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TIME SERIES ANALYSIS OF AEROSOL OPTICAL DEPTH AND CLOUD PARAMETERS OVER ETHIOPIA

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TIME SERIES ANALYSIS OF AEROSOL OPTICAL DEPTH AND CLOUD PARAMETERS OVER ETHIOPIA



**A GRADUATE THESIS SUBMITTED TO THE SCHOOL OF GRADUATE
STUDIES OF BAHIR DAR UNIVERSITY**

**IN PARTIAL FULFILLMENT OF THE REQUIRMENTES FOR THE
DEGREE OF MASTER OF SCIENCE IN PHYSICS**

BY

DEMELASH FIKIRE

BAHIR DAR UNIVERSITY

JUNE, 2019

BAHIR DAR, ETHIOPIA

CERTIFICATION

The undersigned hereby certify that they have read and recommend to the school of postgraduate studies for the acceptance of this project work entitled as “**Time series analysis of Aerosol optical depth and cloud parameters over Ethiopia**” using MODIS Data by Demelash Fikire in Partial Fulfillment of the Requirements for the Degree of **MASTER OF SCIENCE IN PHYSICS** at Bahir Dar University.

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APPROVED BY:

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Internal Examiner _____

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Demelash Fikire hereby authorize the Bahir Dar University to copy and/or release the whole ,part of this research work to other researchers and organizations wishing to use the material for reference and/or research purposes.

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DEDICATION

This work is dedicated to my parents, brothers and sisters.

Acknowledgement

First and for most, I would like to thank the Almighty **God** and his mother Virgin **Mary** for giving health, patience and hope beginning to end of my work. Second, I am sincerely and heartily grateful to my advisor and instructor, Dr. Raju, for the support and guidance he showed me throughout my thesis writing. His tireless follow up and his consistent support will be in my memory forever. I would like to extend my thanks to Mr. Abebe and Megbar Wendie (PhD candidates) inspired me throughout, to constantly strive in all things and instilled in me the vital importance of even the most minor details. I would like to thank collage of science for the sponsorship during my stay at Bahir Dar University. Next to this I would like to convey my deepest thanks for my classmates for their helpful idea at every time from the beginning to the end of this work. I wish to thank all of my teachers. Finally, I would like to pay high regards to my family, for their moral and financial, support; this is last but not least.

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LIST OF ABBREVIATIONS AND ACRONYMS

ACI	Aerosol Cloud Interactions
AOD	Aerosol Optical Depth
CCN	Cloud Condensation Nuclei
CER	Cloud Effective Radii
CF	Cloud Fraction
CTP	Cloud Top Pressure
CTT	Cloud Top Temperature
GIOVANNI	Geospatial Interactive Online Visualization Analysis Infrastructure
ITCZ	Inter Tropical Convergence Zone
LWC	Liquid Water Content
MODIS	MODerate resolution Imaging Spectrometer
NASA	National Aeronautics and Space Administration
PM	Particulate Matter
PPMCC	Pearson Product-Moment Correlation Coefficient
SPM	Suspended Particulate Matter
WV	Water Vapor

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ABSTRACT

Aerosols are microscopic liquid or solid particles which enter the atmosphere through natural and man-made processes. Atmospheric aerosols influence the Earth's weather and climatic system in many ways, both directly and indirectly, although the magnitude of this influence remains uncertain even today (IPCC, 2007). Interactions between aerosols and clouds have become the subject of scientific research because of the importance of clouds in controlling climate. In this thesis, we have examined the temporal variations (time series analysis) in aerosol particles over Ethiopia and the impact of these variations on various optical properties of clouds using Moderate Resolution Imaging Spectroradiometer (MODIS) data from January 2003 to December 2018. The maximum aerosol optical depth (AOD) was found at summer period with minimum values in winter. During summer air temperature is high leads to hold abundant atmospheric water vapor facilitated the hygroscopic growth of aerosols. We then analyzed the relationships between AOD and other cloud parameters, namely water vapour (WV), cloud fraction (CF), cloud top temperature (CTT) and cloud top pressure (CTP) to provide a better understanding of aerosol–cloud interaction. The correlation between AOD and cloud fraction (CF), water vapor (WV) was positive for Ethiopian continent, while negative correlation with cloud top temperature (CTT) and cloud top pressure (CTP).

Key words: MODIS, AOD, CF, CTP, CTT, WV and Ethiopia

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND OF THE STUDY

Aerosol is derived from the Greek word "aero" -air and "sol" -solution, and is a term applied to solid or liquid materials suspended in the air. Atmosphere itself is an aerosol. However, in atmospheric physics, the term “aerosol” is often used interchangeably with “aerosol particle”. In this terminology, atmospheric aerosols are all particles in the atmosphere larger than a few molecules and smaller than cloud droplets (Ramanathan *et al.*, 2001).

The word aerosol was introduced more than 80 years ago as an analogy to the term hydrosol, a stable liquid suspension of solid particles (Hinds, 1999). The study of aerosols began by John Aitkin’s experiments with dust in the 1880s. He built apparatus to count particles in suspension by expanding and then cooling samples of air. Water condensed on the particles, allowing the resulting drops to be counted with the aid of a microscope. The size of aerosol particles ranges from tens of a nanometer to hundreds of micrometers (Chowdhary and Cairns, 2002).

The Earth's Atmosphere is a mixture of different trace gases and very minor constituents such as aerosols. The composition of aerosols, water vapor, carbon dioxide, ozone and other minor particles is less than 1%. However, these minor constituents have been influencing the atmosphere since the beginning of the 2nd industrial revolution (Seinfeld and Pandis, 2006). Aerosols are highly populated in troposphere. Their distribution decreases with altitude. The sources of these particulate matters could be from anthropogenic and natural activities at the surface or within the atmosphere. Troposphere aerosols are usually introduced due to strong volcanic eruptions and gas-to-particle conversions. Because of their highly dynamic nature, aerosol's spatial and temporal distribution is very difficult to predict even if it is known they are populated closer to their source area. The presence of these particulate matters in the Earth's Atmosphere has significant impacts (both positively and negatively) either directly or indirectly on human activities. The direct effect of aerosols is scattering and absorbing both short wave (solar radiation) and long wave (terrestrial radiation). The indirect effect of aerosols is related to their role as cloud condensation nuclei (CCN) which modifies cloud microphysics, and concentration (IPCC, 2007).

Ethiopia is one of the East African countries. Its population is more than 70 millions. Majority of the people (> 85%) live in rural area, where modern energy sources have not reached yet. The population produces energy from biomass burning which results in introduction of particulate matters like soot and ash. Ethiopia has been affected by droughts in different years which are caused by climate change. The drought might be partly due to reduction in forest cover which can be related to increase in aerosol concentration in the air. However, as a developing country, Ethiopia is also undertaking different activities in industrial plantations and constructions in all parts of the country. Therefore, it is now the right time to give attention to air quality and climate change impacts. The Earth's atmosphere consisting primarily of a mixture of gases also contains particles, such as aerosols and clouds (Etyemezian *et al.* 2005).

Cloud parameters such as cloud fraction, cloud top pressure, cloud top temperature and water vapor. Cloud top pressure (CTP) is the average pressure at the top of all clouds (liquid and ice) in a given region. The unit is in hector Pascal (hPa). Cloud top temperature (CTT) is the atmospheric temperature at the level of the cloud top. It is potential for rainfall. Furthermore, if the cloud-top temperature is below 0°C, then ice is possible. The unit is in Kelvin degree (k) and Water vapor (WV) is varies with time and space in the atmosphere. The unit is in centimeter (cm). In order to understand the aerosol impact and the process of the hydrological cycle, we investigated the change in column water vapor in relation to aerosols (Myhre *et al.*, 2007; Balakrishnaiah *et al.*, 2012).

Cloud fraction (also known as cloudiness, cloudage, and cloud cover and cloud amount) refers to the fraction of the sky obscured by clouds when observed from a particular location. In meteorology an oktas is a unit of measurement used to describe the amount of cloud cover at any given location such as a weather station. Sky conditions are estimated in terms of how many eighths of the sky are covered in cloud, ranging from 0 oktas (completely clear sky) through to 8 oktas (completely overcast). Oktas only estimate cloud cover in terms of the area of the sky covered by clouds. It is calculated by dividing the number of cloud pixels by total number of pixels. The amount of sky estimated to be covered by a specific cloud type (cirrus, cirrostratus, cumulus), cloud particle phase (water, ice, liquid, mixed), cloud height (low, mid, high) or all cloud types (total cloud fraction). An increase in the amount of aerosols increases the amount total cloud fraction, and an increase in the amount of aerosols increment the amount of cloudiness (Pfister *et al.*, 2003).

1.2 Statement of the problem

Aerosol particles are even less studied objects than the elementary particles and quarks owing their small sizes do not allow them to be watched through optical microscopes because their particles size (around 100nm) are much smaller than the wavelength of visible light. The concentration of the aerosol particles varies strongly with time and location. Atmospheric aerosol particles are usually decreasing with increasing height because the majority of aerosol particle sources are on the Earth's surface and removal mechanisms operate continuously within the atmosphere aerosol heating within cloud layers reduces cloud cover, whereas aerosol heating above the cloud layer tends to increase cloud fractions. There exists close relationship between atmospheric aerosols and the cloud cover implying a water cycle in the atmosphere. It is precisely this water cycle, made possible by aerosols that represent the most effective process for their removal from the atmosphere (Thomason, 2007). Hence aerosols can change the size and density of cloud droplets thereby modifying the cloud albedo, the cloud lifetime, and the precipitation. Due to their large spatial and temporal extent (desert dust, pollution, etc.) in the atmosphere the interactions between aerosols and clouds can have substantial climatic impacts. In the context of our country, Ethiopia, the effect of aerosols on cloud parameters has not been extensively reported except a few studies on air pollution by King *et al.* (1978). Hence, it is our motivation to observe how the water vapor and cloud parameter affected by aerosols over Ethiopian continent.

1.3 Objectives of the study

1.3.1 General objective

The general aims of this work:

- The general objective of this study is to evaluate time series analysis of Aerosol optical depth and cloud parameters over Ethiopia.

1.3.2 Specific objectives

The specific tasks of this work are:

- To determine the relationships between Aerosol optical depth (AOD) at 550 nm and cloud parameters such as cloud fraction (CF), cloud top pressure (CTP), cloud top temperature (CTT) and water vapor (WV) for 16 years period (January 2003–December 2018) data set using Karl Pearson's Coefficient of Correlation analysis.

1.4 Significance of the study

The significance of this thesis is the effect of aerosols on cloud cover important to decide Surface energy budget, Global warming, Global energy budget, Agriculture, Climate change, Aviation Weather Prediction, Navigation, Greenhouse effect and Polar Wind estimates. Generally to contributes to understanding climatic changes.

1.5 Outline of the thesis

This thesis consists of 5 Chapters. Chapter 2 deal shortly introduction to aerosol-cloud interactions (**ACI**) in addition to the source of aerosols and types of clouds. Chapter 3 provides description of the study area, data types and methodology. Chapter 4 deals the results and discussions, effect aerosols on cloud parameters. Recommendation and Conclusions provided by chapter 5.

CHAPTER TWO

2. Aerosol-Cloud Interactions

Aerosols that can absorb or adsorb water molecules from the ambient atmosphere are important for cloud formation. Since these aerosol particles act as embryos for the formation of cloud droplets, the number of cloud droplets that form is a function of the number of aerosols with affinity for water present in the atmosphere. Because the water-affinity of these aerosols depends on their chemical composition, the chemical composition of the aerosols becomes another important factor in cloud formation. Further, the sizes of the cloud droplets that form also depend on the sizes of the aerosols. If the drops that form are smaller, precipitation formation via collision coalescence is retarded, and the long living clouds reflect the incoming solar radiation longer. Twomey (1977) argued that increases in aerosol concentrations result in smaller cloud droplets that enhance the colloidal stability of the clouds leading to longer living clouds. Thus increased aerosol concentrations lead to cooling the atmosphere as less solar radiation reaches the ground this is the aerosol indirect effect.

At the end of the 19th century, Aitken (1880) and Courier and Mascart (1875) discovered that cloud droplets only form when aerosol particles serve as cloud condensation nuclei, CCN. This was consistent with the finding of Thomson (1871), who showed that the water vapor pressure for which a droplet is in equilibrium with its environment increases massively with decreasing droplet size, causing small droplets to evaporate very quickly. Aitken (1880) also noted that the activation of these particles depends on their chemical composition. He found that natural salts as well as particles produced by burning sulfur, which is the case when burning fossil fuels, are very efficient CCN. As a consequence, he hypothesized that the optical and microphysical properties of fogs and clouds are influenced massively by anthropogenic activities. The theoretical basis of the activation of hygroscopic aerosol particles was derived by Köhler (1936), who described the water vapor pressure at which a solution droplet is in equilibrium with its environment as a function of its size and chemical composition.

Clouds are crucial understanding of weather and climate. It reflects the sunlight, which cools the earth and also traps the long wave radiation resulting in earth warming, same as that of green house effect. The net effect depends upon cloud type, cloud depth and height of the cloud base

from the surface (Coakley *et al.*, 1987). Low clouds and middle clouds mostly consist of water. They reflect more solar radiation than they absorb infrared radiation. Low and middle clouds therefore have a cooling effect. On the other hand, high clouds mostly consist of ice, which absorbs more infrared radiation than water. Since high clouds are thin, they also allow sunlight to pass through to warm the ground (Hansen and Travis, 1974). Hence, high clouds have a warming effect. Clouds are the key to precipitation formation and the global water cycle (Albrecht, 1989).

2.1 Atmospheric aerosols

When the term “Atmospheric aerosol” is being used; it encompasses an extensive range of particle types with different compositions, shapes, sizes and optical properties. The amount of aerosol in the atmosphere sometimes called aerosol loading can be quantified either by mass concentration or an optical measure known as aerosol optical depth (AOD). AOD is dimensionless quantity, the integral of the product of particle number concentration and particle extinction cross-section (which accounts for individual particle scattering plus absorption), along a path length through the atmosphere, usually measured vertically (Andreae, 1995; Satheesh & Krishna Moorthy, 2005).

Aerosols are generally classified into three depending up on their particle size categories: (i) Ultra-fine/Nucleation/ Aitken mode ($0.001 - 0.1 \mu\text{m}$ radius), (ii) Large particles /Accumulation mode ($0.1 - 1.0 \mu\text{m}$ radius) and (iii) Giant particles/Coarse mode ($> 1.0 \mu\text{m}$ radius). Nucleation and accumulation are terms connected with the production processes of aerosols in those particular modes. The Aitken or Nucleation mode aerosols formed by gas-to-particle conversion (GPC) are the most predominant in terms of number though they constitute the smallest percentage of the total aerosol loading due to their smaller size. The process involved in the accumulation mode is usually heterogeneous condensation of gas vapor onto existing smaller nucleation mode particles. Coarse mode aerosols are as a result of mechanical processes such as wind-blown dust; sea-salt aerosols produced by breaking of sea waves. Once aerosols are ejected into the atmosphere they are blown along with air currents until they are finally removed from the atmosphere. Their mass, size and acceleration determines how long they will stay in the atmosphere which is normally being referred to as their residence time. The residence time depends on their average life time. This normally will be for a few days to a week (Raes *et al.*,

2000). The removal of aerosols from the atmosphere can be through wash-out by rain called ‘wet deposition’ or direct uptake known as dry deposition. But aerosols ejected into the stratosphere, they do not get removed easily like the tropospheric ones, sometimes remain for years.

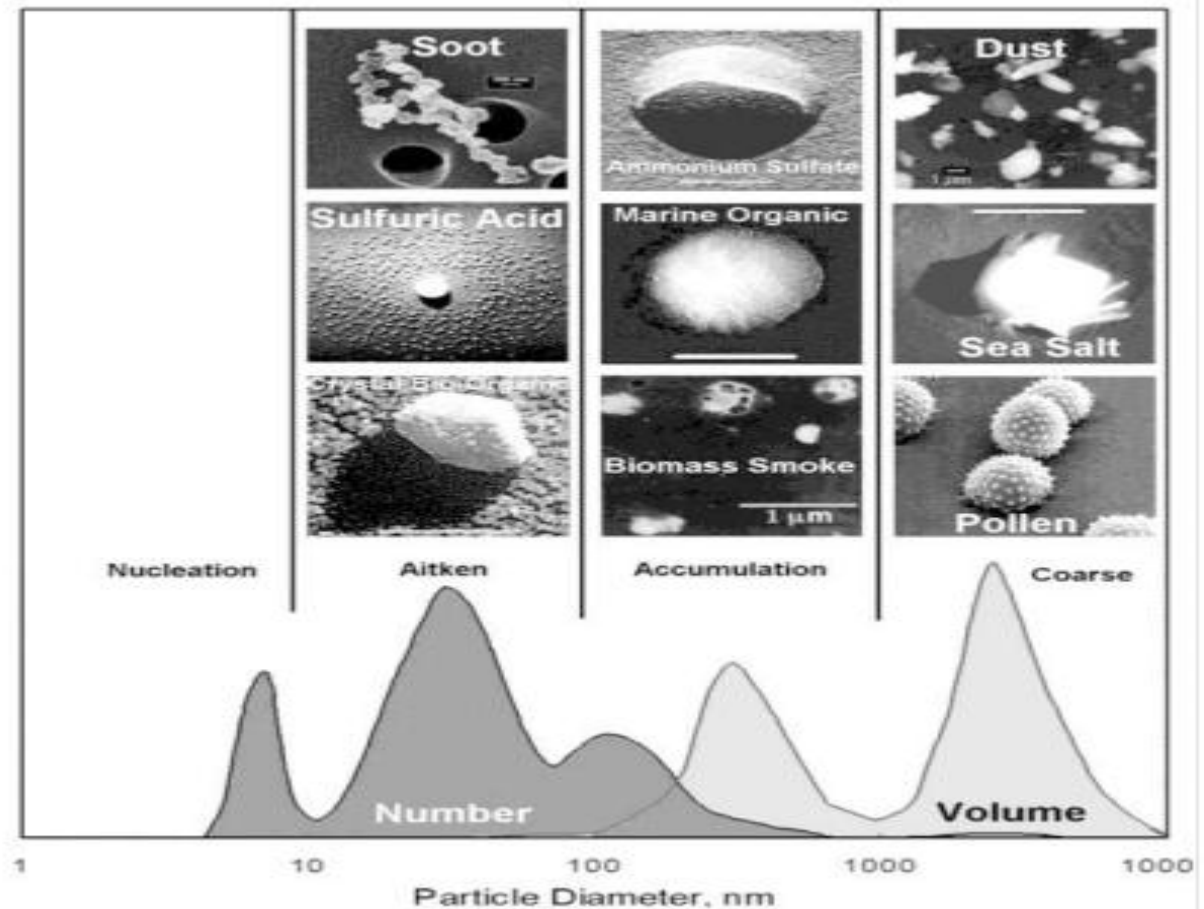


Figure 1: Showing the Aitken mode – 0.01-0.1 μm , Accumulation mode – 0.1-1 μm coarse mode $>1 \mu\text{m}$ and sometimes, the inclusive nucleation mode $<0.01 \mu\text{m}$ (Source: SASAS Conference, 2013).

2.2 Sources of Atmospheric aerosols

Aerosols also sometimes called particulate matter (PM) or by synonymous terms such as Suspended Particulate Matter (SPM), Total Suspended Particulate (TSP) or Total Suspended Particulate Matter (TSPM). They are broadly classified into two according to source of generation.

- a. Natural aerosols and
- b. Anthropogenic aerosols

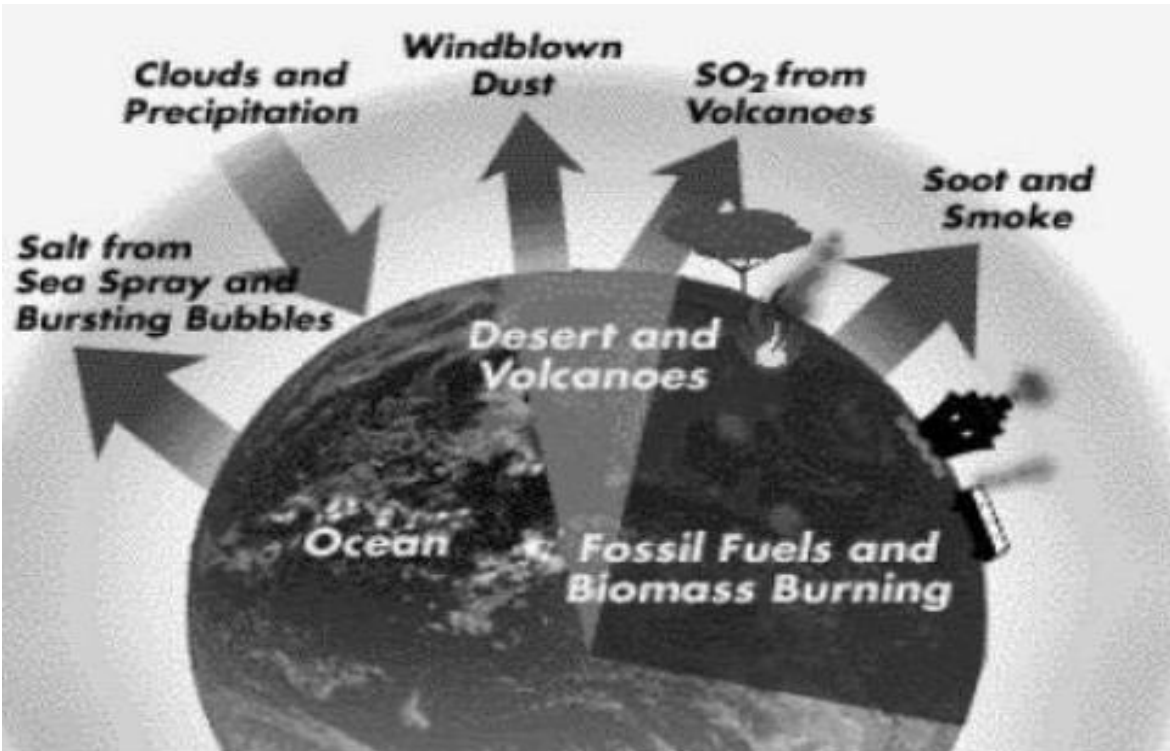


Figure 2: Showing the various tropospheric aerosols sources in the atmosphere (Source: SASAS Conference, 2013).

2.2.1 Natural aerosols

Natural aerosols originate from natural occurrences such as dust storms, sea spray, volcanoes, and forest and grassland fires.

1. Marine aerosols

These are either formed mechanically by the sea waves or by gas-to-particle conversion process of precursor gases over the marine atmosphere. These oceanic origin aerosols are estimated to form 30% of total aerosol loading. Those that are formed by mechanical process are termed sea-salt aerosols while those by gas-to-particle are non-sea salt aerosols e.g dimethyl sulphide (Charlson *et al.*, 1987; Hoppel, 1979).

2. Mineral dust aerosols

These are very common in desert areas where there exists either a low or sparse vegetative cover. Surface winds over these areas often inject the dry soils into the atmosphere (Tegen & Fung, 1994) and at other times they can result from human activities such as construction, agriculture,

transportation and deforestation. Their lifetime is affected by their size. In dealing with these types of aerosols; their radiative effect can only be quantified when their microphysical properties are known.

3. Volcanic aerosols

During a volcanic eruption dust and gaseous sulphur are emitted. The sulphur thus produces more efficient in producing sulphate aerosols (about 4.5 times) than those of anthropogenic origin because they have lower deposition rate (Benkovitz et al., 1994; Graf et al., 1997).

2.2.2 Anthropogenic aerosols

Anthropogenic aerosols come from man-made activities such as industrial emissions, vehicular emissions and burnings from biomass and fossil fuels.

1. Sulphates

Sulphates are produced from activities such as oil refining and smelting, coal and oil combustion and though they are mainly submicron particles, they are capable of being conveyed from their sources to long distances. SO_2 can be quantified as 72% from fossil fuel burning, about 2% from biomass burning, about 19% from dimethyl sulphide emission by phytoplankton and about 7% from volcanoes (Haywood & Boucher, 2000). They can indirectly influence the optical properties of clouds by forming cloud condensation nuclei because they are hydrophilic (Takemura *et al.*, 2000).

2. Nitrates

They are formed by the oxides of Nitrogen like NO_2 , N_2O , N_2O_4 and volatile acids of nitrogen which originates from biomass burning, fertilizers, bacterial actions on soil and vehicular exhaust (Hidy, 1984). The most predominant type is the ammonium nitrate (Pruppacher & Klett, 1978).

3. Carbonaceous Aerosols (soot)

This is a formation arising from a complex mixture of organic carbon (OC) and elemental carbon (EC). Organic carbon (OC) and black carbon (BC) comes from incomplete combustion of carbonaceous materials (Gundel *et al.*, 1989; Reddy & Venkataraman, 1999). They are most significant for their absorption properties and their inhibition of cloud formation (Ackerman *et al.*, 2000; Kaufman & Nakajima, 1993).

2.3 Direct and Indirect effect of Aerosols on climate

The presence of suspended particles in the atmosphere provides a variety of natural phenomena that are of interest and represent an important part of aerosol science. Besides its optical effects (such as scattering and absorption), it also affects the cloud microphysics and thus has an effect on precipitation. Moreover, divided particulate matter is a contributor to respiratory disease. Toxic chemicals and carcinogens, which originate from organic and inorganic compounds, pose a hazard to the well being of the modern world. Aerosols can have significant influence on Earth's climate, although making up only one part in a billion of the mass of the atmosphere. The direct effect of aerosols on climate is caused by scattering and absorption of solar radiation (cooling effect), and absorption of long wave radiation emitted by the Earth (warming effect). Aerosols also indirectly affect by changing the microphysical properties of clouds and strong correlation between cloud condensation nuclei concentrations and aerosol optical depth has been observed. Increasing the aerosol concentration in a cloud can lead to increased numbers of cloud condensation nuclei competing for water vapour which, in a cloud of constant liquid water content, in turn leads to a greater number of smaller droplets (Hansen *et al.*, 1997; Lohmann and Feichter, 2001; Ramanathan *et al.*, 2001).

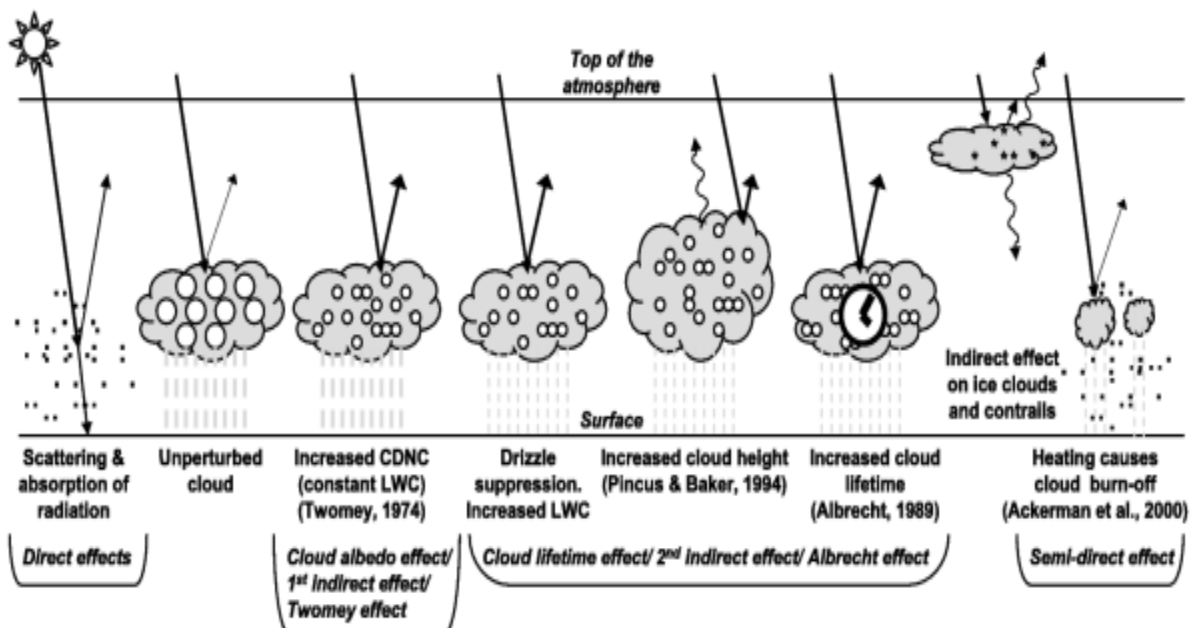


Figure 3: Schematic diagram showing the various radiative mechanisms associated with cloud effects that have been identified in relation to aerosols.

The small black dots represent aerosol particles; the larger open circles cloud droplets. Straight lines represent the incident and reflected solar radiation, and wavy lines represent terrestrial radiation. The filled white circles indicate cloud droplet number concentration. The unperturbed cloud contains larger cloud drops as only natural aerosols are available as cloud condensation nuclei, while the perturbed cloud contains a greater number of smaller cloud drops as both natural and anthropogenic aerosols are available as cloud condensation nuclei. The vertical grey dashes represent rainfall, and LWC refers to liquid water content (Forster *et al.*, 2007).

2.4 Effect of Aerosols on Cloud parameters

The global mean cloud cover is close to 60%; the global average volume fraction of clouds in the troposphere is 7-8%. Since most clouds occur in the lower atmosphere, which involves most of its mass, about 10% of the total mass of the troposphere is contained in cloud systems; the cloud volume fraction in the lower troposphere is about 15%. On the average, only one-tenth of these clouds are in precipitating state. Moreover, the global average precipitation efficiency is about 50%, which means that half of the amount of water entering a precipitating system reaches the Earth's surface (Cotton and Anthes, 1989). Water vapour condenses on aerosol particle that act as CCN. The mean CCN lifetime in the atmosphere is about one week. The life cycle of a cloud- its formation, development (both microphysical and chemical), and dissipation- is linked in part to the nature of the aerosol on which the cloud forms. This property of the aerosols to act as CCN is dependent on their chemical composition and size (Penner *et al.*, 2001). The effects of aerosols on clouds are commonly investigated by analyzing the induced changes in cloud microphysical properties (droplet number concentration and size distributions) (Radke *et al.*, 1989 and Ferek *et al.*, 1998). Cloud parameters such as cloud fraction, cloud top pressure, cloud top temperature and water vapor.

2.4.1 Cloud fraction

Cloud fraction increases with increases in aerosol concentrations and found that cloud properties change as a result of variations in large scale atmospheric circulation and also affect aerosol concentrations. For example, regions of low atmospheric pressure are convergence zones that tend to accumulate aerosols and water vapor, thus generating conditions favorable for cloud formation (Kaufman *et al.*, 2005). Aerosol causes evaporation of existing clouds and blocking of surface heating. This is very strong impact on radiative balance (Johnson *et al.*, 2004; Penner *et*

al., 2003). Studies on ice clouds show that the number of ice nuclei is potentially influenced by anthropogenic aerosols (Lohmann and Feichter, 2005).

2.4.2 Cloud top pressure

Cloud microphysical processes that determine cloud effective radius (CER) inside a cloud, are influenced by the microphysics. Besides, this microphysical process is initiated at the cloud base, and its influence proceeds throughout the cloud as air parcels rise upward, which in turn changes the phase from liquid to ice. Cloud top pressure decreases with AOD, because the cloud effective radius increases with a decreasing cloud top pressure of convective clouds. This is supported by the cloud fraction increase with AOD and cloud top pressure decrease with cloud fraction (Massie et al., 2007).

2.4.3 Cloud top temperature

The cloud top temperature was found to be insensitive to the change in the aerosol number, although there was a distinct negative correlation between the aerosol number and cloud temperature at which the cloud particle grows to a radius of 14 nm. This particular dependency of the cloud temperature suggests that aerosols act on clouds so as to change cloud particle size near the cloud top, optical thickness, and fraction but to keep their cloud-top temperature without causing a significant long wave radiative forcing (Sekiguchi et al., 2009).

2.4.4 Water vapor

The changes in column water vapor in relation to aerosols are examined and this investigation gives an insight to understand the aerosol impact and the speed of the hydrological cycle. The hygroscopic nature of aerosols therefore depends upon the particular mixing of different types of particles as well as on meteorological parameters such as humidity, wind speed, wind direction, and temperature (Myhre et al., 2007). The effect of moisture on the scattering behavior of aerosols. Cloud formation also depends on the amount of water vapor available for condensation onto hydrophilic aerosols. Changes in aerosol water uptake behavior can therefore, at least potentially, lead to changes in both direct and indirect radiative forcing on climate (IPCC, 2001).

CHAPTER THREE

3. DATA AND METHODOLOGY

3.1 MODIS satellite observation system

The Moderate Resolution Imaging Spectroradiometer (MODIS) is an instrument designed by NASA (The National Aeronautics and Space Administration) to provide improved monitoring for land, ocean, and atmosphere research (NASA, 2016). MODIS instrument was designed to remote sense the properties of aerosols and clouds (King et al., 1992). From polar orbit approximately 700 km above the surface. MODIS views the Earth with a swath of about 2330 km, by observing the entire globe on a daily basis and repeating orbits every 16 days. MODIS measures radiance in 36 wavelength bands, ranging from 0.41 to 14.2 μm with nadir on ground spatial resolutions between 250m and 1km. MODIS is a cross-track scanning radiometer constructed to obtain information about many biological and physical processes within the Earth/atmosphere system through visible and infrared measurements. The MODIS measurements are more wide-ranging and multipurpose. The MODIS data will be used to obtain information on atmospheric temperatures and humidities, cloud coverage, cloud properties, aerosol properties, land and sea surface temperatures, ocean color, ocean sediments, chlorophyll fluorescence, vegetation indices and land cover change, natural and human caused fires, continental snow distribution and depth, and sea ice distribution and surface temperature. MODIS sensor is on board two NASA satellites, Terra and Aqua (Salomonson et al., 1989).

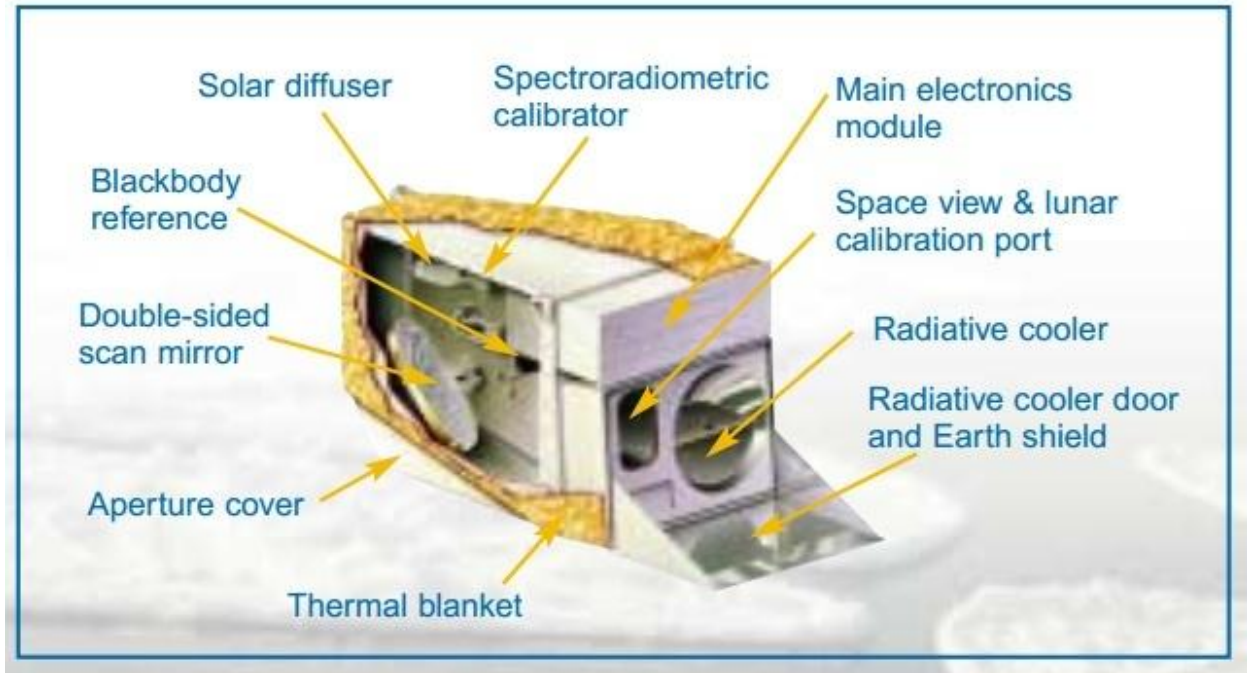


Figure 4: Labeled schematic of the MODIS instrument (Schematic courtesy of Raytheon).

3.1.2 The TERRA and AQUA satellites

Two of the most commonly used satellites in environmental applications are the NASA's TERRA and AQUA satellites. These are part of the NASA-centered international Earth Observing System (EOS). TERRA satellite was launched on December 18, 1999 while AQUA satellite was launched on May 4, 2002.

Terra is the first MODIS that collects data about the Earth's bio-geochemical and energy systems using five sensors that observe the atmosphere, land surface, oceans, snow and ice, and energy budget. Terra satellite orbit around the earth is adjusted that it passes from north to south across the equator in the morning time. Each sensor has unique features that enable scientists to meet a wide range of science objectives.

The five sensors onboard **Terra** (NASA, 2016) are:

- **ASTER**, or Advanced Space borne Thermal Emission and Reflection Radiometer
- **CERES**, or Clouds and Earth's Radiant Energy System
- **MISR**, or Multi-angle Imaging Spectro Radiometer
- **MODIS**, or Moderate-resolution Imaging Spectroradiometer
- **MOPITT**, or Measurements of Pollution in the Troposphere

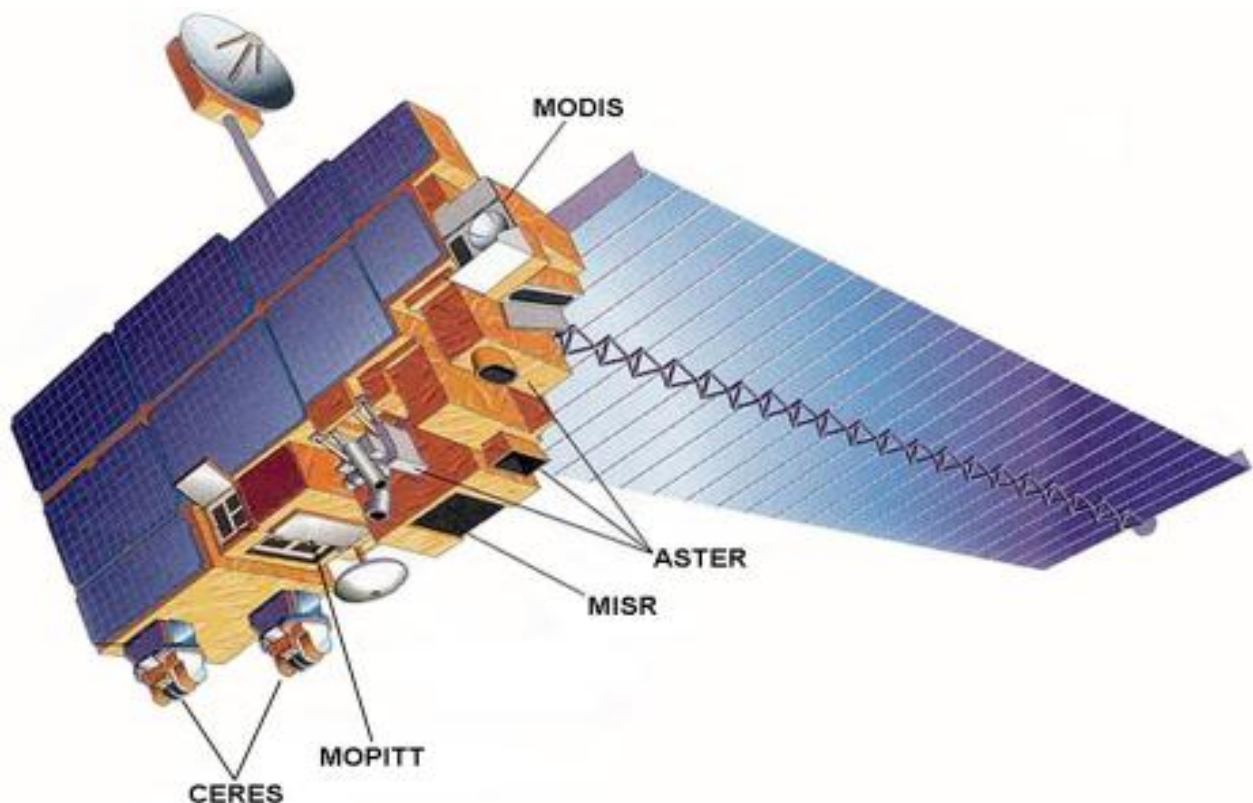


Figure 5: Instruments on board TERRA satellite (Source: NASA, 2016).

The AQUA is the second MODIS satellites that focus on precipitation, evaporation and cycling of water. “Aqua” being Latin for “water”, the Aqua mission is named for the large amount of information it will collect about the Earth’s water cycle and the satellite orbit around the earth is adjusted that it passes from south to north across the equator in the afternoon time. **Aqua** carries six instruments (NASA, 2016), which are:

- **AMSRE**, or Advanced Microwave Scanning Radiometer-EOS
- **MODIS**, or Moderate Resolution Imaging Spectroradiometer

- **AMSU-A**, or Advanced Microwave Sounding Unit
- **AIRS**, or Atmospheric Infrared Sounder
- **HSB**, or Humidity Sounder for Brazil
- **CERES**, or Clouds and the Earth's Radiant Energy System

The parameters measured by the above instruments are: cloud and atmospheric aerosol properties, radiative energy flux, land and sea temperature, and atmospheric temperature and humidity. All sensors share a common platform; they collect complementary observations of Earth's surface and atmosphere. These varying perspectives of the same event can yield unique insights into the processes that connect Earth's systems.

3.2 Data Source

In the present study, used as MODIS satellite data for optical measurement of aerosol (Aerosol optical depth) and cloud parameters namely, cloud fraction (CF), cloud top pressure (CTP), cloud top temperature (CTT) and water vapor (WV) datasets for the 16 year period from January 2003 to December 2018 over Ethiopia the latitude and longitude of the state is a 2–16°N & 32–48°E respectively. The characteristics of data and its sources are discussed below.

3.2.1 MODIS data

MODIS is an extensive program using sensors on two satellites that each provides complete daily coverage of the earth. The data have a variety of resolutions; spectral, spatial and temporal. MODIS products are available at different processing levels. They are categorized as level 1, 2, 3. Level 1 is geolocated and calibrated brightness temperatures and radiances, level 2 is derived geophysical data products, and the level 3 is gridded time average products.

Many aerosol and cloud properties are retrieved using satellite radiometer data. Some of the commonly retrieved properties which are of particular interest when investigating aerosol–cloud interactions are as follows:

Aerosol Optical Depth (AOD) is an integral measurement of light extinction (absorption and scattering) caused by aerosols in a vertical column of air and is central to remote sensing of aerosols. AOD can be defined as:

$$AOD = \int_0^{\infty} \delta \exp(z) dz \quad (1)$$

Where $\delta \exp(z)$ is the aerosol extinction coefficient at elevation z above the ground and dz is the vertical optical path (Schäfer et al. 2008). It makes possible continuous monitoring of the environment by measuring atmospheric trace of gases and aerosol optical properties, and mapping the surface of the land and sea. The seven of which (660, 865, 470, 555, 1240, 1640, 2130 μ m) are used for aerosol characterization. The daily Level-2 aerosol product (MOD08_L2 collection 5.2) is available at 10km² that generated from 20X20 pixels box for 500m spatial resolution Terra-MODIS (collection 5.1) level-2 atmosphere daily global 1⁰×1⁰ grid resolution at AOD at 550 nm data sets can be download from website (<http://modis.atmos.gsfc.nasa.gov/>).

Cloud fraction (CF) gives the total fractional cover of all clouds (liquid and ice) in a given region. It is defined as the fractional area which is covered by the cloud as seen by the satellite from above. It is calculated by dividing the number of cloud pixels by total number of pixels. The plots for cloud fraction have been included for day and night only. MODIS level-3 atmosphere daily global 1⁰×1⁰ CF data has been used along with other cloud parameters. The MODIS Cloud Product (MOD08) combines infrared and visible techniques to determine both physical and radiative cloud properties. The cloud fraction product provides a ratio of cloud contamination for each pixel in the scene, ranging from 0 (no cloud) to 1 (cloud obscured) pixels.

The plots for **cloud top pressure (CTP)** have been studied for day and night only. MODIS level-3 atmosphere daily global 1⁰×1⁰ CTP has been used. Accurate information on CTP and height are needed in order to retrieve properly many atmospheric and surface properties. It also plays an important role in the net earth radiation budget studies.

The plot for **cloud top temperature (CTT)** has been generated for day and night only. The MODIS Cloud Product (MOD08) combines infrared and visible techniques to determine both physical and radiative cloud properties. The cloud top pressure product provides temperature at the cloud-tops. The unit is in degree Kelvin degrees K (Brennguier et al., 2000).

Water vapor (WV) product (MOD08) is an estimate of the total tropospheric column water vapor made from integrated MODIS infrared retrievals of atmospheric moisture profiles. The unit is in centimeter (cm).

The atmospheric parameters being examined in the comparative analysis are the products of MODIS (Moderate - resolution Imaging Spectroradiometer) onboard Terra and Aqua satellites. The Level-3 MODIS Atmosphere Daily Global Product has been derived from 80 scientific parameters from four Level-2 MODIS atmospheric products - Aerosol, Water Vapor, Cloud and Atmosphere Profile. The two MODIS Daily global data product files are one which collected from Terra platform and another collected from Aqua platform. A range of statistical parameters are computed and sorted into $1^\circ \times 1^\circ$ equal angle grid cells that span a 24-hour (00 – 24 GMT) interval (Hubanks *et al.* 2008).

The MODIS data has been analyzed through **Giovanni** (Geospatial Interactive Online Visualization **and** aNalysis Infrastructure). Interactive Visualization and Analysis tool developed by NASA's Goddard Earth Sciences Data and Information Services Center (GES DISC). Through this portal, the atmospheric daily global version 5.1 data has been used for the study. The MODIS datasets used in this study were downloaded from NASA GIOVANNI website (<http://disc.sci.gsfc.nasa.gov/giovanni>) of Level-3 Collection 5.1 for the 16 year period from January 2003 to December 2018 corresponds to Ethiopia location ($2-16^\circ\text{N}$ and $32-48^\circ\text{E}$). Level-3 MODIS data were quality checked and globally gridded over $1^\circ \times 1^\circ$ grid spatial resolution. The obtained atmosphere monthly products of aerosol and cloud parameters data from MODIS Terra and Aqua sensor were averaged into the seasonal and annual values.

3.3 Study area

Ethiopia is located between $2 - 16^\circ\text{N}$ latitudes and $32 - 48^\circ\text{E}$ longitudes which cover the area of Ethiopia as a whole and some part of Kenya, Somalia, Djibouti as a whole, Eritrea and Sudan about 1.11 million square kilometers at the Horn of Africa. It is the most populous landlocked country in the world and the second-most populous country in Africa with a population of around 84 million. Agriculture play a dominant role on the economy of the country; which accounts for about 45% of the Gross Domestic Product (GDP), ~85% of exports and more than 84% of the population earning a living directly or indirectly from agricultural activities (RRC1985;<http://en.wikipedia.org/wiki/Ethiopia>;CIA, 2009). The agriculture sector is very dependent on rainfall, with only 2 percent of the total land being irrigated (FAO/WFP, 2004). Ethiopia is the country, with its topography varying from about 4,500m above sea level in the north and central regions to about 100 m below sea level over the lowland in the north eastern

regions of the country. The main topographic feature of the country consists of a high plateau and mountain chains; which include the great East African Rift Valley that runs northeast to southwest across the country, the highlands to the west and east of the rift valley and the lowlands surrounding the high lands (Chisholm, 1911). The western highlands cover large part of the country and run south to north while the eastern highlands run southwest to east. Because of these complex topographical and geographical features, the climate of Ethiopia exhibits strong spatial variations and different rainfall regimes (National Meteorology Service Agency, 1996). The analysis using statistical tools are considered over Ethiopia (Fig 6).

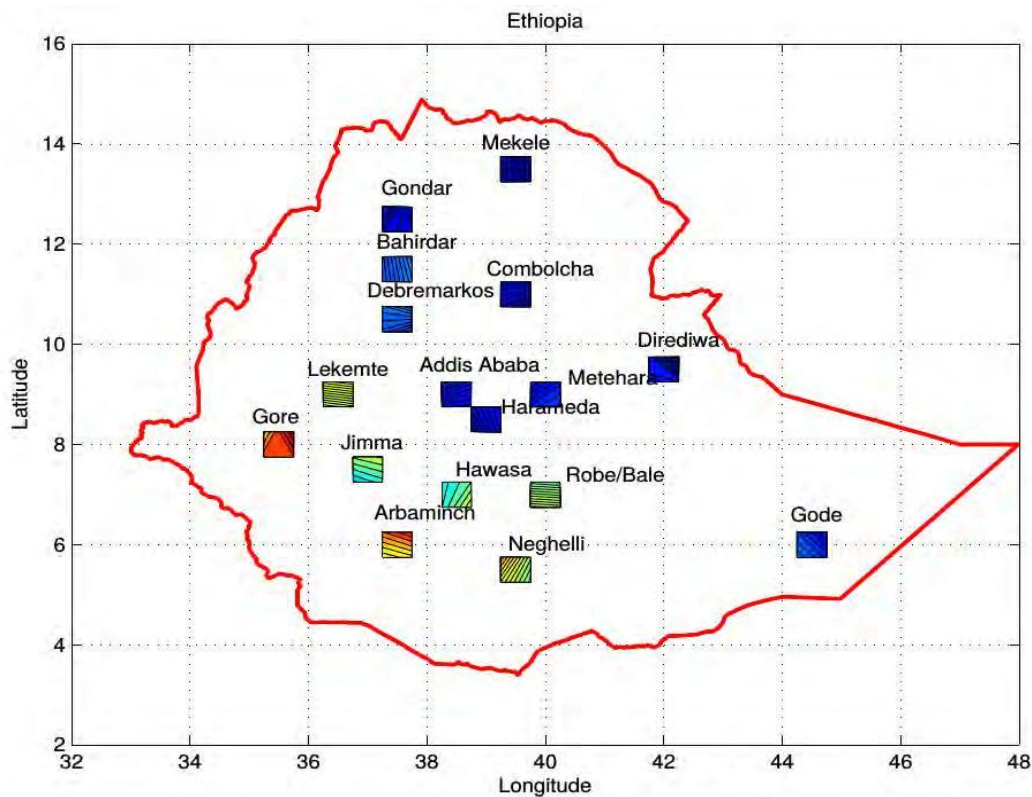


Figure 6: Study area Latitude vs. Longitude, for the domain.

3.4 Methods of Data analysis

3.4.1 Establishment of Correlation

In probability theory and statistics, correlation (often measured as a correlation coefficient) indicates the strength and direction of a linear relationship between two random variables. A number of different coefficients are used for different situations. The best known is the Pearson product-moment correlation coefficient (PPMCC) or bivariate correlation, which is obtained by dividing the covariance of the two variables by the product of their standard deviations. A correlation coefficient is a number that quantifies a type of correlation and dependence, Meaning statistical relationships between two or more values in fundamental statistics. The correlation coefficient is denoted as “ r ” and the coefficient ranges from -1 to $+1$. The “ r ” can be expressed mathematically as:

$$r = \frac{\sum_{i=1}^n (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^n (X_i - \bar{X})^2} \sqrt{\sum_{i=1}^n (Y_i - \bar{Y})^2}} \quad (2)$$

Where $X_1, X_2, \dots, X_n$ are cloud parameter data

$\bar{X}$ = is the average of all cloud parameter data

Where $Y_1, Y_2, \dots, Y_n$ are AOD at 550 nm data

$\bar{Y}$ = is the average of all AOD at 550 nm data

n = total number of data set. A value of 1 show that a linear equation describes the relationship perfectly and positively, with all data points lying on the same line and with Y increasing with X . A score of -1 show that all data points lay on a single line but that Y increases as X decreases. A Value of 0 is no linear correlation, that there is no linear relationship between the variables.

To find out the co-relation between AOD at 550 nm and other cloud parameters CF, CTP, CTT and WV at first the common location and the common period of data have been sorted out. The monthly average data for the 16 years period from January 2003 to December 2018 are considered to identify the relationship.

3.3.2 Linear regression

Linear regression is a statistical approach that attempts to model the relationship between two variables by fitting a linear equation to observed data. Here one variable is considered as a dependent variable and one or more explanatory variable are considered as the independent variable. The case of one explanatory variable is known as simple linear regression. After performing the analyses, the regression statistics can be used to predict the dependent variable based on the known independent variable. The regression equation is expressed as:

$$Y = a + bX \quad (3)$$

Where, X is the explanatory (independent) variable and Y is the dependent variable (response or outcome). The variable 'b' is the slope of the line has been obtained from the liner regression equation, which is the mean temporal and spatial Aerosol optical depth and cloud parameters over 16 years as a function of altitude and months of year and a is the intercept.

CHAPTER FOUR

4. Results and Discussion

This section contains the analyzed data and their interpretation as well as discussions in detail which are related to the studying of this work. The present study analyzes the effect of Aerosols on cloud parameters over Ethiopia with latitude 2-16°N and longitude 32-48°E using MODIS satellite datasets for the 16 year period from January 2003 to December 2018. The statistical analyses of Aerosol optical depth and cloud parameters have been studied. The AOD is calculated at 550 nm from Mie theory using the mass concentrations, extinction efficiency and particle mass density. AOD at 550 nm wavelength is used in this study.

4.1 Time series analysis

Long-term time series analysis one can extract trends i.e. monthly and yearly (seasonal) information. In this study, time series is a collection of observations taken at specified times but at equal intervals. Cyclical trend of the time series was used in studying the temporal variations of CF, CTP, CTT, WV and AOD at 550 nm over Ethiopia for 16 year period (January 2003–December 2018).

4.1.1 Annual and seasonal variations in AOD

The seasonal variations of monthly mean AOD values at a wavelength of 550 nm over Ethiopia have been plotted for the period of January 2003 to December 2018 (see Fig. 7). High mean AOD values (0.33) were observed during the summer season. Similar increase in AOD during the summer season has previously been reported by different authors (Balakrishnaiah *et al.*, 2012, Alam *et al.*, 2010). The winter season shows much low aerosol loading (0.13). Aerosol loading in entire Ethiopian region is low after the summer rainfall washes out most of the aerosol concentration. Generally in summer air temperature are high leads to hold abundant atmospheric water vapor facilitated the hygroscopic growth of aerosols (Masmoudi *et al.*, 2003). Similar results were also reported by several authors that increase in aerosol concentration which changes from season to season (Pan *et al.*, 2010). The rapidly increasing of AOD in the summer season may cause adverse effect to the agricultural crops and also to the human health. Increased aerosol loading may likely affect the rainfall also.

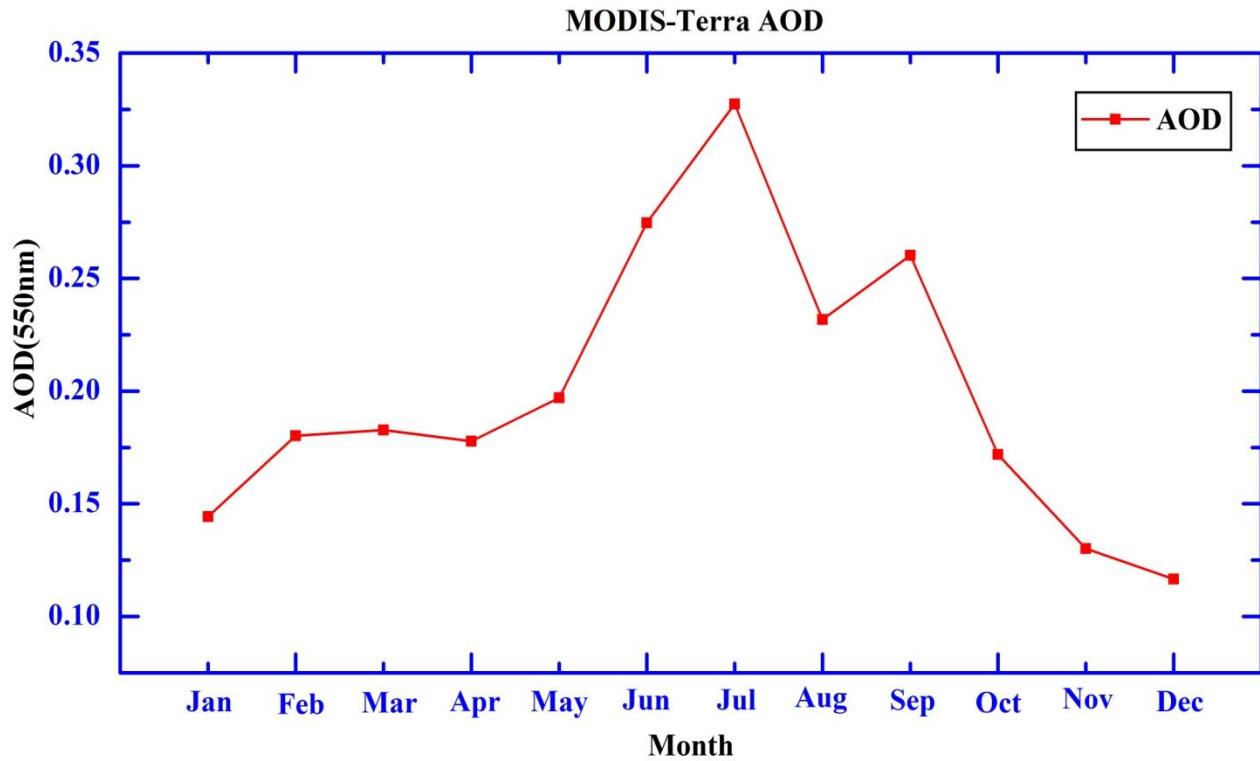


Figure 7: Annual variations in AOD for 16 year period (January 2003– December 2018) over Ethiopia.

4.1.2 Temporal Patterns of the Aerosol optical Depth (AOD)

Figure 8 shows that the AOD for the 16 years period from January 2003 to December 2018 over Ethiopia. Each peak analyzer indicates the values of AOD in the year. The maximum peak analyzer was observed around 2011 during the month of July (0.52) and minimum peak value observed around 2003 during the month of December (0.09) in Ethiopia region. The mean annual cycle of AOD is calculated to know its monthly change. The linear fit is applied on time series data (shown as a red line) has a positive slope indicating an increasing AOD trend during 2003–2018. The time series analysis shows an increase in the aerosols optical depth in the atmosphere. This implies that there has been an increase in the tendency of the atmosphere to absorb light. The regression equation $Y=1.67896X+0.18336$. It shows that from one year to the next year the aerosols have been loading to the atmosphere increasing by a factor of 1.67896. The AOD has the highest value in the summer (June, July, and August) and lowest value in the winter (December, January and February). Our results agrees with previous studies (Jinhuan & Liquan,

2000), high AOD in the summer was explained by the high humidity in the summer which could cause the growth of aerosol particles and by the stronger vertical convection in the summer.

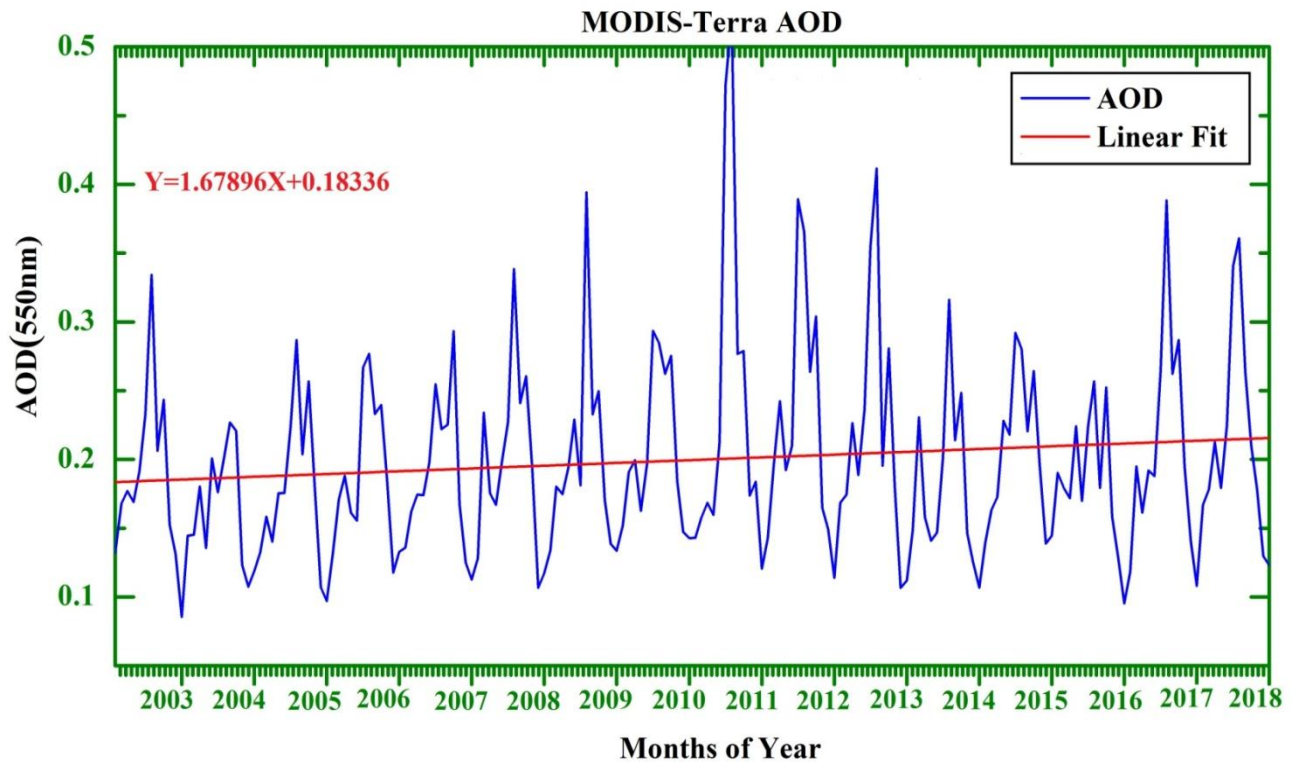


Figure 8: plot showing cyclical time series analysis of the Aerosol Optical Depth (AOD) at 550 nm for 16 year period (January 2003–December 2018) over Ethiopia.

4.1.3 Temporal patterns of the cloud Fraction (CF)

As indicated in Figure 9 increment trend of the cloud fraction for the 16 year period from January 2003 to December 2018 over Ethiopia. Each peak analyzer indicates the values of CF in the year. The maximum peak analyzer was observed around 2013 during the month of July (0.77) and minimum peak value observed around 2016 during the month of December (0.04) in the Ethiopia region. Clouds eventually affect the climate. The changes in the climate system in return affect the clouds. This relationship created a complicated system of the climate feedbacks. Clouds modulate the amount of solar radiation reaching the earth surface and the water balance. By reflecting away some of the amount of incoming radiation and absorbing some of the outgoing solar radiation reflected from the earth surface. The increment in the amount of cloud cover is related to the decrease in the amount of solar radiation. This is also contributed by the direct aerosols effect. An aerosol cools by reducing the amount of solar radiation reaching the

earth surface. This in turn reduces the amount of evaporation, which reduces the upward movement of moisture and hence reduced cloud cover. The red gradient line the trend shows an increase in the amount of cloud fraction in the atmosphere. The value of the gradient line was found to be $Y=6.78218X+0.39218$. It shows that from one year to the next the cloud fraction has been increasing by a factor 6.78218. A possible change in the amount of aerosols and cloud characteristics could have been responsible for this. The CF has the highest value in the summer (June, July, and August) and lowest value in the winter (December, January and February).

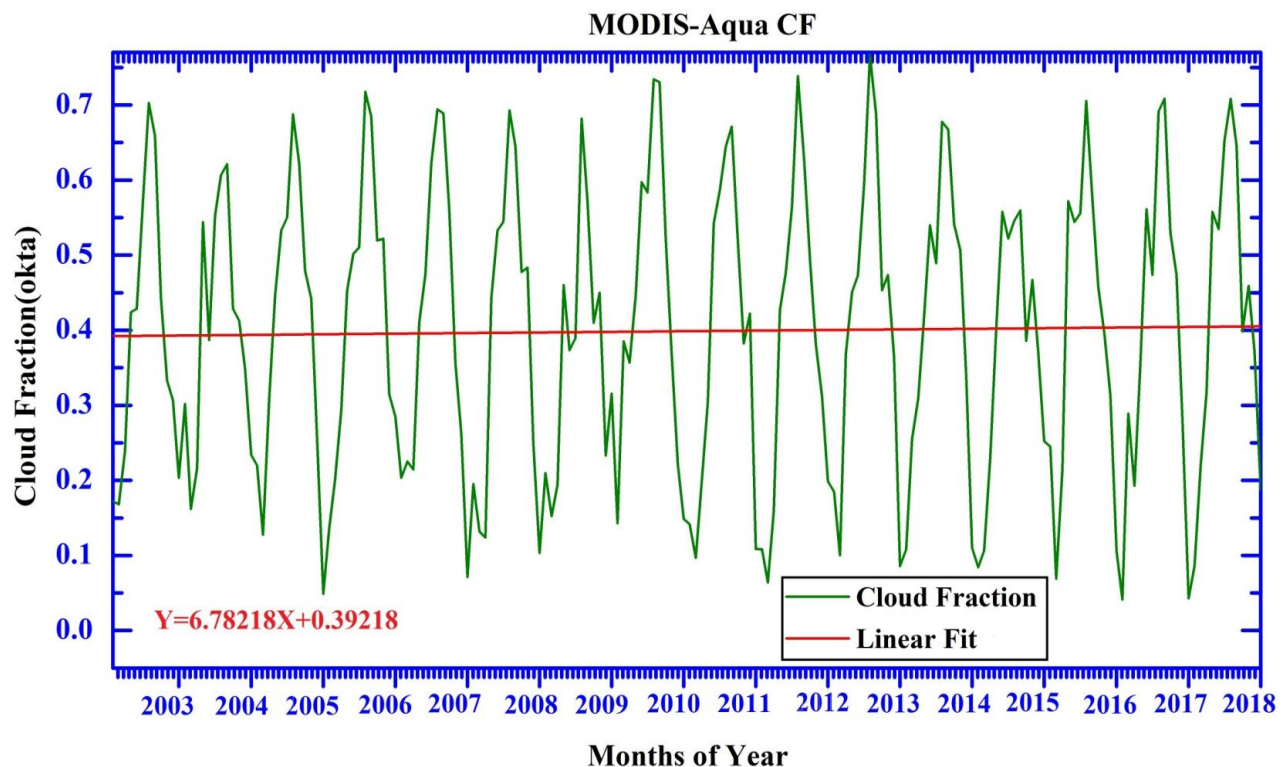


Figure 9: plot showing cyclical time series analysis of the cloud fraction (CF) for 16 year period (January 2003– December 2018) over Ethiopia.

4.1.4 Temporal patterns of the cloud Top Pressure (CTP)

Figure 10 shows that the cloud top pressure for the 16 year period from January 2003 to December 2018 over Ethiopia. Each peak analyzer indicates the values of CTP in the year. The maximum peak analyzer was observed around 2011 during the month of December (725.70) and minimum peak value observed around 2017 during the month of April (437.96) in the Ethiopia region. Red gradient equation of line being $Y=-0.03406X+590.68692$ shows that from one year to the next the average cloud top pressure have been decreasing by a factor 0.03406. The

amounts are slowly declining from that 590.68692 was there at the beginning of the data set. The CTP has the highest value in the winter (December, January and February) and lowest value in spring (March, April and May). The cloud top pressure determines the cloud top height from the mean sea level. As the atmospheric pressure decreases with increasing height, the low cloud top pressure indicates the huge vertical height of the cloud capable of producing heavy rainfall.

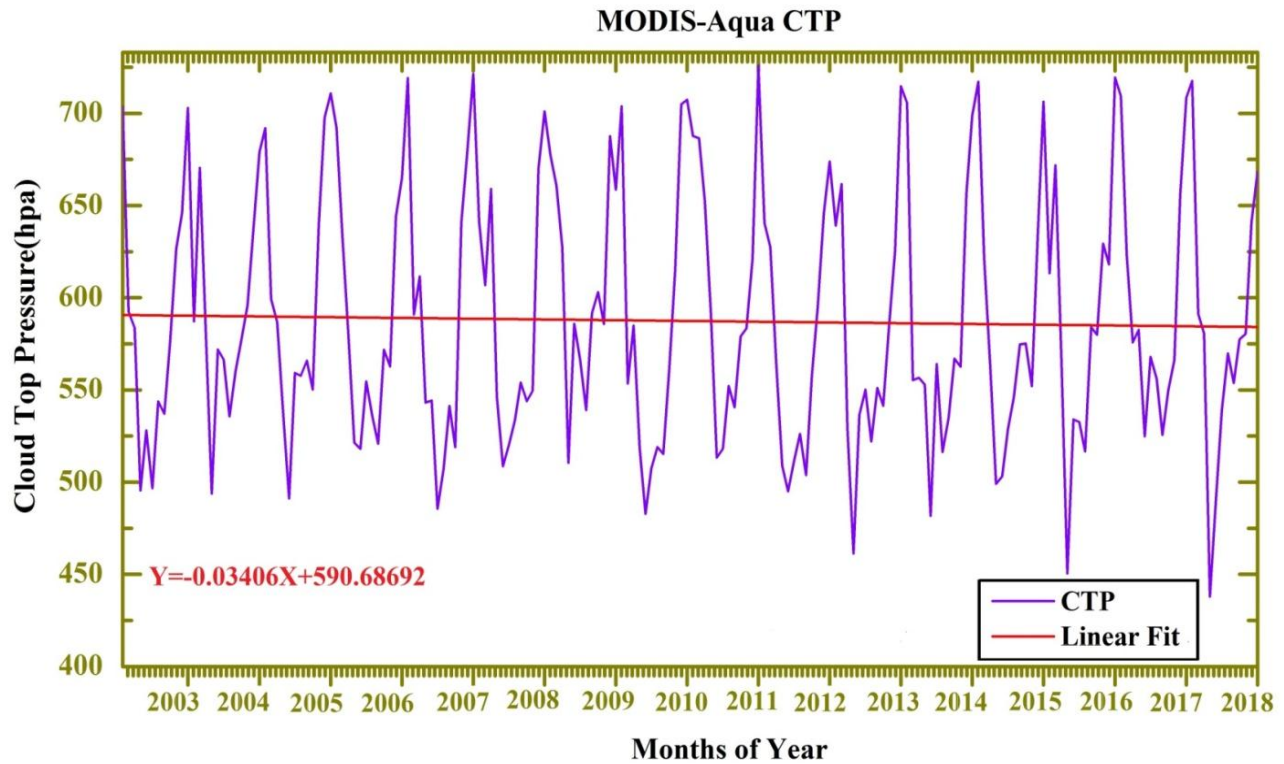


Figure 10: plot showing cyclical time series analysis of the cloud top pressure (CTP) for 16 year period (January 2003–December 2018) over Ethiopia.

4.1.5 Temporal patterns of the cloud Top Temperature (CTT)

As indicated in Figure 11 the cloud top temperature for the 16 year period from January 2003 to December 2018 over Ethiopia. Each peak analyzer indicates the values of CTT in the year. The maximum peak analyzer was observed around 2015 during the month of December (284.79) and minimum peak value observed around 2017 during the month of April (259.05) in the Ethiopia region. The analysis shows that the average cloud top temperature (CTT) has been reducing with a gradient value of $Y = -0.00101X + 273.02885$. There has been a reduction of this parameter by factor 0.00101. The CTT has the highest value in the winter (December, January and February) and lowest value in spring (March, April and May). It is the atmospheric temperature at the level

of the cloud top. Accurate information on cloud top temperature is needed in order to retrieve properly many atmospheric and surface properties. It also plays an important role in the net earth radiation budget studies. The changes in cloud top temperatures (CTTs) and variability could give further insight into aerosol indirect effects .The Brightness temperature is used as a representative of CTT.In general, colder CTT corresponds to higher rainfall rates for convective clouds. Low temperature indicates high cloud tops with greater thickness and larger probability of rain. CTT peaks for heavy rain along with -5° to 0°C (Barrett and Martin, 1981).

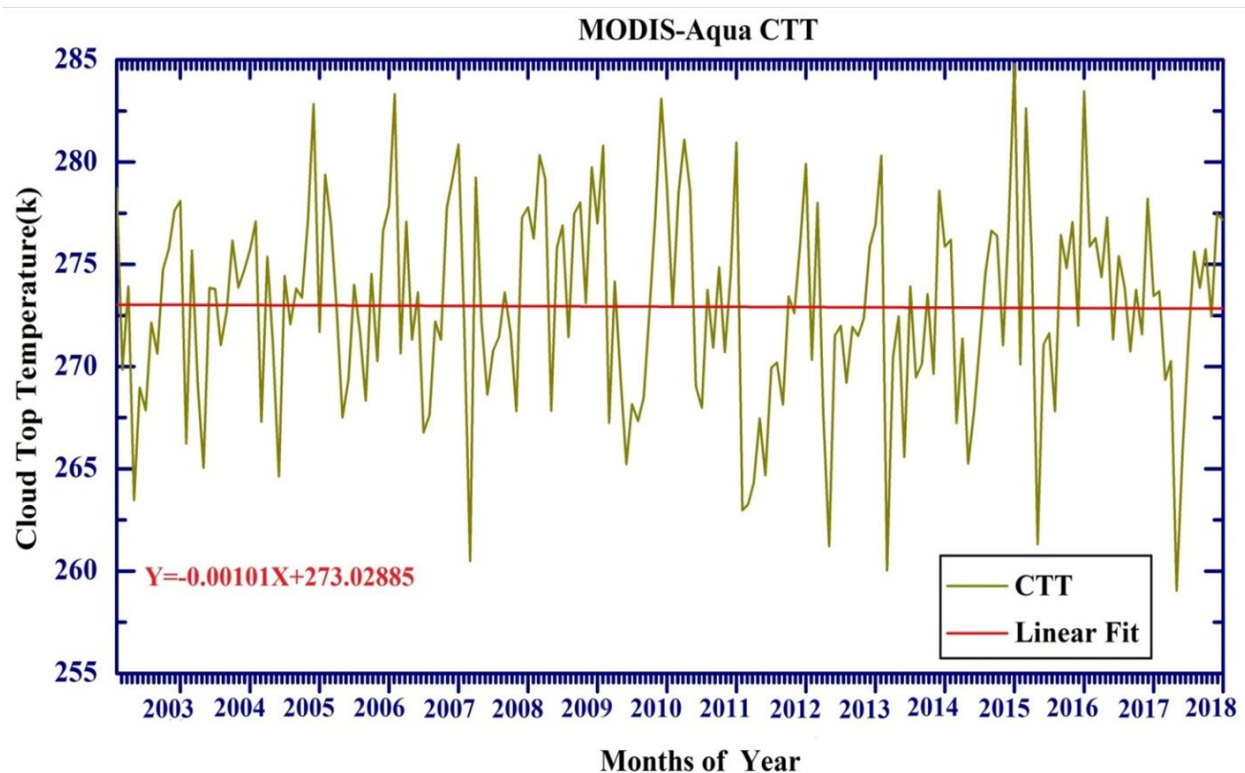


Figure 11: plot showing cyclical time series analysis of the cloud top temperature (CTT) for 16 year period (January 2003–December 2018) over Ethiopia.

4.1.6 Temporal patterns of the water vapor (WV)

As indicated in Figure 12 the water vapors for the 16 year period from January 2003 to December 2018 over Ethiopia. Each peak analyzer indicates the values of WV in the year. The maximum peak analyzer was observed around 2017 during the month of September (2.15) and minimum peak value observed around 2008 during the month of February (1.19) in the Ethiopia region. WV has been increasing. The equation of the gradient line was $Y=5.4683X+ 1.68834$ generally the water vapor has been increasing by about 5.4683. The water vapour content of atmosphere is highly variable both in space and in time due to temperature changes, atmospheric circulation and other micro-physical processes. The atmospheric Holding capacity for water vapour doubles for every 10^0 C rise in temperature (Kaufman *et al.*, 2005).

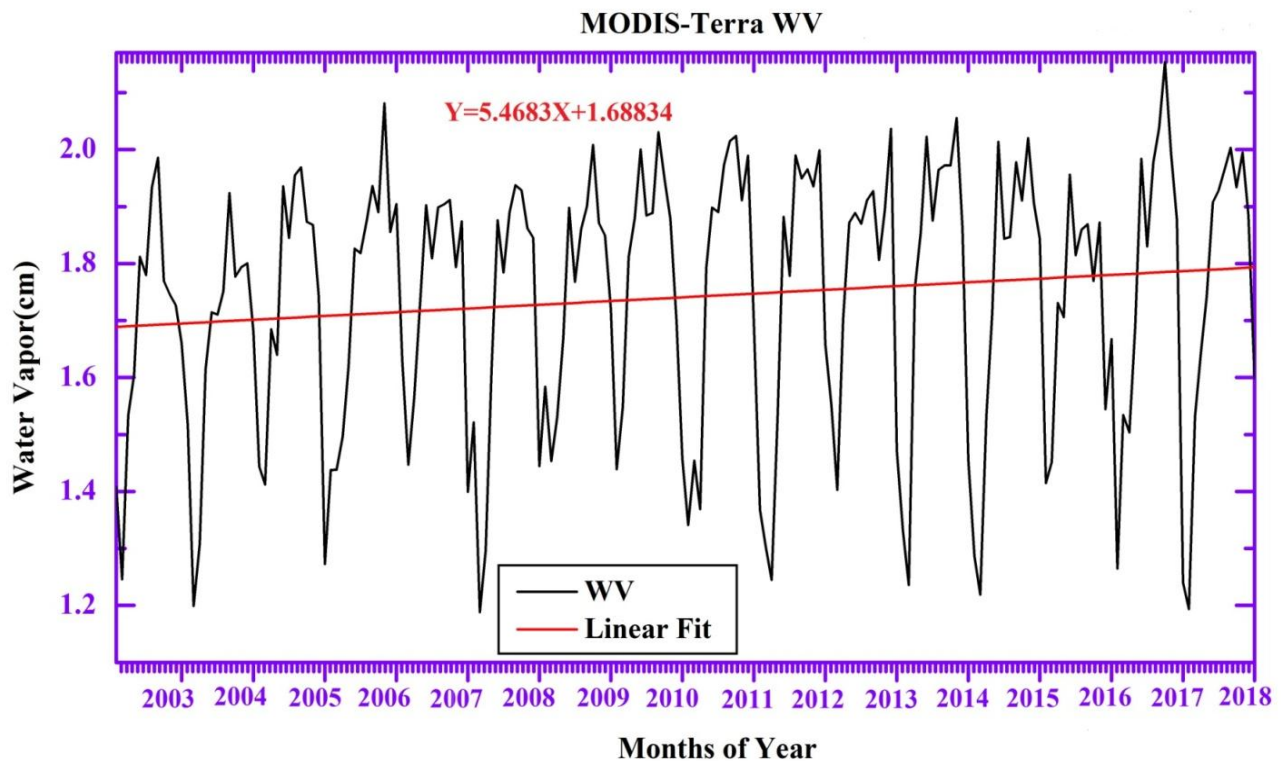


Figure 12: plot showing cyclical time series analysis of the over Water Vapor (WV) for 16 year period (January 2003–December 2018) over Ethiopia.

4.2. Correlation between AOD and Cloud Parameters

Aerosols introduce a complicating factor due to their hygroscopic nature. Therefore, the aerosol-cloud interaction needs to be made by combining several methods (Alam et al., 2014; Kumar, 2014). Here we used AOD as a substitute for aerosol concentration and studied the relationships in detail with the help of correlation studies for each set of parameters on monthly basis for different years throughout the study period (January 2003–December 2018). In this section, the relationship between MODIS derived AOD and cloud parameters such as WV, CF, CTP and CTT for Ethiopian region has been discussed and presented individually through statistical correlation analysis. The results with more details concerned to the relationship between AOD and various cloud properties are discussed in the following sections.

4.2.1. Correlation between (AOD) and cloud fraction (CF)

Fig. 13 shows the temporal correlation between AOD and cloud fraction for Ethiopia. The left hand side of Y –axis is displayed AOD values and the right hand side is CF values. Further it shows an increase in the Cloud Fraction (CF) or cloud cover with increasing AOD. AOD and CF increasing and decreasing simultaneously. CF increased with AOD from May to June and then decreases to lowest value in December at the entire study period. MODIS satellite provides CF data for daytime and night time; we used the combined data in the present study. Correlation coefficients for AOD and CF were 0.678. (Myhre *et al.*, 2007) found that an increase in relative humidity (RH) increases the AOD due to greater water uptake by the particles. Since RH is usually higher close to clouds than in areas of clear sky, an increase in CF with AOD may be a reflection of this effect. Kaufman *et al.* (2005) investigated cloud cover increases in association with increases in aerosol concentrations and found that cloud properties change as a result of variations in large-scale atmospheric circulation that may also affect aerosol concentrations. For example, regions of low atmospheric pressure are convergence zones that tend to accumulate aerosols and water vapour, thus generating conditions favorable for cloud formation (Kaufman *et al.*, 2005; Chou *et al.*, 2002). We know that Ethiopian continent has been passes through ITCZ convergence zone.

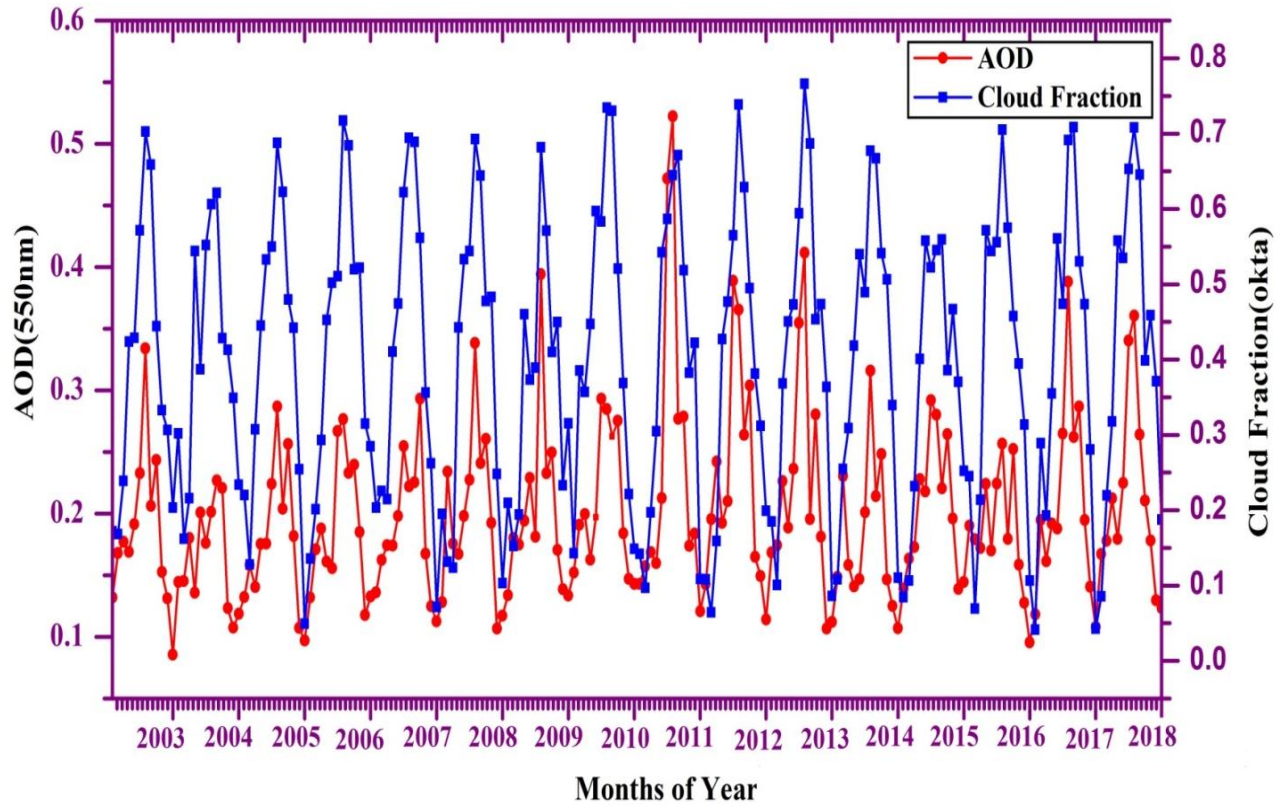


Figure 13: Time series of area averaged of AOD and Cloud fraction for 16 year period (January 2003– December 2018) over Ethiopia.

4.2.2 Correlation between AOD and cloud top pressure (CTP)

The correlation between AOD and cloud top pressure (CTP) for Ethiopian region over the period 2003 to 2018 is shown in Fig. 14. A negative correlation between CTP and AOD has been noticed over entire period. Correlation coefficients for AOD and CTP were -0.582 . Several studies (Myhre *et al.*, 2007; Kaufman *et al.*, 2005) have reported that, CTP decreased as AOD increased. This is due to the suppression of the precipitation by increasing cloud lifetime and thus affecting the cloud albedo and changing the cloud top pressure (Myhre *et al.*, 2007. Rosenfeld and Lensky, 1998) reported that the cloud top pressure decreases there too with AOD, because the cloud effective radius increases with a decreasing cloud top pressure of convective clouds. This is supported by the cloud fraction increase with AOD and cloud top pressure decrease with cloud fraction (Balakrishnaiah *et al.* 2012).

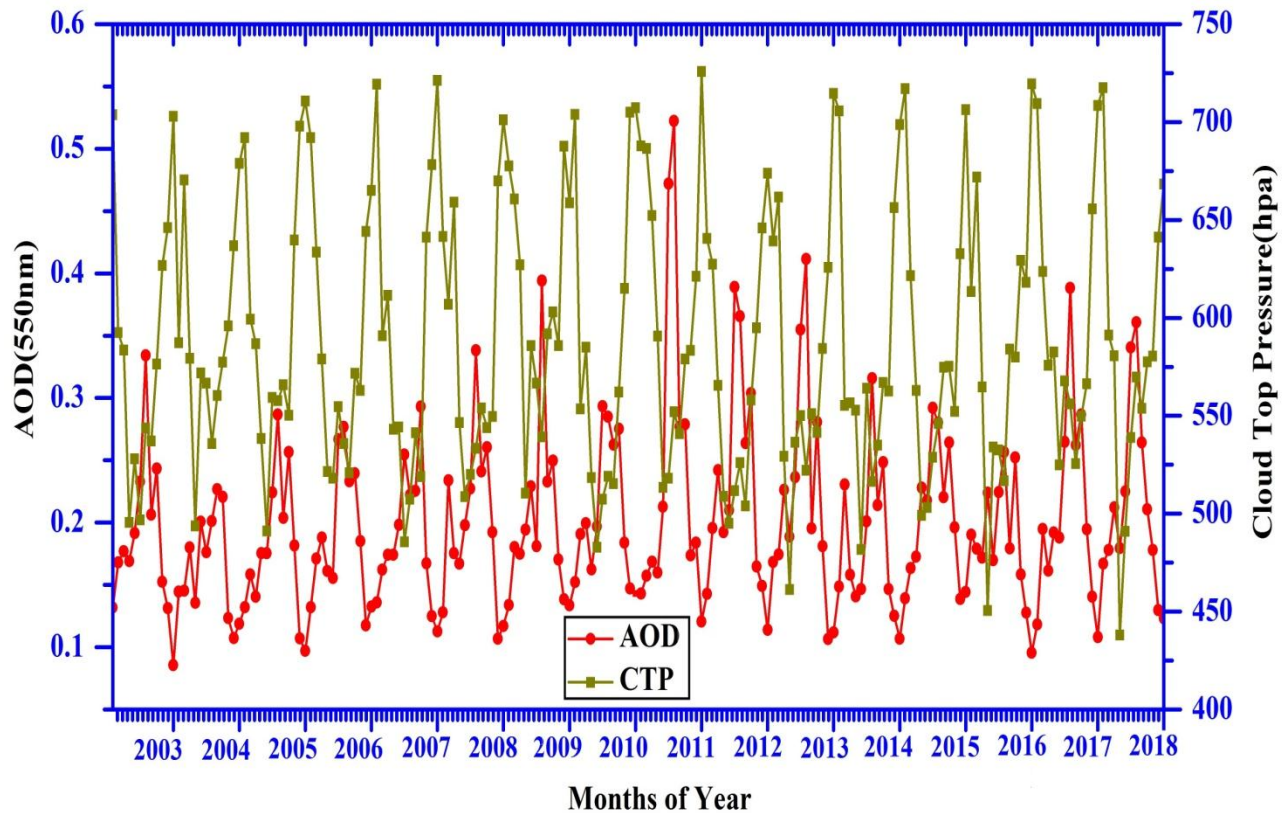


Figure 14: Time series of area averaged of AOD and cloud top pressure for 16 year period (January 2003– December 2018) over Ethiopia.

4.2.3 Correlation between AOD and cloud top temperature (CTT)

In order to correlate atmospheric and surface properties, CTT is needed. It also plays an important role in the earth radiation budget studies. The temporal correlation between AOD and cloud top temperature (CTT) for Ethiopian region over the period 2003 to 2018 indicates that CTT increased as AOD decreased in throughout the period of study (Fig. 15). The correlation between AOD and CTT is negative (correlation coefficient= -0.314). The cloud-top temperature was found to be insensitive to the change in the aerosol number, although there was a distinct negative correlation between the aerosol number and cloud temperature, suggests that aerosols acts on clouds so as to change cloud particle size near the cloud top, optical thickness, and fraction but to keep their cloud-top temperature without causing a significant long wave radiative forcing. Furthermore, increasing anthropogenic aerosol loading change the cloud-top temperature and humidity profiles by the induced secondary circulation, and thus change the cloud top temperature (Sekiguchi *et al.*, 2009).

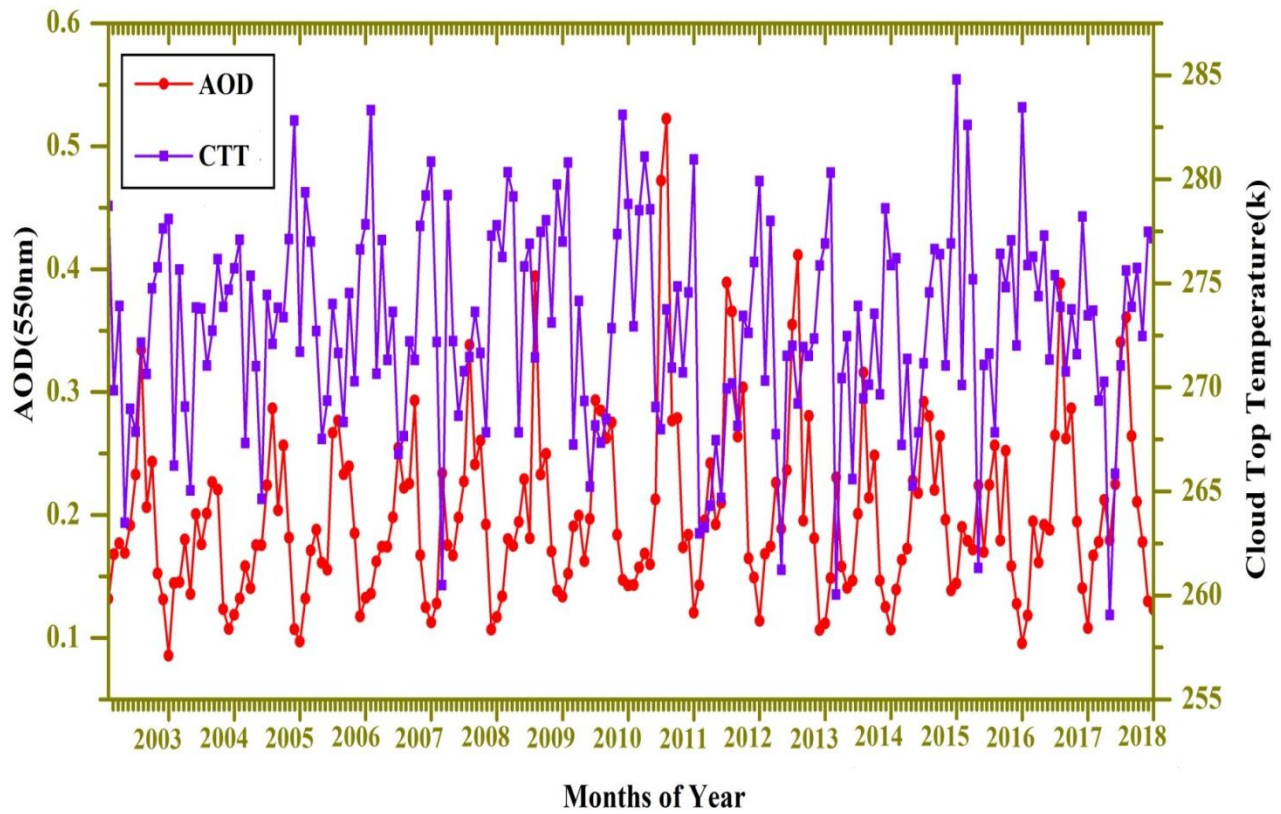


Figure 15: Time series of area averaged of AOD and cloud top temperature for 16 year period (January 2003– December 2018) over Ethiopia.

4.2.4 Correlation between AOD and water vapor (WV)

The aerosols behaviors in response to changes in WV can impacts on Earth's atmosphere (Myhre *et al.*, 2007). The time series plot for AOD and WV is shown in Fig. 16 for Ethiopian region during the period 2003–2018 represents increasing and decreasing pattern simultaneously. The correlation between AOD and WV is positive (correlation coefficient=0.427). The same results are reported by different authors over different countries (Ranjan *et al.*, 2007) and (Alam *et al.*, 2010, 2014). Changes in water uptake of aerosols leads to changes in both direct and indirect radiative forcing on climate (IPCC, 2001) have found that aerosols cause a reduction in cloud droplet size and hence lead to suppression in precipitation. We observed that WV is also higher during the summer, matching the increase in AOD and indicating the possibility of hygroscopic growth of aerosols. This is consistent with results obtained by Ranjan *et al.* (2007). On the other hand, aerosols are less common or even absent in the atmosphere during the winter and, as a result, we also see less WV. It has been observed that the water absorbing ability of aerosols

varies for different types of aerosol found that dust particles, which are dominant in the coarse fractions of aerosols, are mostly insoluble but can be hygroscopic if they become coated with sulphate or other soluble inorganic aerosols during transport. Mineral dust particles with a nitrate coating are also reported to be hydrophilic, while those without coating are commonly hydrophobic (Myhre *et al.*, 2007). The hygroscopic nature of aerosols therefore depends upon the particular mixing of different types of particles as well as on meteorological parameters such as humidity, wind speed, wind direction, and temperature (Aloysius *et al.*, 2009). The water uptake of atmospheric aerosols is important as it can have a number of consequences: it can alter both the size and the chemical composition of particles, and consequently their optical properties. Cloud formation depends on the amount of water vapour available for condensation onto hydrophilic aerosols.

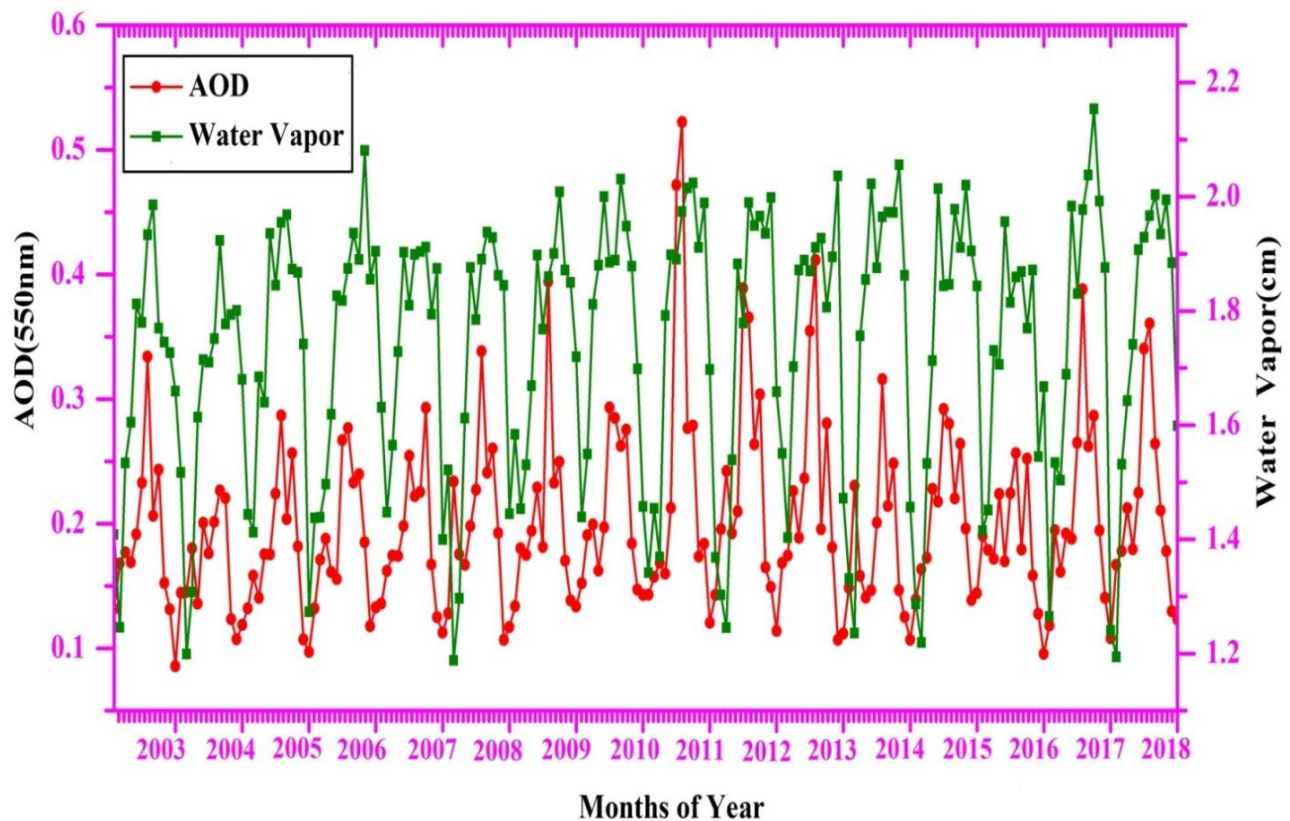


Figure 16: Time series of area averaged of AOD and Water vapor for 16 year period (January 2003– December 2018) over Ethiopia.

CHAPTER FIVE

5. Conclusion and Recommendation

5. 1. Summary and conclusions

The present investigation has revealed the temporal relationship between the AOD and different cloud parameters derived from MODIS data on board Aqua and Terra satellites for the period from January 2003–December 2018 over Ethiopia. The major findings of the present study are:

1. The time series analysis of AOD clearly shows the increasing trend from January 2003–December 2018 over Ethiopia. This increment in aerosol loading might be due to major influential sources such as rapid urbanization results in increase in automobile transportations, industrial emissions, large number of construction activities, and also the increase in amount of aerosols produced from biomass burning. The dense population, geography affected by terrain and local sources, climate and economy are also closely related with the aerosol climatology.
2. The AOD varies seasonally (monthly) from low in the winter months (January/February) to the high in the summer season (June/July) followed by spring and autumn seasons. The reason for high values of AOD in summer is higher air temperatures which tend to hold abundant atmospheric water vapor facilitated the hygroscopic growth of aerosols.
3. The correlation between AOD and CF was found to be high and positive. Ethiopian continent are crossed by convergence zones (ITCZ) that tend to accumulate aerosols and water vapour, thus generating conditions favorable for cloud formation.
4. Negative correlation was observed between AOD and CTP, CTT. AOD increased as CTT decreased throughout the period of study.
5. The correlation between AOD and WV is positive (correlation coefficient=0.427). We observed that WV is also higher during the summer, matching the increase in AOD and indicating the possibility of hygroscopic growth of aerosols. Changes in water uptake of aerosols can therefore, lead to changes in both direct and indirect radiative forcing on climate

5.2 Recommendation

The study only employed cyclical time series analysis, regression models and correlation to analyze the data Aerosol optical depth (AOD) at 550nm, cloud fraction, cloud top pressure, cloud top temperature and water vapor over 16 years of data from MODIS satellite. It is therefore recommended that further research should integrate the ground-based data with satellite in order to deep study the cloud-aerosol interactions. Even one can study the aerosol effect on Ethiopian rainfall distributions to quantify the AOD.

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