“The effect of weather on stock market returns: Evidence from African stock markets”

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THE EFFECT OF WEATHER ON STOCK MARKET RETURNS: EVIDENCE FROM AFRICAN STOCK MARKETS

Abstract

Increasing market volatility and the profound impacts of climate change require a comprehensive understanding of how weather affects stock market performance. This paper aims to investigate the effect of eight weather conditions (clear sky, precipitation, pressure, temperature, relative humidity, specific humidity, wind direction, and wind speed) on the returns of major African stock markets (Botswana, Cote d'Ivoire, Kenya, Mauritius, Morocco, Namibia, Nigeria, Rwanda, South Africa, Tanzania, Tunisia, Uganda and Zambia) over the period from January 2, 1998 to December 30, 2023. Using daily data and a GJR-GARCH (1,1) model with an AR process, the findings reveal that weather conditions influence all African stock markets. Specifically, the markets are categorized according to their sensitivity to weather conditions into three groups: highly affected (5-7 coefficients with $0.001 \leq p < 0.05$), moderately affected (3-4 coefficients with $0.001 \leq p < 0.05$), and slightly affected (1-2 coefficients with $0.001 \leq p < 0.05$). Mauritius and Uganda emerge as the most weather-sensitive countries, with significant impacts ($0.001 \leq p < 0.05$) for seven of the eight weather conditions studied. Understanding the relationship between weather conditions and African stock markets enables investors to adjust their strategies and better manage their portfolios to optimize return opportunities. Ultimately, this study provides essential insights for investors, portfolio managers, and financial decision-makers, aiding them in better assessing the risks and opportunities associated with weather conditions in African stock markets, thereby enhancing their decision-making and investment management.

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INTRODUCTION

Stock market prices have long been governed and understood according to the laws and principles of traditional finance theory, including the assumption of perfect markets and rational representative agents. These are the core findings of the Capital Asset Pricing Model (Markowitz, 1952), the Efficient Market Hypothesis (Fama, 1965), and the Arbitrage Pricing Theory (Ross, 1976). However, financial market anomalies and irrational investor behavior are not adequately explained by these traditional theories, which assume rational economic actors. Behavioral finance, an emerging field of economic research, examines cognitive biases and psychological characteristics such as the disposition effect, overreaction, conservatism, mental accounting, and heuristics to explain asset price fluctuations (Shiller, 2003). Decision-making and judgment are significantly influenced by psychological states, including mood, feelings, emotion, and sentiment (Wright & Bower, 1992). Furthermore, it is well-established that mood and sentiment are significantly influenced by weather, a phenomenon known as the "weather effect" (Rind, 1996). In this context, the behavioral finance literature suggests that various weather conditions can contribute to stock market anomalies to some extent.

There are two primary motivations for this study. Firstly, although existing research explores the correlation between weather and stock market returns, very few studies focus on developing markets. Researchers argue that psychological factors exert a greater influence on investors in developing economies than those in developed ones, due to less developed financial markets (Hasan & Subhani, 2011). They found that in developing economies, positive expectations are primarily shaped by subjective perceptions of the current situation. Consequently, mood and subjective stances, significantly influenced by weather conditions, are more likely to drive market players in developing economies than in developed ones. Given that investors in developing markets tend to be more susceptible to psychological influences than those in developed markets, and considering their increasing role and influence, it is pertinent to examine how weather impacts developing economies. Additionally, African stock markets have not been previously examined to the best of the author's knowledge. Secondly, other weather variables, such as clear sky, specific humidity, and wind direction, have not been examined before. This lack of knowledge about the African stock markets, in addition to other weather variables, is another driving force behind this study, emphasizing the necessity to fill this gap in the existing literature. Therefore, this study seeks to answer the question: How do weather conditions influence African stock market returns?

This study makes several significant contributions to the field. Firstly, it addresses the lack of knowledge tailored to developing economies and specifically to the African context, providing valuable insights into whether African stock market returns are affected by the weather. As a result, investors working with African stock indices can benefit from the findings. Secondly, by focusing on several African stock indices, this study offers a more granular understanding of how weather impacts different African stock markets. This approach allows for a more nuanced assessment of stock market vulnerabilities and resilience to weather conditions. Such insights are invaluable for investors, portfolio managers, and financial decision-makers, helping them to better assess the risks and opportunities associated with weather conditions on African stock markets and thus improve their decision-making and investment management.

1. LITERATURE REVIEW

The influence of weather conditions on human behavior and financial markets has garnered increasing interest in behavioral finance. This literature review is divided into two main parts: the first examines the relationship between weather, human emotional mood, and decision-making, while the second explores the impact of weather on investor behavior and stock market returns. This integration of psychological and financial concepts aims to provide a comprehensive explanation of how weather affects the stock market.

1.1. Weather, human emotional mood, and decision making

Psychologists have extensively studied the effect of weather conditions – such as temperature, humidity, cloud cover, precipitation, etc. – on emotional mood and decision-making. Approximately one-third of humans are weather-sensitive, impacting their emotional mood, mental health, and physical health (Kals, 1982).

Research has shown that sunshine hours and temperature can enhance mood. For instance, Cunningham (1979) found that these factors significantly affect mood, demonstrating that a clear, bright, and sunny day can enhance mood in both winter and summer. This finding is supported by research indicating that mild sunshine has the most significant positive impact on people's mood (Howarth & Hoffman, 1984). Additionally, it has been observed that people are more likely to feel content on a sunny day (Schwarz & Clore, 1983), whereas a cloudy day tends to induce a bad mood (Symeonidis et al., 2010). This phenomenon has been attributed to Seasonal Affective Disorder (SAD), a seasonal form of depression common during the shorter days of the year. Researchers explain that extremely limited sunshine can make people feel weak and, in severe cases, lead to sadness or depressive moods (Kamstra et al., 2003). This analysis is supported by studies showing that lack of sunlight can seriously affect individuals' moods (Eagles, 1994; Tietjen & Kripke, 1994). On the other hand, extreme temperatures can also influence human behavior, making individuals

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more aggressive or passive. Research has observed that these temperatures can reduce people's capacity to carry out activities (Anderson, 2001; Cao & Wei, 2005; Wang et al., 2012). It has been demonstrated that stress and adverse behavior can be influenced by extreme temperatures (Pilcher et al., 2002). Furthermore, studies have found that extremely cold or hot temperatures reduce the desire to help others, confirming significant contributions to psychological literature (Schneider et al., 1980; Forgas, 1995).

The relationship between mood and decision-making is also well-documented (Isen, 1993; Loewenstein et al., 2001; Cao & Wei, 2005; Jiang et al., 2019). Individuals in a good mood are more likely to make wise and faster decisions (Forgas & Bowers, 1987; Wright & Bower, 1992). However, Loewenstein et al. (2001) found that bad mood can hinder rational or optimal decision-making.

The main weather conditions that have been demonstrated in previous research to significantly impact human mood, and subsequently decision-making behavior are sunshine hours (Allen & Fischer 1978; Cunningham, 1979; Howarth & Hoffman, 1984; Watson, 2000; Redelmeier & Baxter, 2009), temperature (Bell & Baron 1976; Schneider et al., 1980; Howarth & Hoffman, 1984; Anderson, 2001; Cao & Wei, 2005; Wang et al., 2012), humidity (Goldstein, 1972; Sanders & Brizzolara, 1982; Viswanathan & Krishnamurti, 1989; Ahrens, 2011), and barometric pressure (Digon & Bock, 1966; Goldstein, 1972; Sanders & Brizzolara, 1982).

1.2. Weather, investor behavior and stock market returns

This section presents several studies focusing on the effect of weather variables, namely, temperature, precipitation, humidity, cloud cover, wind speed, pressure, sunshine hours, visibility, and rainfall, on stock returns, along with their empirical findings (Table 1).

The relationship between weather variables and investor behavior in the stock market became a significant field of research following Saunders's (1993) seminal study. This study demonstrated a negative correlation between cloud cover and New York stock market returns, showing that market returns tend to be significantly lower on cloudy days compared to bright days. Numerous authors have followed Saunders' path, focusing their studies on the impact of cloud cover on stock market performance. The majority has affirmed Saunders's findings, demonstrating a negative impact of cloud cover on stock returns in various global markets (Dowling & Lucey, 2005; Chang et al., 2008; Floros, 2011; Brahmana et al., 2015; Apergis & Gupta, 2017; Kathiravan et al., 2018; Khanthavit, 2019; Hsiao et al., 2020). Conversely, Krämer and Runde (1997), Saporoschenko (2011), Lu and Chou (2012), Pizzutilo and Roncone (2017), Cin et al. (2020), and Muhlack (2022) found that cloud cover has no effect on stock returns in three major stock markets: Italy, Frankfurt, and the New York Stock Exchange.

Temperature is by far the most studied variable in previous research. The majority of studies demonstrate a negative correlation between temperature and stock returns (Gerlach, 2007; Keef & Roush, 2007; Makkonen, 2021; Yan et al., 2022). Extremely cold or hot temperatures might make investors act more aggressively or passively, respectively, and limit their capacity to perform tasks (Wang et al., 2012), which in turn affects their decision-making behavior and subsequently impacts stock market returns. However, some studies found no effect (Worthington, 2009; Lu & Shou, 2012; Andrikopoulos et al., 2019) or even a positive effect (Kathiravan et al., 2017; Kao et al., 2018; Kathiravan et al., 2018) on stock returns.

Other weather variables such as humidity, precipitation, wind speed, and pressure are commonly studied in the literature. Humidity is the second most investigated variable after temperature, followed by wind speed, precipitation, and pressure. Meanwhile, sunshine hours, visibility, and rainfall are less frequently studied. The main impacts of these variables on stock returns are presented in Table 1. The explanation for the relationship between these weather variables and stock returns is as follows: Unpleasant weather can affect an investor's physiological and psychological states, leading to feelings such as pessimism, worry, fatigue, and difficulty concentrating, which in turn can influence their decision-making behavior and subsequently affect stock market returns. Additionally, as previously mentioned, weather influences people's moods (Saunders, 1993; Tranfield et al., 2003; Dowling & Lucey, 2005). Good weather has a positive effect on mood (Pardo & Valor, 2003; Gerlach, 2007; Chang et al., 2008; Floros, 2011), which positively impacts stock returns (Keef & Roush, 2007; Wang et al., 2012; An et al., 2018; Jiang et al., 2021; Muhlack, 2022). However, differences exist between various weather conditions. For instance, most research has shown that temperature has a negative impact on returns; this may be due to individuals being more willing to take risks under certain weather conditions. This line of thinking suggests that colder temperatures are associated with more aggressive behavior, a greater willingness to take risks, and, ultimately, higher returns.

Considering the numerous articles in this area, academic research is still needed to continuously explore the complex dynamics between weather and stock markets. This paper investigates the effect of eight weather conditions on the returns of the main African stock markets.

Table 1. Effect of weather on stock returns

Authors	Period of study	Stock market name	Weather variables								
			TEMP*	PREC*	HUM*	CC*	WS*	PRES*	SH*	VIS*	RAIN*
Saunders (1993)	1927-1989	Dow Jones and NYSE				–					
Krämer and Runde (1997)	1960-1990	Frankfurt Stock Exchange		0	0	0		0			
Pardo and Valor (2003)	1981-2000	Madrid Stock Exchange			0				0		
Dowling and Lucey (2005)	1988-2001	Irish Stock Exchange		–	+	–					
Gerlach (2007)	1980-2003	New York Stock Exchange	–	–							
Keef and Roush (2007)	1992-2003	Australian Securities Exchange (ASX)	–				0	0			
Chang et al. (2008)	1994-2004	New York Stock Exchange	–			–	–				–
Worthington (2009)	1958-2005	Australian Securities Exchange (ASX)	0	0	0		0		0		
Floros (2011)	1995-2007	Euronext Lisbon	–	+	–	–	–	–			
Saporoschenko (2011)	1993-2002	New York Stock Exchange				0					
Lu and Chou (2012)	2003-2008	Shanghai Stock Exchange (SSE)	0		0	0	0	0		0	
Wang et al. (2012)	2001-2007	Taiwan Stock Exchange	0	0					0		
Mraoua et al. (2013)	1992-2011	Casablanca Stock Exchange	–							–	–
Brahmana et al. (2015)	1999-2012	Indonesia Stock Exchange	–			–					
Frühwirth and Sögner (2015)	2002-2006	New York Stock Exchange	–							+	
Apergis and Gupta (2017)	1973-2015	Johannesburg Stock Exchange (JSE)	–		–	–	–				–
Kathiravan et al. (2017)	2000-2015	National Stock Exchange (NSE)	+								
Pizzutilo and Roncone (2017)	2005-2014	Italian Stock Exchange	0		0	0	0	0		0	0
Shim et al. (2017)	2004-2015	Korean Stock Exchange	–		–		–		+		
Kao et al. (2018)	2004-2010	Taiwan Stock Exchange	+								
Kathiravan et al. (2018)	2001-2016	National Stock Exchange (NSE)	+			–	–				
Andrikopoulos et al. (2019)	2002-2018	New York Stock Exchange	0	0	0		0				
Jiang et al. (2019)	2006-2016	Shenzhen Stock Exchange	–		–				+		
Khanthavit (2019)	2002-2017	Stock Exchange of Thailand	–	+	–	–	–			+	–
Cin et al. (2020)	1981-2016	Korean Stock Exchange		0	0	0			0		
Hsiao et al. (2020)	2011-2017	Shanghai, Shenzhen Stock Exchanges				–					
Jiang et al. (2021)	1990-2016	New York Stock Exchange	–		–				+		
Makkonen et al. (2021)	1999-2018	London Stock Exchange	–								
Muhlack (2022)	2003-2017	Frankfurt Stock Exchange	0		0	0	0	–			
Yan et al. (2022)	2007-2019	Shanghai Stock Exchange	–								

Note: * TEMP, PREC, HUM, CC, WS, PRES, SH, VIS, and RAIN refer to Temperature, Precipitation, Humidity, Cloud Cover, Wind Speed, Pressure, Sunshine Hours, Visibility, and Rain, respectively. – Negative impact + Positive impact 0 No impact.

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2. METHODOLOGY

This section presents the characteristics and nature of the data used in this study and the methodological approach, detailing the foundation and composition of the employed empirical models.

2.1. Proposed variables

This section presents definitions of weather variables chosen for the present study based on the literature above: temperature, precipitation, relative humidity, wind speed, and pressure. Additionally, it presents several studies that focus on the effect of these weather variables on the stock returns, mainly its empirical findings. On the other hand, it presents definitions and justification of other weather variables not previously examined, namely, clear sky, specific humidity, and wind direction.

- ***Atmospheric pressure*** denotes either the elastic force or the weight of the air above a unit area of the earth's surface. It is expressed in kilopascal (MD. Zulfequar, 1998). The relationship between atmospheric pressure and stock markets has been the subject of numerous empirical studies. The majority of them found no effect of atmospheric pressure on stock market returns (Krämer & Runde, 1997; Keef & Roush, 2007; Pizzutilo & Roncone, 2017), while very few studies demonstrated a negative correlation between atmospheric pressure and stock returns (Floros, 2011; Muhlack, 2022).

- The solid or liquid products of water vapor condensing that fall from clouds upon the soil are known as ***precipitation***. Precipitation encompasses the following: dew, rain, hoar frost, snow, fog precipitation, hail, and rime. It is expressed in millimeters (Thomas, 2021). Several studies have focused on the relationship between precipitation and stock market returns. The main results found assume that the effect of precipitation on stock returns is mixed between a positive effect (Floros, 2011; Khanthavit, 2019) and a negative effect (Dowling & Lucey, 2005; Gerlach, 2007).

- ***Relative humidity*** measures the quantity of atmospheric water vapor but does so in relation to the air's temperature (Hamid et al., 2014). Investigating the effect of humidity on stock market returns has been the subject of numerous empirical studies. Dowling and Lucey (2005) examined the effect of weather conditions on the Irish Stock Exchange between 1988 and 2001; they discovered that humidity has a positive effect on stock returns. More recently, many authors have demonstrated a negative correlation between humidity and stock returns around the world (Jiang et al., 2019; Khanthavit, 2019; Jiang et al., 2021).

- ***Temperature*** is the measure of how hot or cold a thing or a place is. The actual temperature of a particular place at a particular time depends upon a number of variables, such as the season, latitude, time of day, altitude, etc. It is expressed in degree Celsius (MD. Zulfequar, 1998; Veena, 2022). Several studies have focused on the relationship between temperature and stock markets. The majority of the results found show a negative correlation between temperature and stock returns (Gerlach, 2007; Keef & Roush, 2007; Makkonen, 2021; Yan et al., 2022), While very limited studies found no effect (Worthington, 2009; Lu & Shou, 2012; Andrikopoulos et al., 2019) or positive effect (Kathiravan et al., 2017; Kao et al., 2018; Kathiravan et al., 2018) on stock returns.

- ***Wind speed*** is defined as a fundamental measure of the atmosphere that results from air shifting from a high to a low pressure, typically as a result of temperature variations (Glossary of Meteorology). Numerous empirical studies showed a strong correlation between wind speed and stock market performance. The majority of them found a negative correlation between wind speed and stock returns (Frühwirth & Sögner, 2015; Shim et al., 2017; Khanthavit, 2019).

In this study, three new weather variables have been explored, namely clear sky, specific humidity and wind direction. These variables are defined and justified as follows:

Clear sky is defined as one in which clouds cover less than 30% of the Earth's sphere (Ander, 2003). It has been shown that a clear day can create a good mood, while a cloudy day can create a bad mood (Cunningham, 1979). While all previous studies have focused on cloud cover as a proxy variable for cloudy days to demonstrate its impact on the stock market (Saunders, 1993; Dowling & Lucey, 2005; Floros, 2011; Brahmana et al., 2015; Kathiravan et al., 2018; Khanthavit, 2019; Hsiao et al., 2020). This study aims to fill the existing research gap by focusing on the opposite scenario and examining the impact of clear days on the stock market. To achieve this, this study uses the clear sky as a proxy variable for clear days.

The quantity of atmospheric water vapor, measured in grams per kilogram of air, that is present in a given weight of air is referred to as the ***specific humidity*** (Hamid et al., 2014). All previous studies have focused on relative humidity as a measure of humidity to demonstrate its impact on the stock market (Shim et al., 2015; Jiang et al., 2019, and others). This study uses both relative humidity and specific humidity as key measures of humidity to demonstrate its impact on stock returns.

The direction from where the wind originates is typically used to determine ***wind direction*** (Glossary of Meteorology). In addition to wind speed used by all previous studies as key measure of wind to demonstrate its impact on stock market, this study aims to fill the existing research gap by also examining wind direction as another measure of wind.

2.2. Data

To determine the effect of weather conditions on African stock market returns, a large dataset of stock market prices is employed. This dataset consists of the daily closing prices of main stock indices of African markets accessible in Investing.com financial website. These indices are as follow: BSE Domestic Company for Botswana, BRVM composite for Cote d'Ivoire, Nairobi All Share for Kenya, SEMDEX for Mauritius, MASI for Morocco, FTSE NSX Overall for Namibia, NSE All Share for Nigeria, Rwanda All Share for Rwanda, FTSE South Africa for South Africa, Tanzania All Share for Tanzania, TUNINDEX for Tunisia, Uganda All Share for Uganda and LES All Share for Zambia. Table A1 (see Appendix) represents the sample description.

The selection of sample countries is motivated by the need to conduct a thorough analysis of the effect of weather on stock returns across the African stock markets, aiming to provide solid conclusions and globally significant results. Additionally, the formation of the sample offers the advantage of facilitating periodic and specialized comparisons between countries. This comparison is expected to enhance understanding of the weather effects and how they influence African stock markets.

Due to the characteristics of different indices and data availability, the study's time frame is as follows (Table 2).

Table 2. Data time frame

Financial indices	Starting time of data	Ending time of data
BSE Domestic Company	5/10/2001	12/30/2023
BRVM Composite	3/4/2014	12/30/2023
Nairobi All Share	1/3/2008	12/30/2023
SEMDEX	1/4/2000	12/30/2023
MASI	1/3/2002	12/30/2023
FTSE NSX Overall	10/14/2013	12/30/2023
NSE All Share	2/1/2012	12/30/2023
Rwanda All Share	2/8/2013	12/30/2023
FTSE South Africa	7/3/2000	12/30/2023
Tanzania All Share	8/15/2011	12/30/2023
Tunindex	1/2/1998	12/30/2023
Uganda All Share	8/12/2011	12/30/2023
LES All Share	7/9/2012	12/30/2023

Daily closing prices were converted to returns using the logarithmic return formula:

$$RET_t = \log\left(\frac{X_t}{X_{t-1}}\right), \quad (1)$$

where RET is the returns at the time *t*, X_t represents the prices at the time *t* and X_{t-1} represent the prices at the time *t*–1. Statistically, the large sample size allows for the use of daily frequency data, which often results in a more valid statistical analysis. Additionally, an increasing number of financial studies are beginning to favor high-frequency data over low-frequency data.

The weather data used for this study, which spans from January 2, 1998 to December 30, 2023, was sourced from NASA POWER (https://power.larc.nasa.gov/data-access-viewer/). The weather data were collected from thirteen African countries, specifically from the locations of each country's stock exchange. It is important to note that the coordinates of each stock exchange, determined by latitude and

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Table 3. Weather variables employed in this study

Variable	Measurement	Symbol	Symbol*	Source
Clear sky	Clear sky surface shortwave downward irradiance in kilowatt-hour	CLRSKY	dclrsky	Nasa Power
Precipitation	Precipitation corrected in millimeter	PREC	dprec	Nasa Power
Pressure	Atmospheric pressure in kilopascal	PRESS	dpress	Nasa Power
Relative humidity	Relative humidity at 2 meters in percentage	RHUM	drhum	Nasa Power
Specific humidity	Specific humidity at 2 meters in g/kg	SHUM	dshum	Nasa Power
Temperature	Temperature range at 2 meters in degrees Celsius	TEMP	dtemp	Nasa Power
Wind direction	wind direction at 10 meters in degrees	WD	dwd	Nasa Power
Wind speed	Wind speed range at 10 meters in meter per second	WS	dws	Nasa Power

Note: * For weather variables deseasonalized.

longitude, were obtained from the NASA website (Table A1 in Appendix).

The following are the weather variables selected for this study (Table 3). It should be noted that all the weather variables are limited only during the trading days, not the whole days.

The methodology proposed by Hirshleifer and Shumway (2003) is followed to deseasonalize the weather data. The process begins by calculating the average value for each weather variable across the dataset for a specific market for each week of the year. The deseasonalized values are then obtained by subtracting this average from the actual observations. The day-value of the first week for all years is subsequently subtracted from this average. Additionally, dummy variables for Mondays (Harris, 1986) and January (Chan, 1986) are included as control variables.

2.3. Descriptive statistics

The Jarque-Bera test was applied to assess whether the stock market data are normally distributed. Due to the non-normal distribution of the returns data (Table 4), it is likely that the residuals from the regressions would also not be normal. Consequently, robust standard errors were employed for the significance tests. The Ljung-Box (LB) Q test was used to evaluate the presence of autocorrelation in the data. Significant test results indicated either autocorrelation or white noise. Furthermore, the test findings revealed the presence of autocorrelation and volatility clusters. The ARCH test was utilized to assess the data's heteroskedasticity.

The Augmented Dickey-Fuller (ADF) test was used to examine the stationary nature of stock market data differences. The test findings led to the assumption that all time series were stationary in level. Tables 4 to 6 show the descriptive statistics of the stock market data for the normality test, LB test, ARCH test, and stationarity test.

Table 4. Descriptive statistics of African stock market data I

Variable	Mean	Std. Dev.	Jarque Bera
$RET_{BSE\ Domestic\ Company}$	0.000111	0.001989	1035943***
$RET_{BRVM\ Composite}$	–3.81E-05	0.003306	2137.059***
$RET_{Nairobi\ All\ Share}$	2.63E-05	0.005485	11018234***
RET_{SEMDEX}	0.000117	0.002869	482114.5***
RET_{MASI}	8.96E-05	0.003310	33391.15***
$RET_{FTSE\ NSX\ Overall}$	9.11E-05	0.020256	80664625***
$RET_{NSE\ All\ Share}$	0.000145	0.004211	3609.059***
$RET_{Rwanda\ All\ Share}$	2.65E-05	0.019642	69669177***
$RET_{FTSE\ South\ Africa}$	0.000163	0.005131	5662.769***
$RET_{Tanzania\ All\ Share}$	6.07E-05	0.007029	2259161***
$RET_{Tunindex}$	0.000147	0.003151	90026727***
$RET_{Uganda\ All\ Share}$	3.01E-05	0.008184	4052546***
$RET_{LSE\ All\ Share}$	0.000113	0.003046	77527.35***

Note: Significance codes : * p < 5%; ** p < 1%; *** p < 0.1%.

Table 5. Descriptive statistics of African stock market data II

Variable	Ljung-Box Lag[5]	Ljung-Box Lag[10]	Ljung-Box Lag[15]
$RET_{BSE\ Domestic\ Company}$	254.81***	432.99***	574.11***
$RET_{BRVM\ Composite}$	21.76***	25.67***	33.203***
$RET_{Nairobi\ All\ Share}$	17.64***	25.57***	26.770*
RET_{SEMDEX}	51.68***	83.66***	121.60***
RET_{MASI}	7.7778	20.60*	29.65*
$RET_{FTSE\ NSX\ Overall}$	175.37***	177.47***	178.69***
$RET_{NSE\ All\ Share}$	11.51*	15.36	20.47
$RET_{Rwanda\ All\ Share}$	324.74***	324.75***	324.80***
$RET_{FTSE\ South\ Africa}$	12.57*	33.530***	38.156***
$RET_{Tanzania\ All\ Share}$	95.87***	105.28***	107.81***
$RET_{Tunindex}$	12.34*	23.60**	48.71***
$RET_{Uganda\ All\ Share}$	23.41***	24.20**	25.838*
$RET_{LSE\ All\ Share}$	8.69	20.89*	40.38***

Note: Significance codes : * p < 5%; ** p < 1%; *** p < 0.1%.

Table 6. Descriptive statistics of African stock market data III

Variable	ARCH Lag[3]	ARCH Lag[5]	ARCH Lag[7]	ADF
$RET_{BSE\ Domestic\ Company}$	117.27***	181.07***	183.25***	-16.84***
$RET_{BRVM\ Composite}$	169.70***	178.79***	184.05***	-31.88***
$RET_{Nairobi\ All\ Share}$	1290.26***	1395.35***	1431.181	-41.41***
RET_{SEMDEX}	868.93***	907.04***	972.35***	-31.83***
RET_{MASI}	963.56***	1070.09***	1108.90***	-56.03***
$RET_{FTSE\ NSX\ Overall}$	245.99***	246.24***	246.09***	-34.39***
$RET_{NSE\ All\ Share}$	180.38***	193.43***	198.20***	-38.02***
$RET_{Rwanda\ All\ Share}$	262.22***	263.98***	263.91***	-23.68***
$RET_{FTSE\ South\ Africa}$	1231.11***	1410.034***	1521.006***	-73.96***
$RET_{Tanzania\ All\ Share}$	355.07***	355.97***	355.83***	-41.19***
$RET_{Tunindex}$	2147.66***	2302.56***	2351.31***	-86.79***
$RET_{Uganda\ All\ Share}$	402.04***	401.79***	401.51***	-46.13071
$RET_{LSE\ All\ Share}$	40.47***	41.36***	42.02***	-51.93959

Note: Significance codes : * p < 5%; ** p < 1%; *** p < 0.1%.

2.4. Model

The distribution of time series, often non-normal due to its leptokurtic nature, autocorrelation, and volatility clustering, poses challenges for traditional time series models. Engle (1982) introduced the ARCH model to incorporate these characteristics by modeling conditional variance based on historical data. The GARCH model, developed later, allowed for more efficient handling of financial series' long volatility memory by introducing additional parameters. However, these models assume symmetric volatility responses to positive and negative shocks, an assumption often disproven in capital markets where bad news typically has a greater impact on volatility – a phenomenon known as the leverage effect. To address this, models like GJR-GARCH have been developed to capture this asymmetry. In this analysis of African stock returns, which exhibit non-normality, high autocorrelation, and volatility clustering, GARCH models were utilized following established research (Yoon & Kang, 2009; Floros, 2011; Kao et al., 2017; Cin et al., 2020; Muhlack et al., 2022), which proved effective for modeling heteroskedasticity and capturing volatility patterns.

This study used the GJR-GARCH (1,1) model with an AR process to examine the association between stock returns and weather conditions. AR process with different parameters is considered to correct from autocorrelation of returns. Bollerslev-Wooldridge error terms, which were resistant to conditional non-normality, were applied to all models in accordance with appropriate empirical research standards (Zivot, 2009). The model was set as follows:

$$RET_{i,t} = C_i + \theta k \sum_{i=1}^{k} RET_{i,t-k} + \alpha 1 dclrsky + \alpha 2 dprec + \alpha 3 dpres + \alpha 4 drhum + \alpha 5 dshum + \alpha 6 dtemp + \alpha 7 dwd + \alpha 8 dws + \alpha 9 Monday + \alpha 10 January + \varepsilon_{i,t}, \quad (2)$$

$$\sigma t^2 = \omega + \alpha\varepsilon(t-1)^2 + \gamma\varepsilon(t-1)^2 I[\varepsilon(t-1) < 0] + \beta\sigma(t-1)^2 . \quad (3)$$

In equation (2), $RET_{i,t}$ is the stock returns for market *i* at time *t*, *dclrsky*, *dprec*, *dps*, *drhum*, *dshum*, *dtemp*, *dwd*, and *dws* represent the deseasonalized value of weather variables (clear sky, precipitation, atmospheric pressure, relative humidity, specific humidity, temperature, wind direction and wind speed respectively), *Monday* and *January* are dummy variables representing the Monday and January effect, respectively, ε_t is the error term.

In equation (3), σt^2 is the conditional variance of returns at time *t*, ω is the constant term in the GJR-GARCH model. α is the lagged squared residual, it measures the impact of past volatility, represented by the one-period lag squared error ($\varepsilon (t-1)^2$), on current volatility. γ is the coefficient associated with the term $\varepsilon (t-1)^2 I [\varepsilon (t-1) < 0]$. It captures the effect of past volatility when it is negative. It measures the asymmetry in the response of volatility to positive and negative shocks. When the squared error at a lag ($\varepsilon (t-1)^2$) is negative, the term $\gamma\varepsilon (t-1)^2 I [\varepsilon (t-1) < 0]$ has an additional effect on current volatility, capturing the leverage effect phenomenon where volatility reacts more strongly to bad news than to good news. β is the coefficient associated with the term $\sigma (t-1)^2$. It measures the impact of past conditional volatility ($\sigma (t-1)^2$) on current volatility.

3. RESULTS

Figures A1 and A2 in the appendix provide an overview of the evolution of African stock indices

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prices and returns during the study period. We observe that the BSE Domestic Company, Nairobi All Share, SEMDEX, MASI, NSE All Share, FTSE South Africa, Tanzania All Share, Tunindex, Uganda All Share, and LSE All Share indices have experienced a growing trend over the last decade. In contrast, the BRVM index has undergone an up-and-down cycle, while the FTSE NSX Overall and Rwanda All Share indices have remained almost unchanged.

The empirical analysis of the GJR-GARCH (1,1) model with an AR process presented in Table A2 in the appendix reveals a significant impact of weather conditions on the returns of major African stock markets. Two key observations emerge from this analysis: Firstly, each market is sensitive to particular weather conditions, unlike others. Secondly, the impact of weather conditions on these markets varies, leading to positive or negative effects depending on the market.

Mauritius and Uganda emerge as the most weather-sensitive countries. In Mauritius, all weather variables except precipitation and wind direction significantly affect returns, with relative humidity and temperature having a negative effect, while other variables have a positive effect. In Uganda, all weather variables except precipitation and temperature significantly affect returns, with specific humidity and wind direction having positive effects, while other weather variables have negative effects. Botswana, Namibia, South Africa, and Tunisia also show significant sensitivity to weather conditions, with five out of eight variables showing statistically significant effects. Cote d'Ivoire, Nigeria, and Zambia are also highly weather-sensitive, with four out of eight variables having significant effects. Conversely, Kenya, Morocco, Tanzania, and Rwanda are the least weather-sensitive countries, as more than half of the studied variables are not statistically significant for these countries.

The analysis reveals that pressure is the most determinant of stock market returns in Kenya, Mauritius, Namibia, Nigeria, and Zambia. Indeed, the estimated coefficients for pressure are statistically significant and notably higher compared to other weather variables in these countries (Kenya (1.81E-05), Mauritius (4.51E-07), Namibia (0.000192), Nigeria (4.17E-06), and Zambia (1.33E-05)). Temperature emerges as the key determinant of stock market returns in Morocco (1.35E-07), Tanzania (2.95E-06), and Tunisia (8.86E-08). Regarding precipitation, it emerges as the key determinant of stock market returns in Cote d'Ivoire (7.85E-08) and Rwanda (–4.24E-06). Clear sky, specific humidity, and wind direction represent the key determinants of stock market returns in Botswana (2.39E-06), Uganda (6.99E-06), and South Africa (–7.48E-09), respectively.

The results indicate that sensitivity to weather conditions is an important factor for investors in African stock markets. The differences in sensitivity to weather variables among the countries can be attributed to various economic, geographical, and climatic factors specific to each country. For instance, the significance of pressure in Zambia could be related to its tropical climate and the influence of atmospheric pressure fluctuations on local economic activities. Similarly, temperature plays a crucial role in Morocco due to its Mediterranean climate and the impact of heat waves on the economy. These findings emphasize the need for investors to consider weather conditions when making investment decisions in African stock markets, as the impact of these conditions can vary significantly across different markets and can influence returns both positively and negatively.

4. DISCUSSION

These results highlight the critical importance of weather conditions for African stock markets, with key variables such as pressure and temperature significantly influencing the economic performance of many countries. Pressure and temperature emerge as the most important variables in this study, with statistically significant coefficients for nine out of thirteen countries studied. Pressure shows a dominant negative effect on African stock markets (Botswana, South Africa, Tunisia, and Uganda), which confirms the precedent results of Floros (2011) and Muhlack (2022). Temperature on the other hand, shows a dominant negative effect on African stock markets (Mauritius, Namibia, South Africa, and Zambia), which confirms precedent results (Gerlach, 2007; Keef & Roush, 2007; Makkonen, 2021; Yan et al., 2022) that might be explained by the idea that extremely cold or hot temperatures might make people act more aggressively or passively, respectively (Anderson, 2001; Wang et al., 2012), which create an increased willingness to take risks under these conditions (Muhlack et al., 2021).

After pressure and temperature, a clear sky represents the other most important variable in this study. The estimated coefficients for clear sky are statistically significant for eight out of thirteen countries studied. Generally, clear sky exerts a negative effect on the African stock markets, insofar as only Botswana and Mauritius are positively impacted. Although this positive impact of a clear sky is less dominant, it can be explained by the following reasoning: a bright and clear day will create a good mood (Cunningham, 1979), which has a significant effect on investors' decision-making behavior, which in turn is reflected in stock market returns. Saunders (1993) argues that when compared to bright days, stock returns are much lower on cloudy days.

The variables relative humidity, wind direction, and wind speed share the third place and represent the other most important variables in this study. The estimated coefficients for these variables are statistically significant for six out of thirteen countries studied. Relative humidity shows a dominant negative effect (Cote d'Ivoire, Mauritius, Tunisia, and Uganda), which confirms the precedent of most recent results (Jiang et al., 2019; Khanthavit, 2019; Jiang et al., 2021). Wind speed, on the other hand, shows a dominant negative effect (Kenya, Namibia, South Africa, Tanzania, and Uganda), which confirms precedent results (Frühwirth & Sögner, 2015; Shim et al., 2017; Khanthavit, 2019). While wind direction shows a dominant positive effect (Botswana, Tunisia, and Uganda). Precipitation and specific humidity come in fourth place insofar as the estimated coefficients for these variables are statistically significant only for five out of thirteen countries studied.

Precipitation shows a dominant negative effect on African stock markets (Botswana, Rwanda, and Zambia), which confirms precedent results (Dowling & Lucey, 2005; Gerlach, 2007). This confirms the idea that poor weather conditions, including high precipitation, lead to decreased returns in stock markets (Muhlack et al., 2021). Specific humidity shows a dominant positive effect on African stock markets (Mauritius, Nigeria, and Uganda).

These results highlight the critical importance of weather conditions for African stock markets, with key variables such as pressure and temperature significantly influencing the economic performance of many countries. This suggests that investors and policymakers should consider these weather factors in their analyses and decision-making processes to better understand and predict stock market fluctuations in Africa. Additionally, the findings indicate that the dummy variables "January" and "Monday" significantly affect stock market returns in the studied African countries. January negatively influences returns in eight countries and positively in one, while Monday negatively impacts eight countries and positively affects two. These results emphasize the potential importance of seasonal and weekly factors in the performance of stock markets in Africa.

Future research should delve into the underlying mechanisms driving the impact of weather conditions on stock markets, taking into account psychological and behavioral factors. Additionally, it is proposed that future studies examine the pre- and post-COVID-19 periods to assess alterations in stock markets' responsiveness to weather conditions. Expanding the analysis to include more countries and longer time periods could also provide a more comprehensive understanding of these effects.

CONCLUSION

The objective of this study was to investigate the effects of eight weather conditions on the returns of the main African stock markets. The findings reveal significant weather effects across all African stock markets, with each market showing sensitivity to specific weather conditions. For example,

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Nairobi Securities Exchange is influenced by clear sky, pressure, and wind speed, while these variables do not affect the Casablanca Stock Exchange. Conversely, precipitation, specific humidity and temperature impact the Casablanca Stock Exchange but not the Nairobi Securities Exchange. Additionally, weather conditions have divergent repercussions on the stock markets, resulting in positive effects for some and negative effects for others. The variation observed in the impact of the same weather variable across different stock markets can possibly be attributed to the sensitivity of each market to weather conditions. Notably, the fact that investors come from various geographic locations is possibly the reason why the effect of weather conditions on stock returns is controversial. However, it is difficult to explain why the same variable exerts different impacts on different stock markets. Also, results show that all African stock markets are affected by weather conditions, but at different levels. Some are more severely affected (Mauritius, Uganda, Botswana, Namibia, South Africa, and Tunisia), others more moderately (Cote d'Ivoire, Nigeria and Zambia), while some stock markets have a relatively low impact (Kenya, Morocco, Tanzania, and Rwanda). Finally, this study shows that Mauritius and Uganda are the most weather sensitive. Six out of eight weather conditions have a strong effect on their returns.

Regarding weather variables, the analysis reveals that pressure and temperature are the most important variables in this study, affecting nine out of thirteen countries. Pressure is the most determinant of stock market returns in Kenya, Mauritius, Namibia, Nigeria, and Zambia. Temperature emerges as the key determinant of stock market returns in Morocco, Tanzania, and Tunisia.

This study is of major financial importance because of the significant influence of individual investors on African stock markets. By considering their behavioral tendencies and emotional biases, this study offers an improved comprehension of how weather conditions can specifically affect the performance of major stock markets in Africa. Weather conditions play a crucial role in the performance of African stock markets, influencing investors' emotions and decisions. Weather conditions can trigger panic or uncertainty, leading to temporary variations in asset returns. By comprehending these relationships, investors can maximize return chances in African stock markets by adjusting their strategies and managing their portfolios more effectively. In the end, this study offers crucial information to financial decision-makers, portfolio managers, and investors, enabling them to more accurately evaluate the opportunities and risks related to weather conditions on African stock markets and, consequently, enhance their investment management and decision-making.

AUTHOR CONTRIBUTIONS

Conceptualization: Fouzia Alloul, El Mehdi Ferrouhi.
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Formal analysis: Fouzia Alloul, El Mehdi Ferrouhi.
Investigation: Fouzia Alloul.
Methodology: Fouzia Alloul.
Project administration: Fouzia Alloul, El Mehdi Ferrouhi.
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Validation: Fouzia Alloul, El Mehdi Ferrouhi.
Visualization: Fouzia Alloul, El Mehdi Ferrouhi.
Writing – original draft: Fouzia Alloul, El Mehdi Ferrouhi.
Writing – review & editing: Fouzia Alloul, El Mehdi Ferrouhi.

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APPENDIX A

Table A1. Presentation of African stock markets

Country	Stock market	Location of stock market	Latitude	Longitude	Date of creation	Index
Botswana	Botswana Stock Exchange (BSE)	Gaborone	–24.6549	25.9187	1989	BSE Domestic company
Cote d'Ivoire	Bourse Régionale des Valeurs Mobilières (BRVM)	Abidjan	5.3259	–4.0217	1966	BRVM Composite
Kenya	Nairobi Securities Exchange (NGSEINDEX)	Nairobi	–1.2825	36.8238	1954	Nairobi All Share
Mauritius	Stock Exchange Of Mauritius (SEM)	Port Louis	–20.1649	57.5154	1989	SEMDEX
Morocco	Casablanca Stock Exchange (CSE)	Casablanca	33.5965	–7.6189	1929	MASI
Namibia	Namibian Stock Exchange (NSX)	Windhoek	–22.5707	17.0907	1904	FTSE NSX Overall
Nigeria	Nigerian Stock Exchange (NGSEINDEX)	Lagos	6.4538	3.394	1960	NSE All Share
Rwanda	Rwanda Stock Exchage (RSE)	Kigali	–1.9495	30.0587	2005	Rwanda All Share
South africa	Johannesburg Stock Exchange (JSE)	Johannesburg	–26.2034	28.0387	1887	FTSE South Africa
Tanzania	Dar Es Salaam Stock Exchange	Dar es Salaam	–6.8919	39.2655	1996	Tanzania All Share
Tunisia	Bourse De Tunis (BVMT)	Tunis	36.8004	10.1813	1969	Tunindex
Uganda	Uganda Securities Exchange (USE)	Kampala	0.3161	32.5743	1997	Uganda All Share
Zambia	Lusaka Stock Exchange (LUSE)	Lusaka	–15.4248	28.2787	1994	LES All Share

Table A2. Weather effect on stock returns

	Botswana AR(1)–GJR–GARCH(1,1)	Cote d'Ivoire AR(4)–GJR–GARCH(1,1)	Kenya AR(1)–GJR–GARCH(1,1)	Mauritius AR(3)–GJR–GARCH(1,1)	Morocco AR(1)–GJR–GARCH(1,1)	Namibia AR(2)–GJR–GARCH(1,1)	Nigeria AR(2)–GJR–GARCH(1,1)
C	0.000108	–7.65E–05	–5.40E–05	8.81E–05	8.06E–05	–0.000277	4.52E–06
	(0.0360)	(0.3140)	(0.7829)	(0.0003)	(0.0366)	(0.6569)	(0.9609)
DCLRSKY	2.39E–06	–4.70E–06	–5.70E–06	3.00E–07	–1.42E–08	–0.000125	1.16E–09
	(0.0000)	(0.0000)	(0.0377)	(0.0051)	(0.1966)	(0.0000)	(0.9979)
DPREC	–4.09E–08	7.85E–08	–1.41E–07	1.21E–09	5.19E–08	4.12E–07	4.55E–08
	(0.0133)	0.0446)	(0.7958)	(0.8681)	(0.0214)	(0.4941)	(0.1726)
DPS	–1.95E–06	–2.71E–08	1.81E–05	4.51E–07	2.32E–07	0.000192	4.17E–06
	(0.0000)	(0.9179)	(0.0162)	(0.0000)	(0.2307)	(0.0000)	(0.0132)
DRHUM	1.89E–08	–5.18E–08	–2.39E–08	–7.30E–08	2.54E–08	–4.43E–08	3.23E–07
	(0.0619)	(0.0000)	(0.9245)	(0.0000)	(0.0680)	(0.9775)	(0.0071)
DSHUM	6.23E–08	–4.22E–08	4.95E–07	2.64E–07	–3.37E–07	–2.40E–05	4.45E–08
	(0.3321)	(0.7811)	(0.6799)	(0.0000)	(0.0000)	(0.0017)	(0.8987)
DTEM	1.14E–07	–4.69E–08	–5.08E–08	–8.53E–07	1.35E–07	–7.39E–06	1.16E–06
	(0.0000)	(0.7290)	(0.8798)	(0.0000)	(0.0000)	(0.0061)	(0.0000)
DWD	2.23E–09	–1.60E–08	5.35E–09	7.42E–10	1.89E–10	1.37E–07	–4.68E–08
	(0.0272)	(0.0527)	(0.8648)	(0.3176)	(0.8090)	(0.3711)	(0.0000)
DWS	3.93E–08	9.16E–08	–2.14E–06	1.51E–07	–5.55E–08	–1.59E–05	–3.66E–07
	(0.3868)	(0.5343)	(0.0000)	(0.0000)	(0.4419)	(0.0004)	(0.1070)
JANUARY	–7.95E–07	–7.60E–07	–2.14E–05	5.70E–08	1.72E–07	–0.000212	7.26E–07
	(0.0000)	(0.0000)	(0.0000)	(0.0743)	(0.1533)	(0.0000)	(0.0301)
MONDAY	–3.23E–06	–2.65E–06	–1.09E–05	4.23E–07	–7.56E–07	0.000258	–1.66E–06
	(–3.23E–06)	(0.0000)	(0.0000)	(0.0000)	(0.0001)	(0.0000)	(0.0006)
ω	2.84E–06	3.47E–06	2.75E–05	4.86E–07	1.34E–06	0.000242	1.55E–06
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
α	0.150000	0.149998	0.149992	0.189759	0.206422	0.132565	0.185129
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0003)	(0.0000)
γ	0.050000	0.049995	0.049996	0.061259	0.075202	0.028508	–0.039114
	(0.0032)	(0.1846)	(0.2884)	(0.0000)	(0.0000)	(0.8507)	(0.0240)
β	0.600000	0.599997	0.599944	0.624547	0.629719	0.303824	0.760828
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
AIC	–9.709537	–8.667533	–7.478556	–9.673158	–8.953006	–5.626495	–8.382416
BIC	–9.689458	–8.618172	–7.451767	–9.652264	–8.932940	–5.584003	–8.345228

Note: P-values are in parentheses.

Table A2 (cont). Weather effect on stock returns

	Rwanda AR(1)–GJR–GARCH(1,1)	South Africa AR(2)–GJR–GARCH(1,1)	Tanzania AR(4)–GJR–GARCH(1,1)	Tunisia AR(2)–GJR–GARCH(1,1)	Uganda AR(2)–GJR–GARCH(1,1)	Zambia AR(1)–GJR–GARCH(1,1)
C	0.000395	0.000131	0.000140	0.000121	0.000217	0.000101
	(0.9367)	(0.0214)	(0.4691)	(0.0788)	(0.4841)	(0.3338)
DCLRSKY	–1.36E–05	5.01E–07	–3.62E–06	–7.63E–06	–2.65E–05	–3.46E–06
	(0.8355)	(0.1142)	(0.3621)	(0.0000)	(0.0003)	(0.0000)
DPREC	–4.24E–06	9.27E–08	1.24E–07	–2.99E–09	–3.96E–07	–1.54E–07
	(0.0108)	(0.1608)	(0.4210)	(0.8793)	(0.2943)	(0.0000)
DPS	–7.08E–05	–2.27E–06	–5.94E–07	–3.26E–07	–0.000111	1.33E–05
	(0.7325)	(0.0061)	(0.9126)	(0.0231)	(0.0000)	(0.0000)
DRHUM	–1.36E–06	–1.49E–08	1.79E–06	–9.79E–08	–1.15E–06	–5.58E–08
	(0.8110)	(0.6302)	(0.0000)	(0.0000)	(0.0170)	(0.2849)
DSHUM	4.97E–06	–5.99E–07	2.29E–06	9.96E–08	6.99E–06	–2.62E–07
	(0.8939)	(0.0006)	(0.1084)	(0.5193)	(0.0042)	(0.3733)
DTEM	–1.81E–06	–3.83E–07	2.95E–06	8.86E–08	2.35E–06	–5.27E–07
	(0.8937)	(0.0048)	(0.0097)	(0.0114)	(0.0917)	(0.0002)
DWD	–4.55E–07	–7.48E–09	1.68E–08	4.27E–09	1.10E–07	–3.74E–09
	(0.2554)	(0.0398)	(0.2510)	(0.0003)	(0.0108)	(0.4267)
DWS	7.99E–06	–7.28E–07	–2.86E–06	3.99E–08	–5.45E–06	1.85E–07
	(0.7304)	(0.0000)	(0.0016)	(0.5496)	(0.0070)	(0.3731)
JANUARY	–0.000313	1.35E–07	–2.64E–05	–4.82E–06	–2.30E–05	–6.26E–07
	(0.0000)	(0.2761)	(0.0000)	(0.0000)	(0.0000)	(0.0959)
MONDAY	–2.14E–05	7.89E–07	–9.20E–06	–2.40E–06	–3.45E–05	–5.26E–06
	(0.6765)	(0.3353)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
ω	0.000378	4.05E–07	3.21E–05	6.98E–06	4.53E–05	5.82E–06
	(0.0000)	(0.0215)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
α	0.149934	0.006949	0.149989	0.149998	0.149743	0.150000
	(0.3937)	(0.2125)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
γ	0.049899	0.129850	0.049992	0.049999	0.049864	0.050000
	(0.9199)	(0.0000)	(0.1777)	(0.1137)	(0.3888)	(0.0515)
β	0.596877	0.903543	0.598936	0.599985	0.598574	0.599999
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
AIC	–5.020579	–7.962719	–7.256493	–8.784630	–6.912763	–8.760481
BIC	–4.982117	–7.943298	–7.216047	–8.766148	–6.875915	–8.723790

Note: P-values are in parentheses.

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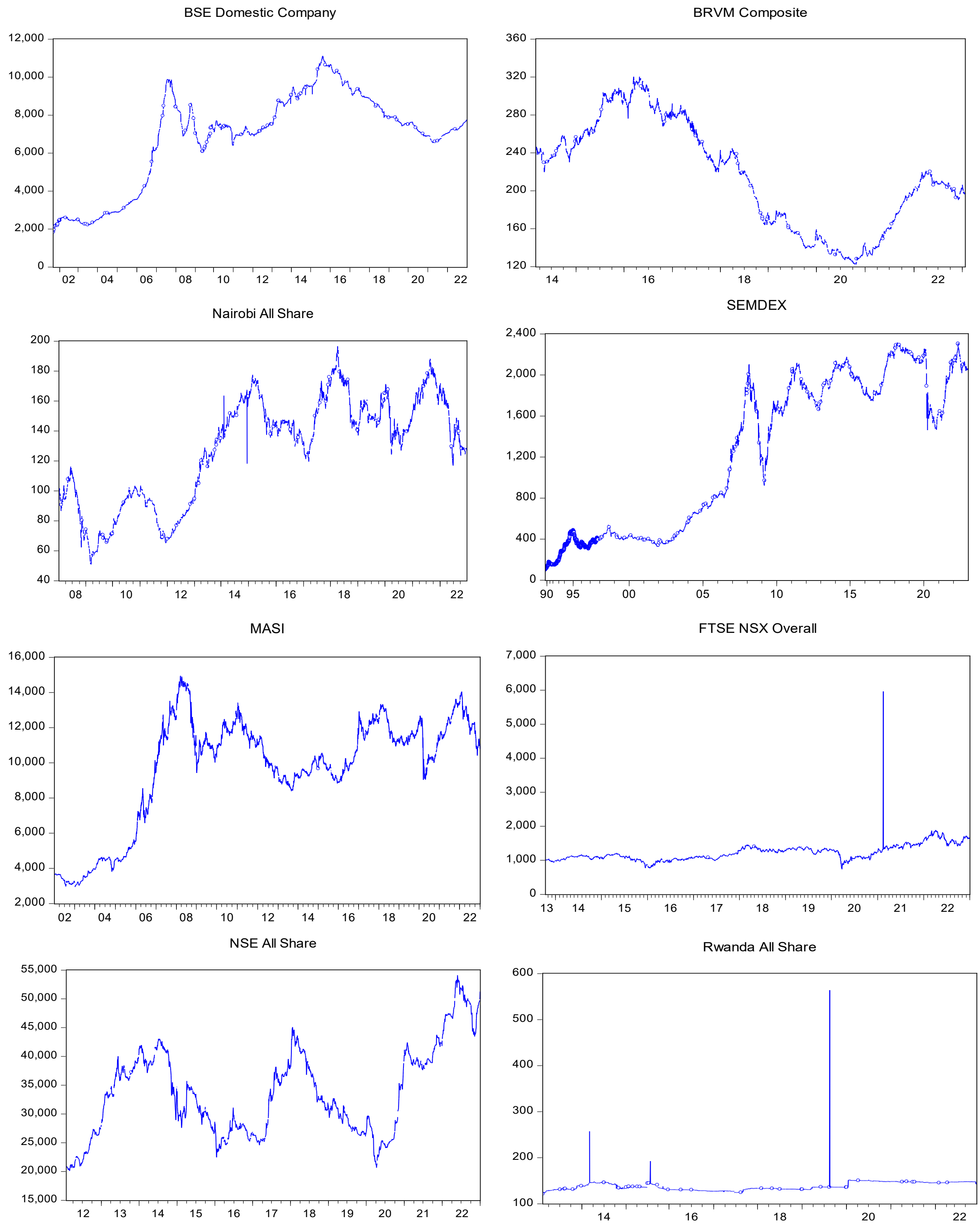

Figure A1. Series evolution of prices

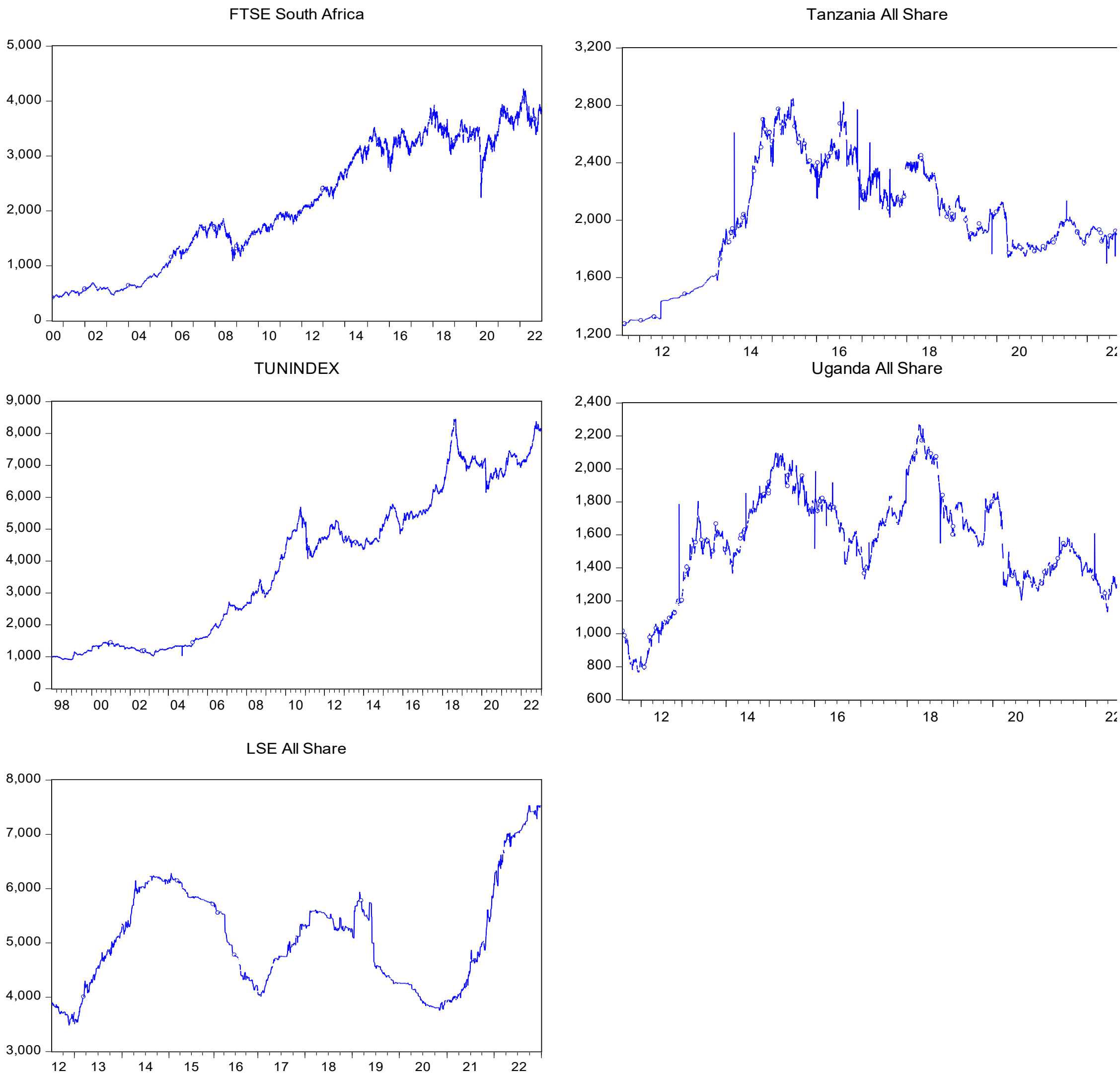

Figure A1 (cont.). Series evolution of prices

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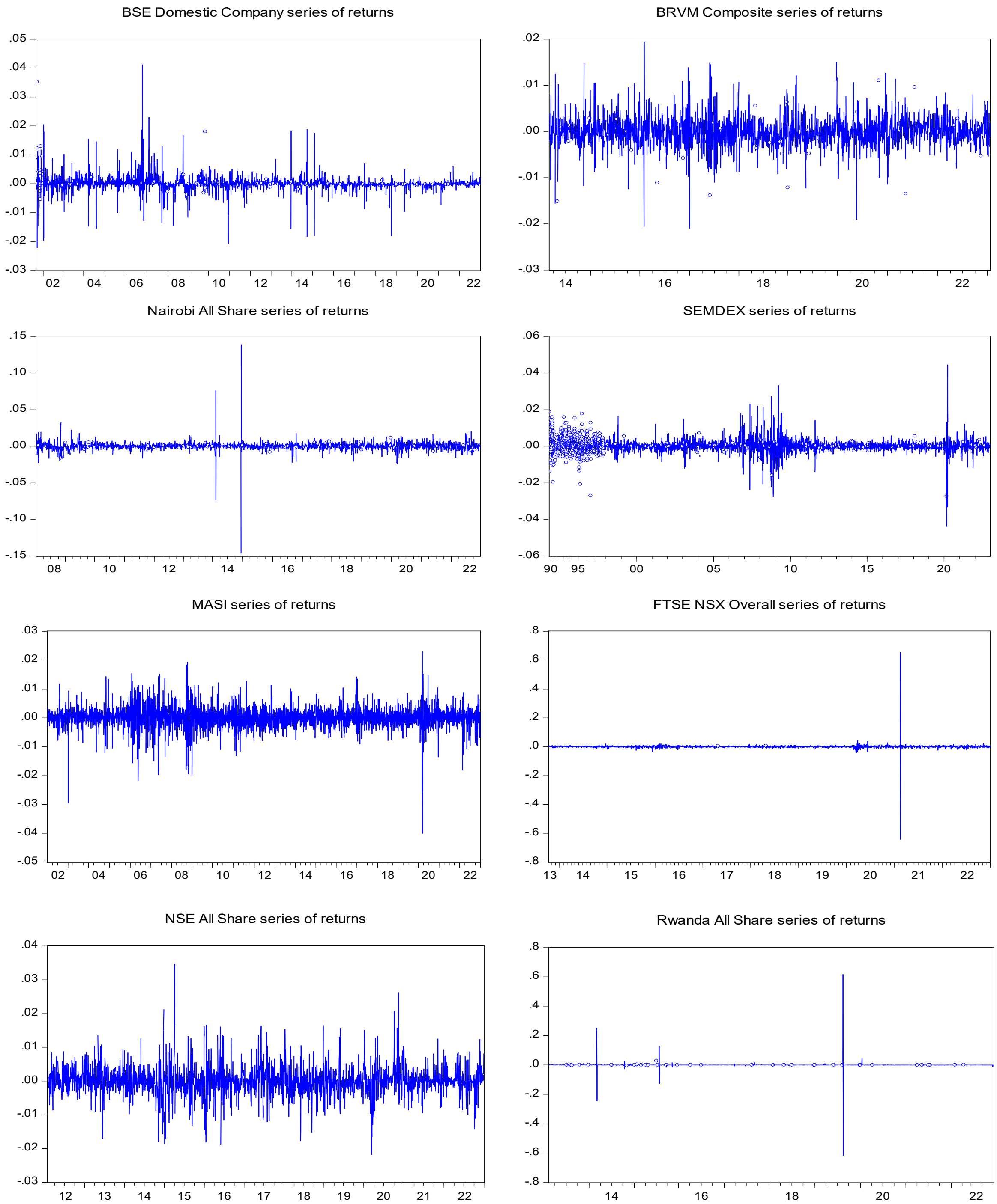

Figure A2. Series evolution of returns

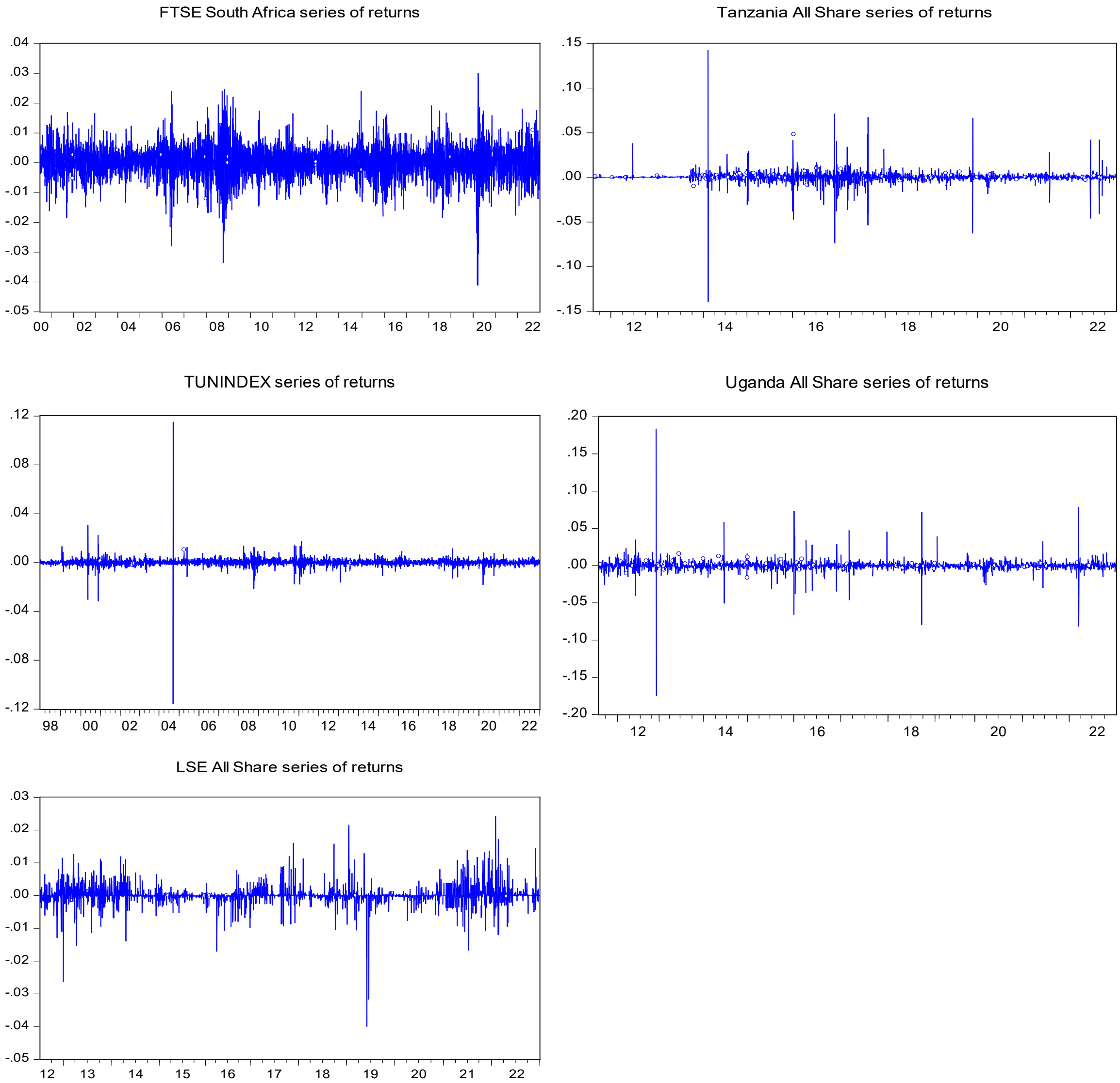

Figure A2 (cont.). Series evolution of returns

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