IMPACTS OF HEATWAVES ON HUMAN HEALTH OVER BURKINA FASO

BY

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June, 2025

DECLARATION

I hereby declare that this thesis was written by me and that it is a correct record of my own research work. It has not been presented in any previous application for any degree of this or any other University. All citations and sources of information are clearly acknowledged by means of references.

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Signature: Date:

CERTIFICATION

We certify that this thesis, entitled "Impact of Heatwaves on Human Health over Burkina Faso," is the outcome of research carried out by Millogo, Zouma Emeline Nadege, under WASCAL DRP-WACS in the Department of Meteorology and Climate Science of the Federal University of Technology, Akure.

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ABSTRACT

Heatwaves have become a serious public health concern around the world in the last few decades. In the Sahel, specifically in Burkina Faso, very little research has been done on heatwaves and their impact on human health. This study comprehensively analyses the impacts of heatwaves on mortality in Burkina Faso, focusing on heatwave characteristics, the Temperature-Humidity Index (THI), and their seasonal and temporal variability. The study used Taylor's diagram to compare climate model simulations (NASA NEX_GDDP) with observational data from Burkina Faso's national meteorological agency (ANAM) and ERA5 reanalysis for the past (1991-2021), near future (2020-2050), and the far future (2051-2100). Heatwave characteristics, including amplitude (HWA), frequency (HWF), duration (HWD), magnitude (HWM), and number (HWN), were computed alongside indices such as TN90, TX90, and the Excess Heat Factor (EHF). The trends of heatwave characteristics were analysed with the non-parametric Mann-Kendall test and Sen's Slope method. The ARIMA Model was used for heatwave and mortality prediction, and the Ensemble Mean (MME) of the NASA NEX-GDDP data was used to project future heatwave characteristics under two Shared Socioeconomic Pathways: SSP2-45 and SSP5-85. The results reveal a north-south gradient in heatwave intensity, with higher values in northern regions. Generally, some models are close to observed in terms of output, while others overestimate the output in all the analysed characteristics. THI showed a weak positive correlation with deaths ($R = 0.272$, $R^2 = 0.074$). The seasonal analysis highlighted strong positive correlations between THI and death ($R= 0.5$ to 0.6) during the dry months (April, May, and December) and negative correlations ($R=-0.2$ to -0.7) during the rainy season (August and September), reflecting reduced heat-related risks. While heatwave exhibited a negligible correlation ($R^2 = 0.018$) with mortality, THI was a more significant predictor of mortality ($R^2 = 0.074$). Projections suggest moderate increases in heatwave characteristics by 2050 under both SSPs, with dramatic increases expected by 2100, particularly under SSP585. The frequency, intensity, and duration of heatwaves are anticipated to rise, posing severe health risks for vulnerable populations. Despite weak correlations, adaptive behaviours such as resting during peak heat, improved hydration, and urban initiatives like tree planting may mitigate immediate risks. However, Ouagadougou's rapid urbanisation and infrastructural challenges exacerbate vulnerability, particularly for the elderly, children, and those with pre-existing health conditions. The findings in this study underscore the urgent need for targeted public health interventions during high-risk months (April, May, December), urban planning to mitigate the urban heat island effect, and investments in healthcare infrastructure and early warning systems. The study concluded that addressing climate impacts on health in Burkina Faso and similar regions requires long-term strategies, such as archiving health-related data, expanding vegetation cover, enhancing access to cooling systems, and improving regional adaptation mechanisms. Without significant action, escalating heat stress under climate change will intensify mortality risks, particularly towards the end of this century.

DEDICATION

This PhD thesis is dedicated to God Almighty, who guided me throughout the study in his infinite mercy and grace. Glory and honour be to HIS Holy Name.

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ACRONYMS

ACASIS:	Alerte aux Canicules Au Sahel et à leurs Impacts sur la Santé
ADF:	Augmented Dickey-Fuller
AIC:	Akaike Information Criterion
ANAM:	Agence Nationale de la Météorologie du Burkina Faso
ARIMA:	Auto Regressive Integrated Moving Average
BCSD:	Bias Correction Spatial Disaggregation
CCF:	Cross-Correlation Function
CDO:	Climate Data Operator
CMIP5:	Coupled Model Intercomparison Project Phase 5
CRMSE:	Central Root Mean Squared Error
EHF:	Excessive Heat Factor
EHF90:	90^{th} percentile of Excessive Heat Factor
GCM:	Global Circulation Model
HWA:	Heatwave Amplitude
HWD:	Heatwave Duration
HWF:	Heatwave Frequency
HWM:	Heatwave Magnitude
HWN:	Heatwave Number
IPCC:	Intergovernmental Panel on Climate Change
ITF:	Inter-Tropical Front
ITCZ:	Inter-Tropical Convergence Zone
MAE:	Mean Absolute Error
Mk:	Mann-Kendal
MME:	Ensemble Mean
NEX-GDDP:	NASA Earth Exchange Global Daily Downscaled Projections
PM: Particulate Mater	
PR:	Precipitation
RMSE:	Root Mean Squared Error
S.D.:	Standard Deviation
SDG:	Sustainable Development Goal
SSP:	Shared Socioeconomic Pathway
THI:	Thermal Humidity Index

Tmax	Maximum Temperature
Tmin:	Minimum Temperature
TN:	Minimum Temperature
TN90:	90th percentile of Minimum temperature
TX:	Maximum Temperature
TX90:	90th percentile of Maximum Temperature
USGCRP:	United State Global Change Research Program
VBD:	Vector-Borne Diseases
WAM:	West African Monsoon
WHO:	World Health Organisation
WMO:	World Meteorological Organisation
YLL:	Years of Life Lost

CHAPTER ONE

INTRODUCTION

1.1 Background to the Study

Recently, global warming has been observed to affect every country, with certain regions identified as the most vulnerable. There was an increase in global mean temperature with an estimated 0.07^{o}C for every decade between 1901 and 2010, indicating that the Earth's climate is warming. It has been estimated that a more significant percentage of the world's landmass will experience an average warming of 4 – 7^{o}C by the end of the 21st century (The World Bank, 2012). We are thus witnessing an increase in extreme heat phenomena, leading to heatwaves. A heatwave, generally described as excessive heat, is a period of abnormally high temperatures of successive days. A heatwave is usually quantified based on the climate of the area and normal temperatures for the season. In a colder region, temperatures that people from hotter climates consider usual can be regarded as a heatwave.

Over time, drought and flooding were categorised as the major extreme climate events.

However, recent heatwave events have posed a notable threat to man and the environment (WMO and WHO, 2015). Russo *et al*. (2014) and Ceccherini *et al*. (2017) equally corroborated the findings of the World Bank in 2012 that asserted the rate of growing and spreading of heatwaves across regions of the world in the last few decades (1980 – 2012), with the possibility of extreme heatwave events happening more frequently (once every two years). Vizy and Cook (2012) predicted that the change in climate would make hot days more common in West Africa by the middle of the twenty-first century (2041–2060). The Sahelian parts of western Africa are especially endangered due to heatwaves. It is one of the hottest areas on the planet (Moron *et al.*, 2016), with 223 hot days in a year where daily $Tmax \geq 35^{0}C$ and 249 tropical nights in a year with $Tmin \geq 20^{0}C$ (Savadogo and Combere, 2018). According to (Abiodun *et al*., 2013), there will be more extreme temperature events across all of Nigeria's ecological zones in the future. Odoulami *et al*. (2017), using the RCP4.5 scenario projected an increase in heatwave characteristics over West Africa, using the heatwave index (EHF or TXI) as a determinant for the variation in changes of the magnitude and location.

As one of the countries in the Sahelian region of West Africa, Burkina Faso is mainly affected by heatwaves. Oueslati *et al*. (2017) looked at temperature extremes in Burkina Faso using the Global Historical Climate Network Daily (GHCND) data from 1959 to 2008. They found that the maximum and minimum temperatures have shown a global warming trend. De Longueville *et al.* (2016) characterised the country's overall temperature from 1981 to 2010 using meteorological data from nine synoptic stations. Their results indicate increase in the frequency of hot temperatures above a certain threshold is general in the country. Conversely, the indices for the most extraordinary conditions show a frequency decrease, particularly at night (Guigma *et al*., 2020).

These heatwaves have become severe and intense in the region, threatening human beings and their environment. The population can be susceptible to climate shocks due to their dependency on some sectors that are climate sensitive, e.g., agriculture, etc., and the lack or inadequacy of other social services, e.g., health services, etc. Aside from the delicate nature of this region's economies, they are underrepresented in current heatwave literature. Thus, heatwaves in this area should receive more attention from the scientific community. Since the findings may

not match those from high-income nations, most heatwave research topics must be investigated further.

Heatwaves can be one of the most dangerous climate hazards affecting the planet, dramatically impacting human health, human activities, natural ecosystems, infrastructures, and the economy. The health sector is the most affected. Heatwaves act on the body's thermal comfort, leading to an increase in morbidity and death (Hajat *et al*., 2006; Kovats and Hajat, 2008; Anderson and Bell, 2009; Rocklöv *et al.*, 2011; Gasparrini and Armstrong, 2011). Heatwaves are "silent killers" because their consequences on human health are not usually immediate (Loughnan, 2014).

Exposure of an individual to high environmental temperatures can lead to direct reactions in the body due to inadequate or insufficient response of the thermoregulatory mechanisms. In addition, heat can aggravate an already existing disease or contribute to triggering it (Nurse, 2015). The 2003 heatwave in France affected the metropolitan city, resulting in more than 140000 deaths (Fouillet *et al.*, 2006). Mortality may be due to heat stroke or to decompensation of underlying pathologies (anterior of cardiovascular, respiratory, neurological, or renal disease). These pathologies are also found to be reasons for hospitalisation during heatwaves in the United States (Jones *et al*., 1982).

Given the issues related to this heatwave phenomenon, it is necessary to be able to determine the frequency of occurrence of these heatwaves to reduce/prevent their impacts. The adverse effects of heatwaves can be mitigated with competent forecasts.

Several countries have developed heatwave-influenced health early warning systems guided by the WMO and WHO (2015). For instance, the Sahelian Heatwave Early Warning and their Impacts on Health (ACASIS) project was developed over the Sahelian region of West Africa to enhance the empirical validation of heatwave drivers and effects. Burkina Faso and Senegal Meteorological Services have regularly monitored heatwaves (Guigma *et al*., 2020). Heatwave processes must be clearly defined and understood for effective forecasting and risk management, especially during the brief (synoptic and intrapersonal) periods.

1.2 Statement of the Problem

Heatwaves have become a serious concern for public health-related issues in recent decades. Many devastating heatwaves have resulted in significant public health consequences, such as the 1987 Athens heatwave with approximately 1,500 to 2,000 deaths, primarily among the elderly and those with underlying medical conditions; the 1995 Chicago heatwave with approximately 739 deaths; The heatwave in Europe in 2003 was particularly devastating, claiming around 70,000 lives across the continent (Oudin-Åström *et al*., 2011). France was particularly hard, with around 14,802 deaths, and the 2011 Sydney heatwave caused significant strain on infrastructure and health services and led to an increase in hospital admissions (Oudin-Åström *et al*., 2011). However, no specific death toll is documented for this event. These events underscore extreme heat's severe public health impacts and the importance of preparedness and response strategies.

In the Sahel, specifically in Burkina Faso, little research has been done on heatwaves and their impact on human health. However, there has been research on rainfall variability and its impact on society. No conventional definition of heat-related diseases exists from the public health perspective due to the intricate relationship between health and climatic conditions. As a result, defining a heatwave in terms of human health is a complex and multifaceted topic (Dimitriadou *et al*., 2021).

Another significant challenge is the eventual outcome of a heatwave. This effect, regarded as the displacement effect or short-term mortality displacement, describes an occurrence in which a particular exposure (for instance, temperature) adversely impacts an already vulnerable population or individuals, leading to increased mortality (Dimitriadou *et al.*, 2021). Excess mortality is observed during heatwave events, mostly among persons with complicated health issues (WMO, 2013). Detailed methods for quantifying the harvesting effect have yet to be developed, leading to an uncertain estimate of harvesting mortality. This uncertainty arises because most studies examining heatwaves fail to report on harvesting impacts due to oversight or because such effects occur infrequently (Åström *et al*., 2011). As the harvesting effect is not reported in numerous studies, it is challenging to draw definitive conclusions or compare the methodological frameworks of various studies regarding the displacement effect (Dimitriadou *et al*., 2021). The main obstacle to a precise definition of heatwaves is that their effects vary substantially from a geographical perspective and are heterogeneous. The essential aspects of a comprehensive definition of heatwaves involve the indices considered, including temperature, humidity, and health effects (mortality and morbidity), along with the heatwave's duration and intensity, which influence the different definitions (Dimitriadou *et al*., 2021).

Recent studies indicate that heatwaves have become longer, more frequent, and more intense over the past few decades (Fontaine *et al*., 2013; Moron *et al*., 2016; Ceccherini *et al*., 2017; Barbier *et al*., 2017) and future forecasts also suggest an increasing risk of extreme heat in Africa (Nangombe *et al*. 2019; Rohat *et al*. 2019). Guigma *et al*. (2020) studied the essential quality and thermodynamics of Sahelian heatwaves. It was discovered that, on average, most locations in the Sahel suffer from one or two heatwaves a year, lasting three to five days but with severe magnitude. Savadogo and Combere, (2018) studied the characteristics and trend of heatwaves from 1961 to 2014 over Burkina Faso and found that the trend toward higher temperatures is general but more noticeable for minimum temperatures, and the trend is significant during all seasons. However,

Some evidence of consistent frequency exists at variance (Adeniyi and Oyekola, 2017), which may be related to the choice of heatwave index. In addition, because of the lack of attention and evidence, heatwaves are not often perceived as a risk by international agencies and national governments, leading to unknown impacts. In some regions, the situation is such that resources to report do not exist (Harrington and Otto, 2020; Brimicombe *et al*. 2021).

This study intends to assess and model the impact of heatwaves on human health in Burkina Faso.

1.3 Aim and Objectives

The aim of the study is to assess the impact of heatwaves on human health over Burkina Faso. The specific objectives of the research are to:

i. characterise heatwave and temperature humidity index in Burkina Faso from 1991 to 2021;

ii. establish the relationship between heatwave and health to develop a statistical model for early warning purposes; and

iii. project future heatwave events in Burkina Faso.

1.4 Justification

Increased ambient temperatures have been linked to mortality, as observed in previous research over northern Ghana, Nairobi (Kenya), and northwest Burkina Faso. However, the relationships vary based on age, gender, and, in certain instances, the cause of death (Diboulo *et al*., 2012; Azongo *et al*., 2012; Kynast-Wolf *et al*., 2010). Given that heatwaves' frequency, duration, and intensity are predicted to rise due to climate change, understanding the relationship between heatwaves and health is critical. Considering the high global health burden associated with heatwaves, as well as the projection of increased frequency and intensity of heatwaves as a result of the change in climate (IPCC, 2013), a better understanding of the characteristics of heatwaves and their effects on health, particularly mortality is important. As in the case of the definition of heatwaves, there is no universal threshold for warning systems (Issa *et al*., 2021). Identifying the thresholds at which heatwaves become a problem in already hot Burkina is necessary. Furthermore, the study of heatwave and human health will help achieve the Sustainable Development Goals (SDG-1) relating to poverty eradication, human health and well-being (SDG-3), and take prompt action to address climate change and its impacts (SDG-13).

1.5 Scope of the Study

The work is to investigate the impacts of heatwaves on human health in Burkina Faso. This also examines the characterisation, trend and projection of heatwaves under a changing climate, especially over Sahelian and Sudano-Sahelian regions. The data used for this study were sourced from Agence Nationale de la Météorologie du Burkina Faso (ANAM), which served as the observed data and eleven (11) climate models included in NEX-GDDP. The observed datasets are daily minimum (TN) and maximum (TX) temperatures. The study will show the relationship between heatwaves and human health and also examine the trend and projections (near- and far-future) under the Shared Socioeconomic Pathways (SSP245 – representing the middle of the road, and SSP858 – representing a future with high greenhouse gas emissions) scenarios.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

The previous chapter presented this study's main focus and highlighted its aim and objectives. Therefore, it is crucial to review past research on climate-related incidents and their possible impacts on human health. This chapter reviews earlier studies on how climate change impacts human health and the environment, particularly focusing on the effects of heatwaves on human well-being. The global climate assessments have shown that Africa is vulnerable to climate change (Orimoloye, 2018). According to studies, the occurrence of storms, extreme heat, drought, and other climate-related extreme events is expected to rise because of natural and human activities (Handmer *et al*., 2012; Kuenzer and Renaud, 2012; Nadin *et al*., 2015; Guigma *et al*., 2021; Sawadogo *et al*., 2024). Recognizing climate risks to human health has led to widespread concern about the linkage between climate adaptation and health threats (Venton and La Trobe, 2008; Benedikter *et al*., 2013; Chen *et al*., 2016). By examining the link between climate change and human well-being in-depth, this study explores the relationship between heatwaves, a consequence of global warming, and human health. Thus, the study seeks to detect heatwaves and understand the significance of their risks on human mortality. Reed *et al*. (2013) discovered that the significant influence of climate-related events on human health is likely to increase soon, even with the unclear relationship between climate variability and extreme weather. A good understanding of this interrelationship is essential, and it can aid in planning to reduce human health vulnerability (Dube *et al*., 2016). Studies demonstrated that alterations in climate parameters, including temperature, humidity, radiation, and wind patterns, are correlated with these extreme weather-related diseases (Glaser *et al*., 2016; Matysiak and Roess, 2017). Heat-related illnesses like cardiovascular disease, diarrhea, sunburn, heat stroke, and skin cancer are significant global health threats. Some of these can lead to death more quickly than tuberculosis and HIV/AIDS, affecting both developed and developing countries (Orimoloye, 2018). Awareness and prevention are now key issues in public health and emergency management (Moore *et al*., 2007). Risk reduction and management should be the priority for health experts and scientists. The realities of climate change provide compelling scientific evidence that greatly aids in managing human health and reducing risks. However, the link between extreme weather events and human activity has yet to be explored or utilised (Nehama *et al*., 2016; Patz and Frumkin, 2016).

2.2 Definition and Reality of Climate Change

The Intergovernmental Panel on Climate Change (IPCC) states that "Climate change is a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period typically decades or longer" (IPCC, 2023).

The United Nations Framework Convention on Climate Change also defines climate change as "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods" (IPCC, 2013).

Climate change can result from factors significantly altering the balance of the Earth's energy (incoming and outgoing) (USGCRP, 2009). As a result of their involvement in the modification of solar radiation, a variety of natural events (for example, air circulation, change in ocean currents, volcanic eruption) can be seen as the principal natural forces regulating the climate system (Pachauri and Reisinger, 2007). However, most of those components are so episodic that they have short-term impacts on climate (USGCRP, 2009).

Observations over the past century show that the global temperature has risen by 0.84 ^{o} C. Over the coming decades, the rate of this temperature rise will increase (Hondula *et al*., 2012).

Global temperature change, accompanied by an expanded range of climate changes, will continue to impact individuals and the environment. In many regions of the world, the frequency of extreme weather events is projected to increase (Hondula *et al.*, 2012).

Current research on climate models predicts substantial modification in precipitation patterns and a gradual rise in temperature across West Africa (Laux. *et al*., 2009; Barry *et al*., 2018; Sawadogo *et al*., 2024). Using the years 1971 to 2000 as references, the five regional climate models predict delayed rainy seasons, prolonged dry spells, reduced rainfall events (0.1 to 5 mm/d), and heightened extreme rainfall events (50 mm/d) (Ibrahim *et al*., 2014). In Burkina Faso, temperatures are anticipated to rise by 2 °C by 2100 compared to the 1990–2000 period (Hondula *et al*., 2015). In Tanzania, a projected 2 °C rise in seasonal temperatures is expected to lower the average yields of key staple crops by 2050, including maize (−13%), sorghum (−8.8%), and rice (−7.6%). (Rowhani *et al*., 2011). In addition to the elevated temperatures, a reduction in water availability and increased evaporation rates are anticipated *(*Sawadogo *et al*., 2024).

2.3 Temperatures in the Sahel

2.3.1 Annual cycle of temperatures

The annual cycle of mean temperature and specific humidity at 2m, as well as precipitation and solar zenith angle, are plotted in the following Figure 2.1 from 2002 to 2007 with data from the automatic meteorological station of Agoufou (Timouk *et al*., 2009), located a few kilometres from the SYNOP station in Hombori, in Mali (15.33°N, -1.8°E).

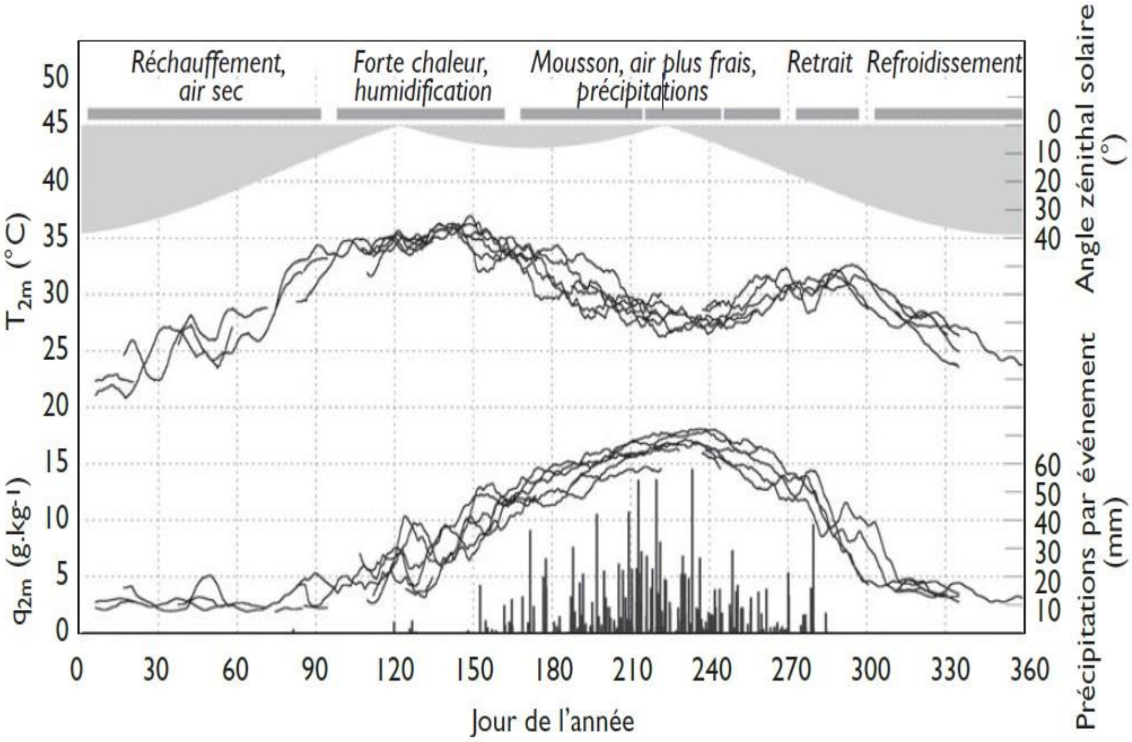

Figure 2. 1: Annual cycle of temperature (upper curves) and spectral humidity (middle curves) at 2m (middle curves) at 2m of the meteorological station of Agoufou (near Hombori) from 2002 to 2007. The observations of several years are superimposed and presented as an average over 10 days. The black bars (bottom) correspond to the cumulative rainfall for each rain event. The lighter areas (top) show the variations of the solar zenith angle (Guichard *et al*., 2015).

Temperatures follow a bimodal curve with a first maximum in spring and the second in autumn, contrary to the annual cycle of the temperate latitudes, which is unimodal. Daily temperatures vary between 20°C in winter and 35°C in spring. The specific humidity increases strongly from

April to May (with Julian Day of 90-150) with the first incursions of the monsoon flow (Guichard et al., 2015). However, it does not start raining until June-July (Julian Day of 150-210) (Guichard et al., 2015). The temperature slowly decreases during the rainy season, which cools the surface via precipitation and evaporation of the latter (by increasing the latent heat flux) (Guichard et al., 2015). The monsoon flows around October (Julian day of 270-300), and the temperatures rise again with a few weeks delay concerning the second solar zenith angle maximum. Its decrease in November coincides with the decrease in sunshine (Guichard et al., 2015). The annual cycles of maximum temperature (Tmax) and minimum temperature (Tmin) are distinct in the Sahel (see Figure 2.2): at the SYNOP station in Ouagadougou, Burkina Faso (13.48°N, 2.17°E), Tmins increase more rapidly and reach their first maximum later than Tmax (Figure 2.2a). Their minimum during the monsoon season is also less marked than the minimum Tmax. Conversely, the second maximum of Tmin is reached earlier than Tmax's. On average, over the Sahel (Figure 2.2b). The first maximum Tmax occurs in April-May and the first maximum Tmin in May-June. Tmax reaches an average of 40°C at its maximum, while Tmin reaches 25°C.

Temperatures in climate models have been studied mainly during the monsoon season. In particular, Roehrig, (2013) showed that the Coupled Model Intercomparison Project Phase 5 (CMIP5) simulations produced a warm bias in sea temperatures near the Guinean coast, inducing a systematic bias in the rain band associated with the monsoon to the south due to the smaller thermal gradient between land and sea. The areas north of the Sahel are then in a rainfall deficit and consequently too hot. Outside the monsoon period, temperatures vary significantly from one climate simulation to another, even when these simulations use identical sea surface temperatures. The differences can reach more than 5°C on a monthly average over the Sahel, indicating that other sources of bias are present.

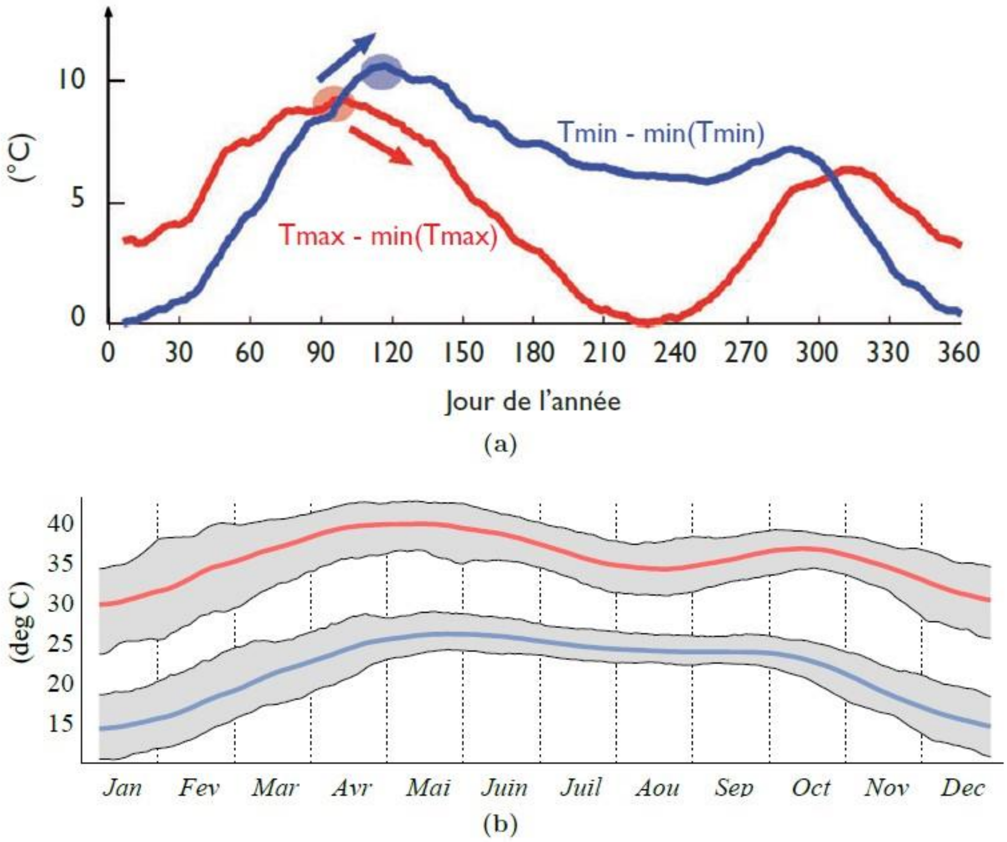

Figure 2. 2: Annual cycles of Tmax and Tmin (a) at the SYNOP station in Ouagadougou (a) over 30 years of daily data after subtracting the annual minimum and (b) averaged over the Sahelian domain over 1950-2012 with data from the BEST observation product. (a): the red disc (blue) indicates the annual maximum of Tmax. (Tmin). (b): The grey range corresponds to the maximum and minimum reached daily over 1950-2012, and the red (blue) curve corresponds to the average Tmax (Tmin). The three curves (maximum, average and minimum) have been smoothed by a sliding average over 15 days (Guichard *et al*., 2015).

2.3.2 Climatic evolution since 1950

Climate change lies at the heart of numerous debates: the Intergovernmental Panel on Climate Change (IPCC) seeks to "provide comprehensive assessments of the state of scientific, technical and socio-economic knowledge about climate change, its causes, potential impacts and adaptation strategies" (https://www.ipcc.ch/index.htm). In 2014, the fifth assessment report indicated that the worldwide average temperature rose by approximately +0.85°C from 1880 to 2012 (IPCC, 2014).

In the Sahel, changes are not homogeneous from month to month. Figure 2.3 shows the monthly temperatures in the Sahel over 1950-2012 and the associated trends: Differences appear between months and also between Tmax and Tmin. At the beginning of the year, in January-February, there is no clear trend. The interannual variability dominates the signal, with differences of up to 5°C from one year to another. In spring, the trends are more linear with strong values: the trends of Tmin are higher than the Tmax with a value at +2°C against +1.5°C on average over April-May. During the monsoon, the quadratic fit is less and less linear and becomes concave. At this time of the year, temperatures and precipitation are strongly correlated (Decharme and Douville, 2006). A drought affected the Sahel during 1970-1990, resulting in hot temperatures. Since then, rainfall totals have increased again, which explains this concave shape, especially on the Tmax (Barbier, 2017; Tefera *et al.*, 2024; Yaméogo *et al.*, 2025).

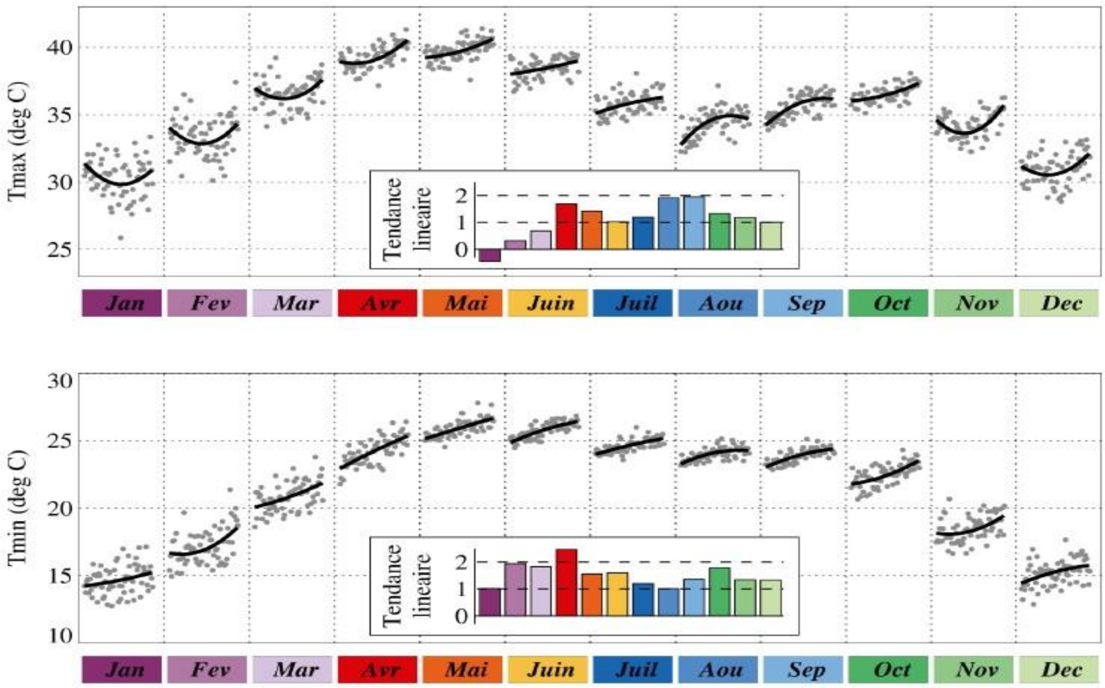

Figure 2. 3: Observed recovery as a function of the month of the year with BEST data, averaged over the Sahelian domain from 1950 to 2012. For each month, the grey points correspond to the average monthly Tmax or Tmin values from 1950 to 2012. A quadratic adjustment is added (black lines). The linear trend per month is indicated in the bottom middle of the graph with coloured bars (Guichard et al., 2015).

Consequently, since 1980, temperatures in the Sahel have not risen during the monsoon season, unlike in the Sahara (Evan *et al*., 2015; Guichard *et al.*, 2015). The higher Tmin has already been highlighted globally (Karl and Knight, 1997; Easterling *et al*., 2000; Hartmann *et al*., 2013).

Therefore, since 1950, temperatures have risen sharply in the Sahelian region in the spring. The change in temperature distribution can have several effects on the temperature extremes. Temperature distribution is characterised in particular by three quantities: its mean, its variance and its skewness (Barbier, 2017). The IPCC report in 2012 illustrates the effects of a change in one of these three quantities on temperature distributions and, thus, the extremes of the climate. In the case of an increase in the average temperature (Figure 2.4a), the whole distribution is shifted towards high temperatures: the highest temperatures are more frequent and reach higher values, in contrast to the lowest temperatures. The increase in variance of a distribution will push the temperatures towards the extremes of the distribution, increasing the occurrence of hot extreme and cold events and the amplitudes reached (Figure 2.4b). Finally, a change in skewness will not affect one side of the distribution but will shift the other side of the distribution to higher values.

By studying temperatures from 90 stations over West Africa, Moron *et al*. (2016) showed that the change observed between 1961-1980 and 1995-2014 was mainly explained by a shift in the mean of the temperature distributions. In the tropics for future climate, Argüeso *et al*. (2016) reach the same conclusions between 1979-2000 and 2071-2100 based on CMIP5 simulations.

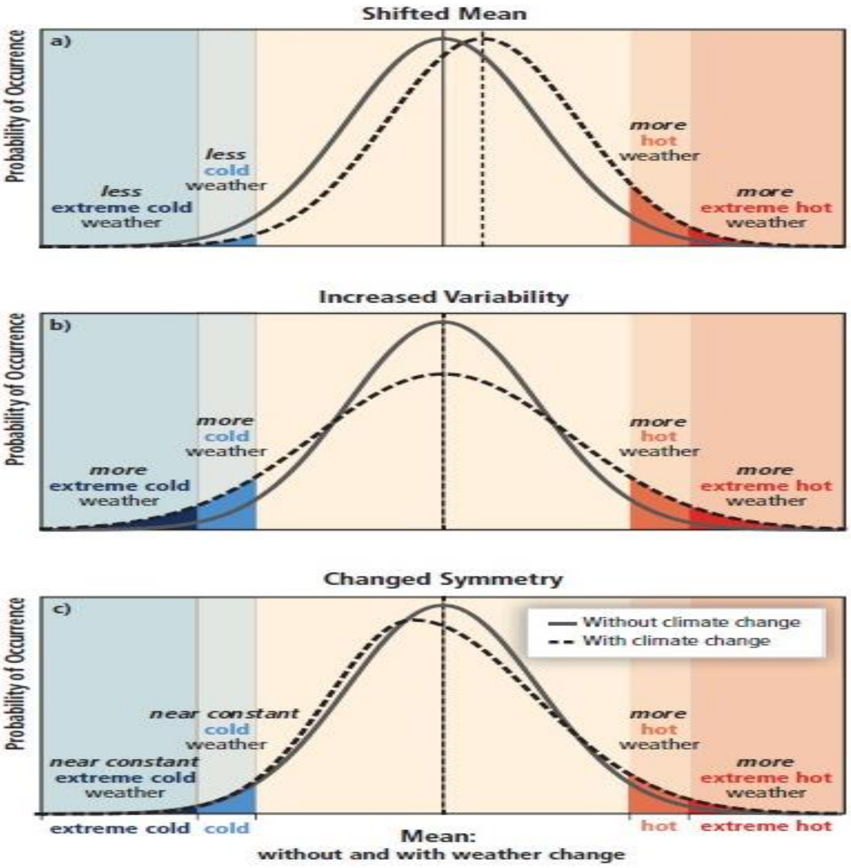

Figure 2. 4: Illustration of the effects of changes in the temperature distribution on the extremes. Example of a change in mean, variance and skewness (IPCC, 2013).

2.4 Climate Change and Health

Weather and climate significantly influence human death rates, health issues, and population movement in various parts of the world. As the global climate evolves, its effects on individuals will vary, occurring through direct means (such as heat-related fatalities in heatwaves) or indirect processes (like prolonged droughts restricting food availability) (Hondula *et al*., 2012). Experts worldwide are assessing the possible impacts of climate change on public health. Climate change threatens human health through various factors, including heat stress, worsening air quality, rising sea levels, and food and water security challenges. It also increases the frequency of extreme weather events such as floods, droughts, earthquakes, volcanic eruptions, tsunamis, and hurricanes, as well as impacts on vulnerable housing and population migration (Kim *et al*., 2014). As a result of human vulnerability to the alterations caused by increasing heatwaves and associated extreme weather events, the potential risks and side effects of climate change are expected to rise significantly (Kim *et al*., 2014; Amnuaylojaroen and Parasin, 2024).

Among the numerous changes, the deterioration of the atmospheric environment is particularly significant, as these changes can ultimately result in a variety of illnesses and diseases, including cardiovascular mortality, respiratory ailments, vector-borne diseases, nutritional disorders due to food scarcity, the transmission of infectious diseases, and diarrhea due to poor sanitation (Confalonieri *et al*., 2007; Costello *et al*., 2009). According to the World Health Organization (WHO), various widespread human diseases (e.g., respiratory illnesses and cardiovascular disease) are associated with climate fluctuations caused by heatwaves and changes in the transmission of infectious diseases (WHO, 2013). As warmer zones expand, parasites from tropical regions may migrate to temperate areas (USCCSP, 2008). Consequently, diseases such as malaria can extend to a broader region. Asthma is also anticipated to increase globally as asthma-triggering allergens become increasingly prevalent

(USCCSP, 2008). The effects of climate change on human health will vary significantly based on a wide range of factors, including an individual's behaviour, age, gender, race, and economic status. Moreover, these variables can also encompass region, population sensitivity, the extent and duration of exposure to climate change, and society's capacity to adapt to such changes (US EPA, 2011). Individuals living on small islands, along coastlines, in megacities, and in mountainous and polar regions, are especially vulnerable to these worsening environmental conditions (Lemke *et al*., 2007).

In the same way, children in impoverished countries, the elderly, and individuals with health issues or pre-existing medical conditions will be particularly sensitive to these changes (Confalonieri *et al*., 2007; Costello *et al*., 2009; Sudharsan *et a*l., 2025).

2.5 Categories of Human Diseases Linked to Climate Change

Extreme weather events, variations in rainfall patterns, and temperature might all contribute to the spread of many human diseases (Kinney, 2008). Smog, pollen pollution, wildfire smoke, and harmful air pollutants can all cause various symptoms, such as eye irritation, headaches, stuffy noses, wheezing, skin irritation, coughing, and chest pain when temperatures rise (Kim *et al*., 2014). Children, seniors, and those with respiratory issues like bronchitis, asthma, and emphysema are particularly at risk from climate change (Kim *et al*., 2014; WHO, 2024).

Figure 2.5 illustrates a flow chart summarising the global burden of diseases attributed to climate change.

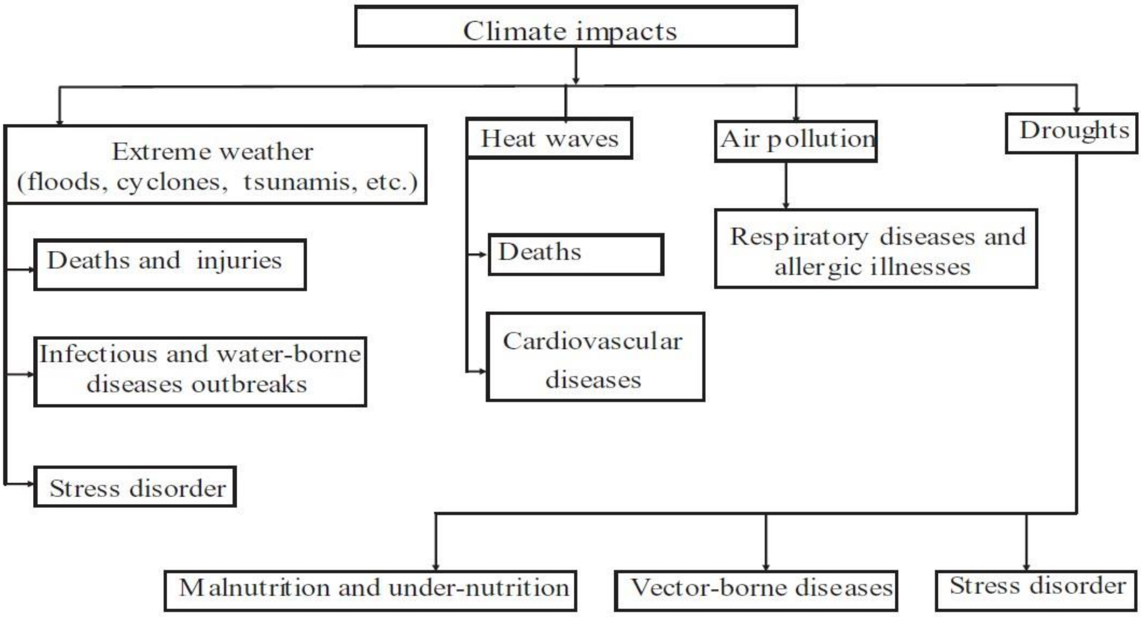

Figure 2. 5: Major known and probable health risks from climate change (Kim *et al*., 2014).

2.5.1 Climate Change and Infectious Disease

Vector-borne diseases

Climate change affects the occurrence of vector-borne diseases (VBD) such as malaria, schistosomiasis, onchocerciasis, trypanosomiasis, filariasis, leishmaniasis, plague, and Rift Valley fever, as well as their transmission cycle (Thompson *et al*., 2024). Species that transmit vector-borne diseases (VBD) primarily include infected arthropods like mosquitoes, ticks, triatomine bugs, sandflies, and blackflies (Confalonieri *et al*., 2007). Ectothermic arthropod vectors are influenced by various factors, including temperature, precipitation, and humidity changes, which impact their biology, ecology, and the hosts they interact with over time and across different regions. The suitability of habitat, as well as the distribution, quantity, intensity, and temporal patterns of vector activity (particularly biting rates), can all be influenced by alterations in the survival and reproduction rates of the vectors (Rogers and Randolph, 2006). From 1997 to 1998, Kenya experienced epidemics of Plasmodium falciparum malaria and Rift Valley fever, attributed to a temporary rise in temperature and rainfall caused by El Nino (Wanjala *et al*., 2011). Mosquito species primarily transmit VBD. Adult female mosquitoes digest blood rapidly and feed frequently, increasing transmission intensity in warmer climates (Hopp and Foley, 2001; Lèo and Surin, 2023).

Additionally, at elevated temperatures, mosquito larvae develop in a relatively brief period. Consequently, during the transmission phase, more offspring can be produced (Kim *et al*., 2014). As temperatures increase, malaria parasites and viruses can rapidly undergo extrinsic incubation inside female mosquitoes (Alonso *et al*., 2011). In northern India, the rate of dengue fever transmission was noted to rise with a 2°C increase in temperature (Dhiman *et al*., 2010). Colón-González *et al*. (2013) discovered considerable impacts of weather on dengue incidences in Mexico. Increasing temperatures have reduced the virus's external incubation time and expedited the mosquito's growth and reproductive cycle, thereby

enhancing the chances of dengue transmission (Lambrechts *et al*., 2011). In the United States, approximately 4,000 instances of dengue fever, both imported and locally spread, were documented from 1995 to 2005 due to increased humidity, precipitation, and heat (Patz *et al*., 2005). Nonetheless, factors like shifts in land use, population density, and human behavior can affect the patterns of vector-borne disease (VBD) occurrence and the level of infection (Rogers and Randolph,
2006).

Diarrhea diseases

The global impact of diarrhea, responsible for the deaths of many children worldwide, is anticipated to rise due to climate change (Rosenthal, 2009). Previous research has linked diarrhea disease to various climatic factors (encompassing relative humidity, precipitation and temperature) (Alexander *et al.*, 2014). diarrhea illness rates, such as cholera, may rise after a flood event, particularly in places with subpar sanitation systems (Jongman *et al*., 2012). Even without floods, heavy rains can raise the prevalence of diarrheal disease because they cause sewage systems or latrines to overflow (Kolstad and Johansson, 2011; Hirabayashi *et al.* 2013). Conversely, drought can reduce the freshwater supply, leading to higher rates of diarrhea and other hygiene-related illnesses (Zhang *et al*., 2007). High temperatures are also linked to a rise in the prevalence of diarrhea diseases such as salmonella and cholera (Friedrich, 2013). During the El Nino event in 1997, many patients suffering from diarrhea and dehydration were admitted to hospitals in Lima, Peru, as temperatures rose unusually high (Meehan and
Ostrander, 1997). An analysis of the hospital's daily admission data confirmed that for every
1
°C rise in temperature, there is an 8% increase in admissions due to diarrhea. (Meehan and Ostrander, 1997).

Cholera

Cholera spreads easily and its severity depends on the dosage ingested, especially through contaminated water and food, particularly seafood (De Magny and Colwell, 2009). Vibrio cholerae, the cholera causative agent, has been linked to plankton and copepods for survival, multiplication, and transmission (Lipp *et al*., 2002). The attachment of V. cholerae to copepods has been reported at salinities of 15% and temperatures between 25 and 30°C (Wang *et al*., 2011). Fernández *et al*. (2009) analyzed data from three cholera outbreaks in Lusaka, Zambia, occurring between 2003 and 2006. They deduced that rising temperatures are controlling the increase in cholera cases. They discovered that during an epidemic, for every increase of 1 °C in temperature, there is an increase of 5.2% in cholera cases (six weeks before the beginning of the outbreak). Between 2002 and 2008, researchers at the International Vaccine Institute in Seoul, South Korea, studied disease and weather data from cholera-prone regions of Zanzibar, Tanzania. They discovered that a cholera outbreak was likely to happen following a rise in the average minimum temperature (by one degree Celsius) and precipitation (to 200 mm) during the preceding month (Reyburn *et al*., 2011). Increases in sea surface temperatures and high plankton levels have been suggested as a factor contributing to cholera outbreaks in the coastal regions of Bangladesh (Kanungo *et al*., 2010). A probable connection between the cholera bacterium, sea surface temperature, and phytoplankton was suggested by de Magny and Colwell (2009). The plentiful presence of phytoplankton resulted in a large zooplankton population as surface temperatures rose, which acted as a reservoir for cholera germs, a waterborne illness (Sack *et al*., 2003). Droughts can increase the salinity of nearby waters, promoting the growth of cholera vibrios and helping Vibrio cholerae attach to copepods. Floods facilitate the broader distribution of the bacteria (Gaffga *et al*., 2007). Storms, flooding, and heavy rainfall fueled by climate change can promote the spread of cholera by severely disrupting sanitation, sewage treatment facilities, and water treatment systems, among other factors.

2.5.2 Climate Change and Non-infectious Disease

Respiratory diseases

Temperature increase (levels of ozone concentration) might raise the burden of various disorders, from acute lung function decline to airway injury and inflammation (Ito *et al*., 2005). Inhaling ozone triggers an inflammatory reaction that increases airway permeability and bronchial overactivity, which may result in asthma and other cardiovascular and respiratory conditions (Filippidou and Koukouliata, 2011). Between August 4 and 13, 2003, England and Wales recorded more than 2,000 additional deaths linked to that year's intense heatwave (Beniston *et al*., 2007). Approximately 25% to 33% of these deaths have been linked to the effects of heightened particulate air pollutants and ozone concentrations, which have risen in concentration along with increasing temperatures (Stedman, 2004). Ozone is acknowledged as a potent oxidant that causes damage to the airway and lung structures, as well as severe asthma symptoms in both Europe and the United States (Zeka *et al*., 2006), often accompanied by phenomena like a rise in respiratory hospital admissions and fatalities. A study found that ozone exposure elevates mortality risk from respiratory issues, as prolonged low-level exposure can be fatal (Jerrett *et al*., 2009). In another study, Bloomer *et al*. (2009) looked at 3 million valid simultaneous measurements of temperature and ozone. The overall results showed that for nearly every degree of warming (°F) recorded in the observed data, ozone pollution increased by 1.2 parts per billion (ppb) (Bloomer *et al*., 2009). Warmer air temperatures like ozone can influence the regional distribution of aeroallergens. Warmer climates promote the growth of allergenic pollens, increasing the risk of respiratory issues like asthma, emphysema, chronic bronchitis, and allergies (D'Amato, 2001). Climate change can impact various lung issues, including chronic obstructive pulmonary disease, pneumothorax, and respiratory infections in children (D'Amato, 2001). Research indicates a connection between air pollution and tuberculosis. Furthermore, evidence suggests that dust storms in deserts and high-altitude regions may lead to respiratory issues in surrounding areas (Griffin *et al*., 2007). Recent studies show that respiratory patients face a risk of premature death that can be up to six times greater than that of the general population when temperatures increase by just one degree Celsius (Ayres *et al*., 2009).

Cardiovascular health

Climate change increases the risk of cardiovascular disease both directly and indirectly, through air pollution and changes in diet (Kim *et al*., 2014). If sufficient liquid is not supplied, the physiological reactions to heightened heat exposure include various symptoms such as an increase in core body temperature and heart rate, a shift of blood flow from central organs to the skin, and enhanced sweating, along with related dehydration (Corris *et al.*, 2004). Extreme cold and heat may lead to an increase in hospital admission for chest pain, stroke, irregular heartbeat, and other heart-related issues (Haines *et al*., 2006). An increase in ozone formation, caused by rising temperatures, is thought to lead to heart attacks by disrupting pulmonary gas exchange processes and elevating heart stress (Lemke *et al*., 2007). Droughts can lead to symptoms including systemic inflammation, heart function issues, deep venous thrombosis, pulmonary embolisms, and blood vessel dysfunction, as they tend to increase PM levels in the air (Pope and Dockery, 2006). The stress and anxiety levels can increase as a consequence of severe weather events, leading to heart attacks, sudden cardiac death, and stress-related cardiomyopathy (heart disease) (Prince *et al*., 2007). According to (Liao *et al*., 2010), an increase of 1% in temperature correlates with a rise of 0.23% in deaths due to cardiovascular diseases. Hajat *et al*. (2006) investigated the combined effects of heat exposure and air pollution on cardiovascular disease in major cities during warm seasons (e.g., Delhi, Sao Paulo, and London).

Mental health

Severe weather events, including hurricanes, tornadoes, floods, wildfires, droughts, and tsunamis, are expected to impact mental health, resulting in anxiety, post-traumatic stress, depression, etc. (Thompson *et al*., 2018). As a result of the loss of homes, livelihoods, and communities, these mental effects can last for a long time. Even without direct physical consequences, the awareness and anxiety surrounding climate change may pose a significant threat to mental health (Hamin and Gurran, 2009). Nonetheless, the effect may change based on the nature, abruptness, and magnitude of the disaster, as well as the cultural, historical, and social factors (Kim *et al*., 2014). Around 63% of Hurricane Katrina evacuees experienced moderate to severe post-traumatic stress disorder symptoms (Hawkes *et al*., 2009). Consequently, most psychosocial effects of climate change are expected to develop gradually and accumulate over time. Droughts are anticipated to occur more frequently and intensely in numerous subtropical regions worldwide due to climate change, resulting in hunger, anxiety, and depression due to declining agricultural productivity (U.S. Global Change Research Program, 2016). As a result, suicide rates, particularly among farmers, have been reported to rise significantly during droughts (Berry *et al*., 2011). Apart from sickening, heatwaves can lead to heightened interpersonal violence, anxiety, depression, and decreased work capacity, as well as the fatalities of individuals who cannot find a means to keep cool (Thompson *et al*., 2018). Social isolation is another consequence of heat stress since some individuals may choose to stay indoors during hot weather days, which may contribute to depression. According to a study conducted in Adelaide, Australia, there was an increase in hospital admissions for individuals with mental health diagnoses during periods of extreme heat (Nitschke *et al*., 2007).

Cancer

Climate change is suspected to impact cancer directly and indirectly through mitigation strategies. Rising temperatures will heighten exposure to suspected carcinogenic chemicals from heavy rainfall and chemical volatilization. As ice sheets and glaciers melt, they can release harmful carcinogenic pollutants into both the oceans and the atmosphere (Bogdal *et al*., 2009). Climate change might elevate UV exposure risks by harming the stratospheric ozone layer, thereby increasing the threat of skin cancer (Makin, 2011; McKenzie *et al*., 2011). Higher UV radiation can impact the human immune system and alter the body's capacity to remove early mutant cells that kickstart the cancer process (Kim *et al*., 2014). Nevertheless, it remains unclear whether these modifications would be beneficial or detrimental. Furthermore, a deterioration in air quality due to rising levels of air pollutants may also elevate the risk of lung cancer (Macdonald *et al*., 2003). As weather patterns become increasingly erratic due to climate change, liver cancer associated with aflatoxin contamination is suspected of becoming a rising concern (Furgal and Séguin, 2006). However, climate change is anticipated to lead to more intense rainfall and flooding. Such conditions can affect toxic runoff from hazardous storage facilities into waterways pollutants. Some of these chemicals are recognised carcinogens, and their overall effect leads to a greater incidence of cancer (Slingo *et al*., 2009).

2.6 Epidemiological Studies of the Effect of Heat on Health

2.6.1 The effects of ambient heat on mortality and morbidity

Generally, researchers evaluate the link between mortality and morbidity due to shifts in ambient temperature through time series regression models or case-crossover designs, producing consistent findings. (Basu, 2009; Xu *et al*., 2012). Researchs generally indicate a UV or J-shaped association between temperature and health impacts, revealing heightened risks of mortality or morbidity both above and below specific threshold or minimum mortality temperatures. Results show the elevated risk of outcomes, the relative risk (RR) for time series studies, and odds ratios (OR) for case-crossover studies, based on each degree Celsius increase over the threshold (Arbuthnott and Hajat, 2017). Most studies applied a 0 to 2 days lag to analyze the link between exposure and outcome. This is because, unlike cold, heat's impact on health typically manifests within a few days of exposure (Pattenden *et al*., 2003).

2.6.2 Effect of ambient heat on mortality

Many studies show that an increasing temperature above threshold values increases the risk of mortality from all causes (Pattenden *et al*., 2003; Gasparrini *et al*., 2015). The effect size differs across regions and studies and is influenced partly by modeling choices such as threshold selection and local variations in climate, demographics, and social factors. Gasparrini *et al*. (2012) discovered that one per cent of all summer deaths in England and Wales were attributed to temperature, and Armstrong *et al*. (2011) found a similar figure. Various studies investigating cause-specific mortality (Pattenden *et al*., 2010; Gasparrini *et al*., 2012) categorized causes of death as cardiovascular, respiratory, or external. Among the various categories of death, respiratory and external causes are most affected by heat regarding relative risk (RR). However, due to the higher overall death toll from cardiovascular diseases, a more significant proportion of heat-related fatalities is attributed to these diseases (Arbuthnott and Hajat, 2017). Gasparrini *et al*. (2012) detailed that among general death categories (e.g., cardiovascular, respiratory), some causes, like atrial fibrillation and pulmonary heart disease, are significantly more sensitive to heat than others. Endocrine, nervous system, and genitourinary causes are also affected by heat sensitivity. Heat also increases the risk of suicide (Thompson *et al*., 2018). Baccini *et al*. (2017) analysed Years of Life Lost (YLL) attributable to heat across multiple cities in Europe. In London, the yearly average of heat-related YLL was estimated at 1914, excluding mortality displacement or harvesting considerations.

2.6.3 Mortality displacement

The phenomenon whereby certain deaths occurring in an already vulnerable population are advanced by several days or weeks is known as mortality displacement or "harvesting" (Arbuthnott and Hajat, 2017). The impact of harvesting on the estimated mortality risk due to a rise in ambient temperature has been studied explicitly for London. Adjusting for short-term harvesting, the estimated heat-related YLL in London for 1914 decreased by 81%, resulting in a total of 356 years (Baccini *et al*., 2017). One study especially analysed the effect of mortality displacement in London across various settings and discovered that the RR of cardiovascular and all-cause mortality did not persist beyond two days and by day eleven (Shakoor Hajat *et al*., 2006). The total effects on all-cause mortality amounted to 0 (contrarily, the mortality risk due to respiratory causes remained elevated over the 28 days studied). Nevertheless, the additional consequence of heat-related mortality continued in Delhi for three weeks (Shakoor Hajat *et al*., 2006). This has been linked to heat-related deaths in children or individuals' mortality. Recent annual time series analyses have been employed to explore the displacement of longer-term mortality in London. However, due to the imprecision of the estimates, the study could not make a firm conclusion regarding how much heat-related death might have advanced advanced (Rehill *et al*., 2011). It should be noted that the mortality displacement assessment may be affected by modelling choices. Most studies, for example, utilise a threshold based on data from the general population, while the threshold for individuals at risk of harvesting may be lower (Arbuthnott and Hajat, 2017).

2.6.4 Effect of ambient heat on morbidity and other indicators of health and wellbeing

No definitive evidence links higher ambient temperatures with total emergencies and hospital admissions (Kovats *et al*., 2004). However, a significant increase in respiratory admissions

(5.4% (95% CI: 1.9%, 9.1%)) occurs for each 1 °C above the 23 °C threshold, as well as for renal disease admissions, which show a 1.3% increase per 1 °C above the 18 °C threshold (95% CI: 0.3%, 2.4%) (Kovats *et al*., 2004). Michelozzi *et al*. (2009) backs up these findings. The disparity between mortality rates and hospital admission may partly arise from heat, leading to a quick decline in at-risk individuals, resulting in their failure to seek medical attention before death. Two studies in England (Atherton *et al*., 2005; Parsons *et al*., 2011) found a link between rising ambient temperature, pediatric emergency and trauma admissions. Atherton *et al*. (2005), for example, report an 11% (95% CI: 12%, 38%) increase in pediatric trauma admissions for every 5 °C rise in maximum temperature (with even more substantial increases using minimum temperatures as an exposure variable). The association was notably stronger for pediatric admissions compared to adult trauma admissions. The latter was deemed non-significant in the Atherton *et al*. (2005) study and showed a smaller effect size in the Parsons *et al*. (2011) research, which reported only a 1.8% increase in adult trauma admissions for every 5 °C rise in temperature. However, statistical significance was not specified (Parsons *et al*., 2011). In a study by Bhaskaran *et al*. (2009), there was no demonstrated increase in myocardial infarction admissions with rising temperatures. Nonetheless, a heightened risk of myocardial infarction has been evidenced 1 to 6 hours after heat exposure (1.9% [95% CI: 0.5%, 3.3%] for each °C above the established threshold) (Bhaskaran *et al.*, 2012). This heightened risk in the shortest lags was succeeded by a decrease at 24 hours, suggesting that the decline at longer intervals results from short-term changes. While preterm birth rates in London were influenced by seasonality, indicating higher rates during winter, no link was found between premature birth and temperature fluctuations up to six days prior to birth (Lee *et al*., 2008).

2.7 Heatwaves

The impact of heatwaves or prolonged periods of elevated temperature on health has been essentially studied through event analysis, in which the results over a specific heatwave period are compared to a predetermined baseline. There is no agreement on what constitutes a heatwave, though most studies include a duration and severity component. A heatwave, for example, is defined by the World Meteorological Organization as "when the daily maximum temperature of more than five consecutive days exceeds the average maximum temperature by 5°C, the normal period being 1961-1990". Given the lack of a standard definition for a heatwave, differences in the selection of baselines for episode analyses, and inconsistencies in the timing of heatwaves during the summer (with heatwaves and hot days occurring earlier in the season potentially exerting a greater influence on mortality) (Anderson and Bell, 2011; Gasparrini *et al*., 2016). Regardless of how extreme heat events are defined, numerous studies have found significant changes in their occurrence. Furthermore, numerous studies have linked recent changes in the risk of individual heat events to anthropogenic-driven warming and the documented global-scale increase in such events. Essential elements of a solid heatwave definition include the indices evaluated, such as temperature, humidity, health effects (mortality and morbidity), as well as the duration and intensity of the heatwave (Dimitriadou *et al*., 2021; Chandra *et al*., 2025).

The consequence of heatwaves on human health led to 70,000 excess deaths in Europe in August 2003, 696 excess deaths in Chicago in July 1995, and 55,000 excess deaths in Russia during the summer of 2010 (Faye *et al*., 2021). In Brisbane, Australia, three significant heatwaves took place in January 2000, December 2001, and February 2004, which collectively caused 51,233 deaths during the study period (Wang *et al*., 2012). Thousands of people perished as a result of the 2017 extreme heatwave in Pakistan (Khan et al., 2019). A recent study by Can *et al*. (2019), conducted in Istanbul, Turkey, found 419 excess deaths during three heatwave episodes in 2015, 2016, and 2017. This finding signifies an elevated risk of 11%,

6%, and 21%, respectively, associated with each heatwave (Can *et al*., 2019).

Although developed nations have extensively discussed heatwaves, especially following the severe one in Western Europe in the summer of 2003, little effort has been made to recognize and assess their impacts in developing countries, especially in Africa, which experiences a warmer climate (Faye *et al*., 2021). Earlier studies have highlighted how different heatwave definitions affect mortality rates in developed nations, but only a handful have examined individual cities in developing countries (Sun *et al*. 2014; Zeng *et al*. 2014). Although definitions of heatwaves vary globally due to climatic zones, the duration of the heatwave, and metrics of temperature and humidity, along with winds to a lesser extent, specific consistent metrics exist that remain (Faye *et al*., 2021).

To quantitatively describe a heatwave event, the definition should be enhanced by detailing the following four metrics: (1) Magnitude: calculated using an index or a collection of indices that reflect thermal conditions surpassing specific thresholds, (2) Duration: assesses the heatwave's persistence by noting both its start and end times, (3) Severity: a measurement method that combines both its magnitude and persistence and (4) Extent: calculated to indicate the geographical area impacted and the reach of the heatwave (Faye *et al*., 2021).

Few researchers define heatwaves using hot days and nights (Habeeb *et al*., 2015) as temperature metrics; they suggest a relative threshold or an absolute threshold (fixed threshold) (Guo *et al*., 2017). A different study conducted in West Africa examined the 90th percentile of minimum and maximum temperatures (Moron et al., 2016). Other studies have looked at different definitions of heatwaves and the effect of heatwaves regarding public health, especially mortality (Zhang *et al*., 2017). Previous research employed the Akaike Information

Criterion (AIC) to detect individuals sensitive to the first, second, and third heatwaves (Tian *et al*., 2013).

Several studies examined relationships related to cause, age, gender, and heat-related mortality, revealing that elderly individuals are at greater risk, and gender sensitivity differs across regions (Dong and Li, 2016). Furthermore, numerous prior studies have found that the relative risk of mortality is greater in women (Son *et al*., 2010; Basagaña *et al*., 2011; Ma *et al*., 2015; Zhang *et al*., 2017), and the elderly were recognised as the most vulnerable group to heatwaves (Kyselý and Kim, 2009; Zhang *et al.*, 2017).

Many studies (Khan *et al*., 2019) identified different time lag impacts and affirmed that the link between heatwave and mortality is immediate (lag0) (Guo *et al*., 2017) or after some delay. The study periods vary by region and encompass hot, summer, warm, and year-round options. Various studies have used different methods, including time-series analyses (Sun *et al*., 2014), both time series analyses and meta-analysis (Guo *et al*., 2017), both systematic review and meta-analysis (Xu *et al*., 2016), case-crossover (Wichmann, 2017), Bayesian hierarchical models (Son *et al*., 2010), and distributed lag non-linear model (Seposo *et al*., 2017), quantile regression forests (Sun *et al*., 2014), and general circulation models (Khan *et al*., 2019). A recent international study indicates that individuals residing in regions characterised by moderate cold and moderate heat seem more vulnerable to heat-related mortality than those living in extremely cold or hot areas (Guo *et al*., 2017). On the other hand, a heatwave is generally defined as a prolonged period of unusually high or extreme temperatures. Most studies (Khan *et al*., 2019) consider the daily maximum temperature, or analyse the daily minimum and maximum temperatures separately (Gershunov and Guirguis, 2012; Mutiibwa *et al*., 2015). As Perkins, (2015) points out, These definitions share common traits:

Temperature is generally used in raw or processed states, often paired with a percentile threshold and commonly calculated from a minimum heatwave duration (Faye *et al*., 2021).

2.7.1 Heatwave indices

Numerous indices have been used to investigate the human health consequences of heatwaves. Some studies utilised Heat Index (Metzger *et al*., 2010), humidex (Smoyer-Tomic and Rainham, 2001)), wet-bulb globe temperature (Kjellstrom *et al*., 2009), and apparent temperature (Anderson and Bell, 2009) to assess Heat Index indications of climate variability. Most studies examining the impact of extreme heat on human thermal comfort and health have used ambient temperatures (maximum, minimum, and average) to explore heat-related illnesses (Hajat *et al*., 2010; Wang *et al*., 2011). Furthermore, the consequences of heatwaves cannot be fully assessed by considering temperature alone; other factors such as radiation, wind, and relative humidity must also be taken into account to ensure precise results. Consequences for human health (Lung *et al*., 2013). Among these indicators, the direct surroundings have a more substantial impact on wind and radiation. For example, buildings or trees nearby reduce wind speed, whereas solar radiation is influenced by local factors such as cloud cover and visibility (Parsons, 2014). When considering these factors (wind and radiation) as variables, they are highly relevant for a specific location due to their significant fluctuations over a relatively short distance. The other two frequently considered factors are air temperature and relative humidity, as they are consistent across space and can reflect thermal comfort over a wide area (Orimoloye *et al*., 2005).

2.7.2 Heatwaves and Human Responses

Heatwaves are recognised as significant threats to human health and the environment, both directly and indirectly (Turner *et al*., 2010; Maréchal *et al*., 2025). Research indicates that people and communities can reduce heatwave risks by adopting effective strategies for mitigation and adaptation that align with their livelihoods (Kim *et al*., 2017).

The term "adaptation" is often used to describe both planned and unplanned structural and policy-level actions that may reduce a population's vulnerability to heat. The extent to which adaptations can take place will depend on the local context, vulnerabilities, and adaptive capacity (IPCC, 2007). Acclimatisation generally refers to improved tolerance, particularly concerning heat, which denotes a temporary physiological adaptation to higher temperatures. is more commonly used to refer to increased tolerance (Arbuthnott and Hajat, 2017). Evidence suggests that populations residing in warmer climates possess higher heat sensitivity thresholds (McMichael *et al*., 2006; Baccini *et al*., 2008; Basu, 2009). Although vulnerability to heat has decreased over time and across multiple regions (Donaldson *et al*., 2003; Ekamper *et al*., 2009; Gasparrini *et al*., 2015; Arbuthnott and Hajat, 2016). Determining the precise adaptive measures that have played a role in this and separating them from demographic or socioeconomic factors that might reduce heat sensitivity is challenging. However, some research suggests a link between reduced vulnerability and greater access to air conditioning (Arbuthnott and Hajat, 2016). Moreover, there is limited evidence demonstrating the effectiveness of policies or interventions designed to specifically decrease negative health outcomes, like mortality and morbidity, through rigorous methods (Kovats and Bickler, 2012; Boeckmann and Rohn, 2014). This section briefly discusses adaptive measures that can potentially mitigate the health effects of heat, ranging from individual actions to national policy levels.

- *Behavioural measures*

Heat-related behavioural measures such as wearing cool clothing, drinking more non-alcoholic fluids, and limiting strenuous activity to cooler times of the day are frequently recommended (Lowe *et al*., 2011; Public Health England, 2017). The effectiveness of behavioural measures will be determined by both the success of the intervention in reducing heat exposure and the willingness of individuals to adopt these behaviours. A survey examined different protective behaviors during the 2013 heatwave and home features (such as air conditioning availability) in a sample of the UK population (Khare *et al*., 2015). Research indicated that older adults often avoid utilising specific personal and home security measures while exhibiting a greater tendency to leave their windows open at night. Those with higher incomes were also more likely to adopt personal and home security measures. Consequently, this highlighted groups for further emphasis in health messaging.

- *Air conditioning and electric fans*

  Research indicates that air conditioning provides health protection from heat exposure. (Arbuthnott and Hajat, 2017) and that seeking out a public space with air conditioning can be beneficial (Bouchama *et al*., 2007). This measure is found in many heatwave plans. However, there are disadvantages to promoting this as an adaptative strategy. For example, there may be equity concerns related to the prevalence and accessibility of air conditioning units.

  Excessive air conditioning use may raise energy demands and add to the urban heat island effect (Salamanca *et al*., 2014). Gupta *et al*. (2012) in a systematic review of the evidence on the use of electric fans did not discover a study that meet its inclusion criteria. He concluded on the insufficient high-quality research to evaluate the evidence.

  The results of fan’s protecting effect were not conclusive in case-control studies. Some studies showed a protecting effect while others indicated the opposite (Arbuthnott and Hajat, 2017).

- *Heat warning systems (heatwave plans)*

  Given the issues related to this heatwave phenomenon, it is necessary to be able to anticipate the appearance of these heatwaves to prevent their impacts. The negative impact of heatwaves can be mitigated with competent forecasts. In various countries, heatwave-health early warning systems are under development, following the guidance of the WMO and WHO (2015). The

ACASIS (Sahelian Heatwave Early Warning and their Impacts on Health) project in the Sahel has bolstered scientific understanding of the causes and effects of heatwaves. In the Sahel, two national meteorological services monitored heatwaves regularly in Burkina Faso and Senegal. Heatwave processes must be clearly defined and understood for effective forecasting and risk management, particularly at short (synoptic and intrapersonal) timescales.

Summarily, the effect of heatwaves on human health should not be taken for granted. Africa is categorised as one of the most exposed regions to climate changeability due to its geographical position, ineffective leadership, and pervasive poverty. These issues are exacerbated by frequent extreme climate events, which hinder individuals and societies from coping with and adapting to these challenges effectively (Lema and Majule, 2009).

2.8 Projected changes in heatwaves

Climate change is highly probable to lead to a sustained rise in heatwaves' frequency, intensity, and duration (Horton *et al*., 2016). Additionally, in many regions, research suggests that extremely high temperatures might increase more rapidly than the average seasonal temperature (Horton *et al*., 2015; McKinnon et al., 2024). Mora *et al*. (2017) found that regions such as Central and South America, Africa, India, Southeast Asia, and northern Australia are more likely than other areas to experience an increasing number of days each year with temperatures exceeding human survivability thresholds. This trend persists across all three projected greenhouse gas concentration scenarios, known as Representative Concentration Pathways (as detailed by the Intergovernmental Panel on Climate Change, 2013). However, despite their vulnerability, these regions are significantly underrepresented in existing research on heatwaves and their health effects (Campbell *et al*., 2018a).

The study of Sahelian heatwaves on climatic timescales has received increasing attention (Guigma *et al*., 2021). CMIP5 projections analyzed by Ringard *et al*. (2016) indicate that heatwaves in the Sahel will follow a significant upward trend regardless of the scenario. Russo *et al*. (2016) suggested that under the most extreme scenario, by 2040, the region's current rare heatwaves will become frequent. Similarly, Dosio *et al*. (2018), using the 1981–2010 period as a reference, projected that under the same scenario, temperatures in the Sahel could rise by +3.5°C to +6°C starting around 2060. Additionally, Déqué *et al*. (2017) estimated that if global temperatures rise by 2°C, the frequency of heatwaves in the Sahel could rise tenfold when using the similar temperature threshold as for the reference climate. Given the increase in heatwaves and their effect on human health, it is essential to systematically document and rigorously assess emerging strategies for adapting to extreme heat. This process is crucial, as it bridges scientific understanding and practical solutions for mitigating the harmful effects of heat waves on population, infrastructure and the environment in the twenty-first century.

Burkina Faso is a country in the Sahelian region of West Africa. Despite the continuous recurrence of heatwaves, little knowledge of these extreme weather events and their impact on human health has ever been quantified. Hence, the work intends to determine, using shared socio-economic pathways, the impact of heatwaves on human health.

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 Study Area

Burkina Faso is a non-coastal nation in West Africa, stretching from south to north between 9.25 and 15.01°N and east to west between 2.22°E and 5.32°W, with its northern part in the Sahel from north to south. Burkina Faso shares its borders with Mali to the north and west, Niger to the northeast, Benin to the southeast, and Togo, Ghana, and Côte d'Ivoire to the south (Figure 3.1). The national territory covers an area of 272,967 km^2 and has a topography with little relief. Despite the absence of an outlet to the sea, three rivers drain the country: the Mouhoun, the Nazinon, and the Nakambé (Bégin-galarneau *et al*., 2021).

Burkina Faso is located chiefly on a savannah plateau, the altitude varying between 250 m and 400 m. The country has two main climates: the north, covered by grasslands, is characterised by steppes and three to five months of precipitations, often erratic. Agriculture is, therefore, less diversified, and the populations are more vulnerable to food insecurity. In the south, where sparse forests dominate vegetation cover, the climate is more tropical, with rainfall. Burkina

Faso receives, on average, between 500 mm and 1,000 mm of rainfall between June and September and has an average annual temperature of about 28 °C (Tomalka *et al*., 2021).

The country has three (3) climatic regions: the Sahelian, Sudano-Sahelian, and Sudanian. From a thermal point of view, average temperatures differ slightly from one zone to another and increase from the South to the North. Burkina Faso has a Sudano-Sahelian climate marked by a dry and rainy season. The dry season lasts about eight months, between October and the end of April or even May in the quasi-desert North. The rainy season, or wintering, lasts from May June to the end of September or the beginning of October and reaches its peak in August.

The hottest months are March, April, May, and June, when the temperature constantly exceeds

40°C. A refreshing but drying north wind blows the harmattan from November to February. It can also, often around mid-February, take the form of a very violent wind that brings the sands of the Sahara and raises the dust off the roads to the point of hiding the sun, sometimes for several days (rare). However, the period remains pleasant because the temperature is between 25 and 30 °C. In the Sahelian zone, rainfall in July and August can be extremely violent. The climate in Burkina Faso is governed by the interaction of complex mechanisms such as the West African Monsoon (WAM), the Harmattan, the Inter-Tropical Discontinuity (ITD), the Eastern Waves, and the squall lines. The dry season is very intense in Burkina because all Sahelian regions have a very high number of arid months that usually receive no rain on average. During the rainy season, the trade winds associated with the anticyclonic regime are temporarily interrupted and give way to the monsoon (south or southwest wind). The climate study over the last decades illustrates the establishment of an increasingly arid climate in the country. This is manifested by decreasing rainfall and increasing temperatures. This climatic trend leads to prolonged periods of drought and desertification (UNDP, 2018). Figure 3.1 shows the map of Burkina Faso with the three different climatic zones.

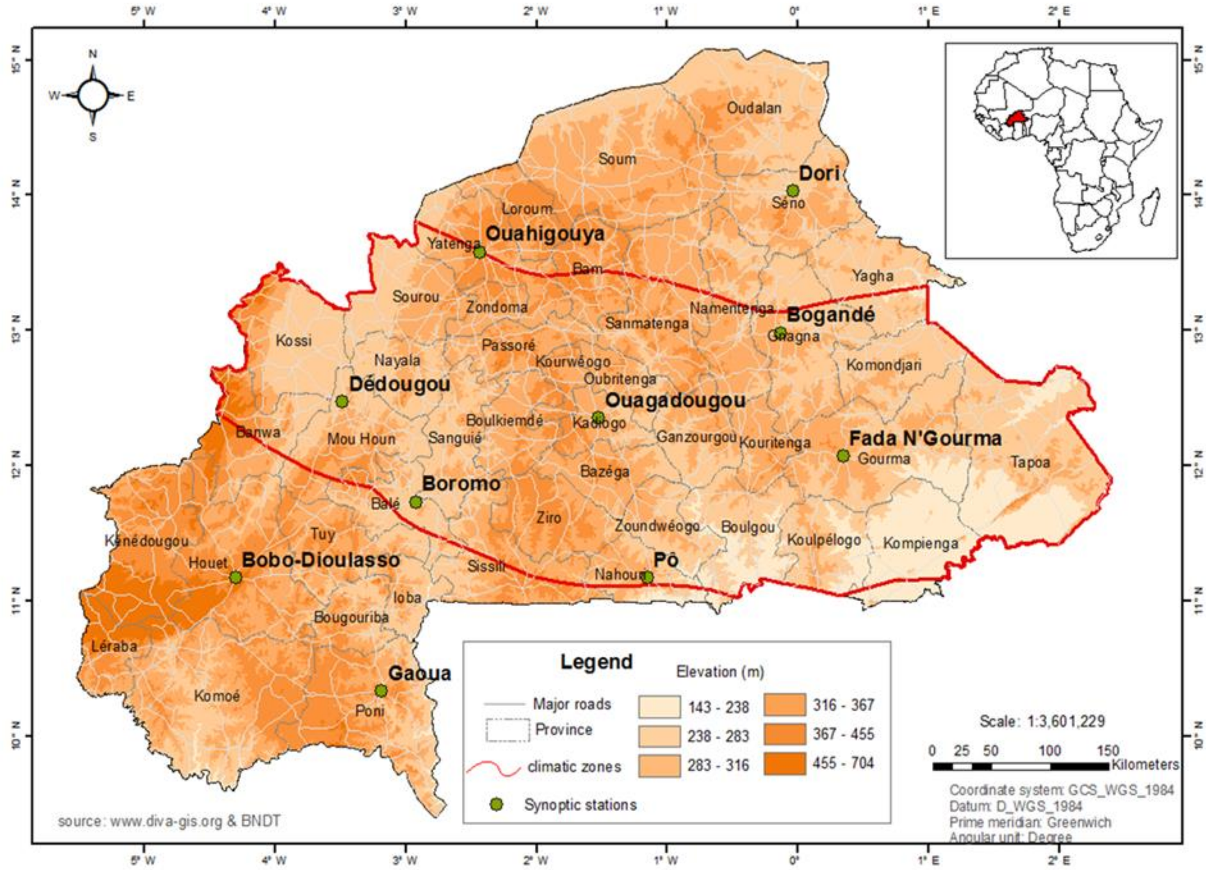

Figure 3. 1: Map of study area showing the three climatic zones of Burkina Faso and the 10 synoptic stations.

3.2 Data

3.2.1 Meteorological data

A self-consistent multivariate dataset is desirable to achieve the research aim of assessing the impact of heatwaves on human health over Burkina Faso. Two types of datasets were utilised: observational and model-simulated datasets. The observational datasets consist of the minimum (TN) and maximum (TX) daily temperatures from ten (10) synoptic stations across Burkina Faso, as represented in Table 3.1, obtained from the Agence Nationale de la Météorologie du Burkina Faso (ANAM) for the period from 1991 to 2021. The model-simulated datasets were sourced from 11 climate models included in the NEX-GDDP dataset. These models, detailed in Table 3.2, provide data at a spatial resolution of 0.25° × 0.25°. The dataset encompasses TX, and TN data for a period of 34 years, that is, from 1981 to 2014, sourced from https://ds.nccs.nasa.gov/thredds/catalog/idd/bypass.html. Additionally, ERA5 (daily TX and TN) data was downloaded from Copernicus from 1991 to 2021.

Table 3.1: Geographical position of the ten synoptic stations of Burkina Faso

Stations Name	Station ID	Latitude (°)	Longitude (°)	Altitude (m)
Dori	65501	14.03	-0.03	276
Ouahigouya	65502	13.58	-2.43	335
Bogandé	-	12.98	0.08	294
Dédougou	65505	12.47	-3.48	299
Ouagadougou	65503	12.35	-2.18	303
Fada N'gourma	65507	12.07	0.35	308
Boromo	65516	11.73	-2.92	270
Pô	65518	11.17	-1.15	321
Bobo-Dioulasso	65510	11.17	-4.3	459
Gaoua	65522	10.33	-3.18	292

Source: Author's Compilation (2025)

Table 3.2: List of the selected models from the NEX-GDDP dataset

S/N	Model	Institute	Resolution (Lon° × Lat°)	References	Resolution
1	ACCESS-CM2	Australian Community climate-earth system simulator	0.25 × 0.25	Bi *et al*. (2020)	daily
2	ACCESSESM1-5	Commonwealth Scientific and Industrial Research Organization and Bureau of Meteorology (Australia)	0.25 × 0.25	Ziehn *et al*. (2019)	daily
3	CMCC-ESM2	CMCC, Italy	0.25 × 0.25	Lovato *et al*. (2021)	daily
4	EC-EARTH3	EC-EARTH consortium	0.25 × 0.25	EC-Earth (2019)	daily
5	EC-Earth3-VegLR	EC-EARTH consortium	0.25 × 0.25	EC-Earth (2020)	daily
6	IPSL6 CM6A LR	Institute Pierre Simon Laplace	0.25 × 0.25	Boucher *et al*. (2018)	daily
7	KIOST-ESM	Korea Institute of Ocean Science and Technology	0.25 × 0.25	Kim *et al*. (2019)	daily
8	MIROC6	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute	0.25 × 0.25	Tatebe *et al*. (2019)	daily
9	MPI-ESM1-2HR	Max Planck Institute (MPI), Germany	0.25 × 0.25	Mauristen *et al*. (2019)	daily
10	MPI-ESM1-2LR	Max Planck Institute (MPI), Germany	0.25 × 0.25	Mauritsen *et al*. (2019)	daily
11	MRI-ESM2-0	Max Planck Institute (MPI), Germany	0.25 × 0.25	Yukimoto *et al*. (2019)	Daily

3.2.1.1 Observation Data

Meteorological stations were chosen due to their reliable data and climatic representativeness location. The ANAM data are of excellent quality and have already been checked (Savadogo and Combere, 2018). ANAM validated and homogenised these data before making them available for use.

3.2.1.2 NASA NEX-GDDP Data

The NEX-GDDP-CMIP6 dataset is generated using the Bias-Correction Spatial Disaggregation (BCSD) method, a statistical downscaling algorithm designed to overcome the limitations of global GCM outputs (Wood *et al*., 2004; Thrasher *et al.,* 2012; Shrestha *et al*., 2017). The algorithm assesses the GCM outputs against relevant climate observations within a standard timeframe. It leverages this comparison to refine future climate projections, making them increasingly aligned with historical climate records and, likely, more realistic for the specific spatial area of interest. Additionally, the algorithm takes advantage of the spatial detail from observational datasets to interpolate the GCM outputs onto higher-resolution grids.

3.2.2 Health data

Health data collection is complex in Burkina Faso. In most cases, these data are not recorded; even if they are, they do not cover an extended period. Nevertheless, we collected monthly data on heart disease-related mortality over seven years (2015-2022) in Ouagadougou, the capital of Burkina Faso, where most seriously ill patients are evacuated.

3.3 Methods of Analysis

3.3.1 Characterisation of heatwave and its Indices Computation

Pre-processing of the original model TX and TN datasets was performed using Climate Data Operators (CDO) (Schulzweida *et al*., 2009; Modali *et al*., 2013) ensuring compliance with

ClimPACT2 instructions (Perkins and Alexander, 2013). The calculations for the heatwave in ClimPACT2 are based on Perkins and Alexander (2013). Corresponding to the framework of Perkins and Alexander (2013). ClimPACT2 utilises three definitions for heatwaves. These are determined using the 90th percentile of minimum daily temperature, referred to as Tn90; the 90th percentile of maximum daily temperature, known as Tx90; and the Excessive Heat Factor (EHF). According to the three definitions of a heatwave (Tn90, Tx90, and EHF), a heatwave event is defined as a period of three or more consecutive days during which one of the following conditions is met.

1. TN > 90th percentile of TN.
2. TX > 90th percentile of TX.
3. EHF is positive

The percentiles for Tn90 and Tx90 span from 1991 to 2014 and are computed using a 15-day running average for each calendar day. In ClimPACT2, all heatwave definitions are assessed during the extended summer period, except for the Excess Heat Factor (EHF) defined by Nairn and Fawcett (2013). For each of the three heatwave definitions mentioned, five heatwave aspects are evaluated annually or over the summer (Table 3.3).

1.) HW Number (HWN): The number of HW events (>= 3 HW days) that begin in the period of interest in addition to those that start prior to but continue into the period of interest.

2.) HW Frequency (HWF): This is the count of days contributing to HWs as defined by HWN, referred to as 'HW days'. For HWs initiating before the period of focus, only the HW days within that period are included. Conversely, for HWs that continue past the period of interest, only up to 14 days beyond this period are counted.

3.) HW Duration (HWD): The number of days comprising the longest heatwave, as defined by HWN.

4.) HW Magnitude (HWM): This is the average of the average HW days for each defined HW HWN.

5.) HW Amplitude (HWA): This represents the highest daily value recorded during the hottest heatwave, identified as the heatwave with the maximum temperatures HWM).

Precautions: When calculating HWs, leap days are ignored and deleted from the data.

Table 3.3: Heatwave Indices and Definition

Short name	Long name	Definition	Plain language description	Units
TX90p	Amount of hot days	Percentage of days when TX > 90th percentile	Fraction of days with hot daytime temperatures	%
TN90p	Amount of warm nights	Percentage of days when TN > 90th percentile	Fraction of days with warm nighttime temperatures	%
HWN(EHF/Tx90/Tn90)	Heatwave number (HWN) as defined by either the Excess Heat Factor (EHF), 90^{th} percentile of TX or the 90th percentile of TN	The number of individual heatwaves that occur each summer (Nov–Mar in the southern hemisphere and May-Sep in the northern hemisphere). A heatwave is defined as 3 or more days where either the EHF is positive, TX > 90th percentile of TX or where TN > 90th percentile of TN. Where percentiles are calculated from the base period specified by the user.	Number of individual heatwave	Events
HWD(EHF/Tx90/Tn90)	Heatwave duration (HWD) as defined by either the Excess Heat Factor (EHF), 90^{th} percentile of TX or the 90th percentile of TN	The length of the longest Heatwave identified by HWN.	Length of the longest heatwave	Days

HWM(EHF/Tx90/Tn90	Heatwave magnitude (HWM) as defined by either the Excess Heat Factor (EHF), 90th percentile of TX or the 90th percentile of TN	The mean temperature of all Heatwaves identified by HWN.	Average temperature across all individual heatwaves	°C (°C 2 for EHF)
HWA(EHF/Tx90/Tn90	Heatwave amplitude (HWA) as defined by either the Excess Heat Factor (EHF), 90th percentile of TX or the 90th percentile of TN	The peak daily value in the hottest heatwave (defined as the heatwave with highest HWM).	Hottest day of the hottest heatwave	°C (°C2 for EHF
HWF(EHF/Tx90/Tn90)	Heatwave frequency (HWF) as defined by either the Excess Heat Factor (EHF), 90th percentile of TX or the 90th percentile of TN	The number of days that contribute to heatwaves as Identified by HWN.		

Source: Author's Compilation (2025)

3.3.2 Taylors Diagram

This study utilises the Taylor diagram, as proposed by Taylor (2001) and Yan *et al.* (2022), to assess the simulation outcomes of 11 climate models from NASA's NEX GDDP CMIP6 dataset. The Taylor diagram allows for a more intuitive comparison of the spatial distribution of each model's simulation results before and after processing, highlighting their consistency with observed data. Taylor diagrams simultaneously incorporate various evaluation metrics such as standard deviation, central root mean squared error (CRMSE), and the correlation coefficient to evaluate how accurately the model fits the observed data. The calculation for the standard deviation of both the observational data and the model is expressed as follows:

$$\boldsymbol{\sigma}_{obs} = \sqrt{\frac{1}{N}\sum_{n=1}^{N}\left(X_{obsn} - \overline{X_{obs}}\right)^2}$$

(3.1)

$$\boldsymbol{\sigma}_{model} = \sqrt{\frac{1}{N}\sum_{n=1}^{N}\left(X_n - \overline{X}\right)^2}$$

(3.2)

Where: N is the Number of observations (i.e., total number of data points)

n is the position or index of a specific observation in the dataset (e.g., 1st, 2nd, 3rd, ..., N-th). It runs from 1 to N

Xobs,n is the n-th observed data point in the dataset.

$\overline{X_{obs}}$ and $\overline{X}$ respectively is the average of the observed data and model data. The central root mean square error, *RMSE*, is defined as:

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{n=1}^{N}\left(\left(X_n - \overline{X}\right) - \left(X_{obsn} - \overline{X_{obs}}\right)\right)^2}$$

(3.3)

The correlation coefficient r of the observed data and the model data is defined as:

$$r = \cdot \left(\frac{1}{N}\sum_{n=1}^{N}\left(X_n - \overline{X}\right) - \left(X_{obsn} - \overline{X_{obs}}\right)\right)/(\sigma_{model}\sigma_{obs}) \quad (3.4)$$

The essence of the Taylor diagram lies in the fact that the standard deviation, correlation coefficient, and central root mean square error of the simulated and observed data adhere to the following relationships:

$$RMSE^2 = \boldsymbol{\sigma}_{obs}^2 + \boldsymbol{\sigma}_{model}^2 - 2\,\boldsymbol{\sigma}_{obs}\,\boldsymbol{\sigma}_{model}\,r$$

(3.5)

3.3.3 Trend Analysis and Significance Testing

The Mann-Kendall test (Mk) (Mann, 1945; Kendall, 1975; Wang *et al.,* 2005) was also utilised to assess the trend analysis. This method was utilised to identify discontinuities resulting from inhomogeneous time sequences. Its uniqueness lies in the absence of presumptions regarding data distribution, making it widely accepted for trend analysis. This characteristic has garnered widespread acceptance for trend analysis (Ajayi and Ilori, 2020; Arowolo and Oluleye, 2022) This is a non-parametric statistical technique used to detect monotonic trends in time series data. Its benefits include not requiring the time series to follow a normal distribution, handling missing data effectively, and being resilient against extreme values. The Mk statistic can be characterised as:

$$K = \sum_{i=1}^{n}\sum_{j=1}^{i-1} sign\,(xi - xj)$$

(3.6)

Where xi and xj are the value of the sequential generic data, n is the data total length,

while sign (xi-xj) can be defined as;

$$\begin{bmatrix} 1, & if(xi - xj) & 0 \\ 0, & if(xi - xj) & 0 \\ -1 & if(xi - xj)\cdots & 0 \end{bmatrix} \quad (3.7)$$

The variance Var(S) was computed based on the assumption that the S statistic is roughly distributed with E(S) mean:

$$E(S) = 0, \quad (3.8)$$

$$\{n(n-1)(2n+5) - \textstyle\sum_t t(t-1)(2t+5)\}$$

(3.9)

where t is any given time extent, $\sum t$ represents the total of all the tie numbers, and n indicates the series length. The Z-standardized statistics for the test can then be assessed using the following equation below:

$$\begin{pmatrix} -1, & if \quad K < 0 \\ 0, & if \quad K = 0 \\ \frac{S+1}{\sqrt{Var(S)}} & if \quad K > 0 \end{pmatrix}$$

(3.10)

In a scenario where a dataset with n independent variables is randomly distributed without any trends or order, the null hypothesis (H_0) can be accepted or rejected based on the significance level (*p*). The absolute value of Z (test statistic) is then compared with the value of $Z\left(1 - \frac{p}{2}\right)$ at a *p*-level of significance to reject or accept the H_0 hypothesis.

3.4 Relationship between Heatwave and Health

3.4.1 Correlation between Temperature Humidity Index and Health, and Heatwave and Health

3.4.1.1 Temperature Humidity Index (THI)

The Temperature Humidity Index is an index to calculate the outdoor thermal comfort felt by humans using indicators of air temperature and relative humidity (Arif *et al.*, 2023). The index value obtained is then used to classify thermal comfort in the research environment. The thermal comfort index based on the THI value was calculated using the equation by Nieuwolt (1977) and classified according to Table 3.4.

$$THI = 0.8T + (RH\ T)/500$$

(3.11)

where: THI: Temperature Humidity Index (Index of thermal comfort)

RH: Relative Humidity (%)

T: Temperature (°C)

Table 3.4: THI Classification adapted from Regional Studies and Biometeorology Literature.

Comfort Level	**THI**
Comfortable	< 25
Uncomfortable	$25 \leq THI < 28$
Very Uncomfortable	$28 \leq THI < 30$
Danger / Heat Stress	≥ 30

Source: Eludoyin *et al*. (2014)

3.4.1.2 Pearson Correlation Coefficient

For both analyses, the Pearson correlation coefficient r was computed to measure the strength and direction of the linear relationship between the environmental variable (x) and mortality(y):

$$R = \frac{\sum_{i=1}^{n}(x_i - x)(y_i - y)}{\sqrt{\sum_{i=1}^{n}(x_i - x)^2}.\sqrt{\sum_{i=1}^{n}(y_i - y)^2}.} \qquad (3.12)$$

Where: xi = value of the environmental variable (e.g., average THI or heatwave days) in month i

yi = mortality count in month i

$\overline{X}$ = monthly means

n = number of months in the dataset

To quantify how much of the variation in monthly mortality can be explained by variation in the environmental variable, the coefficient of determination was calculated:

$R^2 = r^2$

This value ranges from 0 to 1:

- R^2=0: no explanatory power
- R^2=1: perfect explanation of variance

3.4.2 ARIMA Model for Heatwave and Mortality Prediction

The relationship between heatwave occurrences and health outcomes was explored using an Auto Regressive Integrated Moving Average (ARIMA) model. This model is well-suited for time series analysis, particularly in capturing seasonality, trends, and autocorrelation in weather and mortality data.

The heatwave index (HWN, HWF, HWD) and health data (monthly or daily mortality rates) were aggregated into time series datasets from 1981 to 2014.

The Augmented Dickey-Fuller (ADF) test was used to verify the datasets for stationarity. Nonstationary data were differenced to achieve stationarity. The ARIMA model was then utilised on the time series of heatwave occurrences to forecast future heatwave events. Model parameters (p, d, q) were selected based on AIC (Akaike Information Criterion) and BIC (Bayesian Information Criterion) scores to optimise model performance. A cross-correlation function (CCF) was applied to assess the temporal relationship between heatwave occurrences (HWN) and mortality rates. The ARIMA model was used to predict future heatwave events and their impact on mortality rates. The model's performance was evaluated using metrics like Mean Absolute Error (MAE) and Root Mean Squared Error (RMSE). The predicted heatwave occurrences were cross-referenced with mortality data to explore potential correlations, using linear regression to quantify the relationship. The final analysis studied the correlation between predicted heatwave occurrences and mortality rates. A linear regression model (ARIMA model) was fitted to quantify the relationship (Akinbobola and Hamisu, 2018), taking the form:

$$\text{Mortality t} = \beta_{\circ} + \beta_{1} \cdot \text{Heatwave t} + \epsilon \text{ t} \quad (3.14)$$

where:

- Mortality t: Number of deaths in period t.
- Heatwave t: Number of heatwave days in period t.
- β_0: Intercept.

- β_1: Slope coefficient measuring the effect of heatwaves on mortality.
- ϵ_t Error term.

The model results were evaluated based on R-squared, p-value, and residual analysis, determining the strength of the correlation between heatwaves and health impacts (Akinbobola and Hamisu, 2018).

3.5 Projection of Future Heatwaves

3.5.1 Heatwave Projection

To assess future heatwave conditions under climate change scenarios, the ensemble mean of the NEX-GDDP dataset was analysed and compared with ERA5, a widely used reanalysis dataset. This comparison, validated through Taylor diagrams, evaluated the capacity of NEXGDDP to replicate historical conditions, ensuring its reliability for projecting future scenarios. The study considered two Shared Socioeconomic Pathways: SSP245 (moderate emissions), also known as middle of the road, and SSP585 (high emissions), to explore variations in heatwave patterns.

The analysis centered on five heatwave indices (detailed in Table 3.2), which capture extreme temperature events' frequency, intensity, and duration. Composite averages of these indices were calculated, spatially averaged at each grid point within the study area, and examined across three distinct temporal periods: a historical baseline (1981–2014), a near-future projection (2020–2050), and a far-future projection (2051–2100). This method enabled the identification of long-term trends and changes in heatwave behaviour.

Daily heatwave indices were calculated for the baseline and the two projection periods under SSP245 and SSP585. Comparing historical conditions with future projections highlighted the potential evolution of heatwaves under various emissions scenarios. SSP245 offered insights into moderate warming outcomes, whereas SSP585 projected the impacts of higher emissions pathways, enabling a nuanced understanding of climate change’s effect on heatwaves.

3.5.2 Ensemble Mean (MME) Calculation

The MME was validated against ERA5 using the same statistical metrics as individual models to assess its accuracy. Ensemble outputs were evaluated for reduced spread and improved correlation compared to individual models, indicating the added value of MME in minimising model biases (Christiansen, 2020). To ensure comparability, all datasets were re-gridded to a common spatial resolution (25 km) using bilinear interpolation.

$$MME = \left(\frac{1}{N}\right)\sum_{i=1}^{N}(Xi) \tag{3.12}$$

where N is the number of models, and Xi is the output of the i^{th} model.

The MME approach leverages individual models' strengths while reducing the influence of their weaknesses. The ensemble mean provides a more robust and reliable representation of climate variables by averaging multiple outputs.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Characterisation of Heatwave and Thermal Humidity Index in Burkina Faso

4.1.1 Analysis of Heatwave Characteristics

The heatwave characteristics (heatwave amplitude, heatwave duration, heatwave frequency, heatwave magnitude index, heatwave number) and the eleven (11) models were analysed at the 90^{th} percentile of minimum (TN) and maximum (TX) temperatures and excess heat factor (EHF).

Figures 4.1 and 4.2 are Taylor diagrams that show the statistical analyses of observed data against the model data for the minimum and maximum temperature, respectively. The analyses from the figures were standard deviation (S.D.), correlation coefficient (R^2) and the root mean square error (RMSE). The black broken line with a star-like shape at the end of it is the observed data, the red, broken line with an arc shape is the line of root mean square error, the green arc is the line of standard deviation, while the green broken straight line is the line of correlation coefficient. Figure 4.1 shows that most models overestimated by 0.6 with a standard deviation of 0.8 and a correlation coefficient of about 0.82. Figure 4.2 shows the models have overestimated by 0.5 and a standard deviation of 1.0, with a correlation coefficient between 0.87 – 0.89. It can also be deduced from these figures that the closer the root mean square error and standard deviation are to zero, the better the performance of the models. The closer the correlation coefficient values of the models against the observed values are to 1, the better the models. The resultant outcome of these statistical analyses of the models against observed data from Figures 4.1 and 4.2 is summarised in Table 4.1. The results showed MRI-ESM2-0 with low standard deviation (S.D) and root mean square error (RMSE) values of 0.78 and 0.54, respectively, and the highest correlation coefficient of 0.83 when the observed and model minimum temperature data were compared. The best model that statistically mirrored the observed data for maximum temperature was also MRI-ESM2-0, with a correlation coefficient and root mean square error of 0.88 and 0.48, respectively.

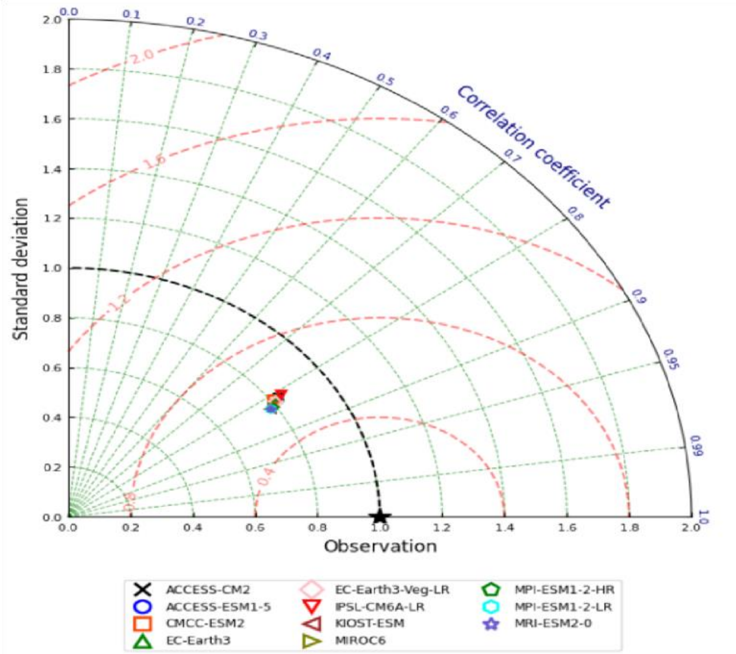

Figure 4. 1: Taylor’s Diagram for Minimum Temperature of observed data against other models

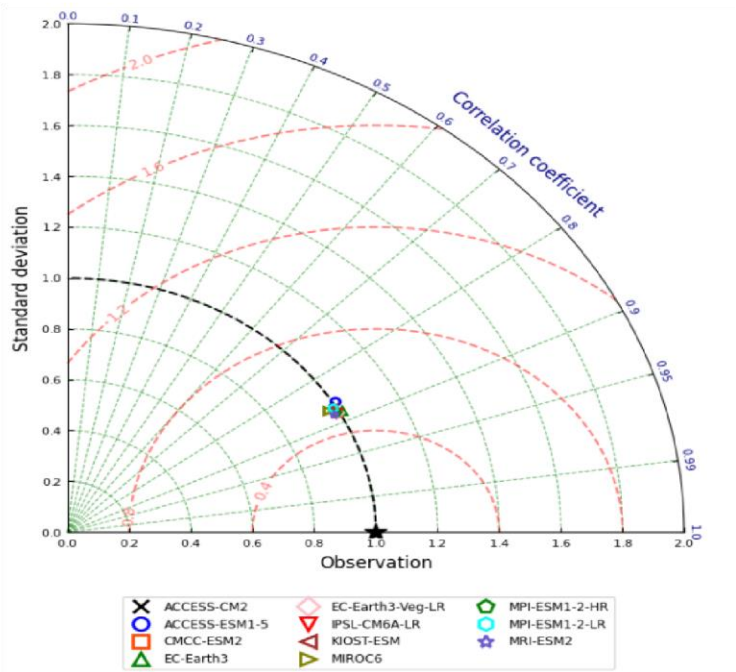

Figure 4. 2: Taylor’s Diagram for Maximum Temperature of observed data against other models

Table 4.1: Standard Deviation (S.D.), Correlation Coefficient (R^2) and Root Mean Square Error (RMSE) of Minimum and Maximum Temperatures from Taylor's Diagram.

S/N	Model	Minimum Temperature			Maximum Temperature		
		S.D.	**R^2**	**RMSE**	**S.D.**	**R^2**	**RMSE**
1.	ACCESS-CM2	0.82	0.81	0.54	0.99	0.87	0.51
2.	ACCESS-ESM1-5	0.82	0.82	0.55	1.01	0.86	0.55
3.	CMCC-ESM2	0.81	0.82	0.63	0.99	0.88	0.49
4.	EC-Earth3	0.83	0.81	0.59	1.01	0.88	0.53
5.	EC-Earth3-Veg-LR	0.81	0.82	0.58	0.99	0.88	0.51
6.	IPSL-CM6A-LR	0.84	0.83	0.64	0.99	0.88	0.48
7.	KIOST-ESM	0.78	0.83	0.64	0.99	0.87	0.52
8.	MIROC6	0.79	0.83	0.58	0.97	0.87	0.51
9.	MPI-ESM1-2-HR	0.79	0.83	0.56	0.99	0.88	0.5
10.	MPI-ESM1-2-LR	0.78	0.83	0.55	0.99	0.87	0.53
11.	MRI-ESM2-0	0.78	0.83	0.54	0.98	0.88	0.48

Figure 4.3 compares observed data and 11 climate model simulations, revealing significant insights into heatwave patterns over Burkina Faso. The observed data show a distinct north-south gradient, with northern regions experiencing the highest heatwave intensities and southern regions experiencing the lowest. This pattern likely results from geographical and climatic influences, such as the proximity of northern areas to the Sahel and the more humid conditions in the south. The amplitude of heatwaves is pronounced over the north of the region, with temperatures rising about 29°C above the 90th percentile. The amplitude of the heatwave measures the severity or intensity of the heatwave. Hence, the result from the observed simulation showed that inhabitants of the northern extreme of Burkina Faso may experience heat-related diseases. Extreme temperatures can damage crops and low crop yield. When examining the climate models, varying degrees of accuracy in replicating the observed gradients were noted. While some models are close to observed in terms of output, others overestimated the output compared to the observed ones. Models such as CMCC-ESM2 closely mirror the observed data, displaying similar wave intensities in the north but with some underestimation in the extreme north. Similarly, IPSL-CM6A-LR, MPI-ESM1-2-HR, ACCESS-CM2, ACCESS-ESM1-5, EC-Earth3, and EC-Earth3-Veg-LR align well with the observed pattern at the southern axis, but with greater intensity in the northern and southern regions. This suggests that these models may be more reliable for future heatwave predictions in Burkina Faso. In contrast, models like KIOST-ESM, MRI-ESM2-0, and MIROC6 exhibit more variability and do not align as closely with the observed gradient. These models show moderate heatwave intensities spread more evenly across the country, diverging significantly from the actual data, indicating limitations in accurately simulating heatwave patterns for this region. Heatwave Amplitude (HWA) at night, using the TN90 (Figure 4.3), ranges between

24-30°C, with a high percentage of most parts of the country experiencing temperatures above

27°C, excluding the extreme southern parts. During the day using TX90 (Figure 4.4), HWA ranges between 32-43°C. These effects are experienced over most of the region, with only the observed and few other models recording heatwave values of less than 35ºC over the extreme southern parts. The Excess Heat Factor (EHF), which combines intensity and duration (Figure 4.5), shows no significant threat from the observed data and other models, excluding ACCESSCM2, ACCESS-ESM1-5, EC-Earth3, and IPSL-CM6A-LR, which indicate a high-level threat over the region with an anomaly of about 5°C. The results from the observed data and other similarly mirrored models imply that the low, excessive heatwave factor will have limited impacts on man, health, agriculture, and the environment. However, if the other overestimated models are considered, there is a need for better preparation and prompt response to mitigate the possible extreme effects.

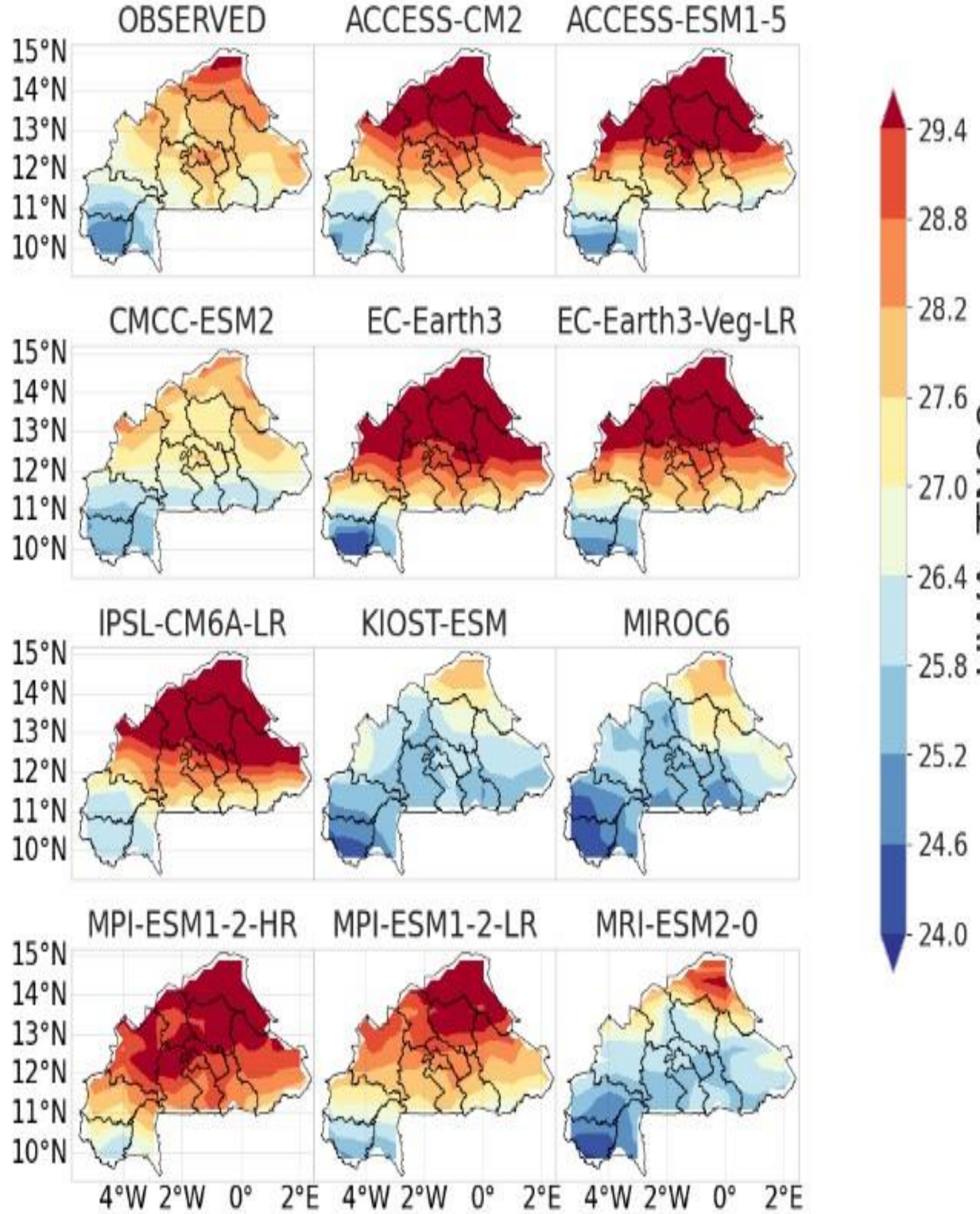

Figure 4. 3: Characterization of heatwaves in Burkina Faso using HWA (Heat Wave Amplitude) °C for nighttime (TN90th percentile) from 1991 - 2014.

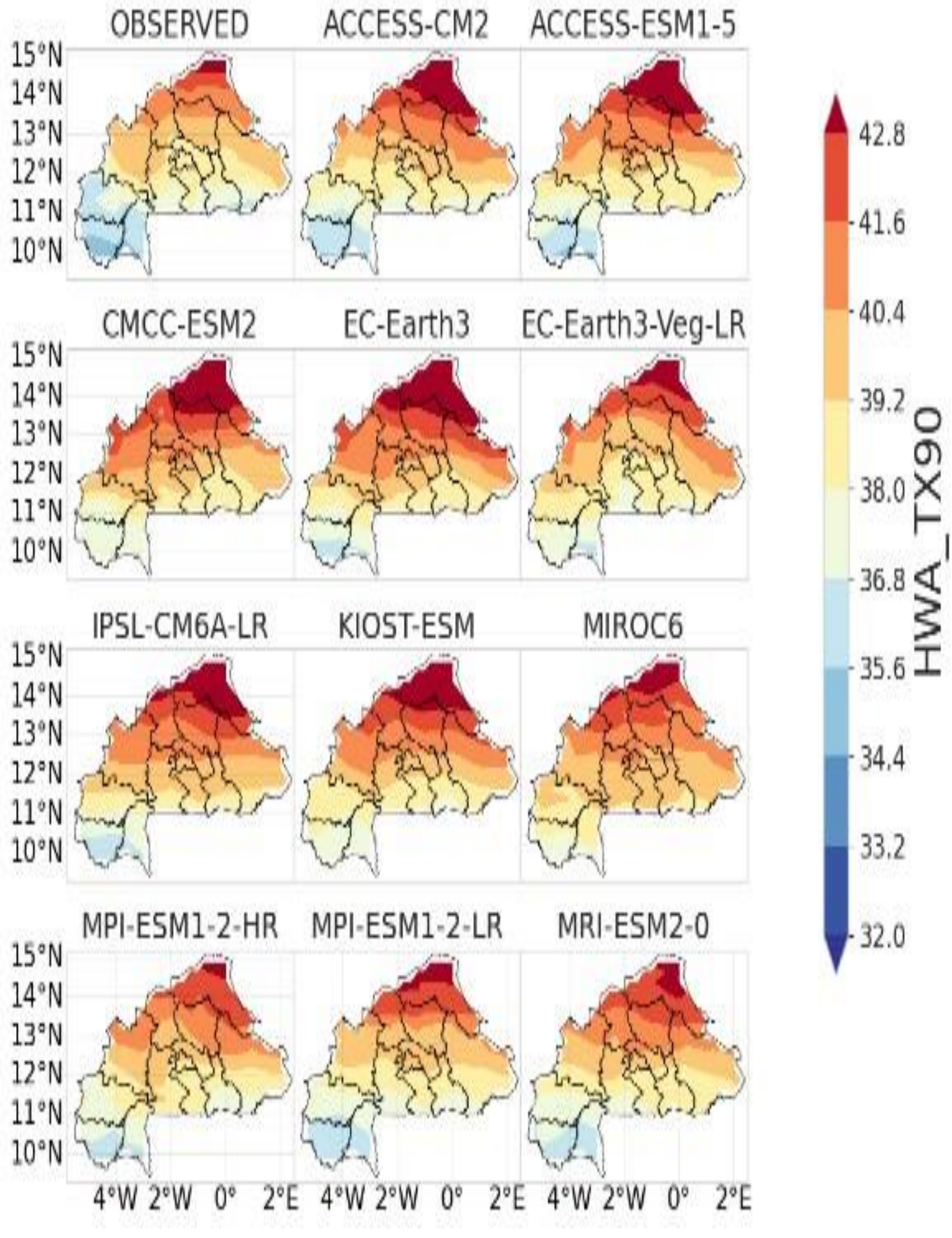

Figure 4. 4: Characterization of heatwaves in Burkina Faso using HWA (Heat Wave Amplitude) °C for daytime (TX90th percentile) from 1991 - 2014.

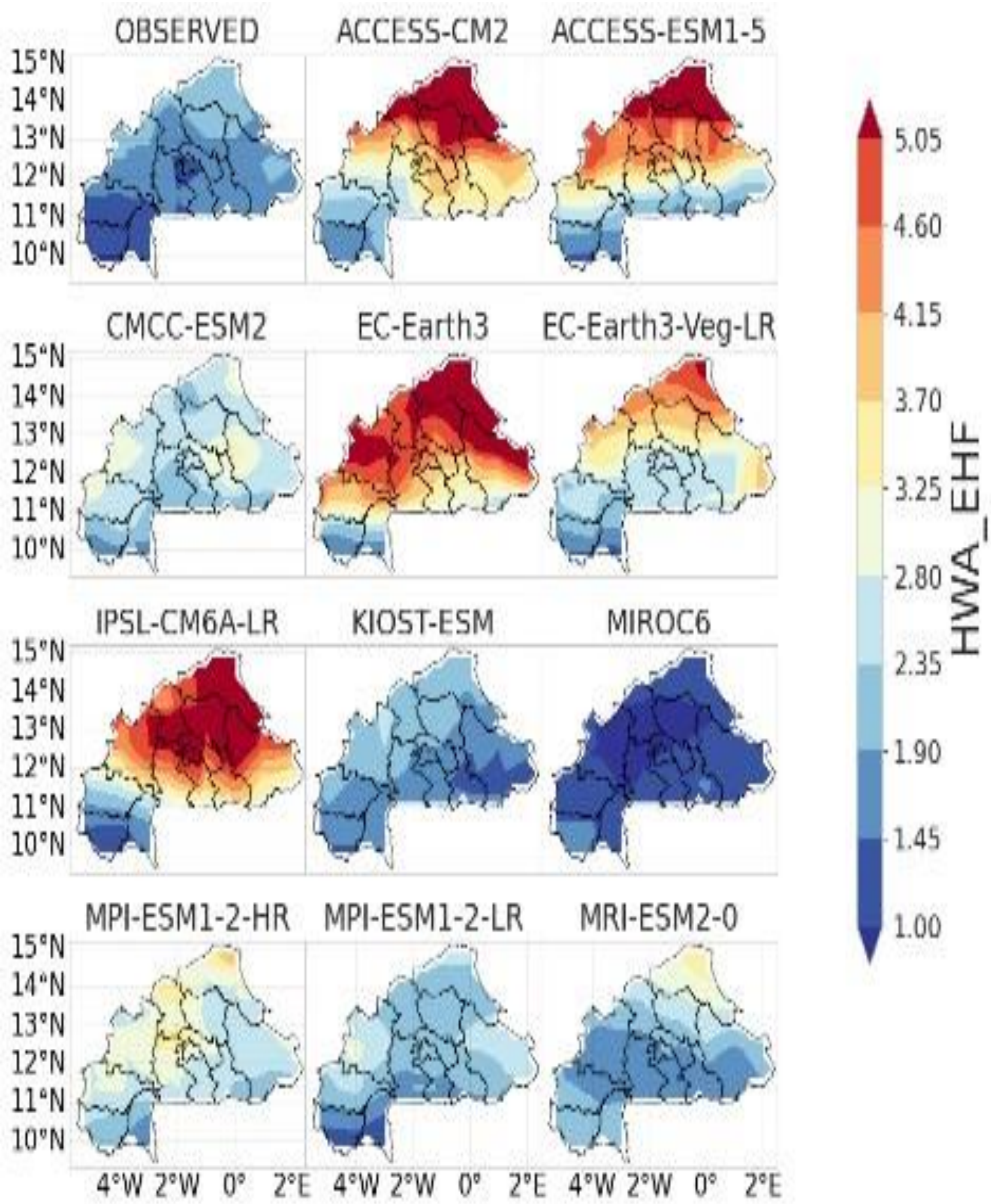

Figure 4. 5: Characterization of heatwaves in Burkina Faso using HWA (Heat Wave Amplitude) °C for Excess Heat Factor (EHF) from 1991 - 2014.

For Heatwave Duration (HWD) (Figures 4.6 to 4.8), five (5) days were observed over the northern region for both nighttime, denoted with TN90 (Figure 4.6) and daytime, represented with TX90 (Figure 4.7). The nighttime heatwave duration characterisation (Figure 4.6) output shows the extreme north to northeastern parts of Burkina Faso to be between 5 and 6 days under the observed figure, thus expressing the strong impact of the excessive days of continuous heatwave on man, health and the environment. However, the central regions and extreme southern parts recorded less than four (4) days of heatwave duration. This shows that these regions do not experience extreme situations as observed in the northern part. Furthermore, comparing the other models to the observed output, it can be revealed that only ACCESS-ESM1-5 had a close resemblance to the observed output, albeit the extreme days of heatwave have not been observed in the northeastern parts of the country. While other models overestimated when comparing them to the observed, CMCC-ESM2 and MRI-ESM2-0 underestimated their outputs. Most models agree with the observed output for the daytime analysis except for KIOST-ESM, which shows durations exceeding seven (7) days (Figure 4.7). This can be said to have exceeded the globally accepted definition of a typical heatwave. It was also observed that some models were underestimated, e.g., ACCESS-ESM1-5, CMCCESM2, MIROC6 and MRI-ESM2-0. Generally, the heatwave duration of the observed and other ten (10) models ranges between 3 – 7 days. In contrast, the only model with a staggering heatwave duration of above seven (7) days was KIOST-ESM. For the analysis of the excess heatwave factor (Figure 4.8) under the heatwave duration characterisation, just as observed during the daytime (Figure 4.7), the CMCC-ESM2 was strongly underestimated compared to the observed and other models. In contrast, four models (EC-Earth3-Veg-LR, KIOT-ESM, MPI-ESM1-2-HR, and MPI-ESM1-2-LR) overestimated. As shown from the observed data, most parts of the region recorded between 4 – 6 days of excess heatwave factor, with an exception of the eastern parts.

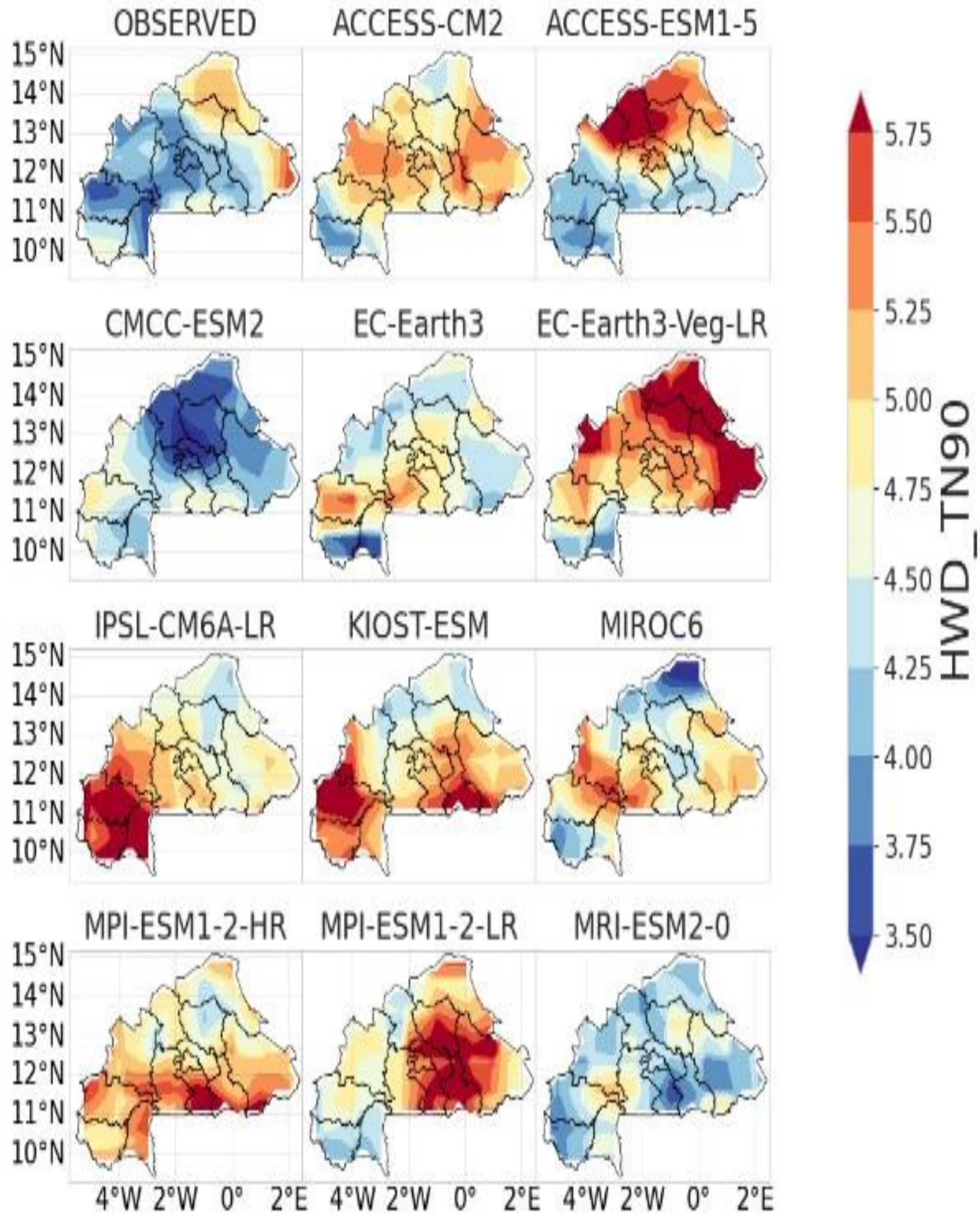

Figure 4. 6: Characterization of heatwaves in Burkina Faso using HWD (Heat Wave Duration) Days for nighttime (TN90th percentile) from 1991 - 2014.

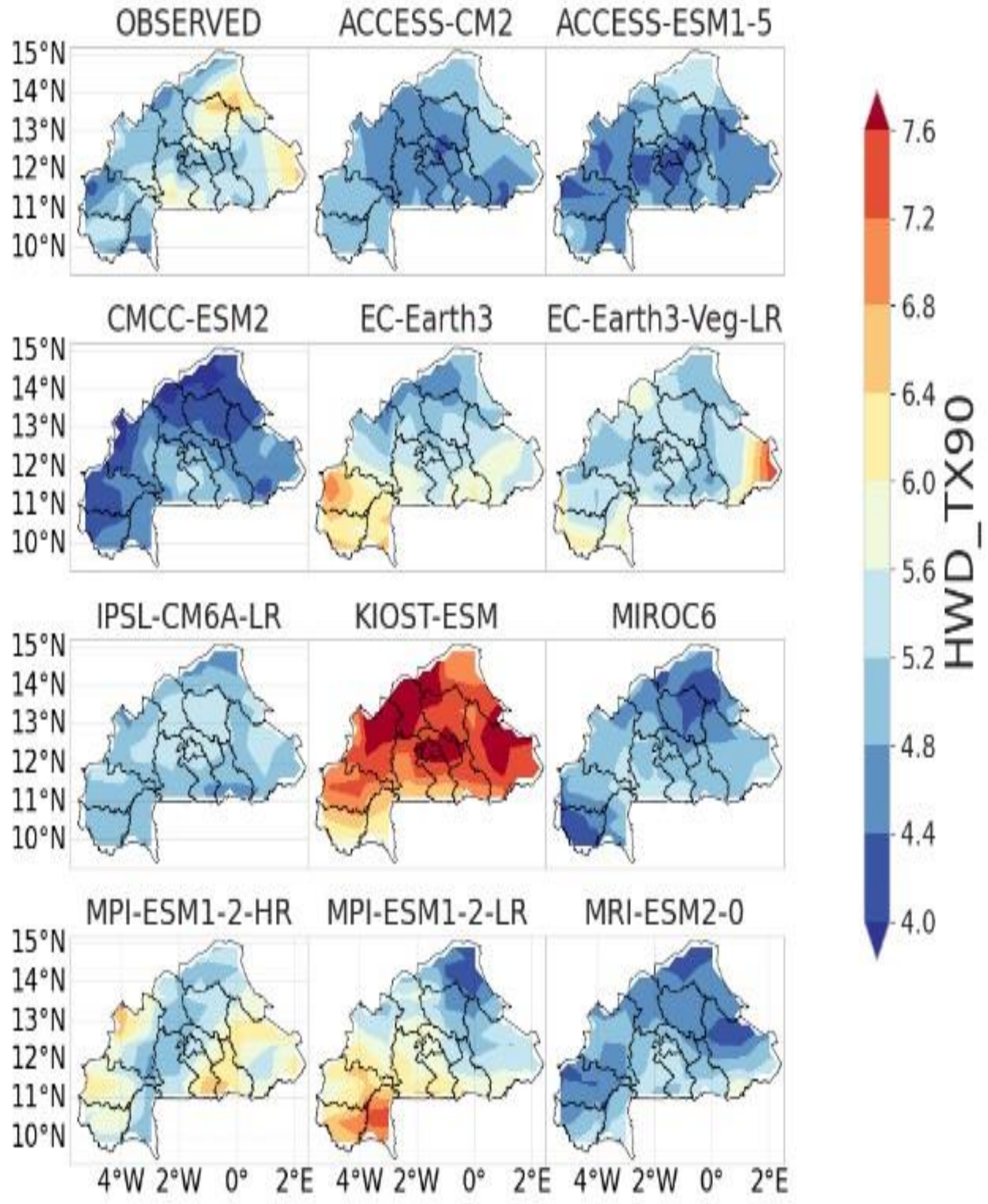

Figure 4. 7: Characterization of heatwaves in Burkina Faso using HWD (Heat Wave Duration) Days for daytime (TX90th percentile) from 1991 - 2014.

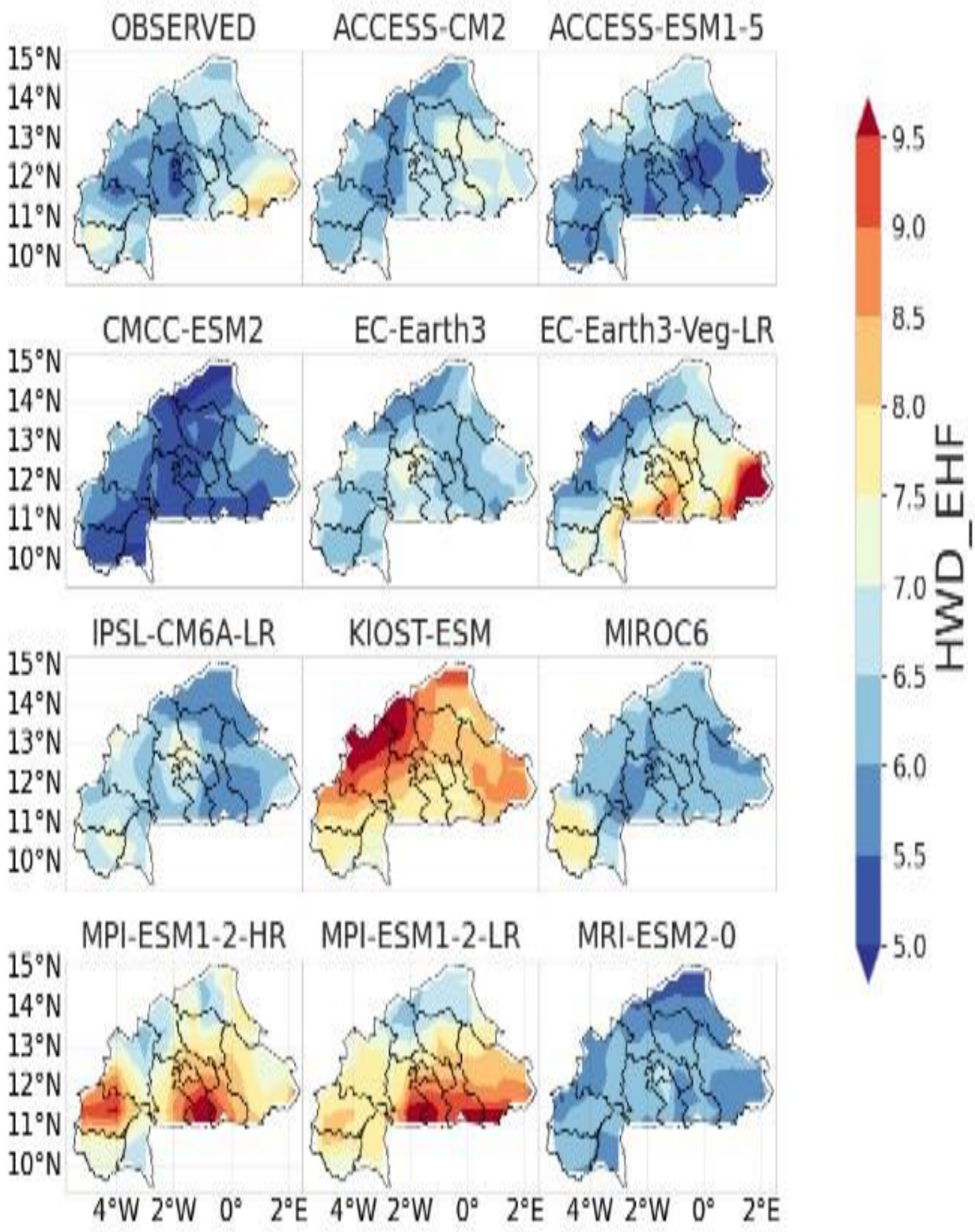

Figure 4. 8: Characterization of heatwaves in Burkina Faso using HWD (Heat Wave Duration) Days for Excess Heat Factor (EHF) from 1991 - 2014.

Figures 4.9 to 4.11 were analysed under heatwave frequency characterisation. The frequency of a heatwave can be referred to as the number of heatwaves occurring in a given period or region. Heatwave Frequency (HWF) values range from less than 2 to above 5 during the nighttime (Figure 4.9), with the maximum frequency recorded in the northeast axis and the minimum in the southern region. This result is because the northern region is located in the Sahelian zone of Burkina Faso, and the southern part is located in the Soudanian zone of the country with a more humid condition. Though the heatwave frequency during the daytime (Figure 4.10) ranges between 2 and above 10, the KIOST-ESM model overestimated, with most areas in the country recording more than 10 times the heatwave occurrence. At the same time, the observed data showed that most parts of the country had a frequency of occurrence between 3 – 5 times, with only the eastern parts having heatwave occurrence of about 5 – 6 times. From the analysis of Figure 4.9, it can be revealed that the frequency of heatwaves is relatively low, which translates to the fact that it is not an extreme issue and will not severely impact man and his environment. When comparing the three (3) ways of characterising heatwave frequency as contained in Figures 4.9 – 4.11, it can be deduced that the HWF for daytime (Figure 4.10) and excessive heatwave factor (Figure 4.11) exhibited the same feature mainly under observed data and KIOST-ESM model. Under the excess heatwave factor (Figure 4.11), it was also observed that MIROC6 was greatly underestimated compared to the observed output and other models. It can be concluded that the MIROC6 model is not suitable for heatwave frequency characterisation of the excess heatwave factor.

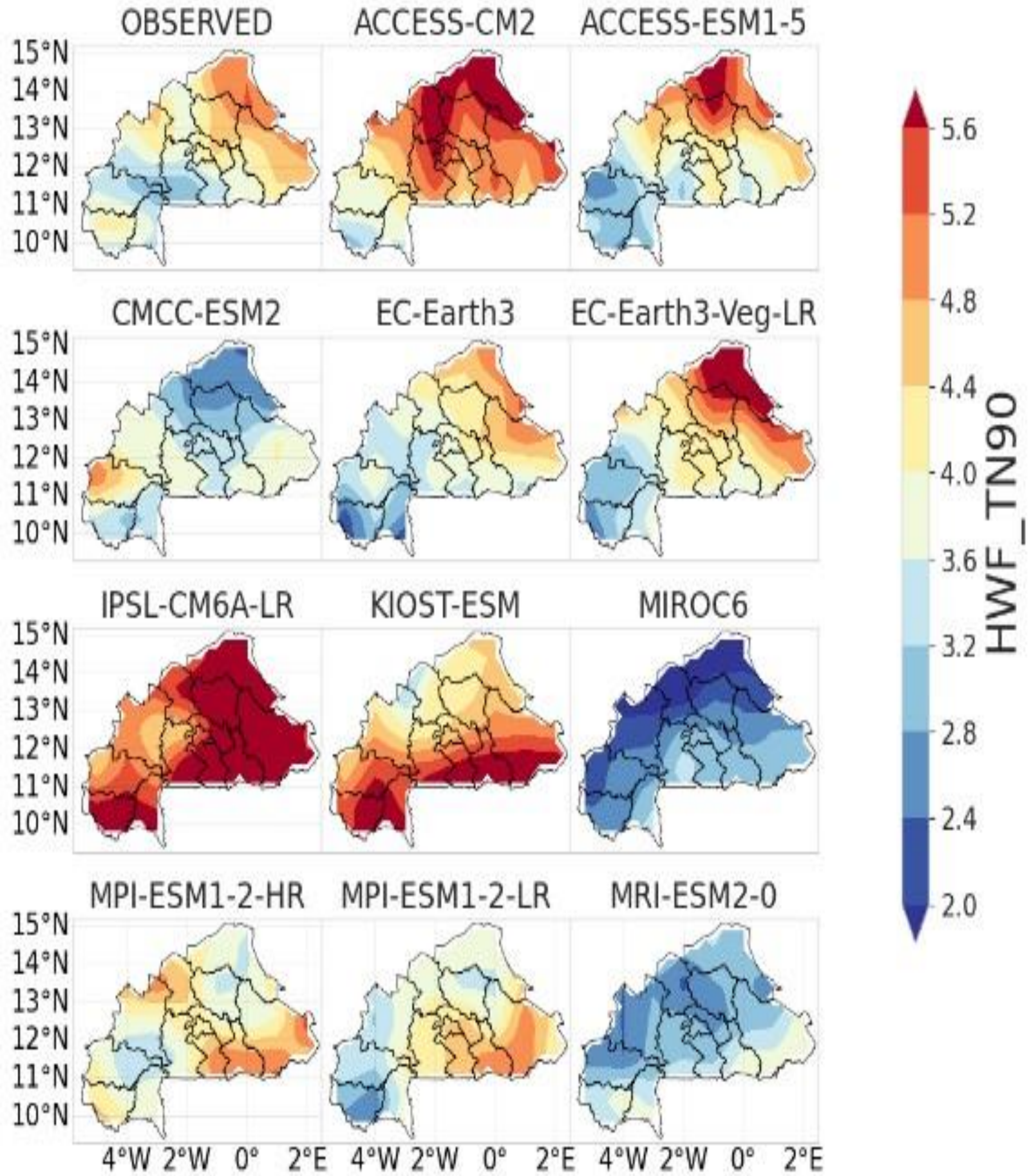

Figure 4. 9: Characterization of heatwaves in Burkina Faso using HWF (Heat Wave Frequency) Days for nighttime (TN90th percentile) from 1991 - 2014.

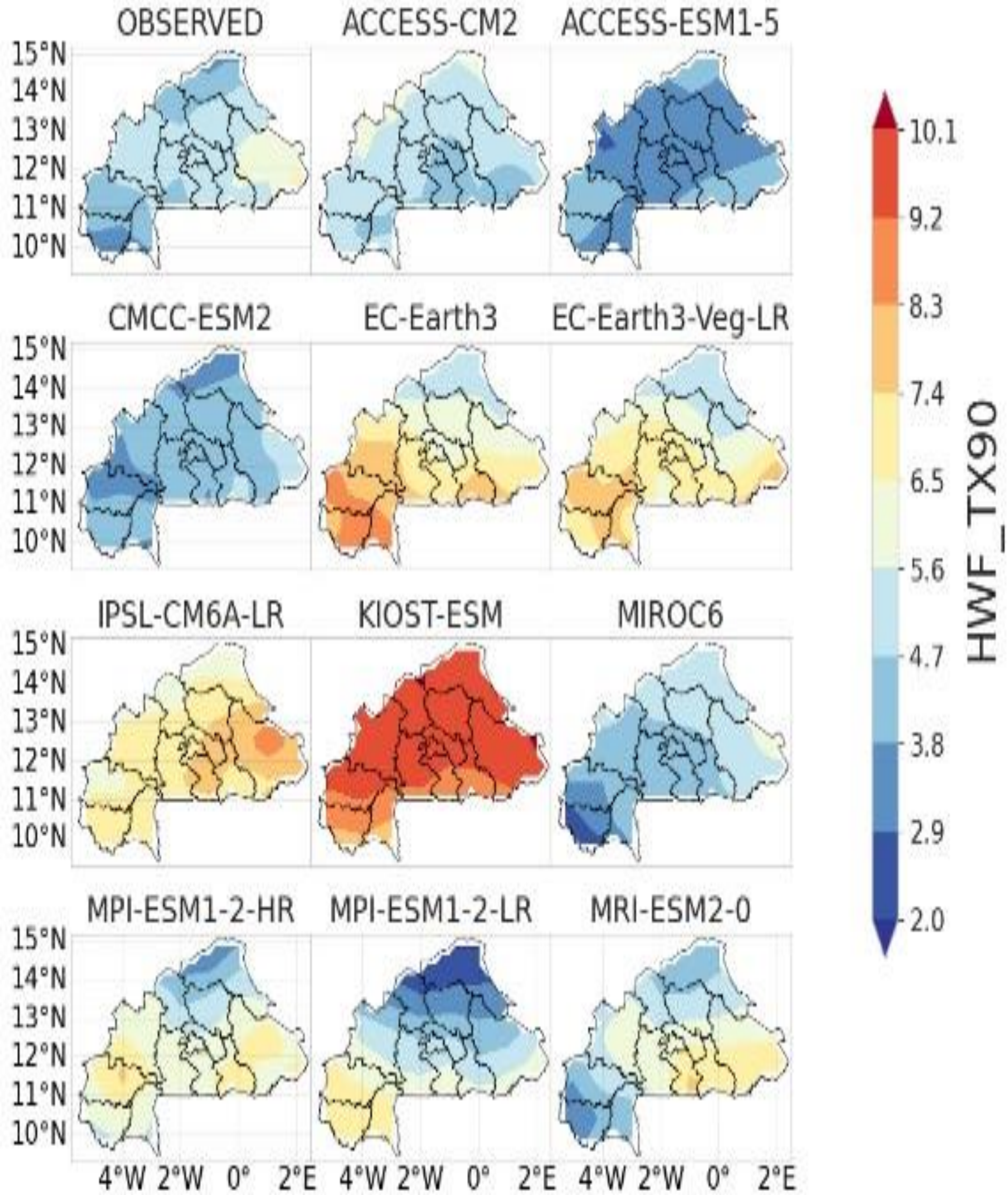

Figure 4. 10: Characterization of heatwaves in Burkina Faso using HWF (Heat Wave Frequency) Days for daytime (TX90th percentile) from 1991 - 2014.

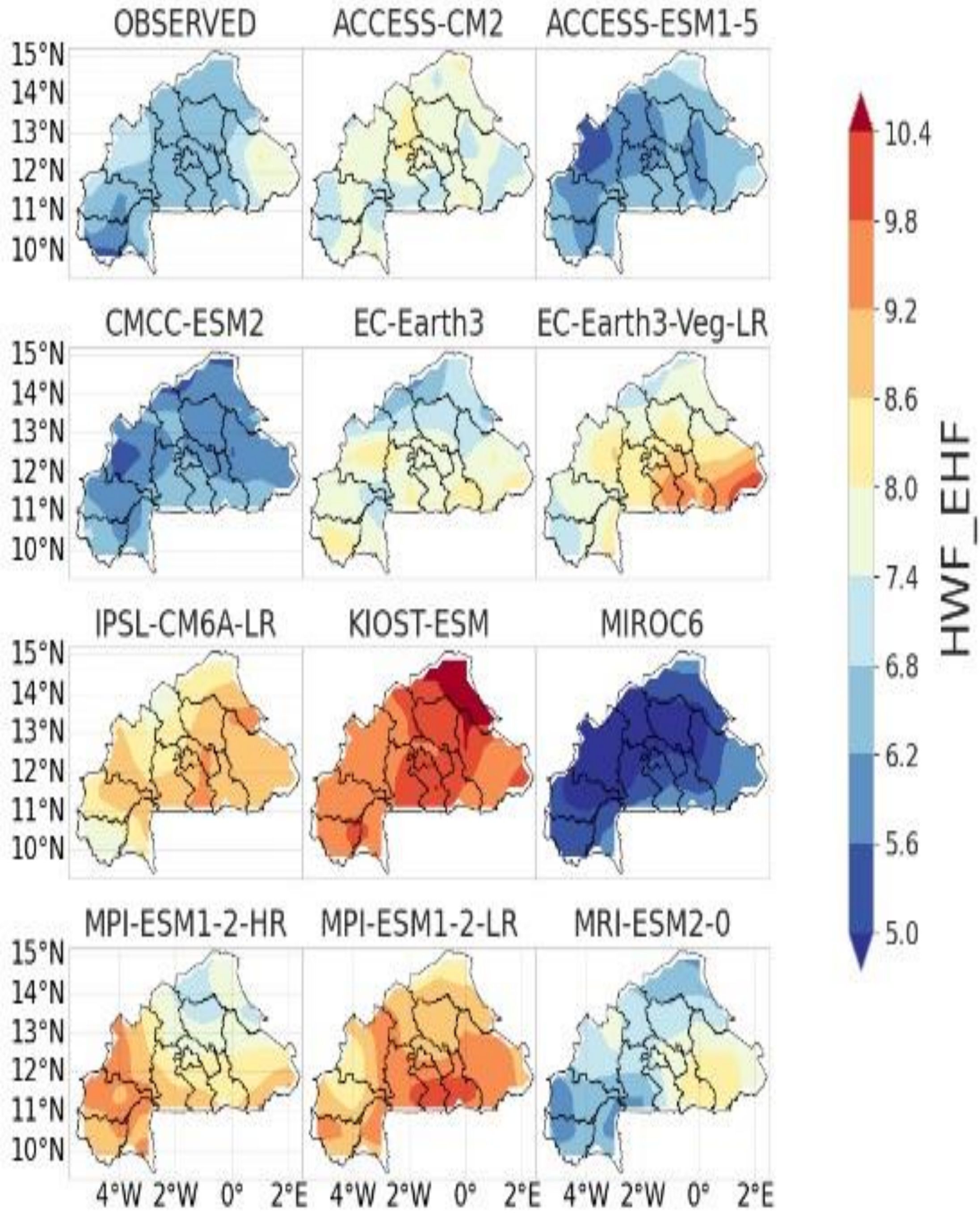

Figure 4. 11: Characterization of heatwaves in Burkina Faso using HWF (Heat Wave Frequency) Days for Excess Heat Factor (EHF) from 1991 - 2014.

Heatwave Magnitude (HWM) indicates how hot and prolonged excessively high temperatures are observed in Burkina Faso for TN90th, representing nighttime conditions (Figure 4.12). The observations are consistent with previous indices in pattern and intensity, ranging from 23^{o}C in the south to about 28^{o}C in the northern region. This can be explained by the geographical position of Burkina Faso and the closeness of the zones to either the Sahelian region or the more tropical-soudanian region. A steady increase is also observed in the models but with higher intensity. All the models are closely similar to the observed except KIOST-ESM, MIROC6 and MRI-ESM2-0. A similar pattern is seen during the daytime, denoted by TX90th (Figure 4.13), across the 11 models, with higher intensities between 33 and 41. The heatwave characterisation under HWM for daytime had almost a perfect replica for all models compared to the observed. It can be concluded that any model outputs can be used in the place of observed data for daytime heatwave characterisation under HWM. Although the excess heatwave factor characterisation under the HWM, with a value <= 2, showed a relatively low impact from the heatwave magnitude, as seen in the observed output (Figure 4.14) with a value of < 1, other models could not replicate a close scenario like the observed output except MPI-ESM1-2-R and MRI-ESM2-0. However, ACCESS-CM2, ACCESS-ESMM1-5, EC-Earth3 and IPSL-CM6A-LR overestimated compared to the observed output.

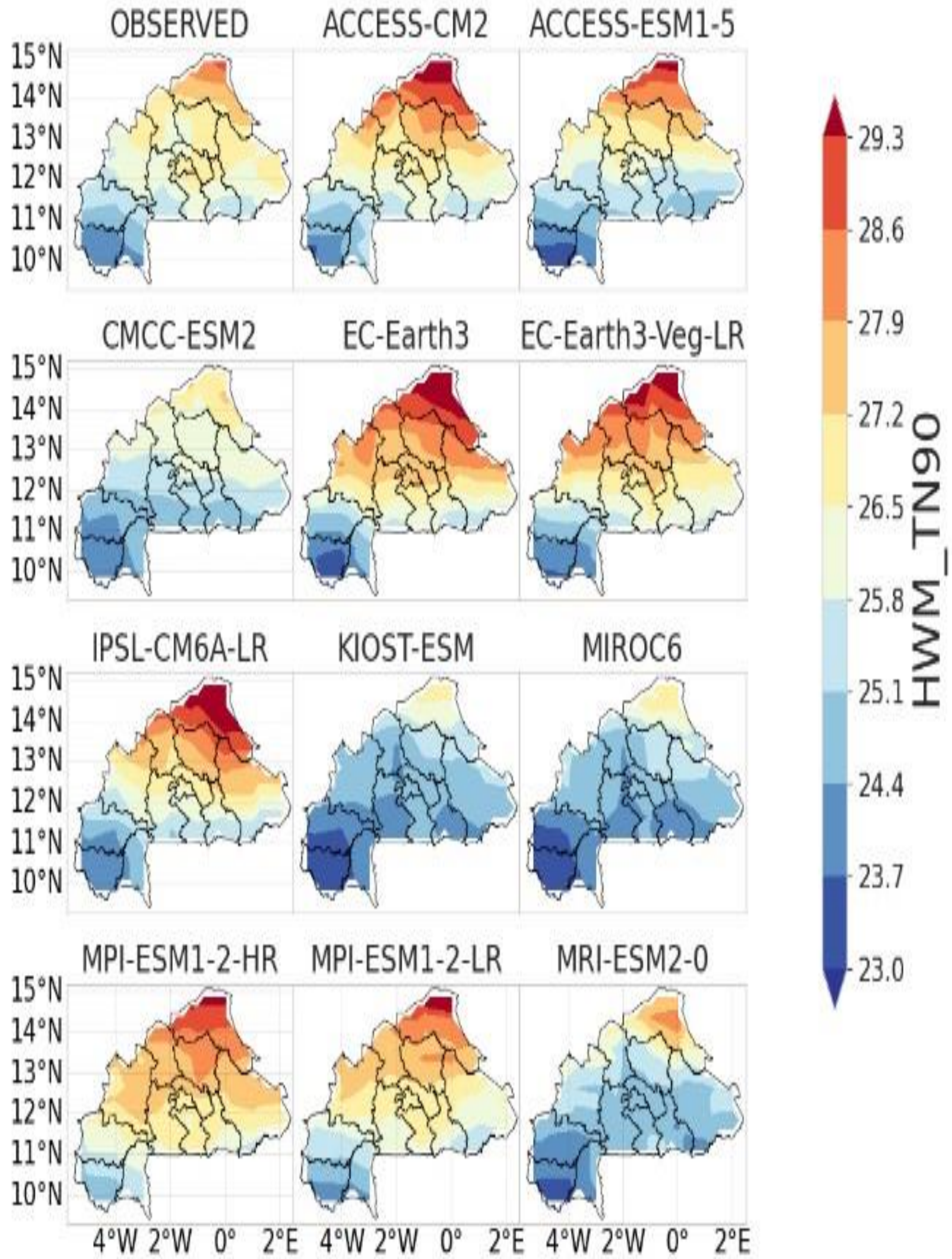

Figure 4. 12: Characterization of heatwaves in Burkina Faso using HWM (Heat Wave Magnitude Index) for nighttime (TN90th percentile) from 1991 - 2014.

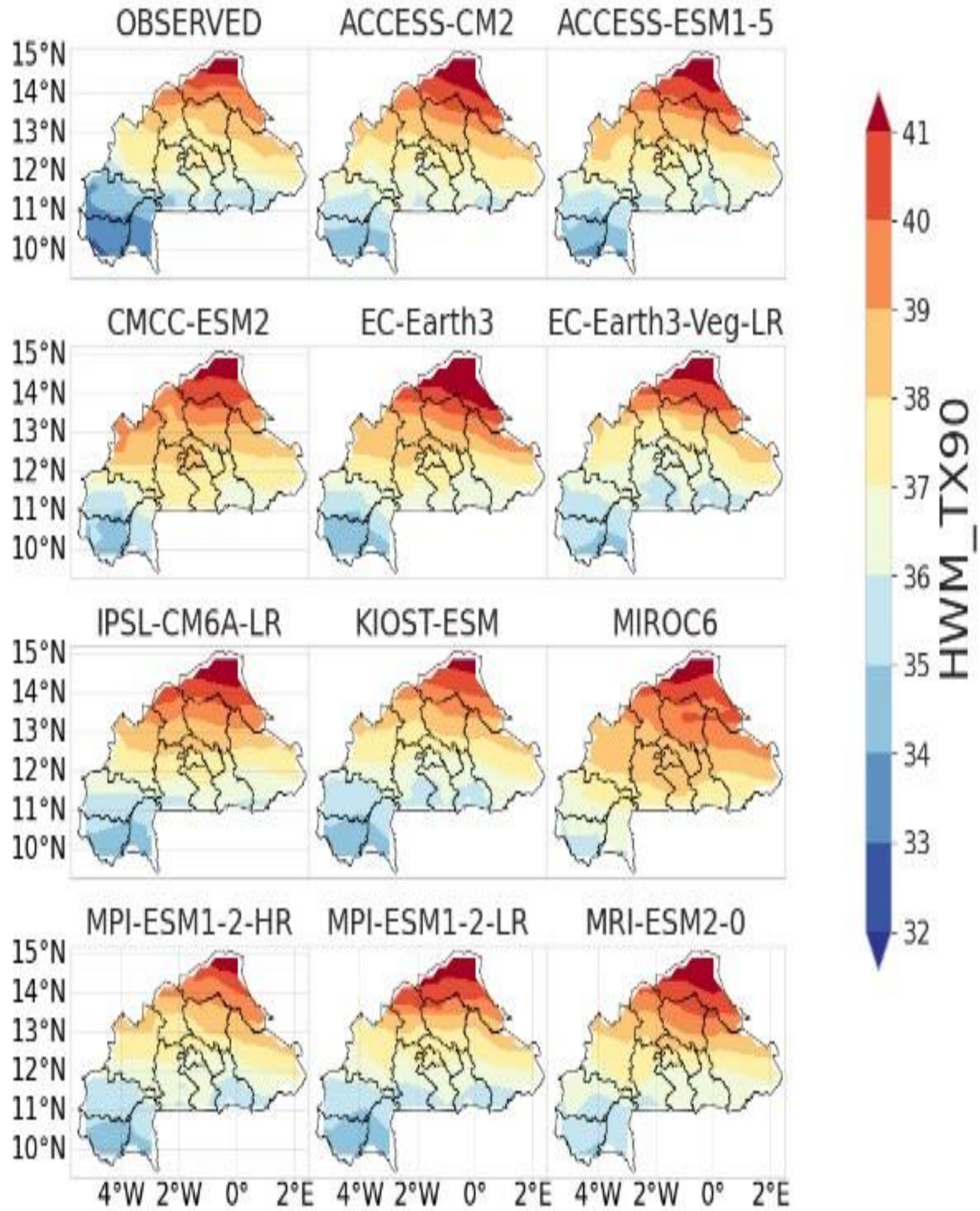

Figure 4. 13: Characterization of heatwaves in Burkina Faso using HWM (Heat Wave Magnitude Index) for daytime (TX90th percentile) from 1991 - 2014.

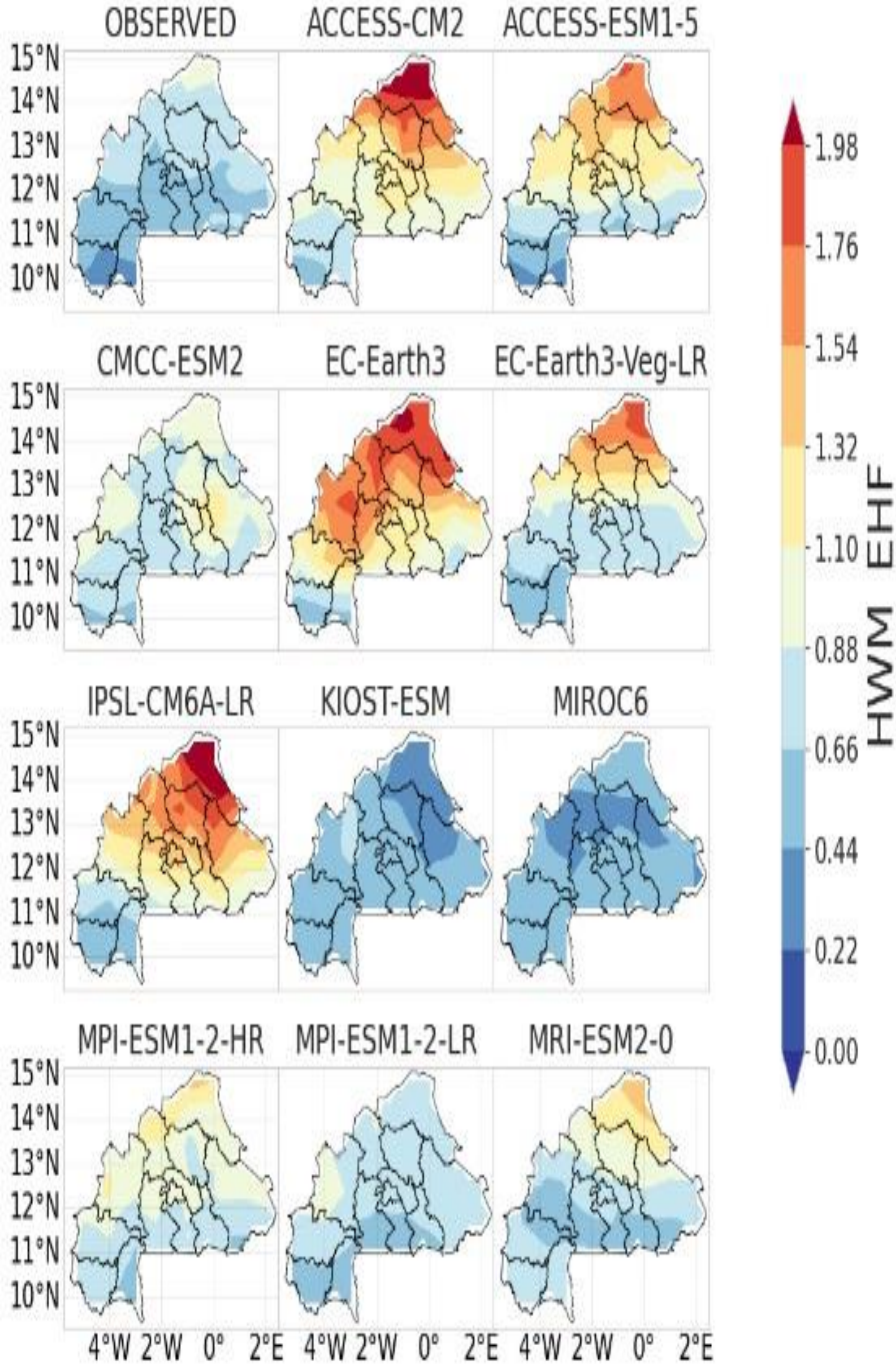

Figure 4. 14: Characterization of heatwaves in Burkina Faso using HWM (Heat Wave Magnitude Index) for Excess Heat Factor (EHF) from 1991 - 2014.

Heatwave Numbers (HWN) for both day (Figure 4.16) and night (Figure 4.15) show a similar range of 0 - 2, but the nighttime recorded more intensity in the number of heatwaves than the daytime, as evident in the observed data. Similar results have been observed in previous studies over West Africa, showing that nighttime heatwaves are becoming more frequent and more intense than daytime heatwaves (Guigma *et al*., 2020).

Models, however, show higher values than the observed data. While the IPSL-CM6A-LR overestimated when compared to the observed output, the MPI-ESM1-2-HR model closely mirrors the observed, and MIROC6 and MRI-ESM2-0 models underestimate the heatwave number scenario for nighttime. On the other hand, MIROC6 seems to mirror the observed output closely than any other model during the daytime. The observed output heatwave number during the daytime ranges between 0 and 1, which makes the heatwave relatively low in the number of occurrences. However, IPSL-CM6A-LR and KIOST-ESM overestimated compared to the other models and the observed output. This overestimation is also apparent under the EHF for HWN. Heatwave number counts the number of events within a given period, highlighting the frequency of these extreme events. An increasing HWN indicates a rising trend in the occurrence of heatwaves, which can signal escalating climate instability and necessitate long-term adaptation strategies (Perkins *et al*., 2012). Addressing climate change requires developing resilient agricultural practices, improving energy efficiency, and raising awareness of climate challenges. For instance, infrastructure may need to be redesigned to withstand more frequent and severe heatwaves, and public health systems may require strengthening to deal with the increased burden (Field *et al*., 2012). Ouedraogo and Stroosnijder, (2006) highlights the importance of developing resilient agricultural practices and adaptation strategies to mitigate the impacts of climate change in the region.

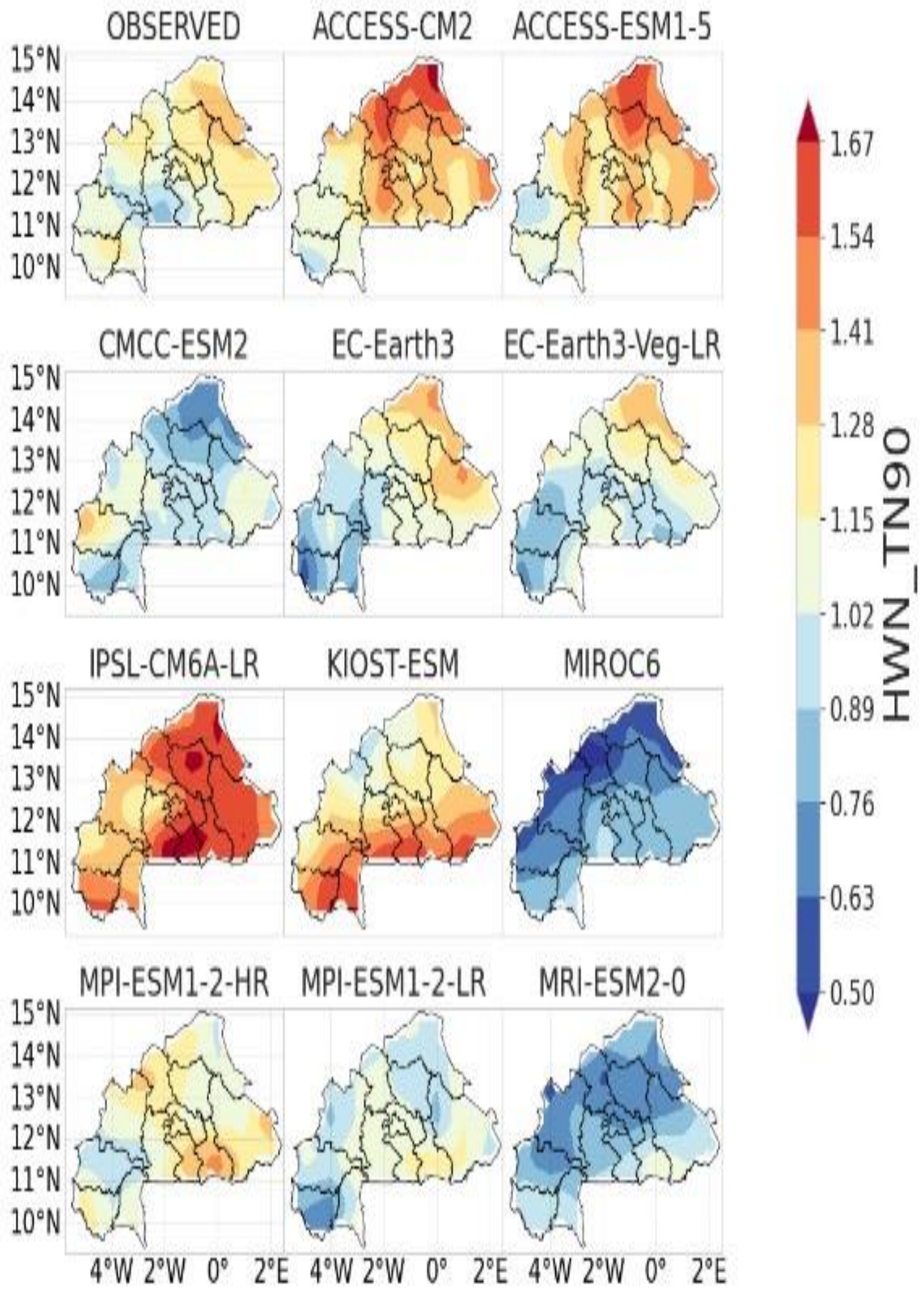

Figure 4. 15: Characterization of heatwaves in Burkina Faso using HWN (Heat Wave Number) for nigttime (TN90th percentile) from 1991 - 2014.

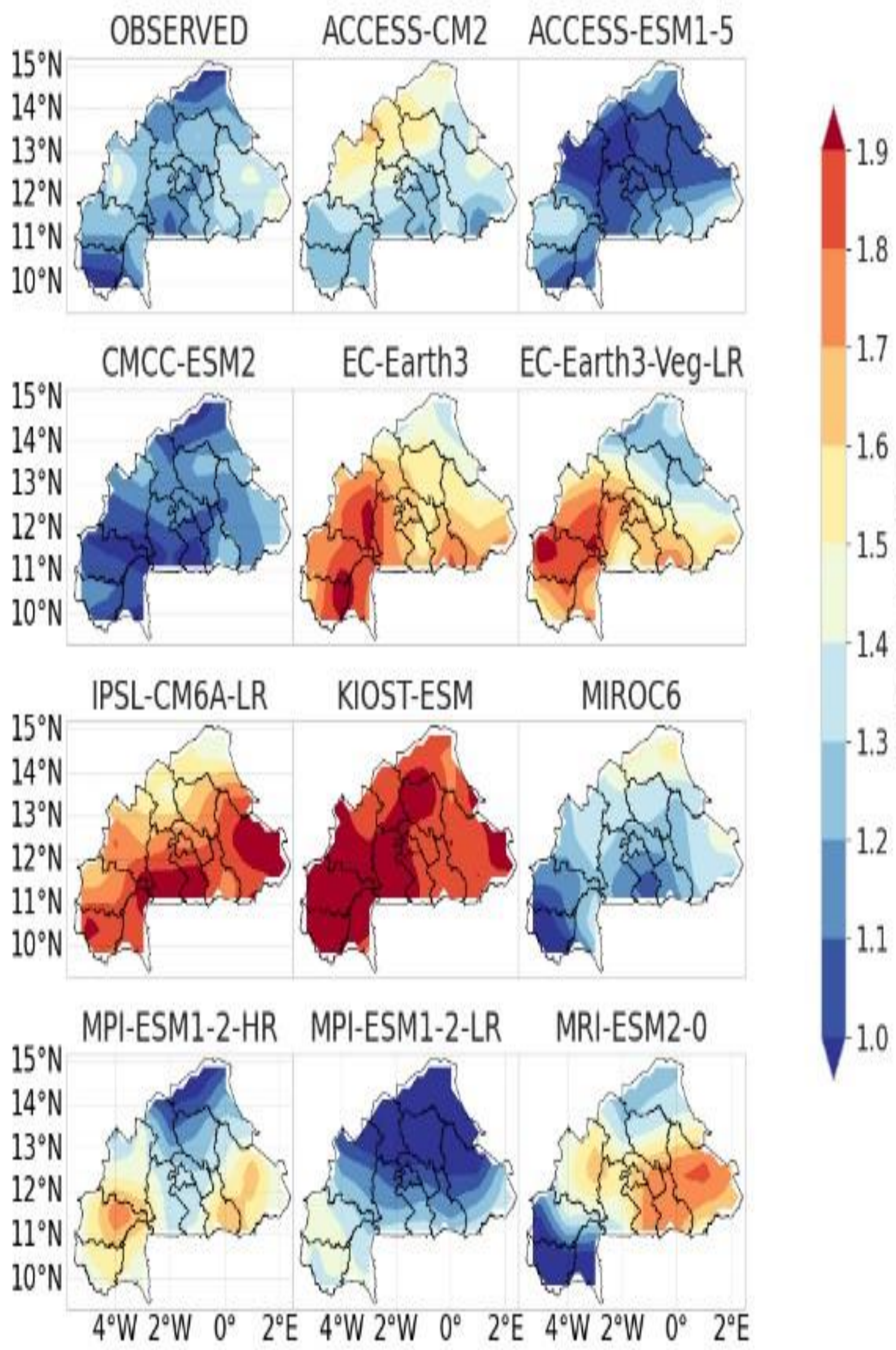

Figure 4. 16: Characterization of heatwaves in Burkina Faso using HWN (Heat Wave Number) for daytime (TX90th percentile) from 1991 - 2014.

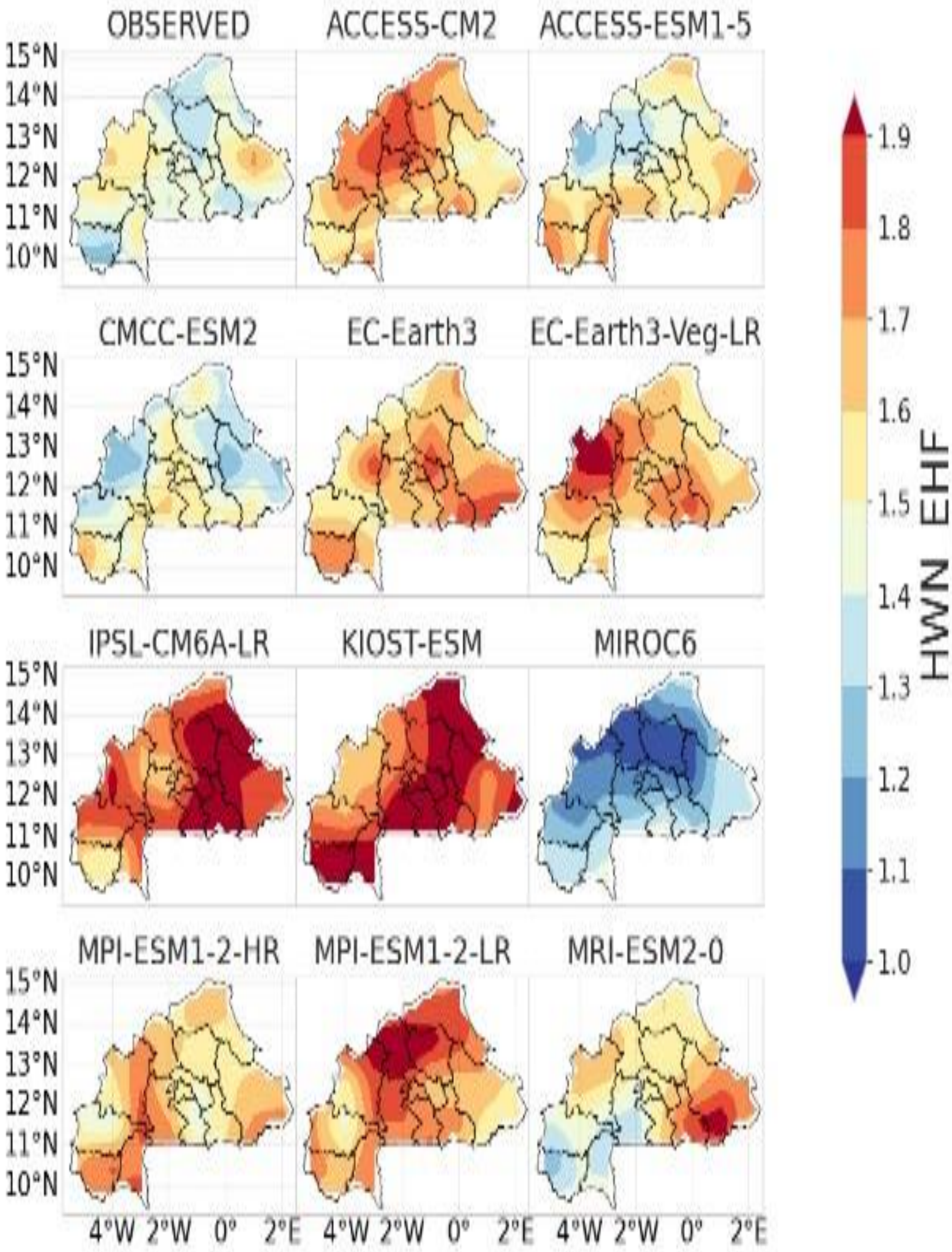

Figure 4. 17: Characterization of heatwaves in Burkina Faso using HWN (Heat Wave Number) for Excess Heat Factor (EHF) from 1991 - 2014.

4.1.2 Trend Analysis of Heatwave Characteristics

The chosen level of significance from the Mann-Kendall test is 0.05. The dots in the figures represent the area where the increase or decrease is statistically significant. Figures 4.18 to 4.32 show the spatial distribution of the calculated trends. Based on the index, the trend of heatwave characteristics-based maps often displays an unmixed pattern of positive or negative changes.

The HWA_TN90 (Figure 4.18) showed a statistically significant downward trend from the eastern to the central and southwestern parts of the country. Similarly, a decreasing trend was observed with models like EC-Earth3 and ACCESS-CM2. Models like ACCESS-ESM1-5, EC-Earth-Veg-LR, IPSL-CM6A-LR, and MPI-ESM1-2-LR showed statistically significant upward trends, while the other models showed a mixed positive and negative trend. The HWA_TX90 (Figure 4.19) depicted a negative statistically significant trend across the country except for the extreme north and the southeastern part, where the trend is insignificant. On the other hand, the simulation models only showed a positive trend with the location of statistical significance depending on the model considered. The HWA_EHF (Figure 4.20) showed a negative significant trend northward. This trend is not significant in central Burkina but is positive in southeastern Burkina. MPI-ESM1-2-LR only showed a negative trend, while models CMCC-ESM2, KIOST-ESM, MIROC6, MPI-ESM1-2-LR, and MRI-ESM2-0 showed a positive trend, and the other models showed mixed positive and negative trends. The trend in HWA is generally negative for the three heatwave definitions.

The three heatwave definitions generally depicted a decrease in the duration of heatwave events over our study area.

Generally, a decreasing trend of HWA was observed across Burkina Faso for the three metrics considered in this study. When comparing the trend of these three metrics, it is clear that the trend of HWA based on minimum temperatures is more coherent than those based on maximum temperature and excess heat factor. Also, changes in trends based on minimum temperatures are minimal (negligible on an individual scale) than those based on maximum temperatures. This is consistent with earlier research on temperature extremes in this region (De Longueville *et al*., 2016) or globally (Alexander *et al*., 2006), which found that minimum temperatures rise faster than maximum temperatures. While high daytime maximum temperatures are known to impact human life and health, abnormally warm nighttime minimum temperatures have been related to increased mortality and adverse health impacts in high-impact heatwaves worldwide over the last few decades (Nissan *et al*., 2017). Consequently, the rising tendency of temperature extremes based on minimum temperatures is concerning and calls for additional mitigation and adaptation actions to lower evening temperatures.

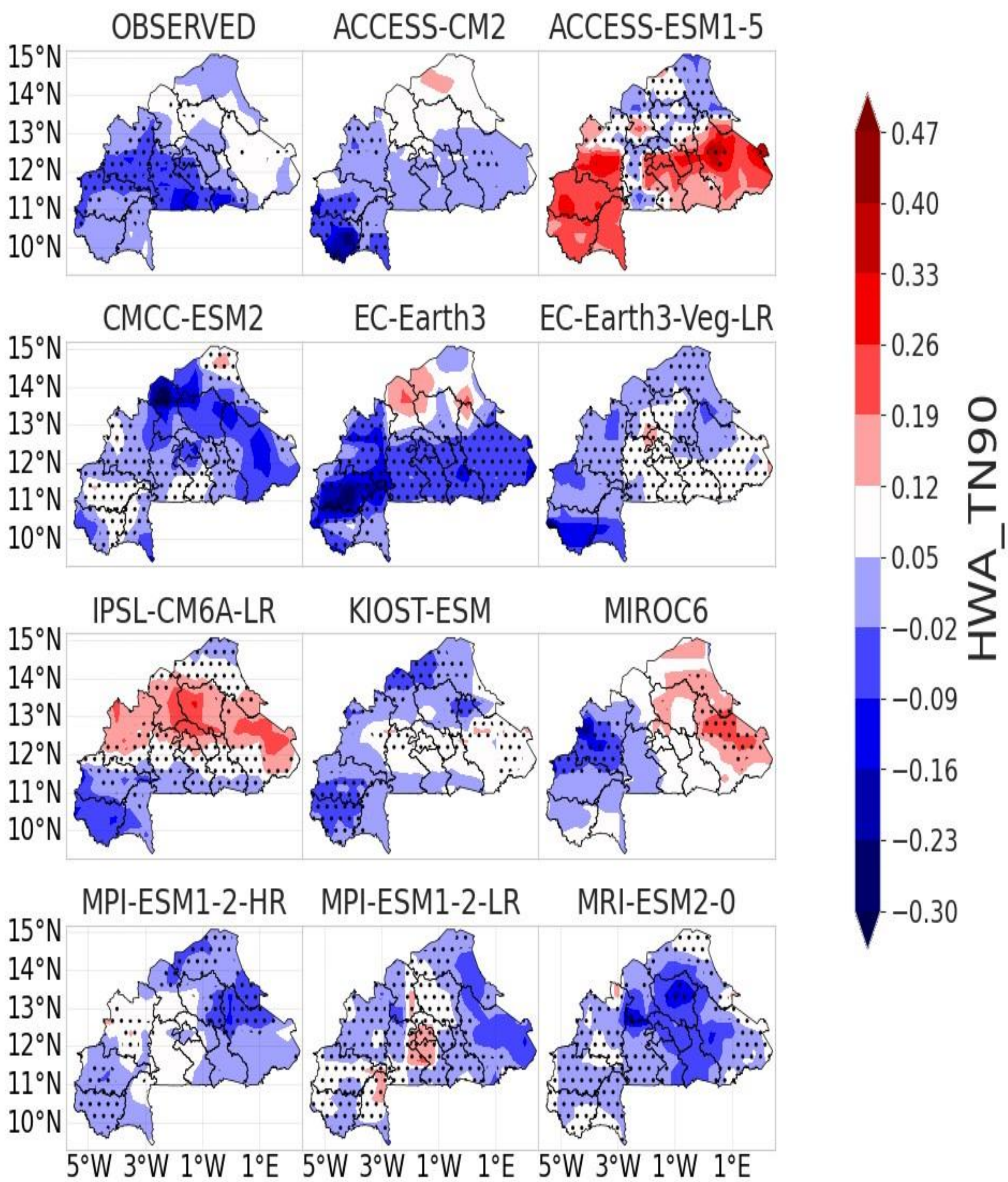

Figure 4. 18: Trend analysis of heatwaves in Burkina Faso for HWA (Heat Wave Amplitude) °C for nighttime (TN90th percentile) from 1991 - 2014.

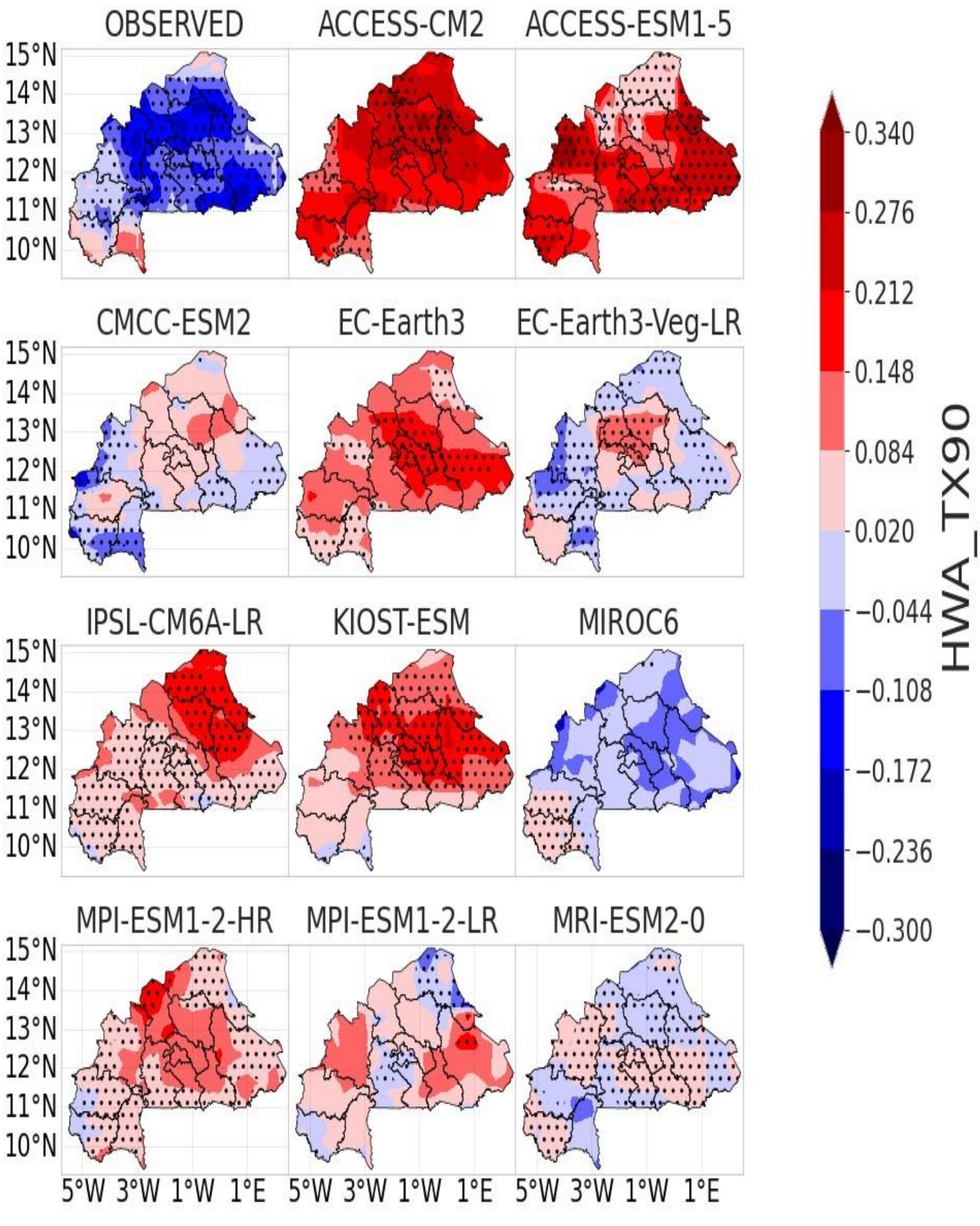

Figure 4. 19: Trend analysis of heatwaves in Burkina Faso for HWA (Heat Wave Amplitude) °C for daytime (TX90th percentile) from 1991 - 2014.

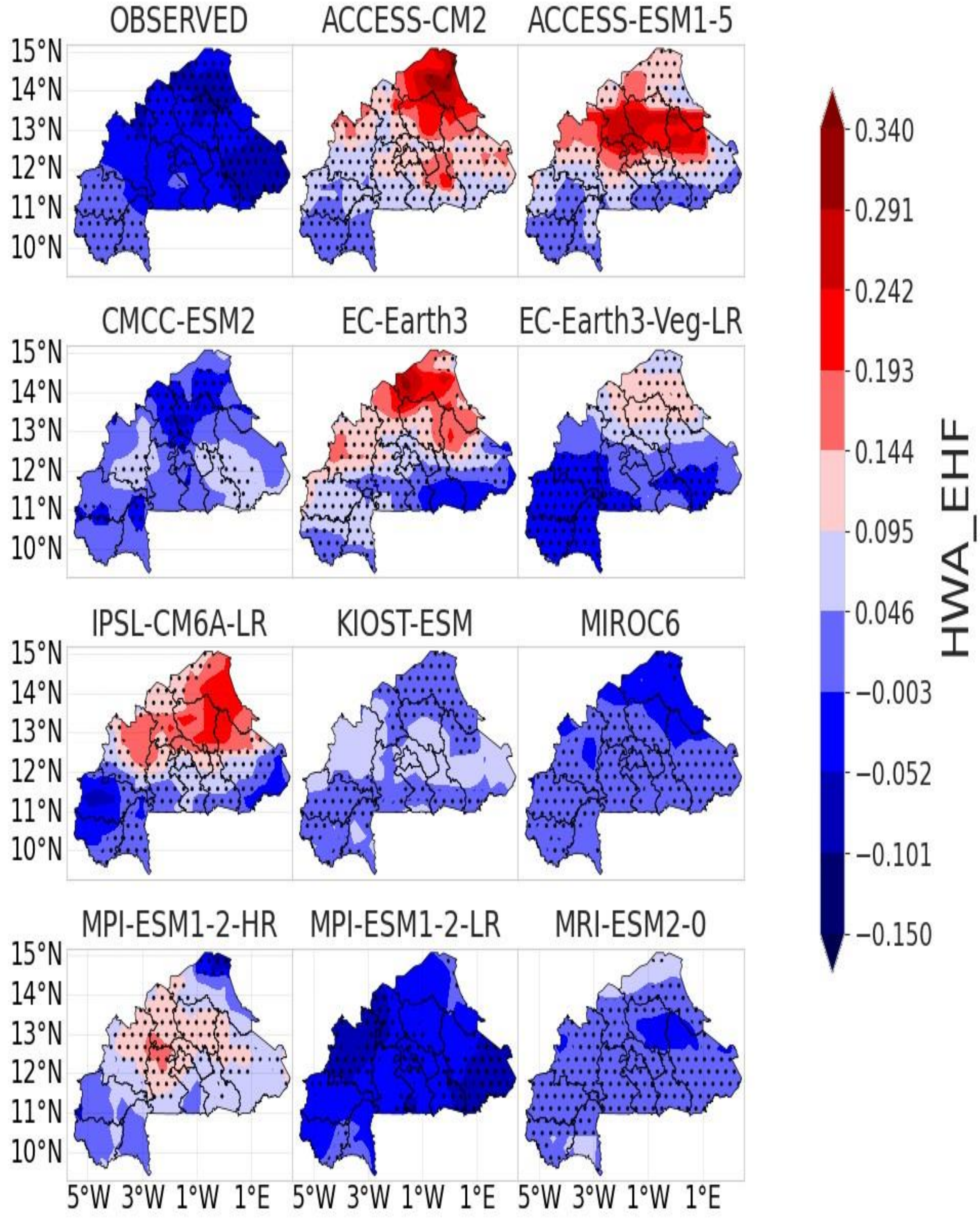

Figure 4. 20: Trend analysis of heatwaves in Burkina Faso for HWA (Heat Wave Amplitude) °C for Excess Heat Factor (EHF) from 1991 - 2014.

Concerning HWD_TN90 (Figure 4.21), the decreasing trend is significant from the north to the northeast and the west of the country. The results obtained with the 11 models also show a decreasing trend in HWD but with different distributions of significance across the country. Models such as ACCESS-ESM1-5, EC-Earth3-Veg-LR, MIROC6, and MPI-ESM1-2-HR showed positive and negative trends. The decrease is significant over the entire country for maximum temperature (Figure 4.22), with greater intensity from the central to the central southern part.

The simulation models showed a mixture of positive and negative trends. The trend in HWD_EHF (Figure 4.23) is statistically significant from the northwest to the south of Burkina Faso. It is negative over a small part of the south-west. The results of the simulation models overestimated positive and statistically significant trends over the whole area.

When analysing the trend observed with the three metrics under the HWD, the outputs from minimum temperature showed scattered decreasing trends across some study area locations, except the MPI-ESM1-2-LR, which shows about 90% of the study area being influenced by the trend. The maximum temperature showed a statistically decreasing trend across Burkina Faso, and the excess heat factor showed a vast variation between the observed and the other models. While the observed data recorded an almost total negative trend over the study area, the other models exhibited positive and statistically significant trends over Burkina Faso. This result again emphasises that Burkina Faso experienced a longer duration of nighttime heat than daytime heat. Over the past several decades, excessively warm midnight minimum temperatures have been linked to higher mortality and adverse health effects, even though high daytime maximum temperatures are known to influence human life and health (Nissan *et al.*, 2017). Thus, the increasing trend of temperature extremes based on minimum temperatures is alarming and necessitates more adaptation and mitigation measures to reduce nighttime temperatures. Therefore, it can be concluded that the relationship between time and temperature is probably accurate, although the strength of the relationship is weak. Our results corroborate the findings of similar analyses conducted by Sanogo *et al*. (2015) on the spatiotemporal characteristics of temperatures in the Sudanian region, highlighting the need for continuous monitoring and an in-depth understanding of local climate change. Burkina Faso is characterized by a semi-arid to arid climate with a short rainy season. Temperatures can be sensitive to climatic variations, mainly due to monsoon variations. Previous studies by Hulme, (2001) highlight the sensitivity of this region to climate variations, which could amplify the impacts of observed warming.

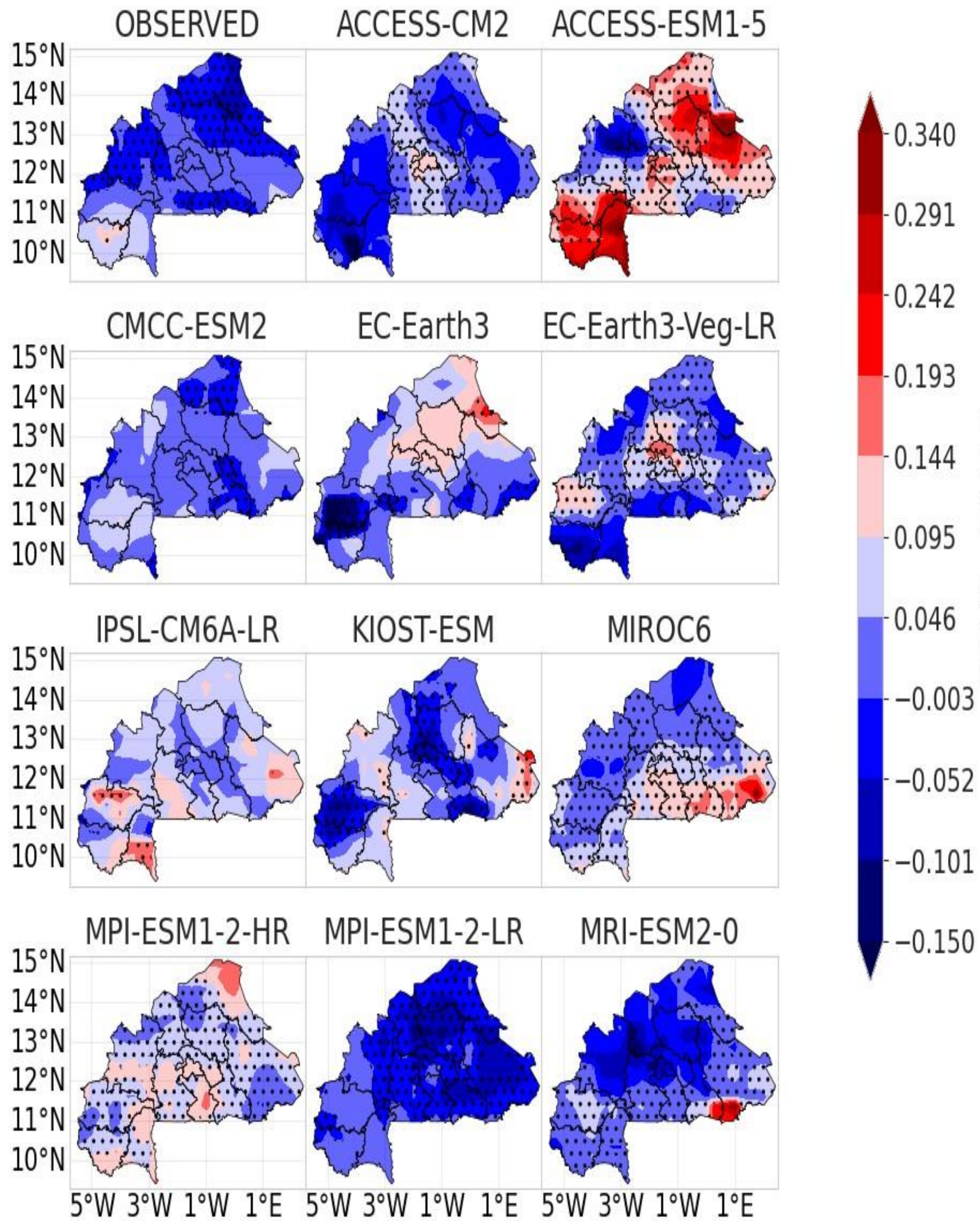

Figure 4. 21: Trend analysis of heatwaves in Burkina Faso for HWD (Heat Wave Duration) Days for nighttime (TX90th percentile) from 1991 - 2014.

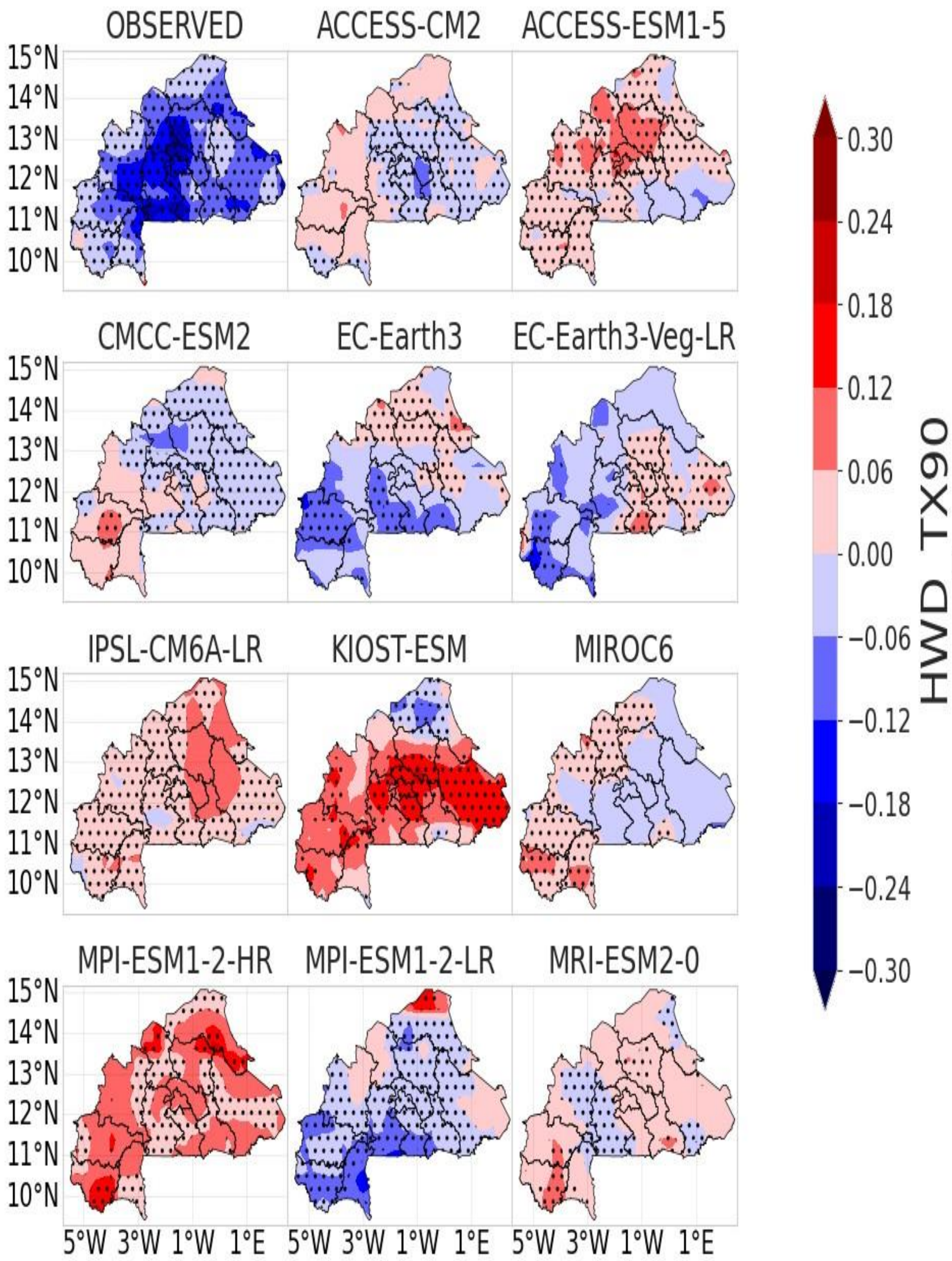

Figure 4. 22: Trend analysis of heatwaves in Burkina Faso for HWD (Heat Wave Duration) Days for daytime (TX90th percentile) from 1991 - 2014.

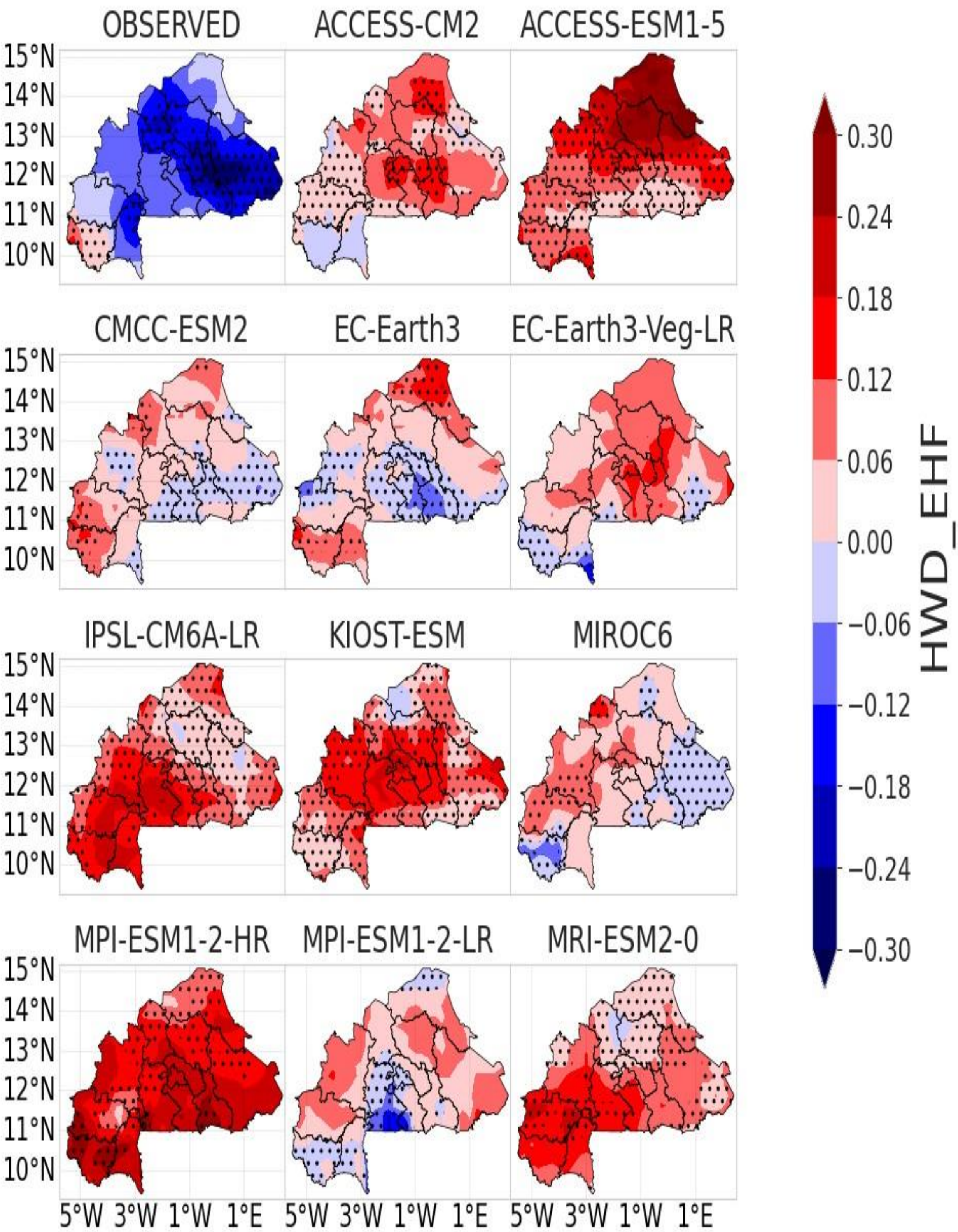

Figure 4. 23: Trend analysis of heatwaves in Burkina Faso for HWD (Heat Wave Duration) Days for Excess Heat Factor (EHF) from 1991 - 2014.

The number of participating heatwave days based on minimum temperature (Figure 4.24) showed a statistically significant upward trend over the study area except for a part of the northeast to the centre and part of the west. All simulation models showed an upward trend across the country. While the trend is not statistically significant for MIROC-6 across the country, it is significant for ACCESS-ESM1-5. The trend is significant in the soudano-sahelian and the soudanian zone for models like EC-Earth3, EC-Earth3-Veg-LR, and significant from Sahelian to soudano-sahelian zone for KIOST-ESM. The HWF_TX90 (Figure 4.25) showed a mixed statistically significant negative trend from the western to the central part of the country and a statistically positive trend in southeastern Burkina Faso. EC-Earth3 and EC-Earth3-VegLR also give a mixture of positive and negative trends, with different locations to the observation data. The other models only showed positive trends. The HWF_EHF (Figure 4.26) depicted a statistically upward trend across the study area except in the central western and eastern Burkina Faso, where the trend decreased. We observed an upward trend for the simulation models, with statistical significance varying from one location to another based on the model.

Generally, the trend is increasing and more important for nighttime temperature than daytime temperature and the excess heat factor. This is consistent with a previous study showing that nighttime heatwave frequency is more important than daytime (Guigma *et al.*, 2020). Over the past several decades, excessively warm midnight minimum temperatures have been linked to higher mortality and detrimental health effects globally. However, high daytime maximum temperatures are recognised to affect human life and health (Nissan *et al*., 2017). These results could motivate adaptation actions to deal with climate change, such as developing resilient agricultural practices, improving energy efficiency, and raising awareness of climate challenges. Previous research (Ouedraogo and Stroosnijder, 2006) highlights the importance of developing resilient agricultural practices and adaptation strategies to mitigate the impacts of climate change in the region.

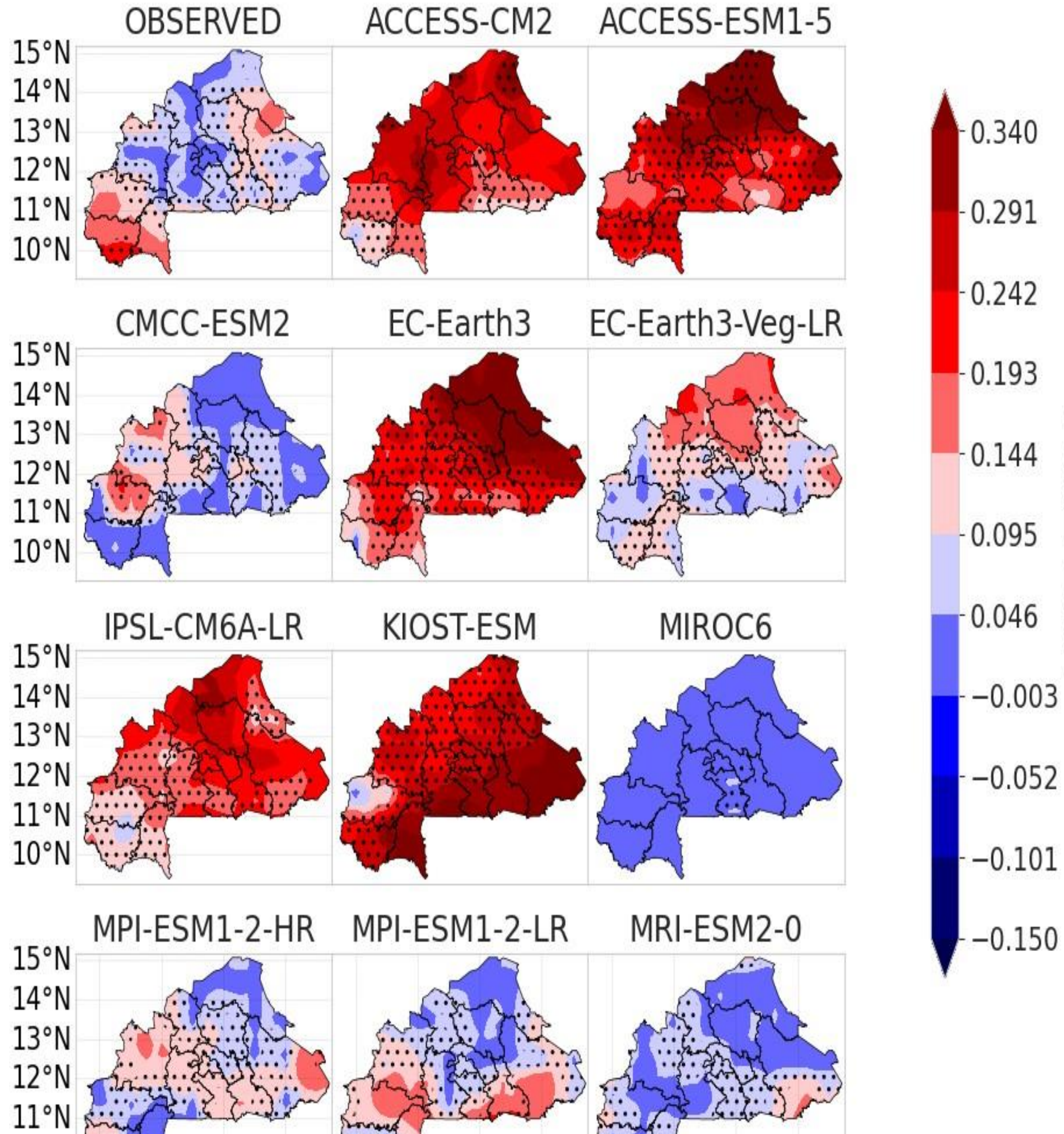

Figure 4. 24: Trend analysis of heatwaves in Burkina Faso for HWF (Heat Wave Frequency) Days for nighttime (TN90th percentile) from 1991 - 2014.

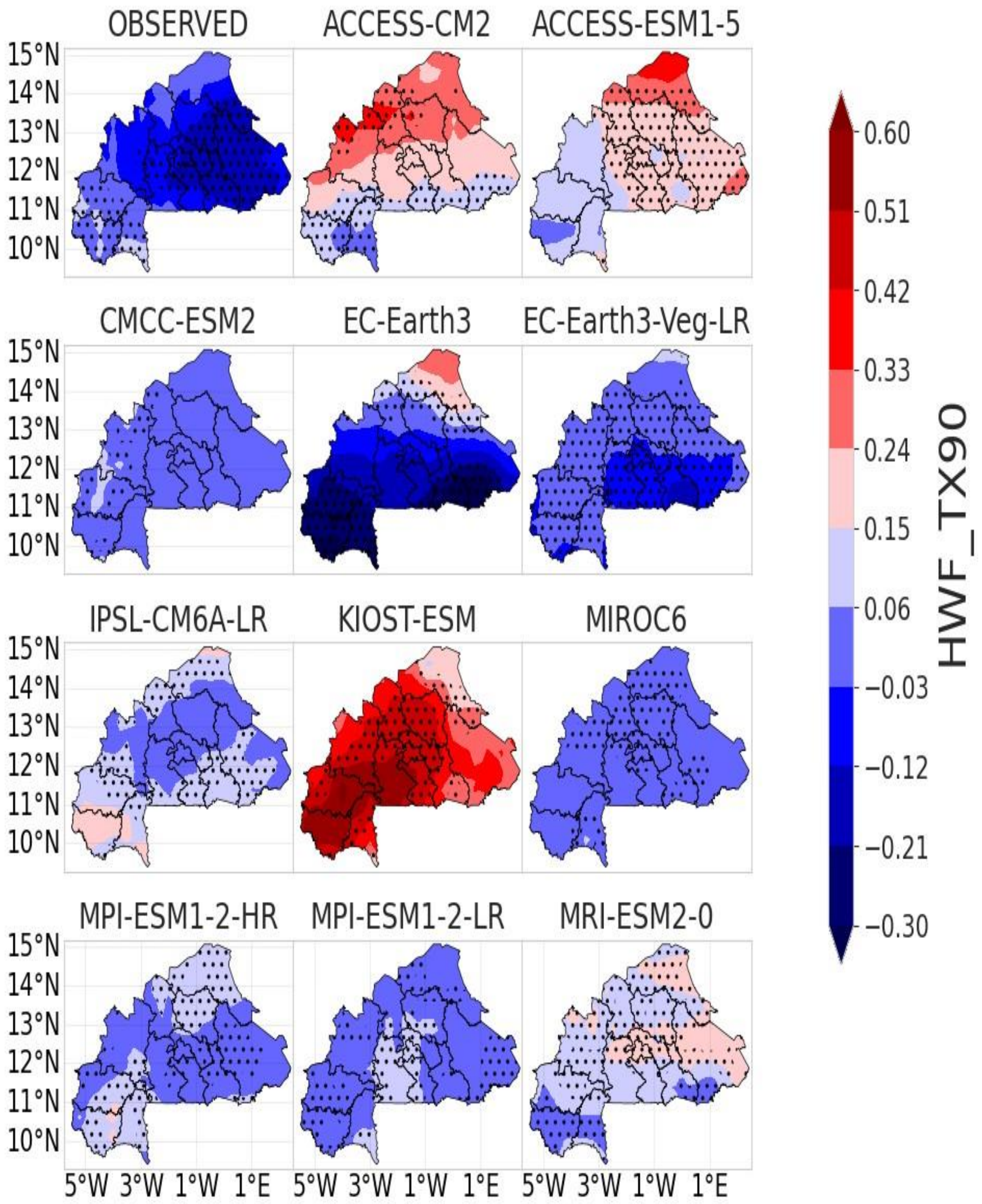

Figure 4. 25: Trend analysis of heatwaves in Burkina Faso for HWF (Heat Wave Frequency) Days for daytime (TX90th percentile) from 1991 - 2014.

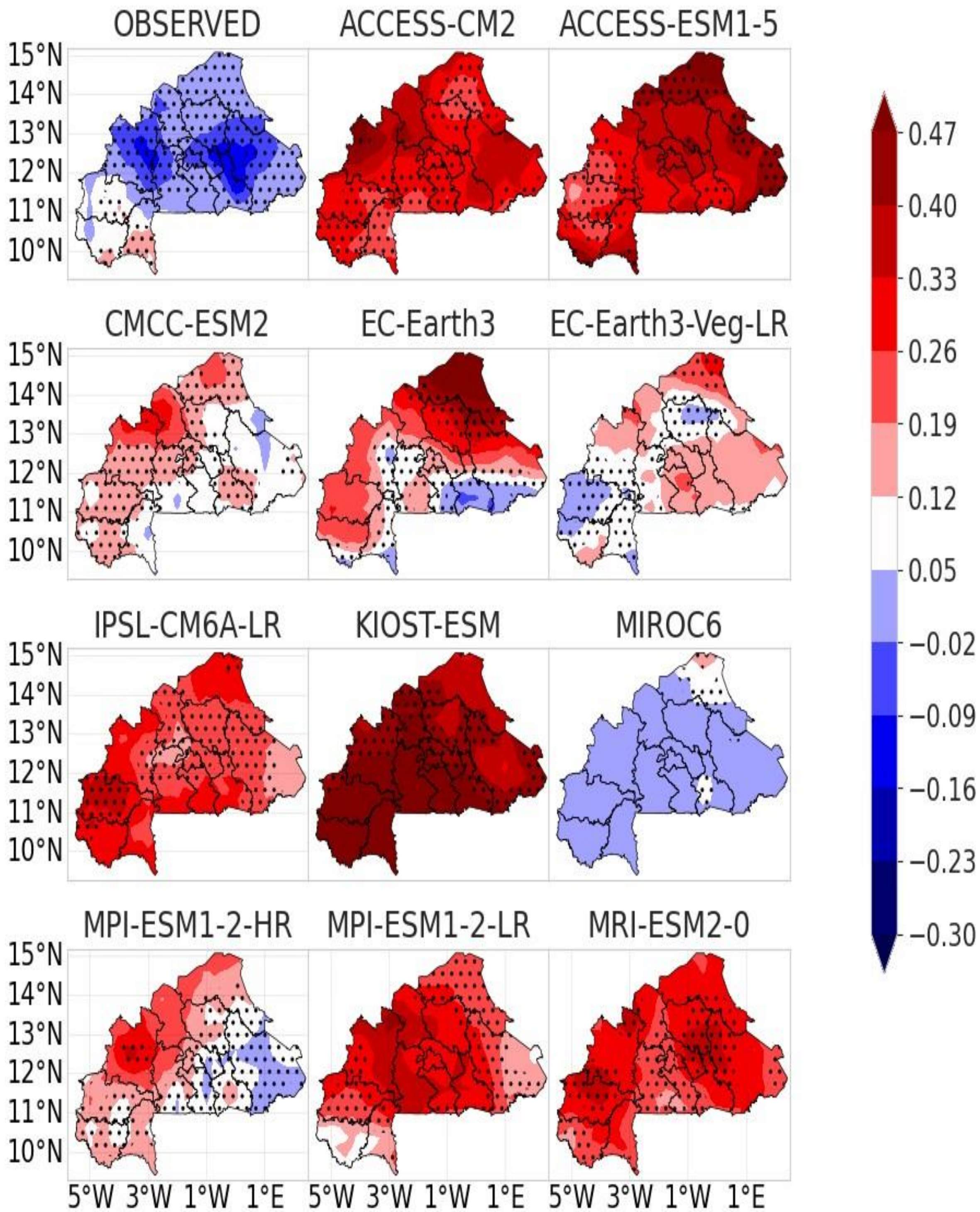

Figure 4. 26: Trend analysis of heatwaves in Burkina Faso for HWF (Heat Wave Frequency) Days for Excess Heat Factor (EHF) from 1991 - 2014.

The HWM_TN90 (Figure 4.27) depicted a statistically significant positive and negative trend across the study area. The downward trend was observed in southwestern and central-eastern Burkina Faso, while the upward trend was observed in other locations. Similarly, mixed trends were observed with the different models but at different locations depending on the model. The HWM_TX90 (Figure 4.28) showed a statistically significant downward trend across the country. The trend is positive in the southeastern part but not statistically significant. A similar result was found with CMCCESM2 (positive and no significant trend in the north). Models such as ACCESS-CM2 and ECEarth3 showed upward trends, while others showed mixed upward and downward trends. The HWM_EHF (Figure 4.29) showed a statistically significant negative trend in a portion of the northern and western parts of the study area and a statistically significant positive trend in the southeastern and central-southern Burkina Faso. Similarly, a mixed positive and negative trend was found for models like MIROC6, MPI-ESM1-2-HR, and MRI-ESM2-0. Only negative trends were found for MPI-ESM1-2-LR, while positive trends were found for ACCESS-CM2, ACCESS-ESM1-5, EC-Earth-Veg-LR, and KIOST-ESM.

The results for HWM showed a significant increase in minimum temperature over maximum and the excess heat factor. This result is consistent with previous research in West Africa, which shows that minimum temperature increases faster than maximum temperature (Guigma *et al.*, 2020). The observed increasing trends align with findings by Perkins and Alexander (2013) and Brimicombe *et al.*, (2022). They emphasise that higher HWM values signify more intense and damaging heatwave events, which pose significant risks to public health, agriculture, and infrastructure. Therefore, mitigation and adaptation strategies are needed.

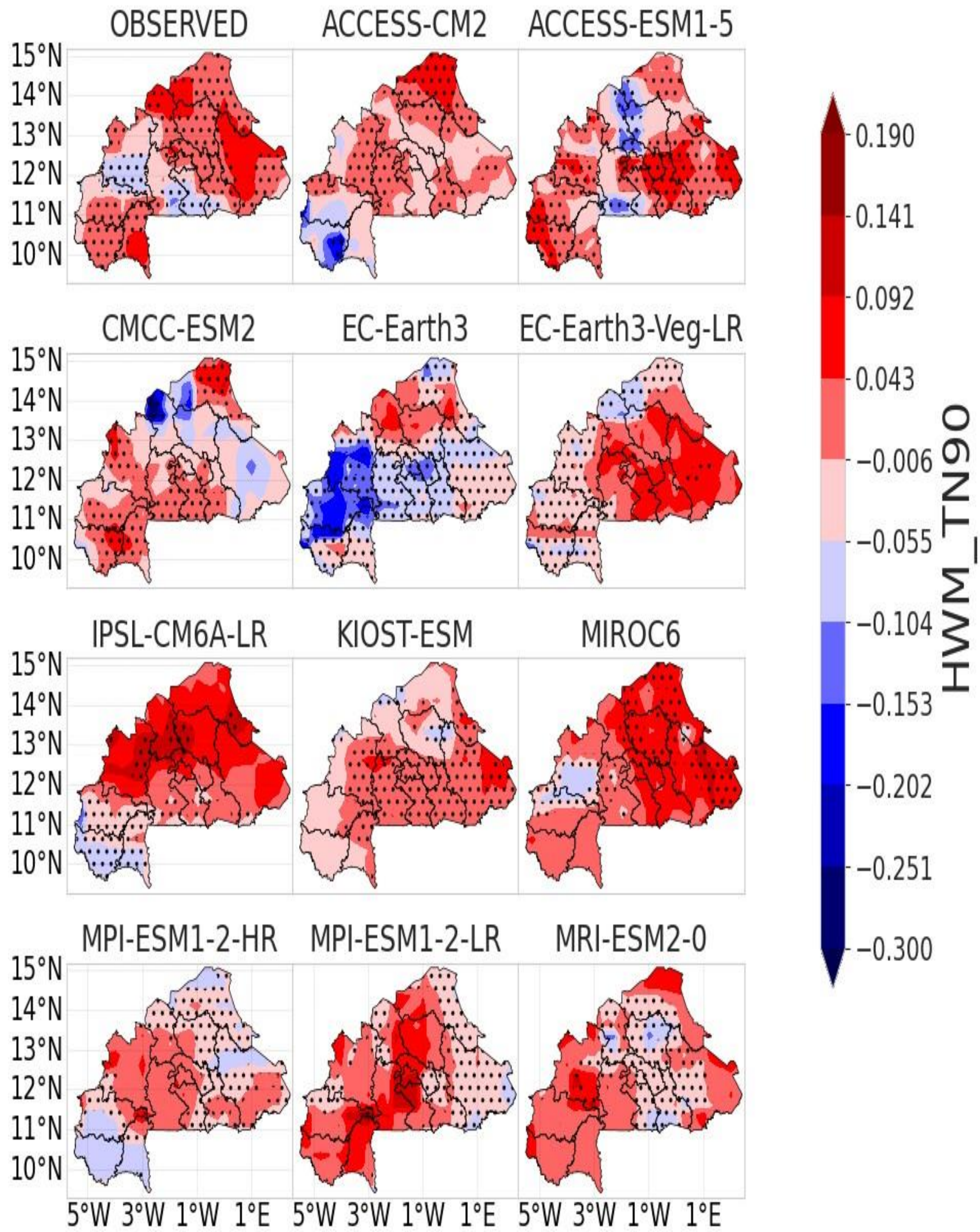

Figure 4. 27: Trend analysis of heatwaves in Burkina Faso for HWM (Heat Wave Magnitude) for nighttime (TN90th percentile) from 1991 - 2014.

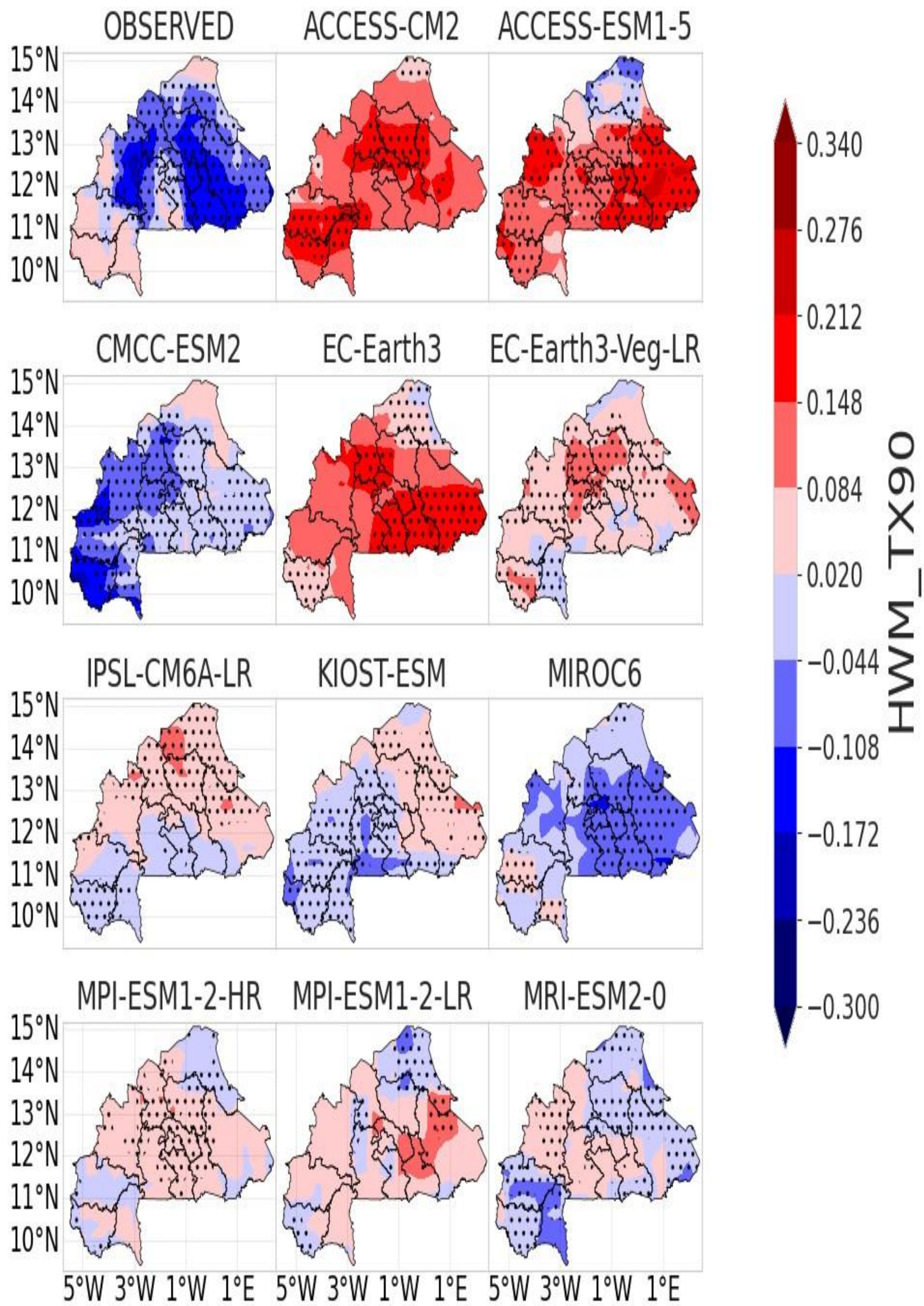

Figure 4. 28: Trend analysis of heatwaves in Burkina Faso for HWM (Heat Wave Magnitude) for daytime (TX90th percentile) from 1991 - 2014.

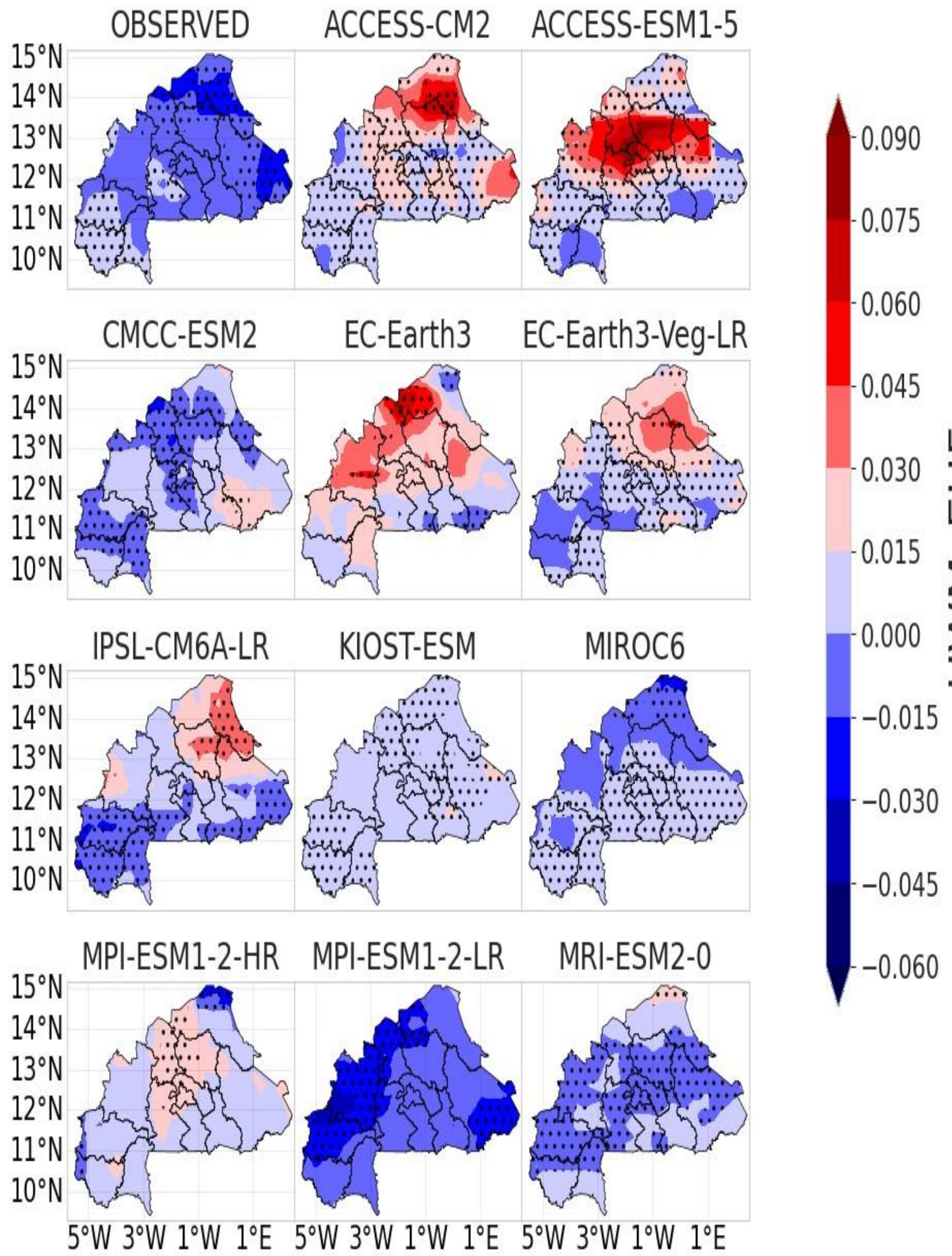

Figure 4. 29: Trend analysis of heatwaves in Burkina Faso for HWM (Heat Wave Magnitude) for Excess Heat Factor (EHF) from 1991 - 2014.

A statistically significant positive trend was observed over the western, southwestern, and northeastern parts of the country for HWN_TN90 (Figure 4.30). A similar result was found with models such as MPI-ESM1-2-HR and MPI-ESM1-2LR, while models ACCESS-CM2, ACCESS-ESM1-5, EC-Earth3, EC-Earth3-Veg-LR, IPSL-CM6A-LR, KIOST-ESM overestimated the results and models CMCC-ESM2, MIROC6, and MRI-ESM2-0 underestimated the results. The HWN_TX90 (Figure 4.31) showed a low positive significant trend over the northern and the northwestern part of Burkina Faso and the southern part. All the models overestimated the results by showing an increased trend across the country except for model CMCC-ESM2, which showed an increasing trend only in the western part, and model EC-Earth3, with a rising trend in the northern part and a decreasing trend in the southern part. A negative significant trend was observed for HWN_EHF (Figure 4.32) in the southern part of the country. The results obtained with models ACCESS-CM2 and KIOST-ESM showed a statistically significant trend across the country, while the other models underestimated the results. The trend in HWN is positive for minimum and maximum temperature while negative for EHF. This indicated that the number of heatwave events is more pronounced at nighttime than at daytime causing more impact on human health.

De Longueville *et al*. (2016) found that minimum temperatures are rising faster than maximum temperatures. While high daytime maximum temperatures are known to impact human life and health, abnormally warm nighttime minimum temperatures have been related to increased mortality and negative health impacts (Nissan *et al*., 2017). Russo *et al*. (2014) and Ceccherini *et al*. (2017) provide evidence of increasing heatwave occurrences in the Sahel. Due to the predicted rise in HWN, excessive heat may become an almost regular occurrence in the area, making it harder for vulnerable communities to remain resilient. This rise in heatwave occurrences increases the probability of overlapping or consecutive incidents, as noted by (Odoulami *et al*., 2017); he noted that prolonged exposure to heat could affect animals, disturb agriculture, and weaken crop resilience, all of which would increase health issues in communities with no access to cooling supplies.

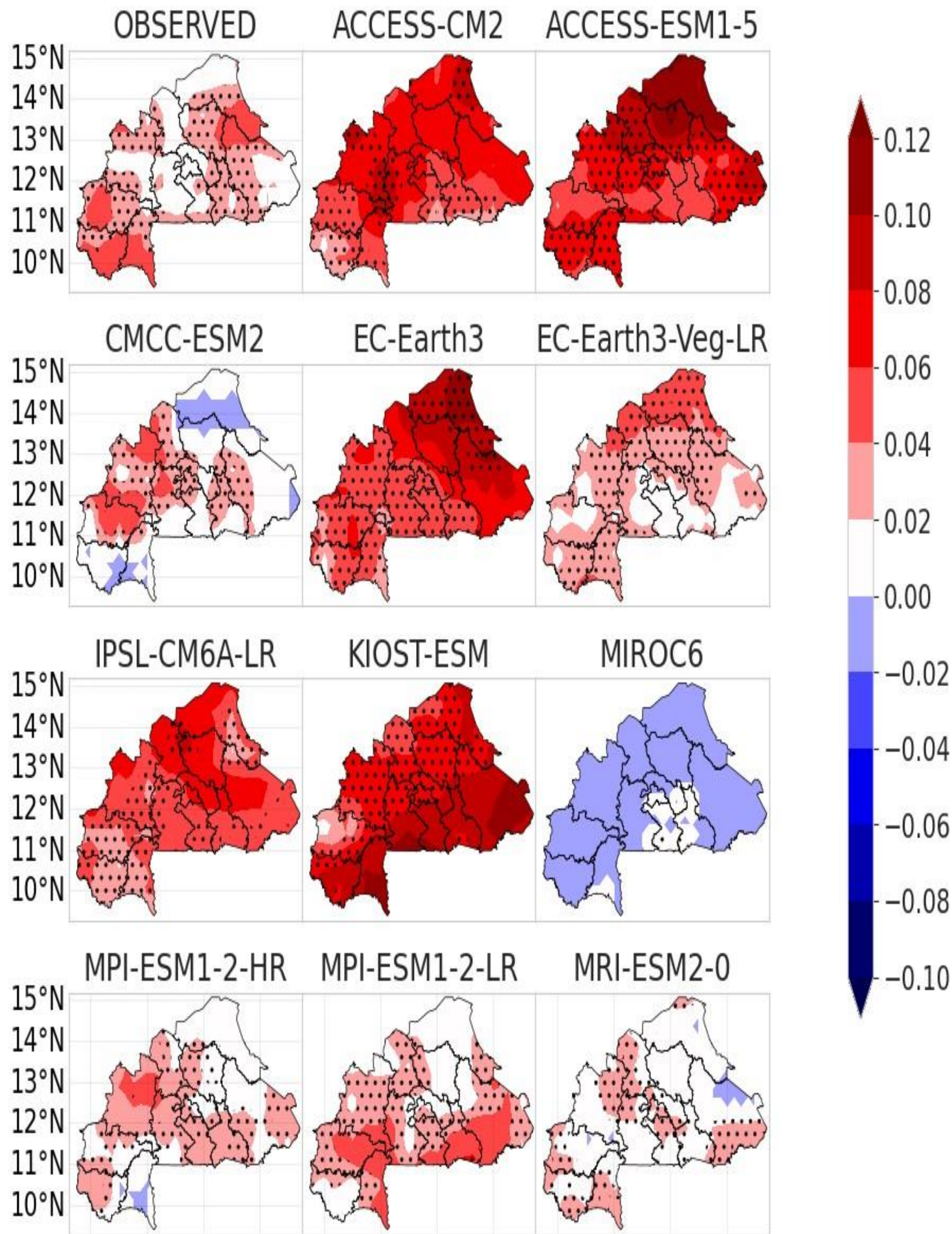

Figure 4. 30: Trend analysis of heatwaves in Burkina Faso for HWN (Heat Wave Number) for nighttime (TN90th percentile) from 1991 - 2014.

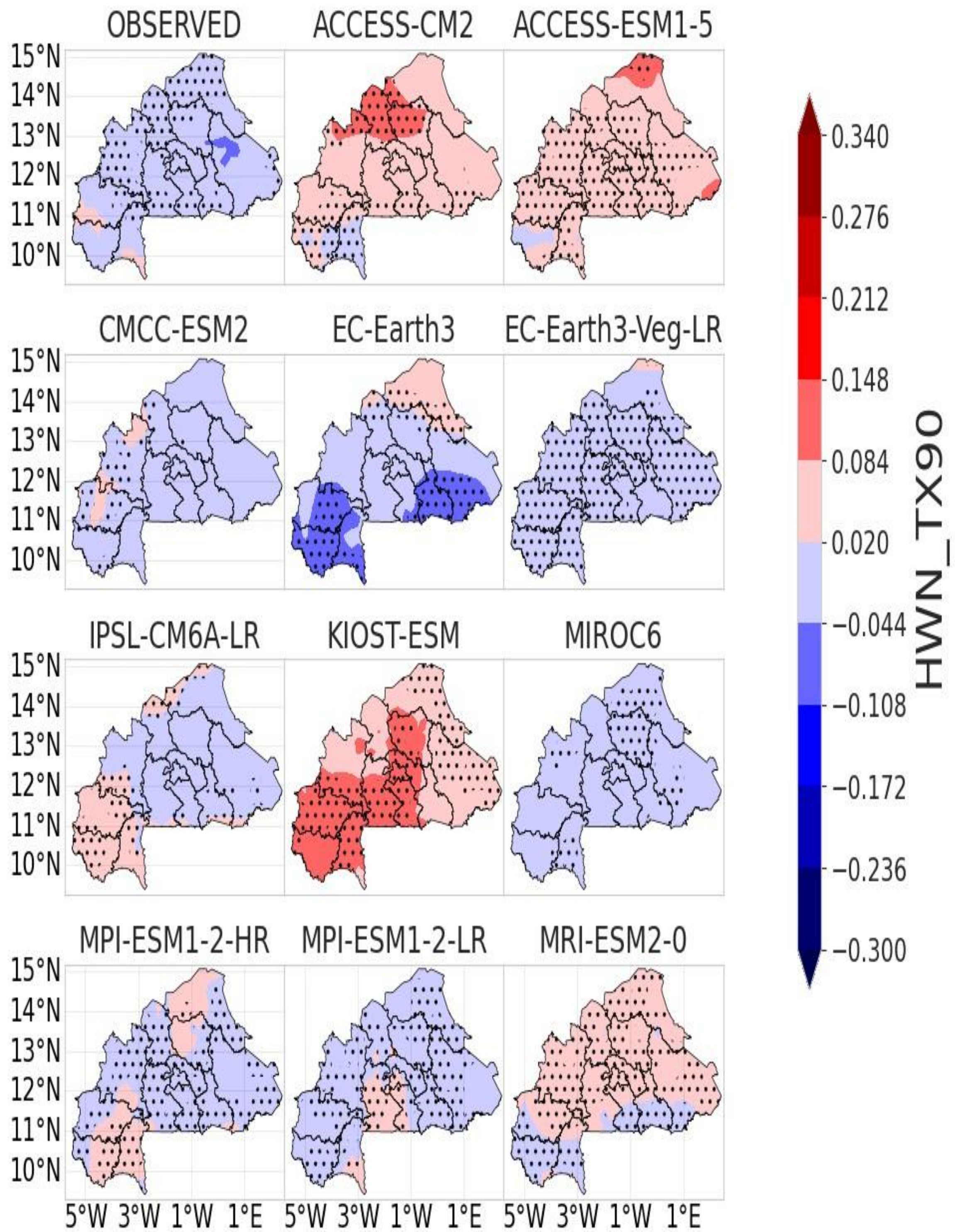

Figure 4. 31: Trend analysis of heatwaves in Burkina Faso for HWN (Heat Wave Number) for daytime (TX90th percentile) from 1991 - 2014.

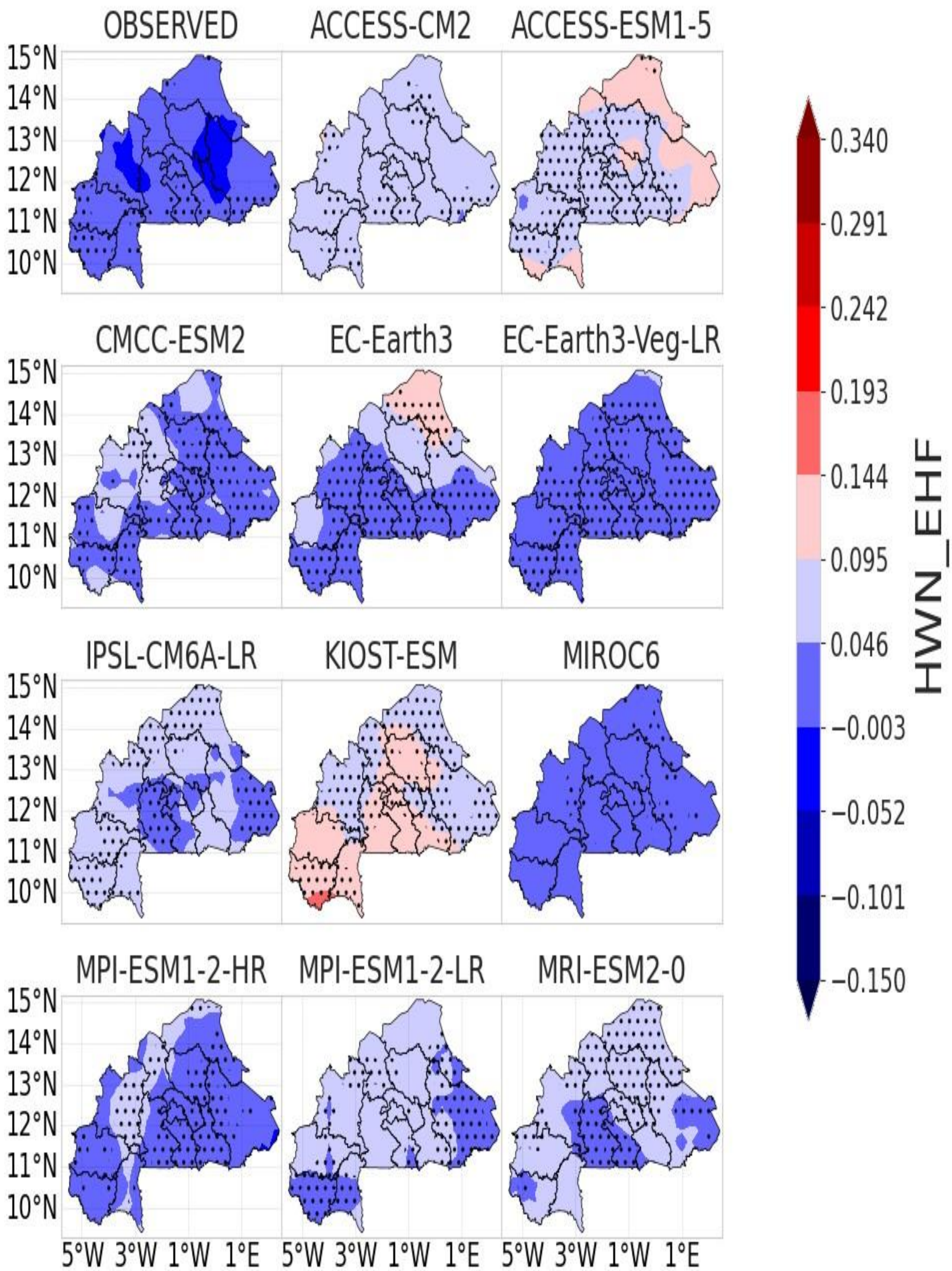

Figure 4. 32: Trend analysis of heatwaves in Burkina Faso for HWN (Heat Wave Number) for Excess Heat Factor (EHF) from 1991 - 2014.

It can be concluded that the relationship between time and temperature is evident, although the strength of the relationship is weak. The results corroborated the findings of similar analyses conducted by Sanogo *et al*. (2015) on the spatio-temporal characteristics of temperatures in the Sudanian region, highlighting the need for continuous monitoring and an in-depth understanding of local climate change. Burkina Faso is characterized by a semi-arid to arid climate with a short rainy season. Temperatures can be sensitive to climatic variations, mainly due to monsoon variations. Previous studies by Hulme (2001) highlight the sensitivity of this region to climate variations, which could amplify the impacts of observed warming.

In summary, these results indicated a statistically significant trend towards an increase in temperature over the years, although the relationship is very weak in magnitude. These outputs could motivate adaptation actions to deal with climate change, such as developing resilient agricultural practices, improving energy efficiency, and raising awareness of climate challenges. Previous research (Ouedraogo and Stroosnijder, 2006), highlights the importance of developing resilient agricultural practices and adaptation strategies to mitigate the impacts of climate change in the region.

4.1.3 Temperature Humidity Index (THI) over Burkina Faso

The THI has been calculated over Burkina Faso. The result is indicated in Figure 4.33, which shows the monthly average Thermal Humidity Index for Burkina Faso from 1991-2021.

The THI is slightly below 27 ˚C in January, indicating a comfortable climate. This aligns with the cooler, dry season in Burkina Faso, where lower humidity reduces the discomfort associated with heat. The THI consistently exceeds 28 °C from February to December, signifying very uncomfortable conditions for most of the year. Notably, April and May exhibit the highest THI values, likely corresponding to peak heat and humidity during the pre-monsoon or dry season. This trend suggests a clear seasonal pattern where the THI peaks in April and May, followed by a slight dip during the rainy season (June-August). However, THI remains above the "very uncomfortable" threshold even during these months. The dry season (November to April) sees high temperatures with moderate to low humidity. Despite lower moisture levels, the persistent heat drives the THI above the threshold for discomfort. As the region transitions to the wet season, April marks a critical point where THI peaks due to high temperatures and rising humidity. Although rainfall cools temperatures slightly during the rainy season (June to October), the accompanying high humidity sustains the THI above 28 °C. This showed that humidity is critical in maintaining thermal comfort during these months.

Extended periods of uncomfortable THI (>28) can exacerbate heat stress, dehydration, and related health risks. Vulnerable populations (e.g., children, the elderly, and individuals with preexisting conditions) may be more susceptible during the peak THI months. Studies by Kjellstrom *et al*. (2009) highlight that high THI levels are associated with heat stress, reduced labour productivity, and increased mortality in tropical regions. This aligns with Burkina Faso's THI data, where most months exceed comfortable thresholds. A study in *The Lancet Planetary Health* (Watts *et al*., 2021) discusses the global increase in heat-related deaths, particularly in Africa, due to prolonged exposure to high heat and humidity indices.

The graph demonstrates that Burkina Faso experiences "very uncomfortable" THI levels for most of the year, with significant implications for public health, productivity, and economic stability. Comparisons with global and regional studies underscore the urgency of implementing adaptation and mitigation strategies to reduce the impact of prolonged heat stress on vulnerable populations.

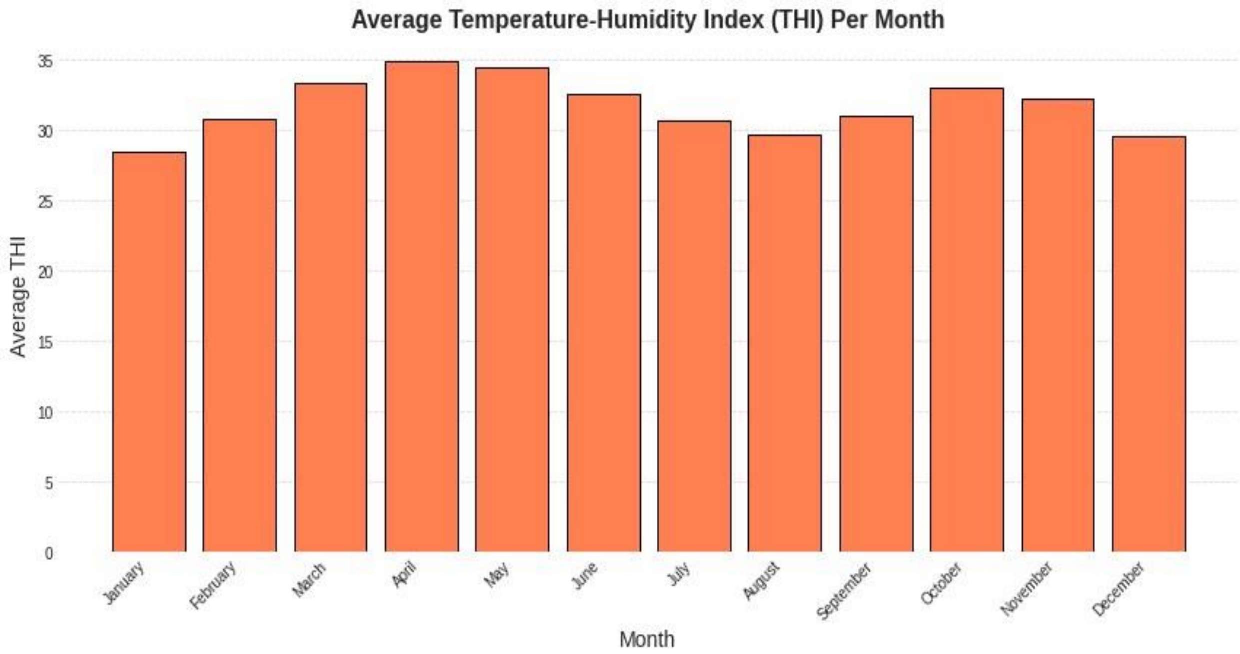

Figure 4. 33: Monthly average Temperature Humidity Index for Burkina Faso from 1991-2021.

4.2 Relation between Heatwave and Health

4.2.1 Relationship between THI and health, and between heatwave and health

The scattered plot in Figure 4.34 showed a weak positive correlation (correlation coefficient of 0.272) between THI and the number of deaths. The R^2 value is 0.074, indicating that only 7.4% of the death variability is explained by changes in THI, suggesting a weak relationship. The red trendline shows a slight upward slope, indicating that as THI increases, deaths are minor. While the relationship is weak, higher THI values (>30) appear to correspond with increased deaths, likely due to heat-related illnesses such as dehydration, cardiovascular strain, and heatstroke. Watts *et al*. (2021) found a stronger relationship between heat stress and mortality in low-income countries, where limited access to healthcare amplifies the impact of high THI. However, individual-level factors (e.g., preexisting conditions, occupation) can weaken aggregate correlations like the one shown in this graph. In a review of heat and mortality relationships, Basu, (2009) studies from temperate and tropical regions showed a similar weak correlation, emphasizing the role of adaptive measures like cooling and hydration in mitigating deaths. Kjellstrom *et al*. (2009) found that the impact of high THI on health is particularly evident in outdoor workers, whose deaths might be underreported in aggregate statistics.

Figure 4.35 represents the relationship between heatwaves and death. The correlation coefficient is weaker (0.11), and the R^2 value is negligible, suggesting almost no relationship between heatwave events and deaths. The red trendline is nearly flat, indicating that the number of heat waves does not significantly influence mortality data. This can be explained by the fact that heatwave definitions may vary, and their short duration might not fully capture the cumulative thermal stress experienced by individuals; deaths attributed to heatwaves may be delayed or misclassified under other causes, and the short heath dataset which may not be enough to capture the relationship between heatwave and health.

Despite the evidence of an insignificant relationship, heatwaves exacerbate health risks for vulnerable populations. Hajat *et al*. (2006) showed that heatwaves are linked to excess mortality in many urban regions. However, the analysed results' lack of significant correlation could reflect Burkina Faso's rural population distribution and adaptive behaviours (e.g., resting during peak heat). For (Anderson and Bell (2009), heatwave effects on mortality are often nonlinear, with significant spikes occurring only at extreme thresholds, which might be less frequent in Burkina Faso. In India, mortality during heatwaves was poorly correlated with event frequency but increased sharply during particularly intense events (Mazdiyasni *et al*., 2017)**.** This could parallel the weak relationship seen here.

In comparison, the relationship between THI and deaths, with a correlation of 0.272, is higher than that between heatwave events and deaths (correlation = 0.09). This suggests that cumulative thermal discomfort (captured by THI) significantly influences mortality more than the frequency of heatwave events.

Weak correlations in both results could reflect adaptive behaviours, such as cultural practices (e.g., resting during peak heat) or the population's physiological adaptation to a hot climate.

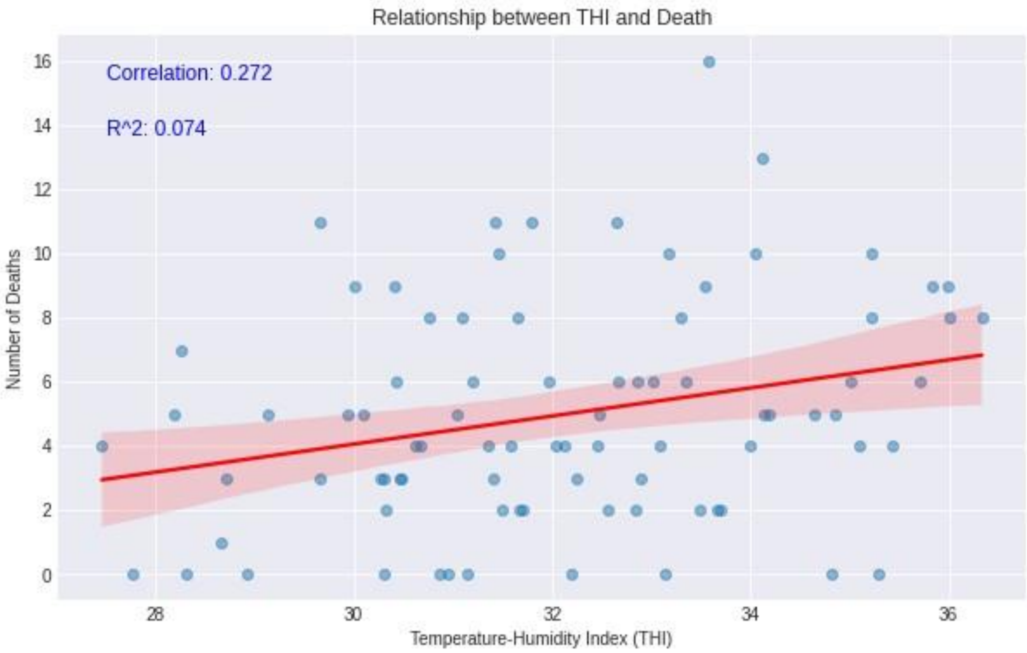

Figure 4. 34: Relationship between THI and death in Ouagadougou.

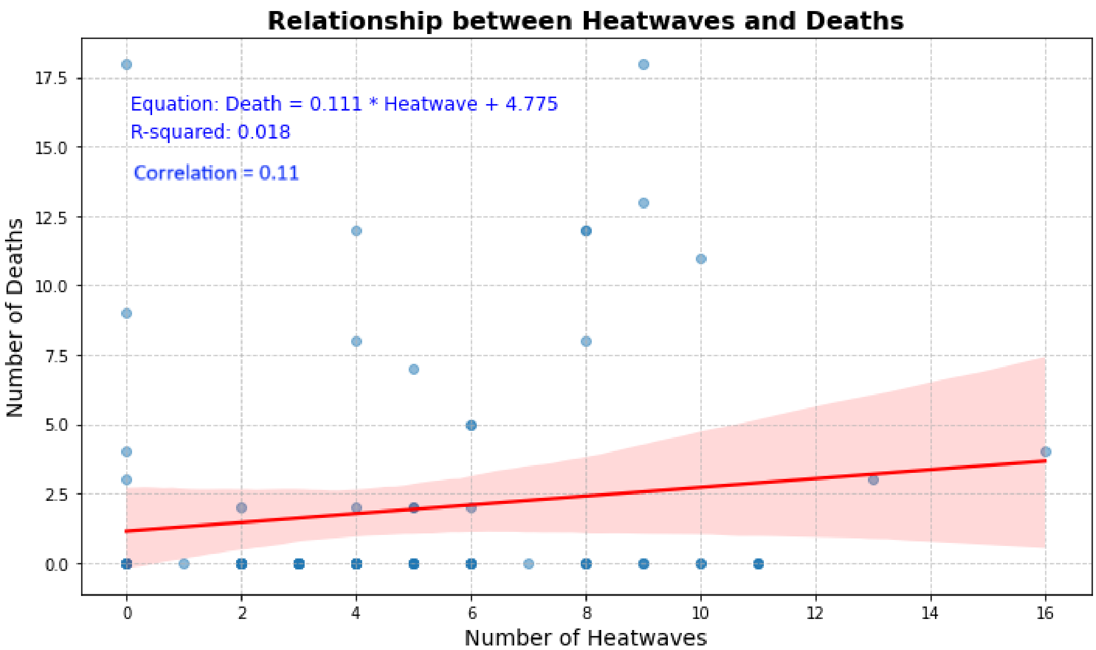

Figure 4. 35: Relationship between heatwave events and death in Ouagadougou.

The result in Figure 4.36 reveals significant seasonal variations in the correlation between the THI and mortality in Ouagadougou. Strong positive correlations in April**,** May**,** and December suggest that elevated THI during the dry season is closely associated with increased deaths. This trend aligns with findings by Diasso and Abiodun (2017), who highlighted the impact of pre-monsoon heat peaks on mortality in West African cities, particularly from cardiovascular and respiratory causes. Urban heat effects, exacerbated by Ouagadougou's limited green cover and high urban density, likely amplify the vulnerability of populations during these months, as described by Dosio *et al*. (2020)**.** Conversely, negative correlations observed in August and September coincide with the rainy season, when cooler temperatures reduce the heat-related mortality risks. However, this period may be influenced by other health challenges, such as infectious diseases linked to increased humidity, requiring further exploration.

These findings underscore the importance of addressing seasonal climate impacts on health in Ouagadougou. During high-risk months, targeted public health interventions, such as heat stress awareness campaigns and improved access to healthcare, are critical to reducing heatrelated mortality. Moreover, urban planning efforts to mitigate the urban heat island effect, such as expanding vegetation cover, could be crucial in long-term resilience. Negative correlations in rainy months suggest that climatic effects are not linear, emphasizing the need to study interactions between heat, humidity, and other seasonal health risks. Comparisons with other regions in Sub-Saharan Africa, such as Accra and Lagos, where similar patterns have been observed, could provide further insights into climate mortality dynamics and inform regional adaptation strategies.

The output in Figure 4.37 shows the correlation between heatwaves and deaths in Ouagadougou for the months when heatwaves were detected (February, March, April, May, and June). In general, temperatures are very high from the end of February to the end of June, when the first rains begin. Negative correlations dominate most months, with February (-0.44), March (-0.45), and June (-0.52) showing significant inverse relationships. May shows a slight positive correlation (0.09), while April (-0.04) displays a negligible negative correlation. These results suggest variability in how heatwaves relate to yearly mortality, potentially influenced by other meteorological, social, and adaptive factors. The negative correlation can also be related to the short dataset, which did not allow for the capture of the relationship between heat waves and health very well.

The slight positive correlation in May could indicate delayed heat effects when compounded with other factors such as humidity, urban heat islands, or socio-economic vulnerabilities. The weak correlation in April suggests that heatwaves might minimally influence mortality during this period due to successful adaptation mechanisms.

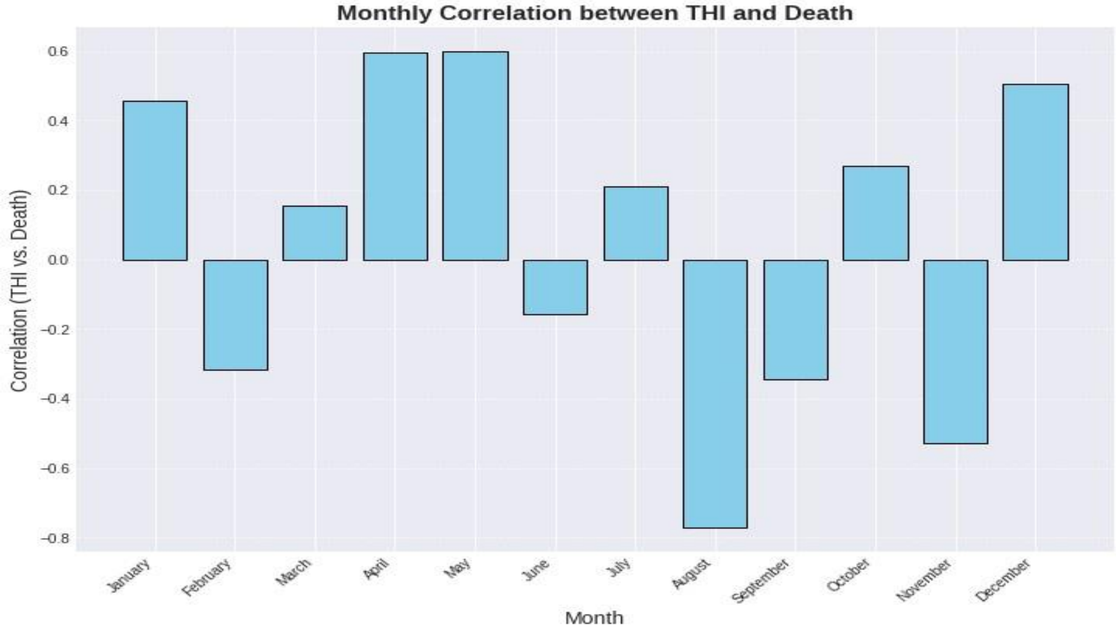

Figure 4. 36: Monthly correlation between THI and death in Ouagadougou.

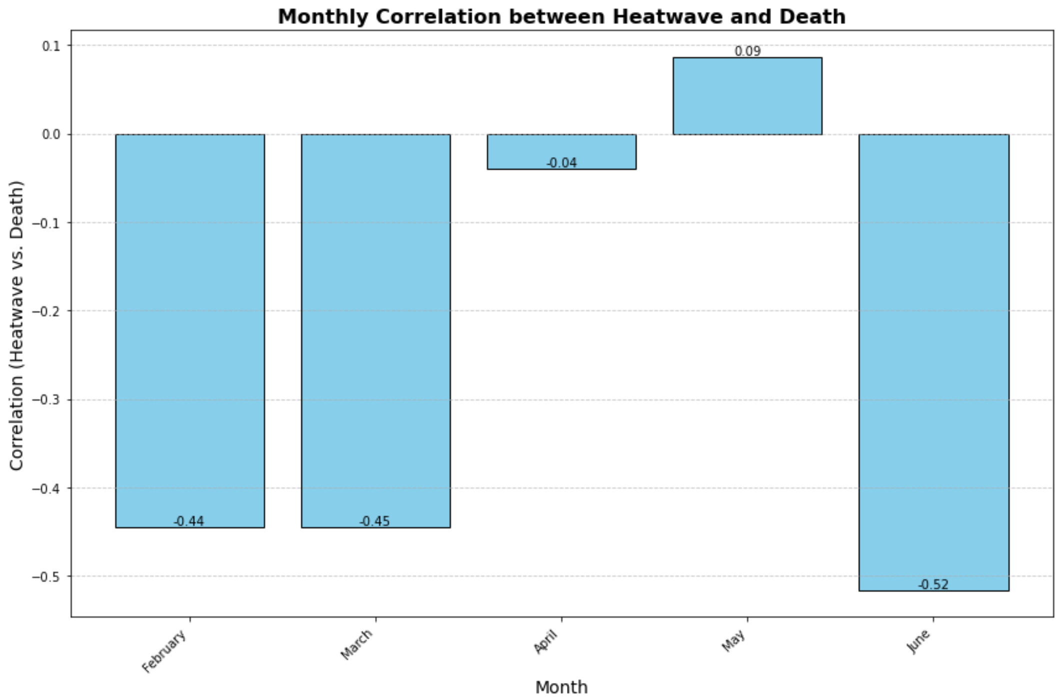

Figure 4. 37: Monthly correlation between heatwave and death in Ouagadougou.

4.2.2. The ARIMA Model

Figure 4.38 illustrates the relationship between heatwave occurrences and deaths over time, analyzed using an ARIMA model to forecast future trends. The blue line represents the actual number of deaths, showing significant variability and recurring peaks. As the orange dots indicate, these peaks often coincide with increases in heatwave occurrences, suggesting a positive relationship between the two variables. The green line represents a lag test or validation phase, demonstrating how well the model captured the underlying trends and relationships in the data during training.

The red dashed line extends beyond the observed data into the future, which shows the ARIMA model's forecasted deaths for the next three years. This forecast captures periodic fluctuations, indicating that the model has successfully identified seasonal patterns in the data. Even though the plot's heatwave occurrences remain constant after 2022, the forecasted deaths still vary, implying that while a relationship between heatwaves and death exists, other drivers also play a role.

The analysis provides valuable insights for future planning by relying on the ARIMA model, which incorporates past death trends and patterns. The model captures the influence of past values (auto-regressive component) and accounts for potential seasonal trends through differencing and error adjustments (integration and moving average components). However, because ARIMA primarily works as a univariate model, it may not fully account for external factors like healthcare advancements or other environmental conditions unless explicitly included.

Although the ARIMA model forecast suggests a flat trajectory of mortality from heatwaves over the next three years, this does not imply reduced risk but reflects a balance of several influencing factors. One key explanation is the possibility of population acclimatization and behavioural adaptation to recurring heat events. Over time, people in Ouagadougou may have adjusted their daily activities, such as limiting outdoor exposure during peak heat hours, improving hydration practices, or seeking shaded areas, which can help reduce immediate mortality risks. Public awareness and education campaigns may also play a role in equipping individuals to take precautionary measures during extreme heat events. Furthermore, modest urban adaptation measures, such as tree-planting initiatives or improved ventilation in homes, may help mitigate the effects of extreme heat. However, given the city's rapid urbanization and infrastructural challenges, their overall impact is likely limited.

However, the consistent frequency of heatwaves underscores the persistent vulnerability of specific population groups, particularly the elderly, children, and those with pre-existing health conditions. While the mortality trajectory appears stable, it may mask underlying risks, such as underreporting heat-related deaths or the cumulative long-term impacts of frequent heatwaves on public health. Additionally, the lack of a rising trajectory may partly reflect the demographic profile of Ouagadougou, where a younger population is generally more resilient to heat stress. Nevertheless, without significant investments in urban planning, healthcare infrastructure, and early warning systems, the flat mortality trend could increase as climate change intensifies heatwave frequency and severity. This highlights the urgent need for comprehensive adaptation strategies, such as improving green infrastructure, enhancing access to cooling systems, and strengthening public health interventions to reduce heat-related mortality further.

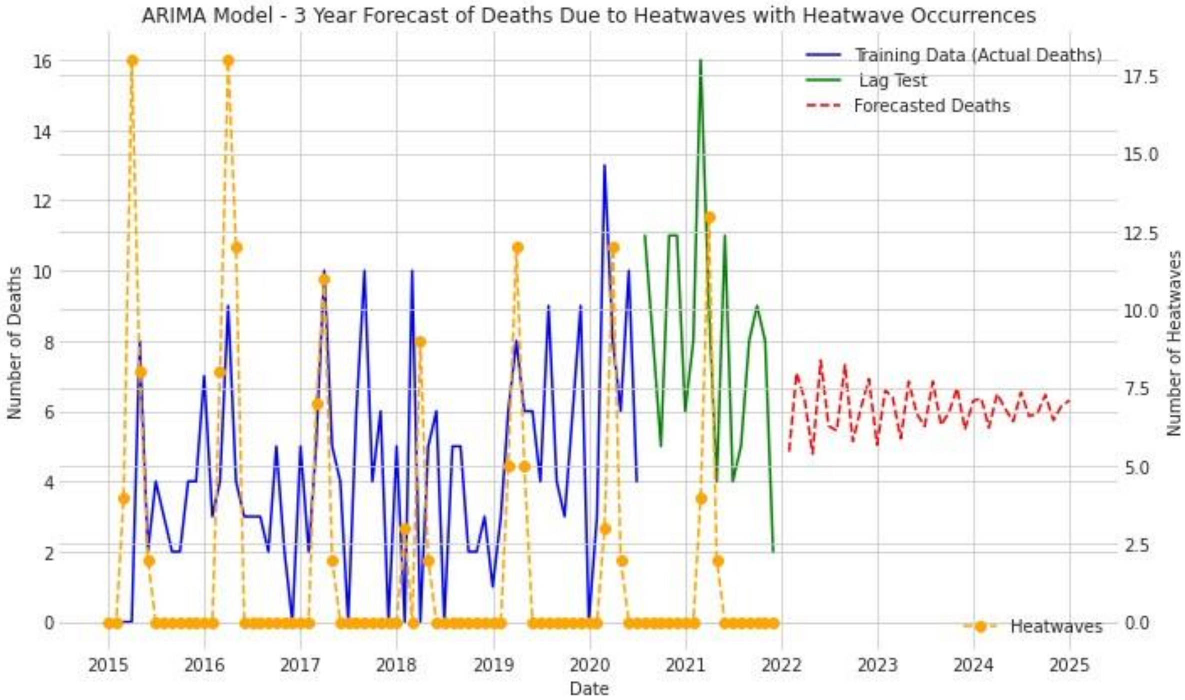

Figure 4. 38: ARIMA Model: Forecasting Deaths Attributed to Heatwaves (2015-2025).

4.3 Projection of Future Heatwave

4.3.1 Future Heatwave Characteristics

This chapter analyses the spatial projection of heatwave characteristics over Burkina Faso for the two future timeframes based on two climate scenarios, SSP245 and SSP585.

The HWA_TN90 (Figure 4.39) showed no increase in HWA over Burkina Faso in the near future for each climate scenario. In contrast, it showed a much sharper northward increase in the far future (Figure 4.40), reflecting a more severe response to continued warming, with the extreme northern part of the country recording about 31^{o}C under SSP245 and over 35^{o}C under SSP585. The spatial distribution of HWA_TX90 (Figure 4.41) in the near future under SSP245 showed a moderate increase. This increase is noticeable in the northwestern (36^{o}C) and central regions (39^{o}C). concerning the SSP585, it did not show a noticeable increase in the near future for HWA. The results for the near future indicated that while heatwaves intensify, they do so at a manageable rate, reflecting a gradual rise in heat extremes. Under SSP245 in the far future,

HWA_TX90 (Figure 4.42) continues to rise northward (38-43^{o}C), though less drastically than in SSP585 (40-46^{o}C), which also rose northward. This progression suggests that while Burkina Faso would face more frequent and severe heatwaves, the increases may allow for phased adaptation strategies for SSP245. The level of warming would likely surpass the country's adaptive capacity, demanding extensive intervention to avoid widespread impact on health, agriculture, and infrastructure under SSP585. Increased HWA_TN90 has been linked to elevated mortality due to prolonged exposure to heat without nighttime relief, preventing cooling relief overnight and compounding health risks, as noted in studies on the Sahel by Oueslati *et al*., (2017), which affirms that higher nighttime temperatures reduce the recovery period from heat, exacerbating health risks by increasing cardiovascular and respiratory strain during sustained heat episodes, and Russo *et al*., (2014) which has shown that this trend is consistent with global warming projections, as nighttime temperatures tend to rise faster than daytime due to increased greenhouse gas concentrations, trapping heat even after sunset.

The HWA_EHF did not indicate any change in the near future (Figure 4.43) for SSP245 and SSP585 over the study area. In both scenarios, HWA_EHF increased significantly by the end of the century (Figure 4.44), with SSP585 showing extreme levels across the country, especially in the northern and central regions (1.7^{o}C). Under SSP245, HWA rises gradually, reflecting a manageable increase of 0.4^{o}C to 1.2^{o}C. This contrast indicates that SSP585 will likely necessitate rapid, large-scale adaptation, while SSP245 offers more time for incremental adaptation efforts. HWA_EHF projections revealed sharper increases in peak intensity, supporting findings from West Africa that rising greenhouse gases contribute to more severe and sustained temperature extremes (Odoulami *et al*., 2017).

The near future showed a moderate increase in HWA for both minimum and maximum temperature and the EHF under the two climate scenarios in Burkina Faso. This indicates that while heatwaves intensify, they do so at a manageable rate. HWA continues to rise under SSP245 in the far future, though less drastically than in SSP585. SSP245 is comparatively less severe and allows for planned adaptation, while SSP585 would expose Burkina Faso to extreme heat impacts, demanding aggressive adaptation measures to manage the anticipated high levels of heatwave amplitude across the country.

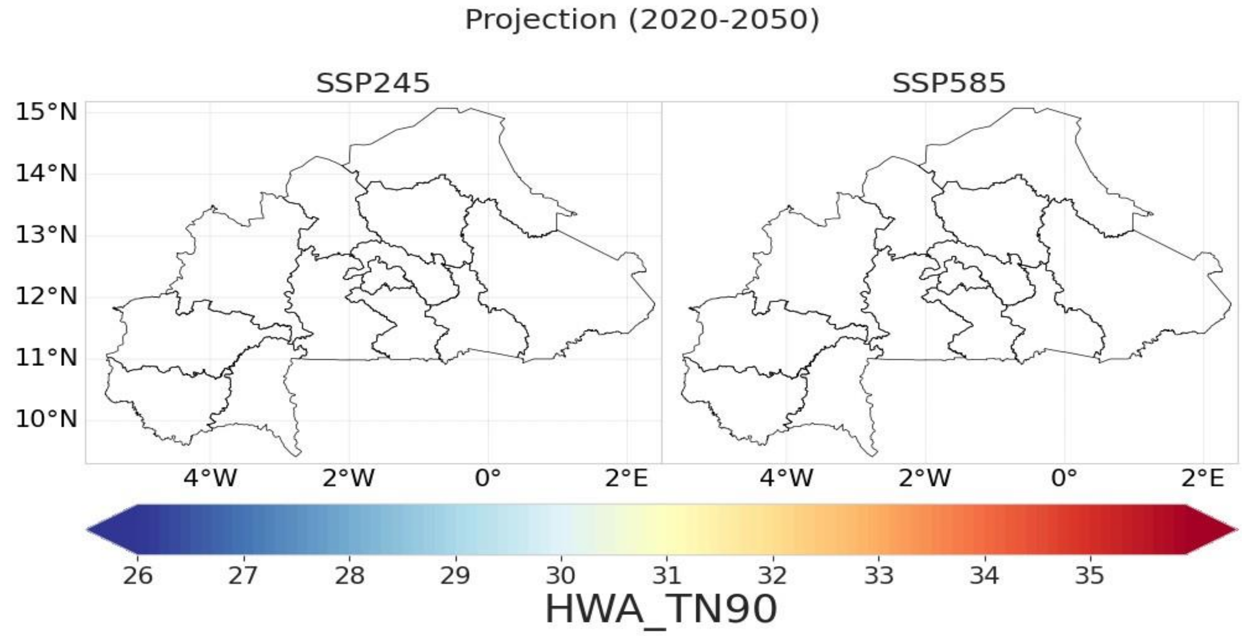

Figure 4. 39: Projection of heatwaves over Burkina Faso for HWA (Heat Wave Amplitude) °C for nighttime (TN90th percentile) from 2020 – 2050.

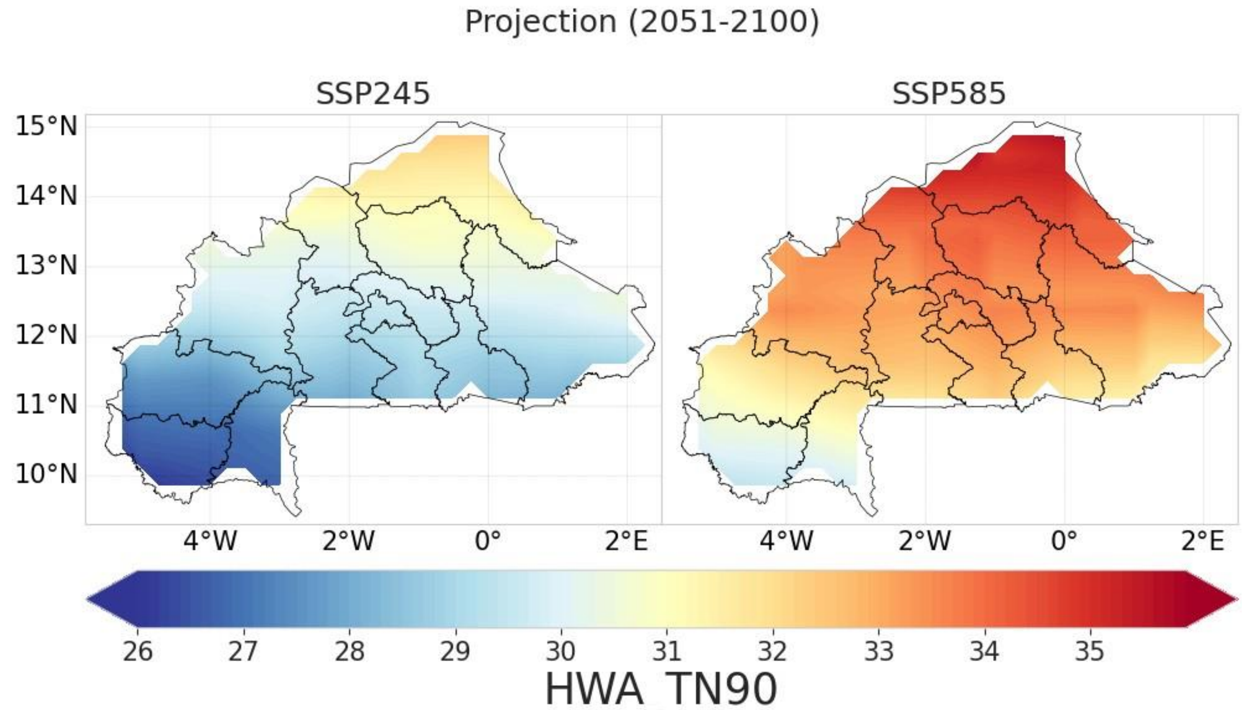

Figure 4. 40: Projection of heatwaves over Burkina Faso for HWA (Heat Wave Amplitude) °C for daytime (TN90th percentile) from 2051 – 2100.

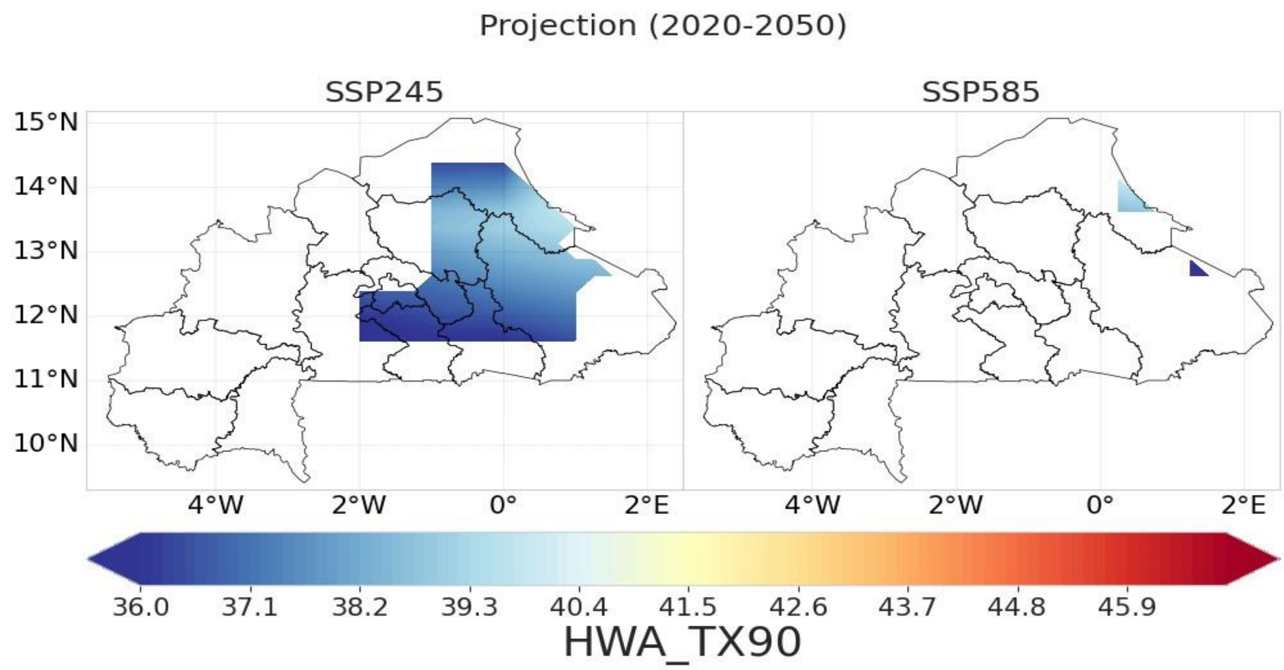

Figure 4. 41: Projection of heatwaves over Burkina Faso for HWA (Heat Wave Amplitude) °C for daytime (TX90th percentile) from 2020 – 2050.

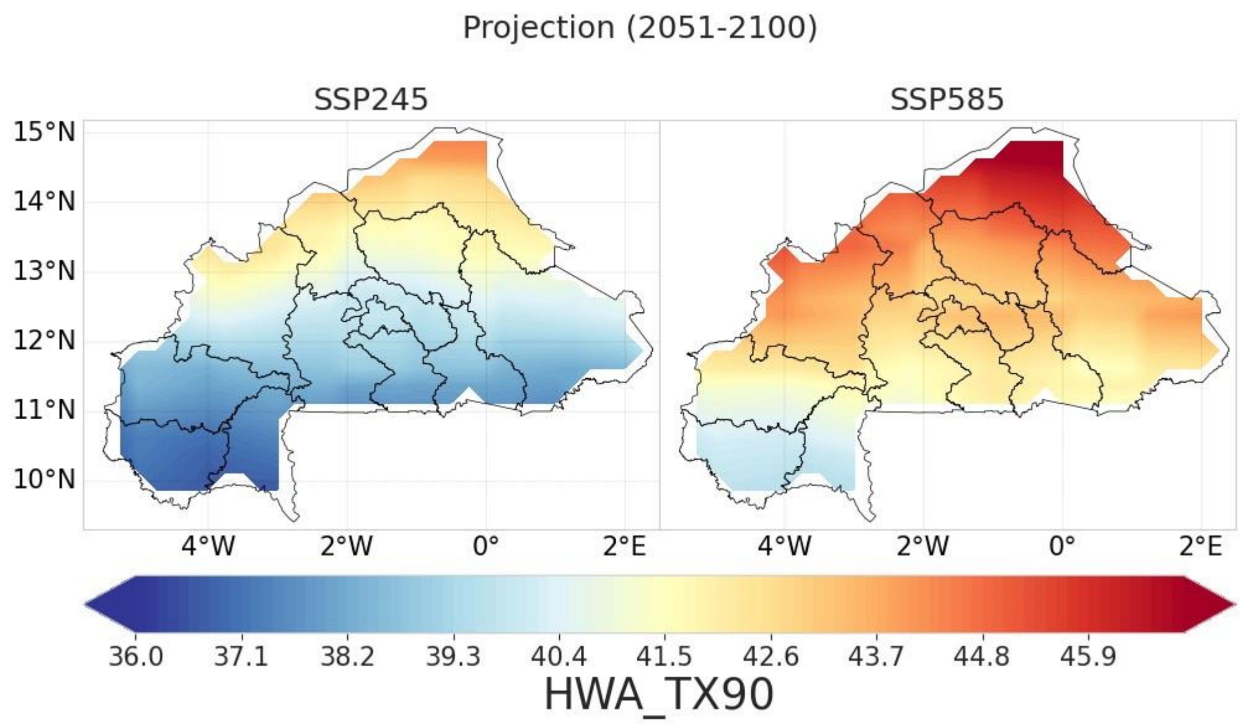

Figure 4. 42: Projection of heatwaves over Burkina Faso for HWA (Heat Wave Amplitude) °C for daytime (TX90th percentile) from 2051 – 2100.

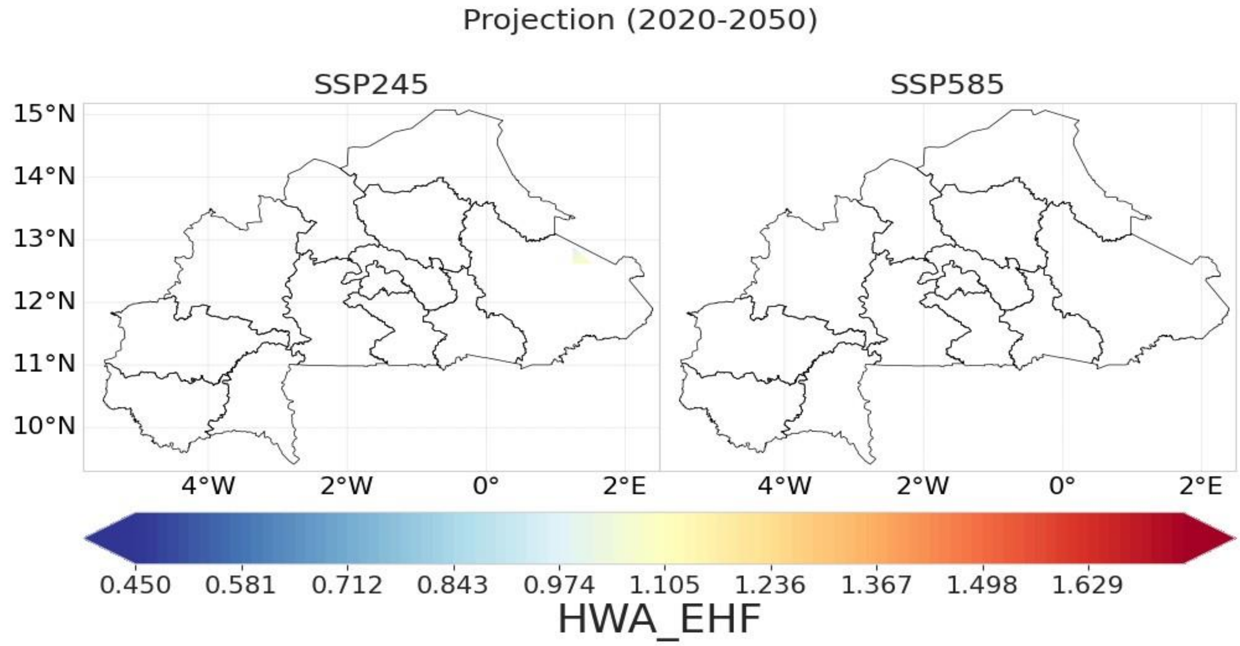

Figure 4. 43: Projection of heatwaves over Burkina Faso for HWA (Heat Wave Amplitude) °C for Excess Heat Factor (EHF) from 2020 – 2050.

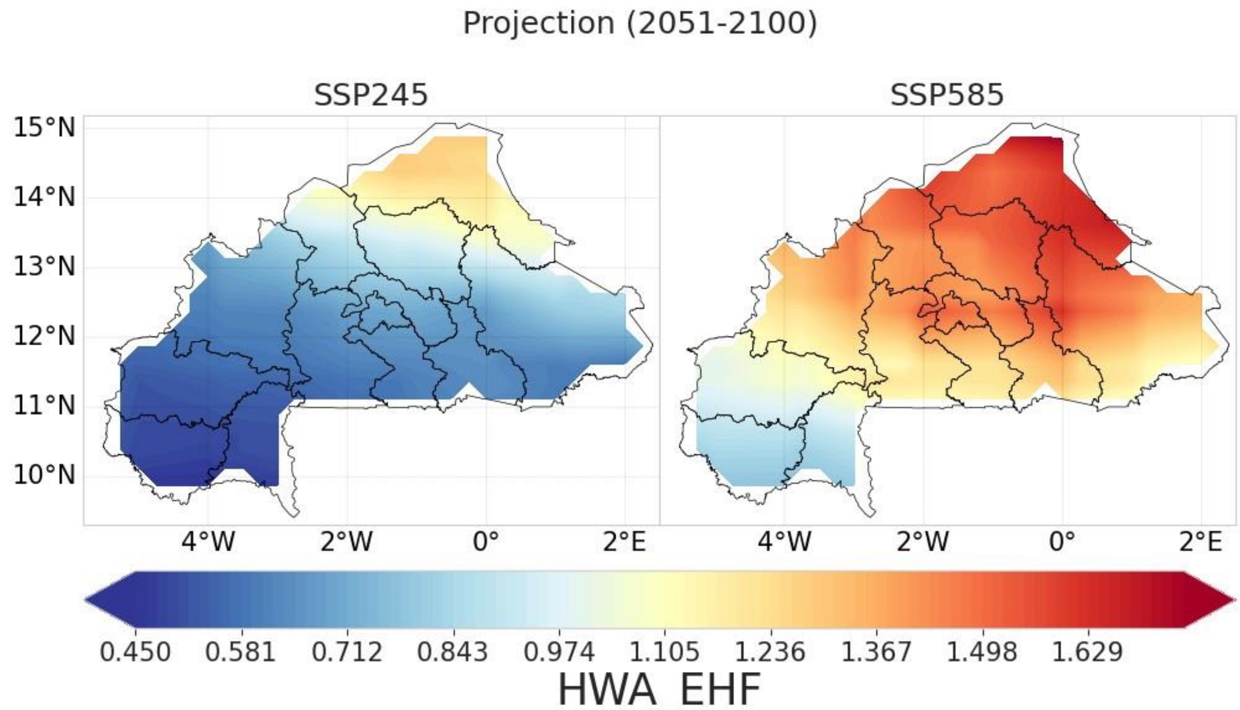

Figure 4. 44: Projection of heatwaves over Burkina Faso for HWA (Heat Wave Amplitude) °C for Excess Heat Factor (EHF) from 2051 – 2100.

The increase in HWD_TN90 (Figure 4.45) remained moderate in the near future for SSP245 and SSP585, indicating a relatively manageable rise in the duration of heatwaves during nighttime. Under SSP245, HWD_TN90 continued rising, but not as drastically as in SSP585 in the far future (Figure 4.46). The projections suggested that the increase would be more substantial under SSP245 (6 to 8 days). Under SSP585, HWD_TN90 is projected to reach extreme levels in the far future. Northern and central areas could experience prolonged heatwaves at night (14 to 21 days), creating conditions where heat stress would become critical due to sustained high temperatures. HWD_TX90 showed a moderate rise under SSP245 and SSP585 in the near future (Figure 4.47). The north and center of Burkina Faso exhibit slightly higher values, indicating longer daytime heatwaves. In the far future, HWD_TX90 (Figure 4.48) indicated a gradual rise of 6 to 9 days under SSP245. The increase is moderate, suggesting a still-manageable trend for adaptation, although northern regions would need additional resources to handle the prolonged heat. Under SSP585, HWD_TX90 (Figure 4.49) reached extreme levels across the country by the end of the century. Projections showed that maximum temperatures will remain at heatwave levels for significantly prolonged periods, with central (more than 15 days) and southern (15 to 16 days) Burkina Faso experiencing the most intense increases. The north also saw substantial increases, though to a lesser extent (11 to 13 days).

HWD_EHF remained moderate in the near future under SSP245 and SSP585 (Figure 4.50). In the far future, HWD_EHF (Figure 4.51) increased steadily across Burkina Faso under SSP245, with the highest values still concentrated in the north (15 days). The projected durations suggested moderate, manageable increases, where adaptation efforts can gradually address the risks. Under SSP585, HWD_EHF reached critical levels across all regions. The HWD is projected to increase southward from 19 to 39 days, indicating that the cumulative impact of high daytime and nighttime temperatures will be severe by the end of the century. The EHF metric highlights the extended duration of extreme heat, which would pose serious risks to public health, ecosystems, and agriculture as highlighted in the study of Dimitriadou *et al*. (2021).

Each metric showed a steeper increase in HWD by 2051-2100, highlighting the cumulative impacts of climate change on heatwaves over time. SSP585 consistently projects more intense and prolonged heatwave days than SSP245 across all three metrics, indicating that highemission scenarios will lead to more extreme heat stress. This increase in duration aligns with Guigma *et al*., (2020), which linked longer heatwave spans to prolonged heat exposure risks, especially in high-temperature regions like Burkina Faso. A higher nighttime HWD is a pressing concern as it suggests limited cooling opportunities, increasing mortality risks among vulnerable populations. Prolonged daytime heatwaves heighten agricultural and water demands, reduce crop yields, and increase the likelihood of droughts, echoing concerns raised by Boureima *et al*., (2017) on climate-induced drought risks in West African agriculture.

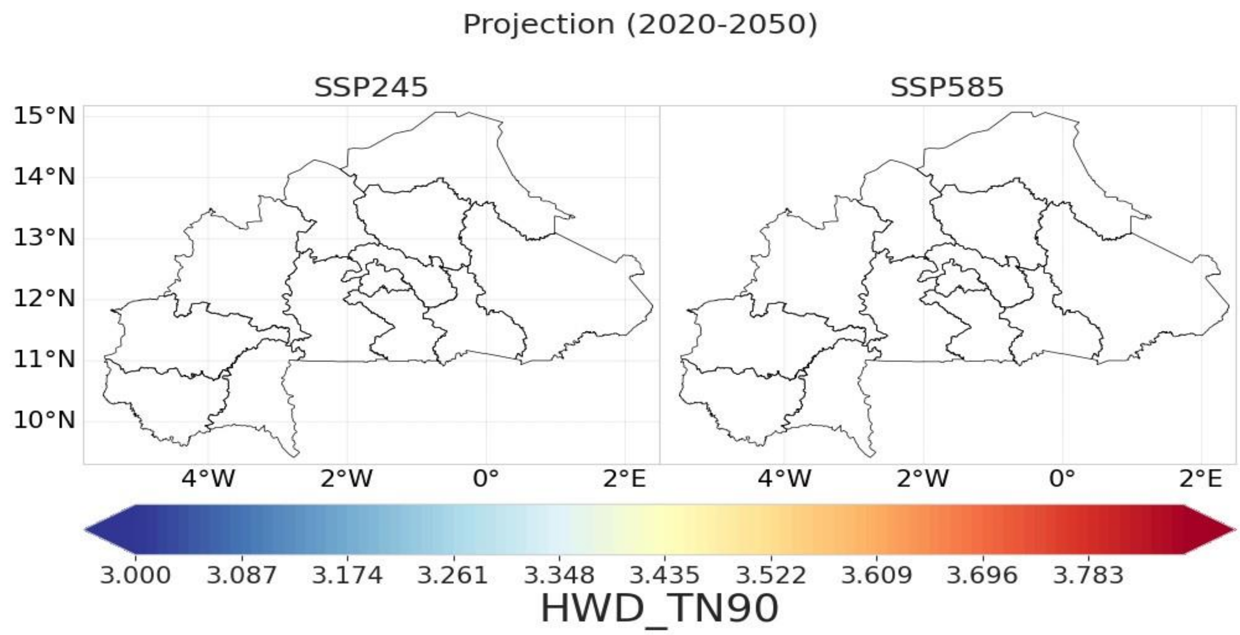

Figure 4. 45: Projection of heatwaves over Burkina Faso for HWD (Heat Wave Duration) Days for nighttime (TN90th percentile) from 2020 - 2050.

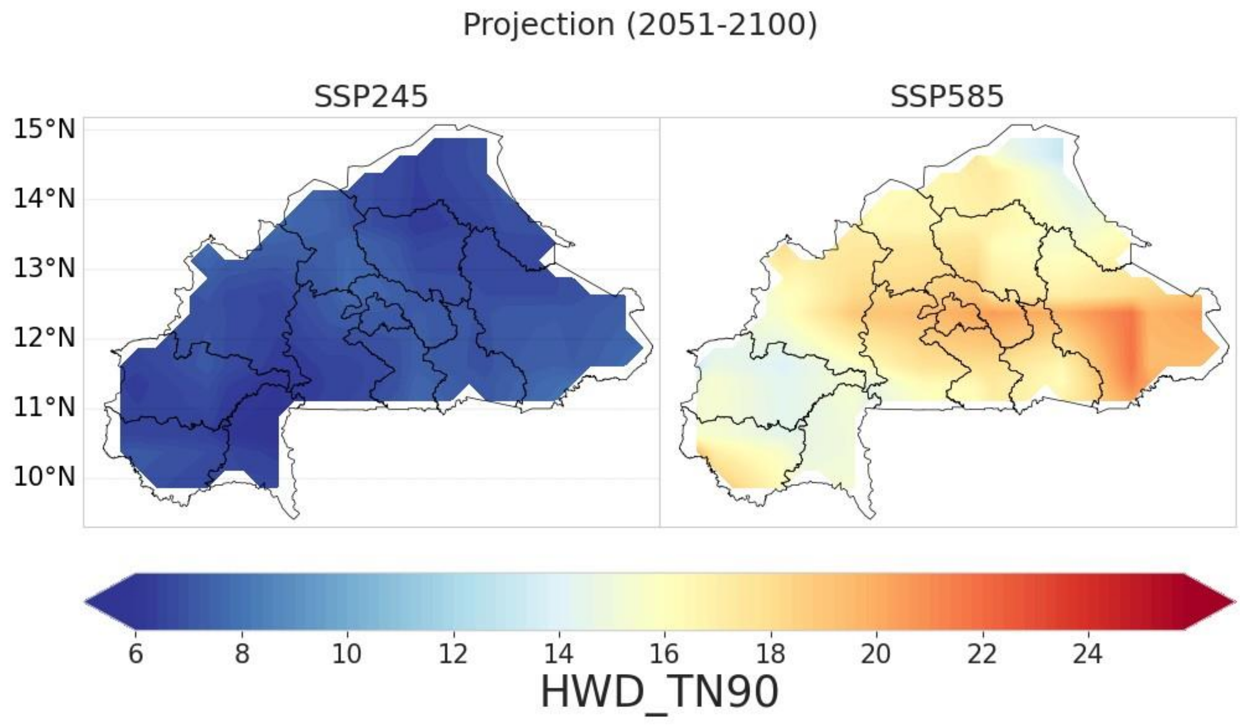

Figure 4. 46: Projection of heatwaves over Burkina Faso for HWD (Heat Wave Duration) Days for nighttime (TN90th percentile) from 2051 – 2100.

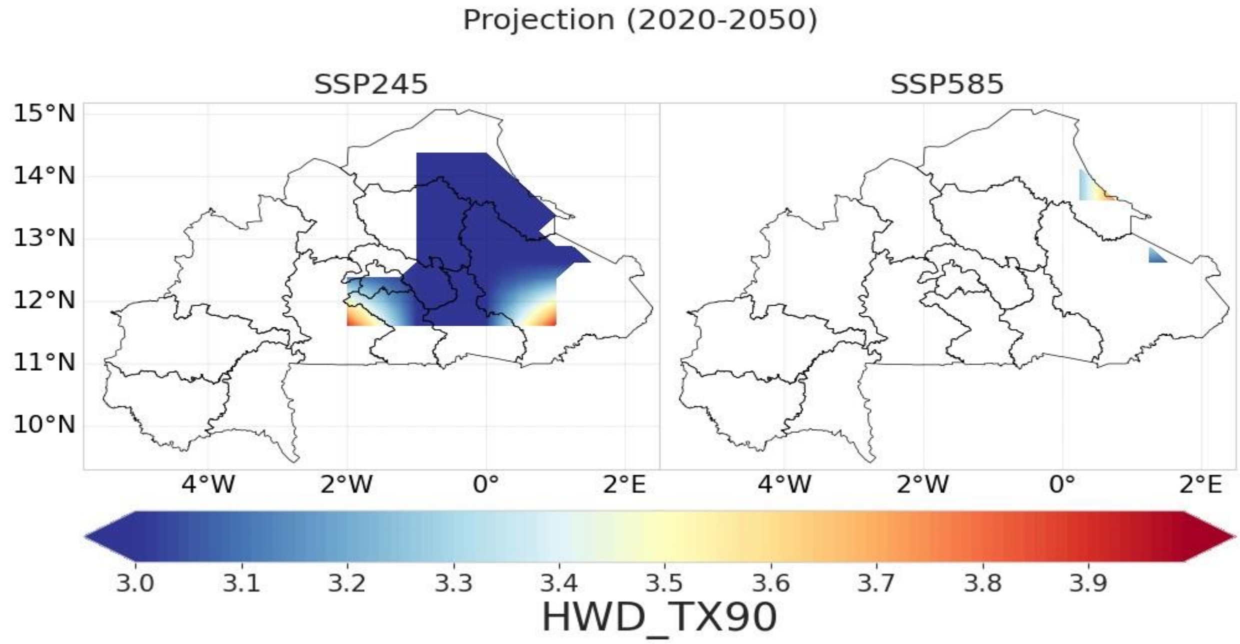

Figure 4. 47: Projection of heatwaves over Burkina Faso for HWD (Heat Wave Duration) Days for daytime (TX90th percentile) from 2020 – 2050.

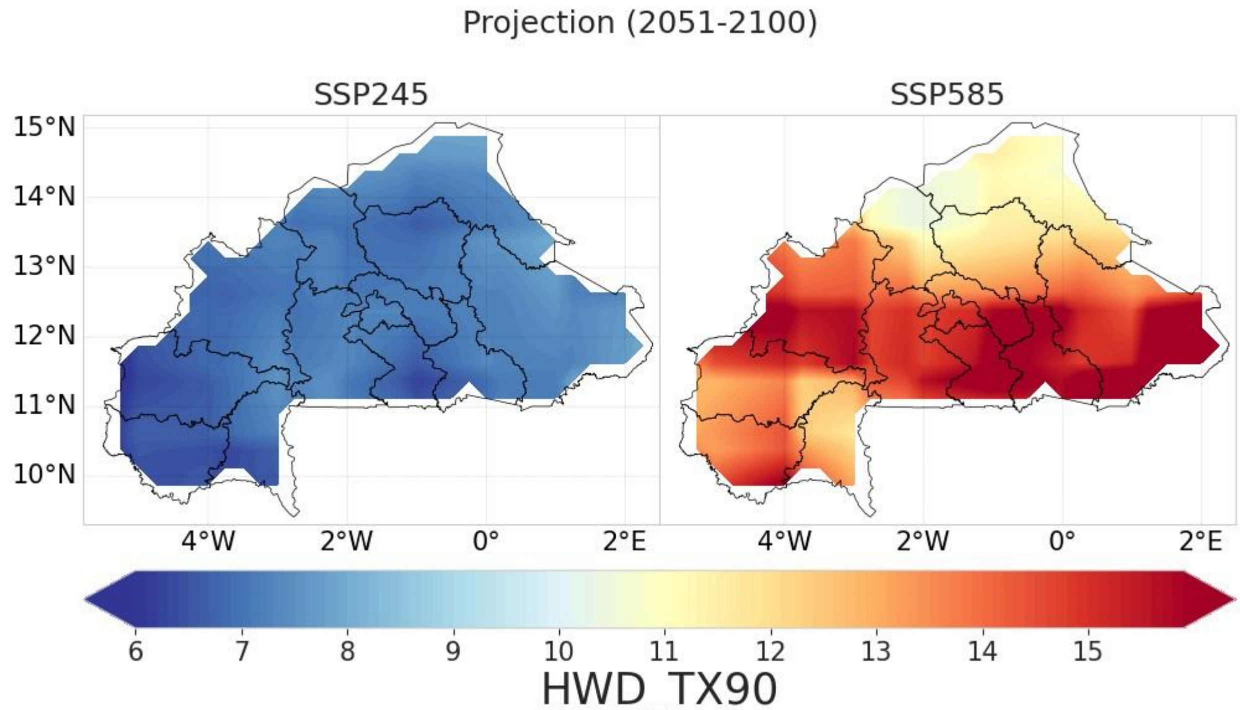

Figure 4. 48: Projection of heatwaves over Burkina Faso for HWD (Heat Wave Duration) Days for daytime (TX90th percentile) from 2051 – 2100

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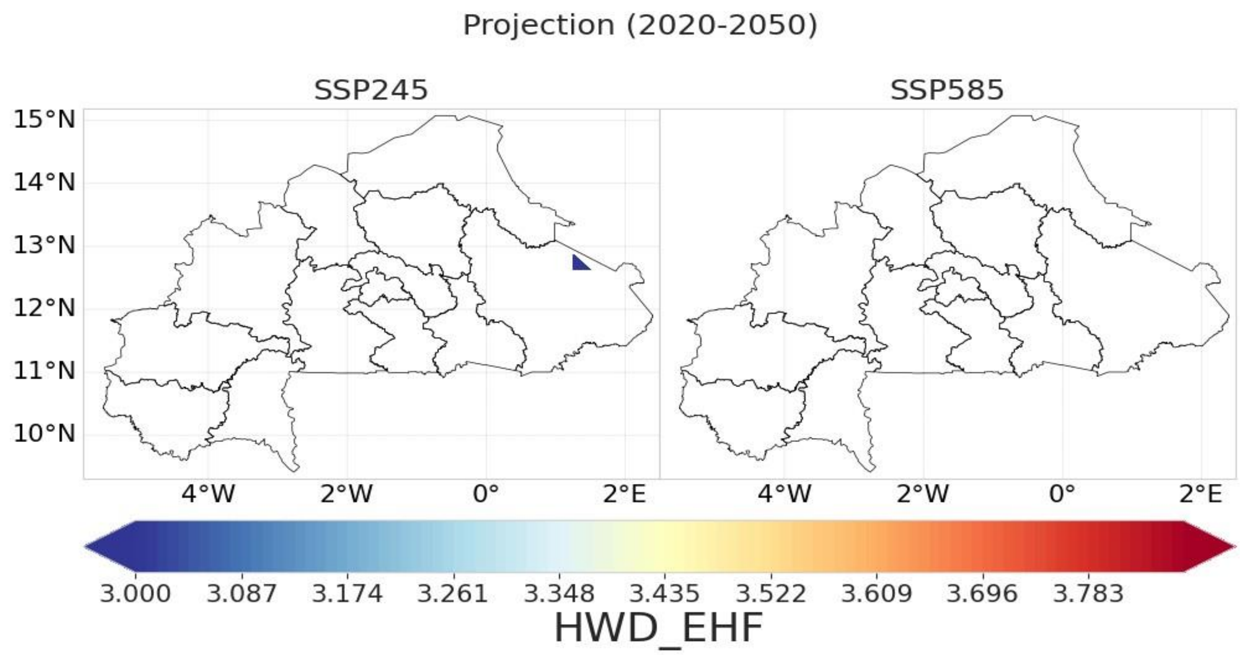

Figure 4. 49: Projection of heatwaves over Burkina Faso for HWD (Heat Wave Duration) Days for Excess Heat Factor (EHF) from 2020 – 2050.

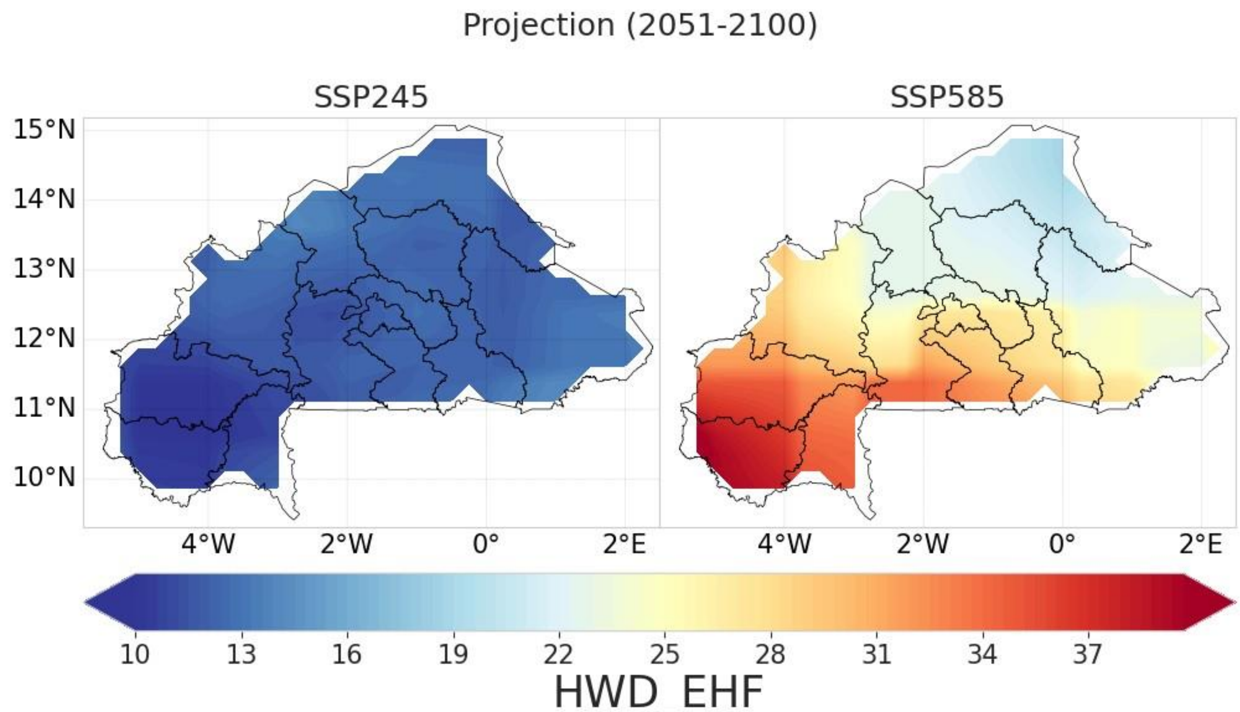

Figure 4. 50: Projection of heatwaves over Burkina Faso for HWD (Heat Wave Duration) Days for Excess Heat Factor (EHF) from 2051 – 2100.

The HWF_TN90 projected in the near future (Figure 4.52) showed a moderate increase for the two climate scenarios. Under the moderate-emission scenario (SSP245), there was a noticeable increase, primarily in the northeastern region of Burkina Faso (the frequency varies from approximately 0.0072 to 0.0144 events per unit time). In the SSP585 scenario, heatwave frequency based on minimum temperature was much more subdued and widespread across Burkina Faso. The HWF values in this high-emission scenario show minimal change compared to SSP245. This moderate increase suggests a moderate rise in nighttime events in the near future. In the far future, HWF_TN90 (Figure 4.53) continues to rise, with frequent nighttime heatwaves becoming more common across the country under SSP245, albeit at a manageable pace (up to 13 days per year). The southeast experienced a more moderate increase (11 days per year). Under SSP585, HWF_TN90 became extremely high, with frequent nighttime heatwaves across Burkina Faso ranging from 19 to 21 days. This poses severe health risks as nighttime relief from heat diminishes, increasing the chances of heat stress-related health issues. The projected HWF_TX90 for the near future (Figure 4.54) under SSP245 showed a decrease of -0.0013 days per year in eastern Burkina Faso, while other regions are expected to see a moderate increase, ranging from 0.06 to 0.16 days per year. Under SSP585, the frequency increases westward, reaching up to 0.29 days per year in the far west, while the south experienced a slight decrease at -0.0013 days per year. Overall, daytime heatwave frequency remained manageable in the near future projection. In the far future (Figure 4.55), SSP245 projected a steady increase in heatwave frequency, especially in the northern and central regions, with rates of 11 to 12 days per year, while the southern areas showed a more modest increase of 9 to 10 days per year. Under SSP585, daytime heatwave frequency is expected to rise sharply across Burkina Faso, reaching between 17 and 19 days per year. Such prolonged daytime heatwaves in SSP585 could have significant impacts on agriculture, energy demands, and human health.

The HWF_EHF projected for the near future (Figure 4.56) showed a moderate increase under SSP245, ranging from 0.012 to 0.086 days per year, with higher frequencies in the western region. Meanwhile, SSP585 projected a moderate rise across the entire study area, ranging from 0 to 0.012 days per year. In the far future, HWF_EHF (Figure 4.57) is expected to increase steadily across Burkina Faso under SSP245, reaching a peak of 18 days per year in the southern region and a low of 16 days per year in the northern region, indicating a consistent, though less intense, rise in prolonged heatwave frequency compared to SSP585. Under SSP585, HWF_EHF reached extreme levels, from 22 to 25 days per year, with frequent, prolonged heatwaves impacting all regions, especially in the south. This cumulative increase highlights the serious impacts of elevated daytime and nighttime temperatures on health, agriculture, and infrastructure.

The projected HWF showed a moderate increase in the near future across all three metrics (TN90, TX90, and EHF). This increase was more significant under SSP245, particularly in the northwestern region, compared to SSP585. In the far future, projections indicated a substantial rise in HWF across Burkina Faso, with the highest increases occurring under SSP585 by 2100, which could have serious implications for health, agriculture, and water resources (Ceccherini *et al.*, 2017). These projections underscore the need for climate adaptation and resilience planning across Burkina Faso, with targeted measures to address increased heatwave frequency and its impacts.

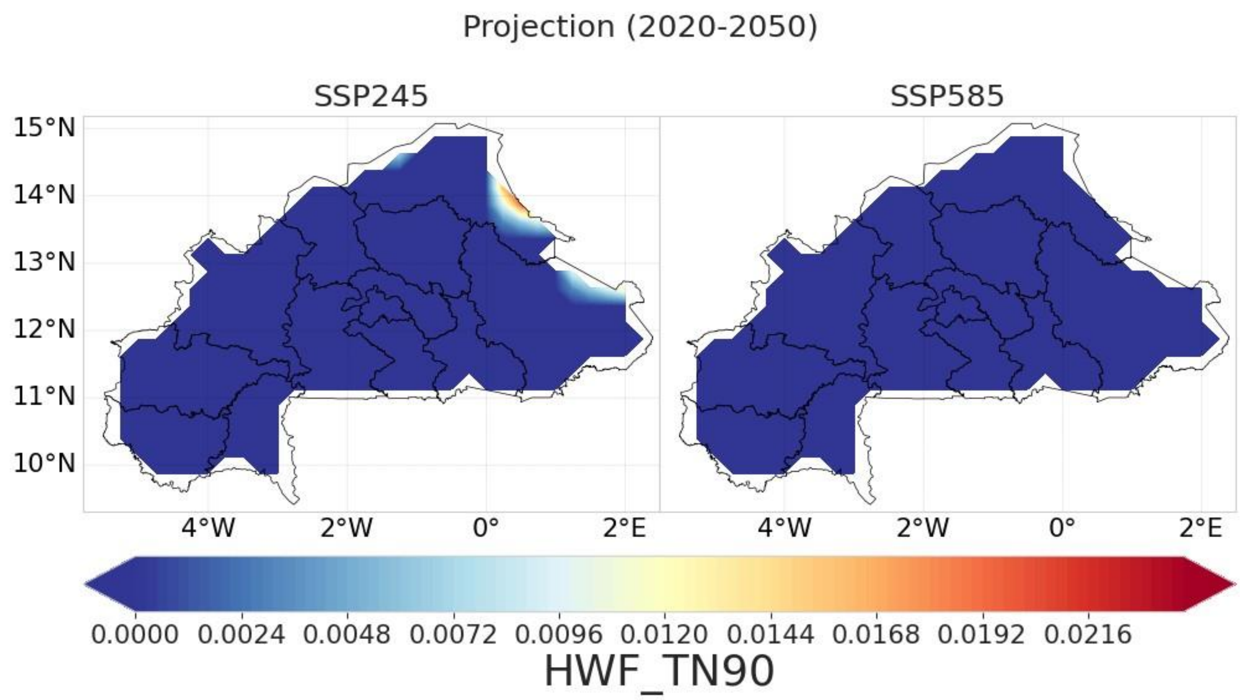

Figure 4. 51: Projection of heatwaves over Burkina Faso for HWF (Heat Wave Frequency) Days for nighttime (TN90th percentile) from 2020 - 2050.

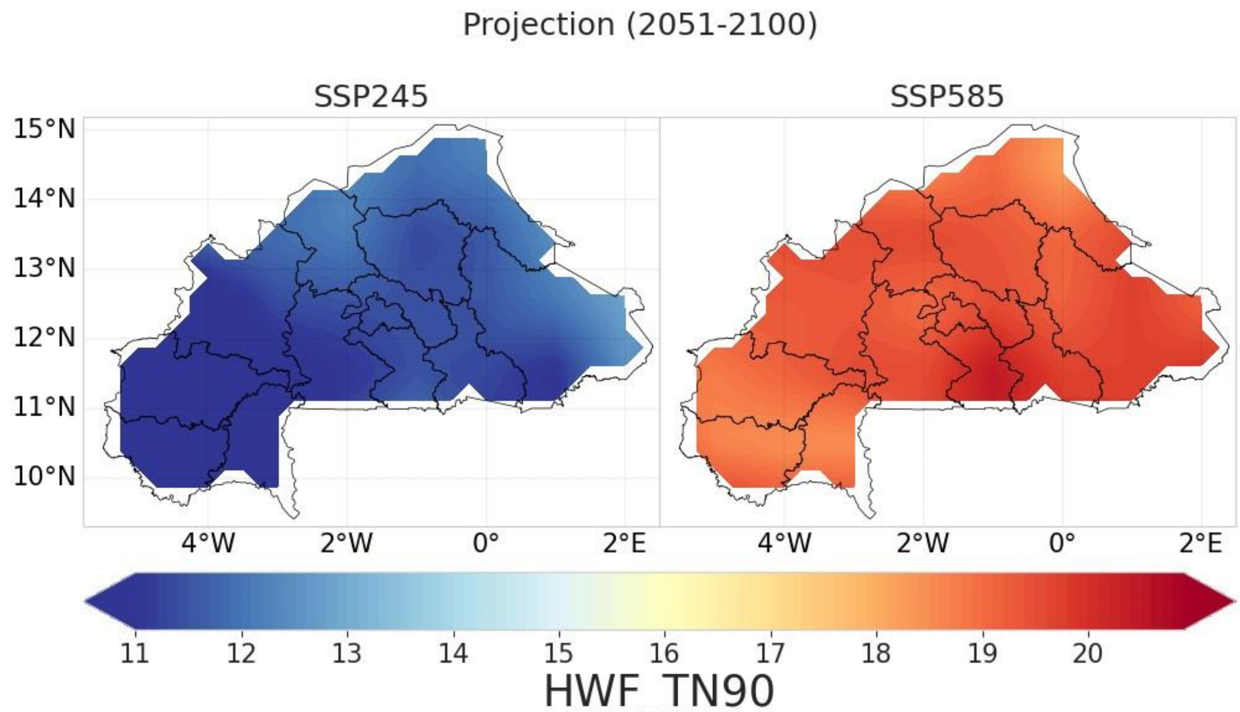

Figure 4. 52: Projection of heatwaves over Burkina Faso for HWF (Heat Wave Frequency) Days for nighttime (TN90th percentile) from 2051 - 2100.

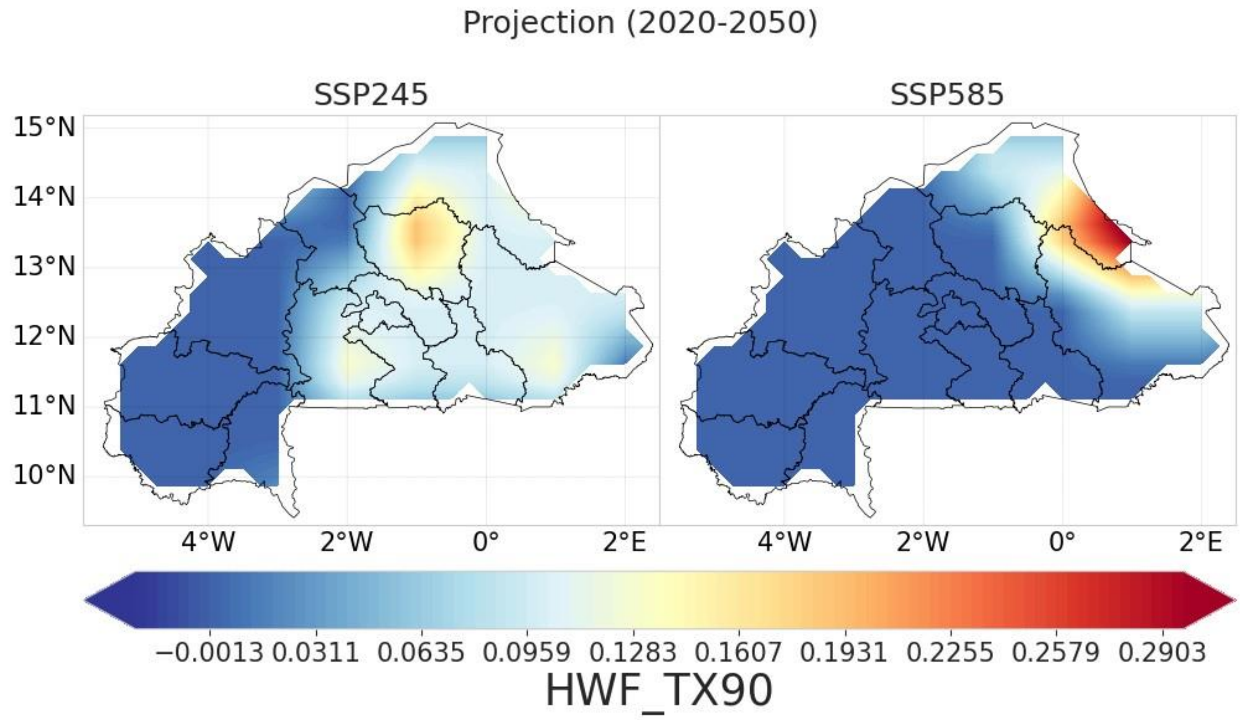

Figure 4. 53: Projection of heatwaves over Burkina Faso for HWF (Heat Wave Frequency) Days for daytime (TX90th percentile) from 2020 - 2050.

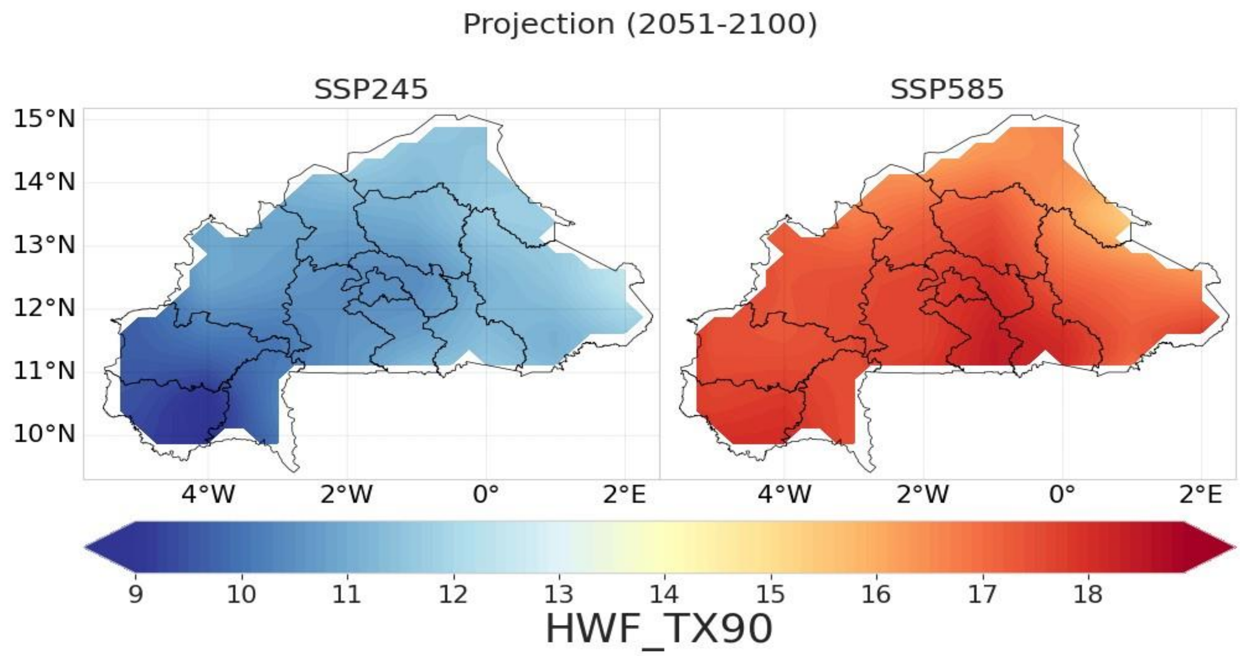

Figure 4. 54: Projection of heatwaves over Burkina Faso for HWF (Heat Wave Frequency) Days for daytime (TX90th percentile) from 2051 – 2100.

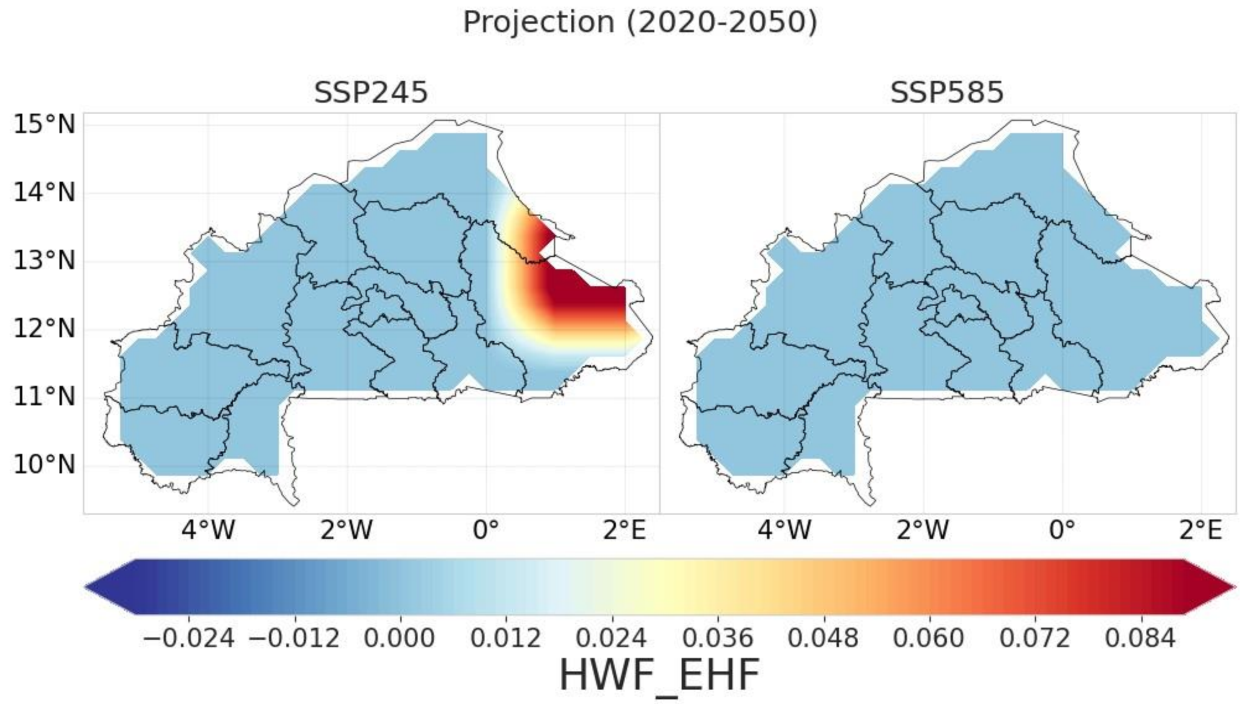

Figure 4. 55: Projection of heatwaves over Burkina Faso for HWF (Heat Wave Frequency) Days for Excess Heat Factor (EHF) from 2020 – 2050.

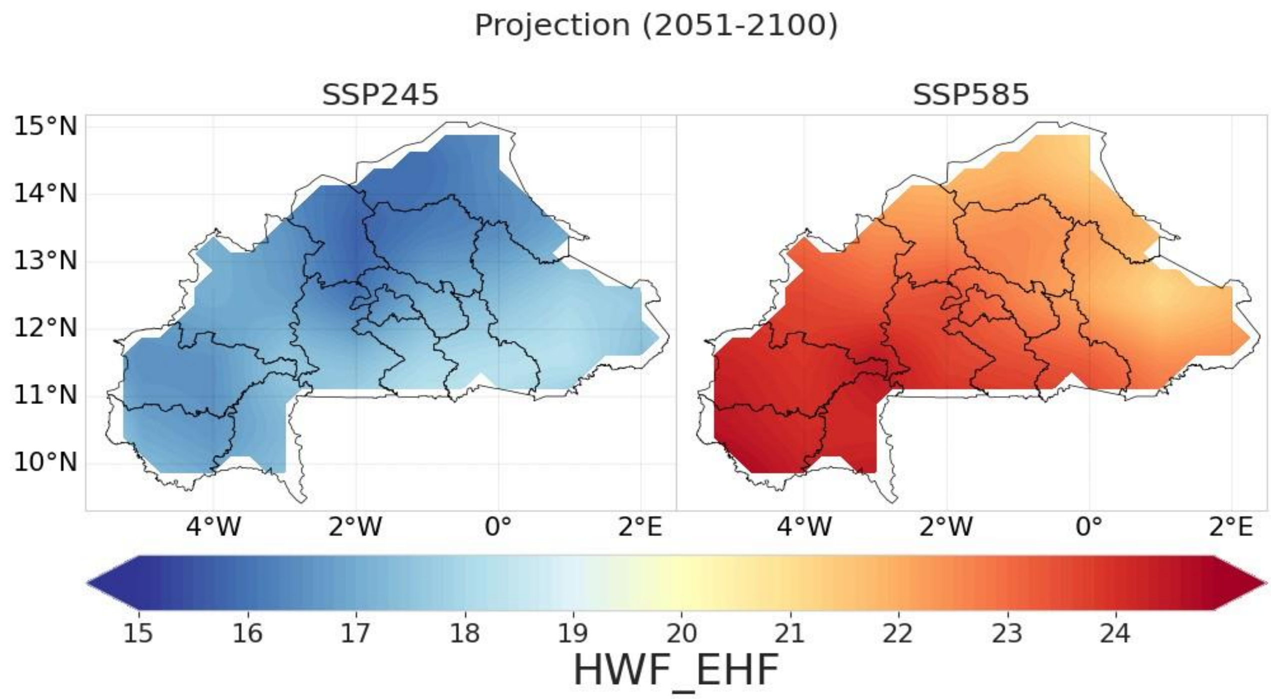

Figure 4. 56: Projection of heatwaves over Burkina Faso for HWF (Heat Wave Frequency) Days for Excess Heat Factor (EHF) from 2051 – 2100.

The near future projection of HWM_TN90 (Figure 4.57) showed that the heatwave magnitude remained relatively low across the country under SSP245 and SSP585. While the HWM_TN90 showed a significant increase in the far future (Figure 4.58) under SSP245, particularly in the northern regions where values approach 28°C to 29.6°C. In the southern and western regions, values are slightly lower (24°C to 27°C). This demonstrates a noticeable rise in heatwave intensity, but still not as extreme as under SSP585. Under the high-emission scenario, the HWM_TN90 increased sharply, with values reaching up to 32°C in northern Burkina Faso. This scenario suggests that by the end of the century, regions in the north and center will experience extreme nighttime temperatures during heatwaves, while the south and west, although experiencing lower values (28°C to 30°C), are still projected to endure significant increases in heatwave intensity.

The projected HWM_TX90 under SSP245 showed a localized increase in heatwave magnitude in the near future (Figure 4.59), with the north-central part of Burkina Faso experiencing the most significant rise, reaching up to 37.6°C. Other regions exhibit more moderate temperature increases. Under SSP585, projected heatwave magnitudes remained comparatively subdued.

The projections in the far future (Figure 4.60) showed that by the end of the century, HWM_TX90 values under SSP245 increase more significantly across Burkina Faso. Northern regions, particularly in the northeast, showed higher magnitudes, with temperatures ranging from 37.6°C to 40.3°C. The SSP585 scenario projects extreme increases in heatwave magnitude by 2100, particularly in northern Burkina Faso. Here, maximum heatwave temperatures reach over 42.1°C, with most regions experiencing temperatures above 40°C. The difference between SSP245 and SSP585 is most pronounced in the north, where temperatures in SSP585 are substantially higher.

The near-future projection of HWM_EHF (Figure 4.61) showed a moderate increase across

Burkina Faso under both SSP245 and SSP585 scenarios. In the far future (Figure 4.62), however, a significant northward increase is anticipated in both scenarios. Under SSP245, the increase ranges from 0.1°C to 0.38°C, while under SSP585, the increase is more substantial, ranging from 0.38°C in the south to 0.49°C in the extreme north.

The projected HWM, which combines both amplitude and duration, indicated a moderate increase in the near future across all three metrics (TN90, TX90, and EHF), with a more pronounced rise under SSP245, especially in the northwest, compared to SSP585. In the far future, projections showed a significant northward increase in HWM across Burkina Faso, with the largest increases expected under SSP585 by 2100. These changes could seriously affect health, agriculture, and water resources. Perkins-Kirkpatrick and Lewis (2020) have shown that under high-emission scenarios, heatwaves not only become more frequent but also more severe, with the cumulative thermal stress exerted by prolonged and intense heat events significantly affecting populations in vulnerable regions like West Africa. The combined nighttime and daytime intensity increase suggests that Burkina Faso will face sustained and extreme thermal conditions, making adaptation strategies essential. This heightened intensity will affect water and energy systems and agricultural productivity, as sustained heat magnitudes increase crop and labor stress (Campbell *et al*., 2018a).

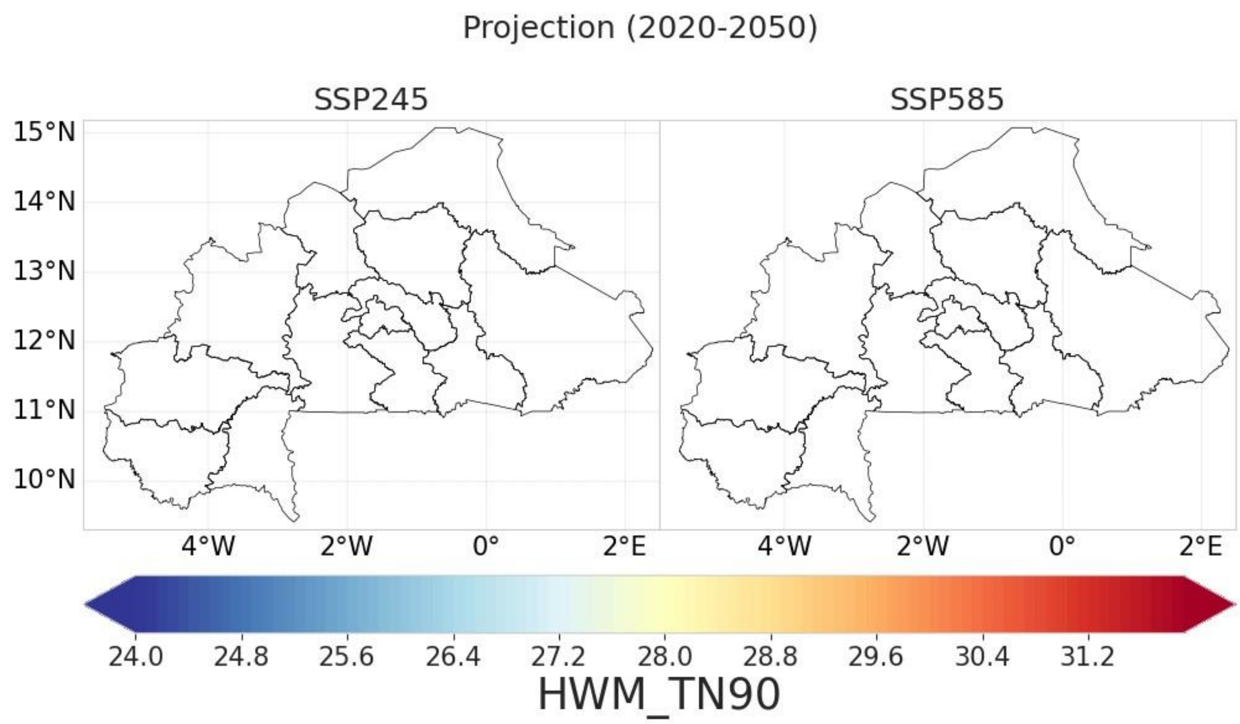

Figure 4. 57: Projection of heatwaves over Burkina Faso for HWM (Heat Wave Magnitude Index) for nighttime (TN90th percentile) from 2020 - 2050.

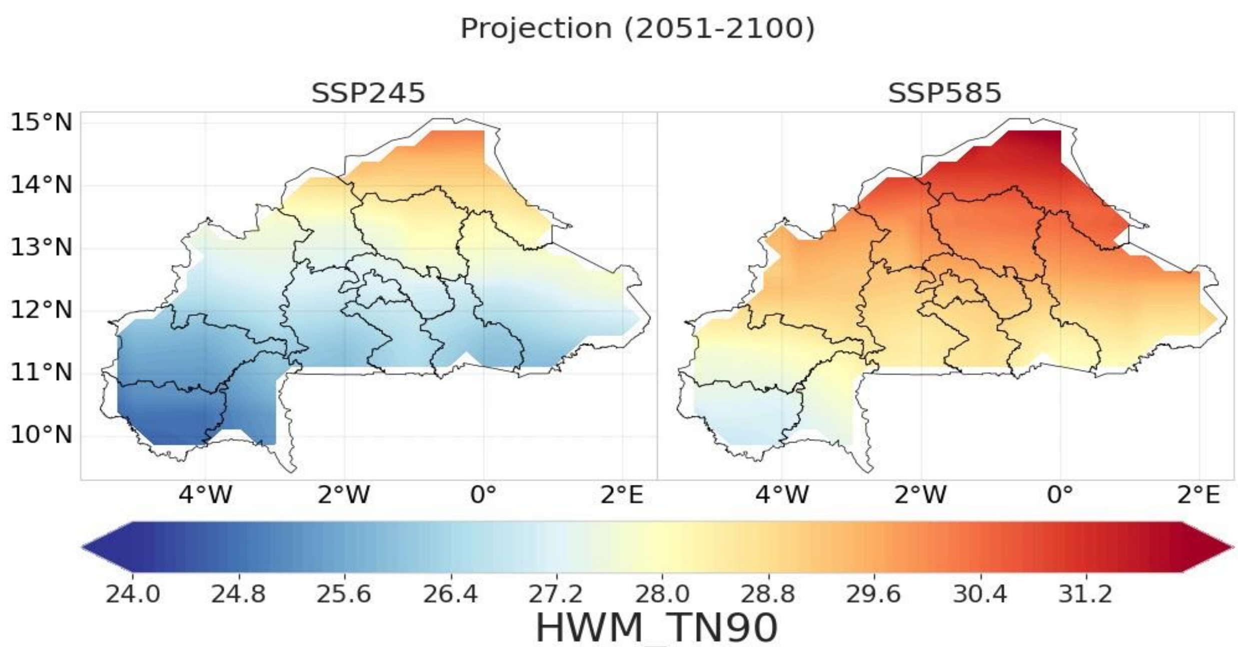

Figure 4. 58: Projection of heatwaves over Burkina Faso for HWM (Heat Wave Magnitude Index) for nighttime (TN90th percentile) from 2051 - 2100.

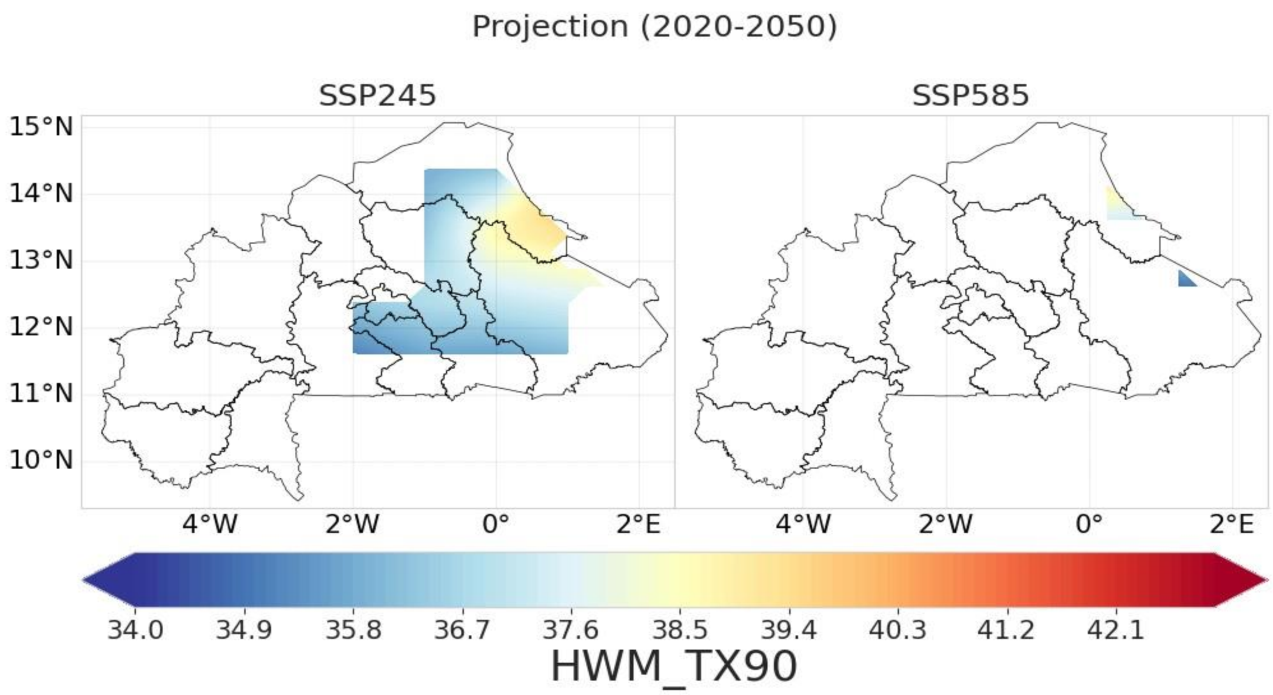

Figure 4. 59: Projection of heatwaves over Burkina Faso for HWM (Heat Wave Magnitude Index) for daytime (TX90th percentile) from 2020 - 2050.

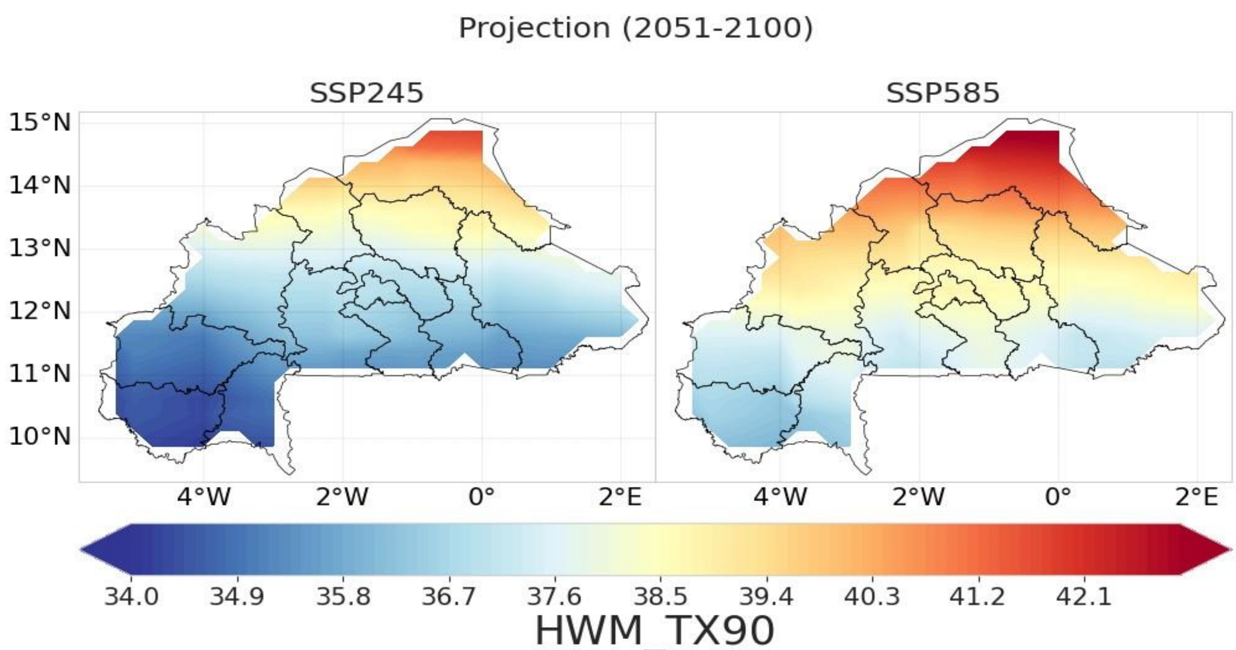

Figure 4. 60: Projection of heatwaves over Burkina Faso for HWM (Heat Wave Magnitude Index) for daytime (TX90th percentile) from 2051 - 2100.

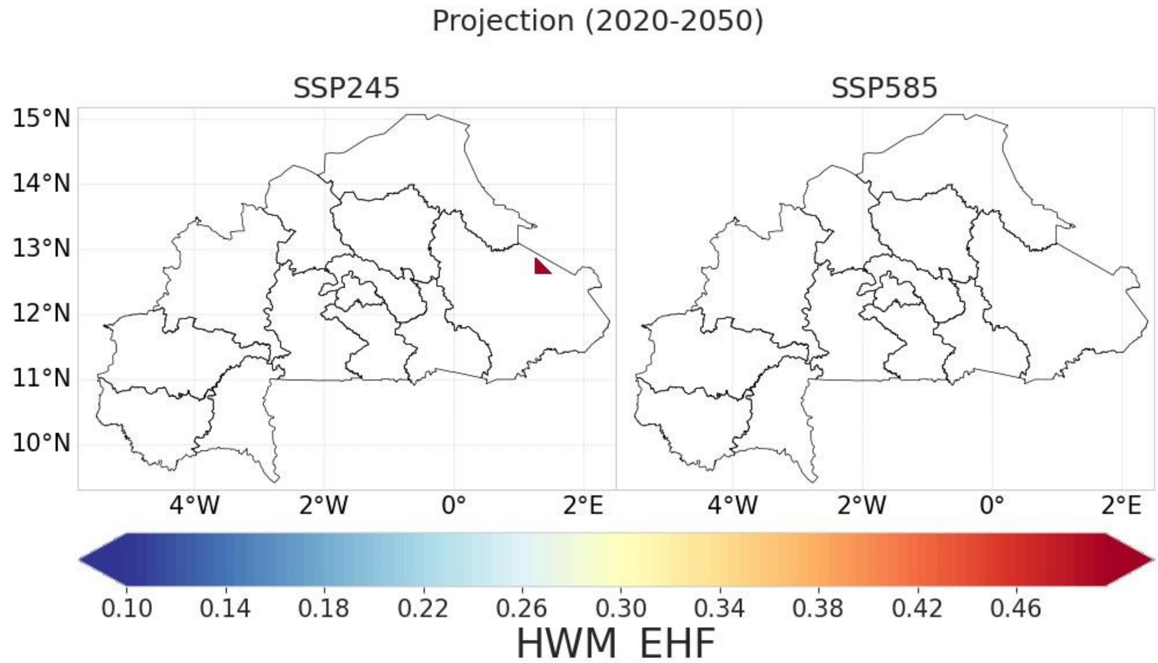

Figure 4. 61: Projection of heatwaves over Burkina Faso for HWM (Heat Wave Magnitude Index) for Excess Heat Factor (EHF) from 2020 - 2050.

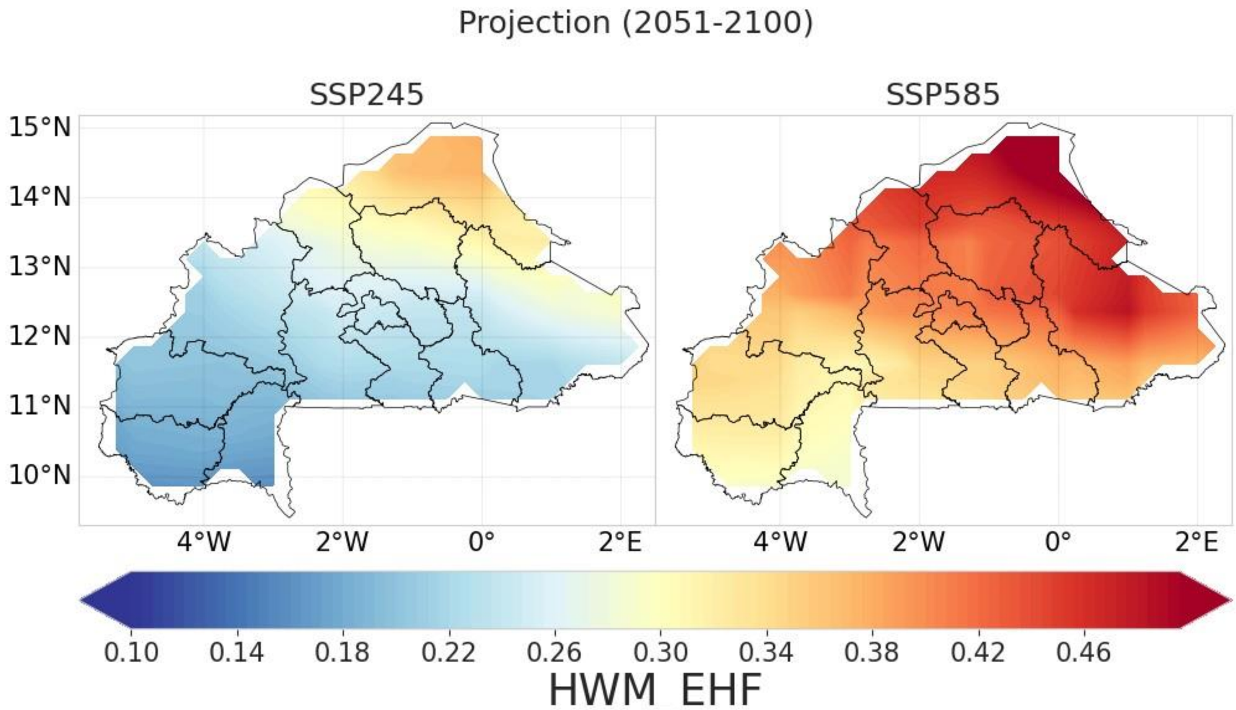

Figure 4. 62: Projection of heatwaves over Burkina Faso for HWM (Heat Wave Magnitude Index) for Excess Heat Factor (EHF) from 2051 - 2100.

In the SSP245 scenario, the northwestern region of Burkina Faso showed a significant rise in HWN_TN90, with values of 0.016 (represented by red and orange areas on the map) in the near future (Figure 4.63). This indicates a moderate increase in heatwave days in this area, while the rest of the country experiences little to no change. Conversely, the SSP585 scenario shows minimal variation across the country, suggesting that the heatwave frequency for minimum temperatures remains largely unchanged in this scenario for the near future. In the far future, projections under the SSP245 scenario showed an increase in HWN_TN90 (Figure 4.64) across Burkina Faso, particularly the northern and central regions experiencing up to 2.72 events per year. Under the SSP585 scenario, there was a more substantial rise in HWN_TN90 across the country, ranging from 2.58 to 2.93 events per year, particularly in the northern and southeastern regions. This suggests a notable increase in the number of heatwave days.

The projected HWN_TX90 for the near future (Figure 4.65) under SSP245 shows increased heatwave events across Burkina Faso. The frequency of events rose from east to west, ranging from 0 to 0.04, with the central northern region experiencing the highest number of heatwave events at 0.064. Similarly, the SSP585 projection also indicated a moderate increase toward the west, with values ranging from 0 to 0.08 across the country. The far-future projection of HWN_TX90 (Figure 4.66) showed increased heatwave events under both scenarios, with a more pronounced rise in SSP585, where values range from 2.57 to 2.9 events per year. The western regions experience fewer heatwave events compared to other areas in SSP585. In SSP245, the increase is more moderate, with values ranging from 2 to 2.35events.

The near future projection for HWN_EHF (Figure 4.67) indicated a moderate rise under both SSP245 and SSP585 across Burkina Faso, with a notable increase in western Burkina Faso reaching up to 0.029 events under SSP245. In the far future (Figure 4.68), however, significant increases in HWN_EHF are projected nationwide under both scenarios. By the end of the century, the increase is expected to be more substantial under SSP245, ranging from 2.55 to

2.9 events per year, compared to SSP585, where the range is between 1.8 and 2.4 events per year.

The projected HWN showed a moderate increase in the near future across TN90, TX90, and EHF, with a more noticeable rise under SSP245, particularly in the western region, compared to SSP585. In the far future, projections indicated a substantial increase in HWN across Burkina Faso, with the largest rises anticipated under SSP585 by 2100, except for HWN_EHF, which is expected to increase more under SSP245. These changes could seriously affect health, agriculture, and water resources. This aligns with research by Odoulami *et al.*, (2017), who observed that climate change will likely increase the occurrence and intensity of extreme heat events, thus calling for a more integrated adaptation strategy in West African regions like Burkina Faso.

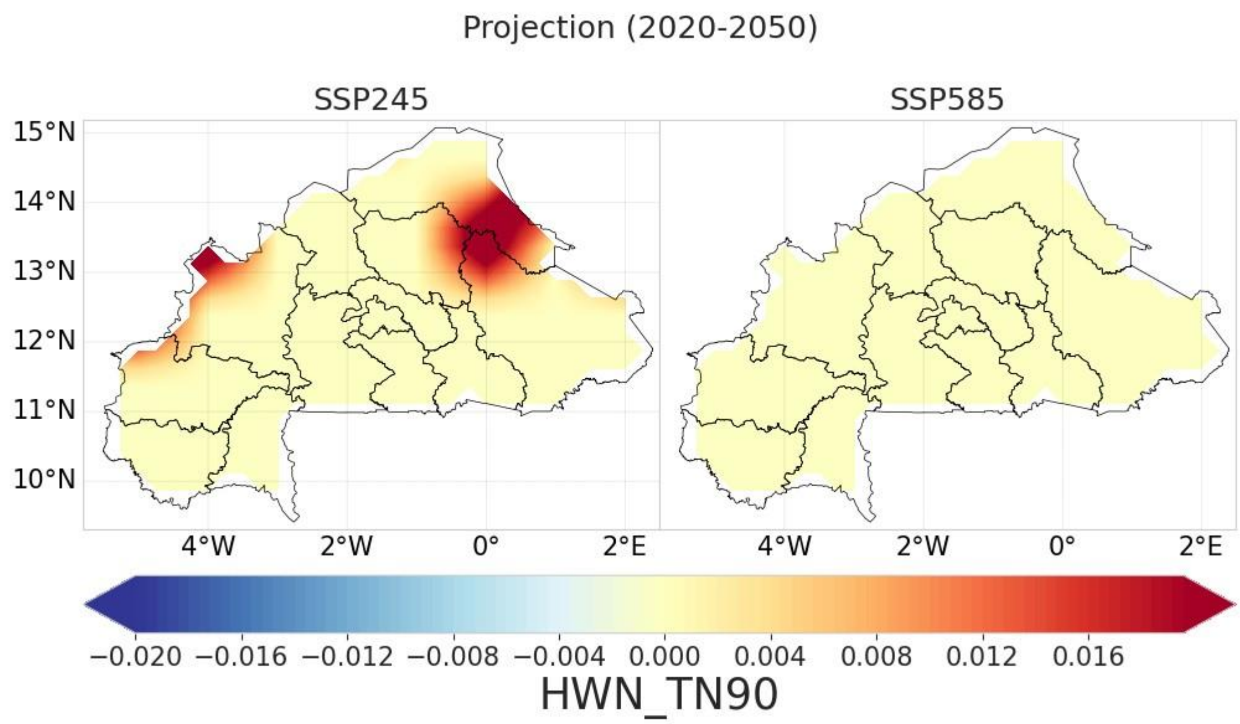

Figure 4. 63: Projection of heatwaves over Burkina Faso for HWN (Heat Wave Number) for nighttime (TN90th percentile) from 2020 - 2050.

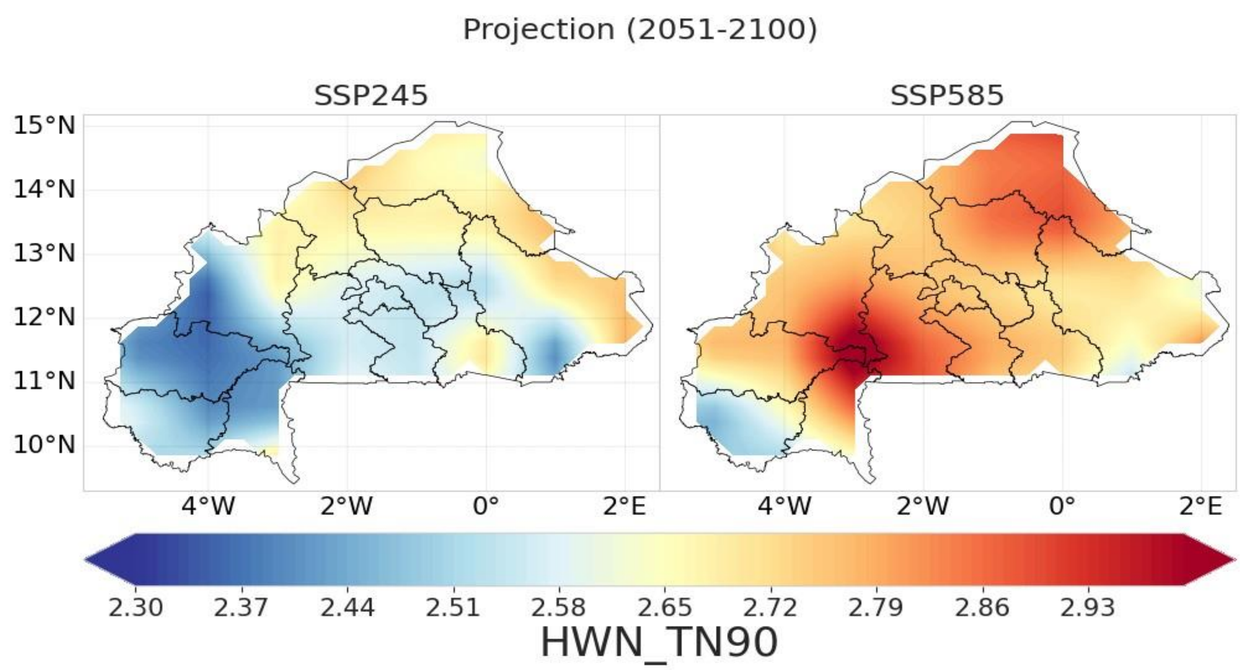

Figure 4. 64: Projection of heatwaves over Burkina Faso for HWN (Heat Wave Number) for nighttime (TN90th percentile) from 2051 - 2100.

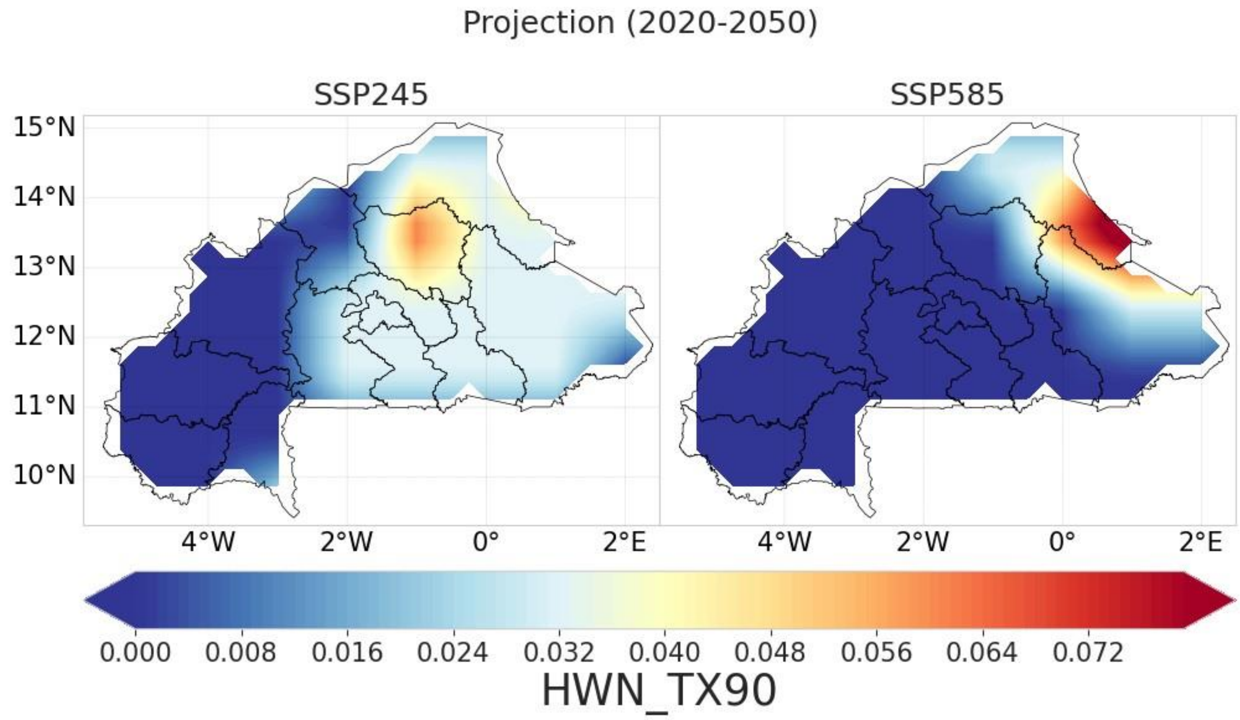

Figure 4. 65: Projection of heatwaves over Burkina Faso for HWN (Heat Wave Number) for daytime (TX90th percentile) from 2020 - 2050.

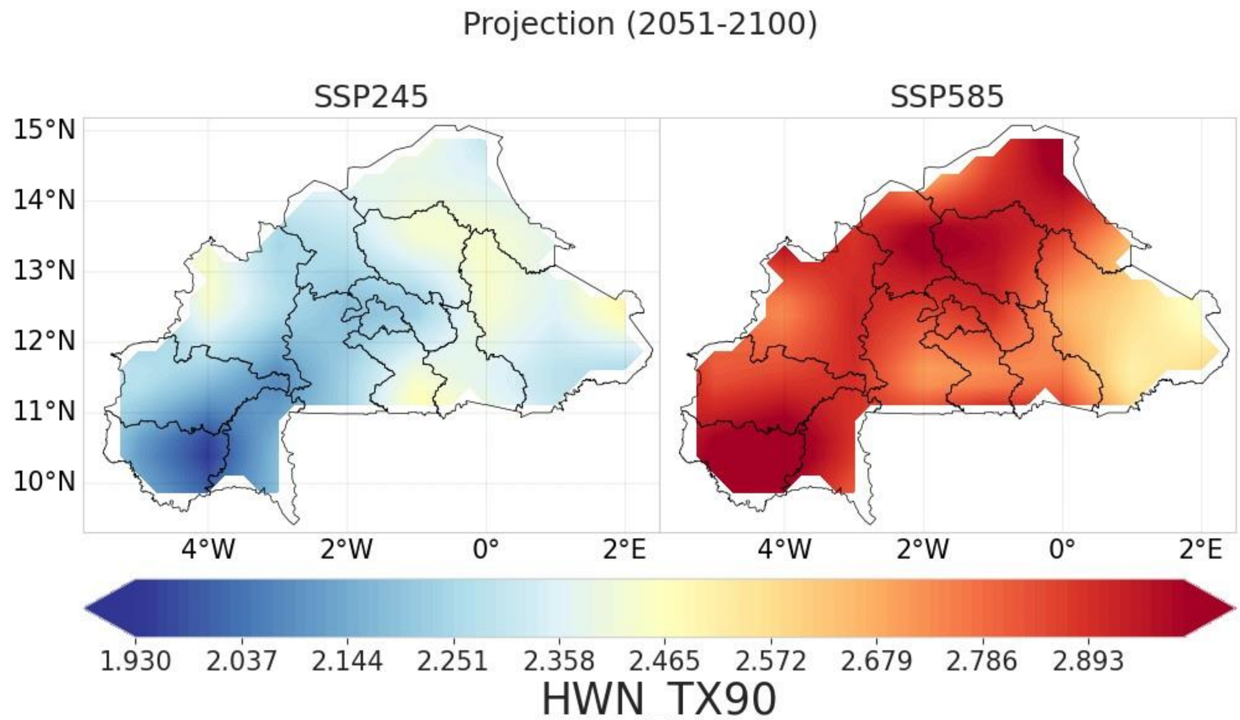

Figure 4. 66: Projection of heatwaves over Burkina Faso for HWN (Heat Wave Number) for daytime (TX90th percentile) from 2051 - 2100.

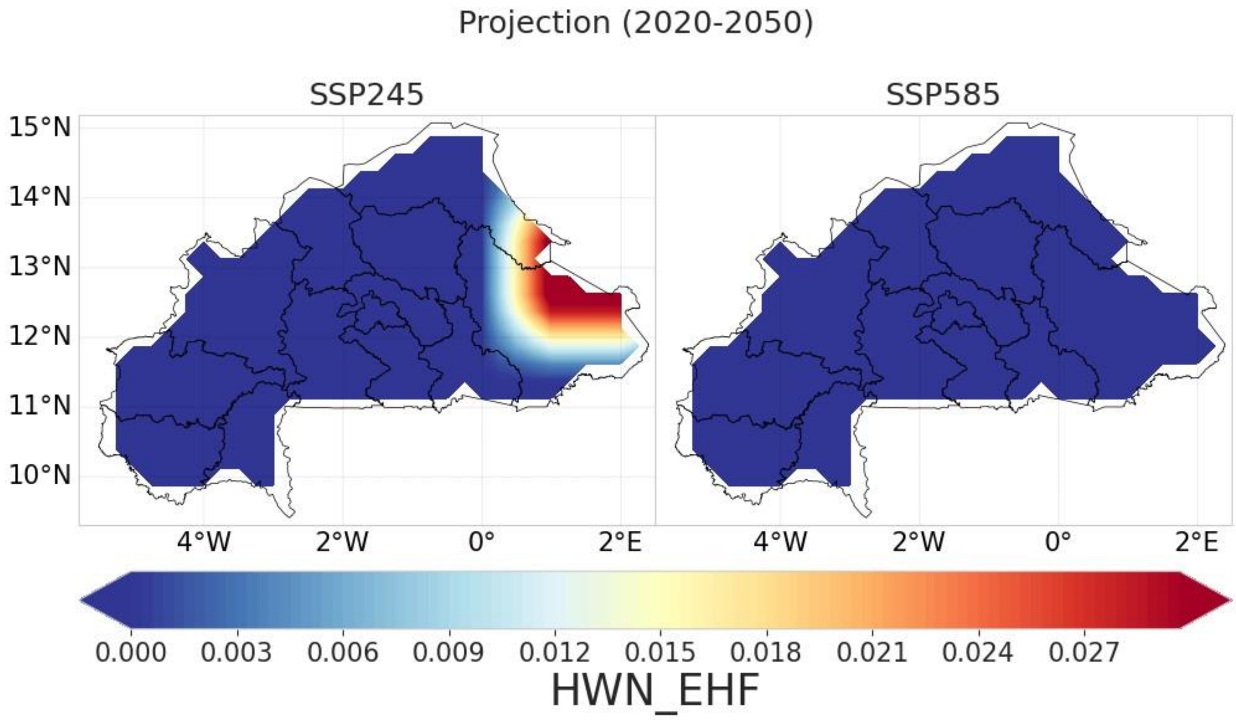

Figure 4. 67: Projection of heatwaves over Burkina Faso for HWN (Heat Wave Number) for Excess Heat Factor (EHF) from 2020 - 2050.

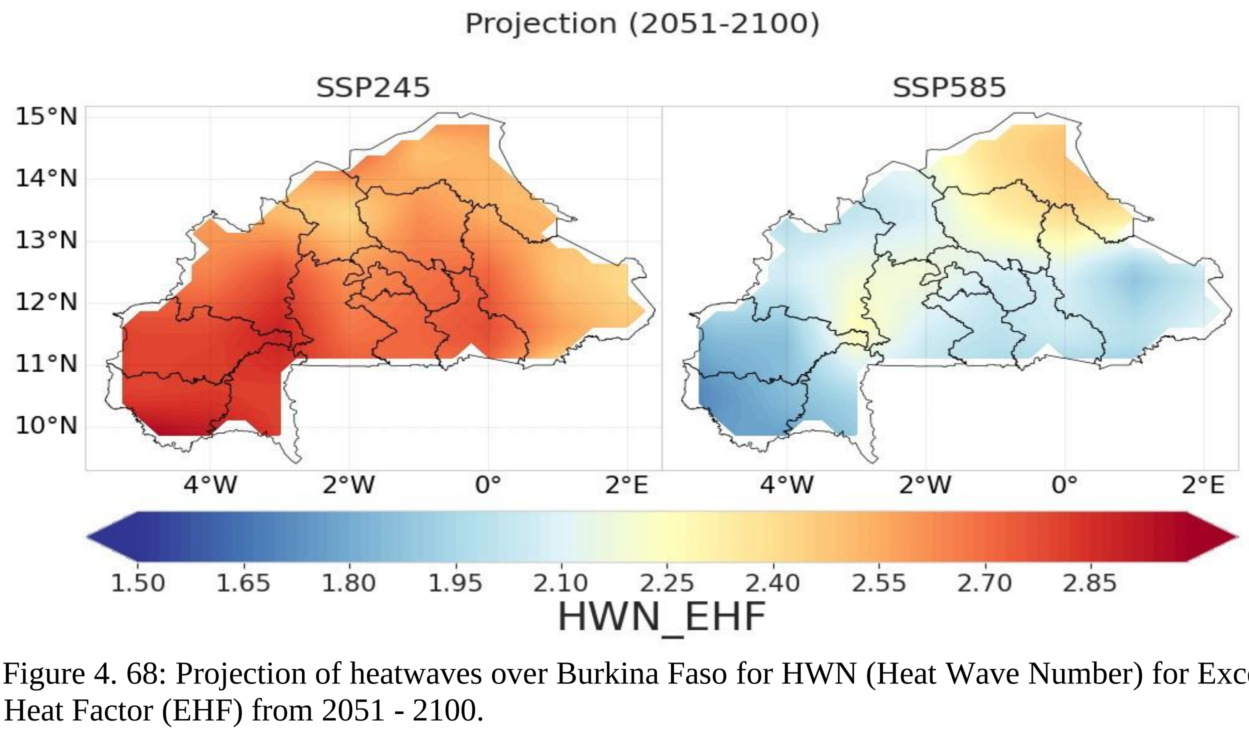

Figure 4. 68: Projection of heatwaves over Burkina Faso for HWN (Heat Wave Number) for Excess Heat Factor (EHF) from 2051 - 2100.

4.3.2 Heatwave Trends Projection

The near future (2020-2050) trend projection of HWA for the three indices, TN90, TX90 and EHF (Figures 4.69, 4.71 and 4.73 respectively), showed no colour in either the SSP245 or SSP585 projections. This indicates that there is no trend in the nighttime, respectively, daytime and EHF-based heatwave amplitude across Burkina Faso. The lack of colour suggests that the change in heatwave amplitude is too small to be depicted on the scale provided, meaning that the model does not project substantial increases or decreases in the amplitude of heatwaves for the near future under either scenario. The lack of values in specific years could be attributed to interannual variability, where conditions did not meet the threshold for heatwave classification in those years, resulting in an absence of recorded heatwave amplitude values.

In the far future (2051-2100), HWA_TN90 (Figure 4.70) revealed distinct patterns of nighttime heatwave amplitude change across Burkina Faso, with differences between SSP245 and SSP585. Under SSP245, the map showed a mix of negative and positive trends. Negative trends are most prevalent in the northern and southeastern regions, while positive trends are observed primarily in the western and central parts of the country. Under SSP585, the projections showed a more widespread increase in heatwave amplitude across Burkina Faso, with positive trends dominating. The most substantial increases occur in the central, southeastern, and northeastern regions, with values reaching approximately 0.19^{o}C. This scenario indicates a more intense increase in heatwave amplitude across the country. The trend projection of HWA_TX90

(Figure 4.72) revealed a difference between the two scenarios. Under SSP245, most areas of Burkina Faso showed a negative trend in heatwave amplitude. The presence of dotted regions suggests that these negative trends are statistically significant, especially in the central and southwestern parts. In contrast, SSP585 showed a positive trend in HWA_TX90 over large parts of the northern and northeastern areas, with statistically significant positive trends in these regions. This indicates an increase in heatwave intensity in these areas. The long-term trend projection of HWA_EHF (Figure 4.74) showed a positive trend across the study area for both climate scenarios. Under SSP245, this trend is statistically significant throughout the region, with a modest increase of 0.005°C. In contrast, under SSP585, the trend is more pronounced, ranging from 0.067°C to 0.083°C across most of Burkina Faso, except in the eastern region, where the trend is not statistically significant. The stark contrast between SSP245 and SSP585 suggests that under higher emissions (SSP585), Burkina Faso may experience more intense and frequent heatwaves in the second half of the century, particularly in northern regions.

The projected increasing trend in Heat Wave Amplitude (HWA) by the end of the century is consistent with studies documenting the effects of rising temperature extremes on West Africa. Moron *et al*., (2016) and Russo *et al.*, (2014) provide extensive evidence that West African temperatures are rising, with nighttime minimum temperatures contributing significantly to the overall warming trend. As observed, this increase in nighttime temperatures is particularly concerning because it limits cooling periods crucial for recovery during heatwave events. Russo *et al*., (2014) emphasize that nighttime heat stress will heighten under these conditions, straining human health and hindering agricultural resilience. Boureima *et al*., (2017) and Guigma *et al*., (2020) further support for this highlights the Sahel region's susceptibility to intensified heatwaves due to climate change. These heat waves have significant impacts on vulnerable populations who may lack access to cooling resources. The projected increases in HWA thus indicate profound health implications, especially in areas with limited infrastructure.

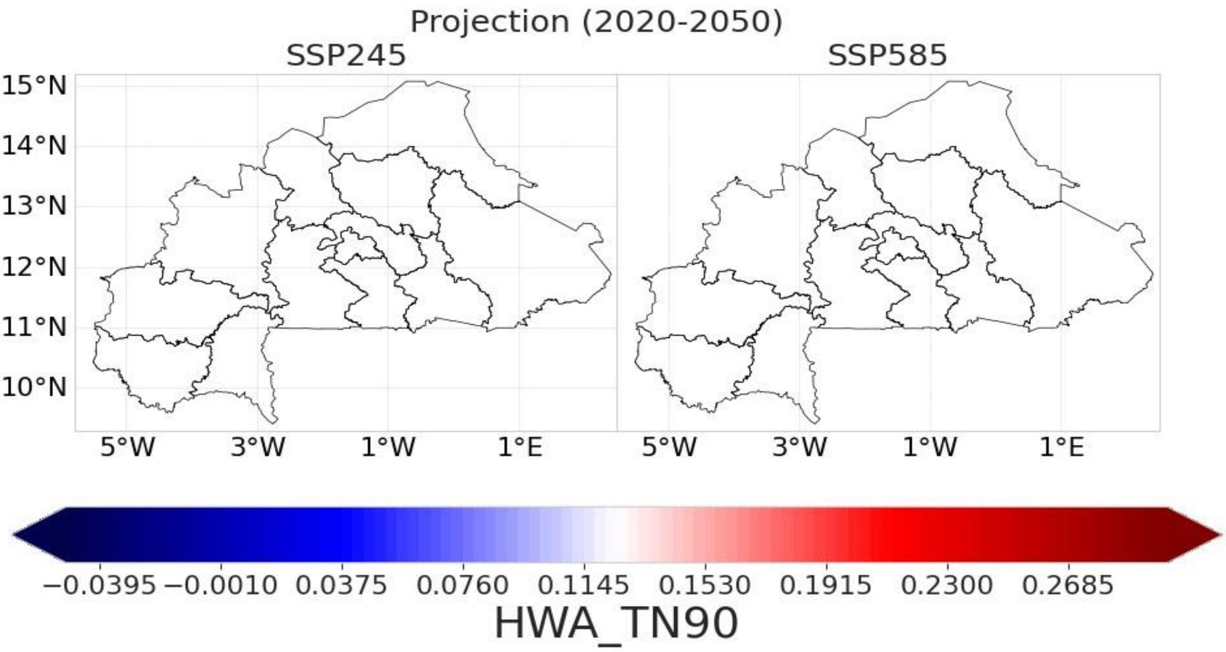

Figure 4. 69: Projected Trend analysis of heatwaves over Burkina Faso for HWA (Heat Wave Amplitude) °C for nighttime (TN90th percentile) from 2020 - 2050.

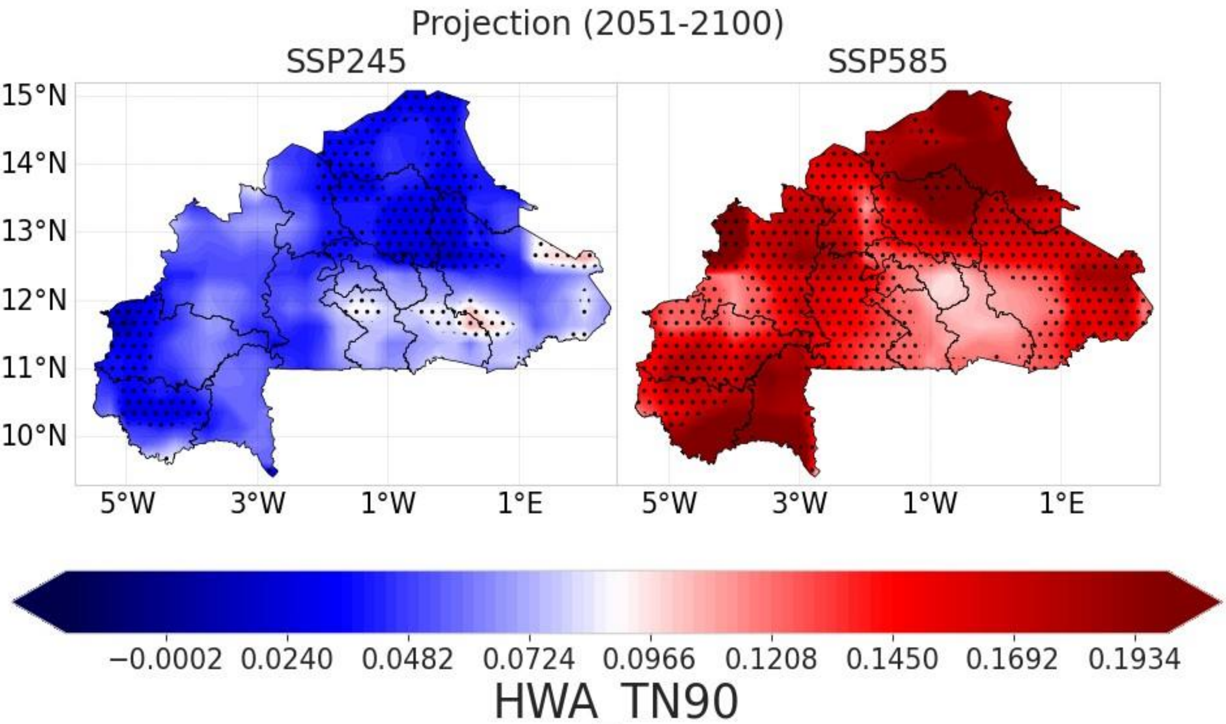

Figure 4. 70: Projected Trend analysis of heatwaves over Burkina Faso for HWA (Heat Wave Amplitude) °C for nighttime (TN90th percentile) from 2020 - 2050.

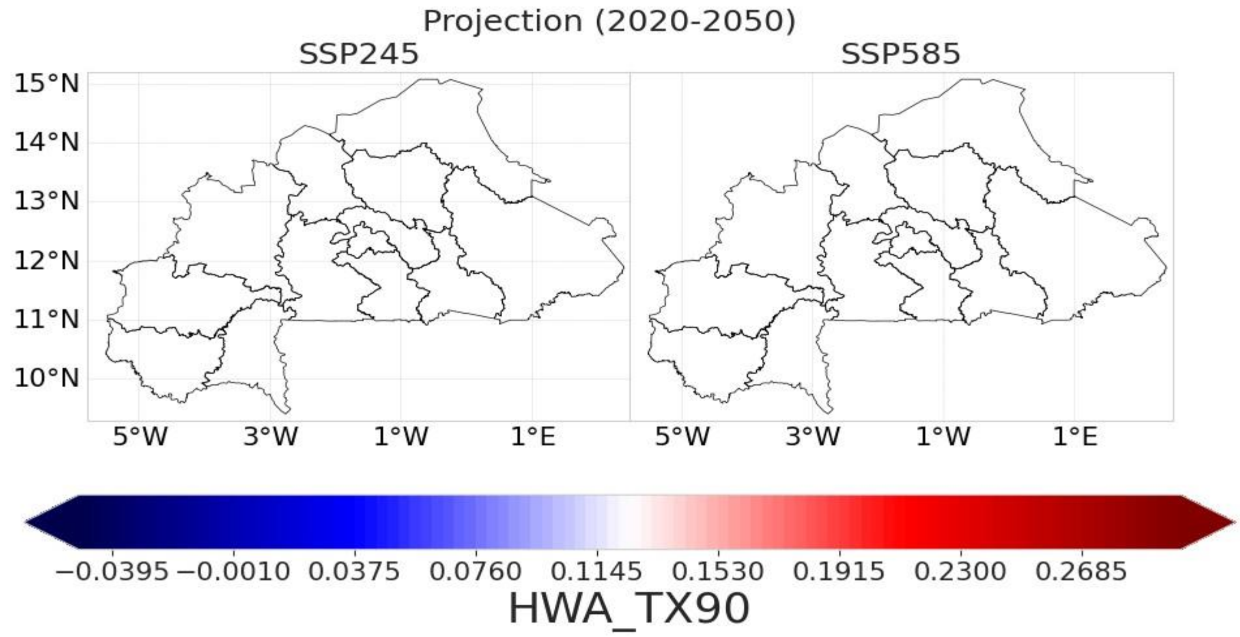

Figure 4. 71: Projected Trend analysis of heatwaves over Burkina Faso for HWA (Heat Wave Amplitude) °C for daytime (TX90th percentile) from 2020 - 2050.

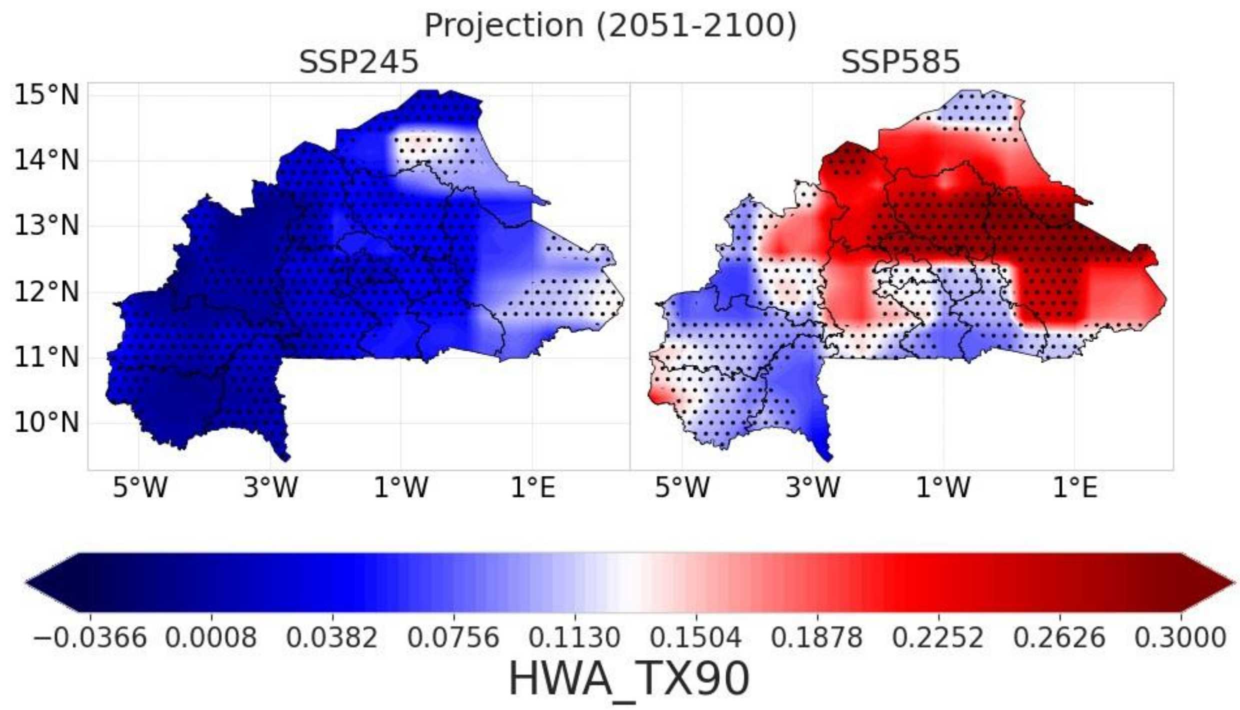

Figure 4. 72: Projected Trend analysis of heatwaves over Burkina Faso for HWA (Heat Wave Amplitude) °C for daytime (TX90th percentile) from 2051 - 2100.

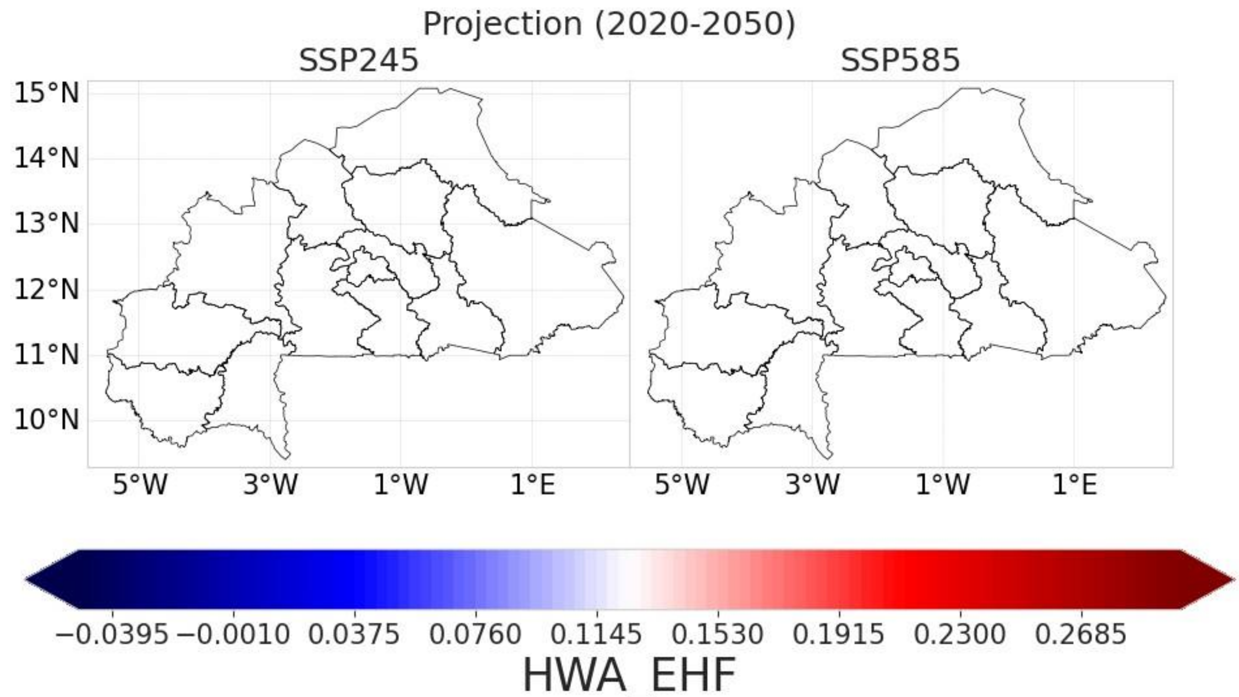

Figure 4. 73: Projected Trend analysis of heatwaves over Burkina Faso for HWA (Heat Wave Amplitude) °C for Excess Heat Factor (EHF) from 2020 – 2050.

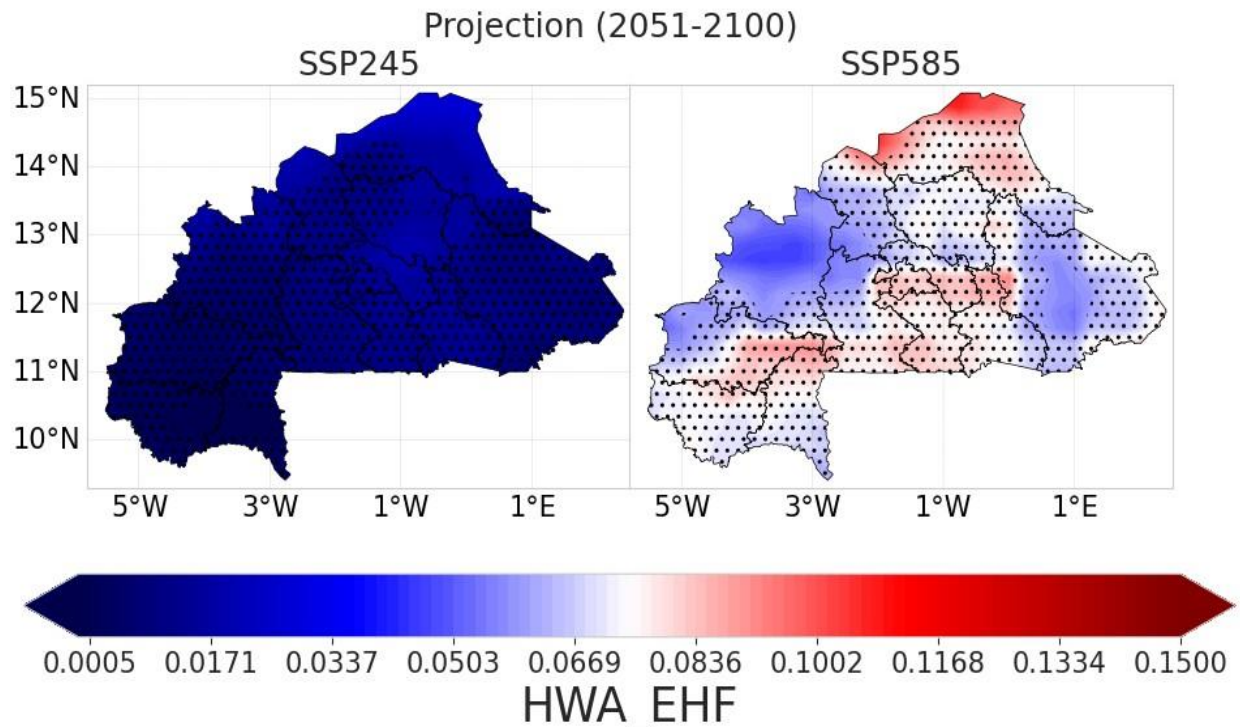

Figure 4. 74: Projected Trend analysis of heatwaves over Burkina Faso for HWA (Heat Wave Amplitude) °C for Excess Heat Factor (EHF) from 2051 – 2100.

The projection of HWD_TN90, HWD_TX90, and HWD_EHF (Figures 4.75, 4.77, and 4.79 respectively) did not show any color shading under either the SSP245 or SSP585 scenarios for the 2020-2050 period. This absence of color indicates no notable trends in heatwave duration projected over Burkina Faso during this timeframe. This suggests that neither of the two scenarios is expected to significantly change heatwave duration in the near future (2020-2050). The lack of results likely reflects natural climate variability, which may limit the occurrence of pronounced heatwave events during this period.

The far-future projections for HWD_TN90 (Figure 4.76) showed positive and negative trends. Under SSP245, a negative trend is projected for heatwave duration (HWD_TN90) across Burkina Faso, suggesting that nighttime heatwave days are expected to decrease across the country in the late 21st century under this moderate-emissions scenario. This decreasing trend is statistically significant in the northeastern, central-eastern, and southwestern regions of Burkina Faso. In contrast, the SSP585 projection for 2051-2100 showed a positive trend in heatwave duration across the country, indicating an expected increase in heatwave days under a high-emissions scenario. However, this positive trend is not statistically significant. The longterm trend projection for HWD_TX90 (Figure 4.78) indicated a positive trend under both climate scenarios. Under SSP245, this trend is statistically significant in the southeastern, far northern, and parts of the southern regions of Burkina Faso. However, under SSP585, the positive trend is not statistically significant. The projected HWD_EHF in the far future (Figure 4.80) indicated a statistically significant increase of 0.007 days over Burkina Faso under SSP245. However, the increase was also positive under SSP585 but not statistically significant. The lack of statistical significance under SSP585 for each of the three indices (TN90, TX90 and EHF) suggests that, although heatwave days are expected to increase, the projected rise may not be robust enough across multiple climate models to be considered statistically reliable.

Findings on an increasing trend for HWD, although not statistically significant (most especially under SSP585), reflect similar concerns in the literature. Vizy and Cook (2012) and Oueslati *et a*l., (2017) have projected that heat events across the region will become more prolonged as the climate continues to warm. This projected duration extension amplifies the risks to health, water resources, and agriculture, creating a scenario where Burkina Faso could experience severe impacts from sustained heat exposure. Studies by Campbell *et al*., (2018b) and Ceccherini *et al*., (2017) underscore that prolonged heat events strain health systems as the risks of heat-related illnesses and mortality rise. These studies highlight that extended heatwaves can lead to higher energy demand for cooling, stressing power systems and compounding drought and water scarcity issues as evaporation rates accelerate under prolonged heat exposure. Davidson *et al.*, (2003) Further, these longer heatwave durations will likely reduce agricultural productivity due to sustained high temperatures, which can inhibit crop growth, degrade soil quality, and reduce yields.

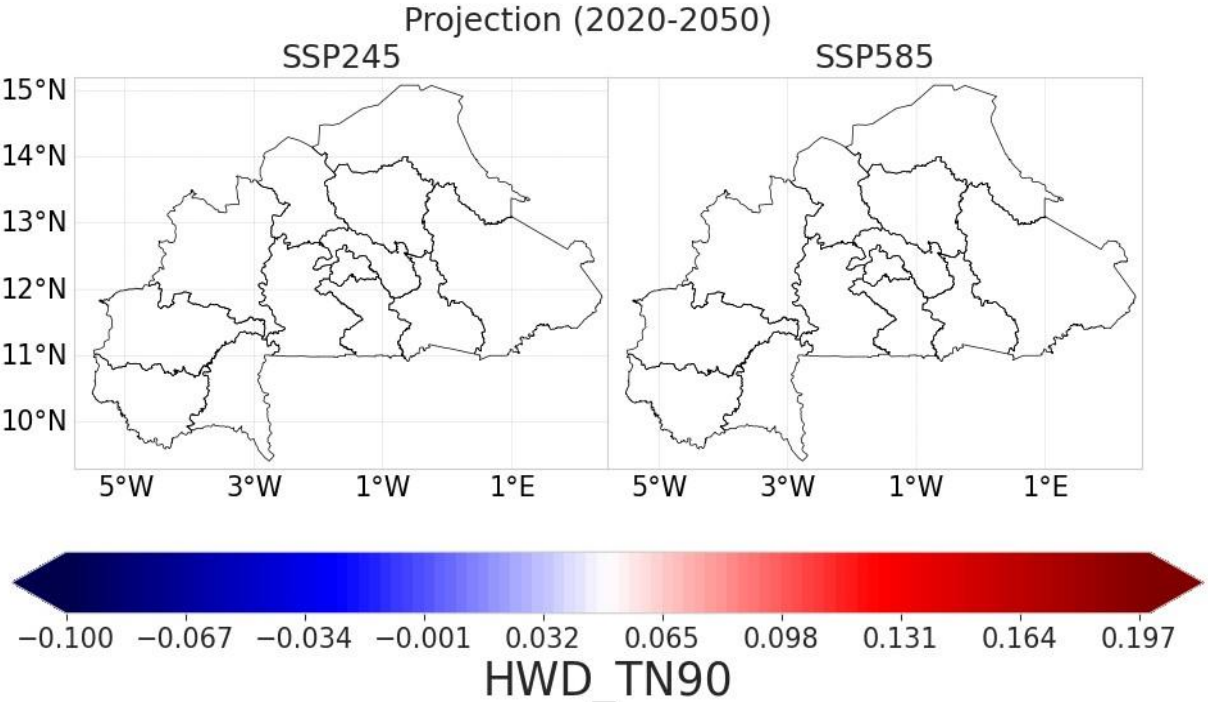

Figure 4. 75: Projected Trend analysis of heatwaves over Burkina Faso for HWD (Heat Wave Duration) Days for nighttime (TN90th percentile) from 2020 – 2050.

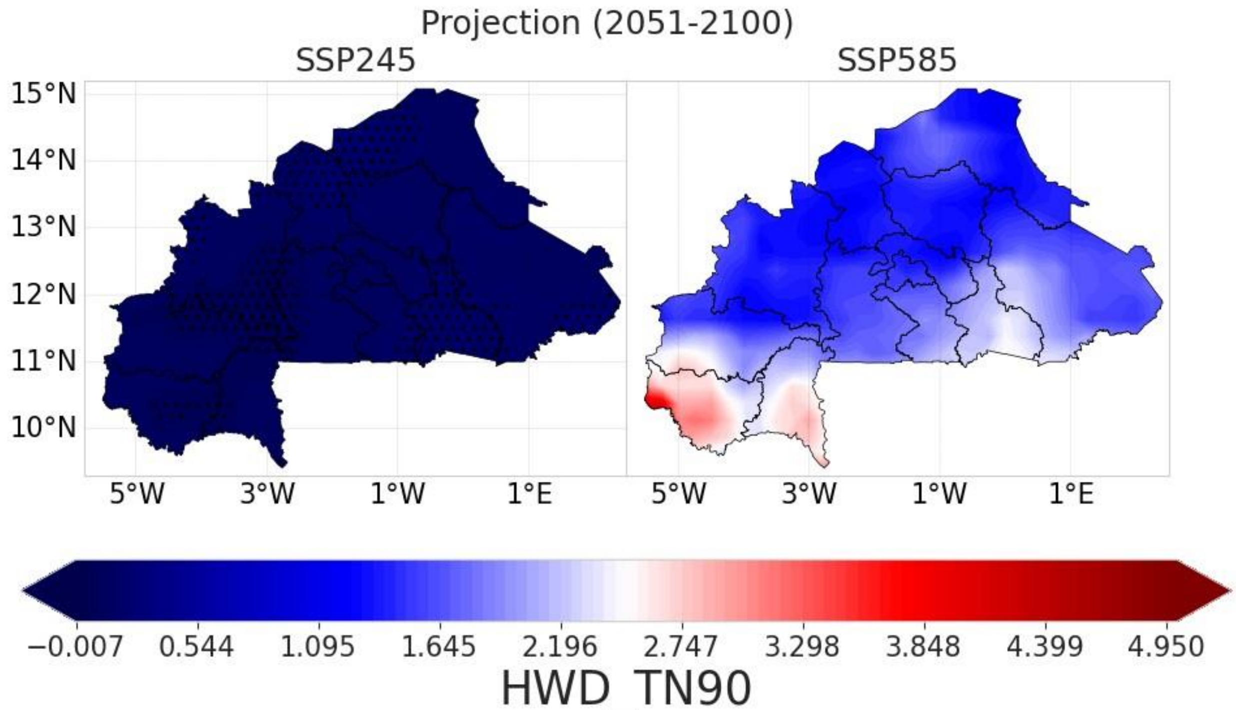

Figure 4. 76: Projected Trend analysis of heatwaves over Burkina Faso for HWD (Heat Wave Duration) Days for nighttime (TN90th percentile) from 2020 - 2050.

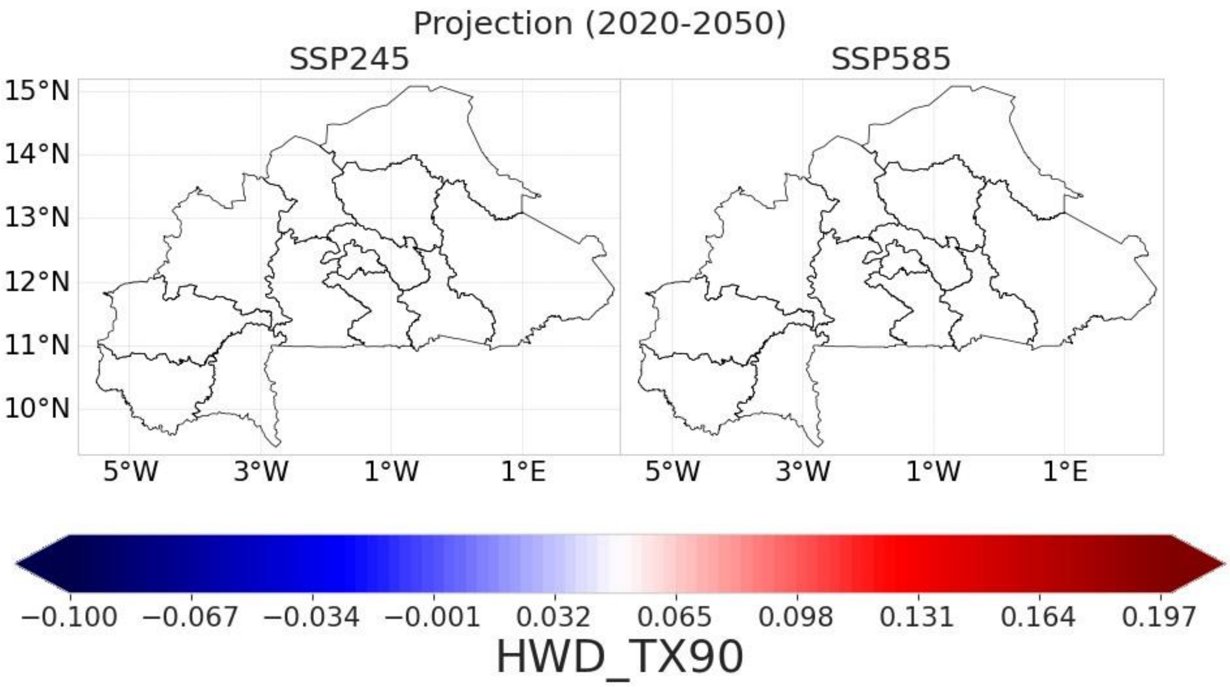

Figure 4. 77: Projected Trend analysis of heatwaves over Burkina Faso for HWD (Heat Wave Duration) Days for daytime (TX90th percentile) from 2020 - 2050.

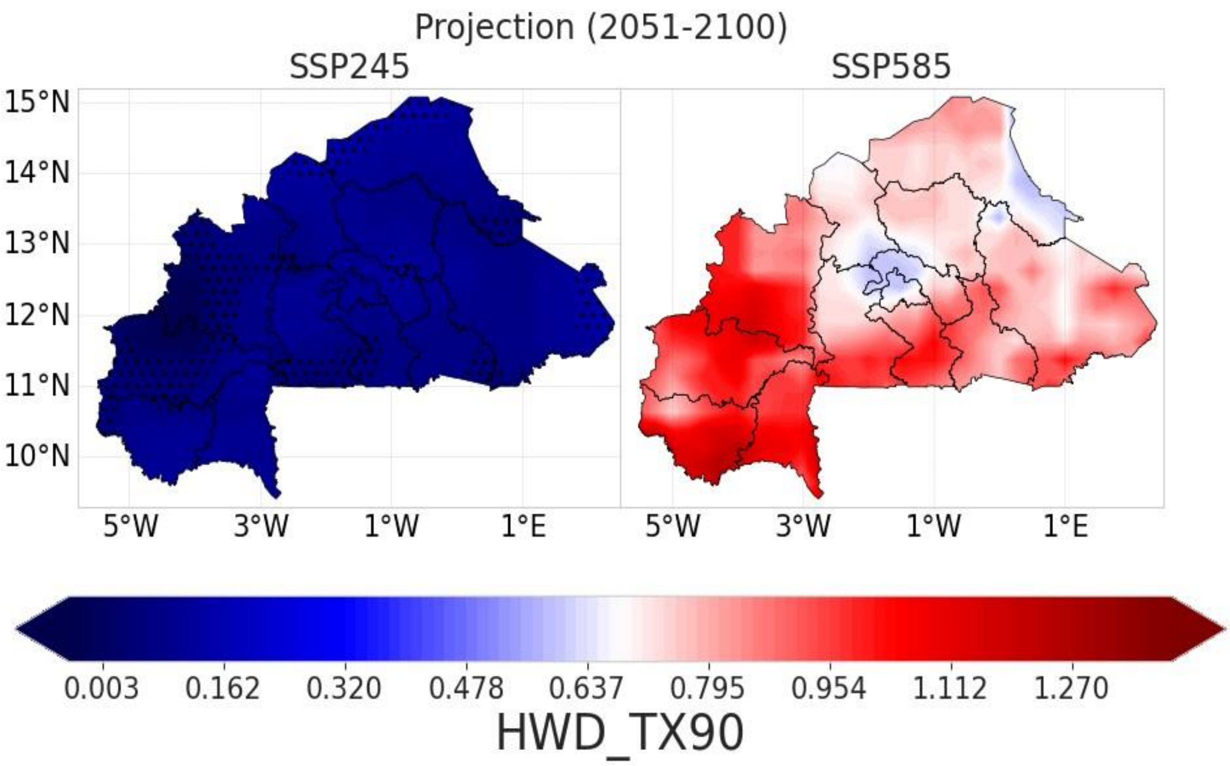

Figure 4. 78: Projected Trend analysis of heatwaves over Burkina Faso for HWD (Heat Wave Duration) Days for daytime (TX90th percentile) from 2051 – 2100

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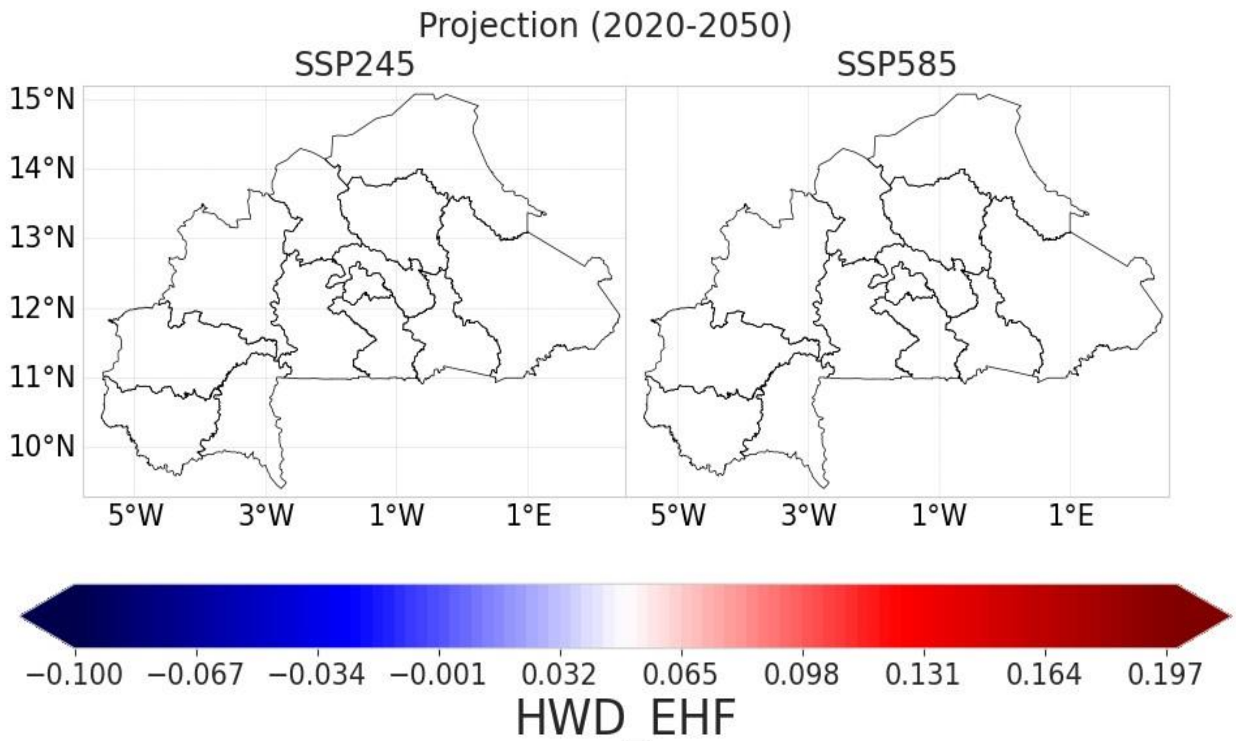

Figure 4. 79: Projected Trend analysis of heatwaves over Burkina Faso for HWD (Heat Wave Duration) Days for Excess Heat Factor (EHF) from 2020 - 2050.

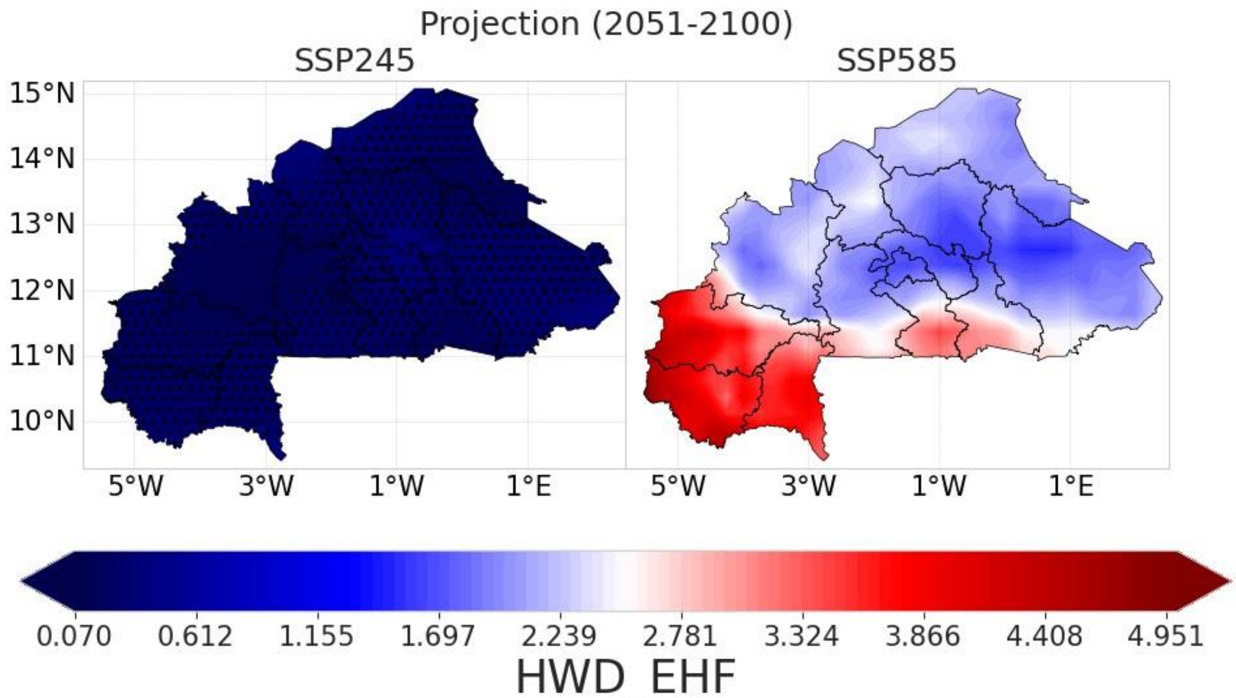

Figure 4. 80: Projected Trend analysis of heatwaves over Burkina Faso for HWD (Heat Wave Duration) Days for Excess Heat Factor (EHF) from 2051 - 2100.

The projected HWF did not indicate any statistically significant trend in the near future. The projected trend for HWF_TN90 (Figure 4.81), HWF_TX90 (Figure 4.83), and HWF_EHF (Figure 4.85) showed downward trends over Burkina Faso, though these trends were not statistically significant in any of the scenarios considered in this study. This suggests that while the number of days affected by heatwaves is expected to decrease, the projected decline may lack sufficient robustness across multiple climate models to be deemed statistically reliable.

In contrast, the long-term projection of HWF showed only positive trends under SSP245 and SSP585. The projected trend of HWF_TN90 (Figure 4.82) was positive across Burkina Faso, with statistical significance in the southeastern region under SSP245 and the central-northern and southeastern regions under SSP585. The projected trend of HWF_TX90 (Figure 4.84) was also positive across the country, with a larger area showing statistical significance under SSP245 compared to SSP585The trend projection for HWF_EHF (Figure 4.86) indicated an upward, though statistically insignificant, trend across Burkina Faso under SSP245. Under SSP585, however, it displayed a significant increasing trend towards the north, with statistical significance observed in the southeastern region.

In discussing HWF, the projections showed that even if the projected trend is positive over Burkina Faso, it is only statistically significant in some regions. This implies that Burkina Faso could experience heatwave conditions almost weekly during peak heat seasons by 2100. This projected increase in HWF aligns with findings from Russo *et al*., (2014) and (Nangombe *et al*., (2019), which document that, under future warming scenarios, extreme heat events in West Africa will become increasingly frequent, with reduced recovery periods between occurrences. These studies provide important insights into how the rising frequency of heatwaves can intensify cumulative stress on health and agriculture, particularly in regions where infrastructure may not be adequate to withstand such frequent heat events. Oueslati *et al*., (2017) discuss the Sahel region’s vulnerability to repeated heat events, which is expected to increase pressures on healthcare and exacerbate water scarcity issues, with significant implications for human populations and natural ecosystems in Burkina Faso.

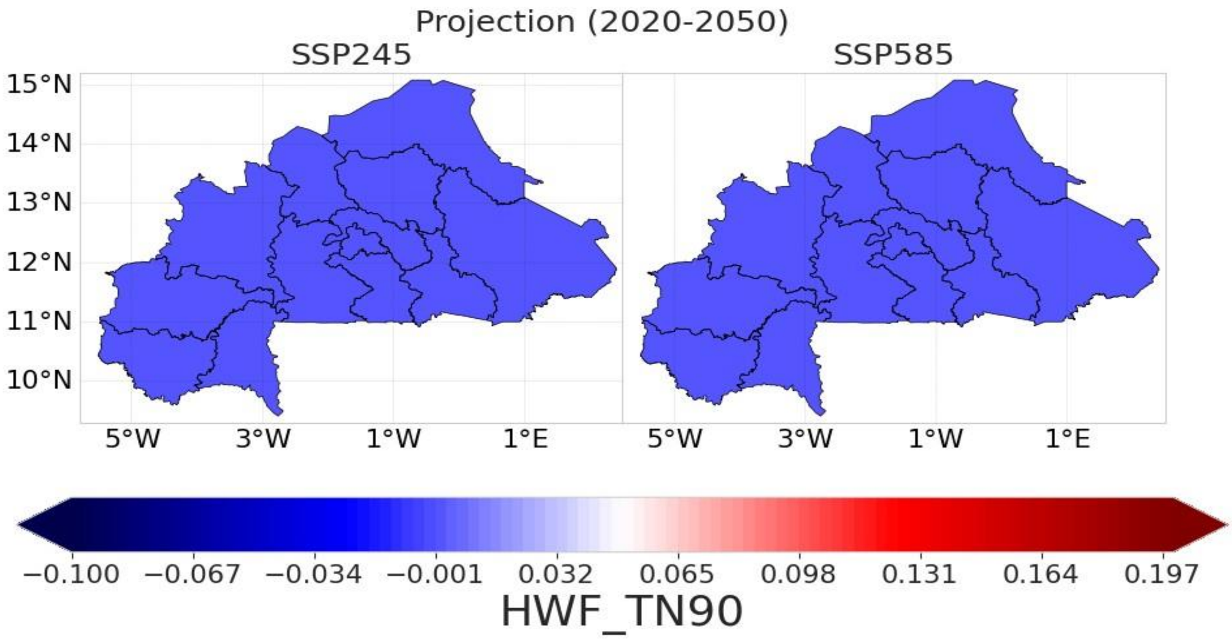

Figure 4. 81: Projected Trend analysis of heatwaves over Burkina Faso for HWF (Heat Wave Frequency) Days for nighttime (TN90th percentile) from 2020 - 2050.

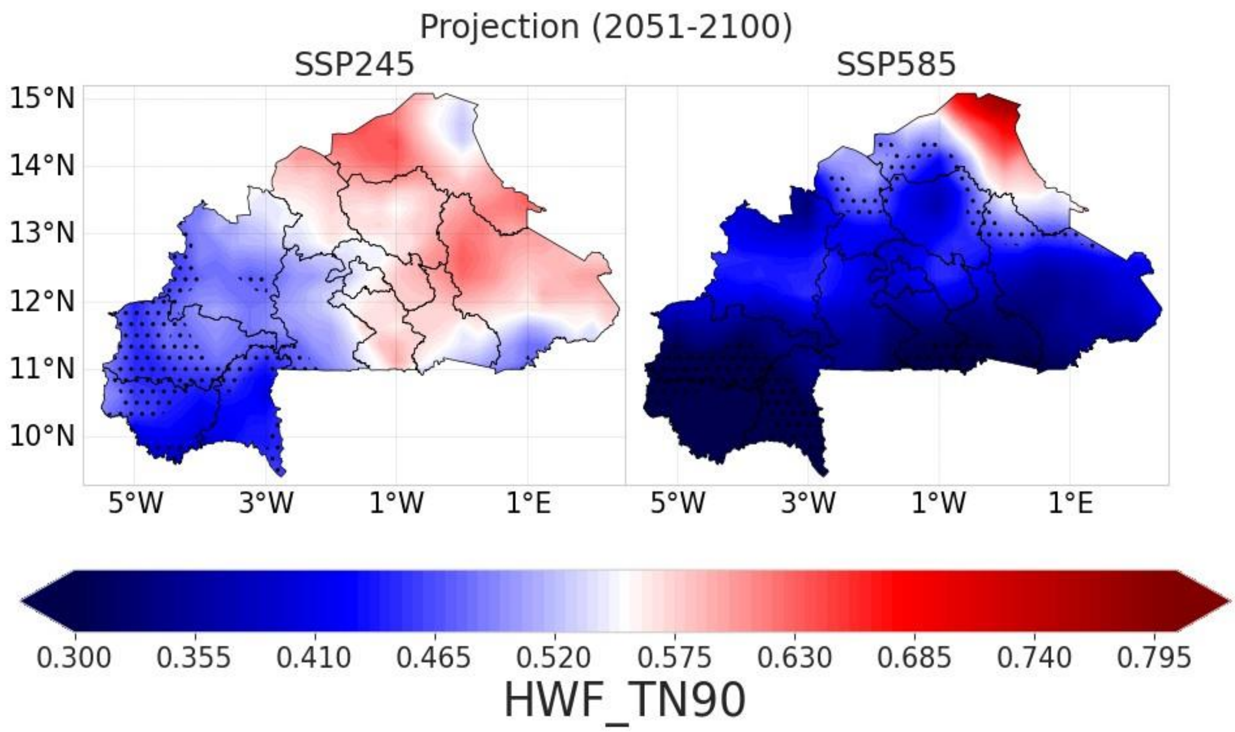

Figure 4. 82: Projected Trend analysis of heatwaves over Burkina Faso for HWF (Heat Wave Frequency) Days for nighttime (TN90th percentile) from 2051 - 2100.

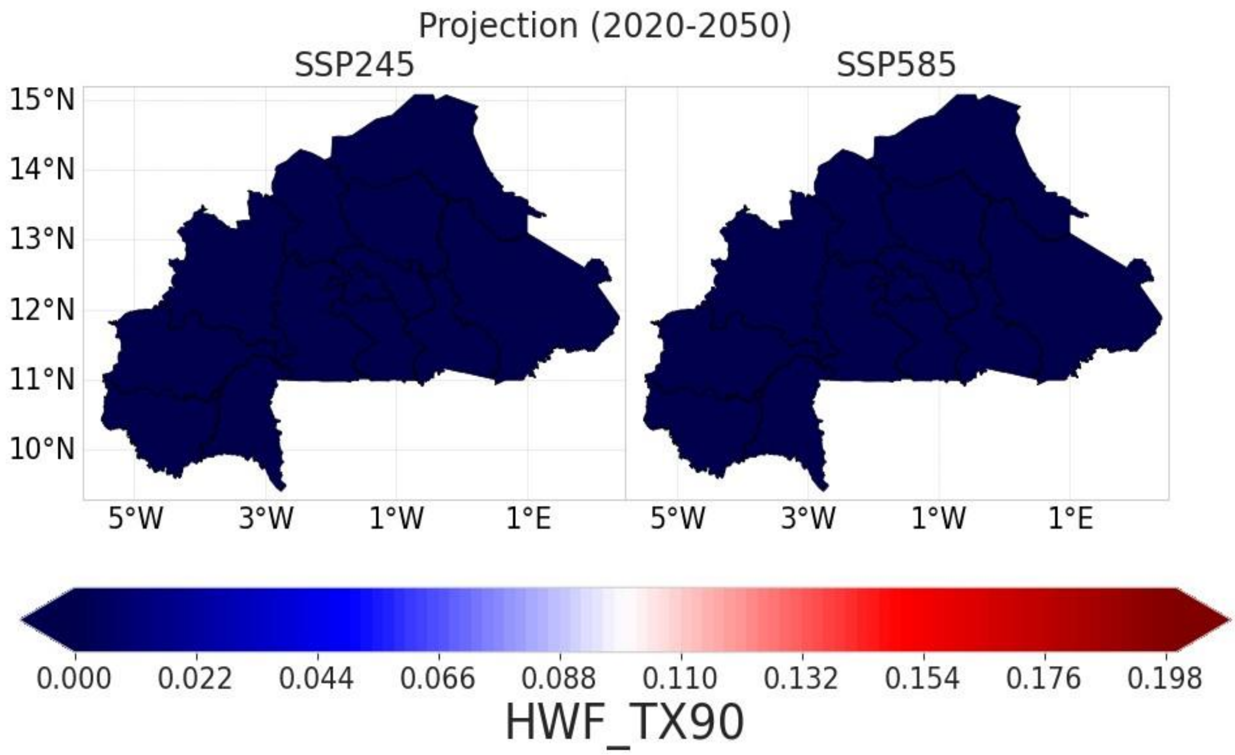

Figure 4. 83: Projected Trend analysis of heatwaves over Burkina Faso for HWF (Heat Wave Frequency) Days for daytime (TX90th percentile) from 2020 - 2050.

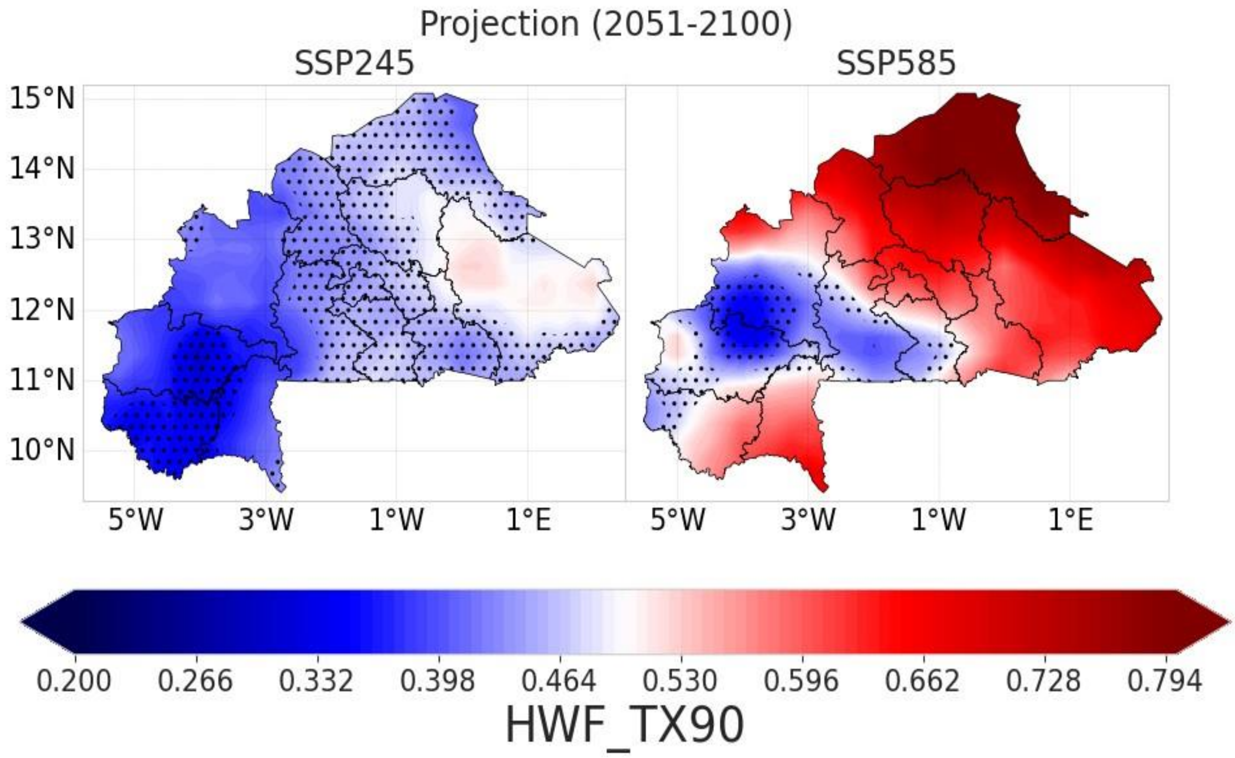

Figure 4. 84: Projected Trend analysis of heatwaves over Burkina Faso for HWF (Heat Wave Frequency) Days for daytime (TX90th percentile) from 2051 – 2100.

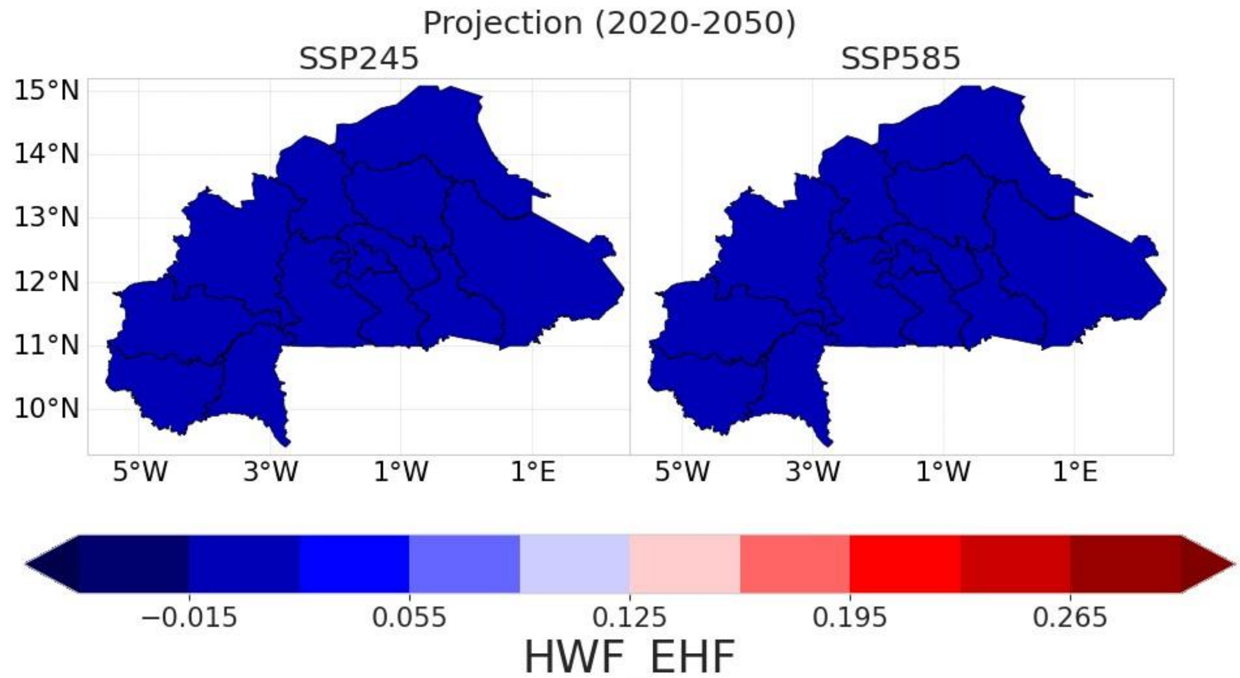

Figure 4. 85: Projected Trend analysis of heatwaves over Burkina Faso for HWF (Heat Wave Frequency) Days for Excess Heat Factor (EHF) from 2020 – 2050.

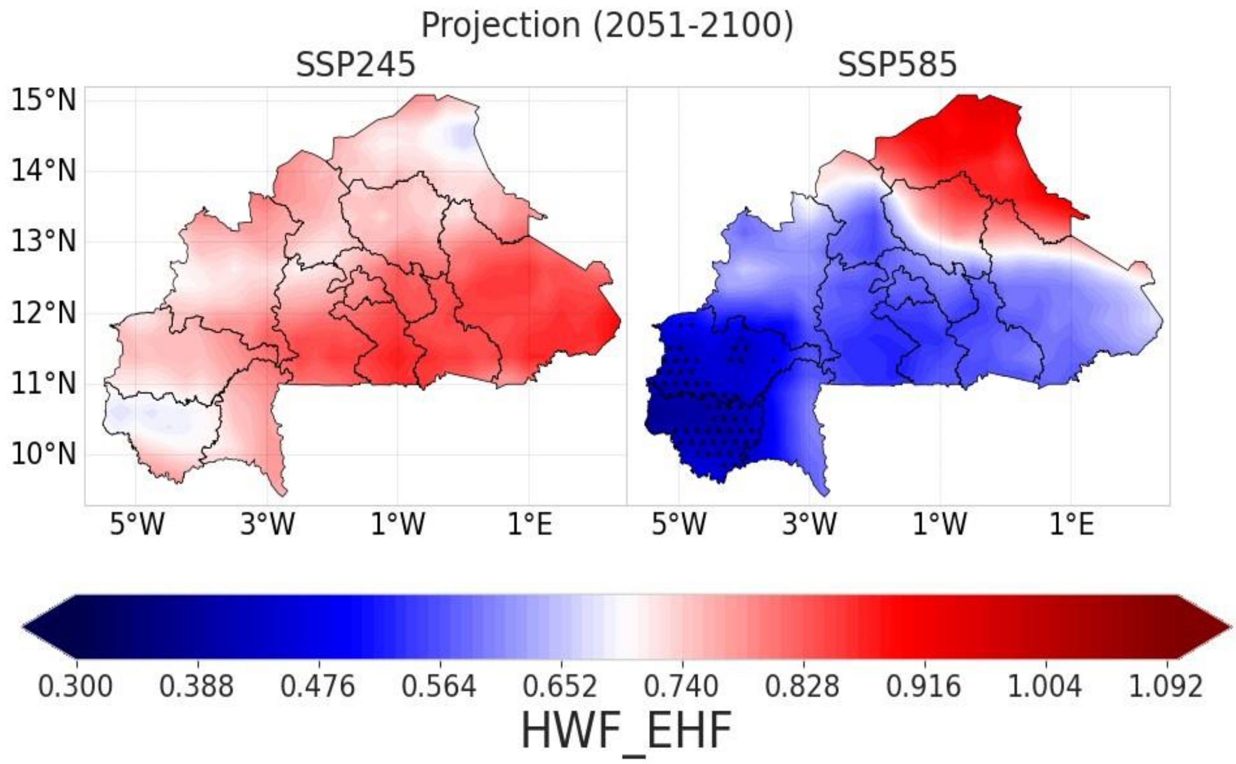

Figure 4. 86: Projected Trend analysis of heatwaves over Burkina Faso for HWF (Heat Wave Frequency) Days for Excess Heat Factor (EHF) from 2051 - 2100.

The near-future (2020-2050) trend projections for HWM across the three indices: TN90, TX90, and EHF (Figures 4.87, 4.89, and 4.91, respectively) showed no colour under either the SSP245 or SSP585 scenarios. This indicates minimal or no statistically significant trends in nighttime, daytime, or EHF-based heatwave magnitudes across Burkina Faso during this period. These results suggest that the model does not project substantial increases or decreases in heatwave magnitude or that conditions did not meet the thresholds for heatwave classification in these years, resulting in an absence of recorded values for heatwave magnitude.

In the far future, the projection for HWM_TN90 (Figure 4.88) under SSP245 showed a mix of positive and negative trends. A statistically significant increase is observed in far eastern Burkina Faso, while a statistically significant decrease is evident in other regions. Under SSP585, however, a statistically significant decreasing trend is projected across the study area. For HWM_TX90 (Figure 4.90), projections indicated positive and negative trends across Burkina Faso, with the northern region experiencing statistically significant positive trends. In contrast, the southeastern regions showed statistically significant negative trends under SSP245 and SSP585. HWM_EHF (Figure 4.92) displayed a negative trend under SSP245, with statistically significant decreases in the southeastern, central, and far northern regions of Burkina Faso. In contrast, under SSP585, the trend is significantly positive.

The projections for Heat Wave Magnitude (HWM) in Burkina Faso displayed a combination of positive and negative trends across the country by 2100. Adeniyi and Oyekola (2017) observed no increase in heatwave frequency, attributing this to the choice of heatwave index used. In contrast, the observed increasing trends align with the findings by Perkins and Alexander (2013) and Brimicombe *et al*. (2022). They emphasize that higher HWM values signify more intense and damaging heatwave events, with significant risks for public health, agriculture, and infrastructure. These studies underscore that extreme temperature peaks can scorch crops, reduce yields, and increase food insecurity in agricultural regions like Burkina Faso. The high-magnitude heatwaves mentioned are expected to challenge public health significantly, as sudden and extreme temperature peaks can increase mortality rates and affect outdoor workers, the elderly, and other at-risk groups. Furthermore, Morice *et al*. (2012) and Barbier (2017) document that rising heatwave magnitudes in the region may place a heavier burden on both economic and health sectors, reinforcing the point that high HWM values will strain healthcare infrastructure and disrupt agricultural systems due to increasingly frequent and severe temperature peaks.

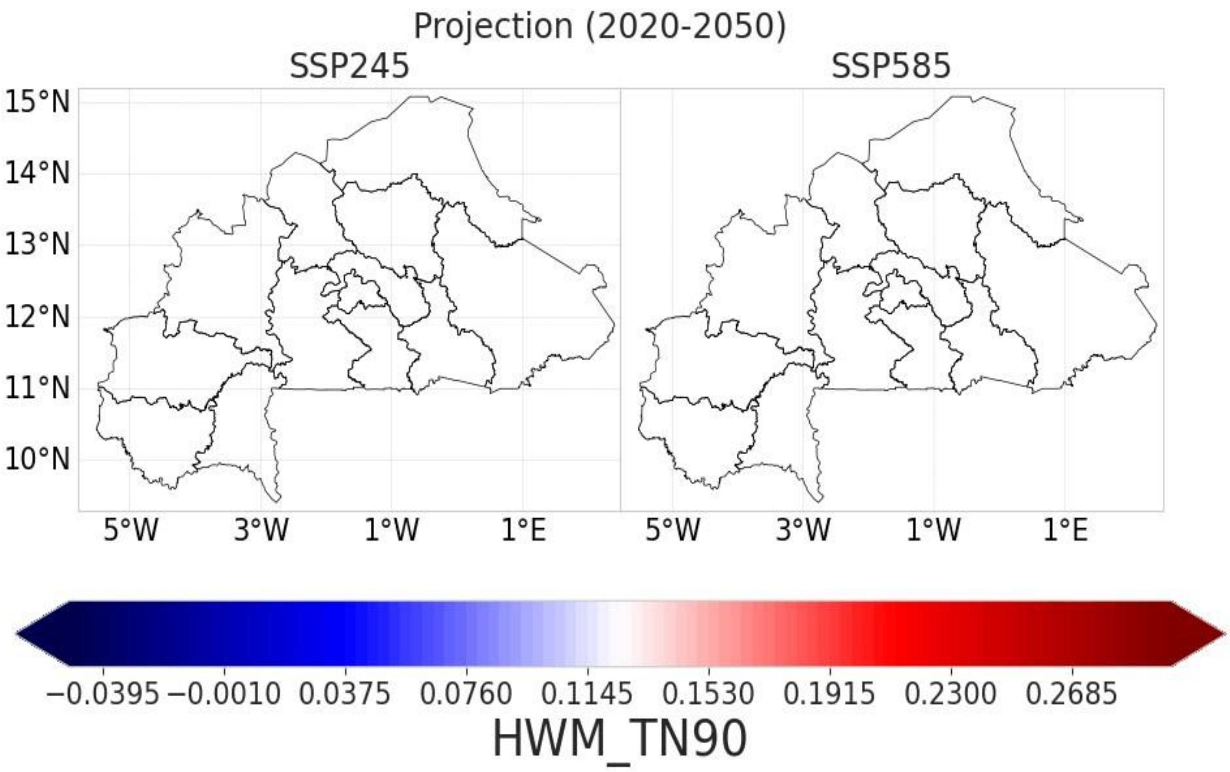

Figure 4. 87: Projected Trend analysis of heatwaves over Burkina Faso for HWM (Heat Wave Magnitude Index) for nighttime (TN90th percentile) from 2020 - 2050.

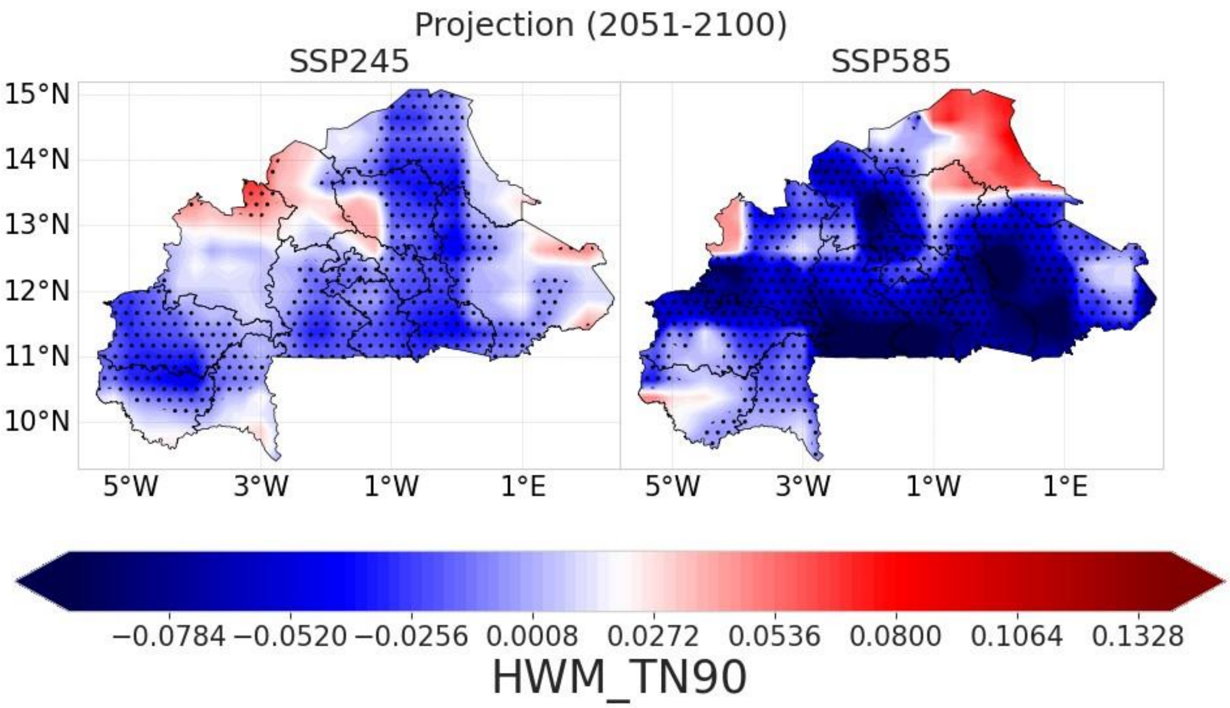

Figure 4. 88: Projected Trend analysis of heatwaves over Burkina Faso for HWM (Heat Wave Magnitude Index) for nighttime (TN90th percentile) from 2051 - 2100.

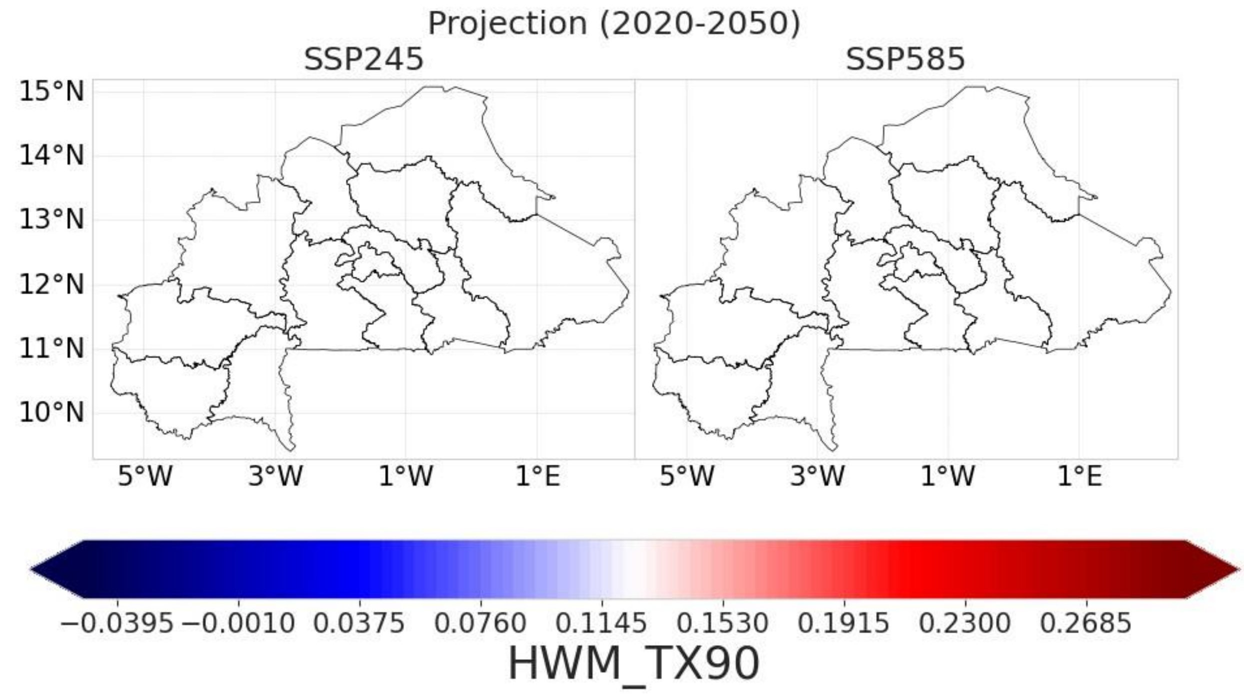

Figure 4. 89: Projected Trend analysis of heatwaves over Burkina Faso for HWM (Heat Wave Magnitude Index) for daytime (TX90th percentile) from 2020 - 2050.

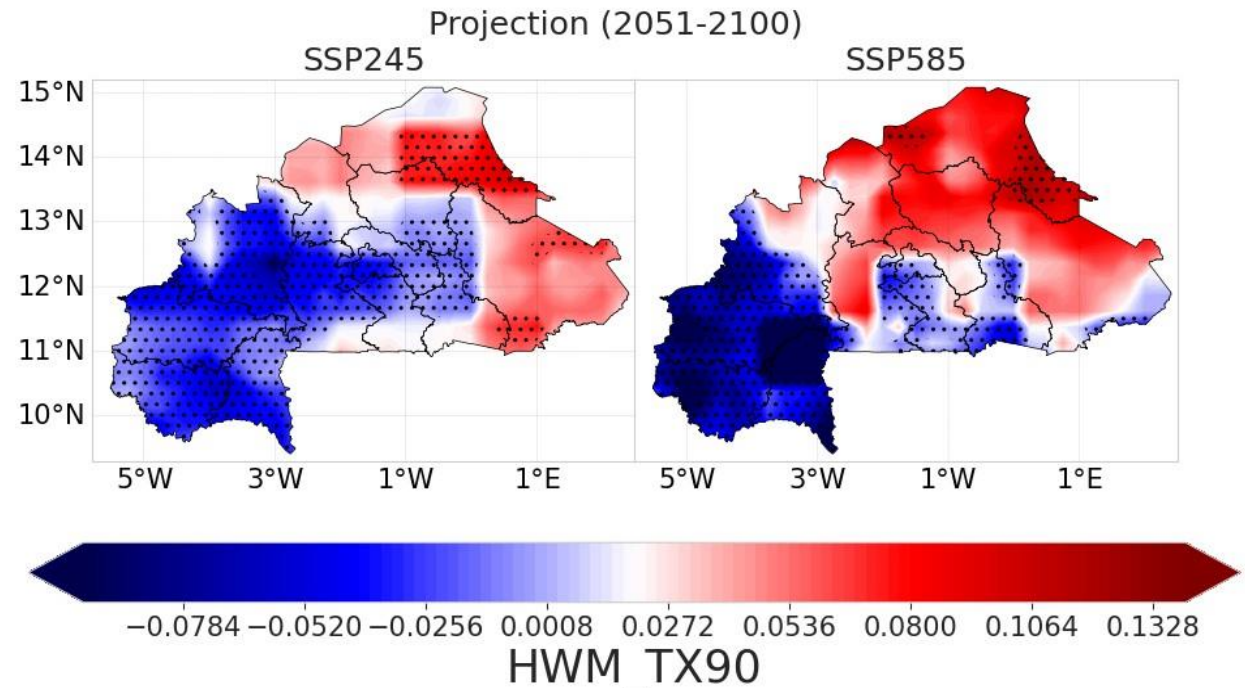

Figure 4. 90: Projected Trend analysis of heatwaves over Burkina Faso for HWM (Heat Wave Magnitude Index) for daytime (TX90th percentile) from 2051 - 2100.

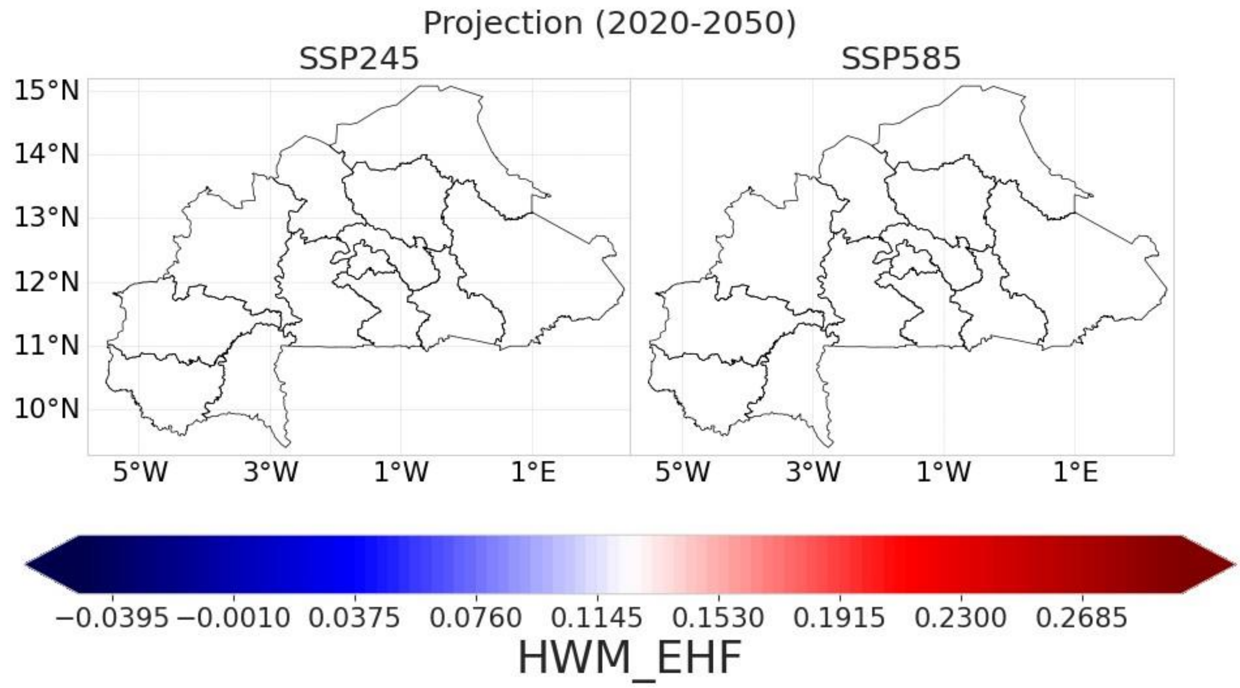

Figure 4. 91: Projected Trend analysis of heatwaves over Burkina Faso for HWM (Heat Wave Magnitude Index) for Excess Heat Factor (EHF) from 2020 – 2050.

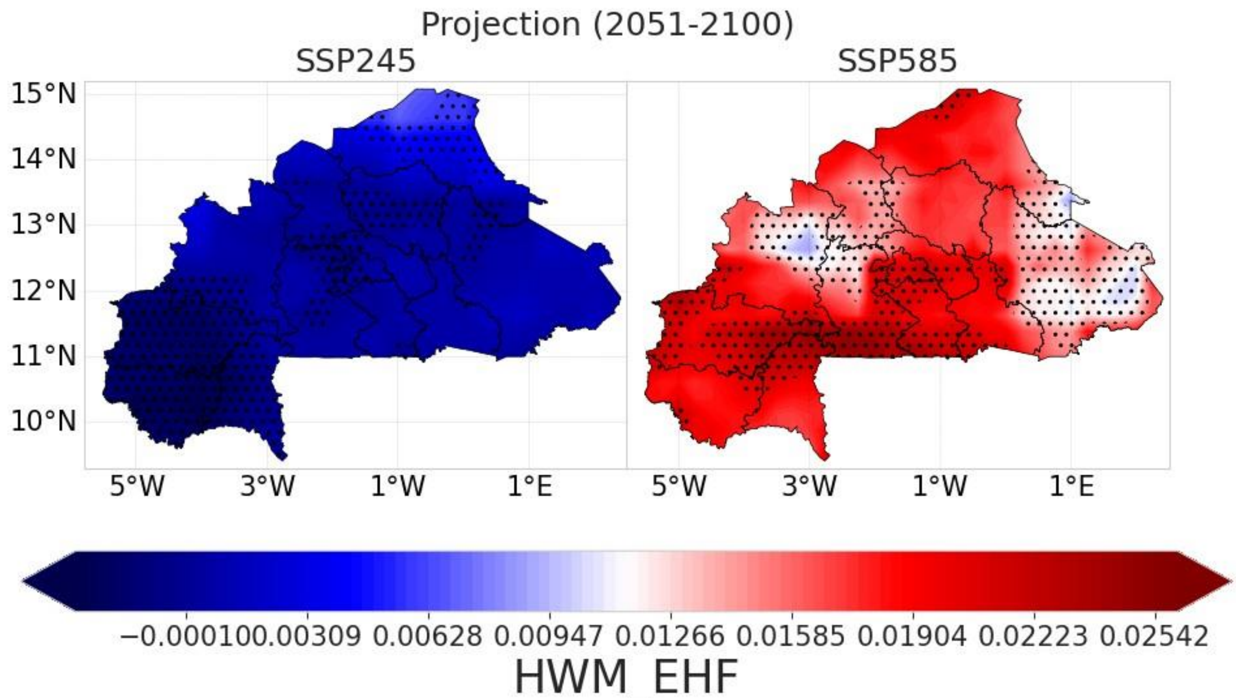

Figure 4. 92: Projected Trend analysis of heatwaves over Burkina Faso for HWM (Heat Wave Magnitude Index) for Excess Heat Factor (EHF) from 2051 – 2100.

In the near future, the projected trends for HWN_TN90 (Figure 4.93), HWN_TX90 (Figure 4.95), and HWN_EHF (Figure 4.97) did not show any trend.

The long-term projections for HWN revealed a positive trend across all three indices (TN90, TX90, and EHF). HWN_TN90 (Figure 4.94) showed a statistically significant northward increase under SSP245, though this trend was insignificant in the central and central-eastern regions. Under SSP585, the projection also showed a northward positive trend throughout the country, though it was less pronounced than under SSP245, and the central northern area showed no statistical significance. HWN_TX90 (Figure 4.96) presented a statistically significant upward trend across Burkina Faso under SSP245, with a more substantial increase under SSP585. The northern regions showed the highest HWN_TX90 values, while the southern regions had comparatively lower values. For HWN_EHF (Figure 4.98), the projected trend was positive across Burkina Faso under SSP245, though it was not statistically significant in the western and southeastern regions while remaining positive in other regions. The SSP585 projection also indicated a positive trend, though it was less pronounced than under SSP245. Under SSP585, the increase was statistically significant in the northern region (with the highest values) and in the southeastern region (with the lowest values).

The projected trend on HWN revealed a statistically significant increasing trend over Burkina Faso. This finding is well-supported by some previous researches. Russo *et al*. (2014) and Ceccherini *et al*. (2017) provide evidence of increasing heatwave occurrences in the Sahel, with projections showing that Burkina Faso may experience up to 10-12 events by 2050 and 15 or more by 2100. This anticipated increase in HWN suggests that extreme heat may become a near-constant feature in the region's climate, posing ongoing challenges to resilience in vulnerable communities. This increase in heatwave events heightens the likelihood of overlapping or sequential events, as noted by Odoulami *et al*. (2017), who observed that repeated heat exposure could disrupt agriculture, reduce crop resilience, and impact livestock, thereby increasing health complications in populations with limited access to cooling resources.

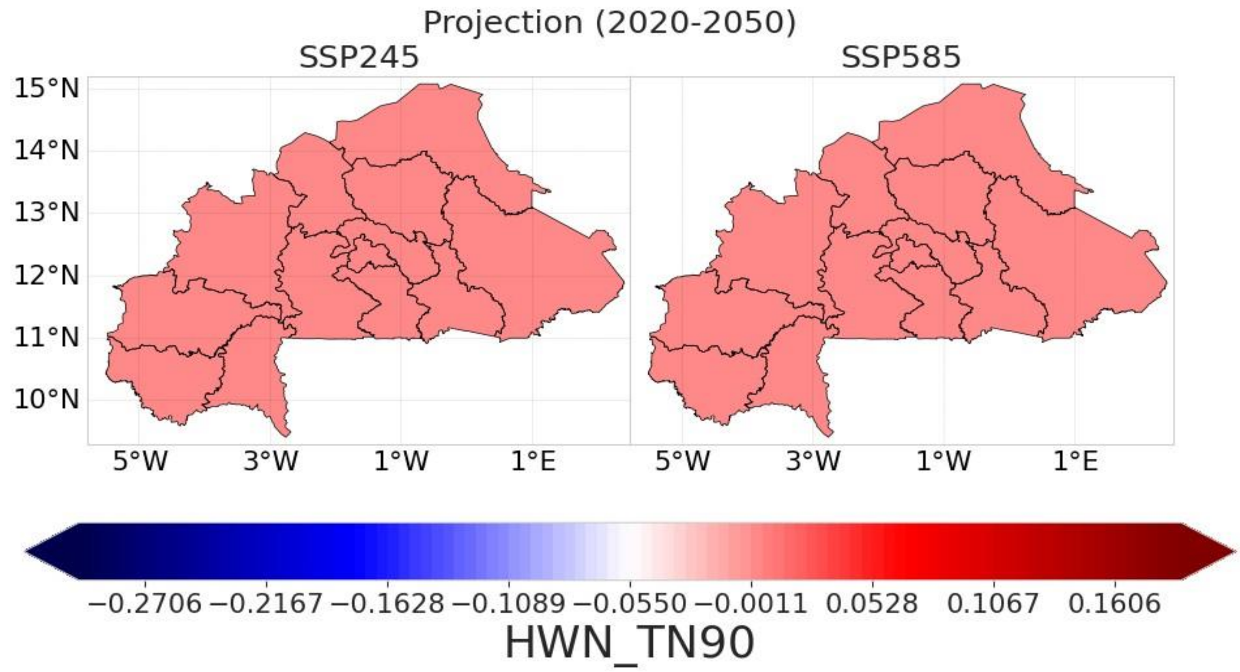

Figure 4. 93: Projected Trend analysis of heatwaves over Burkina Faso for HWN (Heat Wave Number) for nighttime (TN90th percentile) from 2020 - 2050.

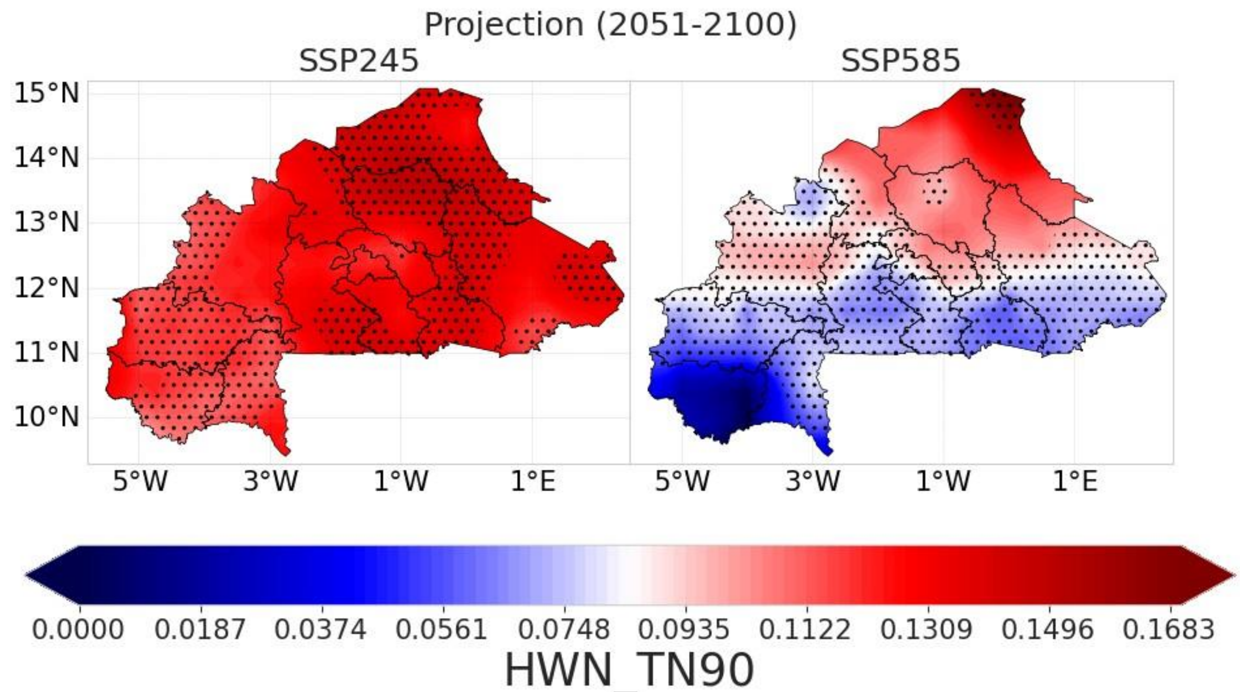

Figure 4. 94: Projected Trend analysis of heatwaves over Burkina Faso for HWN (Heat Wave Number) for nighttime (TN90th percentile) from 2051 – 2100.

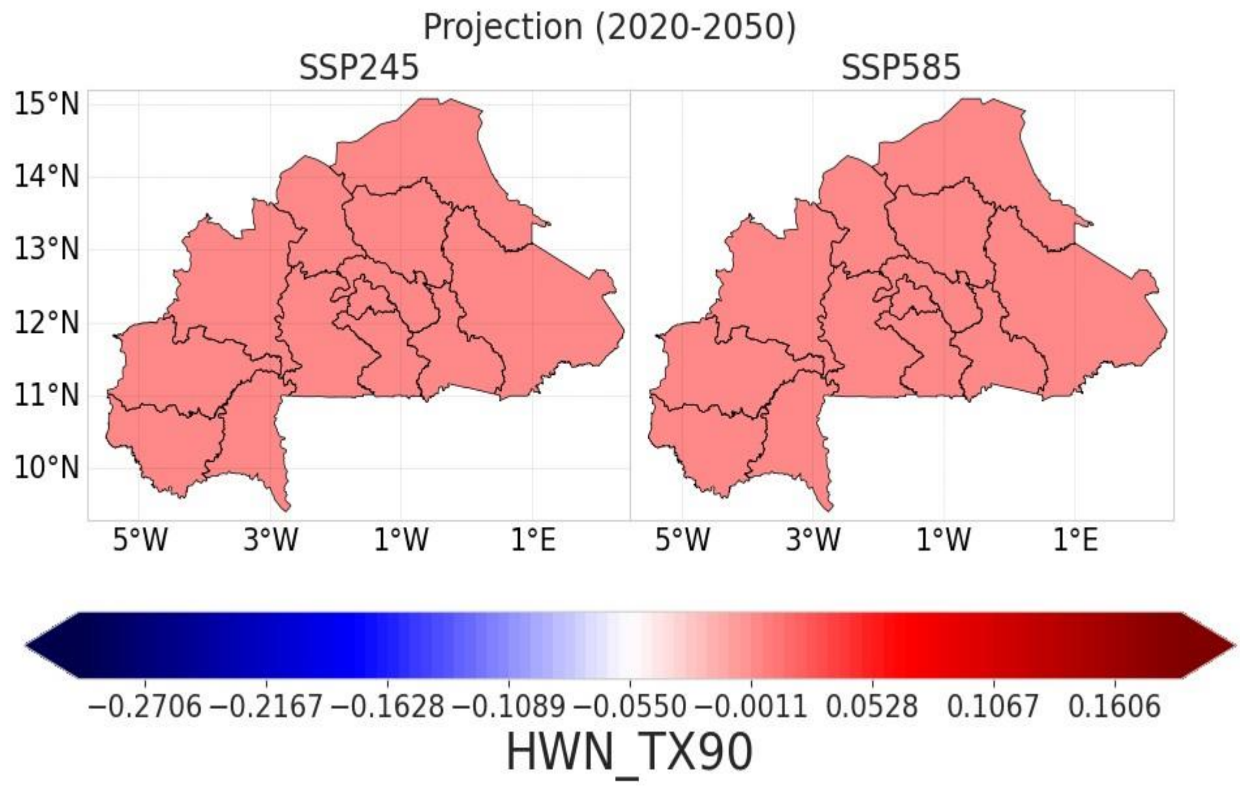

Figure 4. 95: Projected Trend analysis of heatwaves over Burkina Faso for HWN (Heat Wave Number) for daytime (TX90th percentile) from 2020 – 2050.

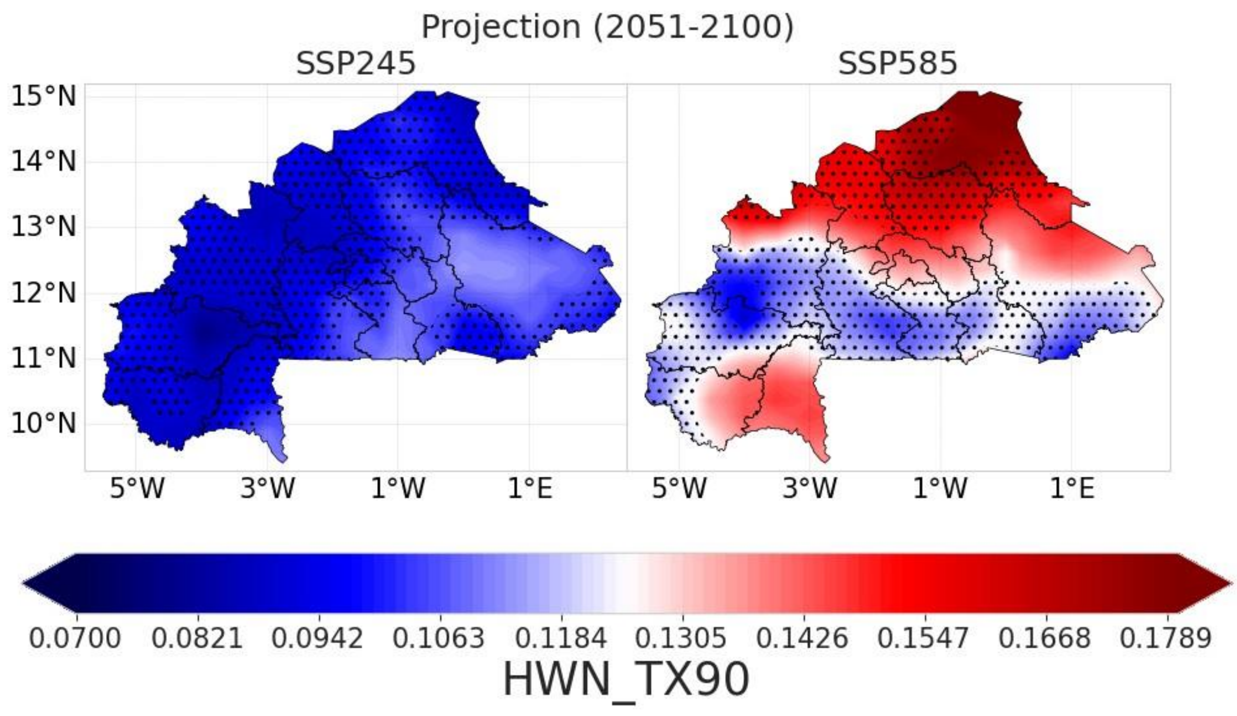

Figure 4. 96: Projected Trend analysis of heatwaves over Burkina Faso for HWN (Heat Wave Number) for daytime (TX90th percentile) from 2051 - 2100.

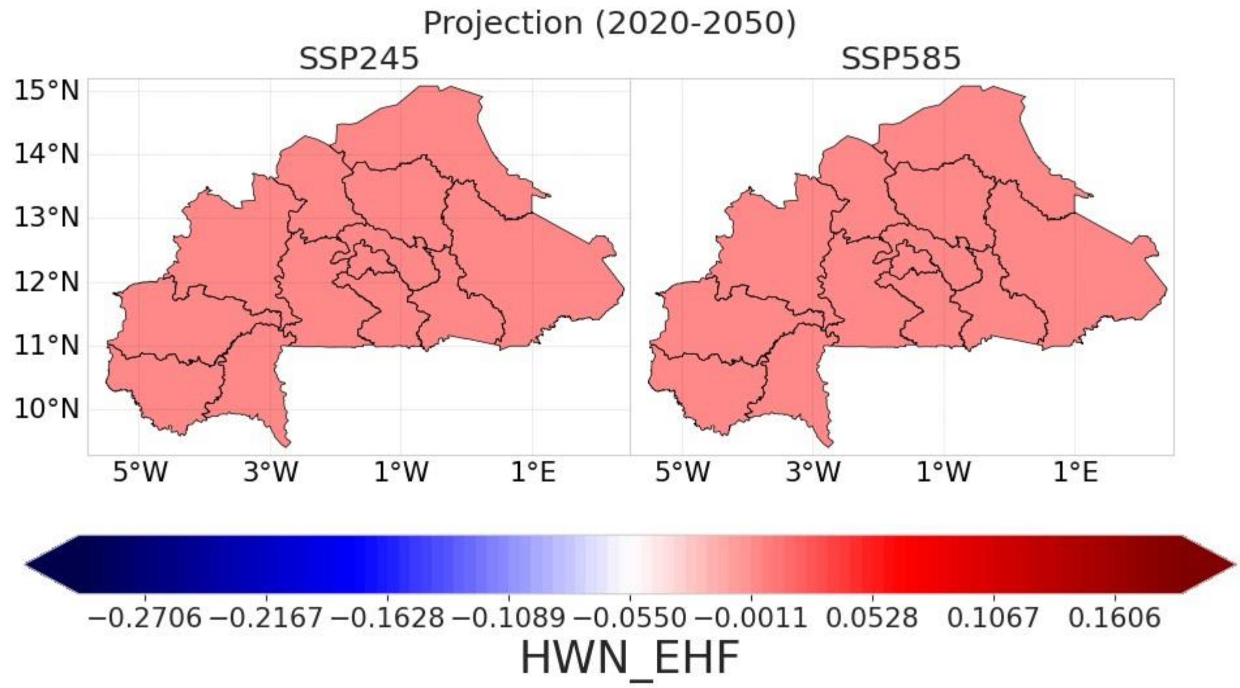

Figure 4. 97: Projected Trend analysis of heatwaves over Burkina Faso for HWN (Heat Wave Number) for Excess Heat Factor (EHF) from 2020 - 2051.

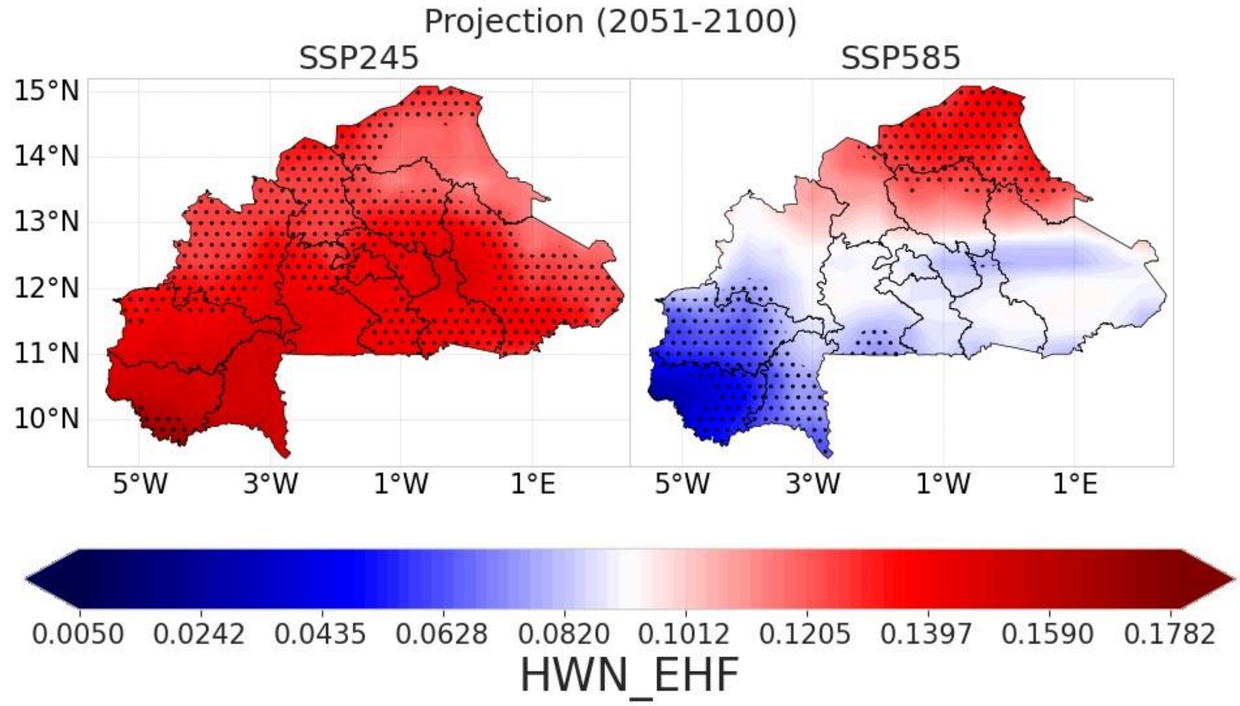

Figure 4. 98: Projected Trend analysis of heatwaves over Burkina Faso for HWN (Heat Wave Number) for Excess Heat Factor (EHF) from 2051 - 2100.

The projected trends for heatwaves in Burkina Faso indicate a concerning future of increasingly intense, frequent, and prolonged heatwaves. Each parameter, HWA, HWD, HWF, HWM, and HWN, contributes to a clear picture of future heat-related challenges with significant implications for the environment, society, and economy.

In conclusion, the projections for Burkina Faso's future heatwave characteristics reveal a dramatic transformation in the region's climate, with substantial increases in intensity, frequency, duration, and magnitude of heatwaves expected by 2100. This shift underscores the need for urgent adaptation measures to address the escalating impact on health, infrastructure, agriculture, and ecosystems. From enhancing health interventions and public cooling resources to promoting heat-resilient agricultural practices, resilience-building strategies are essential to managing the anticipated pressures from an intensifying climate.

CHAPTER FIVE

CONCLUSION, RECOMMENDATION AND CONTRIBUTION TO KNOWLEDGE

5.1 Conclusion

This study highlights the impacts of heatwaves on human health in Burkina Faso. Observation data, climate model simulation data (NEX-GDDP) and ERA5 data were used to analyse five heatwave characteristics based on three heatwave metrics (TN90, TX90, and EHF). The Taylor diagram was used to evaluate the simulation results of eleven (11) climate models from the NASA NEX GDDP CMIP6 dataset. The result underscores the importance of selecting reliable models for future climate projections and planning in Burkina Faso, where observed data is unavailable. The combination of these metrics provides a robust framework for understanding the multifaceted nature of heatwaves. There was a general outcome in the models as it was observed that a north-south gradient exists in most of the analyses (HWA, HWM, HWN, HWF), which can be interpreted as the varying degrees of heatwave characterisation across the country's three (3) eco-climatic regions. Different models showed graphical analytical resemblance with the primary (observed) output at the various percentiles. The summary of the results showed that certain models could capture or show a close resemblance between the observed and simulated. That is, no model could simulate all the characteristics at a go. For instance, while CMCC-ESM2 was able to have a close resemblance with what was observed under minimum temperature for heatwave amplitude, EC-Earth3 was better for heatwave frequency for the same temperature type. This showed that different models could be best used in the absence of observed data, which depends on the type of characterisation being considered.

The investigation of the spatial trend of heatwave characteristics (HWA, HWD, HWM, HWF, and HWN) over Burkina Faso based on three heatwave definitions considered in this study showed that there is a statistically significant trend indicating an increase in temperature over the years. This is because the model output at 95% confidence level showed a probability value (*p*-

value) that is lesser than the significance level (α= 0.05), hence the null hypothesis is rejected in favour of the alternative. This means that there is a relationship between the independent and the dependent variable within the three (3) heatwave definitions considered in this study. However, the relationship is very weak in terms of magnitude. In comparing heatwave trends, it is evident that heatwave characteristics based on minimum temperatures showed greater spatial coherence than those based on maximum temperatures. Additionally, trends associated with minimum temperatures are notably more positive than those related to maximum temperatures. The findings expand our understanding of heatwaves variability over Burkina Faso. A comprehensive approach is crucial for creating effective strategies to adapt to and build resilience against climate impacts, where heatwaves severely affect communities and ecosystems.

Historical, current, and projected analyses of heatwave characteristics and the TemperatureHumidity Index (THI) reveal a complex but critical link between heat events and mortality. While the correlation between heatwaves and deaths is weak, THI is a more reliable indicator of heat-related mortality, particularly during the dry season (April, May, and December), when elevated THI corresponds to deaths.

This study also analysed the projection of heatwave characteristics over Burkina Faso for the near future (2020-2050) and far future (2051-2100) under the SSP245 and SSP585 model schemes. The anticipated changed assessment of these heatwaves' characteristics (amplitude, frequency, duration, magnitude, and the number of occurrences) of the three (3) indices [minimum (TN90) and maximum (TX90) temperatures as well as excess heat factor (EHF)] showed a moderate change in the selected heatwave characteristics in the near future, that is, within the next 30 years. However, there was a noticeable climatic transformation of the region in the far future (2100), but with the significant change more pronounced under SSP585 than the SSP245 pathway.

5.2 Recommendation

To address heatwave challenges, immediate actions are essential. Public health interventions, such as heat stress awareness campaigns, improved healthcare access, and emergency response systems, are critical for reducing mortality during high-risk months. Urban planning efforts, including expanding vegetation cover and enhancing housing ventilation, can mitigate the urban heat island effect. Furthermore, real-time monitoring systems for THI and heatwaves and early warning mechanisms are necessary to improve preparedness.

Long-term strategies, such as integrating climate adaptation policies, sustainable water management, and reducing greenhouse gas emissions, are vital to limit future temperature increases and their associated risks. These measures are crucial to building resilience against escalating heat stress in Burkina Faso.

Further research is needed to explore the interaction between heat, humidity, and other health factors and the cumulative long-term impacts of heat stress on vulnerable populations.

Further studies should also examine the impact of heatwaves on humans and the environment. A suitable threshold for heatwave characteristics should be established in collaboration with relevant stakeholders, taking into account data and insights on the varying impacts across different levels of exposure and vulnerability.

Future studies should account for model uncertainty, which can significantly impact the reliability of climate projections. Enhancing model performance through improved parameterizations and multi-model ensemble approaches can help reduce uncertainties and provide more robust predictions.

Health data should be stored and made available for future studies.

The number of synoptic stations should increase in order to cover all the regions of Burkina Faso.

5.3 Contribution to Knowledge

This research on the impact of heatwaves on human health over Burkina Faso has contributed to characterising heatwaves and the Temperature Humidity Index in Burkina Faso over a 30-year period. It has also contributed to understanding the link between heatwaves and human health and to making a projection of near future (2020-2050) and far future (2051-2100) heatwaves over Burkina Faso.

The findings of this study can support policymakers involved in climate adaptation and assist health professionals in proactively preparing for anticipated outcomes.

This study will help in achieving the Sustainable Development Goals (SDG-1) relating to poverty eradication, (SDG-3) human health and well-being, and (SDG-13) taking urgent action to address climate change and its impacts.

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APPENDIX

PUBLICATIONS SUBMITTED FROM THE THESIS

A.1: Paper1 published in Journal of Earth and Atmospheric Research

Millogo *et al*/JEAR 8 (1) (2025) 1-14 ISSN: 26590530 01

Journal of Earth and Atmospheric Research

TRENDS IN HEATWAVE CHARACTERISTICS OVER BURKINA FASO

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ABSTRACT

In West Africa, particularly in Burkina Faso, heatwave studies are limited. However, several international studies forecast that this region will be especially vulnerable to increased heatwave events due to climate change. The characteristics of heatwaves in Burkina Faso from 1991 to 2021 have been examined by analysing observed data and climate model simulations. The Bias-Correction Spatial Disaggregation (BCSD) method generated the NEX-GDDP-CMIP6 dataset. The algorithm compares the GCM outputs with corresponding climate observations over a standard period. The maximum and minimum temperatures for the models were subjected to root mean square error (RMSE), standard deviation (S.D.) and correlation coefficient (R2) to determine the best substitute for observed data. The Taylor diagram showed that MRI-ESM2-0, with the least RMSE and S.D. values and highest R2 values for both maximum and minimum temperature values, is the best-substituted model for the observed data. According to the heatwave index HWN (Heatwave Number, HWD) (Heatwave Duration), and HWA (Heatwave Amplitude), the trend-based maps of heatwave characteristics often display a consistent pattern of positive or negative changes. The trend for a specific heatwave index characteristic may be either positive or negative, depending on the location and model considered when compared to the observed. The trends in heatwave characteristics concerning minimum temperatures show higher (warmer) values than those relating to maximum temperatures, indicating a situation of unusually warm nights. This study emphasizes trends in heatwave characteristics based on minimum and maximum temperatures, and calls for attention to the associated risk of rising nighttime temperatures during heatwaves.

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1. Introduction

Global average temperatures rose by approximately 0.07°C per decade from 1901 to 2010 (Morice et al., 2012). Questions have emerged regarding the effects of changing climatic conditions onthe environment and humanity. This rise in temperature has been linked to the impact of greenhouse gases and has not been

A.2: Paper 2 accepted in Journal of Meteorology and Climate Science Nigerian Meteorological Society

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NIGERIAN METEOROLOGICAL SOCIETY

Nigerian Meteorological Agency Complex, Blind Centre Road, Cappa, Oshodi, P. M . B. 1215, Oshodi, Lagos

13/05/2025

Dear Nadege Millogo,

NOTIFICATION OF ACCEPTANCE OF MANUSCRIPT FOR PUBLICATION

Your manuscript entitled "The Health Impacts of Heatwaves in a Warming Climate: A Case Study of Ouagadougou, Burkina Faso" has been accepted for publication in the Journal of Meteorology and Climate Science, Volume 24(1) June, 2025 after due consideration by our reviewers.

A.3: Paper 3 under review in International Journal of Biometeorology

International Journal of Biometeorology

Characterisation of Heatwaves over Burkina Faso Using Multi-Model Climate Simulations

--Manuscript Draft--

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Keywords:	Heatwaves; Burkina Faso; HWN; HWF; HWA; HWD; NEX-GDDP CMIP6
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A.4: Paper 4 under review at Theoretical and Applied Climatology