Journal of Engineering and Technology for Industrial Applications

ISSN ONLINE: 2447-0228

ITEGAM-JETIA

Manaus, v.11 n.52, p. 126-135. March./April., 2025.
DOI: https://doi.org/10.5935/jetia. v11i52.1118

RESEARCH ARTICLE OPEN ACCESS

LONG - TERM ASSESSMENT OF THE SPATIAL TEMPORAL TRENDS IN SELECTED CLOUD RADIATIVE PROPERTIES OVER THE THREE DISTINCT SITES IN KENYA

Sostine N. Makokha[1], John W. Makokha[2] and Festus B. Kelonye[3]

[1,2] Department of Science, Technology and Engineering, Kibabii University, P.O BOX 1699-50200, Bungoma, Kenya.
[3] Department of Biological and Environmental science, Kibabii University, P.O BOX 1699-50200, Bungoma, Kenya.

[1]http://orcid.org/0000-0003-3416-5818, [2]http://orcid.org/0000-0003-3267-4512, [3]http://orcid.org/0000-0002-5880-3493

Email: makokhasostine@gmail.com, makokhajw@kibu.ac.ke, fberu@kibu.ac.ke

ARTICLE INFO

Article History
Received: May 11, 2024
Revised: July 20, 2025
Accepted: March 15, 2025
Published: April 30, 2025

Keywords:
MODIS,
MERRA-2,
TRMM, Seasons
Clouds radiative properties

ABSTRACT

The presence of clouds in the Earth's atmosphere plays an important role in regulating the Earth's energy budget. Increased anthropogenic activities and emissions can significantly lead to changes in cloud composition and cloud structure affecting the cloud properties causing alterations in climatic conditions over Kenya. Given this, the present study examined the spatial temporal radiative properties of clouds over Nairobi, Malindi and Mbita by paying a special consideration on cloud parameters such as; Cloud Effective Radius (CER), Cloud Optical Thickness (COT), Water Vapor (WV), Precipitation Rate (PR) and Cloud Albedo (CA). These cloud parameters were retrieved from MODerate resolution Imaging Spectroradiometer (MODIS) sensor, the Modern Era Retrospective analysis for Research and Applications, version2 (MERRA-2) model and Tropical Rainfall Measurement Mission (TRMM) between January 2005 and December 2020. Data retrieved on clouds radiative properties was utilized to estimate the trends and spatial variations and assess their statistical significance on climate over the study domain. The Spatial patterns of seasonal mean of cloud parameters from the sensors and the model were generally characterized with positive and negative trends over Kenya observed during the four seasons Spatial trends in the selected cloud properties were determined and observed to vary both seasonally and regionally, the study revealed patterns of trends in cloud radiative properties and forms a basis for further research on clouds over Kenya.

I. INTRODUCTION

Clouds form a very crucial component of the atmosphere and play a pivotal role in regulating the Earth's energy budget [1]. Apart from other important modulators of climate, Clouds strongly modulate the radiation budget by absorbing and scattering solar and thermal radiation [2]. In particular, they play a key role in determining the solar radiation reaching the Earth's surface by generally reducing it (by up to nearly 80%) depending mainly on the cloud type, its optical thickness and distribution in the sky [3]. They also interact with the solar radiation causing direct effect such as absorption or scattering [4].

The interactions of the clouds and other components in the atmosphere cause both predictable and unpredictable weather patterns affecting the climate of the study domain. These simple processes that takes place in the atmosphere may affect the daily weather patterns over any region and any slightest change in these properties would perturb cloud radiative forcing and modulate the radiative balance of the Earth system [5]. Moreover, temporal trends of the changes in intensity, frequency, and duration of temperature and precipitation events are indicators of a changing climate [6] caused as a result in variations in cloud characteristics. Cloud radiative properties can be assessed through determining the variations in some major cloud parameters such as the Cloud effective radius (CER), Cloud Optical Thickness (COT), Water Vapor (WV), Precipitation Rate (PR) and Cloud Albedo (CA).

Various recent studies have been done on assessing and determining the radiative properties of clouds both regionally and globally with the aim of providing knowledge on cloud properties over those study regions. These studies have provided the necessary knowledge on both methods of data acquisition, processing and analysis of the data obtained with an aim of giving it a statistical significance.

A study was done on the radiative cloud properties in USA by [7]. This study was aimed at studying parameterization of the radiative properties of clouds. Reflection, transmission, and absorption of solar radiation by four cloud types (low, middle, high and stratus clouds) were computed as functions of the solar zenith angle and cloud liquid water/ice content.

The reflection, transmission and emission of the infra-red radiation by cirrus clouds are calculated as functions of the cloud ice content. The plane-parallel radiative transfer program employed is based on the discrete-ordinate method with applications to inhomogeneous absorption in scattering atmospheres covering the entire solar and infrared spectra taking into consideration the gaseous absorption in scattering atmospheres [8].

The resulting values of the solar radiative properties of clouds were fitted with known mathematical functions involving the solar zenith angle and cloud liquid water/ice content as variables. The effects of the atmospheric profile were discussed and the effects of surface reflectivity on the solar radiative properties of clouds were parameterized in terms of the water vapor absorptivity below the cloud ground reflection and average cloud reflection.

The parameterized equations for the infrared flux reflectivity of cirrus clouds were also presented as functions of the cloud ice content. Computations were made for various cloud thicknesses, holding the cloud base at a constant height for each case. The vertical liquid water content W of which cloud thickness is given by $W = w\Delta z$, where w is the mean water/ice content and Δz the geometrical cloud thickness.

The ranges of cloud thicknesses used in the radiative transfer calculations of this study for Cu, As, St and Ci were 0.15-2.25, 0.1-1.5, 0.05-0.75 and 0.1-2.9 km respectively. the corresponding ranges of vertical liquid water/ice content are 49.5-742.5, 24.0-360.0, 39.0-585.0 and 5.2-150.4 gm^{-2} respectively. The findings from this study illuminates our understanding on parameterization of clouds radiative properties and the effect of the variation on climatic variables.

Further studies were carried out by [9] on assessment of optical, microphysical and radiative properties of aerosol over a rural site in Kenya. Ground based remote sensing method was used in data collection by taking direct measurements of direct sun and diffuse sky radiances in 15-30minutes interval between spectral ranges of 340-1640nm and 440-1040nm respectively.

The daily average values were used to derive a long term (2007-2015) climatology of each of the variables over the study area (MBITA) [9]. The data retrieved showed a strong variation with the season of the year [9], this is a clear indicator that the cloud properties (cloud being an aerosol) varies from one region to the other also affects the amount of heat reaching and leaving the surface of the earth.

Also, [10], carried out a study on parameterization of the radiative properties of water clouds suitable for use in climate models over Alaska in the United States of America (USA). It was found out that cloud optical properties depended mainly on the equivalent radius throughout the solar and terrestrial spectrum and they were insensitive to the details of the droplet size distribution such as shape, skewness, width and modality.

This implied that measurements of cloud liquid water content and the extinction coefficient are sufficient to determine cloud optical properties experimentally. The cloud optical properties are then parameterized as a function of cloud liquid water path and equivalent cloud droplet radius by using a nonlinear least – square fitting leading to computations of cloud heating and cooling rates. The findings of this study were then used to infer on the effect of the cloud properties on the climatic patterns over the study domain.

For [11], carried out a study over Bangladesh in South Asia. The study was aimed at investigating Spatiotemporal characteristics of aerosol optical depth (AOD), Cloud properties and Top of Atmosphere (TOA) Net Cloud Radiative Effect (Net CRE) using MODIS, with CERES sensor and a NOAA HYSPLIT model over Bangladesh for the period 2001-2016. The study investigated the relationship of AOD against cloud parameters and Net CRE over the study domain. Linear regression analysis showed increasing trends for AOD, CF, WV, COT, CTP and CTT. Such studies provide very crucial information on instrumentation and dataset for the study of radiative cloud properties over other regions of the world.

A study was carried out on the relationship between clouds radiative forcing, cloud fraction and cloud albedo in the USA [12]. The study was done for the period 1997-2009 mainly putting emphasis on three interconnected topics; quantitative relationship between surface shortwave cloud radiative forcing, cloud fraction, and cloud albedo, also, surface based approach for measuring cloud albedo and multiscale variations and covariations were carried out in order to assess the variations in short wave cloud radiative forcing, cloud fraction and cloud albedo [13].

The study collected hourly datasets on cloud radiative forcing, cloud fraction and cloud albedo over the study domain during the specified study period to explore the expected multiscale variations as per the study objectives. The observations from the study were very pivotal for diagnosing and analyzing deficiencies of cloud – radiation parameterizations in climate models [12], which in turn assisted in learning and understanding the effects of those variations on climate change.

In [14], a study was done on the Cloud - Aerosol - Radiation interaction over South - East Atlantic. This study region was selected for study since it had high atmospheric aerosol loadings and semi-permanent stratocumulus clouds are co-located providing an optimum region for studying the full range of aerosol – radiation and aerosol – cloud interactions and their perturbations of Earth's radiation budget.

One of the main objectives of the study was to improve the knowledge and representation of the processes determining stratocumulus cloud microphysical and radiative properties and their transitions to cumulus regimes. Satellite measurements were used in this study in order to obtain the relationships of the interactions. The observations of the above study lacked the spatial and temporal resolutions, nor the required level of precision to come up with deeper assessment of the interactions as per the objectives of the study.

From the above cited earlier researches and studies done on radiative properties of clouds, it is evident that Kenya still lags behind in terms of data and knowledge on the radiative properties of clouds and the effect of those variations in clouds properties on the Earth's radiation budget. This study seeks to address the knowledge gap over the study sites by assessing the spatial temporal radiative properties of clouds over.Nairobi, Malindi and Mbita study sites for a period of 16 years from 2005-2020. The cloud parameters assessed by this study were; CER, COT, WV, PR and CA [15], Data from MODIS was retrieved for the entire study period and spatial trends and seasonal variations were obtained through a system of algorithms to provide a comprehensive assessment of the clouds radiative properties.

II. MATERIALS AND METHODS

II.1 STUDY AREA

The study was conducted over Kenya, a region that is bounded by Latitudes 5º S - 5º N and Longitudes, 34º E - 42º E. Kenya is an East African country bordered by Ethiopia to the North, Tanzania to the South, South Sudan to the North-west, Uganda to the West and lastly Somalia to the East. The proposed study was done over the Republic of Kenya over three main environmentally distinct regions. The regions of focus were; Nairobi (1º S, 36º E), Mbita (0º S, 34º E) and Malindi (4º S, 40º E).

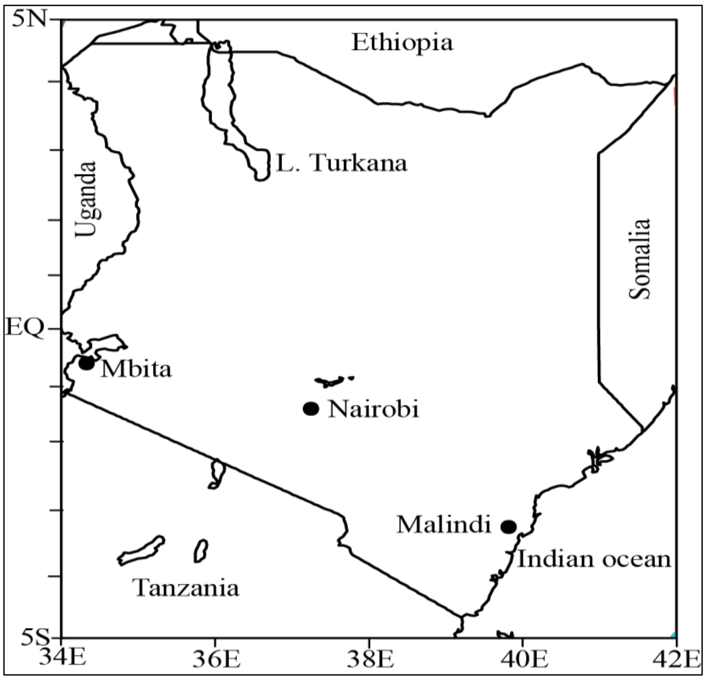


Figure 1: map of Kenya showing the three study sites in Kenya.
Source: Authors, (2025).

Nairobi is 1669 m high above the sea level [16]. The Nairobi region represents the urban climate. The main contributors to the cloud content and characteristics are anthropogenic as a result of industrial-vehicular emissions [17] in the Nairobi area.

The climate here is warm and temperate, and a significant amount of rainfall is received throughout including in the driest month of the year. The annual rainfall is 674mm while the average temperature is 18.8°C. Nairobi has the highest population about 4.397 million people according to the Kenya National Bureau of Statistics [18].

Malindi is a town in Kilifi County on Malindi bay at the mouth of Sabaki River lying on the Indian Ocean coast of Kenya. It is 120 km north-east of Mombasa with a population of 119,859 [18] with an elevation of 118m above the sea level. According to Koppen-Geiger climate classification of climate, Malindi has a hot tropical type of climate with a winter dry season with an average temperature of about 26.2°C. Malindi receives much rain during summer than winter according to the Kopper – Geiger and an annual rainfall of 755mm. Malindi borders the Indian Ocean and as a result, it experiences the maritime atmosphere which is its largest contributors of the cloud content and properties.

Mbita region is in Homabay county on the shores of Lake Victoria, 1125m above the sea level [9], with a population of approximately 14,916 [18]. Mbita in this present study represents the Kenyan rural atmosphere. Mbita experiences tropical type of climate and receives an average annual rainfall of approximately 1259.3mm [20] even the driest month still has a lot of rainfall. The annual average temperatures for Mbita are about 23.7°C.

Based on the prevailing meteorological conditions, a year was then divided into four seasons. December-January-February (DJF), March- April-May (MAM), June-July-August (JJA) and lastly, the September-October-November (SON) seasons. The DJF and JJA represents the local dry seasons characterized by reduced rainfall [21] while the MAM and SON seasons representing the local wet seasons characterized by enhanced rainfall [21],[19].

II.2 MODIS SATELLITE SENSOR

MODerate Imaging Spectroradiometer (MODIS) is a Polar-orbiting satellite sensor launched into the Earth orbit by National Aeronautics and Space Administration (NASA) [22] Goddard Space Flight Center on board the Terra (morning orbit) on 18th December 1999 and Aqua (afternoon orbit) satellite launched on 4th May 2002 [21],[23],[24].

With a band of ~2330 km and time-based (Temporal) resolution of 1-2 days [25], and acquires data globally over 36 spectral bands ranging in wavelengths from 0.415 to 14.235µm at three spatial resolutions (2 bands at 250 m, 5 bands at 500 m, and 29 bands at 1 km). MODIS is a 36-band Spectroradiometer that provides several cloud properties using the spectral bands from visible to thermal infrared [26].

MOD08-D3 product is also used, which includes daily measurements of optical thickness, cloud top pressure and effective particle radius [27] gridded at a latitude and longitude resolution of 1º × 1º (roughly 100 km×100 km at mid-latitudes). The clouds and Earth's Radiant energy system (CERES) is also a radiometer also on board the Terra and Aqua platforms.

CERES measures the radiation on top of the atmosphere in three channels; the first channel is a shortwave channel for the solar reflected radiation in 0.3-5 µm, the second channel measures the Earth's surface emitted radiation in the atmospheric window of 8-12 µm and lastly, the third channel measures the whole spectrum.

MODIS datasets are very important for collecting various statistics on cloud microphysical properties as a result of aerosols [28]. For water vapor, the retrieval for the near infrared region is used. MODIS uses an infrared band to determine the physical properties of clouds in relation to CTT and CTP. Visible and near infrared bands are used to determine the optical and microphysical cloud properties [29].

Daily global level 2 data are provided whereby the cloud particle, phase effective cloud, particle radius and cloud optical thickness are derived using the near infrared channel radiances. Also, the cloud top height, effective emissivity, phases and cloud fraction are produced by the infrared retrieval methods day and night at 5×5 1-km pixel resolution. In summary, MODIS measures the cloud top properties (temperature, pressure and effective emissivity), cloud thermodynamic phase and cloud optical and microphysical parameters (optical thickness, effective particle radius and water path). The MODIS resolution ranges between 0.25 to 1km [27].

The present study utilized the level 3 monthly data on cloud parameters retrieved from MODIS Terra at a spatial resolution of 1° × 1° for a period of 16 years (January 2005 to December 2020) to study trends and their significance levels over Kenya.

These data products were sourced from http://giovanni.gsfc. nasa.gov/giovanni/. The MODIS datasets are preferred because they are open to the public and more precise to spatial and temporal distribution. The dataset can also enable one to find an empirical relationship between the reflectivity and the microphysical cloud properties which in turn can derive a conclusion of variations of cloud physical properties on climatic variables.

II.3 MERRA-2 Model

The Modern–Era Retrospective Analysis and Research and Application, version 2 (MERRA-2) atmospheric reanalysis product was newly released and launched by NASA Global Modeling and Assimilation Office (GMAO) to provide data since 1980 [30]. MERRA-2 replaced the original MERRA dataset [31] because of the advances made in the assimilation system that enable assimilation of modern hyper spectral radiances and microwave observations.

Also uses NASA's Ozone profile observations that began in the late 2004. The model is based on the version of the GEOS-5 atmospheric data from 1980 to 2016 at 0.5° × 0.625° resolution with 72 layers and spanning the satellite observing era from 1980 to the present [21].

Along with the enhancements in the meteorological assimilation, MERRA-2 takes some significant steps towards GMAO's targets of an earth system reanalysis. In the present study, MERRA-2 M2TMNXAER v5.12.4 level-3 monthly time-averaged data on cloud parameters were retrieved at a spatial resolution of 0.5° × 0.625° from January 2005 to December 2020. These data products were sourced from [32].

II.4 TROPICAL RAINFALL MEASUREMENT MISSION (TRMM) - SATELLITE

The Tropical Rainfall Measurement Mission (TRMM) is a research satellite that has been actively in operation between 1997 – 2015 mainly designed to improve the understanding of the distribution and variability of precipitation within the Tropics as part of the water cycle in the current climate system. TRMM provides the necessary information needed on rainfall and its associated heat release that helps to power the global atmospheric circulation which shapes both weather and climate [33].

TRMM uses space-borne instruments to increase our understanding of the interactions between water vapor, clouds and precipitation which are core in regulating the Earth's climate. The satellite has a precipitation Radar that provides information on Tropical storm structure and intensification and the TRMM Microwave Imager (TMI) that measures microwave energy emitted by the Earth and its atmosphere in order to quantify the amount of water vapor, cloud water and the rainfall intensity in the atmosphere.

This study has used TRMM in retrieving data on the precipitation rate over the study domains for the various seasons from January 2005 up to December 2020. The variations in the precipitation rate averages are then used to infer on the variation of the cloud properties on climate. This is so important since precipitation and the hydrological cycle controls the weather and climate of any particular region.

II.5 METHODS

This section highlights the suitable methods used during the analysis of the data retrieved from MODIS and MERRA-2 in order to obtain any significant statistical interpretation of the data obtained.

II.6 LINEAR REGRESSION ANALYSIS

Determination of the combined effect of cloud physical and radiative properties on the climatic parameters such as precipitation rate makes use of the linear regression analysis. Linear regression provides very crucial information and direction on how well a set of variables can predict a particular outcome. It focuses on the conditional probability distribution of the response given the values of the predictors, rather than on the joint probability distribution of all of these variables.

The Linear Regression makes use of the following derivation; let Y denote the "dependent" variable whose values you wish to predict and let $X_1 \ldots X_k$ denote the "independent" variable from which you wish to predict it, with the value of variable X in the period t (or in row t of the dataset) denoted by X_{1t}. Then the equation for computing the predicted value of Y_t is given by;

$$Y_t = b_0 + b_1X_{1t} + b_2X_{2t} + \ldots + b_kX_k \qquad (1)$$

Where Y – is a straight-line function of each of the X-variable holding others constant, the contributions of different X variables to the predictions are additive.

b_1, b_2 …………..... bk are the slopes of their individual straight-line relationships with Y, the coefficients of the variables, b_0 – the intercept is the prediction that the model would make if the *X's* were zero. The coefficients and intercept are estimated by least squares i.e., setting them equal to the unique values that minimize the sum of squared errors within the sample of data to which the model is fitted. And the model's prediction errors are typically assumed to be independently and identically normally distributed.

II.7 TREND ANALYSIS

The study has determined the spatial and temporal variation of clouds radiative properties through assessing the variations in cloud parameters using trend analysis to determine the variability of the trends in Kenya. Numerous statistical methods exist to quantify trends in the time series of a geophysical variable,

Mann Kendall test has been used by this present study to evaluate annual, seasonal and monthly trends of climatic variables [34] for the selected regions in Kenya over a 16-year period (2005-2020). The test has been found to be the most appropriate for analysis of climatic changes in climatological time series for detection of a climatic discontinuity [35].

The method is applied to the long-term data in this study to detect statistically significant trends and the method is preferred when various stations are tested in a single study [36], and for this study, Nairobi, Malindi and Mbita clouds can be studied at the same time using this Mann Kendall test. In this test the null hypothesis (H_o) is that there has been no trend in precipitation over time the alternative hypothesis (H_1) is that there has been a trend (increasing or decreasing) over time.

The mathematical equations for calculating Mann-Kendall statistics S, $V(s)$ and standardized test statistics Z are as follows;

$$S = \sum_{i=l}^{n-l} \sum_{j=i+1}^{n} \text{sig (Xj} - \text{Xi)} \quad (2)$$

The application of trend test is done to a time series X_i that is ranked i=1, 2,………n-1 and X_j, which is ranked from j= i+1, 2……n [36],[37]. Each of the data products X_i is taken as the reference point which is compared with the rest of the data points X_j so that:

$$\text{Sgn (Xj} - \text{Xi)} = \{H\ H\ (xj - xi)\} = 0 \quad (3)$$

$$\text{Sgn (Xj} - \text{Xi)} = \begin{cases} +1\ if\ (Xj - Xi) > 0 \\ 0\ \ if\ (Xj - Xi) = 0 \\ -1\ if\ (Xj - Xi) < 0 \end{cases} \quad (4)$$

$$\text{V (s)} = \frac{1}{18} \left[\!\left[n(n-1)(2n+5) - \sum_{p=1}^{q} tp \right.\right. \quad (5)$$

Equation (3) and (4) yields a standard normal distribution factor Z given by;

$$Z = \begin{cases} \dfrac{s-1}{\sqrt{VAR(s)}} if\ s{>}0 \\ 0 \qquad if\ s = 0 \\ \dfrac{s+1}{\sqrt{VAR(s)}} if\ s{<}0 \end{cases} \quad (6)$$

A positive value of Z i.e. (Sgn (Xj − Xi)) signifies an upward trend while a negative value of Z signifies a downward trend in the time series observations in chronological order [36].

In these equations,

Xi and *Xj* = are the time series observations in chronological order

n is the length of time series

t_p is the number of ties for pth value

q is the number of tied values

Positive *Z* – values indicate an upward trend in the hydrologic time series;

Negative *Z* -values indicate a negative trend. If /Z/>$Z_{1-\alpha/2}$, (H_0) is rejected and a statistically significant trend exist in the hydrologic time series.

The critical value of $Z_{1-\alpha/2}$ for a p value of 0.05 from the standardized normal table is 1.96. In the present work, linear regression analysis was used to estimate monthly trends in key cloud parameters (CA, WV, COT and CER). The method has been discussed widely. This test also assists in determining the variations of the climatic variables with time for the period between the year 2005 and 2020.

III. RESULTS AND DISCUSSIONS

III.1 TRENDS IN CLOUD EFFECTIVE RADIUS

Cloud effective radius (CER) refers to the weighted mean of the size distribution of cloud droplets. A ratio of the third to the second moment of droplet size distribution. The trends in Cloud effective radius retrieved from MODIS data were observed to vary both seasonally and spatially ranging from positive to negative trends as obtained during the whole study period.

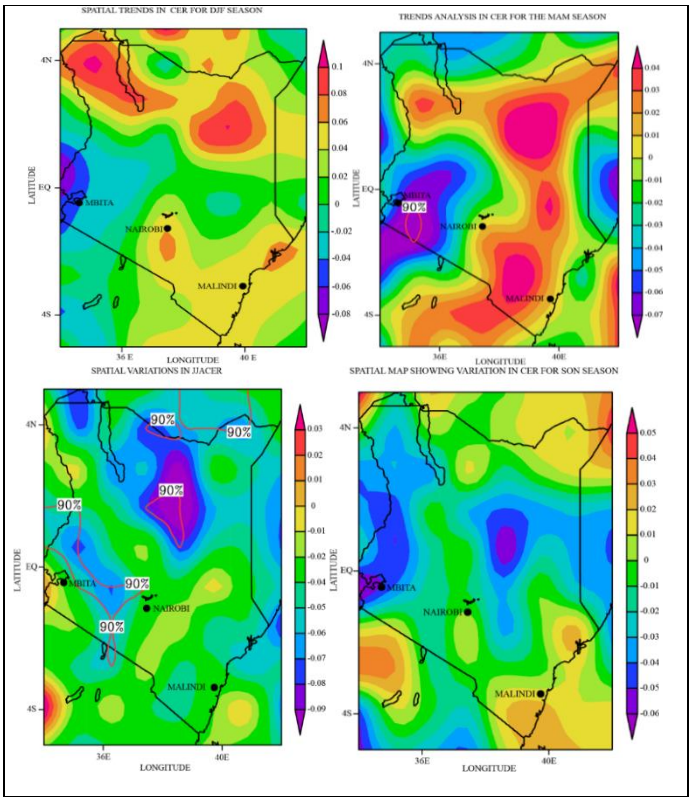


Figure 2: spatial map of Kenya showing the variations of the CER
Source: Authors, (2025).

Positive seasonal trends in CER are observed in all seasons for the Malindi clouds. Positive trends in DJF season over Nairobi with negative trends in both JJA and SON seasons over Nairobi clouds. And lastly negative trends over Mbita clouds except during the JJA season. It is observed that cloud over Malindi has the highest average CER in all the four seasons as compared to Nairobi and Mbita clouds over the whole study period.

CER is higher over oceans than over the ground [25]. Furthermore, it is noted that the effective radius of the polluted cloud will decrease when compared to the pristine cloud [38] and for this reason, clouds over Nairobi region have the smallest effective radius due to the net industrial emissions of gases and other pollutants from the industries, biomass burning and vehicular emissions.

III.2 TRENDS IN CLOUD OPTICAL THICKNESS

COT is a measure of the attenuation of solar radiation passing through the atmosphere; this attenuation is caused by the scattering and absorbing of light by the cloud droplets [39]. The cloud optical thickness together with effective particle radius are the key parameters which determines radiative properties of clouds such as reflectance, transmission and absorption of solar radiation [40].

COT has a number of applications in radiative transfer and climate change as well as in computing the Earth's radiation budget. This study made use of the MODIS terra satellite to retrieve data on COT over the study sites for the 16 years' period. Data obtained was analyzed through linear regression analysis to produce average trends in COT for every season during the study period.

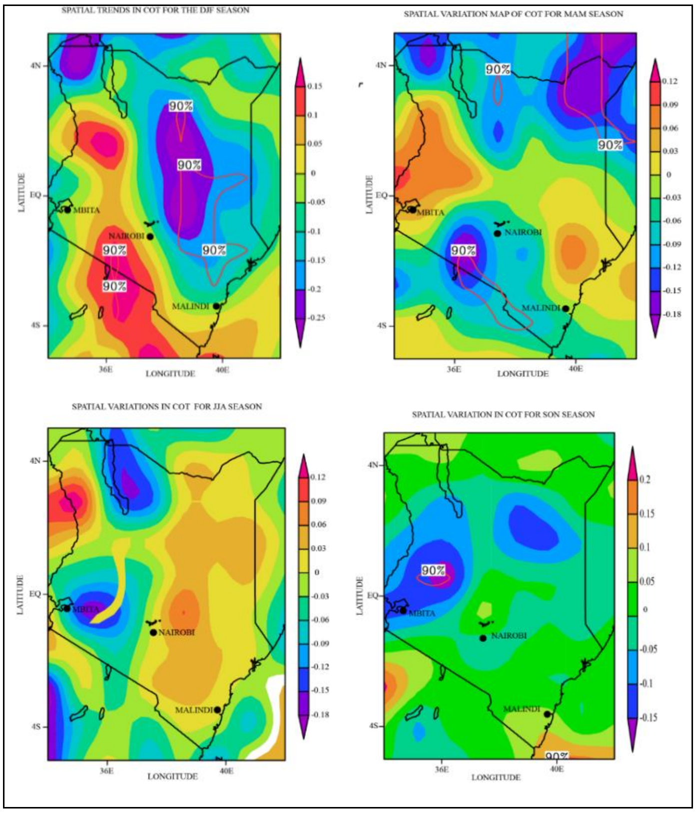


Figure 3: spatial analysis for COT over Kenya.
Source: Authors, (2025).

Using the above displayed spatial maps for the four seasons, COT variation over Kenya can still be analyzed by the use of the different colors displayed in the maps and the color bar shown besides every map, however, this study is only interested in studying the radiative clouds properties over Nairobi, Malindi and Mbita.

Clouds in colder, higher latitudes are optically thicker than clouds in warmer, lower latitudes. Malindi has maritime conditions and aerosols coupled with long range transport of monsoon winds [17], while Nairobi experiences heavy vehicular and industrial emissions dominance.

These explains the higher COT and hence higher reflectance over Malindi and Nairobi [17]. Clouds in Mbita have the lowest COT and hence lowest reflectance as compared to these other two study regions due to biomass burning and lower latitude in Mbita.

These findings clearly state how the clouds radiative properties vary from on region to the other as a result of the shown variations in the clouds optical thickness over the study regions. The variations in COT affects directly the radiative properties of clouds such as extent of reflectivity of clouds on the incoming solar radiation.

The variations in the cloud reflectance on the incoming solar radiations causes significant effect on the prevailing weather patterns, higher reflection cools the atmosphere as a result of a larger percentage of the solar radiations are reflected back in space, this leads to a lower temperature being recorded. Lower cloud reflectivity results to heating of the atmosphere leading to higher atmospheric temperatures. The variations in temperature determines the weather and climate of the study sites.

III.3 TRENDS IN PRECIPITATION RATE

Variations in precipitation rate from one region to another can clearly demonstrate the difference in cloud properties. The precipitation rate depends on several factors such as the prevailing winds, presence of mountains and seasonal winds and the aerosol concentration in those Clouds [41]. Presence of aerosols affects the vertical development of clouds and the precipitation [41].

This study used the TRMM to retrieve data on daily precipitation rate over Kenya, data obtained was merged into monthly and then seasonally using the software MATLAB which then applied the knowledge of linear regression and trend analysis applications, together with the Illustrator and then GRADS, which then assisted in coming up with the trends and the spatial maps showing the variations in PR over the entire Kenya for all the 16 years of study.

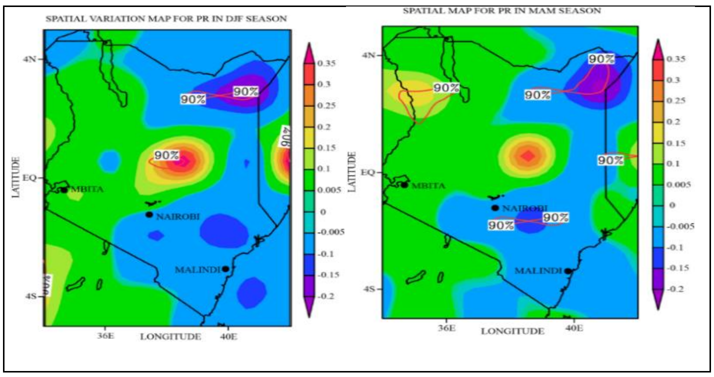
Nairobi and Malindi posted negative trends in PR in all the seasons for all the 16 years of study with no significant trend during the JJA season over Nairobi. Positive trends over Mbita during the DJF, MAM and the SON season, no significant trend in PR during the JJA season over Mbita. It is also evident that spatial variations occur in PR when trend analysis was done over the three study sites in every season.

High precipitation rate is experienced near the equator [42] that is why Mbita receives the highest precipitation rate (0.005mm/day) in almost all the seasons of the year except for JJA season of above 0 when compared with the two other study regions. Heavy precipitation is normally experienced near the equator and decreases with increase in the latitude [43]. This clearly indicates the higher moisture content in the Mbita clouds than over Nairobi and Malindi.

Low precipitation rate is experienced over Malindi. This is attributed to the presence of dry monsoon winds which drive away the moisture reducing the moisture content in clouds over Malindi and causing Atmosphere - ocean mechanisms of rainfall anomalies at the coastal regions [44].

High precipitation rate over Mbita clearly indicates higher moisture supply/content over Mbita clouds. Emission of aerosols into the atmosphere from vehicles, industries, burning of fuels and all other anthropogenic emissions in Nairobi affects the cloud characteristics, cloud lifetime and vertical cloud development and hence the low precipitation rate [41].

The variations in the rate of precipitation depicts its dependency on clouds physical and radiative properties which explains the correlation ship between clouds properties and climate change. Figure 3.3 shows the spatial maps of Kenya representing the trends in the precipitation rates over the study sites.



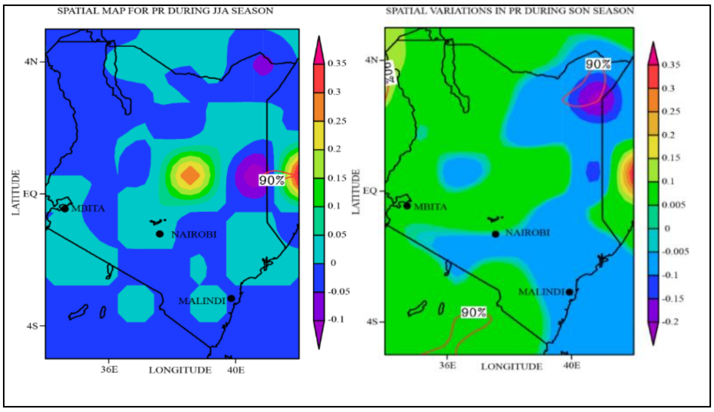


Figure 4: spatial distribution maps for PR over kenya
Source: Authors, (2025).

III.4 TRENDS IN WATER VAPOR

Water vapor is the absolute amount of water dissolved in air. It is measured in millimeters (mm). Water vapor in the atmosphere is a parameter of great importance in climate models because it plays a role as a greenhouse gas [45]. In fact, studies show that only an increase of water vapor in the atmosphere by only 20 percent would cause a larger impact than doubling of carbon (iv) oxide concentration [46]. The study made use of the MODIS data during the study period to investigate the variation of the cloud water vapor content and the net effect of the WV on the prevailing climatic conditions.

This cloud parameter is also important in the study of clouds and climate since the amount of water vapor in the atmosphere normally affects the formation of secondary aerosols such as nitrates and sulfates which in response affects the cloud characteristics and the climate [47]. Values of the cloud water vapor content were obtained from the models and satellites described in the chapter three of this study, monthly averages for all the study period were merged into seasons so that the average values and spatial variation maps are drawn for the study domains.

Positive trends in water vapor across all the seasons apart from the DJF season over Nairobi where negative trends were observed. Malindi and Mbita experiences almost similar trends most of the seasons as a result of both being closer to the large water bodies that is the Indian ocean and the Lake Victoria respectively. The amount of water vapor contained in the clouds and the hydrological cycle cannot be separated this is due to the fact that the hydrological cycle transports the water vapor present in the clouds [48], this indicates the high dependence of climate on the clouds and the hydrological cycle. MODIS – Terra retrieval separately reveals the outcomes for WV in the clouds over Nairobi, Malindi and Mbita. Clouds over Mbita has the highest average water vapor content in the atmosphere (between 0 and 0.015) as compared Malindi and Nairobi clouds with the least averages for all the four seasons of the study duration. It is also observed that Malindi and Mbita produced the highest averages of the amount of water vapor during the DJF season.

The difference in the amount of WV content is attributed to the variations in the temperature of these study regions. This is because the temperature of the surrounding atmosphere limits the maximum amount of water vapor the atmosphere can contain [49] (https://www.acs.org/climate science). WV accounts for about 60% of the Earth's greenhouse warming effect and the amount of water vapor is controlled by the temperature of that particular region [49].

The two study regions Mbita and Malindi experiences relatively higher amounts of temperature that causes the higher rate of both surface water evaporation and the evaporation of the waters from both Lake Victoria and the Indian ocean respectively, this higher rate of water evaporations leads to higher WV content in the clouds over those two regions as compared to the clouds over Nairobi. Figure 5 shows the spatial map showing the variation in water vapor content in clouds over the three study regions for the period 2005-2020.

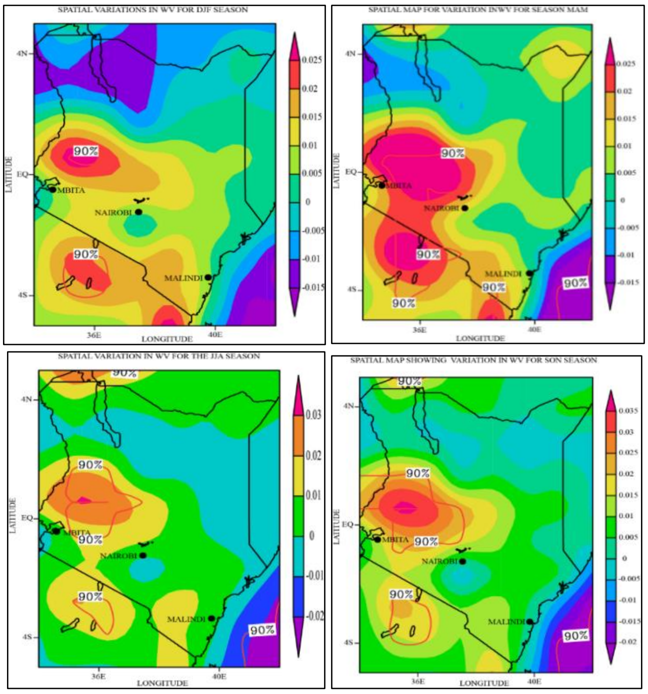


Figure 5: showing the spatial variation map for water vapor content.
Source: Authors, (2025).

Looking at the spatial distribution maps, the values of water vapor content varies periodically and seasonally throughout the study period which in turn indicates the changes in the atmospheric content and hence change in climate.

There is a possibility that adding more WV to the atmosphere could produce a negative feedback effect [50]. This could happen if more WV leads to formation of clouds.

Water vapor equably lies at the heart of all key terrestrial atmospheric processes [50], presence of water vapor in the atmosphere is essential for development of disturbed weather influences both directly and indirectly through formation of clouds, affecting the planetary radiative balance and influences surface fluxes [50]. Clouds reflect sunlight and reduce the amount of energy that reaches the Earth's surface to warm it. If the amount of solar warming decreases, then the temperature of that particular region also decreases. In that case, the effect of adding more water vapor would be cooling rather than warming. These indicates the high dependency of both regional and global climates on the cloud characteristics.

Since the amount of water vapor in the atmosphere acts as the greenhouse gases, variations in its content great influences the climate of any regions just like other greenhouse gases which causes global warming, higher precipitation rates, melting of ice, increase in sea, ocean and lake water levels as a result of melting of ice and high precipitation levels. All these effects result into adverse weather patterns.

Water vapor content in the clouds becomes one of the major parameters that can indicate and also be used to assess clouds physical characteristics and hence its study and findings can enable scholars to clearly explain the concepts of climate change since water vapor has a strong positive feedback on climate changes driven by other influences [50].

III.5 CLOUD ALBEDO

Cloud albedo is a measure of the albedo or reflectivity of cloud. Higher albedo implies higher cloud cover and lower absorption of solar energy. This parameter strongly influences the Earth's energy budget [51].

Cloud albedo depends on several factors which includes the total mass of water, size and shape of the cloud droplets and the distribution of the particles in space [52]. The major causes of the variation in cloud albedo are the liquid water path, aerosol indirect effect and the Zenith angle [53]. Seasonal values of Cloud Albedo were retrieved from MERRA-2 model for the years 2005 -2020 the spatial maps showing the variations in trends were done in order to assess the significance of the trends using trend analysis.

Negative trends in MAM and JJA seasons for all the study sites, negative trends in CA over Nairobi and Malindi during the SON season with positive trends over Mbita during the same season. And lastly, positive trends in spatial variations during the DJF season over the three study sites. These variations in CA are key in assessing the general characteristics of clouds and their effect on climatic variables. It is evident that variations in the cloud albedo has an effect on the regional climate, when Cloud Albedo increases, reduction in the absorbed solar radiation takes place leading to cooling of the atmosphere [54], it is also taken into account that variations in air pollutions leads to variations in cloud condensation nuclei, creating a feedback loop that influences the atmospheric temperature, relative humidity and cloud formation [55] depending on cloud and regional characteristics eg; aerosols reduces the precipitation efficiency resulting in positive feedback loop in which decreased precipitation efficiency increase aerosol atmospheric longevity.

High cloud albedo represents thick clouds such as stratocumulus, reflect a large amount of incoming solar radiation [56][57], low solar radiation represents cooling of the atmosphere. Low cloud albedo represents thin clouds such as cirrus clouds, transmit more solar radiation, heating up the atmosphere causing warming of the atmosphere. The variations in cloud Albedo over Kenya can be represented in spatial maps. See Figure 6:

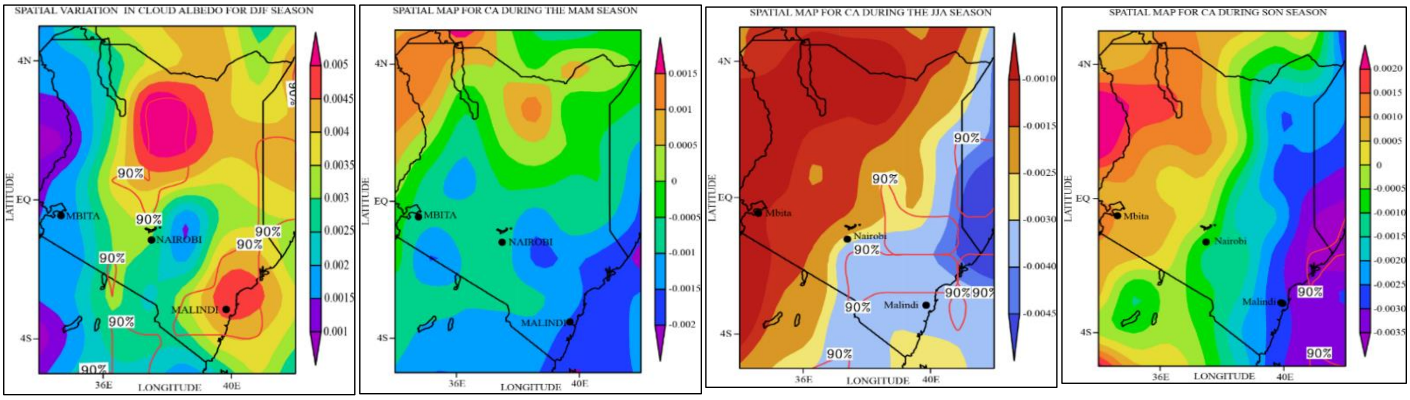


Figure 6: showing the spatial variation map for Cloud Albedo.
Source: Authors, (2025).

IV. CONCLUSIONS

Using the data sets retrieved from MODIS sensor, MERRA-2 model and the TRMM, the present study revealed an in depth understanding of trends in CER, COT, WV, PR and CA as well as the spatial distribution in the above parameters over Kenya for the period 2005-2020. The spatial variations in cloud parameters from MODIS- sensor, the MERRA-2 model and the TRMM were used to infer on the general radiative properties of clouds over the three study sites and their effect on the climate.

The study domains were dominated by positive trends in most of the cloud parameters, with a significance of 90% in most of the seasons. The variation in trends in clouds radiative properties is attributed to biomass burning, vehicular and industrial emissions that contributes to foreign materials into the atmosphere over the study domain.

The study domain was dominated by negative trends in CER, CA and COT except for CER over Malindi in all seasons and Nairobi during the DJF and MAM seasons. Seasonally, positive trends in Water vapor (WV) were observed in all the season over the study domain due to changes in climatic condition and anthropogenic activities such as biomass burning and both vehicular and industrial emissions which increases the cloud lifetime and aerosols acting as the condensation nuclei in the atmosphere increasing the cloud formation and hence increasing the amount of water in the atmosphere.

The study domain significantly exhibited decreasing and increasing trends in all the cloud parameters over the study period clearly indicating variations in clouds physical properties caused as a result of different clouds contributors and modulators of cloud characteristics.The knowledge on spatial trends and spatial distribution maps is very important. Both seasonal and regional variations in clouds parameters would mean variations in climatic variables which then form a basis of understanding the concepts of climatic variations and climate change. This important information and data is lacking over Kenya hence opening a link and a need for further investigation and research on clouds radiative properties.

V. AUTHOR'S CONTRIBUTION

Conceptualization: Sostine N. Makokha[1], John W. Makokha[2] and Festus B. Kelonye[3].
Methodology: Sostine N. Makokha[1] and John W. Makokha[2].
Investigation: Sostine N. Makokha[1] and John W. Makokha[2].

Discussion of results: Sostine N. Makokha[1], John W. Makokha[2] and Festus B. Kelonye[3].
Writing – Original Draft: Sostine N. Makokha[1].
Writing – Review and Editing: Sostine N. Makokha[1] and John W. Makokha[2].
Resources: John W. Makokha[2].
Supervision: John W. Makokha[2] and Festus B. Kelonye[3].
Approval of the final text: Sostine N. Makokha[1], John W. Makokha[2] and Festus B. Kelonye[3].

VI. ACKNOWLEDGMENTS

The authors wish to pass their sincere gratitude to the NASA and Giovanni online analysis and visualization system for providing and processing MODIS, MERRA-2 data used in this study. The lead author (Mr. Sostine N. Makokha) extends sincere gratitude to the Ministry of Higher Education, Science and Technology of Kenya and Kibabii University, Kenya, for providing an opportunity to undertake Masters of Science (physics) studies.

VII. REFERENCES

[1] Zhang, J., Liu, P., Zhang, F., and Song, Q. (2018). Cloud Net: Ground‐based cloud classification with deep convolutional neural network. *Geophysical Research Letters*, *45*(16), 8665-8672.

[2] Roebeling, R. A., Feijt, A. J., and Stammes, P. (2006). Cloud property retrievals for climate monitoring: Implications of differences between Spinning Enhanced Visible and Infrared Imager (SEVIRI) on METEOSAT‐8 and Advanced Very High Resolution Radiometer (AVHRR) on NOAA‐17. *Journal of Geophysical Research: Atmospheres*, *111*(D20).

[3] Calbo, J., Pages, D., and Gonzale, J., (2005): Empirical studies of cloud effects on UV radiation; a review, Review Geophysics,43, 1-28.

[4] Ichoku C., Kaufman, Y.J, Remor, L. A. and Levy R. (2004). Global aerosol remote sensing from MODIS. Advances in Space Research 34: 820-827.

[5] George, R. C., and Wood, R. (2010). Subseasonal variability of low cloud radiative properties over the southeast Pacific Ocean. *Atmospheric Chemistry and Physics*, *10*(8), 4047-4063.

[6] Audu, M. O., Ejembi, E., and Igbawua, T. (2021). Assessment of Spatial Distribution and Temporal Trends of Precipitation and Its Extremes over Nigeria. *American Journal of Climate Change*, *10*(3), 331-352.

[7] Liou, K. N., and Wittman, G. D. (1979). Parameterization of the radiative properties of clouds. *Journal of Atmospheric Sciences*, *36*(7), 1261-1273.

[8] Li, W., Zhang, F., Shi, Y. N., Iwabuchi, H., Zhu, M., Li, J., and Ishimoto, H. (2020). Efficient radiative transfer model for thermal infrared brightness temperature simulation in cloudy atmospheres. *Optics Express*, *28*(18), 25730-25749.

[9] Boiyo, R.K, Kumar, R. and Zhao, T. (2018) Optical, Microphysical and Radiative properties of Aerosols over a tropical Rural site in Kenya, East Africa: source Identification, Modification and Aerosols Type Discrimination. Journal Atmospheric Environment, 177, 234-252.

[10] Hu, Y. X., and Stamnes, K. (1993). An accurate parameterization of the radiative properties of water clouds suitable for use in climate models. *Journal of climate*, *6*(4), 728-742.

[11] Ali, M. A., Islam, M. M., Islam, M. N., and Almazroui, M. (2019). Investigations of MODIS AOD and cloud properties with CERES sensor based net cloud radiative effect and a NOAA HYSPLIT Model over Bangladesh for the period 2001–2016. *Atmospheric Research*, *215*, 268-283.

[12] Liu, Y., Wu, W., Jensen, M. P., and Toto, T. (2011). Relationship between cloud radiative forcing, cloud fraction and cloud albedo, and new surface-based approach for determining cloud albedo. *Atmospheric Chemistry and Physics*, *11*(14), 7155-7170.

[13] *Mueller, Richard; Trentmann, Jörg; Träger-Chatterjee, Christine; Posselt, Rebekka; Stöckli, Reto (2011).* "The Role of the Effective Cloud Albedo for Climate Monitoring and Analysis". Remote Sensing. 3 (11): 23052320. Bibcode:2011RemS3.2305M. *doi:10.3390/rs3112305. ISSN 2072-4292.*

[14] Haywood, J. M., Abel, S. J., Barrett, P. A., Bellouin, N., Blyth, A., Bower, K. N., and Zuidema, P. (2021). The CLoud–Aerosol–Radiation interaction and forcing: Year 2017 (CLARIFY-2017) measurement campaign. *Atmospheric Chemistry and Physics*, *21*(2), 1049-1084.

[15] Zhao, C., Chen, Y., Li, J., Letu, H., Su, Y., Chen, T., and Wu, X. (2019). Fifteen‐year statistical analysis of cloud characteristics over China using Terra and Aqua Moderate Resolution Imaging Spectroradiometer observations. *International Journal of Climatology*, *39*(5), 2612-2629.

[16] Mideva, E. M. (2021). *Atrium Daylight Penetration in Dense Apartment Blocks. a Case of Roysambu Nairobi, Kenya.* University of Nairobi School of the Environment Department of Architecture NS Building Science, Nairobi.

[17] Makokha, J. W., and Angeyo, H. K. (2013). Investigation of radiative characteristics of the Kenyan atmosphere due to aerosols using sun spectrophotometry measurements and the COART model.

[18] KNBS and Republic of Kenya (2019a), 2019 Kenya Population and Housing Census: Vol 1: opulation by County and Sub-County.

[19] Boiyo, R.K, Kumar, R. and Zhao, T. (2018) Optical, Microphysical and Radiative properties of Aerosols over a tropical Rural site in Kenya, East Africa: source Identification, Modification and Aerosols Type Discrimination. Journal Atmospheric Environment, 177, 234-252.

[20] Bakayoko, A., Galy-Lacaux, C., Yoboué, V., Hickman, J. E., Roux, F., Gardrat, E., ... and Delon, C. (2021). Dominant contribution of nitrogen compounds in precipitation chemistry in the Lake Victoria catchment (East Africa). *Environmental Research Letters*, *16*(4), 045013.

[21] Khamala, G. W., Makokha, J. W., Boiyo, R., and Kumar, K. R. (2022). Long-term climatology and spatial trends of absorption, scattering, and total aerosol optical depths over East Africa during 2001–2019. *Environmental Science and Pollution Research*, 1-15.

[22] Barnes, W. L., Xiong, X., Guenther, B. W., and Salomonson, V. (2003). Development, characterization, and performance of the EOS MODIS sensors. *Earth Observing Systems VIII*, *5151*, 337-345.

[23] Mito, C. O., Boiyo, R. K., & Laneve, G. (2012). A simple algorithm to estimate sensible heat flux from remotely sensed MODIS data. *International Journal of Remote Sensing*, *33*(19), 6109-6121.

[24] Remer, L. A., Kaufman, Y. J., Tanré, D., Mattoo, S., Chu, D. A., Martins, J. V., and Holben, B. N. (2005). The MODIS aerosol algorithm, products, and validation. *Journal of the atmospheric sciences*, *62*(4), 947-973.

[25] King, M. D., Platnick, S., Menzel, W. P., Ackerman, S. A., and Hubanks, P. A. (2013). Spatial and temporal distribution of clouds observed by MODIS onboard the Terra and Aqua satellites. *IEEE transactions on geoscience and remote sensing*, *51*(7), 3826-3852.

[26] Cao, C., De Luccia, F. J., Xiong, X., Wolfe, R., and Weng, F. (2013). Early on-orbit performance of the visible infrared imaging radiometer suite onboard the Suomi National Polar-Orbiting Partnership (S-NPP) satellite. *IEEE Transactions on Geoscience and Remote Sensing*, *52*(2), 1142-1156.

[27] Platnick, S., King, M., Ackerman, S., Menzel, W., Baum, B., Riedi, J., and Frey, R., (2003): The MODIS cloud products; algorithms and examples from Terra, IEEE Transactions on Geoscience and Remote sensing, 41, 459-473.

[28] Platnick, S., Meyer, K. G., King, M. D., Wind, G., Amarasinghe, N., Marchant, B., ... and Riedi, J. (2016). The MODIS cloud optical and microphysical products: Collection 6 updates and examples from Terra and Aqua. *IEEE Transactions on Geoscience and Remote Sensing*, *55*(1), 502-525.

[29] Alam, K., Iqbal, M. J., Blaschke, T., Qureshi, S., & Khan, G. (2010). Monitoring spatio-temporal variations in aerosols and aerosol–cloud interactions over Pakistan using MODIS data. *Advances in Space Research*, *46*(9), 1162-1176.

[30] Randles, C. A., Da Silva, A. M., Buchard, V., Colarco, P. R., Darmenov, A., Govindaraju, R., and Flynn, C. J. (2017). The MERRA-2 aerosol reanalysis, 1980 onward. Part I: System description and data assimilation evaluation. *Journal of climate*, *30*(17), 6823-6850.

[31] Bosilovich, M. G., Lucchesi, R., and Suarez, M. (2015). *MERRA-2: File specification*. Global Modeling and Assimilation Office, Maryland.

[32] https://svs.gsfc.nasa.gov/30007. 04/10/2022.

[33] Xie, P., and Arkin, P. A. (1997). Global precipitation: A 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model outputs. *Bulletin of the american meteorological society*, *78*(11), 2539-2558.

[34] Audu, M. O., Ejembi, E., and Igbawua, T. (2021). Assessment of Spatial Distribution and Temporal Trends of Precipitation and Its Extremes over Nigeria. *American Journal of Climate Change*, *10*(3), 331-352.

[35] Wanjuhi, D. M. (2016). *Assessment of Meteorological Drought Characteristics in North Eastern Counties of Kenya* (Doctoral dissertation, University of Nairobi).

[36] Mondal, A., Kundu, S., and Mukhopadhyay, A. (2012). Rainfall trend analysis by Mann-Kendall test: A case study of north-eastern part of Cuttack district, Orissa. *International Journal of Geology, Earth and Environmental Sciences*, *2*(1), 70-78.

[37] Yadav, Reshu et al. Trend analysis by Mann-Kendall test for precipitation and temperature for thirteen districts of Uttarakhand. Journal of Agrometeorology, v. 16, n. 2, p. 164-171, 2014.

[38] Saponaro, G. (2020). *Application of remotely-sensed cloud properties for climate studies*. *Journal of Geophysical Research: Atmospheres,* 185, 1-5. http://hdl.handle.net/10138/308930.

[39] https://svs.gsfc.nasa.gov/30007. 04/10/2022.

[40] Kikuchi, N., Nakajima, T., Kumagai, H., Kuroiwa, H., Kamei, A., Nakamura, R., and Nakajima, T. Y. (2006). Cloud optical thickness and effective particle radius derived from transmitted solar radiation measurements: Comparison with cloud radar observations. *Journal of Geophysical Research: Atmospheres*, *111*(D7).

[41] Li, Z., Niu, F., Fan, J., Liu, Y., Rosenfeld, D., and Ding, Y. (2011). Long-term impacts of aerosols on the vertical development of clouds and precipitation. *Nature Geoscience*, *4*(12), 888-894.

[42] Tandon, N. F., Zhang, X., and Sobel, A. H. (2018). Understanding the dyamics of future changes in extreme precipitation intensity. *Geophysical Research Letters*, *45*(6), 2870-2878.

[43] Hopkins, L. C., and Holland, G. J. (1997). Australian heavy-rain days and associated east coast cyclones: 1958–92. *Journal of Climate*, *10*(4), 621-635.

[44] Hastenrath, S., Nicklis, A., and Greischar, L. (1993). Atmospheric-hydrospheric mechanisms of climate anomalies in the western equatorial Indian Ocean. *Journal of Geophysical Research: Oceans*, *98*(C11), 20219-20235.

[45] Nilsson, T., and Elgered, G. (2008). Long-term trends in the atmospheric water vapor content estimated from ground-based GPS data. *Journal of Geophysical Research: Atmospheres*, *113*(D19).

[46] Buehler, S. A., Von Engeln, A., Brocard, E., John, V. O., Kuhn, T., and Eriksson, P. (2006). Recent developments in the line-by-line modeling of outgoing longwave radiation. *Journal of Quantitative Spectroscopy and Radiative Transfer*, *98*(3), 446-457.

[47] Ding, J., Dai, Q., Zhang, Y., Xu, J., Huangfu, Y., and Feng, Y. (2021). Air humidity affects secondary aerosol formation in different pathways. *Science of The Total Environment*, *759*, 143540.

[48] Quan, Q., Liang, W., Yan, D., and Lei, J. (2022). Influences of joint action of natural and social factors on atmospheric process of hydrological cycle in Inner Mongolia, China. *Urban Climate*, *41*, 101043.

[49] https://www.acs.org/climate science.

[50] Sherwood, S. C., Roca, R., Weckwerth, T. M., and Andronova, N. G. (2010). Tropospheric water vapor, convection, and climate. *Reviews of Geophysics*, *48*(2).

[51] Feinberg, A. (2022). A re-radiation model for the earth's energy budget and the albedo advantage in global warming mitigation. *Dynamics of Atmospheres and Oceans*, *97*, 101267.

[52] Schulze, B. C., Charan, S. M., Kenseth, C. M., Kong, W., Bates, K. H., Williams, W., and Seinfeld, J. H. (2020). Characterization of aerosol hygroscopicity over the Northeast Pacific Ocean: Impacts on prediction of CCN and stratocumulus cloud droplet number concentrations. *Earth and Space Science*, *7*(7), e2020EA001098.

[53] Gryspeerdt, E., Goren, T., Sourdeval, O., Quaas, J., Mülmenstädt, J., Dipu, S., and Christensen, M. (2019). Constraining the aerosol influence on cloud liquid water path. *Atmospheric Chemistry and Physics*, *19*(8), 5331-5347.

[54] Bala, G., Caldeira, K., Nemani, R., Cao, L., Ban-Weiss, G., and Shin, H. J. (2011). Albedo enhancement of marine clouds to counteract global warming: impacts on the hydrological cycle. *Climate dynamics*, *37*(5), 915-931.

[55] Wiedensohler, A., Cheng, Y. F., Nowak, A., Wehner, B., Achtert, P., Berghof, M., ... and Pöschl, U. (2009). Rapid aerosol particle growth and increase of cloud condensation nucleus activity by secondary aerosol formation and condensation: A case study for regional air pollution in northeastern China. *Journal of Geophysical Research: Atmospheres*, *114*(D2).

[56] Liou, K. N. (1976). On the absorption, reflection and transmission of solar radiation in cloudy atmospheres. *Journal of Atmospheric sciences*, *33*(5), 798-805.

[57] Liou, K. N. (1986). Influence of cirrus clouds on weather and climate processes: A global perspective. *Monthly Weather Review*, *114*(6), 1167-1199.