

Research Article

Rainfall Climatology and Variability in Ethiopian Airports

Getahun Bekele Wolde*, Mussie Tizazu Bogale 

Aviation Meteorology Service, Ethiopian Meteorology Institute, Addis Ababa, Ethiopia

Abstract

Understanding rainfall characteristic is very important for aviation operational planning and for other activities. This study investigated annual, seasonal and monthly rainfall climatology and variability in Ethiopian Active airports from 1991-1994 using time series Climate Hazards Group Infrared Precipitation with Stations (CHIRPS) rainfall datasets. Long year mean, standard deviation and coefficient of variations were used to analyze Annual, Monthly and seasonal rainfall climatology and variability spatially and on active airports as a point. Western and southwestern airports such as Jimma, Asosa, Bahir Dar, and Gambella exhibit the highest annual mean rainfall, consistently exceeding 1,200mm, while eastern and northeastern Airports like Gode and Semera, experience very low annual totals (often below 300mm. For instance, Jimma airport records monthly averages exceeding 200mm in peak months, while Airports like Axum, Humera, and Gode receive less than 1mm in dry months. The Kiremt season contributes the bulk of annual rainfall in most parts of the country, for instance Nekemte Airport (1324.5mm), Bahir Dar airport (1147.4mm), and Jimma airport (881.0mm) leading as high climatological mean rainfall. Belg (February-May) and Bega (October-January) are secondary rainfall seasons and dry seasons respectively but are significant in southern and southwestern parts of the country such as Jinka and Arba Minch. More than 80% of airports fall under low annual rainfall variability ($CV < 20\%$), indicating high reliability for long-term aviation planning. Only Gode airport shows high annual rainfall variability ($CV = 41\%$), indicating operational unpredictability and risk exposure. CV values during dry months often exceed 200%, particularly in arid and semi-arid regions, indicating unreliable rainfall patterns. In contrast, wet months (July-August) in western airports exhibit low CVs (e.g., Bahir Dar: 11.8% in August), supporting predictable seasonal operations. Generally climatological and variability insights highlight the spatial and temporal heterogeneity of rainfall across Ethiopian airports, driven by topography, regional climate systems, and global drivers like ENSO. Understanding both average conditions (climatology) and year-to-year fluctuations (variability) is critical for aviation safety, infrastructure resilience, and operational efficiency.

Keywords

Rainfall, Climatology, Variability, CDT

1. Introduction

Since the beginning of air transportation, weather has played a vital role in ensuring aviation safety. Understanding of rainfall climatology and its variability is part of climatic characteristics critical for ensuring safe and efficient airport operations. It is

essential to analyze how environmental conditions affect lift, drag, and thrust to ensure safe aircraft operations [1]. Climate change has been linked to an increase in the frequency and severity of extreme weather events, including intense rainfall and

*Corresponding author: getahunbekele48@yahoo.com (Getahun Bekele Wolde)

Received: 9 July 2025; **Accepted:** 21 July 2025; **Published:** 15 August 2025



Copyright: © The Author(s), 2025. Published by Science Publishing Group. This is an **Open Access** article, distributed under the terms of the Creative Commons Attribution 4.0 License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution and reproduction in any medium, provided the original work is properly cited.

high winds, which pose significant operational and safety challenges to the aviation sector [2]. Rain is liquid water in form of droplets that have been condensed from atmospheric water vapour and then becoming heavy enough to fall under gravity. Rain is a major component of the water cycle and is responsible for depositing most of the fresh water on the Earth [3]. Rainfall had a greater impact on aircraft cancellations than wind speed, based on a Multilayer Complex Network (MCN) analysis of aircraft, rainfall, and wind speed across 14 Korean airports. In Madrid airport during winter, more than 45% of the variability in daily punctuality is related to local weather impacts [4]. Study conducted on Harcourt international airport, Nigeria revealed that thunderstorm-associated rainfall showed a strong positive correlation with all aspects of aircraft operations, explaining over 88% of the variations in flight delays, cancellations, and diversions [5]. In Ethiopia, the diversity in climate and topography leads to significant spatial and temporal rainfall variability [6-8]. Ethiopia's vast landmass and highly varied topography contribute to a wide range of climatic zones and substantial disparities in temperature and precipitation across the country. The country hosts equatorial rainforests in the south and southwest, which are characterized by high rainfall and humidity, while the Afro-Alpine zones on the summits of the Semien and Bale Mountains experience cold conditions. Conversely, the north-eastern, eastern, and south-eastern lowlands exhibit desert-like climates with minimal rainfall [6, 9]. The central and northern highland regions are cooler and receive relatively higher rainfall, whereas the eastern lowlands remain arid with sporadic precipitation. These variations are largely influenced by Ethiopia's complex terrain and the seasonal migration of the Inter-Tropical Convergence Zone (ITCZ), which serves as the principal driver of the country's rainfall patterns [7]. Ethiopia experiences three distinct rainfall seasons Kiremt (June to September) main rainy season, contributing 50-80% of rainfall the country's, particularly affecting the central and northern highlands. Belg (February to May) is secondary and often erratic rainy season in most part of airports in Ethiopia, particularly in central and southern regions of the country. Bega (October to January) on the other hand typically dry in most parts of the country but provides rainfall to southern Ethiopia [10].

Mean annual rainfall can vary greatly from over 2,000mm in the south-western highlands to less than 300mm in the arid

south-eastern and north-eastern lowlands [11]. Rain or snow reduces visibility depending on intensity and drop or flake size. Light drizzle has minimal impact on Visual Flight Rules (VFR) operations, but heavy precipitation in cumulonimbus (Cb) or towering cumulus (TCu) clouds can reduce visibility to 100 meters or less, often accompanied by wind shear and turbulence [12]. Temperature variability is also notable from below 15 °C in the highlands to above 25 °C in the lowlands [13]. These climatic variations directly affect aviation meteorology, influencing visibility, wind shear, turbulence, and runway conditions, which are critical for safe airport operations across the country.

Airports are particularly sensitive to weather conditions, and rainfall plays a major role in flight delays, runway safety, and operational planning. providing meteorological service for international air navigation by supplying operational meteorological information's, weather forecast and enhancing automatic and weather observing stations is the responsibility of Ethiopian Meteorology Institute at each airports in Ethiopia [14]. This paper aims to analyze rainfall characteristics at Ethiopian airports selected based on the availability of historical rainfall records including satellite reanalysis rainfall products to include all active airports temporal coverage.

2. Materials and Methods

2.1. Study Area Description

Ethiopia, located in the Horn of Africa, spans approximately 1,104,300 square kilometers, making it the 26th-largest country globally. The country is geographically situated between latitudes 3 °15' N and longitudes 33 °48' E. The nation's terrain is diverse, featuring high plateaus, mountains, and dry lowland plains. In this study collected daily rainfall datasets was converted to monthly, seasonal and annual from 1991 to 2024. Ethiopia has 23 active airports with scheduled flights. Addis Ababa Bole International Airport serving as the main hub connecting domestic airports and 129 international destinations across 70 countries, primarily operated by Ethiopian Airlines as shown in Figure 1 and Table 1 below.

Table 1. Location of Ethiopian Airports.

No	Airport	Lat	Lon	ICAO Code	No	Airport	Lat	Lon	ICAO Code
1	Axum	14.144	38.775	HAAX	13	Gode	5.934	43.576	HAGO
2	Arba Minch	6.039	37.590	HAAM	14	Gondar	12.521	38.500	HAGN
3	Asosa	10.023	34.578	HASO	15	Debrezeit	8.716	39.008	HAHM
4	Awassa	7.067	38.500	HALA	16	Humera	13.836	36.881	HAHU
5	Bahir Dar	11.606	37.317	HABD	17	Jigjiga	9.332	42.908	HAIJ

No	Airport	Lat	Lon	ICAO Code	No	Airport	Lat	Lon	ICAO Code
6	Bale Goba	7.120	40.069	HAGB	18	Jimma	7.665	36.817	HAJM
7	Addis Ababa	8.977	38.800	HAAB	19	Jinka/Baco	5.784	36.562	HABC
8	Dessie	11.083	39.714	HADC	20	Lalibela	11.975	38.981	HALA
9	Dire Dawa	9.623	41.854	HADR	21	Mekele	13.467	39.517	HAMK
10	Dembidolo	8.550	34.850	HADO	22	Semera	11.789	40.990	HASM
11	Gambella	8.132	34.565	HAGM	23	Nekemte	9.030	36.359	HANK
12	Gore	8.16	35.55	HAGR	24	Shire	8.16	40.433	HASH

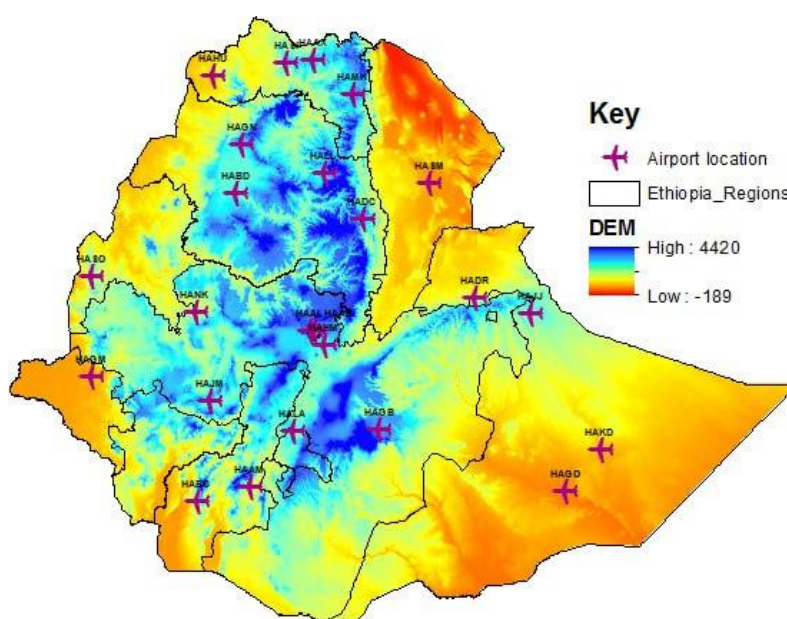


Figure 1. Map of study Area (Active Airports) in Ethiopia.

2.2. Data

2.2.1. Meteorological Station Data

Daily historical rainfall data from 1991 to 2023 for 23 meteorological stations were obtained from the Ethiopian Meteorology Institute (EMI), and the data were analyzed using Climate Data Tool (CDTv8.0) [15]. Information's about Aeronautical meteorological station data at the aerodromes of Ethiopian Airports were listed above Table 1.

2.2.2. Satellite with Station Data (CHIRPS Data)

Due to the availability in time series data of more than 30 years, free access datasets, and spatiotemporal resolution of $0.05^\circ \times 0.05^\circ$, daily and widely used, Climate Hazards Group InfraRed Precipitation (CHIRPS) satellite product was selected. CHIRPS satellite rainfall product was previously evaluated against surface rain gauges observations in different parts of Ethiopia such as [16, 17] over Fincha, Nesh and Lake Ziway

watershed respectively. Others studies similarly evaluate performance of CHIRPS rainfall products in drought monitoring and variability studies such as [18] in different parts of Ethiopia. In this study, the CHIRPS rainfall product was used for daily comparison from the period 1991-2024, which show matched with the period of ground-based rainfall data.

2.3. Method

2.3.1. Performance Evaluation of CHIRPS Rainfall

Satellite-based rainfall datasets (CHIRPS) was compared with ground-based observed rainfall to evaluate CHIRPS rainfall performance.. Integrate station rainfall data with CHIRPS satellite estimates, thereby addressing temporal and spatial gaps in the observational record. This integration enhances the completeness and reliability of the rainfall dataset, especially in data-scarce regions. Five statistical metrics such as RMSE, MAE, bias, NSE, and correlation coefficient (R) were used to compare CHIRPS with station observations on a

daily timescale (Table 2).

2.3.2. Statistical Methods

The approach employed in this study is based on rainfall statistical analysis, where precipitation is analyzed annually (January-December) and seasonally for JJAS (June-September), ONDJ (October-January), and FMAM (February-May). In this study, rainfall climatology was analyzed for 23 selected airports in Ethiopia using the CHIRPS satellite rainfall product. Among the aeronautical meteorological stations, only eight (Gondar, Dire Dawa, Gode, Gore, Jimma, DebreZeit, Mekele Airport, and Addis Ababa Bole Airports) had rainfall records with less than 20% missing values, and these were primarily used to validate the CHIRPS data by incorporation the remaining airports in the analysis. Statistical analysis methods of rainfall characteristics were Mean, standard deviation and coefficient of variation.

$$\text{Mean} = X_{avg} = \sum \frac{x_i}{n} \quad (1)$$

Where X is the rainfall magnitude inmm, i = 1, 2, to n and n is the length of the sample.

Standard deviation, with symbol

$$\Sigma = [(X_i - X_{avg})^2 / (n - 1)^{\frac{1}{2}}] \quad (2)$$

X is the rainfall magnitude inmm, i=1, 2, to n and n is the length of the sample.

Coefficient of Variation,

$$Cv = 100 \times \left(\frac{\sigma}{X_{av}} \right) \quad (3)$$

Where Xav is the Mean, σ is the Standard deviation.

2.4. Operational Tools

The operational tools for result of this study are Geographic information systems (GIS) and Climate Data Tool (CDT). CDT is a free and open-source R package designed for climate data analysis [15]. It has been effectively utilized for processing and analyzing both CHIRPS data and station observations.

3. Results and Discussion

3.1. Evaluation of Satellite Rainfall

In this study, the CHIRPS satellite rainfall product was investigated to analyze the spatial and temporal distribution of rainfall characteristics at daily, monthly seasonal and annual timescales. Evaluation was carried out using data for the period from 1991 to 2022. Performance of the CHIRPS satellite-based rainfall estimates was analyzed based on different statistical performance evaluation criteria, which are listed in Table 2, and the result of a summary of statistical error metrics was presented in figure 2. Results obtained from these evaluation criteria show that the CHIRPS satellite rainfall estimates performed well as compared to ground-based rainfall datasets with CDF, Scatter plot and line Charts in figure 2 below. As presented in Table 2, CHIRPS satellite product performance evaluation statics performed very well with (NSE=0.948 and CORR=0.974). Therefore HIRPS has good performance over Ethiopia at a monthly scale and can be valuable precipitation products. Eight Aeronautical Meteorological weather stations have been selected for validation and performance test due to the data availability and completeness of the station below table 3.

Table 2. Performance Analysis between Station and CHIRPS Rainfall Products.

Name	Statistics	Description	Range	Perfect Score
CORR	0.974	Correlation	-1 to 1	1
BIAS	1.021	Bias	0 to ∞	1
PBIAS	2.093	Percent Bias	$-\infty$ to ∞	0
MAE	11.269	Mean Absolute Error	0 to ∞	0
RMSE	16.578	Root Mean Square Error	$-\infty$ to ∞	0
NSE	0.948	Nash-Sutcliffe Efficiency	$-\infty$ to ∞	1

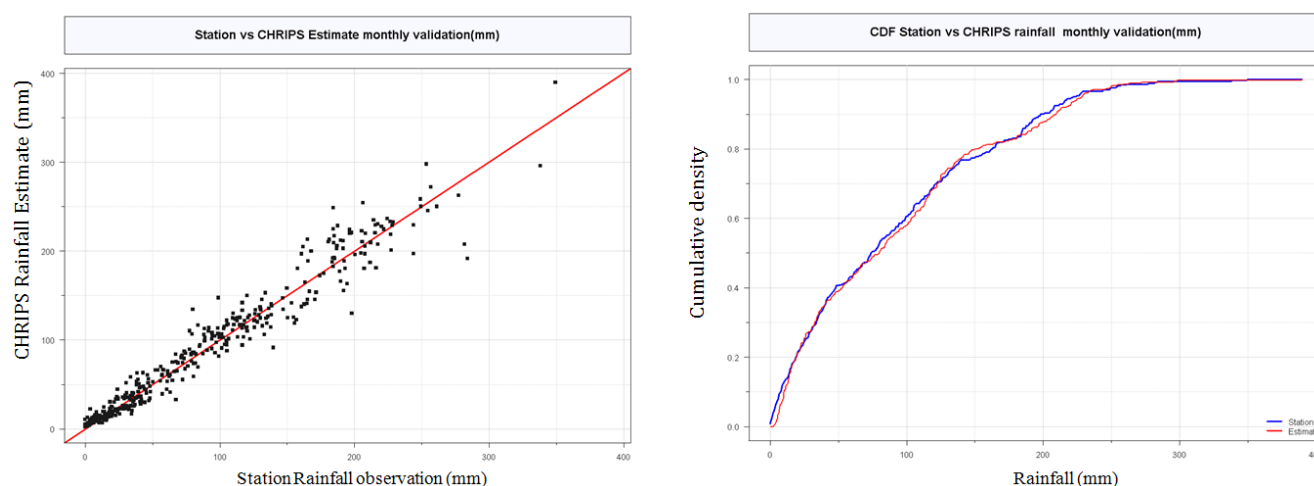


Figure 2. Station and CHRIPS Monthly Rainfall Validation with Scatter plot and CDF.

3.2. Annual Rainfall Analysis

Analysis of long term annual rainfall in Ethiopia spatially and for selected active airports reveals significant spatial variations in its distribution as shown in figure 3 and table 3 below. In Ethiopian air ports the mean annual rainfall ranges from 206mm at Semera Airport to higher than 1953mm in Nekemte Airport. These variations are a reflection of Ethiopia's diverse topography and regional climate regimes, ranging from semi-arid lowlands in the east to humid highlands in the west. Airports located in Western and south west parts of Ethiopia (e.g., Nekemte, Jimma, Dembidolo, Gambella) consistently receive more than 1000mm of annual rainfall. Airports located in Eastern and North eastern parts of Ethiopia (such as Semera, Gode, Jijiga and Diredawa) characterized by much lower annual rainfall often less than 600mm owing to their position in rain shadow areas and semi-arid to arid climatic zones.

The analysis of Inter-annual rainfall variability across Ethiopia's active airports reveals significant spatial differences when evaluated using the Coefficient of Variation (CV), a metric that indicates the degree of rainfall consistency. Based on the classification by [19], stations with $CV < 20\%$

are considered to have low rainfall variability, those with $20\% \leq CV < 30\%$ exhibit moderate variability, and $CV \geq 30\%$ indicates high variability. In this study, the majority of stations (over 80%) fall within the low variability category, with CV values ranging between 7% and 18%. Notable among these are Asosa (7%), Dembidolo (8%), Bahir Dar (9%), and Gambella (9%), all located in the western and southwestern parts of the country. These regions benefit from relatively stable rainfall regimes, which enhance the reliability of seasonal aviation planning and reduce operational risks related to rainfall extremes.

Airports located in Eastern and North Eastern parts of Ethiopia such as Semera and Dire Dawa fall under moderate annual rainfall variability group prevailing more noticeable inter-annual fluctuations. These Aeronautical Meteorological Stations located in the Eastern lowlands and rift margins more susceptible to erratic rainfall patterns influenced by local and global climate systems such as El Niño and La-Niña. This degree of variability may enhance challenges seasonal scheduling, Airport drainage and infrastructure resilience. Gode Aeronautical Meteorological station only indicates high annual rainfall variability with a CV of 41%, reflecting arid and semi-Arid conditions south Eastern Ethiopia.

Table 3. Statistical Parameters for Active Airports Annual Rainfall Analysis.

Station	Mean	Std	Cv	Station	Mean	Std	Cv
Axum	792	83	11	Gondar	846	98	12
ArbaMinch	870	112	13	Debrezeit	920	144	16
Asosa	1202	87	7	Humera	1058	139	13
Awassa	991	116	12	Jigjiga	543	95	18
BahirDar	1388	129	9	Jimma	1562	165	11
BaleGoba	947	108	11	Jinka	1283	185	14

Station	Mean	Std	Cv	Station	Mean	Std	Cv
AddisAbaba	1273	163	13	Lalibela	823	103	12
Dessie	1018	134	13	Mekele	662	120	18
DireDawa	576	115	20	Semera	206	46	22
Dembidolo	1347	109	8	Shire	905	87	10
Gambella	1193	110	9	Nekemte	1953	189	10
Gode	278	115	41				

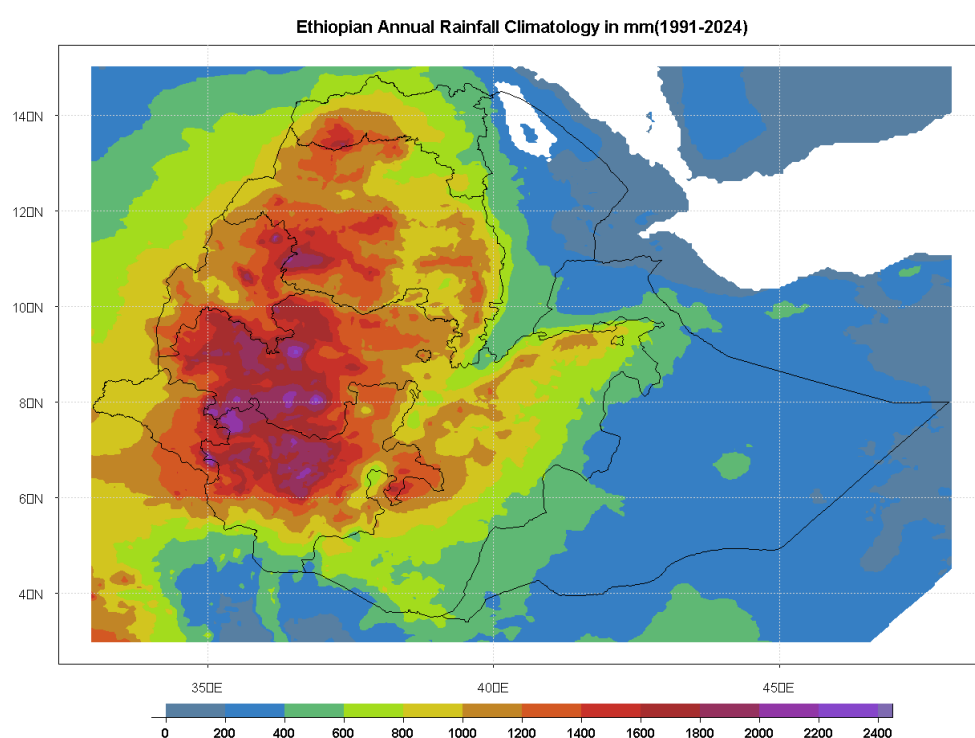


Figure 3. Ethiopia Annual Rainfall Climatology (1991-2024).

3.3. Monthly Rainfall Analysis

Mean monthly reflects strong seasonality in most Aeronautical Meteorological Stations (Aerodromes) as peak rainfall mostly occurring during summer (*Kiremt*) months (June to September), aligning with the main rainy season in Ethiopia. For example Airports Jimma, Bahir Dar, Gondar, Addis Ababa and Awassa reveals high rainfall during these months, with Jimma notably receiving over 200mm on average per month, making it one of the wettest aerodromes in the network. These rainfall peaks pose operational challenges for aviation due to low visibility and wet runway conditions. Conversely, the Bega season (October-January), especially December to February, is characterized by widespread dryness. This is particularly evident in northern and eastern Ethiopia Aerodromes such as Axum, Gode, and Humera, where mean monthly rainfall often falls below 1mm, indi-

cating prolonged dry spells. These conditions, while beneficial for aviation visibility, may limit moisture availability for local ecosystems and water supply. While in the Belg season (February-May), typically represents a secondary rainy period, although its onset and strength are more variable. Aerodromes in southern and central Ethiopia (e.g., Awassa, Jinka, Bale Goba) shows moderate rainfall during this time as shown in figure 4 and table 4 below.

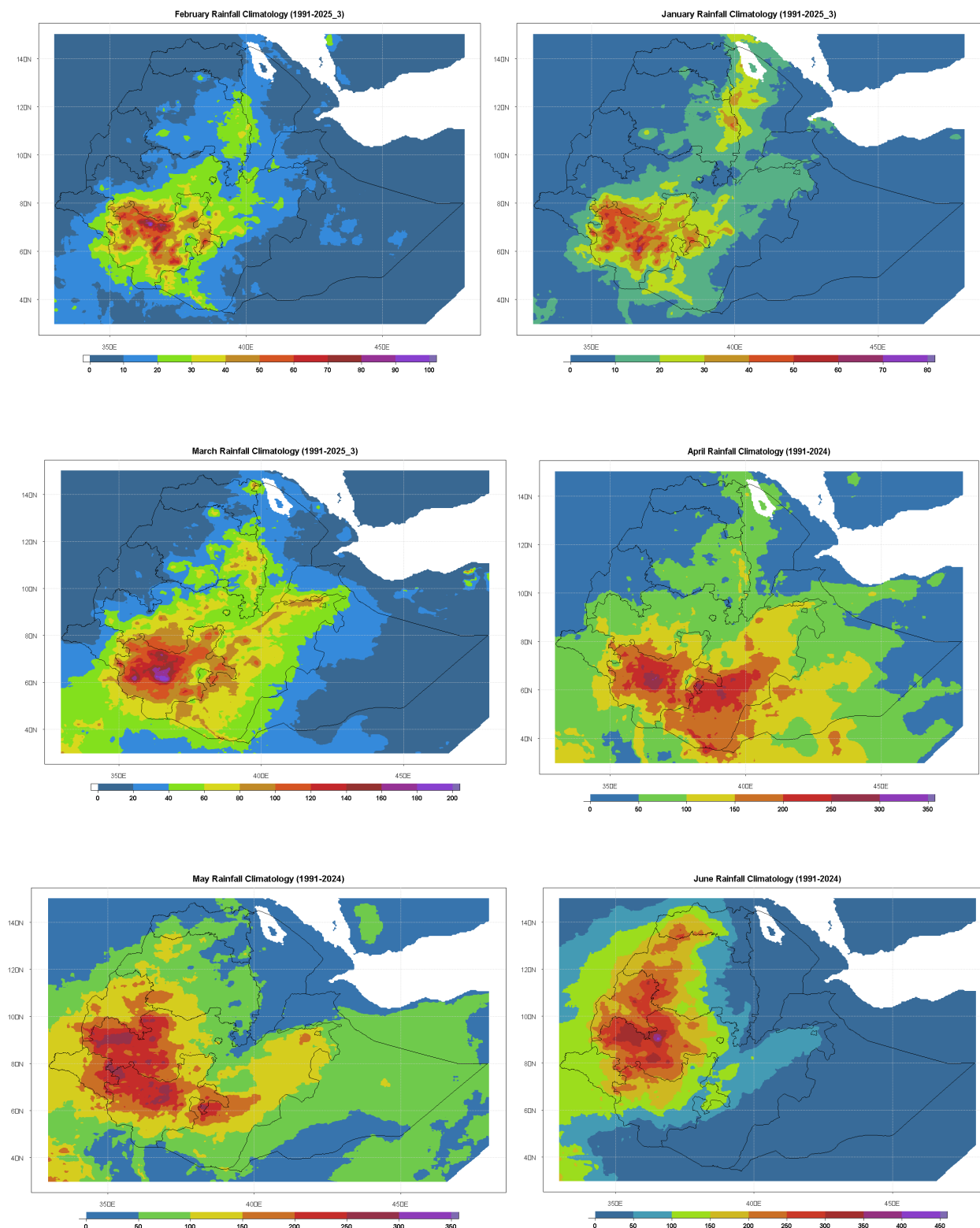
From Monthly Coefficient of variation aerodromes like Jimma, Assosa and Bahir Dar exhibit low CVs (<20%) during the main rainy season (especially in July and August), indicating reliable and consistent rainfall patterns. For instance, Bahir Dar coefficient of variation in august is 11.8% confirming its climatological operational predictability. Moderate variability (CV between 20% and 30%) is observed in Aerodromes like Addis Ababa and Awassa during transitional seasons, especially the Belg (February-May) period, reflecting some inter-annual fluctuations that require cautious in-

terpretation in seasonal planning.

High rainfall variability ($CV > 30\%$) dominates arid and semi-arid location Aerodromes in the months of *Bega* and *Belg* seasons. Aerodromes such as Gode, Jigjiga and Humera often exhibit extremely high CVs, occasionally surpassing 200% to 400%, especially during drier months. This implies that rainfall events in these areas are highly erratic and unpredictable; ne-

cessitating enhanced monitoring and contingency strategies for flight operations and water resource management.

Some Aerodromes like Debrezeit and Dire Dawa fall in the moderet to high cv range hroughout much of the year. Though they receive moderate amounts of rainfall, the irregular and intensity shows the need for localized forecasting to mitigate climate risk in aviation and other weather-sensitive sectors.



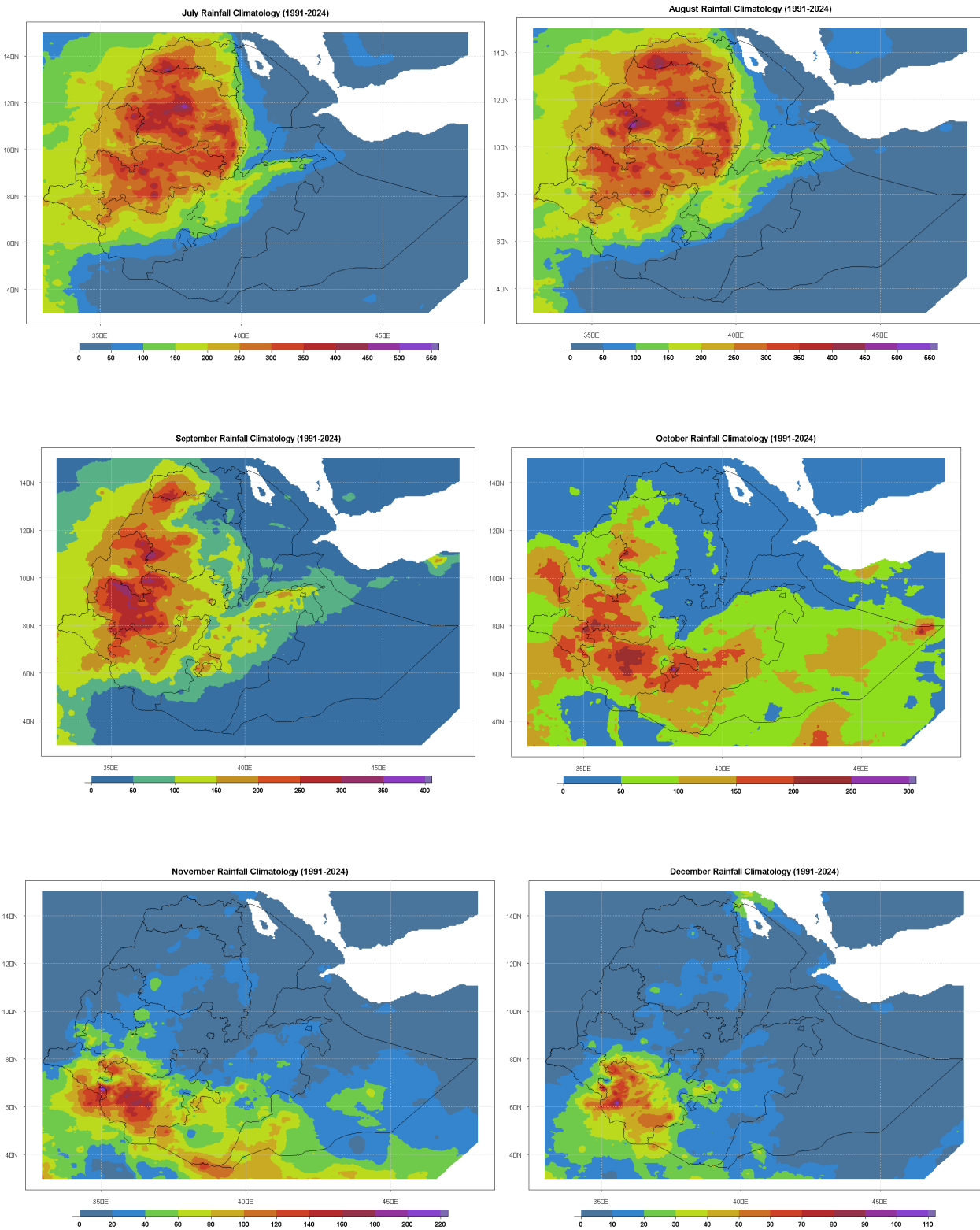


Figure 4. Spatial Monthly Rainfall Climatology (Jan-Dec).

Table 4. Statistical Parameters for Monthly Rainfall Analysis of Active Airports in Ethiopia.

Aerodrome	Statistics	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Axum	Mean (mm)	0.0	0.1	14.4	34.6	40.4	98.6	222.4	248.9	91.5	33.4	7.2	0.1

Aerodrome	Statistics	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
ArbaMinch	Std (mm)	0.1	0.4	8.4	17.3	23.7	35.4	43.2	44.1	35.4	20.3	6.5	0.3
	CV (%)	600.0	354.5	58.3	50.1	58.6	35.9	19.4	17.7	38.7	60.6	90.3	377.8
	Mean (mm)	28.8	25.7	64.5	153.6	137.2	60.9	47.0	54.7	81.7	119.6	61.0	35.0
	Std (mm)	15.2	15.1	26.2	49.6	45.0	20.2	17.2	18.4	32.4	33.9	36.0	23.9
	CV (%)	52.6	58.8	40.6	32.3	32.8	33.1	36.6	33.7	39.7	28.4	59.1	68.3
	Mean (mm)	0.1	0.1	20.4	43.9	134.1	213.0	221.3	236.2	198.1	112.8	21.9	0.5
Asosa	Std (mm)	0.3	0.4	9.7	21.4	38.1	35.3	43.2	40.7	28.9	25.6	15.2	1.2
	CV (%)	261.5	583.3	47.6	48.8	28.4	16.6	19.5	17.2	14.6	22.7	69.1	252.2
	Mean (mm)	28.7	34.3	76.1	115.9	123.9	103.0	125.9	126.5	117.5	89.5	30.5	19.3
Awassa	Std (mm)	16.7	21.6	30.8	42.1	33.9	19.2	29.9	23.2	21.7	41.7	19.3	14.1
	CV (%)	58.3	62.9	40.5	36.3	27.4	18.6	23.8	18.3	18.4	46.6	63.1	73.3
	Mean (mm)	0.5	0.3	5.3	26.0	92.7	196.3	420.3	333.6	197.2	95.3	19.5	1.3
BahirDar	Std (mm)	1.4	1.3	5.1	13.5	46.1	46.0	57.9	39.4	38.2	44.3	9.7	2.3
	CV (%)	287.8	422.6	95.7	51.9	49.8	23.4	13.8	11.8	19.4	46.5	49.5	174.6
	Mean (mm)	15.9	20.3	69.9	146.6	97.5	61.9	93.3	133.7	135.3	112.4	45.1	15.6
BaleGoba	Std (mm)	12.1	17.6	39.8	45.4	27.2	25.0	32.4	38.4	32.1	47.2	25.9	10.5
	CV (%)	76.2	86.5	56.9	31.0	27.9	40.4	34.7	28.7	23.7	42.0	57.4	66.9
	Mean (mm)	20.2	34.0	78.2	95.7	92.1	155.6	272.4	286.0	149.5	63.0	14.0	11.9
AddisAba-ba	Std (mm)	13.4	27.4	46.6	42.0	51.7	43.8	48.7	42.1	49.9	40.4	10.6	8.0
	CV (%)	66.3	80.6	59.6	43.9	56.1	28.2	17.9	14.7	33.3	64.1	75.3	67.2
	Mean (mm)	22.9	26.6	70.0	93.9	61.0	23.7	259.2	280.8	103.3	42.6	18.9	15.6
Dessie	Std (mm)	14.1	15.8	40.5	45.8	40.7	13.1	79.9	63.2	33.8	32.0	14.7	9.5
	CV (%)	61.6	59.4	57.8	48.8	66.8	55.3	30.8	22.5	32.7	75.2	77.5	60.6
	Mean (mm)	16.5	15.9	77.0	100.2	42.4	16.0	84.1	110.2	65.5	31.3	12.7	3.7
DireDawa	Std (mm)	13.8	14.7	61.8	52.2	19.2	8.6	28.8	22.1	25.2	24.6	9.5	5.3
	CV (%)	83.4	92.3	80.3	52.1	45.4	53.5	34.2	20.0	38.5	78.6	74.3	142.7
	Mean (mm)	7.4	18.9	58.7	123.1	216.5	198.2	190.2	169.8	195.3	110.6	40.7	18.0
Dembidolo	Std (mm)	5.4	8.8	31.3	43.5	57.4	34.8	28.0	23.1	32.8	22.9	22.9	10.2
	CV (%)	72.5	46.5	53.4	35.4	26.5	17.6	14.7	13.6	16.8	20.7	56.1	56.8
	Mean (mm)	3.2	6.6	28.8	70.3	165.5	155.9	211.7	211.0	141.7	126.1	58.8	12.9
Gambella	Std (mm)	3.6	4.7	14.9	26.1	35.7	29.5	32.5	45.7	24.3	29.8	39.5	8.6
	CV (%)	112.3	72.1	51.8	37.1	21.5	18.9	15.3	21.6	17.2	23.7	67.2	66.4
	Mean (mm)	0.0	0.6	7.3	88.4	46.7	0.3	0.1	0.2	2.4	80.9	50.7	0.3
Gode	Std (mm)	0.1	1.2	12.4	43.8	24.1	1.5	0.4	0.8	3.0	49.1	60.7	1.3
	CV (%)	700.0	201.7	170.5	49.5	51.6	531.0	433.3	394.7	129.4	60.7	119.8	431.0
	Mean (mm)	9.5	11.0	23.4	49.1	45.2	72.6	256.1	293.3	37.9	23.0	18.0	7.0
Gondar	Std (mm)	4.7	5.4	9.7	19.6	21.6	28.6	63.7	61.3	14.2	15.5	11.4	5.1
	CV (%)	50.1	49.4	41.2	39.8	47.7	39.4	24.9	20.9	37.5	67.5	63.2	72.7
Debrezeit	Mean (mm)	5.3	21.9	51.6	62.2	75.5	118.6	219.3	244.6	100.6	16.1	3.5	1.1

Aerodrome	Statistics	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Humera	Std (mm)	7.6	19.7	32.7	32.6	46.2	36.6	49.9	50.3	34.9	15.9	5.4	2.7
	CV (%)	143.9	89.8	63.3	52.3	61.2	30.8	22.7	20.6	34.7	98.7	156.5	261.0
	Mean (mm)	0.1	0.1	0.5	17.7	59.9	166.1	260.7	317.6	187.5	44.7	3.1	0.0
Jigjiga	Std (mm)	0.3	0.2	1.4	11.5	25.2	46.0	48.4	51.3	50.5	26.2	3.8	0.1
	CV (%)	400.0	300.0	266.7	64.8	42.1	27.7	18.6	16.2	26.9	58.6	124.2	433.3
	Mean (mm)	1.9	5.1	49.1	79.1	78.2	38.7	56.8	89.0	89.1	38.7	16.5	0.9
Jimma	Std (mm)	3.6	9.6	42.2	31.4	31.5	17.5	22.9	27.4	31.1	31.4	15.5	2.6
	CV (%)	190.0	188.1	85.9	39.7	40.3	45.2	40.3	30.8	34.9	81.1	93.9	281.3
	Mean (mm)	31.0	46.3	87.9	132.1	177.5	232.0	238.8	224.0	186.3	112.8	58.3	34.7
Jinka	Std (mm)	18.0	32.4	42.8	37.0	44.8	39.6	36.0	41.2	35.3	59.5	45.5	26.1
	CV (%)	58.1	70.0	48.7	28.0	25.2	17.1	15.1	18.4	18.9	52.7	77.9	75.1
	Mean (mm)	45.3	47.9	103.4	178.5	158.1	104.4	80.0	99.4	126.2	166.3	129.9	44.0
Lalibela	Std (mm)	39.7	33.2	48.5	54.5	45.7	41.0	36.1	41.0	46.5	46.9	76.9	37.8
	CV (%)	87.5	69.2	46.9	30.5	28.9	39.3	45.1	41.3	36.8	28.2	59.2	85.9
	Mean (mm)	17.0	15.6	36.9	53.0	42.2	48.0	254.6	264.7	42.6	19.6	18.6	10.5
Mekele	Std (mm)	8.5	7.6	18.3	28.1	24.3	25.2	64.4	60.4	12.4	12.0	16.3	5.8
	CV (%)	50.3	48.5	49.6	52.9	57.5	52.5	25.3	22.8	29.1	61.1	87.6	54.8
	Mean (mm)	0.0	2.8	20.6	33.1	34.7	41.7	218.5	257.9	43.8	4.8	4.6	0.0
Semera	Std (mm)	0.1	4.7	12.6	18.4	17.7	15.8	71.5	77.0	20.9	4.7	5.9	0.1
	CV (%)	500.0	164.3	60.9	55.5	50.9	37.8	32.7	29.8	47.7	98.7	130.0	500.0
	Mean (mm)	10.4	7.1	11.4	28.8	11.7	0.5	41.3	75.3	8.1	0.7	8.4	2.0
Shire	Std (mm)	4.4	9.5	9.4	22.3	9.3	0.8	19.2	29.6	2.6	1.0	6.2	3.8
	CV (%)	42.0	133.5	83.0	77.6	79.1	163.3	46.4	39.3	31.9	153.7	74.6	191.9
	Mean (mm)	0.3	0.1	1.7	26.2	49.4	118.2	258.5	299.3	115.0	23.6	12.7	0.0
Nekemte	Std (mm)	0.9	0.2	2.3	13.8	25.8	37.8	39.0	41.1	39.0	13.3	6.9	0.0
	CV (%)	330.8	420.0	138.7	52.6	52.4	32.0	15.1	13.7	33.9	56.5	53.8	300.0
	Mean (mm)	7.2	10.1	54.7	93.8	238.0	349.3	359.8	341.2	274.1	164.1	46.4	14.7
	Std (mm)	5.2	9.0	31.9	46.8	76.6	51.4	47.9	60.2	46.2	67.8	27.7	8.6
	CV (%)	72.5	88.5	58.3	49.9	32.2	14.7	13.3	17.6	16.9	41.3	59.8	58.2

3.4. Seasonal Rainfall Analysis

The seasonal rainfall climatology for Ethiopian active airports from 1991 to 2024 highlights marked regional and seasonal differences in rainfall distribution shown in [figure 5](#) and [table 5](#) below. Summer (*Kiremt*), is the dominant rainy season for most parts of the country, with the highest mean rainfall values recorded at Nekemte (1324.5mm), Bahir Dar (1147.4mm), and Jimma (881.0mm). Aeronautical Meteorological Stations located in the western and

central highlands, consistently receive the largest share of annual rainfall during Kiremt. In the southern and south-western parts of Ethiopia, such as Jinka (488.0mm), Jimma (443.8mm), and Arba Minch (381.1mm), the Belg season (February-May) also contributes significantly to the annual total, indicating a bimodal rainfall regime. Meanwhile, the Bega season (October-January), generally regarded as the dry season, shows notable rainfall contributions in a few Aerodrome like Jinka (382.2mm), Arba Minch (243.7mm), and Jimma (235.5mm), suggesting localized seasonal rainfall extension from [table 5](#) below. In contrast, airports

in northeastern and eastern lowland regions such as Gode, Semera, and Mekele experience relatively low rainfall across all seasons, with Gode recording negligible Kiremt

rainfall (2.9mm), reflecting the arid climate of those regions.

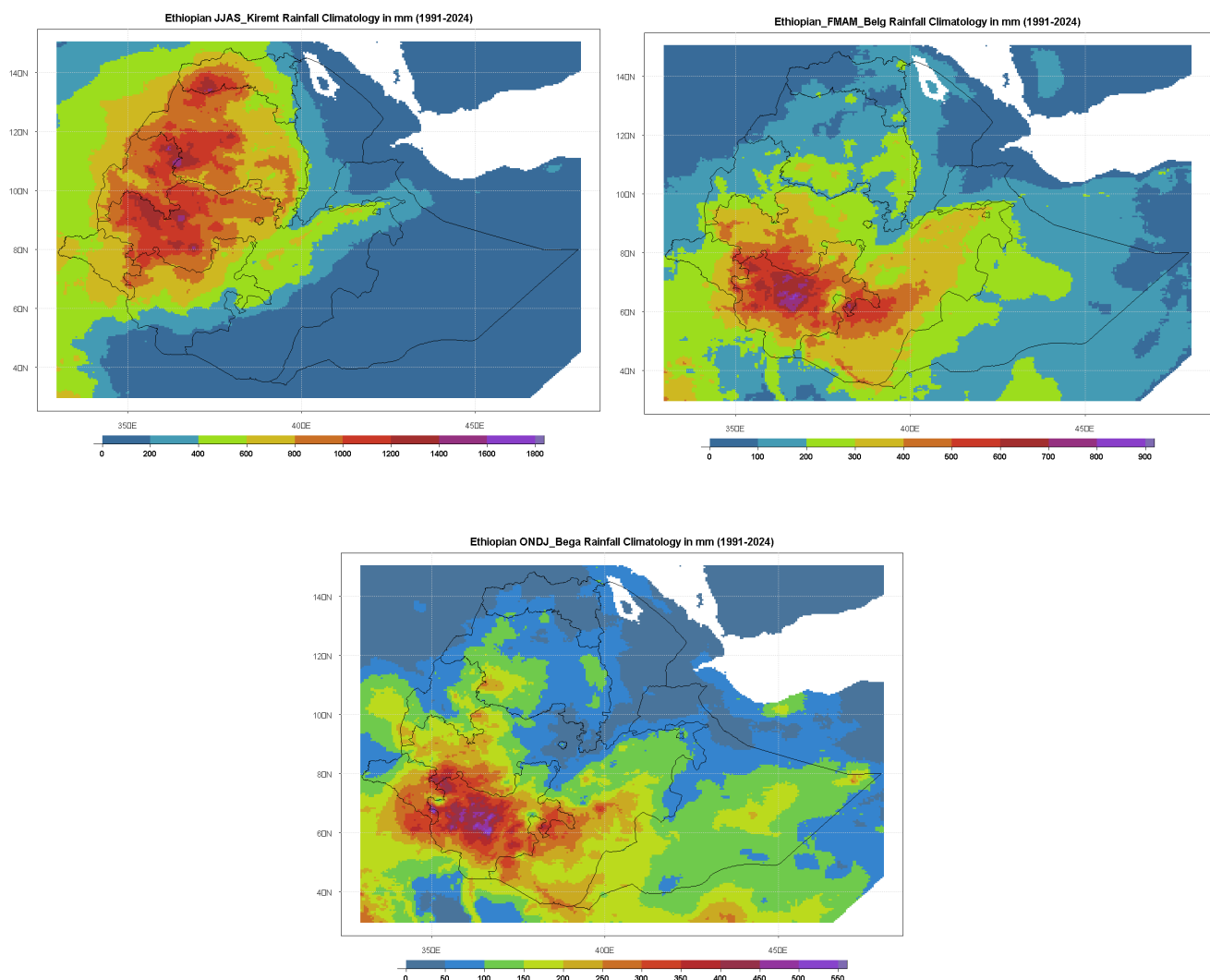


Figure 5. Ethiopian Seasonal Rainfall Spatial Mean Climatology.

As shown in table 5 below seasonal rainfall variability, analysed using standard deviation and the coefficient of variation (CV), shows considerable inter-annual inconsistencies, especially during the Belg and Bega seasons. The Summer (Kiremt) season demonstrates the most consistent rainfall patterns across much of the country, with low CV observed in airports like Asosa (9.5%), Jimma (7.9%), Dembi Dolo (7.8%), and Bahir Dar (8.5%), indicating a reliable and predictable rainy season that supports stable agricultural planning. On the other hand the Belg season exhibits higher variability, with CV values exceeding 35% in airports like Axum (41.9%), Mekele (41.1%), and Dire Dawa (41.0%), suggesting less dependable rainfall for agricultural use and Aviation opera-

tional planning problems. The Bega season is the most erratic, with extreme variability in Airports such as Mekele (CV = 81.9%), Debrezeit (74.7%), Gode (73.9%), and Jigjiga (72.9%), emphasizing its unreliability as a moisture source.

Even in areas with relatively high Bega rainfall, such as Jinka and Jimma airports, the standard deviation remains high, reflecting significant inter-annual fluctuations. Overall, these findings underscore the seasonal and spatial variability of rainfall in Ethiopia, with implications for water resource management, crop planning, and climate risk mitigation for aviation operation, particularly in semi-arid and arid regions where rainfall unpredictability is most pronounced.

Table 5. Seasonal Rainfall Climatology and Variability for Active Airports (1991-2024).

Season	Belg			Kiremt			Bega		
Airport	Mean	Std	CV (%)	Mean	Std	CV (%)	Mean	Std	CV (%)
Axum	89.5	37.5	41.9	661.3	84.7	12.8	40.7	23.3	57.2
Arba Minch	381.1	80.7	21.2	244.2	57.6	23.6	243.7	75.9	31.1
Asosa	198.5	46.5	23.4	868.5	82.5	9.5	135.3	33.4	24.7
Awassa	350.1	68.3	19.5	473.0	54.9	11.6	167.8	55.1	32.9
Bahir Dar	124.3	54.9	44.2	1147.4	97.7	8.5	116.6	47.9	41.1
Bale Goba	334.3	70.1	21.0	424.2	77.7	18.3	188.8	64.8	34.3
Addis Ababa	300.1	96.9	32.3	863.4	125.6	14.5	109.0	47.4	43.5
Dessie	251.5	89.0	35.4	667.0	119.5	17.9	99.9	42.9	42.9
Dire Dawa	235.5	96.6	41.0	275.7	48.8	17.7	64.0	37.6	58.8
Dembi dolo	417.2	78.1	18.7	753.5	59.0	7.8	176.5	37.0	20.9
Gambella	271.2	43.0	15.8	720.3	69.4	9.6	200.9	51.7	25.7
Gode	143.0	52.8	36.9	2.9	3.4	117.8	131.9	97.5	73.9
Gondar	128.8	38.3	29.7	659.9	110.1	16.7	57.5	26.5	46.1
Debrezeit	211.2	83.2	39.4	683.1	103.1	15.1	26.0	19.4	74.7
Humera	78.1	29.5	37.7	931.9	133.0	14.3	47.9	27.1	56.5
Jigjiga	211.4	71.4	33.7	273.6	54.3	19.9	57.8	42.1	72.9
Jimma	443.8	93.6	21.1	881.0	69.7	7.9	235.5	95.1	40.4
Jinka	488.0	103.7	21.3	410.0	103.9	25.3	382.2	143.9	37.7
Lalibela	147.7	49.1	33.3	609.9	108.5	17.8	65.7	26.7	40.7
Mekele	91.3	37.5	41.1	561.8	126.4	22.5	9.4	7.7	81.9
Semera	59.0	28.7	48.6	125.2	36.0	28.8	21.5	8.2	38.0
Shire	77.3	33.6	43.5	791.0	83.2	10.5	36.6	16.9	46.3
Nekemte	396.5	85.8	21.6	1324.5	136.5	10.3	232.3	81.4	35.0

4. Conclusion and Recommendations

4.1. Conclusion

This study provides a comprehensive climatological and variability analysis of rainfall across active Ethiopian airports, using long-term Aeronautical meteorological station and CHRIPS _satellite Estimate rainfall data from 1991 to 2024. The findings reveal significant spatio-temporal patterns in rainfall climatology and variability. Western and southwestern airports such as Jimma, Asosa, Bahir Dar, and Gambella exhibit the highest annual mean rainfall, consistently exceeding 1,200mm, while eastern and northeastern Airports

like Gode and Semera, experience very low annual totals (often below 300mm). Most airports prevail a strong seasonal cycle, for monthly climatology with peak rainfall during June-September (*Kiremt*) and dry conditions during December-February (*Bega*). For instance, Jimma airport records monthly averages exceeding 200mm in peak months, while Airports like Axum, Humera, and Gode receive less than 1mm in dry months. The *Kiremt* season contributes the bulk of annual rainfall in most parts of the country, for instance Nekemte Airport (1324.5mm), Bahir Dar airport (1147.4mm), and Jimma airport (881.0mm) leading as high climatological mean rainfall. *Belg* (February-May) and *Bega* (October-January) are secondary rainfall seasons and dry seasons respectively but are significant in southern and southwestern parts of the country such as Jinka and Arba Minch.

More than 80% of airports fall under low annual rainfall variability ($CV < 20\%$), indicating high reliability for long-term aviation planning. Only Gode airport shows high annual rainfall variability ($CV = 41\%$), indicating operational unpredictability and risk exposure. CV values during dry months often exceed 200%, particularly in arid and semi-arid regions, indicating unreliable rainfall patterns. In contrast, wet months (July-August) in western airports exhibit low CVs (e.g., Bahir Dar: 11.8% in August), supporting predictable seasonal operations. When we compare to seasonal rainfall variability *kiremt* season provide low inter-annual variability ($CV < 10\%$) in money airports making it most reliable season making complicated the operation planning. On the other side *Belg and Bega* exhibit higher rainfall variability ($CV > 40\%$ in Mekele, Dire Dawa, Axum), suggesting greater uncertainty the given periods.

Generally climatological and variability insights highlight the spatial and temporal heterogeneity of rainfall across Ethiopian airports, driven by topography, regional climate systems, and global drivers like ENSO. Understanding both average conditions (climatology) and year-to-year fluctuations (variability) is critical for aviation safety, infrastructure resilience, and operational efficiency.

4.2. Recommendations

Based on the rainfall climatological and variability findings across annual, monthly, and seasonal scales, the following strategic recommendations are proposed for aviation stakeholders:

Integrate Climatology into Operational Planning: prepare and use long-term monthly and seasonal rainfall climatology to inform flight scheduling, runway usage strategies, and ground operations planning, particularly during the wettest months (June-September).

Expand Probabilistic Forecasting for High-Variability Zones: For airports in arid and semi-arid regions (e.g., Gode, Semera, Dire Dawa), develop risk-based forecasting tools that incorporate high CV values and historical patterns to better manage uncertainty.

Tailor Infrastructure Based on Climatology: Design and maintain airport drainage, runway surfaces, and storm water management systems using regional rainfall climatology (e.g., over 1,000mm/year in Jimma vs. under 300mm/year in Gode).

Reinforce Resilience in Variable Zones: Aerodromes expecting seasonal or monthly extremes (e.g., erratic Belg rainfall) should incorporate adaptive infrastructure designs to accommodate both floods and droughts.

Strengthen Monitoring in Data-Sparse Regions: Enhance rainfall observation networks, particularly at newer or less-monitored aerodromes, to ensure complete, accurate climatological baselines for future aviation risk management and operational planning compliance.

Mainstream Seasonal Climatology into Emergency Response: Integrate seasonal rainfall climatology and variability

into airport contingency planning, including diversion scenarios, delays, and hazard alerts.

Promote Multi-Scale Climatology Training for Aviation Staff: enhance meteorological personnel and airport decision-makers with skills to interpret and apply monthly, seasonal, and annual rainfall climatology in operational contexts.

Abbreviations

Cb	Cumulonimbus
CDT	Climate Data Tool
CDF	Cumulative Distribution Function
CHIRPS	Climate Hazards Group InfraRed Precipitation
CV	Coefficient of Variation
EMI	Ethiopian Meteorology Institute
FMAM	February, March, April, May
GIS	Geographic Information Systems
ITCZ	Inter-tropical Convergence Zone
JJAS	June, July, August, September
MAE	Mean Absolute Error
MCN	Multilayer Complex Network
NSE	Nash-Sutcliffe Efficiency
ONDJ	October, November, December, January
RMSE	Root Mean Square Error
STD	Standard Deviation
TCu	Towering Cumulus
VFR	Visual Flight Rules

Acknowledgments

This research did not receive any specific grant or funding support. We, the authors of this research article, would like to express our sincere gratitude to the Ethiopian Meteorology Institute for providing access to rainfall datasets and for offering valuable training on data analysis tools. We also acknowledge the use of the CHIRPS (Climate Hazards Group InfraRed Precipitation with Station data) dataset, available from the Climate Hazards Group at <http://chg.geog.ucsb.edu/data/chirps>, for its extensive spatial and temporal coverage, including near-real-time data. We are also thankful to the reviewers, their insightful comments and constructive suggestions have significantly improved the quality of this manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

References

- [1] O. M. Haji *et al.*, "The Influence of Climate Change and Variability on Aircraft Take-off and Landing Performance; a Case Study of the Abeid Amani Karume International Airport-Zanzibar," *J. Transp. Technol.*, vol. 12, no. 03, pp. 453-474, 2022, <https://doi.org/10.4236/jtts.2022.123028>

- [2] K. Kim, H. Lee, M. Lee, Y. H. Bae, H. S. Kim, and S. Kim, "Analysis of Weather Factors on Aircraft Cancellation using a Multilayer Complex Network," *Entropy*, vol. 25, no. 8, 2023, <https://doi.org/10.3390/e25081209>
- [3] E. A. Adeleke, "Climate Change in Kwara State, Nigeria: Evidence of Rainfall and Temperature Variations," vol. 2, no. 1, pp. 48-63, 2024.
- [4] Á. Rodríguez-Sanz, J. Cano, and B. R. Fernández, "Impact of weather conditions on airport arrival delay and throughput," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 1024, no. 1, 2021, <https://doi.org/10.1088/1757-899X/1024/1/012107>
- [5] V. E. Weli and G. C. Emenike, "Turbulent Weather Events and Aircraft Operations: Implications for Aviation Safety At the Port Harcourt International Airport, Nigeria," *Clim. Chang. Conserv. Res.*, vol. 2, no. 1, pp. 11-21, 2016.
- [6] K. Fekadu, "Ethiopian Seasonal Rainfall Variability and Prediction Using Canonical Correlation Analysis (CCA)," *Earth Sciences*, vol. 4, no. 3, p. 112, 2015. <https://doi.org/10.11648/j.earth.20150403.14>
- [7] G. T. Diro, T. Toniazzo, and L. Shaffrey, "Ethiopian Rainfall in Climate Models," no. February, 2011, <https://doi.org/10.1007/978-90-481-3842-5>
- [8] T. Gebre, Z. Abraha, A. Zenebe, and W. Zeweld, "Precipitation variability and its teleconnection with the global SST and ENSO indices in the food-insecure rural areas of Tigray," *Theor. Appl. Climatol.*, no. 2019, 2023, <https://doi.org/10.1007/s00704-023-04717-5>
- [9] Y. Seleshi and U. Zanke, "Recent changes in rainfall and rainy days in Ethiopia," *Int. J. Climatol.*, vol. 24, no. 8, pp. 973-983, 2004, <https://doi.org/10.1002/joc.1052>
- [10] Z. T. Segele, "Characterization and variability of Kiremt rainy season over Ethiopia Characterization and variability of Kiremt rainy season over Ethiopia," no. August, 2014, <https://doi.org/10.1007/s00703-005-0127-x>
- [11] M. L. Berihun et al., *Examining the past 120 years' climate dynamics of Ethiopia*, vol. 154, no. 1-2. Springer Vienna, 2023. <https://doi.org/10.1007/s00704-023-04572-4>
- [12] T. Hassan, S. A. Gadzama, and L. U. Solomon, "International Journal of Research Publication and Reviews Effects of Weather Parameters on Flight Operations and Passenger Security in Nigeria," vol. 5, no. 9, pp. 624-631, 2024.
- [13] E. A. Mohammed, X. Zhi, and K. A. Abdela, "Extreme Weather Patterns in Ethiopia: Analyzing Extreme Temperature and Precipitation Variability," *Atmosphere (Basel)*, vol. 16, no. 2, 2025, <https://doi.org/10.3390/atmos16020133>
- [14] F. T. Tola, D. K. Dadi, T. T. Kenea, and T. Dinku, "Weather and climate services in Ethiopia: progress, challenges, and opportunities," *Front. Clim.*, vol. 7, no. April, pp. 1-17, 2025, <https://doi.org/10.3389/fclim.2025.1551188>
- [15] T. Dinku, R. Faniriantsoa, S. Islam, and G. Nsengiyumva, "The Climate Data Tool: Enhancing Climate Services Across Africa," vol. 3, no. February, pp. 1-16, 2022, <https://doi.org/10.3389/fclim.2021.787519>
- [16] C. D. Geleta and T. A. Deressa, "Evaluation of Climate Hazards Group InfraRed Precipitation Station (CHIRPS) satellite-based rainfall estimates over Fincha and Neshe Watersheds, Ethiopia," *Eng. Reports*, vol. 3, no. 6, pp. 1-16, 2021, <https://doi.org/10.1002/eng2.12338>
- [17] Z. Watershed, "Evaluation and Bias Correction of CHIRP Rainfall Estimate for Rainfall-Runoff Simulation over Lake," 2019.
- [18] M. A. Kidie and A. Teklay, "Journal of Environmental And Sciences (ISSN 2836-2551) Evaluation of multi-source satellite rainfall products in tekeze basin, Ethiopia Journal of Environmental And Sciences (ISSN 2836-2551)," pp. 1-18, 2023.
- [19] A. Asfaw, B. Simane, A. Hassen, and A. Bantider, "Variability and time series trend analysis of rainfall and temperature in northcentral Ethiopia: A case study in Woleka sub-basin," *Weather Clim. Extrem.*, vol. 19, no. June 2017, pp. 29-41, 2018, <https://doi.org/10.1016/j.wace.2017.12.002>