-sky conditions. Moreover, they emphasize the significance of selecting appropriate radiation schemes and considering aerosol effects in GHI forecasting models, while also shedding light on the relatively minor role of the shallow scheme in improving GHI representation. However, it is important to note that the model still exhibits significant biases, particularly under cloudy sky conditions. This indicates the challenge of accurately simulating GHI under such conditions in Senegal. Consequently, further adaptation and development of the WRF-Solar model, including the improvement of aerosol-cloud-radiation feedback, are necessary to improve GHI forecasting accuracy. For the location of Senegal, it is recommended to off the shallow convection scheme and allow the model to run in convective permitting mode since at 3 km of the resolution, the microphysics scheme is explicitly able to develop convection on the model grid.

Chapter 5: Conclusion and Recommendations

5.1 Summary of the main findings and Conclusion

In the current global context where climate change and the need for sustainable development are at stake, a global drive is underway toward the widespread use of renewable energy. However, as the energy sector becomes more reliant on weather-dependent renewable sources, it becomes crucial to incorporate weather and climate services. This thesis provides a thorough assessment of climate services for the energy sector in Senegal, investigates climate impacts on the sector at regional and country levels with a specific focus on renewable energy, and evaluates the performance of the WRF-Solar model for forecasting GHI in Senegal. The findings offer valuable insights into the current state, improvement prospects, and the crucial role of climate services and renewable energy in addressing climate change challenges.

The evaluation of climate services revealed existing challenges, including inadequate access to climate services, a weak communication framework, and a lack of collaboration between the meteorological office and the IPPs. These shortcomings underscore the urgent need for enhanced communication, coordination, and capacity building among stakeholders involved in the development and delivery of climate services to the energy sector. By addressing these issues, more effective and efficient climate services can be provided, ensuring decision-makers have access to reliable information. The study identified opportunities for enhancing current climate services, including strengthening capacity and resources to support the use of climate services, building expertise in utilizing climate data and services, and promoting the integration of climate services into decision-making processes. The aim is to ensure that energy sector decision-makers have access to reliable and accurate climate services. Strengthening the current climate services framework will contribute to more efficient and effective decision-making processes, enabling the energy sector to navigate climate-related risks.

Furthermore, the study explored the importance of climate services for the energy sector, specifically renewable energy, and examined the climate impacts on the energy sector, particularly regarding renewable energy, at both regional and country levels. The findings highlighted that climate variability and change have significant implications for renewable energy generation. While solar PV potential is projected to decrease at both regional and country levels, wind power potential is expected to increase in the region, under RCP 8.5 and 2.6. This underscores the

importance of incorporating climate services into energy planning, policies, and decision-making to optimize the utilization of renewable energy resources and mitigate climate-related risks. The following are some key results from this investigation:

- The assessment of the climate models used reveals a relatively precise representation of annual and monthly patterns in simulated solar PV potential, wind power density, and associated variables. However, there were notable biases of both underestimations and overestimations, particularly in the wind variables.
- The projections under the RCP8.5 scenario indicate a reduction in solar irradiance and solar PV potential across West Africa. The solar PV potential is anticipated to undergo a notable decrease across all RCMs and the ensemble mean, both in the near future (2021-2051) and the far future (2071-2100).
- Conversely, the projections indicate a prominent increase in wind power over West Africa for the two future periods. While the RCMs exhibit greater consistency in projecting other climate variables, there are divergences in the projections of wind speed and wind power density.
- In Senegal specifically, the projections indicate a slight decrease in energy production for various plants between 2006 and 2050. However, the degree of the reduction varies among the different plants.

Moreover, the study evaluated the performance of the WRF-Solar model for forecasting GHI in Senegal. The results indicated that the RRTMG_AERO scheme exhibited superior performance in predicting GHI compared to other schemes, emphasizing the significance of considering aerosol effects in GHI forecasting. However, challenges remain in accurately simulating GHI under cloudy sky conditions, indicating the need for further refinement and adaptation of the model, particularly regarding aerosol-cloud-radiation feedback. A summary of the results is as follows:

- The WRF modelling system performed better in the dry season (DJF-MAM) than in the wet season (JJA) and on days with low AOD values than under high AOD conditions.
- Under clear sky conditions, the model accurately replicated the diurnal variation and magnitude of GHI, with slight underestimation at Ten Merina. However, under cloudy sky conditions, the model's performance was noticeably diminished at both stations.

- In general, the RRTMG_AERO scheme demonstrated the best performance in predicting GHI at the studied stations. It was followed by the Dudhia scheme, which also exhibited relatively good performance under all sky conditions.
- Including shallow clouds in the model did not significantly improve GHI forecasting under clear and all-sky conditions, except for some differences under cloudy skies at Ten Merina.
- The overall performance of the model in forecasting GHI is relatively good. This suggests that it can be effectively utilized in Senegal for GHI forecasting purposes.

5.2 Limitations of the study

The study has some limitations that should be acknowledged. One of the limitations of this study is the limited sample size of interviews conducted to achieve the first specific objective. With a total of sixteen experts, the study may not fully capture the diverse range of perspectives and experiences within the energy and meteorological sectors. In addition, the data collected through interviews represent the opinions and experiences of the interviewed experts. While their insights are valuable, they may not always align with objective or comprehensive data. The findings should be considered in conjunction with other sources of information and data to ensure a comprehensive understanding. Another limitation related to the method used is that thematic analysis involves data reduction, where redundant or less relevant information is discarded to focus on the important themes. While this helps in summarizing and organizing the data, it can also result in the loss of information that could provide a more thorough understanding of the topic.

The second specific objective of the study is also subject to some limitations. The study is based on a relatively small ensemble of three RCMs due to the limited availability of participating modelling groups in the CORDEX-CORE. This small ensemble size may not fully capture the inherent uncertainty of climate projections, and additional simulations from more RCMs would enhance the robustness of the results. The model biases should also be considered as the RCMs simulations exhibit strong underestimations and overestimations, particularly for the wind variables. These biases may affect the accuracy of the projections.

For the third specific objective, the limitations may be related to the evaluation period used for the WRF-Solar simulations. The evaluation process of the model was conducted using hourly instantaneous measurements of GHI obtained from the two solar plants for the single year 2020. By focusing on a specific evaluation period, there is a potential limitation in capturing the full

range of variability and long-term trends in the GHI. Another limitation of the study is the presence of biases under cloudy sky conditions. The model exhibits significant biases, particularly under cloudy sky conditions. This indicates a limitation in accurately simulating GHI under such conditions in Senegal. The study's findings may be more reliable under clear-sky conditions.

5.3 Recommendations for further research

Based on the limitations identified in this study, as well as the potential areas for improvement, the following recommendations for further research can be suggested.

For future research, it is recommended to explore different interview methods, increase the number of expert interviews, and compare data collected through various data collection methods. It would be interesting to compare the data collected through the semi-structured interview method to other methods of data collection, such as questionnaires and surveys.

Additionally, the study suggests the need for additional analyses to further evaluate the robustness of the projected changes in wind and solar energy potential in West Africa, especially for wind. There is a higher degree of variation in the projected wind potential across West Africa compared to the solar potential. Future research should focus on addressing the biases observed in the RCMs simulations regarding wind variables. They could expand the ensemble size by considering the new modelling groups participating in the CORDEX-CORE and evaluate the consistency of results across different approaches and datasets, and consider additional variables or factors that may influence energy potential. Another option is to incorporate ground-based measurements if available. This would help to strengthen the findings, providing more confidence in the projections.

Furthermore, the evaluation period used for the WRF forecasting of GHI in Senegal could be extended in future studies to fully capture the variability and representativeness of GHI over a longer time period and gain a better understanding. It is important for future research to address the issue of biases under cloudy skies. Studies should also explore the use of alternative sources of aerosol data, such as AERONET data, to force the model and compare its outputs with these findings.

By addressing these recommendations in future research, a deeper understanding of the subject can be achieved, leading to more informed decision-making and effective planning for renewable energy projects in the region.

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APPENDIX

Interview Questions

Assessment of current climate services for energy resilience in West Africa: case of Senegal

Semi-structured interviews with actors

Name and function:

Institution/Company:

Email:

Cell:

Interviewer (S): Aissatou Ndiaye, PhD candidate, Climate Change and Energy/WASCAL

DATE:

Introduction

Thank you very much in advance for accepting this interview in the framework of my Ph.D. research as titled above.

The main audience for this interview is the producer of climate services in Senegal. The producer of climate services in Senegal is the National Agency for Civil Aviation and Meteorology (ANACIM) and the users in the energy sector are the National Agency

for Renewable Energies (ANER), the National Electricity Company (SENELEC) and the IPPs. The power utilities experts both conventional and renewable (solar and wind) will be interviewed especially those in charge of the technical service.

The interview aims to establish the baseline of communication and assess the performance of the climate services for the energy sector.

Part 1. Addressed to the Meteorological Office (ANACIM)

NB: Energy sector refers to SENELEC, ANER, and the IPPs throughout the questionnaire.

	Questions
Introduction	<ol style="list-style-type: none"> 1. What is the name of your institution? 2. Could you give a short description of your institution, its role, and its responsibilities? 3. What are the types of climate parameters you produce and how many climatic stations do you have?
Communication framework	<ol style="list-style-type: none"> 4. Is there a communication framework between your institution and the energy sector (Senelec, Aner, IPPs)? <ol style="list-style-type: none"> a. If yes, does the existing framework enable regular interaction between your institution and the energy sector? Is it appropriate? b. If no, did the energy sector suggest/request to have climate information? 5. Which types of climate information are provided to the energy sector? 6. Which types of climate information are requested by the energy sector? 7. How is the climate information delivered to the energy sector: reports, bulletins, maps, etc.? 8. What type of communication channels are used to deliver climate information to the energy sector: email, text message, and hard copies (courier)? Are they appropriate?

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	<p>9. Does your institution have mechanisms in place to facilitate two-way dialogue and feedback between itself and users within the energy sector?</p> <p>10. Does your institution collect or receive positive/ negative feedback from the energy sector users?</p> <ul style="list-style-type: none"> a. If yes, please give your users appreciation for the products b. If no, do you have a plan for collecting your users' feedback? <p>11. Do you have an idea about how climate services are used by the energy sector?</p> <p>12. Is there a request for new products to be developed?</p> <ul style="list-style-type: none"> a. If yes, please provide the list of the new products to be developed. What do you need for them and the constraints you have to generate them? b. If no, have you identified useful products that can help the energy sector to be more resilient and sustainable?
<p>The type of climate services produced and provided to the energy sector</p>	<p>13. What kinds of climate products and services does your institution provide to the energy sector, encompassing both renewable and conventional energy? This includes climate monitoring products, seasonal/interannual/decadal predictions, and projections.</p> <p>14. The products you are providing, do they include information on temperature, rainfall, wind, etc.?</p> <p>15. Are your products/services designed on daily, sub-seasonal (weeks), seasonal (months), and annual timescales?</p> <p>16. Do your products include information on climate projections?</p> <p>17. Does your institution provide day-to-day information/forecasts to the energy sector? (i.e. what is the frequency at which the information is provided: daily, weekly, monthly, etc.) and in what form is it delivered?</p>

	<p>18. Does your institution provide services on climate extremes (heat waves, drought, strong wind, rainfall, flood, etc.)?</p> <p>19. What is the frequency of deliverance of the climate extreme products?</p> <p>20. In what form does your institution provide such products: bulletin, map, etc.?</p> <p>21. Are your products useful/appropriate for energy users?</p> <p>22. To what extent is the climate information customized or tailored specifically for the energy sector?</p> <p>23. Could you pick a number on a scale of 0 to 10 for the tailoring?</p> <p>24. Do you have any project to improve the products/services being provided?</p> <p>25. Does your institution often verify whether it meets the needs of the energy sector?</p> <p>26. What and how is the verification method applied in practice, if any?</p>
<p>Early warning system (EWS)</p>	<p>27. Does your institution provide a multi-hazard early warning system to the energy sector?</p> <p>28. What type of early warning system is being provided?</p> <p>29. In what form is the information given: map, bulletin, online platform, etc?</p> <p>30. What is the frequency of the EWS being provided (monthly, yearly, seasonal, etc.)?</p> <p>31. Does your institution receive feedback about the EWS from the energy sector?</p> <p>32. Which of the EWS is the energy sector likely to be more interested in?</p> <p>33. Is there any mechanism to support the coordination of EWS?</p> <p>34. Does your institution provide seasonal outlooks of probabilities of potential hazards?</p> <p>35. What type of current and past climatic hazards are mostly seen in Senegal and which one is mostly impacting the energy sector?</p>
<p>Legislation/Policy/plan</p>	<p>36. Is there national legislation or a mandate in place that organizes the delivery of climate services?</p>

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	<p>37. Is there a national strategy/policy for climate services?</p> <ul style="list-style-type: none">a. If yes, does it have clear goals and responsibilities?b. If no, is there an ongoing procedure to set up this strategy and policy? <p>38. Are roles and responsibilities for the generation, customization, and communication of climate services clearly defined?</p> <p>39. Is there a process established for integrating climate services into relevant sectoral policies, strategies, and plans?</p> <p>40. Does Senegal have a national action plan specifically dedicated to climate services?</p>
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Assessment of current climate services for energy resilience in West Africa: case of Senegal

Semi-structured interviews with actors

Name and function:

Institution/Company:

Email:

Contact/Cell:

Interviewer (S): Aissatou Ndiaye, PhD candidate, Climate Change and Energy/WASCAL

DATE:

Introduction

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The interview aims to establish the baseline of communication and assess the performance of the climate services for the energy sector.

Part 2. Addressed to the energy sector: ANER, SENELEC, and IPPs (conventional and renewable)

Introduction	<ol style="list-style-type: none"> 1. What is the name of your institution? 2. Could you give a short description of your institution, its role, and its responsibilities? 3. What is the installed capacity of your plant (farm)? Is it private or public?
The type of climate services received	<ol style="list-style-type: none"> 4. What type of climate information does your institution receive? 5. What institution is providing climate information? 6. Does your institution receive information on the variability of the temperature, solar irradiance rainfall, wind, etc. and does it impact the production and supply? 7. Does your institution receive information on the intra, inter-seasonal, and annual timescale on the variability of the climate parameters? 8. Does your institution receive information on climate extremes: flooding, drought, heat waves, strong wind, etc? 9. Does your institution receive products/services on climate projections? 10. Does your institution receive day-to-day warnings from its climate information provider? 11. Do you receive those services upon request or is there a policy for the delivery of climate services? 12. How often do you receive the services? 13. Through what channels do you receive the services/information?

14. How does your institution use climate information, and for which purpose?
15. Are the climate services tailored/appropriate for your needs?
16. How does your institution assess those services?
17. Are there established feedback mechanisms to provide your evaluation of the relevance and quality of the products or services you receive?
18. Are you providing feedback to your climate information provider?
19. Could you please list the other types of climate services you currently need and which are not provided?
20. How often do you need those services?
21. What are the primary improvements you would require to achieve a more customized service?
22. How would the additionally requested climate information products be used?
23. Does your institution record the climate extremes (strong wind and rainfall, heat wave, etc.? Do you have some value available (statistics)?
24. How does your institution adapt to the extremes?
25. Some climate extremes like flooding and drought have negative impacts on infrastructure and thermal power plants for cooling. Have you experienced such an impact in the past 10 years?
26. If yes to question 24, how did you handle the situation?
27. Heatwave is happening in our region almost every summer now; how do you manage to cover the energy demand during that time?
28. Is your institution resilient to climate extremes? How?
29. Based on scientific research the extremes are likely to increase in frequency in the future; can we say that your institution is ready to face such a situation?

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	<p>30. Is there any plan to make it more resilient in the future?</p> <p>31. According to you, what is needed for a more resilient energy sector?</p>
<p>Communication framework</p>	<p>32. What is the communication framework between your institution and your climate information provider?</p> <p>33. In what manner does your institution access climate services? (e.g., online platforms, bulletins, courier services, etc.)</p> <p>34. Do you find the communication channels through which you receive climate information to be appropriate? Please explain.</p> <p>35. Do you want some improvement? Explain</p> <p>36. Does your institution have mechanisms in place to facilitate two-way dialogue and feedback between your institution and your climate information provider?</p> <p>37. Does your institution give feedback to your climate information provider?</p> <p>38. How is it done?</p>
<p>Early warning system</p>	<p>39. Does your institution receive a multi-hazard early warning system?</p> <p>40. What type of early warning system is being provided to you?</p> <p>41. In what form is the climate information given: map, bulletin, online platform, etc?</p> <p>42. What is the frequency of the EWS being provided (monthly, yearly, seasonal, etc.)?</p> <p>43. Does your climate information provider provide seasonal outlooks of probabilities of potential hazards?</p> <p>44. Is your institution satisfied with the EWSs or do you need some improvements?</p> <p>45. What types of EWSs does your institution need?</p>

 Publication



Article

Projected Changes in Solar PV and Wind Energy Potential over West Africa: An Analysis of CORDEX-CORE Simulations

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Abstract: Renewable energy development is growing fast and is expected to expand in the next decades in West Africa as a contribution to addressing the power demand and climate change mitigation. However, the future impacts of climate change on solar PV and the wind energy potential in the region are still unclear. This study investigates the expected future impacts of climate change on solar PV and wind energy potential over West Africa using an ensemble of three regional climate models (RCMs). Each RCM is driven by three global climate models (GCMs) from the new coordinated high-resolution output for regional evaluations (CORDEX-CORE) under the RCP8.5 scenario. Two projection periods were used: the near future (2021–2050) and the far future (2071–2100). For the model evaluation, reanalysis data from ERA5 and satellite-based climate data (SARAH-2) were used. The models and their ensemble mean (hereafter Mean) show acceptable performance for the simulations of the solar PV potential, the wind power density, and related variables with some biases. The Mean predicts a general decrease in the solar PV potential over the region of about –2% in the near future and –4% in the far future. The wind power density (WPD) is expected to increase by about 20% in the near future and 40% in the far future. The changes for solar PV potential seem to be consistent, although the intensity differs according to the RCM used. For the WPD, there are some discrepancies among the RCMs in terms of intensity and direction. This study can guide governments and policymakers in decision making for future solar and wind energy projects in the region.

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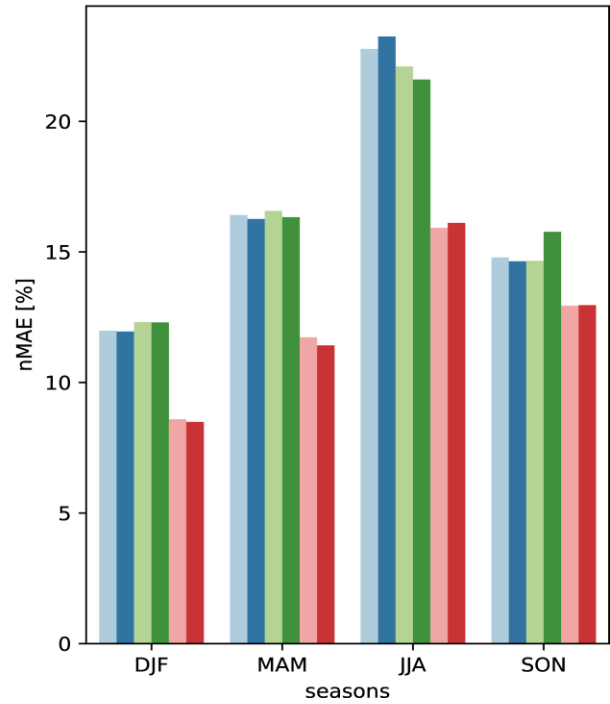
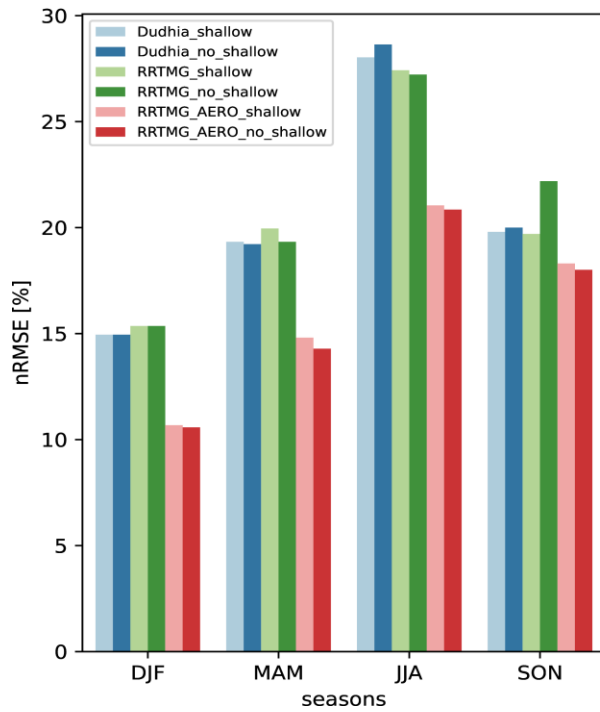
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Seasonal performance of the GHI simulations per station

Diass



TenMerina

