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Dust Aerosols And Climate: A Brief Review

Rabia S. Sa'id
Department of Physics, Bayero University, PMB 3011, Kano, Nigeria
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Abstract

In Africa and particularly in areas prone to desertification, dust aerosols are impacting considerably. The Third Assessment Report (TAR) of the Intergovernmental Panel on Climate Change (IPCC) reported that the Radiative Forcing (RF) due to anthropogenic dust lies in the range of +0.4 to –0.6 Wm^{-2}. Although, the RF efficiency of anthropogenic dust has not been differentiated from that of natural dust, it is assumed to be equal. In this paper, journal articles dealing with different aspects of dust aerosol effects on climate have been reviewed. Particular attention has been paid to research articles on the effect of dust aerosols on climate. The review shows that majority of studies indicate that dust aerosols have a direct and indirect effect on climate. The review further highlights the recent research findings that the optical properties of the mineral constituents of dust aerosols play an important role in determining the physical and chemical equilibrium of the atmosphere.

Keywords: Dust Aerosols, Radiative Forcing, Climate

1.0 Introduction

A vast body of literature on dust aerosol research is now readily available and research is still ongoing. On the effect of dust aerosols on incident radiation, current literature available are also many and deal with different aspects of dust aerosol interactions with incident radiation. A review of past and current research on the subject is presented.

Dust aerosols are tiny solid and liquid particles suspended in the atmosphere. Depending on their size, type and location, aerosols can either cool the surface of the atmosphere or they can cause warming. Dust aerosol sizes range between 1–10 microns. Fine or accumulation mode dust aerosols are in the range of 1-2 microns, while larger particles (coarse mode) have radial sizes greater than 2 microns. Dust aerosols also help in cloud formation. Although dust aerosols occur naturally in the atmosphere and are useful in climate processes where they influence radiative forcing directly through reflection and absorption of solar infrared radiation in the atmosphere, the increase in anthropogenic dust aerosols have been shown to have significant net (direct and indirect) global mean radiative forcing (Ingold, 2001). The IPCC report (2007); surmises the likelihood that more solar radiation is now being reflected from earth's surface as a result of dust resulting from human activities. These changes have been shown to result in negative radiative forcing (Forster, et al. 2007). However, there are uncertainties particularly due to the uneven distribution of dust aerosols in the atmosphere. Sokolik et al. (1998) show that the uncertainties in radiative forcing of dust aerosols are due to: mineralogy, size distribution and albedo effects. Prospero et al. (1996) in their research, show that the uncertainties are also due to difficulty in quantifying the human impact of dust aerosols in the atmosphere. Dust aerosol that originate as surface windblown dust and from specific landscapes such as desert areas, which are then transported annually to different regions by air masses are referred to as natural dust. Natural dust would therefore refer to dust resulting from Aeolian processes that mobilize and suspend large quantities of dust into the atmosphere. The Sahara Desert is a major source of natural mineral dust aerosols transported across the Caribbean, Mediterranean, the Americas and Europe, while the Gobi Desert is the source of natural dust that affects eastern Asia and the western part of North America. If the dust emanate from land use, cultivation and road construction, then it is referred to as anthropogenic dust aerosol. Human activities contribute about 30% (Ge, et al. 2010) of dust load in the atmosphere.

Author's E-mail: rssaid2001@yahoo.co.uk, saidur2776@buk.edu.ng

Averaged over the globe, anthropogenic dust aerosols account for about 10% of the total amount of aerosols in the atmosphere. Most of the 10% is concentrated in the Northern Hemisphere, especially downwind of industrial sites, agricultural regions and overgrazed grasslands (Hardin and Kahn, 2009). Dust aerosols are mainly composed of mineral components such as silicate clays (Illite, Kaolinite and Montmorillonite), Oxides (quartz and hematite) and carbonate (calcite). For this reason, they are also referred to as mineral dust.

2.0 Dust Aerosol Radiative Forcing

Radiative forcing (RF) is a concept used for quantitative comparisons of the strength of different human and natural agents in causing climate change. The RF represents the stratospherically adjusted radiative flux change evaluated at the tropopause, as defined in the Third Assessment Report (TAR) of the Intergovernmental Panel on Climate Change (IPCC). Positive RFs lead to a global mean surface warming and negative RFs to a global mean surface cooling. Radiative forcing, however, is not designed as an indicator of the detailed aspects of climate response. Unless otherwise men-tioned, RF usually refers to global mean RF. Radiative Forcings are calculated in various ways depending on the agent: from changes in emissions and/or changes in concentrations, and from observations and other knowledge of climate change drivers. RF values are usually given in units of W m^{-2} (IPCC, 2001). Ge, et al., (2010) in their research of dust aerosol radiative forcing, illustrate that the primary role of dust aerosol is to alter distribution of solar radiation within the climate system rather than reflect solar energy to space. If this result is further rested and extended to other regions where dust loading in the atmosphere is significant and for all dust loading situation, it could provide significant contribution to global warming mitigation strategies.

3.0 Dust Aerosols and Role of the Constituents

Kaufman et al. (1997) studied dust transport and deposition over the Atlantic Ocean and the study provides a first example of quantitative use of the Moderate Imaging Spectro-Radiometer (MODIS) aerosol data for geophysical study. African dust column concentration, transport and deposition measurements show that 230 $\pm$ 80 tg of dust transported annually from Africa to the Atlantic Ocean, while only about 30 tg returns to Africa and Europe (Kaufman et al., 1997). Global dust source areas' studies have shown that dust originate from specific landscape, one of which is the Sahara (Koven and Fung, 2008). Windblown dust simulations (Strand et al., 1999) have been used to determine long term patterns of mineral dust produced in the Sahara region of Africa. However, a most relevant study is the aerosol dust remote sensing study of Sokolik (2002). The study performed detailed forward modeling to determine the sensitivity of regional dust properties and provided correction algorithm for dust laden conditions of the atmosphere. A similar study is that of Ou and Liou (2009). Ou and Liou undertook a new approach to investigate the aerosol indirect effect of the first kind on cloud formation by using available data from MODIS. This resulted in a physical understanding of the interaction between aerosols and clouds. Their analysis focused on the examination of the variability in the correlation between cloud parameters (optical depth, effective particle size, cloud/water path and cloud number concentration) and aerosol optical depth. They presented correlation results for a number of selected scenes containing dust and clouds.

The study of Kallos et al., (2006) is on transatlantic transport of Saharan dust using model simulation as is the study of Tegen et al., (2006). While the study of Kallos et al., (2006) provided methods for describing phases of atmospheric dust life cycle, the study of Tegen et al., (2006) modeled soil dust aerosols in the Bodele Depression. The model used in the Tegen study computed dust emission fluxes (F) in non-vegetated areas depending on surface wind friction velocities, surface roughness, soil particle size distribution, soil moisture, and snow cover. This study provided vital information to help minimize dust storm events. The Bodele Depression in the Chad Basin is the prominent source of harmattan dust in the northern regions of African countries. Dust emissions computed with observed wind speed were compared with emissions calculated with wind speeds from regional model simulations. The study found that dust aerosols interact with solar and thermal radiation and is responsible for a decrease in maximum daytime temperatures by about 5K at the beginning of the dust storm in the month of March. Dust from the Bodele is therefore an important contributor to dust crossing the African Savannah region towards the Gulf of Guinea and the equatorial Atlantic and it contributes up to 40% to dust optical thickness. These vital data could help in determining visibility ranges for flight plan and routes.

The 30-year Barbados desert dust record of Prospero and Nees (1986), which is a continuous in-situ atmospheric desert dust measurement, is the only available study on mass concentration of desert dust. The study showed fluctuations of a factor of 4 in surface mass concentrations between 1960s and 1980s. These large fluctuations indicate the influence of anthropogenic factors in sources, transport, distributions and depositions. The study is however inconclusive since available data is from one location only. There is therefore a need for expansion of study to more locations to better determine the actual contribution of anthropogenic activity to dust mass concentration and thus provide better data of influence on atmospheric changes. The study of Mahowald, et al., (2002) sought an understanding of the large fluctuations in surface mass concentrations between the 1960s and 1980s as presented in the 30-year Barbados in-situ measurements. The study attributed the large fluctuations and the observed mineral dust increase at Barbados to the Sahel drought and/or human land use changes and new land use policies. The study further tested the hypothesis that the sources of desert dust are dry topographic lows and not disturbed sources such as cultivated areas and new desert regions. The study therefore established the known facts that dust from desert sources can be classified as natural phenomenon. Tegen and Fung (1995) had earlier argued that cultivated soils and soils disturbed by human activities such as land use changes are responsible for about 50% increase in atmospheric mineral dust, while, Marticorena and Bergametti (1996) showed that the sources of atmospheric mineral dust aerosols are dry, un-vegetated soils in regions with strong surface winds and easily erodible soils. Mahowald et al. (2002) using a hierarchy of models and meteorological data sets concluded that it is impossible to make a definitive statement about the role of disturbed sources and cultivated areas as sources of atmospheric mineral dust. This is because it is difficult to distinguish cultivated areas from topographic lows due to their similar geographic locations.

The role of the constituents of mineral dust aerosols in affecting optical properties such as the single scattering albedo can be determined from the complex index of refraction. The complex refractive index is a key parameter in determining the optical properties of dust. The imaginary part represents the strength of the absorption or the ability to deplete light or radiation at a particular wavelength (McConnel, et al., 2008) Studies (Shettle and Fenn, 1979: Balkanski, et al. 2007) have shown that the real part determines the amount of scattering and has been found to be relatively well defined. Studies have also shown estimates of the imaginary part of the complex refractive index at 550nm to range from 0.004 (Osborne, et al. 2008) to 0.008 (Shettle and Fenn, 1979). These values correlate with the WMO (1986) data. However, value estimates of 0.001 and 0.006 have also been recorded (Patterson, et al., 1977; Dubovik, et al., 2002; Haywood, et al., 2003; Kandler, et al. 2009; Petzold, et al. 2009). Sokolik, et al., (1993) show that the variation in the imaginary part of the complex refractive index may be due to variable composition of the constituents of the dust having different refractive indices in varying proportion depending on their source region of emission. This has generated a wide range of interest in the constituents of dust in different regions of the world. Lafon, et al. (2006) show the importance of the concentration of oxides of iron in dust samples in controlling the spectral dependence of absorption at UV and visible wavelengths. Thus high concentration of oxides of iron such as hematite (Fe_2O_3) and goethite (FeO-OH) in dust at UV and visible wavelength would be highly absorbing. Sahelian dust has been found to have higher concentration of oxides of iron than Saharan dust (Claquin, et al. 1999; Formenti, et al. 2003).

4.0 Dust Aeosol Interections and Effect on Incident Radiation

Research literature on dust aerosol interactions with incident radiation fall under four broad categories: dust aerosol direct effects, dust aerosol cloud effects, dust aerosol semi-direct effects and dust aerosol radiative heating.

4.1 Dust Aerosol Direct Effects

Dust aerosol direct effect involves a mechanism (direct Radiative Forcing or RF) in which dust aerosols in the atmosphere scatter and absorb shortwave and longwave radiation (Direct Solar Effect). The direct terrestrial effect on the other hand occurs when large-sized dust aerosols behave like greenhouse gases (see Figures 1 and 2). These effects result in alteration of the radiative balance of the earth-atmosphere system. Dust aerosols direct effects are determined from the dust aerosol scattering albedo, the specific extinction coefficient and the scattering phase function. These key parameters vary with wavelength, relative humidity and the vertical and horizontal distribution of the dust aerosols with time (Haywood and Boucher, 2000). Scattering aerosols are expected to exert a net negative direct RF, while partially absorbing aerosols are expected to exert a negative Top of the Atmosphere (TOA) RF over oceans and forest surfaces. A positive direct RF is expected over desert regions and snow-covered landscapes. Chylek and Wong, (1995); Haywood and Shine, (1995) showed that dust aerosols above cloud also exert a positive RF. Both the positive and the negative Radiative Forcing reduce the shortwave irradiance at the surface of the atmosphere. Tegen, et al., (1996) showed that the longwave direct RF are only relevant for large sized aerosols when they occur in high concentrations at high altitudes.

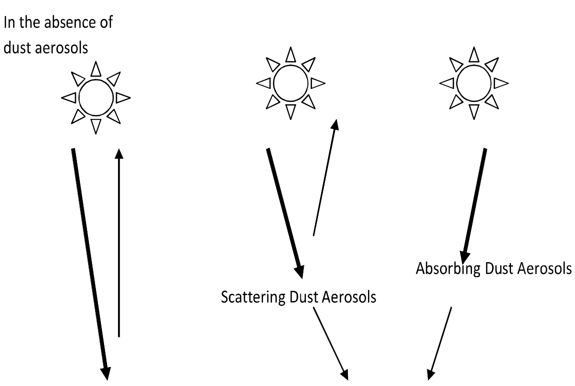

Figure 1: Direct Solar Effects; Dust Aerosols Scatter and Absorb Solar Radiation

4.2 Dust Aerosol Cloud Effects

Dust aerosol cloud effects are of two types: the first indirect effect, which is also known as the cloud albedo effect or Twomey effect after the study of Twomey (1974; 1977), which showed that by

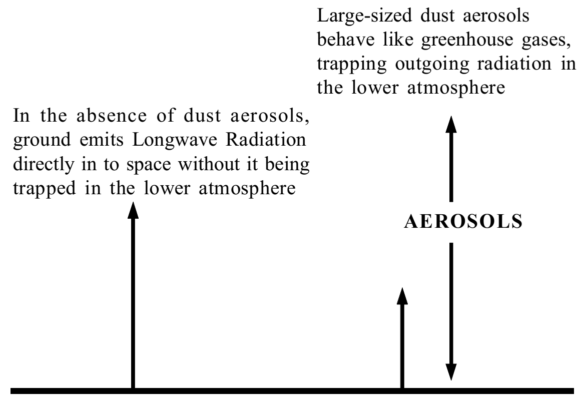

Figure 2: Direct Terrestrial Effect, with large-sized dust aerosols behaving like greenhouse gases

increasing droplet concentration, aerosols act to increase the albedo (reflectance) of clouds. The second indirect effect or cloud lifetime effect involves the study of drizzle suppression and increased liquid water content of clouds. The second indirect effect is also known as the Albrecht effect; named after Bruce Albrecht for his study of aerosol cloud microphysics. Albrecht (1989), studied the effect of increased aerosol concentration over oceans and showed that increased concentrations could increase the amount of low-level cloudiness through a suppression of drizzle, resulting in the increase of global albedo, which together with the reflectivity associated with decreased droplet size may contribute to a cooling of the earth's surface. The study also hypothesized that aerosol enhancement could lead to an increase in cloud lifetime. The study of Pincus and Baker (1994) further showed that in the presence of polluting aerosols, cloud height would increase. The study of Q-L Min et al. (2008) investigated the impact of mineral dust on cloud properties and precipitation processes in meso-scale convective systems. The study showed that for a given convective strength, small hydrometeors were dominant in the rain regions where dust was present. (Hydrometeors are particles involved in clouds and precipitation. They are mostly made up of solid and liquid water: rain, hail, sleet and snow). The study further showed that at altitudes where nucleation process of mineral dust prevails, there are observed changes in precipitation. Thus, microphysical effects of dust aerosols resulted in a shift in the precipitation size spectrum from heavy precipitation to light precipitation and subsequently to suppression of precipitation. DeMott, et al. (2003) showed from laboratory and aircraft campaign that dust particles can initiate ice formation at relatively warm and dry conditions in the atmosphere. This effect has been observed in Saharan dust plumes.

4.3 Dust Aerosol Semi-direct Effects and Dust Aerosol Radiative Heating

Dust Aerosol Semi-direct effect is the mechanism, by which absorption of shortwave radiation by aerosols leads to heating of the troposphere, which in turn changes the relative humidity and the stability of the troposphere and thereby, influences cloud formation and lifetime. The semi-direct is a relatively new concept within the aerosol-cloud-climate study and less attention has been paid to it in literature than the direct and indirect effects (Johnson, 2003). It has, however been studied by some researches including: Hansen et al. (1997), Ackerman, (2000), Jacobson (2002) and Menon et al (2003). Ackerman et al. (2000) showed that heating as a result of dust aerosols absorption of radiation causes cloud burn-off with indirect effect on ice clouds and contrails. The study also evaluated Twomey's 1991 parameterization of cloud susceptibility using measurements of ship tracks. Cloud physics assumptions such as the independence of cloud-liquid water content and width of the droplet concentrations were used in the study. The 69 ship track penetrations studied showed that Twomey's parameterization represents the trend of albedo changes with droplet concentrations very well. The limitation of the study is that systematic measurements of cloud thickness were not made for most of the ship tracks observed. A systematic measurement of cloud thickness for each ship track penetration would have further provided validation of the changes in albedo with changes in aerosol concentration. In the Third Assessment Report (TAR) of the Intergovernmental Panel on Climate Change (IPCC, 2001), the semi-direct effect was not included in the evaluation of the radiative forcing by aerosols because of uncertainties associated with the ice-cloud nucleation theory. The physics is regarded as complex and non-linear. The study of Johnson (2003) is an attempt to reduce the uncertainties associated with how the semi-direct effect works and how to incorporate it in climate models in order to quantify the RF from all the effects: direct, indirect and semi-direct.

The CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations) study estimated the dust aerosol radiative heating rate and the radiative effect during the dust events that occurred over the Taklimakan Desert in the summer of 2006. The Taklimakan Desert is a significant source of airborne dust that affects much of Eastern Asia, the Northern Pacific, and sometimes North America (Huang et al., 2008).

The CALIPSO study found that in atmospheres containing light, moderate and heavy dust layers, the dust aerosols heat the atmosphere (daily mean) by up to 1, 2, and 3 Kday-1, respectively. The maximum daily mean radiative heating rate reaches 5.5 Kday-1 at 5 km on 29 July. The averaged daily mean net radiative effect of the dust are 44.4, “41.9, and 86.3 $Wm^{"2}$, respectively, at the top of the atmosphere (TOA), surface, and in the atmosphere. Among these effects about two thirds of the warming effect at the TOA is related to the longwave radiation, while about 90% of the atmospheric warming is contributed by the solar radiation. At the surface, about one third of the dust solar radiative cooling effect is compensated by its longwave warming effect. The recent study of Satheesh et al. (2006), which studied the atmospheric warming due to dust aerosols over the Afro-Asian region, however found a reduction of solar radiation heating at the surface with a lower atmospheric warming of 0.3 to 0.5 Kday-1.

5.0 Conclusion and Recommendations

Journal articles on dust aerosol effect on climate have been reviewed. The review showed that dust aerosol is a major contributor to aerosol mass loading in the atmosphere. Continuous research into dust aerosol optical properties is therefore likely to provide essential data that will offset the uncertainties observed in regional and global radiative forcing by dust aerosols. All the articles surveyed highlight the importance of dust aerosols in arid and semi-arid regions in increasing solar absorption at the top of the atmosphere, while decreasing solar absorption at the surface. This significant result is major area of interest since the impacts of this finding s are still being investigated. Finally, the review serves as a summary of journal articles on dust aerosol research, particularly for new research students.

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