STATISTICAL ASSESSMENT OF TERRA MODIS AEROSOL OPTICAL DEPTH (C051) OVER COASTAL REGIONS

SAHABEH SAFARPOUR NIKOU LANGEROODI

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BY

SAHABEH SAFARPOUR NIKOU LANGEROODI

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LIST OF MAJOR ABBREVIATIONS

ACE	Aerosol Characterization Experiment
ADEOS	for Japan's Advanced Earth Satellite System
AERONET	Aerosol Robotic Network
AI	artificial intelligence
ANFIS	Adaptive Neural-Fuzzy Inference System
ANN	Artificial neural network
AOD	aerosol optical depth
ATSR	Along Track Scanning Radiometers
AVHRR	Advanced Very High Resolution Radiometer
BP Algorithm	Back Propagation Algorithm
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation
CE	coefficient of efficiency
CNES	French National Space Agency
DB	Deep-Blue
DT	dark-target
EARLINET	European Aerosol Lidar Network
EPA	Environmental Protection Agency
ERS	European Remote Sensing
EU	European Union
FCM	Fuzzy C-means
FMF	fine mode fraction
GDAS	Global Data Assimilation Model
GEOs	geostationary satellites
GMD/ERDL	Global Monitoring Division/Earth Research Laboratory
GOME	Global Ozone Monitoring Experiment
HDF	Hierarchal Data Format Files
ICARB	Integrated Campaign for Aerosols, gases, and Radiation Budget
LEOs	Low-Earth Orbit Satellites
LIDAR	Light Detection and Ranging
LMA	Levenberg- Marquardt Algorithm
LMS	least-mean-square
MAPSS	Multi-Sensor Aerosol Product Sampling System
MC	multicollinearity
MCST	MODIS Characterization Support Team
MISR	Multi angle Imaging Spectroradiometer
MLP	Multilayer Perceptron

MLR	Multiple linear regression method
MODIS	MODerate resolution Imaging Spectroradiometer
MSE	mean squared error
MSRE	mean squared relative error
NAAQSs	National Ambient Air Quality Standards
OMI	Ozone Monitoring Instrument
POLDER	Polarization of Directionality of the Earth Reflectance
RADAR	Radio Detection and Ranging
RMSE	Root Mean Square Error
SDSs	Scientific Data Sets
SHADE	Saharan Dust Experiment
TARFOX	Tropospheric Aerosol Radiative Forcing Observational Experiment
TOMS	Total Ozone Mapping Spectrometer
trainlm	Levenberg-Marquardt backpropagation
trainbr	bayesian regulation backpropagation
WHO	World Health Organization

PENILAIAN STATISTIK KEDALAMAN OPTIK AEROSOL TERRA MODIS (CO51) DI KAWASAN PESISIR

ABSTRAK

Produk aerosol dari Spektrometer Pengimejan Resolusi Sederhana (MODIS) telah digunakan secara meluas untuk menangani alam sekitar dan isu-isu berkaitan perubahan dengan liputan global setiap hari. Kedalaman optic aerosol (AOD) yang diambil oleh algoritma yang berbeza berdasarkan permukaan piksel, menentukan antara tanah dan laut. Produk MODIS-Terra dan Global Aerosol Robotik Network (AERONET) boleh didapati daripada Multi-sensor Aerosol Product Sampling System (MAPSS) bagi kawasan-kawasan pantai sepanjang tahun 2000-2010. Dengan menggunakan data yang dikumpul daripada 83 stesen pantai dan 158 bukan pantai di seluruh dunia dari AERONET 2000-2010, penilaian ketepatan dibuat untuk kedalaman optic aerosol pantai (AOD) diambil dari MODIS di atas satelit Terra. Tujuan utama penilaian statistik AOD di kawasan pantai adalah untuk melahirkan MODIS AOD terubahsuai dengan ralat yang minimum berbanding dengan nilai rujukan yang diberikan oleh AERONET. Mula-mula ketepatan data MODIS AOD algoritma yang berbeza dinilai mengikut musim dan kawasan geografi di kawasan pantai dan bukan-pantai dengan menggunakan maklumat daripada rangkaian AERONET. Selepas menginkir data dengan aras kualiti di bawah 1 untuk algoritma lautan dan di bawah 3 untuk algoritma tanah, ketepatan AOD dari algoritma MODIS sasaran gelap pada lautan adalah lebih besar daripada algoritma MODIS sasaran gelap pada daratan dan algoritma biru terang. Sebab-sebab ralat di AOD didapati daripada pantulan permukaan yang pelbagai. Dalam langkah seterusnya, model linear am (GLM) dibangunkan yang dapat menjelaskan pengaruh rantau geografi dan musim untuk menghubungkan di antara MODIS dan AERONET. Didapati bahawa model GLM adalah lebih baik di kawasan bukan pantai. Selepas itu, model regresi linear berbilang (MLR) dimajukan menggunakan sesuatu produk MODIS AOD (MODIS AOD, pecahan awan dan pantulan min) yang boleh menghasilkan MODIS AOD terubahsuai yang memppnuyai hubungan tinggi dengan AERONET untuk musim dan kawasan geografi lyang berbeza di kawasan pantai. Ia telah menunjukkan regresi linear berbilang bermusim lebih baik daripada regresi linear berbilang yang umum dan regresi linear berbilang musim bunga adalah model terbaik untuk model bermusim. Apabila model MLR digunakan di setiap kawasan, satu model dengan korelasi tertinggi boleh dianggap sebagai yang terbaik untuk AOD di rantau tersebut. Teknik kepintaran buatan telah berjaya digunakan dalam pemodelan fenomena yang sangat kompleks dan bukan linear. Teknik kepintaran buatan yang berjaya digunakan dalam pemodelan fenomena yang sangat kompleks dan bukan linear. Dalam kajian ini, rangkaian neural buatan (ANN) dan system inferen neural kabur ubahsuai (ANFIS) telah dibangunkan untuk ramalan AOD dengan menggunakan produk aerosol MODIS di kawasan pantai. Akhir sekali, perbandingan antara ANN, ANFIS dan MLR yang dibangunkan telah dibuat dan hasil mendedahkan bahawa model rangkaian neural lata boleh meramalkan kedalaman optik aerosol lebih baik daripada model ANFIS dan MLR. Dua kawasan geografi yang berbeza di lokasi yang berbeza telah dipilih untuk penilaian model ANN, ANFIS dan MLR dalam musim yang berbeza. ANN memberikan korelasi yang lebih baik berbanding dengan ANIFS dan MLR samaada secara umum atau secara bermusim.

STATISTICAL ASSESSMENT OF TERRA MODIS AEROSOL OPTICAL DEPTH (C051) OVER COASTAL REGIONS

ABSTRACT

Moderate Resolution Imaging Spectroradiometer (MODIS) aerosol products have been widely used to address environment and climate change issues with daily global coverage. Aerosol optical depth (AOD) is retrieved by different algorithms based on the pixel surface, determining between land and ocean. MODIS-Terra and Global Aerosol Robotic Network (AERONET) products can be obtained from the Multi-sensor Aerosol Products Sampling System (MAPSS) for coastal regions during 2000-2010. Using data collected from 83 coastal and 158 non-coastal stations worldwide from AERONET from 2000-2010, accuracy assessments are made for coastal aerosol optical depth (AOD) retrieved from MODIS aboard the Terra satellite. The main aim of this statistical assessment of AOD over coastal regions is to produce modified MODIS AOD with minimum error when compared with the reference value given by AERONET. At first we evaluate the accuracy of MODIS AOD data under different algorithm, season and geographical region over the coastal regions and non-coastal regions using information from the AERONET network. After removing retrievals with quality flags below1 for Ocean algorithm and below 3 for Land algorithm, the accuracy of AOD retrieved from MODIS Dark Target Ocean algorithms is greater than the MODIS Dark Target Land algorithms and the Deep Blue algorithm. The reasons of the retrieval error in AOD are found to be the various underlying surface reflectance. In the next step, we developed a general linear model (GLM) that can explain the influence of geographical region and season on the association between MODIS and AERONET. We found that the GLM model performed better work on the noncoastal regions. After that we developed multiple linear regression models (MLR) using MODIS AOD product (MODIS AOD, Cloud Fraction and Mean reflectance) that can effectively produce modified MODIS AOD of high relationship with AERONET for different season and geographical region over coastal regions. It has showed that seasonal multiple linear regression is better than general and the spring multiple linear regression is the best model for seasonal model. When the MLR models are synchronizing in each region, a model with highest correlations can be considered as the best for AOD retrieval in the region. Artificial intelligent techniques are successfully used in modeling of highly complex and non-linear phenomena. In this study, we developed artificial neural networks (ANN) and adaptive neuro fuzzy inference system (ANFIS) for prediction of AOD by using MODIS aerosol products over the coastal regions. Finally, a comparison between developed ANN, ANFIS and MLR was made and the outcomes disclosed that cascade neural network model can predict aerosol optical depth retrieval better than does ANFIS and MLR model. We selected two different geographical regions in different location for evaluation of ANN, ANFIS and MLR models in different season. The ANN provides better correlation compared to ANIFS and MLR both generally and seasonally.

CHAPTER 1

INTRODUCTION

1.1 Introduction

Atmospheric aerosols emanate from a variety of sources, ranging from natural to anthropogenic, and exhibit a wide range of sizes and chemical properties. Due to their impact on both the environment and people's health, there has been rising research focus on aerosols in the recent years. With this rising trend of research on changes in the climatic condition, researchers have come to confirm that human activities have a lot of impact on the rising world heat levels. From the perspective of the optimists, who hold the limited emission view of greenhouse gases, the global surface temperature increased by 2.4^{o} compared to pre-industrial average (Solomon, 2007a). Both atmospheric aerosols and greenhouse gasses cause disturbances to the radiation pattern of the earth. These products not only affect the quantity of solar radiation reaching the Earth's surface, but also influence the behavioral pattern of cloud conditions. From the global perspective, the release of aerosol nullifies or lowers the impact of greenhouse gases, in that it cools down the global temperatures. Nevertheless, anthropogenic aerosols can downgrade the quality of air in the atmosphere, and rising quantity of particles in the atmosphere increases the threat of health problems. Thus, even where it is cumbersome to quantify, quantification of the relative influence of both artificial and natural aerosols is quite vital. The inconsistency in the chemical, physical and optical composition makes the assessment of the impact these particles on both humans and the global climatic changes. In general, aerosol measurements generated from the ground-based stations are some of the most trusted results; however, it is difficult to generate spatial extrapolation for this measurement method. A more recent method of extracting the properties of aerosols generated from space-based observations, presents a more explicit method of enabling measurements at the global level. The current investigation is focused on the Statistical Assessment of Terra-MODIS Aerosol Optical Depth over coastal regions.

1.2 Atmospheric aerosols

1.2.1 Definition

By definition, an aerosol is a collection of airborne liquid or solid particles suspended in a gas (Seinfeld and Pandis, 2012). Therefore, atmospheric aerosols are those aerosol particles in suspense in the atmosphere. From the perspective of atmospheric science, the term aerosol is mainly associated with particulate components; and is generally found in the two lower layers namely, the troposphere and the stratosphere. Being mainly categorized based on size, the majority of aerosols range from a few nanometers up to a hundred micrometers.

1.2.2 Sources and Formation of Aerosols

As mentioned earlier, atmospheric aerosols can be sourced from both anthropogenic and natural origins, or through the process of chemical reactions in the atmosphere (Seinfeld and Pandis, 1998). Thus, primary aerosols are those aerosols released into the atmosphere. Among the primary aerosols are the natural primary aerosols, which entail those released into the atmosphere through such mechanical activities as sea spray, mineral dust, volcanic ash, plant and animal debris, etc (Seinfeld and Pandis, 1998). These include the disintegrated and dispersed remains of plants and animals, as well as the dispersed remnants of microbial activities. For example, when a volcano erupts, a substantial quantity of particles is generated with high velocity into the atmosphere, thereby reaching altitudes as high as 10 km (Robock, 2000; Thomason et al., 2007). Moreover, human activities such as manufacturing, automobile transportation, household waste generation, combustion of biomass as well as agricultural production, result in the formation of anthropogenic aerosols. Specifically, these activities often contain substantial quantities of such precursors as SO_2, NO_2, and Volatile Organic Compounds (VOC), which are critical components of the gas-to-particle conversion, resulting in the formation of secondary aerosols. A comparison of the strengths of the different aerosols is presented in Table 1.1 based on their mass fluxes (Andreae, 1995).

Table 1.1. Sources of natural and anthropogenic aerosols with the global annual burden of their emission (Andreae, 1995).

Source	Annual Emission ($Tg.yr^{-1}$)
Natural Particles	
Primary	
Soil and rock debris	1500
Forest fires and slash burning	50
Sea salt	1300
Volcanic debris	33
Gas to particle conversion	
Sulfate from sulfure gases	102
Nitrate from NOx	22
VOC from plants exhalation and fires	55
Subtotal	3060
Anthropogenic Particles	
Primary	
Industrial, transportation, etc.	120
Gas to particle conversion	
Sulfare from SO^2 and H_2S	120
Nitrate from NOx	36
VOC conversion	90
Subtotal (Anthropogenic)	366
Total	3430

1.2.3 Aerosol Optical Depth

Aerosol Optical Depth (AOD) is a dimensionless quantity commonly employed in the study of atmospheric radiation. In simple terms, AOD is the result of the integration of the extinction coefficient across the atmospheric layer (i.e. from the surface z = 0 to the Top of the Atmosphere z = h_{TOA}) (Seinfeld and Pandis, 2012). Mathematically, AOD is expressed as:

$$\tau(\lambda) = \int_0^{h_{TOA}} \sigma_{ext,aer}(\lambda, z). dx \quad (1.1)$$

From the mathematical expression, one can clearly conclude that AOD is a dependent variable of the vertical profile of the aerosol extinction, which is also dependent on its own physical and chemical compositions. Research models for the study of aerosols often investigate the relationships between the phase function, the extinction coefficient, and the single scattering albedo of the specific aerosols and the particles' physical and chemical composition (Shettle and Fenn, 1979; Hess et al., 1998). For example, Reddy (2005) employed the general circulation model to estimate the major players in the global AOD concentration (0.12 at 0.55μm); and found that over 58% of the global deposits are due to natural sources, 26% due to burning of fossil fuels while 16% are due to the burning of biomass.

In most cases, the spectral dependence of AOD is afforded using the power law as shown below:

$$\tau(\lambda)\ \alpha\ \lambda^{-\alpha} \quad (1.2)$$

From the power law function, α, which is an Angstrom coefficient, increases when the particle size distribution mainly involves smaller particles, and the reverse is the case when the particle distribution mainly involved large particles (Kuśmierczyk-Michulec et al., 2001). However, the value of α is mainly within the region defined by ($0 \leq \alpha \leq 3$). In this way, α values of zero or even negative values are registered for scenarios with newly developed sea salt particles or desert dust, which are mainly larger, while pollutions mainly involving particles of sulfates and nitrates result in α value of 2 or even 3. The burning of biomass, in most cases, also results in the formation of smaller particles, thus leading to higher α value (Seinfeld and Pandis, 2012).

Aerosol size distribution represents the number of particles as function of the particle diameter or radius. The number size distribution of a polydispersed aerosol type can be well described by the superposition of one or several lognormal distribution functions:

$$n_N(D) = \frac{dn}{dD} = \sum_{i=1}^{k} \frac{n_i}{D\cdot\sqrt{2\pi}\cdot \ln \sigma_{g,i}} \exp \frac{-(\ln D - \ln \bar{D}_{g,i})^2}{2\cdot \ln^2 \sigma_{g,i}} \tag{1.3}$$

With this parameterization, the number size distribution is fully determined by k pairs of parameters: the mean geometric diameter $D_{g,i}$ and the geometric standard deviation $\sigma_{g,i}$ of each mode i. From this expression, a similar description can be derived for the size distribution of the aerosol surface area $n_S(D_{gS}, \sigma_g)$, and volume $n_V (D_{gV} , \sigma_g)$. Hence:

$$\ln \bar{D}_{gS,i} = \ln \bar{D}_{g,i} + 2 \cdot {\sigma_{g,i}}^2 \tag{1.4}$$

$$\ln \bar{D}_{gV,i} = \ln \bar{D}_{g,i} + 3 \cdot {\sigma_{g,i}}^2 \tag{1.5}$$

In the model proposed by Jaenicke (1993), the size distribution of the different ambient aerosols is described by the sum of three lognormal modes, for marine, urban, rural, continental, and desert environments. Based on the data of this study, Figure 1.1 shows a representation of the surface number size distribution for these backgrounds.

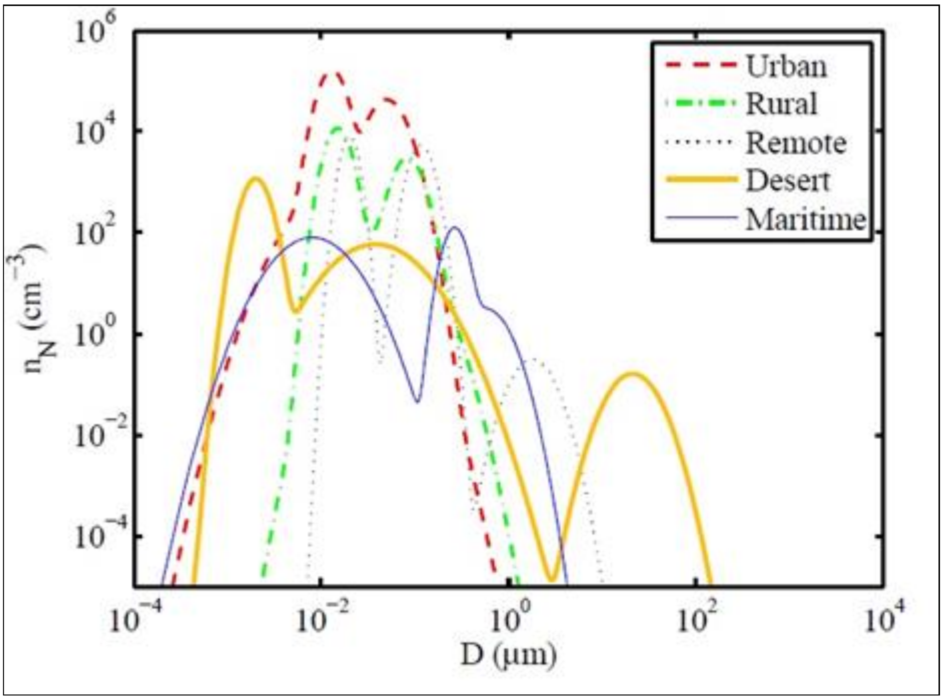

Figure 1.1: Number size distributions as described by the trimodal lognormal parametrization proposed by Jaenicke (1993) for urban, rural, remote, desert and marine environments.

A dominant accumulation mode in the number size distribution indicates the presence of aged particles, and a trimodal structure is usually observed for rural and natural aerosols (Mäkelä et al., 2000). Aerosols found in the remote maritime environment have a very broad size distribution, and are generally characterized by three modes, in the nuclei, the accumulation and the coarse mode. Although most of the mass is contained in the coarser mode (Fitzgerald, 1991), the number of particles is higher for the finer modes. The largest particles are produced by wave-wind interactions at the sea surface e.g. (De Leeuw, 1986), and the number concentration and the size distribution are strongly dependent on both wind speed e.g. (Andreas, 1998) and fetch i.e. the wind's trajectory over water (Piazzola et al., 2002; Piazzola and Despiau, 1997). Urban aerosols are mainly influenced by primary emissions from human activities; therefore most particles have a radius below 0.1 μm. For many urban sites, it was shown that the mass distribution has two modes in the accumulation and in the coarse mode (Lioy and Daisey, 1987; Aceves and Grimalt, 1993). The size distribution of aerosols is highly variable within an urban area, and the highest concentration levels are found at the sites downwind of the sources. The rural continental background mainly contains aerosols of natural origin, and undergoes a moderate influence from nearby urban areas. The size distribution of ultrafine particles in urban and rural regions is modulated by many parameters such as photochemical generation during the summer months, vehicle emissions at rush hours, and downwind long-range transport of particles originating from highly polluted industrial or urban sites to rural areas (Kim et al., 2002). In remote continental regions or desert, the anthropogenic influence is negligible, and the number size distribution is trimodal. The desert dust number distribution spreads over a wide range of diameters, and the shape of the distribution is strongly related to wind speed (Schütz and Jaenicke, 1974; Longtin et al., 1988).

Atmospheric aerosols are often classified according to their size range or mode. According to the classification proposed by Whitby and Cantrell (1976), coarse particles generally have a diameter greater than 2.5 μm, below this limit they are referred to as fine aerosols (see Figure 1.2). This distinction in size in general, is also valid in terms of sources, formation, chemical composition, optical properties, removal processes, and health effects. It should be noted, however, that other definitions for fine/coarse mode aerosols are used as well. Coarse mode aerosols consist of mechanically produced natural and anthropogenic aerosols. Because of their large size, these particles do not remain suspended for long before falling out of the atmosphere by dry deposition. The fine mode can distinguish two sub modes: a smaller mode called the nuclei or the Aitken mode, and a larger mode called the accumulation mode. Particles in the nuclei mode have typical diameters below 0.1 μm. They are usually secondary aerosols which are formed by nucleation or condensation of atmospheric gas compounds, but also primary sea salt particles have been observed in this mode.

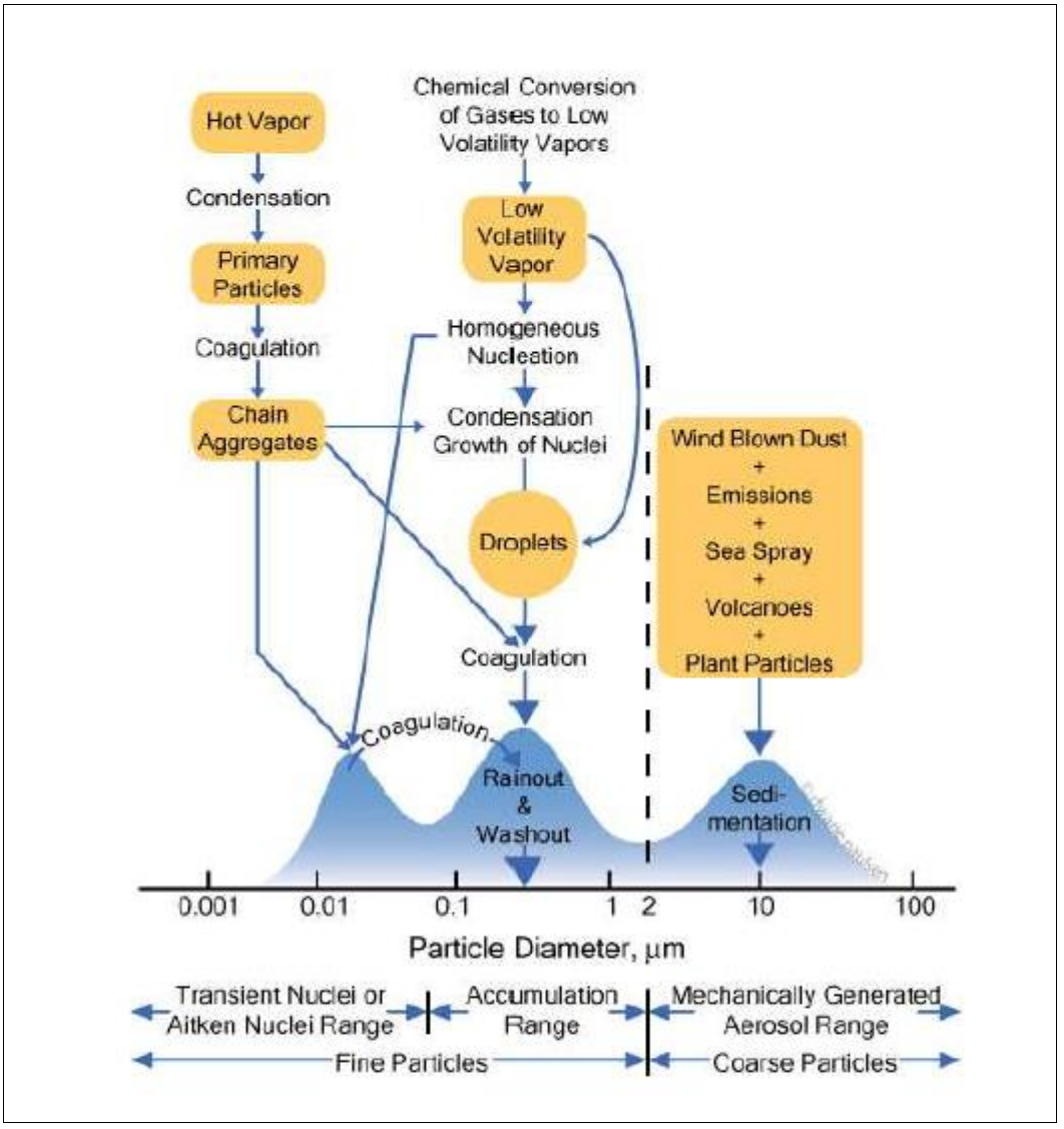

Figure 1.2: Conceptual representation of the principal size ranges for atmospheric particles and their associated sources, and removal processes, adapted from the work of Whitby and Cantrell (1976). The blue curve is a plot of the idealized surface area distribution of an atmospheric aerosol, and blue arrows identify the different physical and the chemical processes responsible for aerosol formation and changes in size. Source: http://www.dwanepaulsen.net/blog/category/aerosols/.

Their number concentration in the atmosphere is the highest; however they represent only a small mass fraction of the total aerosol load. For these particles, Brownian motion is the dominant mechanism for deposition, and is responsible for their short lifetime in the atmosphere. Accumulation mode particles are produced by the growth of Aitken particles by either coagulation or condensation of gases, and have sizes in the range of 0.1 μm to 2.5 μm. Removal processes have little effect on these particles, and thus have a long residence time in the atmosphere (~weeks), which is principally reduced due to washout and rainout (i.e. wet scavenging) (Hoppel et al., 1994). In the litterature the terms ”giant”(Kim et al., 1990), or ”ultrafine” (Bates et al., 1998b) are also employed, and the number of different modes can reach 4. The terminology used to refer to the different modes depends very much on the authors.

1.3 Problem Statements

With increasing population densities and energy demand globally, aerosol emission have been gradually increasing worldwide. This is revealed by several studies using aerosol observations from ground base measurement (AERONET) and satellite data (Kaskaoutis et al., 2012). It is well known that the increase in aerosol concentration is hypothesed to play an important role in the earth climate, radiation budget as well as air quality studies. Aerosols airborne particles can also minimize the visibility and harm human health (Samet et al., 2000). It is also worthy of note that over half the world’s population resides in the coastal region (Tibbetts, 2002), which implies that assessment of AOD above the coastal area should be given a special consideration. This can have important implications for future air quality studies.

Even though, the Aerosol Robotic Network (AERONET) design by US NASA can effectively provide global network of AOD at ground station for aerosol monitoring and air quality study, the method is based on a point measurement (Kaskaoutis et al., 2012). This means that the data from AERONET is limited by low spatial density. Therefore the need arise for employing a model that can use aerosol parameters from MODIS to produce AOD with a high relationship with AERONET. However, recent researchers have used different satellite data for the development of air quality prediction models which have been used as an aid for air pollution forecasting in recent years (Hooyberghs et al., 2005; Hoi et al., 2009; Li et al., 2011; Zhang et al., 2013).

This study focuses on the characterization of MODIS AOD uncertainty over the coastal regions because: (a) The MODIS AOD product over the coastal region is a simple union of the retrievals from algorithms that are designed for either over land only or over open ocean only, and neither algorithm has a dedicated scheme to characterize the surface reflectance over the coastal region that is often influenced by a sand_water mixture and water reflectance contributed by the underlying sea shore and suspended matter in the coastal ocean; (b) the coastal region is often of high importance to its local economic development through either tourism or serving as a hub for freight transportation (Tibbetts, 2002). Therefore, the assessment of the MODIS AOD product over the coastal region is critical for studying the trend of regional anthropogenic AOD and air pollution.

Some of these statistical methods are Adaptive Neural-Fuzzy Inference System (ANFIS), support vector machine, artificial neural networks, nonlinear regression and multiple linear regressions. Although, linear regression modeling finds some applications in the air quality prediction (Ziomas et al., 1995; Shi and Harrison, 1997), it generally does not permit for consideration of complex and non-linearity in data (Gardner and Dorling, 1998). Atmospheric dispersion models (Cimorelli et al., 2005; United, 2004; Kesarkar et al., 2007; Bhaskar et al., 2008) are required to have sufficient knowledge about the several source parameters and the meteorological conditions (Collett and Oduyemi, 1997). Therefore some of these models limitations can lead to in accurate estimation or prediction. Although due to different satellites data products use for various prediction models, the accuracy of the model depends on the integrated aerosol parameters, season and geographical location.

In this study, we focus on the AOD evaluation and refinement and accuracy extracted from MODIS above the coastal areas in context of trend analysis of satellite-based AOD. This is in view of producing a prediction model of higher accuracy, reliability and precision. To achieve that, AOD, mean reflectance and cloud fraction were integrated. The general linear regressions, multiple linear regressions, ANN (Artificial neural network) and ANFIS were utilized to analyze the association between MODIS from AERONET and other categorical variables such as season, geographical conditions over coastal regions by using the MODIS and AERONET data. Multiple regression analysis predicts a dependent variable from more than one independent variable. It also determines the influential independent variables.

In this study regression analyses were conducted using the SPSS system under different climatic and geographical conditions. The MATLAB program used the Comprehensive Software Package for programming algorithms and neural networks and fuzzy systems of rules.

1.4 Research Objectives

The main aim of this statistical assessment of aerosol optical depth over coastal regions is to produce modified MODIS AOD with minimum error when compared with the reference value given by AERONET. While doing that, the following experimental objectives are set;

i. To evaluate the accuracy of MODIS AOD data over the coastal and non-coastal regions using information from the AERONET network. And to apply a general linear model (GLM) that can explain the influence of geographical region and season on the association between MODIS and AERONET.

ii. To improve multiple linear regression models using MODIS AOD product, that can effectively produce modified MODIS AOD of high relationship with AERONET for different season and geographical region over coastal regions.

iii. To investigate artificial neural networks (ANN), Adaptive Neuro Fuzzy Inference System (ANFIS) and multiple linear regression (MLR) models for prediction of aerosol optical depth over coastal regions.

1.5 Scope and limitations of the study

The fact that all coastal areas round the world are one of the major sources of anthropogenic aerosols (Anderson et al., 2013), we collected 83 coastal stations

AERONET data worldwide during 2000- 2010. This is in addition to the corresponding aerosol optical depth (AOD) extracted from the Terra satellite by MODIS at the rate of (the Collection 5.1 MOD04 data product generated by the MODIS atmosphere group). Therefore the models obtained from this study will be a viable tool applicable in air quality study in any part of the world. Even though the research is limited to coastal region, our general linear models can be used to produce AOD over a non-coastal surface. This was possible due to different data set considered in this model. Hence, this study includes in its scope, the development of AOD prediction models using multiple linear regression method, General linear, ANN and ANFIS for onward estimation and prediction of AOD. Beside this, comparison between ANN, ANFIS and multiple regression models is another scope of this work. Furthermore, the scope of this study also involves MODIS AOD evaluation as well as descriptive analysis of both MODIS and AERONET.

One major limitation of this study regarded the data available for modeling on the world. Although there is theoretically a large network of AERONET stations, not all of the data for the stations were available and some stations did not record daily data. When station data were available, the records were incredibly messy. This required reformatting and cleaning of the data (as there was inconsistency between stations) and filling in missing records when possible. Issues with the data were another reason why experiments with a more parsimonious model were undertaken. It is clear that adding more upstream stations often improved the ANN and ANFIS. However, to have complete records at all stations for the same event was quite rare. Thus, the use of more stations meant less data for training and testing because of missing data. ANN and ANFIS require a considerable amount of data. Conceptual models have a definite advantage over data-driven models when the available data are sparse.

1.6 Novelty

The MODIS and AERONET products for different season and geographical regions of the world were assessed and used in the context of managing error between the satellite and the reference data. In view of this, a model that can predict AOD with higher accuracy was estimated. Within the scope of our literatures, this approach of using AOD from MODIS, cloud fraction and mean reflectance integrated together to produce a model AOD with lower bias when compared to AERONET will be the first globally. Therefore our study is very unique in this regard. This modelling approach can provide AOD model tools for air quality study, climate change study, radiation budget and aerosol monitoring. The use of ANN, ANFIS and multiple regression analysis as a tool to produces different models that can be used for the prediction has also appeared to be unique. A novel approach has also been made to study the effect of season and geographical locations associated with MODIS and AERONET.

1.7 Thesis outlines

The flow chart of the methodologies used in this study is shown in Figure 3.4. The content of this thesis is organized as follows:

Chapter 1 contains the introduction to this study. It explains the context of study, atmospheric aerosols, the role of aerosols in climate and air quality, remote sensing, problem statement, research scope and the objectives of the study. The outline of the thesis organization is also provided in this chapter.

Chapter 2 discusses about the literature review of this study. This chapter is organizes as follow. Firstly is the discussion about the MODIS aerosol retrieval algorithms including the dark target land algorithm, the dark target ocean algorithm and the deep blue algorithm. Secondly is the discussion about the literature review of the air quality prediction model and finally discusses about theoretical framework of the statistical models used in the study.

Chapter 3 discusses the materials used in this study. The discussion starts with the MODIS and AERONET AOD products and the MODIS-AERONET Collocation and Coastal Site Classification used in this study and describe the methodology of multiple linear regressions, ANN and ANFIS in this study.

Chapter 4 discusses the results related to evaluate of accuracy of MODIS AOD data under various geographical, algorithms and climatic conditions over the coastal regions and non-coastal regions using information from the AERONET network And discusses the results related to analyzed influence factors such as geographical location and season on the strength of the association between MODIS and AERONET using general linear model and then indicated relationship between AERONET AOD, MODIS AOD, Cloud Fraction and Mean Reflectance using by multiple linear regression models in different season and geographical region over coastal regions. Finally discusses the results of the prediction of aerosol optical depth using ANN, ANFIS and MLR method. Finally, a comparison between developed ANN, ANFIS and proposed MLR was made for prediction aerosol optical depth over coastal regions.

Chapter 5 concludes this thesis by providing a summary of the work. This chapter also discusses the contributions of the research work and the future directions that can be further taken from this work.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this chapter, the discussion starts with the literature review for the role of aerosols in climate and air quality, application of remote sensing, research instrument, the application of artificial intelligence (AI) techniques in air pollution prediction, the application of regression techniques in air pollution studies, background theory related to methodology used in the study are given.

2.2.1 The role of aerosols in climate and air quality

2.2.1 The Earth's energy balance

It is common knowledge that the main source of energy on earth is the sun. Solar energy is primarily generated in the form of ultraviolet, visible and near-infrared (short waves). The earth, on the other hand, emits thermal infrared (long waves). With the assumption that the sun is a dark object with a 6000 K surface temperature, the Planck's law can be employed to generate the spectral solar irradiance as shown in Figure 2.1. Using this method, the state of thermal equilibrium is attained by the sun when the quantity of radiated long wave energy is equal to the quantity of shortwave energy absorbed. This radiative equilibrium continues to keep the Earth's temperature at 288K. Given the fact that the Earth's rotational axis is inclined, solar energy is not uniformly spread across the earth's crust. In this way, the tropical regions tend to enjoy substantial energy from the sun compared to the rest of the globe, given the fact that in the tropics, the rays of the sun are almost orthogonal to the orbit plane of the earth. The polar caps, on the other hand, attain much less solar energy compared to the other regions.

On average, the mean annual energy received by the globe from the sun is 1370 J/s. In other words, the solar energy flux at a unit area perpendicular to the solar rays at the top of the atmosphere is almost 342 W.m $^{-2}$. This total energy is what is then scattered across the earth through the different dispersing agents such as reflection and absorption as shown in Figure 2.1.

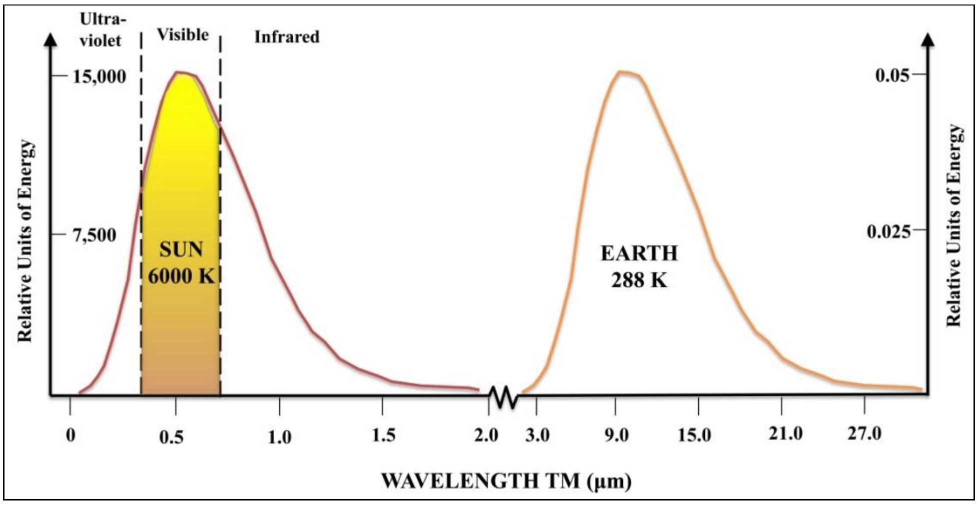

Figure 2.1: comparison of the emission spectra of the sun and the earth. Note the huge disparity in the amount of energy emitted by the sun (left-hand scale) and the earth (right-hand scale). Source: http://ockhams-axe.com/global warming.

In fact, almost a third of the total shortwave is radiated back into space due to the presence of clouds, aerosols and atmospheric molecules (~ 77 W.m $^{-2}$) as well as the earth's surface (~ 30 W.m $^{-2}$). Yet, the atmospheric greenhouse gases also absorb a substantial amount (~ 67 W.m $^{-2}$) of the total energy that successfully hit the surface. In this way, only half of the overall short-wave radiated by the sun is actually absorbed into the earth in the form of heat (~168 W.m $^{-2}$). Nevertheless, since the greenhouse gases are capable of absorbing the radiated long waves, the thermal energy radiated by the surface also warms the atmosphere. Moreover, the thermal waves radiated by both the atmosphere and the earth's surface are exposed to absorption by the clouds as well as the aerosols, both of which re-emit long waves. In this way, the energy is trapped between the Earth's surface and the clouds. While the earth's average temperature would have been 33º less when there are no greenhouse gases, clouds or aerosols; it would be about 293 K with the presence of greenhouse gases, but no clouds or aerosol.

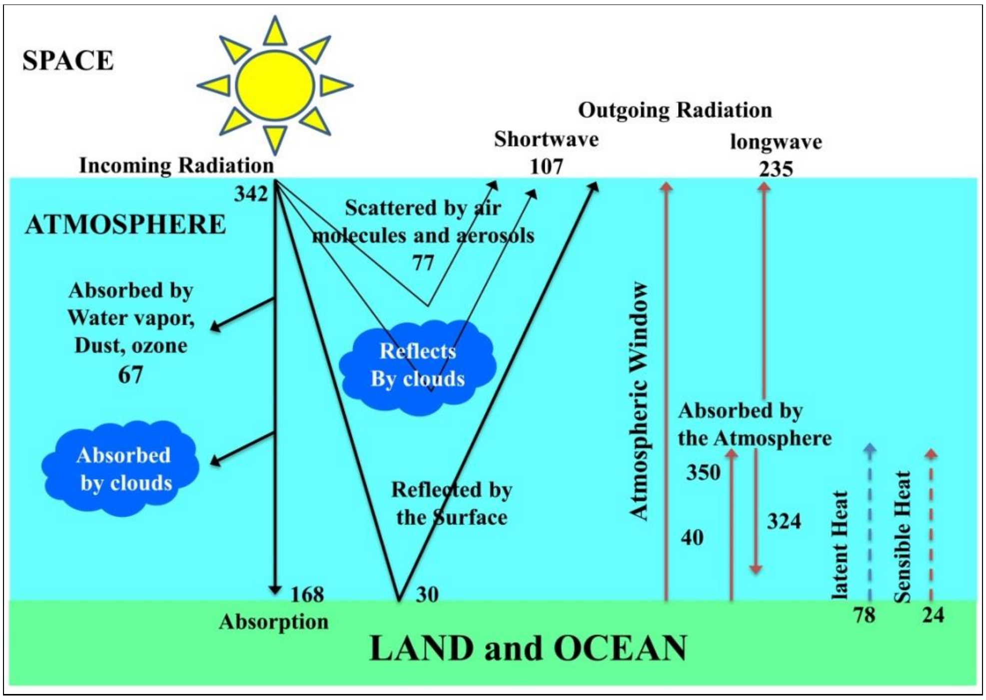

Figure 2.2: The global annual energy balance of the Earth. The contributions of the different components are expressed in Wm−2. Source http://www.hamburger-bildungsserver.de/welcome.phtml?unten- =/klima/greenhouse/radiation.html, based on data from (Kiehl and Trenberth, 1997), Figure 2.1"The Climate System: an Overview" of the Working Group I Report in the 2001 Intergovernmental Panel on Climate Change.

2.2.2 Aerosol radiative forcing

From the dawn of the industrial revolution, the concentrations of the majority of the greenhouse gases and aerosols have been on the increase. The rise in these anthropogenic emissions has resulted in the alteration of the natural balance of the global radiance referred to as the climate radiative forcing (Myhre, 2009). Climate forcing is said to occur when there is a mismatch between the earth's absorption level of the solar energy, and the earth's emission of the long waves; thus resulting in mediation for the setting up of a new point of equilibrium. In general, a positive change in the point of equilibrium is associated with warming up, while a net negative change is associated with cooling down effect of the earth. According to studies, however, human activities since the industrial revolution, results in a net positive change of 1.6 W. m^{-2} with a high degree of confidence [+0.6 to +2.4][1] (Solomon, 2007a). Figure 2.3 shows the various agents of radiative forcing, together with their level of involvement in radiative forcing in the year 2005. In comparison to aerosols, the majority of the greenhouse gases such as CO_2, CH_4 and N_2O have been known for more than a decade; and thus, are well mixed in the relatively. Accordingly, their influence on climate at the global scale is more easily identifiable compared to the aerosols. At the troposphere, for example, these greenhouse gases absorb radiations in the solar rays with near-infrared wavelengths, thus resulting in a net positive change in the global equilibrium. This phenomenon is called is commonly called global-warming. Specifically, the rising CO_2, CH_4, and N_2O levels have contributed up to 2.3 W.m^{-2} [+2.1 to +2.5][1] on the impact of global warming (Solomon, 2007a). Anthropogenic aerosols, on the other hand, are reported to exhibit cooling down effect on the global temperatures, and can thus be used to offset the positive net radiative forcing of the greenhouse gases (Haywood and Boucher, 2000; Penner et al., 2001). Nevertheless, the impact of these particles on the global climatic system is much more complex compared to the greenhouse gases. Thus, despite the numerous attempts towards investigating the impact of aerosols on the global climate system, it remains a green area in climate research.

Aerosols can affect the global climatic condition in two main ways. These are direct effect and indirect effect. Various research works have been carried out in an attempt to evaluate these effects using ground-based analysis (Yu et al., 2006), satellite-based and mathematical calculations (Schulz et al., 2006; Solomon, 2007b). An overview of radiative forcing of aerosols at the global scale is afforded in the work by Haywood and Boucher (2000) and Lohmann and Feichter (2005) for the direct and indirect effects respectively; where recent study reported that the aerosol-induced radiative forcing has a net cooling effect of -1.3 Wm−2 [-2.2 to +0.5][1] (Solomon, 2007a).

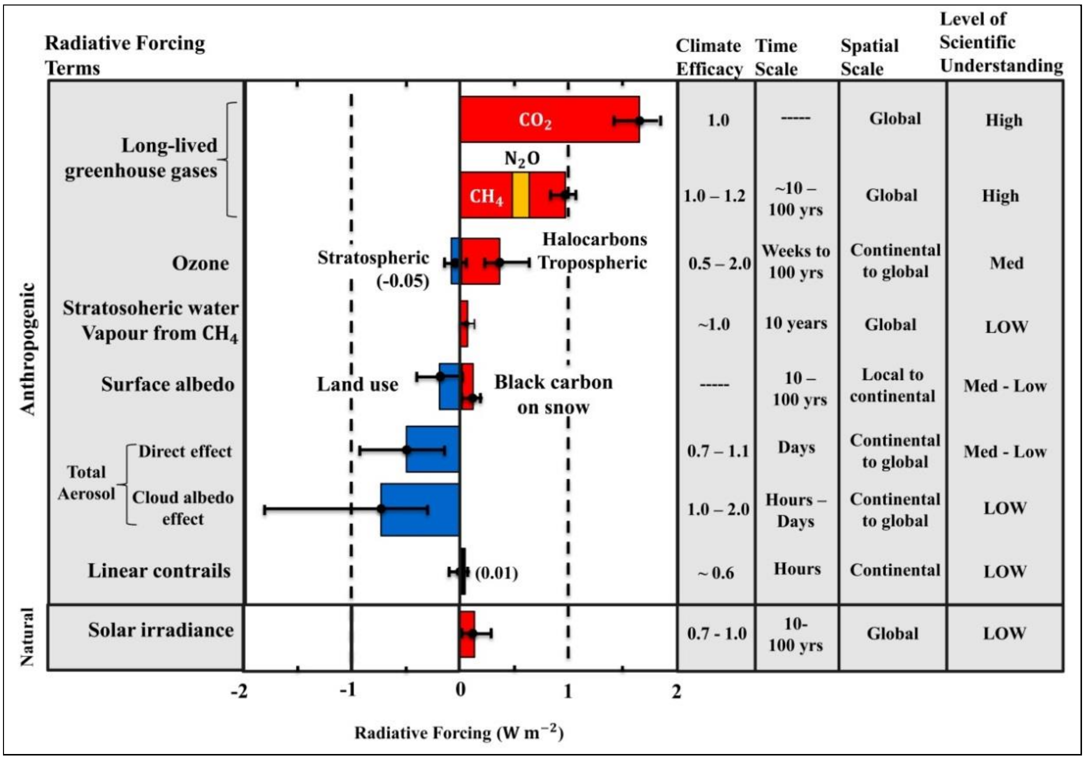

Figure 2.3: Global average estimates (in W.m−2) of the contributions from the different radiative forcing components of the Earth climate for the year 2005. Source: Figure SPM.2 from the Summary of Policymakers of the Working Group I Report in the 2007 Intergovernmental Panel on Climate Change.

- **Direct effect**

The direct effect of aerosols on the global climate entails the capacity of aerosols for absorbing and scattering solar and thermal radiations (Chýlek and Coakley, 1974). By the absorption and scattering, the quantity of shortwave radiation reaching the surface of the earth is reduced substantially. In this way, the reflection of the radiations into space has a cooling down effect, while the absorption phenomenon has a warming up effect. The investigation by Yu et al. (2006) found that aerosols have a direct radiative effect of global cooling of -5.5 ± 0.2 $W.m^{-2}$ and -4.9 ± 0.7 $W.m^{-2}$ over ocean and land respectively. Similarly, the overall direct radiative forcing due to anthropogenic factors was reported to be -0.5 Wm^{-2} [-0.9 to -0.1][1] (Solomon, 2007a). In another study by Reddy et al. (2005), it is reported that the major constituents of aerosol, namely, sulfate, black carbon, organic matter, dust and sea salt, provide -0.62, +0.55, -0.33, -0.28 and 0.30 $W.m^{-2}$ respectively to the overall global yearly average disturbance to the shortwave range regardless of the prevailing sky condition. However, in the case of long waves, these figures are almost lowered by 50%.

- **Indirect effect**

Aerosols may also alter the Earth's atmospheric radiation equilibrium by disturbing the albedo. The term albedo refers to the quantity and duration of clouds; which are basically droplets of water or crystals of ice suspensions in the atmosphere. Here, the particles of aerosols act as cloud condensation nuclei (CCN) for the water droplets. As the relative humidity rises, the droplets condense on these aerosol particles expand in size until the critical diameter is attained beyond which they transform into activated CCN; and eventually drop down as rain. Hence, a cloud's microphysical and radiative characteristics have close linkages with those of the aerosols they emanated from. Anthropogenic processes in general result in the formation of various hygroscopic particles, with their corresponding impacts on the microphysical and radiative characteristics of clouds. Among these indirect effects is the rise in the quantity of the CCNs for a constant quantity of water vapor. In this way, individual CNNs can condensate the cloud droplets, thereby making the cloud droplets smaller (Twomey et al., 1984). In this way, the smaller droplets exhibit better scattering potential which results in higher albedo (Twomey, 1977). Another indirect effect is associated with reducing the efficiency of precipitation as a result of the rise in the number of smaller droplets, which do not precipitate readily; thereby