Climatology and Variability of Aerosol over Africa, the Atlantic, and the Americas

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the requirements for the degree of
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CLIMATOLOGY AND VARIABILITY OF AEROSOL OVER AFRICA, THE
ATLANTIC, AND THE AMERICAS

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Using Vertical Feature Mask (VFM) data from Cloud - Aerosol Lidar Infrared Pathfinder Satellite Observations (CALIPSO), I have documented 3-dimensional (3D) structures in occurrence probabilities of aerosol over a broad region of Africa, the Atlantic, Europe, and Americas. The 3D structures illustrate the seasonal means and seasonal cycle in the zonal and meridional variability of the vertical profiles of mineral dust, biomass burning smoke, and polluted dust (external mixture of dust and smoke), and their emissions sources and transport pathways.

Emission sources vary by geographical location. The persistent Saharan dust source is evident throughout the year and observed and recorded by CALIPSO 70-80% of the time over Africa. Horizontal and vertical occurrence of dust is variable in time with maximum heights and westward transport occurring in boreal summer and minimum heights and transport occurring in boreal winter. The southern African biomass burning source is also evident throughout the year, through westward transport over the Atlantic is only evident in boreal summer and fall; mixing with dust over the continent limits westward transport of pure smoke to the continent in winter and spring. Other smaller smoke and dust sources are discussed.

The role of the Inter-Tropical Convergence Zone (ITCZ) in limiting the southward transport of dust and northward transport of smoke over Africa is
demonstrated. Surprisingly, the highest probability of polluted dust is found in the ITCZ, even though the probabilities of dust and smoke are low. Wind trajectories reveal smoke of southern African origin is transported northward at the lower levels, but rarely penetrating through ITCZ rainband while Saharan dust is transported southward at higher levels, crossing the ITCZ frequently. This quasi-circulation of aerosol is shown to be the mixing mechanism of dust and smoke into polluted dust in the area of the ITCZ.
Dedicated to everyone considering finishing or continuing their education.

I did it and so can you.
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LIST OF ABBREVIATIONS

3D – Three dimensional
AERONET – Aerosol Robotic Network
AOD – Aerosol optical depth
CALIOP – Cloud-Aerosol Lidar with Orthogonal Polarization
CALIPSO – Cloud-Aerosol Lidar Infrared Pathfinder Satellite Observations
CCN – Cloud condensation nuclei
E - East
ECMWF – European Centre for Medium-Range Weather Forecasts
FIR – Finite impulse response
GOCART – Goddard Chemistry Aerosol Interactions and Chemistry
IGBP – International Geosphere/Biosphere Programme
IN – Ice nuclei
IPCC – Intergovernmental Panel on Climate Change
IR – Infrared
ITCZ – Intertropical Convergence Zone
Km – Kilometer
MOSAIC – Model with Model for Simulating Aerosol Interactions and Chemistry
N – North
NASA – National Aeronautics and Space Administration
PDF – Probability Density Function
S – South
SCA – Scene Classification Algorithm
SFC – Surface
SIBYL – Selective Iterated Boundary Location
TOA – Top of the atmosphere
TRMM – Tropical Rainfall Measuring Mission
US – United States
VFM – Vertical Feature Mask
W – West
WRFC – Weather Research and Forecasting with Chemistry
CHAPTER 1

INTRODUCTION

Natural and anthropogenic aerosols play important roles in Earth’s climate by altering the radiation budget and influencing key processes (e.g., rain formation) in the hydrological cycle. Aerosol direct radiative effect is associated with its ability to scatter and absorb solar and longwave radiation (McCormick and Ludwig, 1967). Aerosol indirect radiative effect is typically divided into two categories. The first indirect effect refers to as the impact of anthropogenic aerosol on cloud brightness thus altering cloud albedo (Twomey, 1967). The second indirect effect refers to as alteration of cloud lifetime due to decreased precipitation efficiency (Albrecht, 1989). Based on the 2007 IPCC report, estimates vary between 0.61 to 2.43 W m\(^{-2}\) for all sky direct effect and -0.22 to -1.85 W m\(^{-2}\) for cloud albedo effect. Our understanding of aerosol effects on the global hydrological cycle as active cloud condensation nuclei (CCN) and ice nuclei (IN) suffers even greater uncertainties (Forster et al., 2007). Reducing the uncertainties in aerosol climatic effects is an inevitable step toward increasing the reliability of global climate models in reproducing the current climate and projecting the future one.

To reduce uncertainty in aerosol direct and indirect radiative effect thereby attaining a better understanding of climate implications, global and regional circulation models in concert with in-situ and remote sensing measurements must be employed (Horowitz et al., 2005; Kaufman et al., 2002a; Ming and Ramaswamy, 2008; Penner et al., 1994). Numerous direct radiative effect studies using model simulations typically calculate radiative fluxes at the top of the atmosphere (TOA) and at the surface (SFC) using various model estimations for pre-industrial and post-industrial aerosol loading
(Chung and Seinfeld, 2005; Myhre et al., 2007; Shell and Somerville, 2007). Results are often inconsistent in magnitude and, in some cases, sign of TOA and SFC radiation fluxes (Forster et al., 2007; Shultz et al., 2006; Yu et al., 2006). Several sources of error are described in the literature that contributes to study discrepancies, the most predominant deficiency being a need to more accurately resolve aerosol vertical distribution (Claquin et al., 1998; Kahn et al., 2004) as the vertical distribution affects precipitation patterns (Huang et al., 2009), surface temperature changes, and available atmospheric energy (Menon, 2004). Model simulations based on dynamical equations are most effective in evaluating aerosol indirect effect (Pierce et al., 2007). These models attempt to resolve cloud microphysical processes by predicting aerosol size distribution and therefore number concentration of cloud condensation nuclei to predict radiative forcing. Accurate prediction of the size distribution is the largest source of error in evaluating aerosol indirect effect (Penner et al., 2006) and can be reduced by improving the size distribution of emissions (Pierce et al., 2007).

Until recently, analysis of vertical aerosol distribution was confined to small spatial scales with focus on a specific city or region due to coverage limitations. Although still used today, aircraft missions to collect aerosol samples and measure size distributions (Kaufman et al., 2003; Liu et al., 2009; Shinozuka et al., 2007) and ground-based lidar (Chazette, 2003; Huang et al., 2010; Matthias et al, 2004) were necessary to examine vertical profiles of aerosol extinction as satellite data was restricted to column values or averages. With the continued advancement of remote sensing technology, new tools are becoming available to study aerosol profiles. The launch of Cloud - Aerosol Lidar Infrared Pathfinder Satellite Observations (CALIPSO) in 2006 allows for aerosol
profiling with unprecedented vertical resolution and a first glimpse into 3-dimensional (3D) aerosol profiles.

Since the launch of CALIPSO, various methods have been employed to use the data. CALIPSO data has been used in concert with model simulation and additional remote sensing instruments to evaluate aerosol vertical distribution (Bou Karam et al., 2010; Huang et al., 2009; Yu et al., 2010), validate model simulations (Generoso et al., 2008), and to assimilate observations into a model simulation to correct for non-homogeneous background error statistics (Sekiyama et al., 2010). Despite efforts to evaluate vertical distribution, a lack of global assessment still exists.

Given the current need of a better understanding of vertical and horizontal aerosol distribution and structure in order to quantify aerosol effects on climate and the hydrological cycle through model simulation, this study aims to describe the frequency of occurrence of aerosol species. I describe the spatial and temporal distribution of aerosol using unique 3D aerosol seasonal average and seasonal cycle occurrence probabilities in a region composed of the African continent, tropical Atlantic, Caribbean, South America, and eastern United States using CALIPSO Vertical Feature Mask (VFM). Robust aerosol frequency structures for dust, smoke, polluted dust (externally mixed dust and smoke), and total aerosol are described. Chapter 2 contains the descriptions of the data used in this study and data processing methodology. Results are described in Chapter 3, followed by conclusions in Chapter 4.
2.1 CALIPSO Satellite Data

The CALIPSO satellite was launched into the A-Train satellite constellation on April 28, 2006. The payload of CALIPSO includes a high resolution Cloud - Aerosol Lidar with Orthogonal Polarization (CALIOP) which consists of a dual wavelength polarization lidar (532 nm and 1064 nm) in concert with three receiver channels that measure the backscatter intensity at 532 nm, polarized 532 nm, and 1064 nm wavelengths with a pulse energy of 110 mJ/channel and repetition rate of 20.25 Hz (Hunt et al., 2009).

Figure 2.1: Representation of NASA's A-Train constellation of satellites. Photo from NASA.
One of its products is the Vertical Feature Mask (VFM). The VFM algorithm is described in the CALIOP Algorithm Theoretical Basis Document, Part 3: Scene Classification Algorithms (Liu, 2005). It identifies the presence of clear air, cloud type, or aerosol type at each horizontal and vertical grid point. Areas identified by the Selective Iterated Boundary Location (SIBYL) as an area of enhanced scattering are first evaluated by the Scene Classification Algorithm (SCA) as to whether or not the area is an elevated or non-elevated nonclear-air feature, the surface, or totally attenuated.

![CALIPSO Scene Classification Algorithm](image)

**Figure 2.2:** CALIPSO Scene Classification Algorithm used to classify and subtype cloud and aerosol. From Liu et al., 2005.

Upon detection of a feature, the SCA evaluates if the feature is a lofted layer or near surface layer then identifies the layer as cloud or aerosol based upon a confidence function computed from the layer mean value of the attenuated backscatter coefficient at 532 nm, the ratio of the backscatter at 1064 nm and 532 nm (volume color ratio), the height of the center of the layer, and an existing PDF database. Once the SCA
determines the feature is aerosol, it is categorized into six aerosol types: desert dust, biomass burning smoke, polluted dust (externally mixed desert dust and biomass burning smoke), polluted continental aerosol (urban pollution), clean continental aerosol (background aerosol), and marine aerosol (sea salt). Input parameters including integrated attenuated backscatter coefficient ($\gamma'$), integrated volume depolarization ratio ($\delta$), altitude, location, and International Geosphere/Biosphere Programme (IGBP) surface type are used to determine aerosol type (Liu et al., 2005). The depolarization ratio, a ratio of the parallel and perpendicular backscatter at 532nm, relates the extent the particles are spherical; a value of 0 indicates the particles are spherical whereas values between 0.2 and 0.5 indicate non-spherical particles. Integrated backscatter indicates the magnitude of the aerosol loading in the layer.

The flowchart in Figure 2.3 describes the eleven pathways used for the six aerosol identification types. Only one pathway for dust identification exists; if the IGBP surface type is not snow/ice tundra and $\delta > 0.2$ the classification is dust (path 4). Polluted dust classification is recorded if $0.075 < \delta < 0.2$ (path 3) or if $\delta < 0.075$, it is over land, $\gamma' < 0.0005$, and IGBP surface type is desert (path 5). The aerosol is identified as smoke if $\delta < 0.075$, it is over land, $\gamma' > 0.0005$, and is an elevated layer (path 10) or $\delta < 0.075$ and it is an elevated marine layer (path 11). Polluted continental is the determined to be the type if IGBP surface type is snow/ice tundra and $\gamma' > 0.0015$ (path 2). If the surface type is not snow/ice tundra, $\gamma' > 0.0005$, and it is over land but not elevated (path 7) or it is a non-elevated marine layer with $\gamma' > 0.0015$ (path 8).

This study focuses on desert dust, smoke, and polluted dust, but includes polluted continental when describing total aerosol. Level 2 VFM Validated Stage 1 version 3 data
(CAL_LID_L2_VFM-ValStage1-V3) and Level 2 5km provisional aerosol layer version 3 data (CAL_LID_L2_05km_Alay-Prov-V3) are used in this study.

Figure 2.3: Flowchart of CALIOP color ratio ($S_a$) determination scheme through aerosol identification. $\gamma'$ is the integrated attenuated backscatter coefficient, $\delta$ is the integrated volume depolarization ratio, and the values are the determined $S_a$ at 532nm and 1064nm.

The analysis period of this study includes all available VFM data in the period June 16, 2006 through February 28, 2011. Boreal summer includes June, July, and August 2006 - 2009 with an additional June 1 - 16 in 2010 to complete the season as the 2006 data begins on June 16. Fall includes September, October, and November 2006 - 2010. Winter includes December, January, and February 2006/2007 - 2009/2011. Spring includes March, April, and May 2007 - 2010. Only night-time data (descending orbits) are used since returns are of significantly better quality during the night than during the day due to a reduction in the signal to noise ratio due to the solar background (Powell et al., 2009). Horizontal and vertical spatial resolution varies with height. In this study,
only the lower 8.17 km of the troposphere is examined. For these altitudes, the VFM has a vertical resolution of 30m and horizontal resolution of 333m.

2.2 CALIPSO Vertical Feature Mask Error Statistics

The accuracy of CALIPSO VFM is generally high, particularly for dust and polluted dust classification (Mielonen et al., 2009), but is prone to misclassification errors under certain circumstances. The most prominent error is the misclassification of dust or smoke as cloud which occurs when the dust or smoke layer is thick, replicating cloud optical properties, and near a cloud layer (Liu et al., 2009). Liu et al found this type of error to be less than 1% of cases involving dust and suggested smoke misclassification is much less. Misclassification of aerosol under thin ice clouds may also be a problem (Liu et al., 2009). Classification in the boundary layer is also questionable (Omar et al., 2009).

Mielonen et al. compared daily CALIOP and Aerosol Robotic Network (AERONET) aerosol classifications at 38 AERONET sites worldwide, comparing a total of 277 days (satellite passes) yielding a 71% agreement. Their results are shown in Figure 2.3 where CALIOP aerosol types are 1) dust, 2) polluted dust, 3) smoke, 4) marine, and 6) clean and polluted continental (note 5) is not used). The vertical black line indicates the AERONET classification.

Best agreement between AERONET and CALIOP classification is in the case of dust with an agreement of 91% (Figure 2.4a). For polluted dust, the agreement reduces to 53% (Figure 2.4b) as CALIOP’s classification was often dust. Smoke agreement reduces to 37% (Figure 2.4c) where CALIOP often identified polluted dust or continental.
largest difference was found with continental aerosol where agreement was only 22% (Figure 2.4d).

**Figure 2.4:** VFM aerosol classification comparison with AERONET classification. CALIOP aerosol types are (1) dust, (2) polluted dust, (3) smoke, (4) marine, and (6) clean and polluted continental. The vertical black line is the AERONET aerosol classification. From Mielonen et al., 2009.

**2.3 TRMM Precipitation**

Tropical Rainfall Measuring Mission (TRMM) 3B42 precipitation data were used to describe the location of the ITCZ and precipitation estimates. This is a TRMM-adjusted merged-IR precipitation estimate (Kummerow et al., 2000). TRMM payload is described in Kummerow et al. (1998). The daily gridded (0.25°x25° resolution, 50N - 50S) data cover the analysis period described above.
2.4 ERA-Interim Wind

Some plots include European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim wind reanalysis data. Product description is found in Simmons et al. (2006). Vertical wind (w) is exaggerated by a factor for 5 before wind vectors are plotted. The daily gridded (2.5°x2.5° resolution) data cover the described analysis period.

2.5 Seasonal Averaged Occurrence Probability

VFM Level 2 swath data were gridded into a three dimensional latitude, longitude, and height matrix with dimensions of 1° x 1° x 30m for 290 levels with a range of -0.5 km to 8.17 km. The rectangular domain of interest covers 40S – 60N and 60E – 100W. This domain includes regions that are known for their aerosol sources and concentrations, such as Africa, the Atlantic Ocean, South America, Caribbean, and the eastern United States.

Figure 2.5: Vertical slice of total aerosol during summer at 20E. The colorbar represents the number of times an aerosol was found at each grid point.
There are 161 x 101 x 290 horizontal and vertical grid points in this 3D domain. At each grid point, the occurrence of dust, polluted dust, polluted continental, and smoke was tallied. An example of meridional data slice is shown in Figure 2.5, where the colorbar represents the number of occurrences of total aerosol in summer at 20E. The lack of global coverage due to the narrow lidar beam width is apparent.

The total occurrence number of each types of aerosol was then normalized by the total number of valid satellite passes at that grid point. A valid satellite pass is defined here as a VFM indication of clear air, aerosol, or cloud. This yields the percentage of time the aerosol was identified at each grid point.

**Figure 2.6:** Vertical slice of aerosol identification tally of total aerosol during summer at 20E, normalized by the number of valid satellite passes. A valid satellite pass is defined to be a VFM identification of clear air, cloud, or aerosol. Colorbar represents the fractional amount of time an aerosol was identified.

An example is given in Figure 2.6 where the colorbar represents the fractional amount of time aerosol was identified and yields a noticeably different aerosol
representation than that of Figure 2.5. The number of valid satellite passes is highly variable horizontally and vertically, with highest values at upper altitudes (maximum approximately 7000 per season at a grid point, and minimum approaching 0 near the surface).

A grid point is considered invalid and treated as no data if its total number of valid satellite passes is less than a threshold in order to minimize the spread of anomalous aerosol identifications or misclassification due to running mean averaging (discussed next) such as the vertical line with a value of one seen in Figure 2.5 near 20S. This threshold is defined to be 15% of the maximum number of valid satellite passes through the domain during a season over the observing period. Additionally, values less than a specified threshold are not plotted. In Figure 2.7, the cutoff value is 0.15.

![Graph](image)

**Figure 2.7:** Vertical slice of the normalized total aerosol identification during summer at 20E. Values less than 0.15 are removed and a satellite threshold of 15% of the maximum number of valid satellite passes is imposed. Values less than the threshold are treated as no data.
The normalized data were then smoothed to highlight coherent large-scale structures. First a 13-point zonal running mean finite impulse response (FIR) filter was applied. For this, data outside the analysis domain were used for the grid points near the boundaries. A second smoothing was applied using a 3-point meridional running mean FIR filter in a similar manner. An example of the final product is given in Figure 2.8.

![Figure 2.8](image)

**Figure 2.8:** Vertical slice at 20E of the total aerosol final product after normalization, imposing satellite cutoffs, removing values less than 0.15, and smoothing.

The thus processed data yielded a 3-dimensional (3D) structure of occurrence frequency or probability. It can be visualized by meridional-vertical cross-sections at every 10° longitude. Averages in the zonal, meridional, and vertical directions are projected onto the right side, back, and base of the figure, respectively. An example is given in Figure 3.1 which shows the summer mean structure of occurrence probability for total aerosol. Hereafter, such a structure of occurrence probability will be referred to simply as a structure.
2.6 Seasonal Cycles of Occurrence Probability

In addition to seasonal averages, a 3D seasonal cycle of occurrence probability was produced yielding a zonally integrated 3D structure as a function of latitude, height, and time. The VFM data were first tallied into a daily 3D array at each latitude (1°), longitude (1°), and height (30m) over the same analysis domain. Occurrences in longitude (x) are summed and normalized by the total valid satellite passes in a given longitudinal range (not the entire longitudinal extent of the whole domain):

\[
p(y,z,t) = \frac{\sum_{n=0}^{N} p(x + n, y, z, t)}{\sum_{n=0}^{N} s(x + n, y, z, t)} \quad \forall x, y, z, t
\]

where \( p \) is the resulting occurrence probability at the grid point, \( s \) is the total number of valid satellite passes at the same grid point, and \( N \) is variable based upon the number of grid points in a specified longitudinal range. The 3D dataset is then smoothed twice using a 29-day running mean FIR filter and once using a meridional three point running mean FIR filter. As in the seasonal average plots, a satellite cutoff of 15% of the maximum number of valid satellite passes is imposed and values less than 5% are not shown.

The ITCZ location was estimated using TRMM rainfall. Daily TRMM daily data were re-gridded into a 1° x 1° x 365 day matrix to match the resolution of occurrence structure and then integrated over a specified longitudinal range. A least-squares spline fitting was applied to zonally averaged TRMM rainfall maxima as a proxy of the position of the ITCZ. Precipitation contours are overlaid on the base of the figure.
Meridionally averaged seasonal cycles were created using the same methods as the zonally integrated seasonal cycle with the exception of meridional integration instead of zonal integration:

\[
p(x, z, t) = \frac{\sum_{n=0}^{N} p(x, (y + n), z, t)}{\sum_{n=0}^{N} s(x, (y + n), z, t)} \quad \forall x, y, z, t
\]  

(2)

where \( p \) is the resulting occurrence probability at the grid point, \( s \) is the total number of valid satellite passes at the same grid point, and \( N \) is variable based upon the number of grid points in a specified latitudinal range.

2.7 Aerosol Optical Depth and Layer Thickness

Aerosol optical depth (AOD) plots are created using CALIOP layer data are used for AOD and layer thickness analysis. AOD is recorded and tallied at each vertical gridpoint in an identified layer of dust, polluted dust, smoke, and total aerosol (combination of dust, smoke, and polluted dust) in the analysis domain for each season. The number of times each AOD occurs is normalized by the number of satellite passes in that season, then plotted as a function of height. The x-axis (AOD axis) is shown on a log scale is small plots for better visualization. Layer thickness is recorded at the center of the layer and is also normalized by the number of satellite passes. This yields a relative number concentration of layer thickness vs. height. Again the x-axis is shown on a log scale in small plots for better visualization.
CHAPTER 3

3D AEROSOL SEASONAL AVERAGES

Characteristics of 3D aerosol structures in the analysis domain, such as source regions, transport patterns, vertical, longitudinal and latitudinal distributions, and locations and sizes of most frequent aerosol regions, all vary significantly with season. There are also large differences in such characteristics for dust and smoke. In this chapter, the 3D aerosol seasonal averages are discussed. The 3D structures help reveal some interesting details that may bear significant implications.

3.1 Total Aerosol

In our analysis domain, boreal summer is indisputably the season with the most frequent occurrence of total aerosol (Figure 3.1a), followed by fall (Figure 3.1b) and spring (Figure 3.1d). Aerosol occurs the least frequently in winter (Figure 3.1c). The general seasonality of aerosol over the analysis domain has been documented by many (e.g., Carlson and Prospero, 1972; Torres et al., 2001; Kaufman et al., 2005; Huang et al., 2010). In Figure 3.1a, there are clear separations of regions with high aerosol probabilities: West Africa and the Atlantic corridor of the Saharan Air Layer (Carlson and Prospero, 1972), southern Africa, South America, and the northeastern US. North-south separations over Africa and America are evident in both vertically integrated probability (pattern at the base of the upper panel) and latitudinal-vertical cross sections. I will show that these separations are due to the ITCZ for the zonal mean (pattern at the right-side wall of the upper panel) as well as at each longitude during summer and fall, but tends to straddle the ITCZ during winter and spring. Near the western boundary of the domain, aerosol over the Caribbean and southeastern continental US are also separated. I
will show that this reflects two types of aerosol: dust over the Caribbean originated from Africa (Prospero and Lamb, 2003) and smoke presumably originated from fossil fuel combustion and biomass burning over the US. The east-west separation in the southern hemisphere (between Africa and South America) is mainly due to different source regions and a lack of zonal transport between them. In the northern hemisphere, the separation can be better perceived from the meridionally averaged probability pattern (on the back wall of the upper panel) though this is less apparent during winter (Figure 3.1c) and spring (Figure 3.1d). I will show that the three sections of high probabilities are due respectively to African dust, South American smoke, and southeastern US smoke/pollution.

Other details in the 3D structure include differential height between aerosol over northern and southern Africa and between Africa and Americas, fast increases in the vertical extent of the “aerosol core” (probability > 80%) from north to south over West Africa, sharp cutoffs in aerosol probability at all vertical levels at their southern boundary over West African and at their northern boundary over southern Africa, and “aerosol anvils” at certain longitude (20°W – 10 °E). These and other features will be discussed in detail in the rest of this section.
Figure 3.1a: Summer 3D seasonal average occurrence probability for total aerosol. Meridional, zonal, and vertical averages are projected on the back, right side, and base of the upper figure, respectively. Some slices are projected below the main figure for better viewing and contain topographic representations (black). Red dashed line is the ITCZ location estimated from TRMM.
**Figure 3.1b:** Fall 3D seasonal average occurrence probability for total aerosol. Meridional, zonal, and vertical averages are projected on the back, right side, and base of the upper figure, respectively. Some slices are projected below the main figure for better viewing and contain topographic representations (black). Red dashed line is the ITCZ location estimated from TRMM.
Figure 3.1c: Winter 3D seasonal average occurrence probability for total aerosol. Meridional, zonal, and vertical averages are projected on the back, right side, and base of the upper figure, respectively. Some slices are projected below the main figure for better viewing and contain topographic representations (black). Red dashed line is the ITCZ location estimated from TRMM.
Figure 3.1d: Spring 3D seasonal average occurrence probability for total aerosol. Meridional, zonal, and vertical averages are projected on the back, right side, and base of the upper figure, respectively. Some slices are projected below the main figure for better viewing and contain topographic representations (black). Red dashed line is the ITCZ location estimated from TRMM.
3.2 Dust

In boreal summer, several distinct dust source regions can be seen in Figure 3.2a. The primary dust source is over northern Africa. While the dust emission from the Sahara extends eastward over the tropical Atlantic Ocean, to its east, there appears to be another region of high dust occurrence over Middle East that is separated from Saharan dust. This separation is evident in the meridional average (projected on the back wall). In fall (Figure 3.2b), this separation remains identifiable, but to a much less extent. It is no longer present in winter (Figure 3.2c), but reappears in spring (Figure 3.2d). There might be two interpretations for this separation. One is that there are two distinct dust sources. One is the well-known Saharan source (Middleton and Goudie, 2001; Prospero et al., 2002; Engelstaedter et al., 2006); the other is a Middle East source originating from the eastern and southern Arabian Peninsula (Prospero et al., 2002; Washington et al., 2003). The second interpretation is that the separation of source region is due to the seasonal variability of the prevailing wind. Northerly wind, associated with the North Atlantic High, dominates the structure in summer coinciding with south-westward transport over the Arabian Peninsula. In winter, the northerly winds are still present, but transport direction over the Arabian Peninsula is defined by easterly and south-easterly winds resulting in a more uniform meridional average.

There are additional but much weaker dust sources. A persistent one is visible in southern South America, particularly Argentine Patagonia. Another one, much less frequent and more isolated, is located over southern Africa in Namibia and Botswana (Prospero et al., 2002). Both are visible throughout the year. There seems to be dust
presence over continental US, especially in fall and spring that is separated from the other
dust regions. The vertical extents of these regions of weak dust are very limited (< 2 km).

The westward transport of dust from North Africa undergoes substantial structural
variability in space and season. During boreal summer, dust is observed across the
Atlantic Ocean and extends to the Caribbean as far as 100W. Its observed frequency
varies from greater than 65% in the core at 20W to less than 30% in the core at 80W, the
center of the core remaining approximately constant at 3.5 km. The vertical extent
gradual decreases from about 6 km near the West African coast to less than 2 km over
Central America. The meridional coverage of dust also reduces from the east to west.
Over the Sahara, the structure maintains a maximum altitude of 6 km with a well-defined
maximum frequency core extending from the ground to about 5km with probability
values near 75%.

In fall, the westward extent of dust is greatly reduced; a coherent structure is
visible to ~50W with an observed frequency of approximately 15%. While the vertical
extent of dust is reduced from the summer almost everywhere, its reduction in longitude
toward the west remains clear, and so does the meridional coverage. The separation of the
two regions of maximum dust probability over North Africa is still evident. Maximum
altitude of ~5.5 km is relatively constant, but the core >75% extends only to 2 km. In
winter, the vertical extent of dust is further reduced from fall. There are no longer two
separated regions of high dust probability over North Africa. Maximum altitude reduces
to ~3.5 km with a core ~75% only extending to 1.5 km. Dust transport west of the West
African coast is minimal, with an abrupt cutoff in the probability from 50% to 15%
between 20W and 30W. The meridional coverage is expanding southward, presumably due to the southward movement of the ITCZ.

In spring, the general characteristics of dust are on their way to be fully recovered back to their summer structures, except the dust coverage reaches its most southward position over the Atlantic Ocean, apparently penetrating through the ITCZ rainband. This is possible because ITCZ rainfall is intermittent and strong, shallow northerly flows (immediately above the boundary layer) exist in winter and spring.

Compare Figures 3.1 and 3.2, it is clear that dust contributes substantially, but not completely, to total aerosol north of the equator. The dust contribution to total aerosol south of the equator is negligible, where smoke dominates, as will be discussed next.
Figure 3.2a: Summer 3D seasonal average occurrence probability for dust. Meridional, zonal, and vertical averages are projected on the back, right side, and base of the upper figure, respectively. Some slices are projected below the main figure for better viewing and contain topographic representations (black). Red dashed line is the ITCZ location estimated from TRMM.
**Figure 3.2b:** Fall 3D seasonal average occurrence probability for dust. Meridional, zonal, and vertical averages are projected on the back, right side, and base of the upper figure, respectively. Some slices are projected below the main figure for better viewing and contain topographic representations (black). Red dashed line is the ITCZ location estimated from TRMM.
Figure 3.2c: Winter 3D seasonal average occurrence probability for dust. Meridional, zonal, and vertical averages are projected on the back, right side, and base of the upper figure, respectively. Some slices are projected below the main figure for better viewing and contain topographic representations (black). Red dashed line is the ITCZ location estimated from TRMM.
Figure 3.2d: Spring 3D seasonal average occurrence probability for dust. Meridional, zonal, and vertical averages are projected on the back, right side, and base of the upper figure, respectively. Some slices are projected below the main figure for better viewing and contain topographic representations (black). Red dashed line is the ITCZ location estimated from TRMM.
3.3 Smoke

The 3D structure of smoke reveals four distinct sources in the analysis domain: southern Africa, South America, the southeastern United States, and Europe, all varying seasonally (Figure 3.3). The most robust and persistent source is located in southern Africa, a known location of extensive biomass burning (Cooke et al., 1996; Hao and Liu, 1994). Smoke occurrence probability is the highest (75-80%) in boreal summer (Figure 3.3a) and fall (Figure 3.3b) and is the lowest (<40%) in winter (Figure 3.3c). It reaches the highest level (5 – 6 km) in fall and lowest in winter and spring (< 5 km). It propagates westward into the Atlantic Ocean (~ 30W) only in summer and fall.

The second most prominent smoke source is over South America. It is presumably biomass burning mostly in the Amazon, but also in regions of southern Brazil, Paraguay, Uruguay, and northern Argentina. It is the most frequent (~50-60%) and most extensive in horizontal coverage in local spring (boreal fall) and the least in local fall (boreal spring), when non-negligible smoke frequency is observed only in isolated areas of Columbia and Venezuela to the north, and southern Brazil, Uruguay, and northeastern Argentina to the south. There is not much sign of zonal transport out of the continent in any season. The vertical extent of smoke over South America is noticeably lower than that over southern Africa.

The other two much weaker sources of smoke is the southeastern US and Europe. They are presumably due mainly to industrial domestic pollution and are possibly misclassified as smoke instead of polluted continental. No propagation from these sources is detected, but their seasonal variability is obvious. Smoke in the southeastern US is non-negligible only in summer. It is observable over Europe in all seasons, with the
maximum in probability and horizontal coverage in summer and minimum in winter. The vertical extent of smoke in both regions is generally limited (< 2 km) except in summer. In summer and fall, there is an interesting “overhang” extending westward from Africa at 3 – 6 km. The “vacancy” underneath is partially filled by polluted dust (Figure 3.5) and cloud (Figure 3.3) but is likely a result of differing wind trajectories between the levels (Figure 3.3, 5.1).

**Figure 3.3:** Summer vertical aerosol occurrence probability slices with ERA-Interim Reanalysis wind vectors and cloud (pink). Vertical wind is increased by a factor of five. Shaded gray is dust, green/blue contour is smoke, and red/yellow contour is polluted dust for a) 0 and b) 20W. Contours are plotted in 10% intervals and no cutoff is imposed.
Figure 3.4a: Summer 3D seasonal average occurrence probability for smoke. Meridional, zonal, and vertical averages are projected on the back, right side, and base of the upper figure, respectively. Some slices are projected below the main figure for better viewing and contain topographic representations (black). Red dashed line is the ITCZ location estimated from TRMM.
Figure 3.4b: Fall 3D seasonal average occurrence probability for smoke. Meridional, zonal, and vertical averages are projected on the back, right side, and base of the upper figure, respectively. Some slices are projected below the main figure for better viewing and contain topographic representations (black). Red dashed line is the ITCZ location estimated from TRMM.
Figure 3.4c: Winter 3D seasonal average occurrence probability for smoke. Meridional, zonal, and vertical averages are projected on the back, right side, and base of the upper figure, respectively. Some slices are projected below the main figure for better viewing and contain topographic representations (black). Red dashed line is the ITCZ location estimated from TRMM.
Figure 3.4d: Spring 3D seasonal average occurrence probability for smoke. Meridional, zonal, and vertical averages are projected on the back, right side, and base of the upper figure, respectively. Some slices are projected below the main figure for better viewing and contain topographic representations (black). Red dashed line is the ITCZ location estimated from TRMM.
3.4 Polluted Dust

In all seasons, polluted dust encompasses the majority of the analysis domain with the exception of the western Sahara, the Atlantic south of ~10S and east of ~10W (Figure 3.5). In boreal summer (Figure 3.5a), the largest occurrence probability is found near the surface over the Caribbean, extending eastward to ~30W, with occurrences ~65% in the boundary layer that quickly diminish with height. The southward extent appears to be limited by the ITCZ. Polluted dust over South America is primarily collocated with smoke, but with decreased maximum altitude. The northern extent of South American polluted dust also appears to be limited by the ITCZ. That is not true of the polluted dust from central Africa; in this area the occurrence near 50% is in the vicinity of the ITCZ. The latitude-height slices of 10-30W reveal an elevated probability oval extending upward to ~5km. It will be shown that this is collocated with the dust structure (Figure 3.2a) and is the result of smoke/dust mixing during westward transport from Africa.

Boreal fall (Figure 3.5b) structure exhibits a similar spatial pattern as in summer, though maximum altitude and occurrence are decreased over the US and South America. Over central and southern Africa, the same is true north of the ITCZ, but south of the ITCZ maximum altitude and frequency increases slightly. The gap observed in the 20 and 30E latitude-height slices in Figure 3.5a is significantly decreased. Boreal winter (Figure 3.5c) displays the same general spatial pattern in the vertical average, but the vertical distribution is changed from the other seasons. The structure’s maximum frequency of occurrence straddles the ITCZ throughout the Atlantic basin, decreasing in altitude in the westward direction and can be seen in the meridional average. The structure of boreal spring (Figure 3.5d) is almost identical to fall (Figure 3.5b).
Figure 3.5a: Summer 3D seasonal average occurrence probability for polluted dust. Meridional, zonal, and vertical averages are projected on the back, right side, and base of the upper figure, respectively. Some slices are projected below the main figure for better viewing and contain topographic representations (black). Red dashed line is the ITCZ location estimated from TRMM.
Figure 3.5b: Fall 3D seasonal average occurrence probability for polluted dust. Meridional, zonal, and vertical averages are projected on the back, right side, and base of the upper figure, respectively. Some slices are projected below the main figure for better viewing and contain topographic representations (black). Red dashed line is the ITCZ location estimated from TRMM.
Figure 3.5c: Winter 3D seasonal average occurrence probability for polluted dust. Meridional, zonal, and vertical averages are projected on the back, right side, and base of the upper figure, respectively. Some slices are projected below the main figure for better viewing and contain topographic representations (black). Red dashed line is the ITCZ location estimated from TRMM.
Figure 3.5d: Spring 3D seasonal average occurrence probability for polluted dust. Meridional, zonal, and vertical averages are projected on the back, right side, and base of the upper figure, respectively. Some slices are projected below the main figure for better viewing and contain topographic representations (black). Red dashed line is the ITCZ location estimated from TRMM.
3.5 Polluted Continental

I have included polluted continental (Figure 3.6) for completeness though I have low confidence in this aerosol classification type because it is confined to the boundary layer and has been shown to have high misclassification rate (Mielonen et al., 2009). During all seasons, the highest occurrence values are found in southern Africa and South America, areas known to be locations of high biomass burning activity. The maximum occurrence is found during boreal fall (Figure 3.6b), where values reach ~80% South America at 50W. Interestingly, this is an area with high smoke identification probability. Further investigation is required to ensure this is in fact industrial pollution or misclassification of smoke.
Figure 3.6a: Summer 3D seasonal average occurrence probability for polluted continental. Meridional, zonal, and vertical averages are projected on the back, right side, and base of the upper figure, respectively. Some slices are projected below the main figure for better viewing and contain topographic representations (black). Red dashed line is the ITCZ location estimated from TRMM.
Figure 3.6b: Fall 3D seasonal average occurrence probability for polluted continental. Meridional, zonal, and vertical averages are projected on the back, right side, and base of the upper figure, respectively. Some slices are projected below the main figure for better viewing and contain topographic representations (black). Red dashed line is the ITCZ location estimated from TRMM.
Figure 3.6c: Winter 3D seasonal average occurrence probability for polluted continental. Meridional, zonal, and vertical averages are projected on the back, right side, and base of the upper figure, respectively. Some slices are projected below the main figure for better viewing and contain topographic representations (black). Red dashed line is the ITCZ location estimated from TRMM.
Figure 3.6d: Spring 3D seasonal average occurrence probability for polluted continental. Meridional, zonal, and vertical averages are projected on the back, right side, and base of the upper figure, respectively. Some slices are projected below the main figure for better viewing and contain topographic representations (black). Red dashed line is the ITCZ location estimated from TRMM.
CHAPTER 4

3D AEROSOL SEASONAL CYCLES

4.1 Seasonal Migration

The seasonal cycle of zonally integrated total aerosol in the eastern side of the region (60E-31W) is shown in Figure 4.1a. Red contours are zonally integrated precipitation, the black line estimating the location of the ITCZ based upon rainfall maxima. The large signal south of the ITCZ is primarily smoke (Figure 4.2c); the signal north of the ITCZ is primarily dust (Figure 4.2b); polluted dust is throughout the region (Figure 4.1d). Maximum heights in the seasonal cycle are consistent with maximum heights seen and described previous sections.

Dusts and smoke are observed in areas of minimum rainfall, overlapping only in late summer/early fall. The area of observed African smoke south of the ITCZ occurs in an area of rainfall minima. The northerly extent of smoke increases from 10S in June to 5N in mid-September, then retreats southward to 10S in early November. This coincides very closely with the annual migration of the ITCZ. Observation of dust also occurs in an area of rainfall minima north of the ITCZ, the southern extent penetrating through and crossing the ITCZ throughout the year.

Horizontal polluted dust characteristics are quite different than those of dust and smoke (Figure 4.1d). The most frequent occurrences of polluted dust are located in the vicinity of the ITCZ, but with an inverse relationship to rainfall amount; in winter when rainfall rates are decreased, polluted dust observation is at maximum; when rainfall is more abundant in summer polluted dust observation is minimum. Despite the inverse
relationship, the seasonal cycle of polluted dust closely resembles maximum rainfall seasonal cycle.

**Figure 4.1a:** Total aerosol 3D seasonal cycle integrated over longitude 60E-31W. Black line is the estimated ITCZ from TRMM. Red dashed and solid lines represent longitudinally integrated TRMM precipitation with dotted lines indicating minimum values and solid lines indicating maximum values. Note that colorbar units are higher than seasonal average plots.

**Figure 4.1b:** Dust 3D seasonal cycle integrated over longitude 60E-31W. Black line is the estimated ITCZ from TRMM. Red dashed and solid lines represent longitudinally integrated TRMM precipitation with dotted lines indicating minimum values and solid lines indicating maximum values. Note that colorbar units are higher than seasonal average plots.
**Figure 4.1c:** Smoke 3D seasonal cycle integrated over longitude 60E-31W. Black line is the estimated ITCZ from TRMM. Red dashed and solid lines represent longitudinally integrated TRMM precipitation with dotted lines indicating minimum values and solid lines indicating maximum values. Note that colorbar units are higher than seasonal average plots.

**Figure 4.1d:** Polluted dust 3D seasonal cycle integrated over longitude 60E-31W. Black line is the estimated ITCZ from TRMM. Red dashed and solid lines represent longitudinally integrated TRMM precipitation with dotted lines indicating minimum values and solid lines indicating maximum values. Note that colorbar units are higher than seasonal average plots.

The zonally integrated seasonal cycle for the western side of the region (31W-100W) is shown in Figure 4.2. Red contours are zonally integrated precipitation, the
black line estimating the location of the ITCZ based upon rainfall maxima. Again, the dust is located north of the ITCZ (Figure 4.2b) and smoke is located south of the ITCZ (Figure 4.2c), though the smoke source here is primarily of South American origin with some minimal contribution from Africa. Unlike the eastern side of the region, the southward extent of dust only slightly crosses the ITCZ region. Largest occurrence probabilities of polluted dust (Figure 4.2d), with values greater than 25%, are primarily below 2km and are located north of the ITCZ throughout the year with little variability near the ITCZ throughout the year. This is in sharp contrast to the eastern side of the basin (Figure 4.1d) where polluted dust straddled the ITCZ with maximum values November through June.

**Figure 4.2a:** Total aerosol 3D seasonal cycle integrated over longitude 31W-100W. Black line is the estimated ITCZ from TRMM. Red dashed and solid lines represent longitudinally integrated TRMM precipitation with dotted lines indicating minimum values and solid lines indicating maximum values. Note that colorbar units are lower than seasonal average plots.
Figure 4.2b: Dust 3D seasonal cycle integrated over longitude 31W-100W. Black line is the estimated ITCZ from TRMM. Red dashed and solid lines represent longitudinally integrated TRMM precipitation with dotted lines indicating minimum values and solid lines indicating maximum values. Note that colorbar units are lower than seasonal average plots.

Figure 4.2c: Smoke 3D seasonal cycle integrated over longitude 31W-100W. Black line is the estimated ITCZ from TRMM. Red dashed and solid lines represent longitudinally integrated TRMM precipitation with dotted lines indicating minimum values and solid lines indicating maximum values. Note that colorbar units are lower than seasonal average plots.
Figure 4.2d: Polluted dust 3D seasonal cycle integrated over longitude 31W-100W. Black line is the estimated ITCZ from TRMM. Red dashed and solid lines represent longitudinally integrated TRMM precipitation with dotted lines indicating minimum values and solid lines indicating maximum values. Note that colorbar units are lower than seasonal average plots.

The meridionally integrated seasonal cycle of aerosol is shown in Figure 4.3, integrated over 30S-30N. The east-west separation observed in the total aerosol 3D seasonal average (Figure 3.1a) is evident in the meridionally integrated total aerosol seasonal cycle (Figure 4.3a). East of 20W, aerosol is observed throughout the year, with maximum height and probabilities June through September. This represents all aerosols over Africa. At the lower levels, dust (Figure 4.3b) and polluted dust (Figure 4.3d) are primary contributors, with little to no contribution of smoke (Figure 4.3c). Polluted dust is rarely observed above 4km, but dust is observed June through November. Smoke also contributes to total aerosol observation above 4km, but is limited to September through November. Smoke is observed over land throughout the year with an abrupt cutoff at 20E, the western continental boundary in southern Africa. The westward transport over ocean begins very quickly in August and abruptly ends in November near the continent,
clearly evident in the 10E time-altitude slice of Figure 4.3c. To the west the observed period becomes shorter; at 30W, occurrence is observed mid-August through mid-September.

Although the western side of the region (west of 20W) contains total aerosol occurrence throughout the year, a clear seasonality is detected both in maximum height and occurrence probability. Between 20W and 60W, a ~2km increase in maximum height is evident June through November, though the peak altitudes decrease from 6km to 4km westward. 30 and 40W contain little variability in occurrence during the year, while a clear fluctuation is evident at 50 and 60W where probabilities greater than 40% are observed August and September. Each aerosol type contributes to this fluctuation; it is observed in the dust migration from Africa and the polluted dust and smoke observations from the US and South America.

**Figure 4.3a:** Total aerosol 3D seasonal cycle integrated over latitude 30S-30N. Note that colorbar units are lower than all previous plots.
Figure 4.3b: Dust 3D seasonal cycle integrated over latitude 30S-30N. Note that colorbar units are lower than all previous plots.

Figure 4.3c: Smoke 3D seasonal cycle integrated over latitude 30S-30N. Note that colorbar units are lower than all previous plots.
**Figure 4.3d:** Polluted dust 3D seasonal cycle integrated over latitude 30S-30N. Note that colorbar units are lower than all previous plots.
CHAPTER 5

AEROSOL INTERCOMPARISON AND TRANSPORT

5.1 Summer

Visualization of combined dust and smoke with polluted dust contours on the latitude-height slices for the summer season is presented in Figure 5.1. This is useful in evaluating the longitudinal and latitudinal range of each individual aerosol leading to the possible limiting mechanisms of each and conversion from pure dust or smoke to polluted dust.

Over the African continent, some overlap of dust and smoke exists (Figures 5.1a, b). The overlap is distinguishable from 30E (not shown) to 0 (Figure 5.1b). As seen in the slices and the seasonal cycle, this location marks an abrupt southward limit of dust and northward limit for smoke due to the ITCZ.

Polluted dust is dominant in this area, near the northern dust limit where dust combines with European smoke, and near the southern limit of smoke in southern Africa. At the southern dust/smoke boundary, the presence of polluted dust is probably due to mixing across the ITCZ. As dust and smoke propagate to the west, a clear separation of the two signals diminishes. The smoke is converted to polluted dust and the locations of the dust and polluted dust signals coincide west of 20W (Figure 5.1c).

At 20W, a circulation is present transporting smoke downward, shifting to northward transport below 1.5km into the observed dust vicinity, then transporting dust upward and southward back into the smoke region. Polluted dust is found throughout the circulation, except in the area of highest smoke observation. One must be careful in interpreting this mixing mechanism as the prevailing wind is zonal at the top of the
apparent circulation transporting dust and smoke westward north of the ITCZ (Figure 5.2c), and south of the ITCZ at 1km transporting dust westward(Figure 5.2a).

The South American smoke source emerges in the 40W (Figure 5.1d) and is fully present at 60W (Figure 5.1e). Two areas of polluted dust observations increase at these longitudes; one is over South America and the other is in the area where dust is observed. This would seem to indicate the dust originating from Africa (5-30N in Figure 5.1e) and dust originating is southern South America (15-40S in Figure 5.1e) is mixing with smoke to form the external mixture of polluted dust, confirmed by the southeasterly wind seen in the horizontal slices of Figure 5.2 at 1 and 2km. However, there may be some contribution to polluted dust via transport from European sources. The southern polluted dust is likely due to the to the northerly wind south of 15S, transporting smoke to the dust source region.

5.2 Fall

In boreal fall, the general transport and mixing mechanisms exist on both sides of the region are quite similar. In the east, the vacancy beneath the African smoke is also filled by polluted dust (Figure 5.3a,b), but with higher occurrence probability values in the area of the dust and smoke overlap. The west also exhibits the same dust and polluted dust patterns, but the altitude and frequency of dust and polluted dust north of the ITCZ are significantly reduced.
Figure 5.1: Summer vertical aerosol occurrence probability slices with ERA-Interim Reanalysis wind vectors. Vertical wind is increased by a factor of five. Shaded gray is dust, green/blue contour is smoke, and red/yellow contour is polluted dust for a) 20E, b) 0, c) 20W, d) 40W, e) 60W, and f) 80W. Contours are plotted in 10% intervals and no cutoff is imposed.
Figure 5.2: Summer horizontal aerosol occurrence probability slices with ERA-Interim Reanalysis wind vectors. Shaded gray is dust, green/blue contour is smoke, and red/yellow contour is polluted dust for a) 1km, b) 2km, c) 3km, and d) 4.2km. Contours are plotted in 10% intervals and no cutoff is imposed.
Figure 5.3: Fall vertical aerosol occurrence probability slices with ERA-Interim Reanalysis wind vectors. Vertical wind is increased by a factor of five. Shaded gray is dust, green/blue contour is smoke, and red/yellow contour is polluted dust for a) 20E, b) 0, c) 20W, d) 40W, e) 60W, and f) 80W. Contours are plotted in 10% intervals and no cutoff is imposed.
Figure 5.4: Fall horizontal aerosol occurrence probability slices with ERA-Interim Reanalysis wind vectors. Shaded gray is dust, green/blue contour is smoke, and red/yellow contour is polluted dust for a) 1km, b) 2km, c) 3km, and d) 4.2km. Contours are plotted in 10% intervals and no cutoff is imposed.
5.3 Winter

The aerosol structure and is markedly different in boreal winter. Figures 5.5a and 5.5b indicate there are two sources of smoke over Africa, one north and a larger one south of the equator. This was not visible in Figure 3.4d due to the 15% cutoff imposed. The strong northerly component of the wind in the below 2km in Figure 5.5a do agree with the generally northerly component at 1km (Figure 5.6a) and 2km (Figure 5.7a) and can be more readily interpreted than in summer and fall. Dust is transported southwestward over Africa into the northern smoke region, then lofted upward where the two combine to form polluted dust. Additional smoke is added from the southern source due to the southerly wind component at 3km (and possibly below). It is possible that at 3km (Figure 5.6c) the east-south-easterly wind transports the polluted dust and dust over the Atlantic where dry deposition occurs and thus is observed at the levels below. The wash-out effect is clear over the Atlantic where a sudden 10% decrease then increase occurrence is observed. Dust and polluted dust are observed through 40W (Figure 5.5d), but have very low occurrence probabilities (10% or less) west of 40W.

5.4 Spring

In boreal spring, the spatial pattern begins to return to the summer structure with some exceptions. Dust transport over Africa is much like winter; dust propagates generally southward, across the ITCZ, but not at the lower levels as in winter. Instead, the transport occurs above 2.5km (Figure 5.7a). At the lower levels, smoke is transported northward where it combines with the dust. In Figures 5.8b and 5.8c, an area of high occurrence frequency is observed west of Africa and north of the ITCZ. The mechanism creating this isolated occurrence is unclear.
Figure 5.5: Winter vertical aerosol occurrence probability slices with ERA-Interim Reanalysis wind vectors. Vertical wind is increased by a factor of five. Shaded gray is dust, green/blue contour is smoke, and red/yellow contour is polluted dust for a) 20E, b) 0, c) 20W, d) 40W, e) 60W, and f) 80W. Contours are plotted in 10% intervals and no cutoff is imposed.
Figure 5.6: Winter horizontal aerosol occurrence probability slices with ERA-Interim Reanalysis wind vectors. Shaded gray is dust, green/blue contour is smoke, and red/yellow contour is polluted dust for a) 1km, b) 2km, c) 3km, and d) 4.2km. Contours are plotted in 10% intervals and no cutoff is imposed.
Figure 5.7: Spring vertical aerosol occurrence probability slices with ERA-Interim Reanalysis wind vectors. Vertical wind is increased by a factor of five. Shaded gray is dust, green/blue contour is smoke, and red/yellow contour is polluted dust for a) 20E, b) 0, c) 20W, d) 40W, e) 60W, and f) 80W. Contours are plotted in 10% intervals and no cutoff is imposed.
Figure 5.8: Spring horizontal aerosol occurrence probability slices with ERA-Interim Reanalysis wind vectors. Shaded gray is dust, green/blue contour is smoke, and red/yellow contour is polluted dust for a) 1km, b) 2km, c) 3km, and d) 4.2km. Contours are plotted in 10% intervals and no cutoff is imposed.
CHAPTER 6

AEROSOL OPTICAL DEPTH AND LAYER THICKNESS

Currently there are no techniques to evaluate vertical aerosol optical depth (AOD) profiles except by looking at the AOD of an individual aerosol layer. In effort to gain insight into vertical AOD and layer thickness climatology, CALIPSO layer data are seasonally combined and used to are used to evaluate AOD and aerosol layer thickness.

6.1 Aerosol Optical Depth

Aerosol optical depth (AOD) as a function of height for boreal summer is shown in Figure 6.1 for a) total aerosol, b) dust, c) smoke, and d) polluted dust where the colorbar indicates the relative number of occurrences of AOD found at each altitude. The small plots are the same as the large plots but with a log scale on the x-axis. Total aerosol AODs above 0.5 are found between the surface and 6km, but with a small number of occurrences (Figure 6.1a). The largest number of occurrences coincides with AOD values of ~0.01 – 0.1 between 0.5 and 2km. An interesting separation of AOD occurrences exist with an average AOD of ~1.5. It is unclear as to the reason for this separation, but it is possible that it is misclassification of cloud features. Further analysis is required.

It is clear and expected that dust (Figure 6.1b) is the primary contributor to the AOD of total aerosol at all levels. Dust AODs of 0.01 occur from 0.5km to 6km. It is interesting that with larger AOD, the height of the layer decreases rapidly such that an AOD of 0.1 is primarily confined to 1-2km and a plateau of sorts is present at the higher altitudes. Maximum AOD value for a dust layer approaches 0.75.
Smoke (Figure 6.1c) and polluted dust (Figure 6.1d) also display the rapid decrease in occurrence when AOD is less than 0.1. However, AOD values less than that are found above 8km for smoke and polluted dust. The largest occurrences of polluted dust mimic that of total aerosol; AODs of 0.01 to 0.1 are found between 0.5 and 2km. The distribution of smoke AODs includes a unique feature in that the smallest AODs are not found below 2.5km. This vacancy coincides with the largest AOD occurrences for dust and polluted dust and may be a result of the aerosol typing algorithm; a necessary condition for the smoke classification is that the layer be elevated.

Figure 6.1: Summer AOD vs. aerosol height for a) total aerosol, b) dust, c) smoke, and d) polluted dust. AOD is recorded at every grid point in the layer. Small plots with the x-axis shown on a log scale are overlaid. Colorbar represents number concentration.
AOD in boreal fall is much like that of summer for total aerosol (Figure 6.2a). The largest AOD values remain between 0.01 and 0.1, primarily between 0.5 and 2km. However, total aerosol AODs greater than ~0.8 are not observed as they are in summer and dust maximum AOD is reduced from ~0.75 to 0.5 (Figure 6.2b). Smoke layers with AODs greater than 0.01 are still confined to the altitudes above 2.5km (Figure 6.2c) while polluted dust exhibits a structure similar to dust, particularly at the lower AOD values.

![Figure 6.2](image)

**Figure 6.2:** Fall AOD vs. aerosol height for a) total aerosol, b) dust, c) smoke, and d) polluted dust. AOD is recorded at every grid point in the layer. Small plots with the x-axis shown on a log scale are overlaid. Colorbar represents number concentration.

The same general structures appear in boreal winter (Figure 6.3). Three main differences are found. Although the range of the most probable AODs remains, this range is confined to layers at lower altitudes. Second, polluted dust and dust AOD
distributions are more similar than in other seasons. This may be due to lack of smoke transport away from the source regions, while polluted dust is often collocated with dust as they propagate over the Atlantic. Finally, smoke AOD maxima reaches only ~0.25, about half of the polluted dust maxima, whereas in the other seasons, smoke and polluted dust AOD maxima were approximately equal.

Figure 6.3: Winter AOD vs. aerosol height for a) total aerosol, b) dust, c) smoke, and d) polluted dust. AOD is recorded at every grid point in the layer. Small plots with the x-axis shown on a log scale are overlaid. Colorbar represents number concentration.

Boreal spring AOD structures are much like winter structures. Smoke still has maximum AOD values less than the other aerosol types (Figure 6.4c). Polluted dust AOD maxima decreases, particularly at above 1km where decreasing AOD occurrences quickly drop with height (Figure 6.4d). Dust layers begin to reemerge at higher altitudes
after decreasing in fall and winter. This is consistent with the 3D seasonal average structures and seasonal cycles shown in the previous chapters.

Figure 6.4: Spring AOD vs. aerosol height for a) total aerosol, b) dust, c) smoke, and d) polluted dust. AOD is recorded at every grid point in the layer. Small plots with the x-axis shown on a log scale are overlaid. Colorbar represents number concentration.

6.2 Layer Thickness

Layer thickness as a function of height is shown in Figures 6.5 – 6.9 where the colorbar indicates the observation number concentration and the x-axis is shown on a log scale in the small overlaid plots. The layer thickness is recorded in the center of the layer, so these figures indicate the most likely vertical location of the layer. Like the AOD structures shown previously, layers are generally found most often between 1 and 2 km, though the thickness varies with season and aerosol type.
During boreal summer, maximum layer heights of total aerosol occasionally reach 7km but are limited to a thickness of ~0.5km (Figure 6.5a). As expected, as the layer thickness increases, the height of the layer decreases; a layer 3km thick is most likely found between 3 and 4km. Rarely are layers thicker than 2km found above 4km. The highest relative occurrences are near surface layers displayed as a linear line with a slope of ~0.5. As with all previous cases, the primary contributor to the total aerosol structure is dust (Figure 6.5b) reaching the same maximum heights as total aerosol. Dust layers are most often centered between 0.25km and ~3km with layer thickness ranging between 0.1 and 0.5km, but some bimodality is present in the structure indicating thinner layers at lower altitudes and thicker layers centered between 3 and 4km. Polluted dust layer thickness location is similar to dust except the layers are rarely centered above 2 or 3km and the near surface layers (the linear line of occurrence) dominates the contribution to total aerosol (Figure 6.5d). Smoke layers are never found close to the surface, but instead are elevated and exhibit a layer trimodality which is also visible in the total aerosol distribution (Figure 6.5c).
Figure 6.5: Summer layer thickness vs. layer height for a) total aerosol, b) dust, c) smoke, and d) polluted dust. Layer thickness is recorded at the center of the layer. X-axis is shown on a log scale in small plots. Colorbar represents number concentration.

Layer thickness distribution in boreal fall is similar to the summer distribution (Figure 6.5a). There are two distinctions noticeable between the seasons. During fall, the maximum observed layer altitude decreases by a little over 1km for total aerosol (Figure 6.5a) and dust (Figure 6.5b) while the maximum altitude of smoke (Figure 6.5c) and polluted dust (Figure 6.5d) both have increased observations at higher altitudes and therefore have more contribution to the total aerosol layer distribution above 2km. Additionally, the bimodality exhibited in the summer dust structure is no longer present.
Figure 6.6: Fall layer thickness vs. layer height for a) total aerosol, b) dust, c) smoke, and d) polluted dust. Layer thickness is recorded at the center of the layer. X-axis is shown on a log scale in small plots. Colorbar represents number concentration.

A slight decrease in observed layer altitudes is detected for total aerosol in boreal winter (Figure 6.7a) compared to all other seasons. This is expected as the 3D seasonal average plots indicate that aerosol occurrence altitudes are lowest during this season. Also consistent with the 3D structures is the lower observed altitudes of dust (Figure 6.7b) where the layer average reaches 3.5km (maximum height of ~4km) and further increased altitudes of polluted dust (Figure 6.7d) compared to that of winter. Smoke no longer exhibits a trimodalidy, but instead a bimodality with further vertical separation between the observed layer occurrences (Figure 6.7c).
Figure 6.7: Winter layer thickness vs. layer height for a) total aerosol, b) dust, c) smoke, and d) polluted dust. Layer thickness is recorded at the center of the layer. X-axis is shown on a log scale in small plots. Colorbar represents number concentration.

As with the all previous discussions, the spring season marks the transition of aerosol maximum height to summer levels. Total aerosol (Figure 6.7a) and dust layers are detected up to ~6km (Figure 6.7b). However, smoke layers (Figure 6.7c) and polluted dust layers (Figure 6.7d) do not display the variability in observed occurrences above 2km as summer layers do and even less occurrences of smoke layers are observed. Smoke layers are distributed approximately the same as in winter.
Figure 6.8: Spring layer thickness vs. layer height for a) total aerosol, b) dust, c) smoke, and d) polluted dust. Layer thickness is recorded at the center of the layer. X-axis is shown on a log scale in small plots. Colorbar represents number concentration.
Before the launch of CALIPSO, it has not been possible to analyze the climatology of vertical aerosol profiles; scientists have relied on short-term flight measurements and single point ground-based lidar and sun photometer measurements which is hardly enough data to build a climatological data set. In this study I have created 3D representations of the climatological aerosol occurrence probabilities for the Atlantic Basin and the surrounding continents in order to gain a better understanding of the temporal and spatial variability and structure of aerosol. I created 3D seasonal average and seasonal cycle probabilities using CALIPSO Vertical Feature Mask, a dataset which classifies aerosol and cloud types with extraordinary vertical and horizontal resolution. A depiction of the ITCZ is included, derived from TRMM rainfall maxima estimates. To date, this is the first analysis of its kind.

7.1 Seasonal Averages

Well known source regions of dust and smoke are clearly depicted in the 3D occurrence probability seasonal averages. High probabilities extending from ground level and the structure of the meridional average indicate the Sahara Desert and the Middle East as primary dust source regions, with secondary sources originating from southern Africa and southern South America. A lofted core of dust occurrence extends from Africa over the Atlantic except in boreal winter. Smoke source regions are identified as southern Africa, South America, the eastern US, and Europe and are characterized with lower altitudes than dust over the source and for the duration of transport. Another interesting lofted core of smoke from the biomass burning regions of
Africa is present in boreal summer and fall over the Atlantic. The vacancy under the smoke core is partially filled by polluted dust and by cloud. The probability of westward transport and vertical extent of dust and smoke vary with season; the furthest westward transport and highest occurrence probabilities taking place in boreal summer and spring.

There is some question regarding the differentiation of polluted dust, smoke, and polluted continental aerosol classifications so caution is necessary when evaluating these aerosol types.

### 7.2 Seasonal Cycles

The ITCZ is the limiting factor throughout the year for the southern (northern) extent of dust (smoke) originating from the African continent. The vicinity of the ITCZ rainband appears to be an area of external dust and smoke mixing. In this area, dust and smoke occurrence probabilities are at a minimum, while the probability of polluted dust is at a maximum. Southern African smoke does not penetrate through the ITCZ during northward transport, but dust crosses southward through the ITCZ region throughout the year reaching south to areas of minimum rainfall in boreal summer.

The western side of the Atlantic basin has different characteristics than the east, probably due to the difference in smoke source region and because the meridional extent of dust on this side of the basin is smaller than that on the eastern side. Neither dust nor smoke probabilities cross the ITCZ rainband at any point in the year; dust is confined north of and smoke is confined south of the ITCZ. Higher polluted dust probabilities are found north of the ITCZ, which is consistent with the seasonal average structures. Once the mixing of dust and smoke takes place on the eastern side of the region, the transport pathway of polluted dust is primarily in line with the dust pathway.
7.3 Aerosol Mixing and Transport

For a polluted dust classification, mixing of dust and smoke must occur. Since smoke never crosses northward across the ITCZ rainband over Africa but polluted dust does exist south of the ITCZ, it must be due to the southward transport of dust crossing the ITCZ. This appears to be the case. Although there the flow is generally zonal, over Africa there is a southward component above 3km in boreal spring and summer (2km in fall and winter) responsible for the migration of dust across the ITCZ. The quasi-circulation centered around the smoke structure transports dust southward at the higher altitude, sinks, then transports northward with smoke at the lower altitudes creating polluted dust. It is possible that additional dust is added from the smaller southern Africa dust source at the lower levels and included in polluted dust. The southward migration of the ITCZ in boreal winter promotes a different spatial pattern of polluted dust than the other seasons; polluted dust straddles the ITCZ at all levels with a 10% decrease at the ITCZ rainband as opposed to ~5° to its north and south. The lack of a coherent smoke propagation signal over the Atlantic in winter and spring can be attributed to mixing over a smaller horizontal distance; the smoke and dust mix to form polluted dust east of 10E rather than 20W as in summer and fall.

7.4 AOD and Layer Thickness

Using CALIPSO aerosol layer data, occurrences of AOD and layer thickness are evaluated as a function of height. In all seasons, the most frequent AOD values for all aerosol types range between 0.01 and 0.1, located between 1 and 2km in height, though AOD frequently exceeds 0.75, attributable primarily to dust distribution. This is also the primary altitude of aerosol layer frequency. As with the 3D structures, aerosol maximum
layer height occurs in boreal summer, decreasing in fall and winter, and then deepens as it recovers to summer altitudes. An unusual area of observed occurrence is detected in the AOD – height plots; as of yet this cannot be explained, but it is possible that this is an example of misclassification of aerosol as cloud. The maximum AOD of polluted dust is slightly lower than that of smoke in summer and fall, but AOD maxima decreases during winter and spring such that the maximum AOD of polluted dust is much higher than that of smoke. This could be due to the lighter aerosol loading of smoke and dust during these seasons and their contributions to the polluted dust classification.
CHAPTER 8

FUTURE WORK

8.1 CALIPSO Validation

A limited number of CALIPSO Level 1 and Level 2 lidar product validations have been completed. Of these, the primary validation tool has been ground-based Raman lidar comparisons at various sites globally using differing validation techniques, but to date no one has utilized the Raman lidar in Barbados. This site is of great importance because all aerosol types identifiable by CALIPSO (i.e. dust, smoke, polluted dust) are transported into this vicinity and is a perfect test to test the CALIOP retrievals and scene classification algorithms.

It is difficult to validate CALIPSO’s data products for many reasons. CALIPSO’s lidar, CALIOP, is a downward looking lidar and cannot be directly compared with upward looking lidars. Adjustments and assumptions must be made either to the ground-based or CALIOP profiles in order to perform a direct comparison. Near or direct overpasses to the ground-based stations can be limited because CALIOP’s lidar footprint is so small, and can be further limited if the ground-based lidar is not functioning 100% of the time or is contaminated by cloud cover. CALIOP profiles can become contaminated by background aerosol in the boundary layer.

My research depends on the proper classification of CALIPSO VFM aerosol identification. Consequently, I will institute a 2-part approach to the validation representing each constituent of the identification scheme (Figure 2.3) as well as the lidar ratio assigned to each classification used in the Level 2 products using collocated CALIPSO overpasses and the Max-Planck-Institut für Meteorologie’s Raman lidar
located at Deebles Point in Barbados. CALIPSO overpasses will be constrained to within 1° of latitude or longitude from the Deebles Point location.

Part 1: convert CALIOP’s downward looking attenuated backscatter for direct comparison with upward-looking lidar.

The most difficult step will be the conversion of the downward-looking lidar’s attenuated backscatter coefficient at 532nm to values that can be directly compared using the technique outlined in Mona et al. (2009).

Part 2: compare CALIOP’s depolarization ratio with that of the ground-based lidar.

A simple volume depolarization ratio comparison will be performed and assessed between the two lidars. Reliability of CALIPSO’s depolarization ratio is directly attributable to the accuracy of the attenuated backscatter at 532nm and the perpendicular 532nm bands and could contribute to biases in aerosol classification.

This validation approach has been started using data from University of Miami’s lidar site in Barbados, very close to the Max-Planck site. However, only 19 occurrences of collocated data exist due to lidar outages. In addition, the University of Miami’s lidar is a single wavelength instrument and not suitable for this type of validation as a Raman lidar is necessary. Although the Max-Planck lidar has only been operational for approximately one year, it is possible that more collocated overpasses will be available resulting in a high-quality validation of CALIPSO data.
8.2 Aerosol Effect on Precipitation Using Climate Models and Remote Sensing

Until recently, vertical aerosol profiling throughout the depth of the troposphere has not been possible. With the recent availability of data from CALIPSO, vertical aerosol profiles can be used to validate model simulations. This project will systematically evaluate and explain possible model biases in Goddard Chemistry Aerosol Interactions and Chemistry (GOCART), Weather Research and Forecasting with Chemistry (WRFC) with GOCART and WRFC with Model for Simulating Aerosol Interactions and Chemistry (MOSAIC) aerosol modules. The large and continuous emission transport of African dust and smoke from biomass burning makes the African continent and tropical Atlantic Ocean basin an ideal location for regional study of climatic aerosol effects before expanding the technique to the global scale. Observational diagnostics of aerosol effects on precipitation in this region have been done (Huang et al., 2009). I will therefore focus on this region.

This project will yield a better understanding of the importance of the vertical structure of aerosol in hydrological cycles. Additional insight will be attained of potential dynamical, hydrological and interactive processes associated with aerosol than is currently available and the implication these dynamical processes may or may not have on Earth’s climate system.

The objective of this project is to quantify the level of uncertainty associated with aerosol effects on climate, especially the hydrological cycle, through 3D comparisons between observations and model simulations. I hypothesize that biases or discrepancies among simulated aerosol effects on precipitation caused by errors in the reproduced vertical structure of aerosol are similar to or greater than those caused by other factors,
including differences between direct and indirect radiative effects of aerosol. If this is true, then aerosol effect on precipitation can be adequately assessed by using a model only if the model reproduces reasonably well vertical distributions of aerosol. This hypothesis will be tested by systematically comparing 3D structures of aerosol simulated by a regional model of different configurations against observations.

The primary element of my current research is the documentation of 3D occurrence frequency/probability structures spanning a region encompassing Africa, the Atlantic, and Americas derived from CALIPSO VFM. This 3D structure of aerosol will serve as the main validation base for aerosol model simulations. The general approach of this project is to compare aerosol effects on large-scale precipitation simulated by a numerical model of different configurations and to access the extent to which their discrepancies come from their disagreement with each other and with observations in 3D structures, especially vertical profiles of aerosol. Different model configurations include the source of meteorological fields (wind, temperature, humidity, etc.) and direct vs. indirect aerosol effects.

Models to be used are GOCART, and WRFC using aerosol modules of GOCART and MOSAIC. The NASA global data assimilation product MERRA and TRMM precipitation will also be used. The research in this project is described in two parts, not necessarily in chronological order.

Part I. Model simulations and data preparation

Seven model ensemble runs will be made:

1. GOCART driven by MERRA (GM)
2. WRFC with GOCART, no radiative effect (WG)

3. WRFC with GOCART, with direct effect (WGD)

4. WRFC with MOSAIC, no radiative effect (WM)

5. WRFC with MOSAIC, with direct effect only (WMDO)

6. WRFC with MOSAIC, with indirect effect only (WMIO)

7. WRFC with MOSAIC, with both direct and indirect effects (WMDI)

In 2-6, boundary and initial conditions for WRFC will be from MERRA. The WRFC domain will be over tropical Africa and Atlantic Ocean. In each ensemble, short-term (5-10 days) simulations will be made with different initiation conditions. The size of the ensemble will be 10 – 20.

Based on my experience from my current research, I will document 3D structures of aerosol from model simulations. This will be done using information of 3D occurrence of specific types of aerosol (e.g., black carbon, dust, total aerosol, etc.). The 3D structure of aerosol from the model simulations will be in the same format as CALIPSO VFM for direct comparisons. In addition, 3D structures of extinction coefficient from CALIPSO’s Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) and the model simulation will also be documented and compared.

Part II. Data comparison and diagnostics

Each model run will be compared to observation in effort to identify and quantify model biases in aerosol distribution. Several steps will be taken:
Step 1: Compare 3D structure of aerosol from GM and observations. When GOCART is driven by MERRA, GM should give the best possible aerosol distribution among all proposed simulations. Systematic biases in GM should be attributed to GOCART. This is the benchmark simulation.

Step 2: Compare 3D structure of aerosol from GM to WG. When radiative effect of aerosol is turned off in WRFC, differences between these two runs come from meteorological fields in MERRA and WRFC. This comparison would identify biases introduced by WRFC.

Step 3: Compare precipitation, 3D structure of aerosol and other meteorological fields from WG and WGD. Any differences between these two runs would come from the direct radiative effect of aerosol.

Step 4: Compare precipitation, 3D structure of aerosol and other meteorological fields from WG to WM. Any differences between these two runs would come from differences in the two aerosol modules GOCART and MOSAIC. In the case neither coincides with observation, I will quantify the differences between model and observation due to model bias attributable to vertical profile differences.

Step 5: Compare precipitation, 3D structure of aerosol and other meteorological fields from WM and WMDO. This is parallel to Step 3. Results from Steps 3 and 5 will reveal uncertainties in direct radiative effects due to different aerosol modules.

Step 6: Compare precipitation, 3D structure of aerosol and other meteorological fields from WMDO and WMIO. This will quantify differences between direct and indirect effects of aerosol.
Step 7: Compare precipitation, 3D structure of aerosol and other meteorological fields from WMDO, WMIO and WMDI. This will reveal possible nonlinear interaction between direct and indirect radiative effect of aerosol, if aerosol effects on precipitation in WMDI are not simply a combination of those from WMDO and WMIO.

To determine the extent of aerosol effect on precipitation specifically, diagnosis of model simulations will follow the tercile method used in my previous black carbon research and described in Huang et al. (2009). Using this method, differences in precipitation anomalies between high and low anomalous aerosol conditions (difference composite) is calculated for each model run and compared to observations based on TRMM rainfall estimates and either Ozone Monitoring Instrument (OMI) in the case of dust and black carbon or total column Aerosol Optical Depth (AOD) in the case of total aerosol observations. Because Moderate Resolution Imaging Specroradiometer (MODIS) AOD error decreases with larger optical depth and CALIOP AOD error decreases for smaller optical depth (Winker, 2009), a combination of MODIS and CALIOP AODs will be used.

My hypothesis would be disapproved by any of the following scenarios:

(a) Aerosol effects on precipitation simulated by a model configuration match well the observation while the simulated vertical distribution of aerosol disagree substantially with the observed
(b) Aerosol effects on precipitation simulated by two model configurations match well with each other while their simulated vertical distributions of aerosol disagree substantially.

If neither scenario occurs, then by the systematic comparisons of steps 1 – 7, I would be able to quantify the extent that vertical distributions of aerosol cause discrepancies in aerosol effects on precipitation between model simulations and observations as well as between different model simulations.

Through the systematic comparisons between different model simulations and between simulations and observations, I expect to accomplish the following: (1) Identify the source(s) of model biases in 3D structure of aerosol, (2) quantify the extent to which model biases in aerosol effect on precipitation is related to the biases in 3D structures of aerosol in simulations, (3) distinguish direct and indirect radiative effects on precipitation, and (4) identify nonlinearity in aerosol effects on precipitation. Although these results are constrained by the particular models I propose to use, the results would provide insight to help improve our understanding of aerosol effect on precipitation.

The research described above will be completed by the end of three academic years and will serve as my PhD dissertation. Milestone timeframes are outlined below:

- First year: run and diagnose GM, WG and WGD (Steps 1 – 3) while running WM and WMDO.
- Second year: diagnose WM and WMDO (Steps 4 – 6) while running WMIO and WMDI.
- Third year: diagnose WMIO and WMDI (Step 7). Complete dissertation.
REFERENCES


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