PhD Prospectus

Saharan Mineral Dust Aerosols and the Inter-Annual Variability of the African Easterly Jet-African Easterly Wave System

Emily Bercos-Hickey
Atmospheric Science Graduate Group
University of California, Davis

Committee Members

Shu-Hua Chen
Ian C. Faloona
George N. Kiladis
Terrence R. Nathan
Paul A. Ullrich (chair)

August 25, 2017

Table of Contents

1. Introduction

North Africa occupies only ~2% of the Earth's surface, yet the atmospheric circulation in this region can have a global impact. The atmospheric circulation often includes tropical wave development over Africa and the episodic formation of Saharan dust storms. The tropical waves may develop into hurricanes, which can eventually affect the Caribbean and the eastern United States, while the dust storms often migrate westward, reaching as far as the Americas (Engelstaedter and Washington 2007).

Among the prominent weather features that characterize the summertime circulation over North Africa are the African easterly jet (AEJ) and African easterly waves (AEWs). The AEWs contribute to the mobilization of Saharan mineral dust (SMD) aerosols into the atmosphere to form dust storms. The absorption, scattering and emission of radiation by SMD can affect the energy balance of the atmosphere, which in turn can affect the evolution of the AEJ-AEW system.

This prospectus centers on the **hypothesis** that SMD can significantly affect the inter-annual variability of the AEJ-AEW system. I will test this hypothesis by conducting a series of experiments using the Weather Research and Forecasting (WRF) dust model. The experiments will have among their **objectives** the following: Provide a deeper understanding of the SMD-modified AEJ-AEW system; improve forecasting of AEWs and the AEJ; and lay the foundation for future work on the connection between AEWs and the development of hurricanes.

The research tasks to be described later will address several important **questions**, among which are the following:

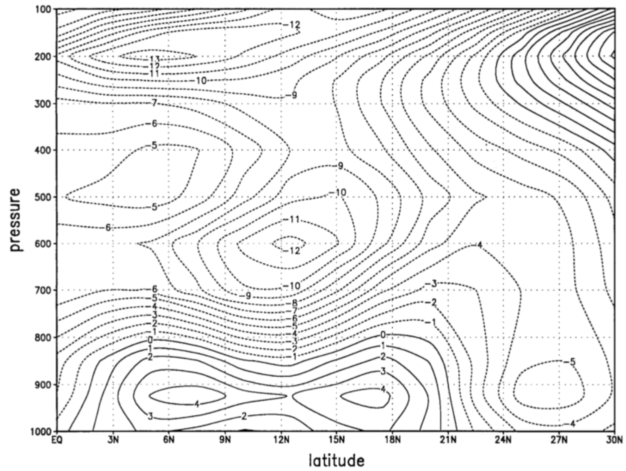
How do the AEJ and AEWs respond to SMD events of varying frequency and magnitude?
How does SMD affect the location, structure and variability of the AEJ?
How does SMD affect the tracks, propagation speed and strength of the AEWs?

2. Present State of Knowledge

The AEJ and AEWs form a complex system that not only affects regional weather (Reed et al. 1977), but also extends its influence beyond North Africa to affect the weather over the eastern Atlantic Ocean, and even as far as the Caribbean (Frank 1970). For example, the AEJ-AEW system has been shown to affect convection and rainfall over West Africa (Carlson 1969a,b; Reed et al. 1977), while more than half of the tropical cyclones that developed over the eastern Atlantic Ocean from 1967-1991 had AEW origins (Landsea 1993).

The **AEJ is a mid-tropospheric jet** located near 12-15°N and 600 hPa with a maximum speed of ~12 ms^{-1} (see Fig. 1). The AEJ is primarily attributed to thermal wind balance: a positive surface temperature gradient resulting from the cool Sahel region in the south to the warm Saharan Desert in the north produces easterly vertical shear (Cook 1999; Thorncroft and Blackburn 1999). Dry convection in the Saharan heat-low region, and deep moist convection in the intertropical convergence zone (ITCZ) are additional influences on the AEJ (Thorncroft and Blackburn 1999).

Figure 1. Vertical cross-section of the zonal wind (ms^{-1}) from the 40-year NCEP July climatology. The AEJ is clearly visible at ~600 hPa and ~13°N. Figure from Cook (1999).



AEWs are synoptic-scale, westward-propagating disturbances over North Africa. AEW activity is most prominent during the Northern Hemisphere summer, with waves forming over Northeast Africa. The waves travel westward with periods of ~3-5 days, wavelengths of ~2000-4000 km, and speeds of ~7-9 ms^{-1} (Burpee 1972; Albignat and Reed 1980; Reed et al. 1988). AEW activity is generally observed along two tracks, one south of the AEJ at ~700 hPa and the other north of the AEJ at ~950 hPa (Reed et al. 1988; Pytharoulis and Thorncroft 1999).

For more than thirty years, the genesis and growth of AEWs was largely attributed to the barotropic-baroclinic energy transfer from the AEJ to the AEWs (Burpee 1972). Studies have shown, however, that instability alone does not fully account for the genesis of AEWs (Kiladis et al. 2006; Hall et al. 2006; Thorncroft et al. 2008; Leroux and Hall 2009). For example, Hall et al. (2006) found that realistic damping can stabilize the AEJ and concluded that AEWs may require a trigger mechanism, such as convection. Thorncroft et al. (2008) used localized heating associated with convection and found that a deep convective heat source in the Darfur region favors the formation of AEWs more so than heating in other regions of West Africa. Leroux and Hall (2009) found that a convective trigger and the intra-seasonal variability of the AEJ determine the development of AEWs. While the above studies found that a convective trigger is required for AEW genesis, they also conclude that the instability of the AEJ contributes to the growth of the AEWs.

Recently, Nathan et al. (2017) demonstrated that neither combined barotropic-baroclinic instability nor localized convective heating may be required for AEW growth. They showed that for an AEJ that is subcritical with respect to the barotropic and baroclinic instability threshold, SMD can destabilize the AEJ to produce AEW-like disturbances with growth rates that are commensurate with those obtained from supercritical AEJs.

SMD is lofted from the Sahara Desert to form vast plumes of dust that diabatically force the AEJ-AEW system. The lofting of SMD into the atmosphere results from a variety of mechanisms, such as dry convection, nocturnal low level jets and mesoscale convective systems (Knippertz and Todd, 2012). For example, dry convection during the daytime in the summer is associated with enhanced turbulence and vertical wind speed near the surface, which results in dramatic SMD emissions from the arid landscape (Engelstaedter and Washington 2007). AEWs have also been shown to contribute to the emission and transport of SMD (Jones et al. 2004; Knippertz and Todd 2010). Once formed, the synoptic-scale plumes of SMD are carried in a layer of warm, dry air that moves westward. When the dry dusty air reaches the Atlantic Ocean (see Fig. 2), it is elevated by the encroaching cool, moist marine air to form the Saharan air layer (SAL). The dust plumes often continue to move westward, reaching the United States, Caribbean and South America (Engelstaedter et al. 2006). Throughout their westward migration, the plumes alter the energy budget of the atmosphere (Zhu et al. 2007), which, in turn, alters the atmospheric circulation (Tompkins et al. 2005; Chen et al. 2010; Wilcox et al. 2010; Reale et al. 2011).

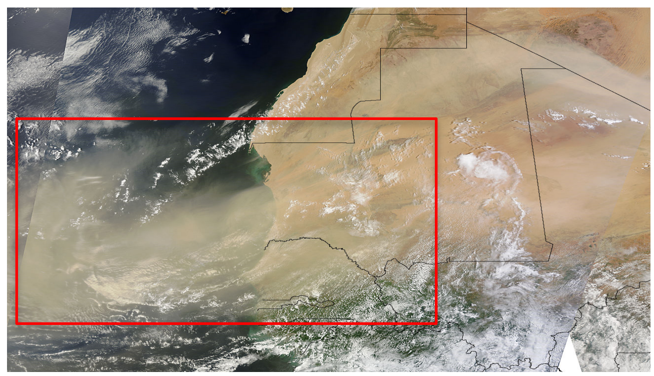


Figure 2. Composite image of a dust plume over North Africa and the eastern Atlantic Ocean. The image was captured on July 31, 2013 by the Moderate Resolution Imaging Spectroradiometer (MODIS) flying onboard NASA's Terra satellite. Within the box, the plume spans about 2,000 km in the zonal direction.

(http://modis.gsfc.nasa.gov /gallery/individual.php?db_date=2013-08-11)

Although the AEJ-AEW system is highly complex, progress has been made in understanding how the SMD affects its structure and evolution. For example, reanalysis studies (Tompkins et al. 2005; Wilcox et al. 2010) and numerical modeling studies (Reale et al. 2011) have found that the location of the AEJ is in closer agreement with observations when the feedbacks involving SMD are accounted for. Tompkins et al. (2005) found, for example, that the use of an updated aerosol climatology greatly improved 5-day reanalysis forecasts of the AEJ. Wilcox et al. (2010) used nine years of satellite and reanalysis data to show that SMD outbreaks produce a northern shift of the AEJ. And Reale et al. (2011) used the NASA GEOS-5 model to run 5-day forecasts and found that the inclusion of aerosols in the model changed the temperature field, causing the AEJ to shift northward and upward, in better alignment with the climatological location.

Studies examining the effects of SMD on AEWs have produced contradictory results. Some studies have shown that the SMD can strengthen AEWs (Jones et al. 2004; Ma et al. 2012; Grogan et al. 2016, 2017), whereas other studies have shown that it can weaken AEWs (Karyampudi and Carlson 1988; Reale et al. 2009; Jury and Santiago 2010). The modeling study by Reale et al. (2009) and the statistical study by Jury and Santiago (2010) both find that as SMD increases in the SAL, the dust-radiative heating causes mid-level temperatures to increase relative to those below.

The result is an increase in the static stability over the Atlantic Ocean, which creates less favorable conditions for the strengthening of AEWs.

In contrast, Jones et al. (2004) used reanalysis data and dust from a global transport model and found that SMD enhances the AEWs over the Atlantic Ocean through SMD-induced warming in the lower troposphere, which reduces static stability. Ma et al. (2012) used the WRF model with a prescribed dust layer to conclude, like Jones et al. (2004), that a reduction in static stability strengthens the modeled AEWs. More recently, Grogan et al. (2016) used a linearized version of the WRF model coupled to an interactive dust model to examine the effect of SMD on the linear dynamics of AEWs. They found that for realistic background wind, temperature and SMD distributions, the SMD-radiative feedbacks increase the growth rate of the AEWs by ~5-20%. The SMD-modified energetics were largest between the AEJ core and the SMD maximum, a region where the meridional SMD gradient is coincident with the critical surface.

Although the studies cited above have advanced understanding of the effects of SMD on the AEJ-AEW system, several unresolved issues remain. For example, although it has been shown that the SMD can affect the meridional and vertical location of the AEJ (Tompkins et al. 2005; Wilcox et al. 2010; Reale et al. 2011), it is unclear how the plumes of SMD—their frequency of formation, areal extent and magnitude—affect the zonal location, structure and stability of the AEJ. In addition, it is unclear how the variability of the SMD affects the tracks, wavelengths and strength of the AEWs. Previous studies have attributed AEW growth to SMD-induced changes to static stability (Jones et al. 2004; Reale et al. 2009; Jury and Santiago 2010; Ma et al. 2012), but this provides an incomplete picture. Barotropic and baroclinic energy conversions are also important to the growth of AEWs and, as shown in the linear analyses of Grogan et al. (2016) and Nathan et al. (2017), these conversions increase with SMD.

3. Model, Methods, and Experiments

Experiments will be carried out using the **WRF-dust model** developed by Chen et al. (2010). Briefly, SMD is modeled by five particle sizes to represent the spectrum of mineral dust in the atmosphere. The rate of change of the mass coupled dust mass mixing ratio is due to the flux divergence of SMD, mixing of SMD by boundary layer turbulence and sub-grid scale convection, sedimentation, scavenging, dry and wet deposition, and surface emission. Surface emission occurs when the soil volumetric moisture is less than 0.2, the 10 m wind speed exceeds a threshold of 6.5 ms^{-1}, and the vegetation type is barren (Tegen and Fung 1994; Chen et al. 2010). The emissions are particle size dependent, where the percentage of SMD emission for each particle size is based on a dust size distribution (Kok 2011).

Radiative forcing due to SMD is incorporated in the thermodynamic equation using the Rapid Radiative Transfer Model for Global Climate Models (Iacono et al. 2008). The SMD optical properties, which are used as inputs for the radiation scheme, are calculated using the Optical Properties of Aerosols and Clouds (OPAC) software package (Hess et al. 1998). The SMD optical properties include the asymmetry parameter, single scatter albedo, and extinction coefficient, all as a function of wavelength and SMD particle size. Fourteen wavelength bands are included in the shortwave, varying from 0.25-7.9 microns.

The numerical **experiments** are divided into two categories: those with the radiative effects of SMD and those without. Experiments will be run for July, August and September (JAS) for the ten-year period spanning 2006-2015. This period was chosen because of the availability of NASA Moderate Resolution Imaging Spectroradiometer (MODIS) Aqua and Terra satellite aerosol optical depth (AOD) data, which will be used to verify the model SMD simulations. The experimental domain will be centered over North Africa; European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis interim data will be used to generate the boundary and initial conditions.

Model validation will be performed to determine the accuracy of the WRF-dust model. This will be an important first step before carrying out the research tasks discussed below. MODIS AOD data will be compared with the model produced AOD to assess the accuracy of the simulated SMD plumes. ECMWF reanalysis data, which includes the radiative effects of SMD, will also be used to verify the numerical simulations. The zonal wind and temperature fields from the ECMWF data will be compared with the WRF-dust model experiments. The expectation is that with SMD, the WRF-dust model will be in closer alignment with the ECMWF data.

4. Preliminary Results

The proposed research builds on my recently accepted paper (Bercos-Hickey et al. 2017). In that paper, the WRF-dust model was used to examine the radiative effects of SMD on the energetics, structure and location of the AEJ-AEW system for a single summer, July-September 2006. The key results are: enhancement of the zonal expansion of the AEJ-AEW system; shifts in the location of the AEJ-AEW system; and increases in the energetics of the AEJ-AEW system. Here I present a highlight from the paper: the AEW track and energetics analyses.

The location of the AEW tracks was calculated for July-September 2006 using the zonally averaged eddy kinetic energy (EKE). Figure 3 shows, consistent with previous studies (Reed et al. 1988; Hsieh and Cook 2007), distinct northern and southern tracks for both experiments. With SMD (Fig. 3a), the northern track is located at ~18.5°N and ~900 hPa, and the southern track is located at ~9.5°N and ~650 hPa. Without SMD (Fig. 3b), the northern track is located at ~17.5°N and ~900 hPa, and the southern track is located at ~8.5°N and ~700 hPa. A comparison of the two experiments shows that the SMD shifts the northern and southern AEW tracks ~1° (~100 km) north. Figure 3 also shows the EKE in the northern and southern tracks is on average ~150% larger with SMD. The maximum EKE with SMD is located where the meridional SMD gradient is largest (~18.5°N), consistent with Grogan et al. (2016). These results have two important consequences. First, the SMD-induced shift in the AEW tracks can affect where the AEWs exit North Africa, which can affect the location of tropical cyclogenesis. Second, the SMD increases the transfer of energy to the AEWs, resulting in stronger waves.

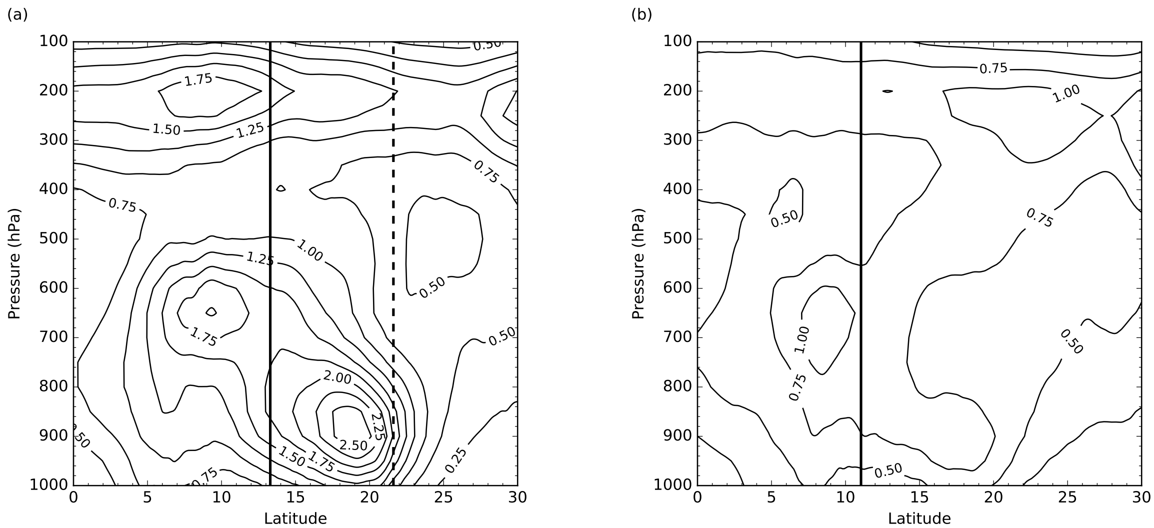


Figure 3: Eddy kinetic energy distribution, averaged in time and between 30°W and 0° for (a) DUST-ON and (b) DUST-OFF (units: m^2s^{-2}). Vertical solid lines indicate the location of the AEJ maximum. Vertical dashed line indicates the location of the SMD concentration maximum.

5. Research Tasks

The research tasks described below are designed to build systematically on the prior studies discussed in section 2 and the preliminary results discussed in section 4. The research tasks center on the radiative effects of SMD on the *inter-annual variability* of the AEJ-AEW system.

Observations have shown that the AEJ-AEW system exhibits strong inter-annual variability (Grist and Nicholson 2001; Grist 2002; Dezfuli and Nicholson 2011). For example, the average latitude of the AEJ core can vary from 12-15°N during the summer, with a more poleward (equatorward) location associated with wet (dry) years (Grist and Nicholson 2001). Wetter years are also marked by AEWs with stronger amplitudes than in drier years (Grist 2002).

Like the AEJ-AEW system, SMD also exhibits inter-annual variability. Strong source regions, such as the Western Sahara and the Bodélé depression in East Africa (Engelstaedter et al. 2006), experience seasonally varying emission mechanisms, such as surface winds (Fiedler et al. 2013) and AEWs (Knippertz and Todd 2012). Inter-annual variability of SMD is strongly related to the rainfall of the previous year, where years of drought are followed by an increase in SMD emissions (Engelstaedter et al. 2006).

As described below, before examining the inter-annual variability of the AEJ-AEW system, I will first focus on the inter-annual variability of SMD. I will then examine the effects of SMD on the AEJ. This will be followed by an examination of the effects of SMD on the AEJ-AEW system.

This approach will ease comparison with previous SMD-free studies and will provide a logical sequence, building from the simpler to the more complex. The following tasks, which extend the single season results summarized in section 4, will examine the 10 summers of WRF-dust model simulations. Analysis of these simulations will establish any long-term trends in the SMD-modified AEJ-AEW system and will confirm the generality of the preliminary results.

SMD Climatology

Task 1: *Determine the inter-annual variability of the frequency, location and magnitude of SMD events.*

This task will be used to determine to what extent the inter-annual variability of SMD is related to the inter-annual variability of the AEJ-AEW system. Previously, the inter-annual variability of SMD emissions over Africa has been attributed to variability in the surface wind speeds and the rainfall of the previous years (Engelstaedter et al. 2006; Laurent et al. 2008). For example, years of drought are followed by years of higher SMD emissions, while wetter years are followed by reduced SMD emissions (Engelstaedter et al. 2006). Laurent et al. (2008) used a dust emission model and found that the largest contribution to the inter-annual variability of dust emissions was the surface wind.

While the above studies provide some analysis of the inter-annual variability of SMD, they do not provide an SMD climatology for 2006-2015. This task will use the WRF-dust model to establish the JAS SMD climatology for the ten-year period; the model results will be compared with satellite data. Hovmöller diagrams of the AOD will be used to quantify and compare SMD events for each season. SMD events will be identified by AOD values greater than one, as in Jury and Santiago (2010). To test the sensitivity of this AOD threshold, alternative AOD values will be used, such as the mean AOD over West Africa for a given summer. The Hovmöller diagrams will establish the number of SMD events per summer and the average duration of SMD events. A time average will be used to determine the average location and extent of the SMD plume for each summer. A domain average over North Africa and the eastern Atlantic Ocean will be used to create a series of average AOD values for each summer, similar to Jury and Santiago (2010). The calculations in this task will allow the 10 summers to be organized by the number of SMD events, the average location of the SMD, and the average magnitude of the SMD. The average total accumulated rainfall for each year will be compared with the SMD characteristics from this task to establish if wetter years are followed by a decrease in SMD emissions.

SMD-Modified AEJ

Task 2.1: *Determine the relationship between the inter-annual variability of SMD and the location and structure of the AEJ.*

There has been extensive research on the generation and maintenance of the AEJ, but relatively few studies have examined its inter-annual variability. One such study by Nicholson and Grist (2003), who do not consider SMD effects, found that the inter-annual variability of the AEJ is related to West African rainfall. Using forty years of reanalysis data, they found that during wet years, the AEJ is farther north and weaker in magnitude than during dry years (Nicholson and Grist 2003). The effect of SMD on the inter-annual variability of the AEJ is less clear. Studies that have examined the SMD-modified AEJ found that the radiative effects of SMD shift the AEJ northward (Tompkins et al. 2005; Wilcox et al. 2010; Reale et al. 2011; Bercos-Hickey et al. 2017). But these studies did not address the effects of SMD on the inter-annual variability of the AEJ.

In this study, I will determine the effects of SMD on the inter-annual variability of the location and structure of the AEJ. To achieve this, I will examine the time-averaged zonal wind for each summer. Linear regressions of the time-averaged zonal wind will be used to calculate the AEJ axis for each summer. This will allow for a comparison of the location and horizontal orientation of the AEJ. A comparison between the experiments with and without SMD will be used to establish how SMD affects the location, structure and horizontal asymmetry of the AEJ over the 10-year period. The results from this task will then be compared to those from Task 1 to determine any correlations between the inter-annual variability of the SMD and the SMD-modified AEJ. Model-produced rainfall data will be used to determine wet and dry years and will be compared with the AEJ locations and magnitudes, similar to Nicholson and Grist (2003).

Task 2.2: *Determine how the potential vorticity (PV) varies inter-annually and how this is related to the variability of SMD.*

PV is a quantity that can provide insight into the behavior of geophysical fluids (Rossby 1940; Hoskins 2015). Defined as $PV = \rho^{-1}\vec{\omega}_a \cdot \nabla\theta$, where $\vec{\omega}_a$ is absolute vorticity, θ is potential temperature, and ρ is density, PV is approximately conserved for large-scale atmospheric circulations (Hoskins 2015). PV can be used to provide information on the stability of a flow, yielding, for instance, necessary conditions for the instability of a zonally averaged current (Charney and Stern 1962). With regard to the AEJ-AEW system, Burpee (1972) established that the AEJ satisfies the necessary condition for instability, i.e., the background meridional PV gradient changes sign within the domain (Charney and Stern 1962; Pedlosky 1987, Chapter 7). Indeed, as discussed earlier, the instability of the AEJ plays an important role in the growth of AEWs (Burpee 1972; Thorncroft et al. 2008; Leroux and Hall 2009). The above studies clearly establish the importance of PV for understanding AEJ instability, but they do not address the effects of SMD.

In addition to stability, PV can also be used to diagnose the maintenance of the AEJ and regions of deep convection (Thorncroft and Blackburn 1999; Berry and Thorncroft 2005; Hsieh and Cook 2008). For example, Thorncroft and Blackburn (1999), who do not consider SMD effects, used the PV distribution over North Africa to distinguish between two separate diabatically forced circulations that maintain the AEJ. Regions of positive PV were associated with deep convection in the ITCZ and regions of negative PV were associated with dry convection over the Sahara Desert.

In light of the above results, in this task, I will examine the time-averaged PV distributions, as in Thorncroft and Blackburn (1999), and the magnitude of the PV gradients for each summer. The PV distributions will be compared with and without SMD to determine how SMD affects the inter-annual variability of the PV of the AEJ-AEW system. The location and strength of the SMD-modified PV gradients will also be compared with the results from Task 1 to establish a correlation between SMD events and the AEJ.

SMD-Modified AEJ-AEW System

Task 3.1: *Determine the effect of the inter-annual variability of SMD on the inter-annual variability of the energetics of the AEJ-AEW system.*

Energy transfer calculations have been used in many AEJ-AEW studies (Kiladis et al. 2006; Hall et al. 2006; Hsieh and Cook 2007). For example, Kiladis et al. (2006) found that the barotropic and baroclinic energy conversions contribute to the maintenance and growth of AEWs. Hall et al. (2006) found that the baroclinic energy conversion had a greater contribution to AEW growth, underscoring the importance of the vertical shear. Hsieh and Cook (2007) extended their energetics analysis to include the diabatic generation of eddy available potential energy (APE). They noted a similarity between the distributions of the diabatic generation of eddy APE and the baroclinic energy conversion and suggested that the generation term supplements the baroclinic term.

While the above studies examine the energetics of the AEJ-AEW system, they do not address the effects of SMD. Grogan et al. (2016), Nathan et al. (2017) and Bercos-Hickey et al. (2017) examined the SMD-modified energetics and found that the diabatic generation of eddy APE due to radiative heating is largest where the SMD gradients are maximized. These studies, however, do not address the inter-annual variability of the SMD-modified energetics. In this study, I will examine the relationship between the inter-annual variability of SMD and the energetics of the AEJ-AEW system. I anticipate that the inter-annual variability of SMD will affect the diabatic generation of eddy APE, which, in turn, will affect the barotropic and baroclinic energy conversions, the EKE, and therefore the strength of the AEWs. To quantify these effects, I will compute the time and domain averaged barotropic and baroclinic energy conversions, the EKE, and the diabatic generation of eddy APE for each summer and for both experiments. A comparison of the two experiments will be used to determine how the inter-annual variability of SMD affects the energetics of the AEJ-AEW system.

Task 3.2: *Determine how the inter-annual variability of SMD affects the propagation speeds and tracks of the AEWs.*

Accurately representing the speeds and tracks of AEWs is important for forecasting tropical cyclogenesis. SMD-induced changes to the AEW speeds and tracks will affect the potential timing and location of where storms leave the coast of Africa. Using reanalysis data, which includes SMD, Kiladis et al. (2006) found that the speed of AEWs slows with westward propagation. Using the WRF-dust model, Bercos-Hickey et al. (2017) found that, with SMD, there was a larger increase in AEW speeds downstream and connected this to an increased zonal expansion of the AEJ with SMD. While both of these studies include the effects of SMD, neither addresses how the inter-annual variability of SMD affects the phase speeds and tracks of the AEWs.

To determine the inter-annual variability of the AEW tracks, the time and zonally averaged EKE will be used to locate the main AEW tracks for each summer and for both experiments, following Hsieh and Cook (2007). The average AEW phase speed will be calculated for each summer using phase difference diagrams, as in Reed et al. (1988), and Hovmöller diagrams, as in Kiladis et al. (2006). The results from the phase speed and track analyses will be compared for both experiments to determine how SMD affects the zonal scale and location of the AEWs over the ten-year period. The inter-annual variability of the zonal structure of the AEJ (Task 2.1) will also be compared with the inter-annual variability of the AEW phase speeds to determine how the asymmetry of the AEJ affects the zonal scale of the AEWs. The SMD-modified phase speeds and tracks will be compared with Task 1 to establish correlations between the variability of the speed and location of the AEWs and the variability of SMD.

Task 3.3: *Determine how SMD affects the inter-annual variability of the strength of the AEWs.*

The AEJ modifies the development and organization of precipitation via AEWs; thus AEW strength has important implications for weather forecasting (Nicholson and Grist 2003). Pytharoulis and Thorncroft (1999) connected PV gradients to the strength of the AEWs by relating the magnitude of the meridional PV gradient to the growth rate of the disturbance. They determined that the meridional PV gradients in the AEJ core are strongest in August and therefore concluded that August has the strongest AEWs out of their May-September 1995 dataset (Pytharoulis and Thorncroft 1999). Similarly, Leroux and Hall (2009) measured the strength of AEWs in a rectangular area by examining where the PV gradient was negative and the zonal wind was less than -9 ms^{-1}. They found that the percent of the rectangular area that was encompassed by the negative PV gradient and the AEJ core was a better indicator of AEW strength than the average magnitude of the PV gradient and the AEJ core (Leroux and Hall 2009).

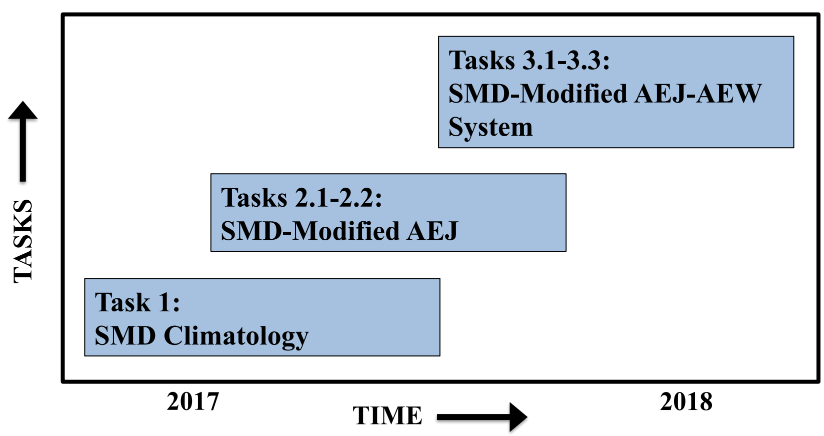
To make the theoretical connection between PV gradients and AEW strength, we use an upper bound on the growth rate of a quasigeostrophic disturbance, which can be written as (Pedlosky 1987, eqn. 7.5.25):

$$B \propto (U_0 - c_r)\frac{\partial \Pi_0}{\partial y} \tag{4.1}$$

where B is the upper bound, U_o is the zonal-mean wind, c_r is the (real) phase speed, and $\frac{\partial \Pi_0}{\partial y}$ is the meridional PV gradient. At the AEJ core, both $(U_o - c_r)$ and $\frac{\partial \Pi_0}{\partial y}$ are negative, so that B is positive.

The previous studies described above, i.e., Pytharoulis and Thorncroft (1999) and Leroux and Hall (2009), which do not examine the effects of SMD, have calculated B at the level of the jet core. With SMD, however, fixing a specific altitude is not appropriate because the AEJ changes in both the horizontal and the vertical. Therefore, I will calculate a domain averaged strength parameter, denoted by <*B*>, for each summer and for both experiments. To avoid picking an arbitrary box for the average, the domain will be chosen based on the half-width of the maximum kinetic energy of the AEJ. The region encompassed by <*B*> will also be calculated, where a larger region would indicate stronger AEWs (Leroux and Hall 2009). The two experiments will be compared to determine how SMD affects the strength of the AEWs over the 10-year period. The SMD-modified strength calculations will also be compared with Task 1 to determine a relationship between SMD variability and AEW strength.

Timeline for Completing the Research Tasks



6. Summary

The proposed research seeks to advance knowledge of the radiative effects of SMD on the AEJ-AEW system. To carry out this research, I will examine the radiative effects of SMD on the inter-annual variability of the AEJ and AEWs. This research will advance understanding of the structure, characteristics, energetics and stability of the AEJ-AEW system. The **broader impacts** of this work will include a better understanding of how SMD affects the circulation over North Africa and will provide a more accurate representation of the SMD-modified AEJ-AEW system. Together these impacts will help improve forecasts of the strength and location of the AEJ-AEW system, which are key to improving tropical cyclone forecasts over the eastern Atlantic Ocean.

7. Final Remarks

The original plan for this prospectus was to examine the effects of SMD on the inter-annual and intra-seasonal variability of the AEJ-AEW system. As the prospectus developed, however, it became clear that focusing on inter-annual variability alone would constitute a sufficient body of original work for my dissertation (likely 2-3 journal articles).

Nevertheless, time permitting, I will begin *preliminary work* on examining the intra-seasonal effects of SMD on the AEJ-AEW system. Previous SMD-free studies have shown that the AEJ exhibits strong intra-seasonal variability (Afiesimama 2007). For example, over the course of the year the AEJ location migrates northward and upward, reaching approximately 14°N and 600 hPa during summer and retreating to 2°N and 700 hPa during winter (Afiesimama 2007).

Like the AEJ, AEWs exhibit strong intra-seasonal variability of their wavelengths, phase speeds and amplitudes (Berry and Thorncroft 2005). The AEW speeds, for example, are indicators of how long it will take an AEW to traverse North Africa, while the AEW amplitudes are measures of AEW strength.

Similarly, SMD exhibits intra-seasonal variability. For example, the AEWs have been shown to play a role in SMD mobilization, resulting in varying SMD events over a season (Jones et al. 2004). Jones et al. (2004) also found that the radiative effects of SMD modify the AEWs, forming a possible feedback mechanism between the AEWs and the SMD.

Preliminary work will address the following tasks:

- *Determine how the intra-seasonal variability of SMD affects the structure and location of the AEJ.*
- *Determine the relationship between the intra-seasonal variability of SMD and the structure and location of the AEWs.*
- *Determine how the intra-seasonal variability of SMD affects the PV and the strength of the AEWs.*
- *Determine how the intra-seasonal variability of SMD affects the energetics of the AEJ-AEW system.*

8. References

Afiesimama, E. A., 2007: Annual cycle of the mid-tropospheric easterly jet over West Africa. *Theor. Appl. Climatol.*, **90**, 103–111, doi:10.1007/s00704-006-0284-y.

Albignat, J. P., and R. J. Reed, 1980: The Origin of African Wave Disturbances during Phase III of GATE. *Mon. Weather Rev.*, **108**, 1827–1839, doi:10.1175/1520-0493(1980)108< 1827:TOOAWD>2.0.CO;2.

Bercos-Hickey, E., T. R. Nathan, and S.-H. Chen, 2017: Saharan Dust and the African Easterly Jet-African Easterly Wave System: Structure, Location and Energetics. *Q. J. Roy. Meteor. Soc. (accepted).*

Berry, G. J., and C. D. Thorncroft, 2005: Case Study of an Intense African Easterly Wave. *Mon. Weather Rev.*, **133**, 752–766, doi:10.1175/MWR2884.1.

Burpee, R. W., 1972: The Origin and Structure of Easterly Waves in the Lower Troposphere of North Africa. *J. Atmos. Sci.*, **29**, 77–90, doi:10.1175/1520-0469(1972)029<0077 :TOASOE>2.0.CO;2.

Carlson, T. N., 1969a: Synoptic Histories of Three African Disturbances that Developed into Atlantic Hurricanes. *Mon. Weather Rev.*, **97**, 256–276, doi:10.1175/1520-0493(1969)097<0256:SHOTAD>2.3.CO;2.

Carlson, T. N., 1969b: Some Remarks on African Disturbances and Their Progress Over the Tropical Atlantic. *Mon. Weather Rev.*, **97**, 716–726, doi:10.1175/1520-0493(1969)097<0716:SROADA>2.3.CO;2.

Charney, J. G., and M. E. Stern, 1962: On the Stability of Internal Baroclinic Jets in a Rotating Atmosphere. *J. Atmos. Sci.*, **19**, 159–172, doi: 10.1175/1520-0469(1962)019<0159: OTSOIB>2.0.CO;2.

Chen, S.-H., S.-H. Wang, and M. Waylonis, 2010: Modification of Saharan air layer and environmental shear over the eastern Atlantic Ocean by dust-radiation effects. *J. Geophys. Res.*, **115**, D21202, doi:10.1029/2010JD014158.

Cook, K. H., 1999: Generation of the African Easterly Jet and Its Role in Determining West African Precipitation. *J. Climate*, **12**, 1165–1184, doi:10.1175/1520-0442(1999)012 <1165:GOTAEJ>2.0.CO;2.

Dezfuli, A. K., and S. E. Nicholson, 2011: A note on long-term variations of the African easterly jet. *Int. J. Climatol.*, **31**, 2049–2054, doi:10.1002/joc.2209.

Engelstaedter, S., and R. Washington, 2007: Atmospheric controls on the annual cycle of North African dust. *J. Geophys. Res.*, **112**, D03103, doi:10.1029/2006JD007195.

Engelstaedter, S., I. Tegen, and R. Washington, 2006: North African dust emissions and transport. *Earth-Sci. Rev.*, **79**, 73–100, doi:10.1016/j.earscirev.2006.06.004.

Fiedler, S., K. Schepanski, B. Heinold, P. Knippertz, and I. Tegen, 2013: Climatology of nocturnal low-level jets over North Africa and implications for modeling mineral dust emission. *J. Geophys. Res.*, **118**, 6100–6121, doi:10.1002/jgrd.50394.

Frank, N. L., 1970: Atlantic tropical systems of 1969. *Mon. Weather Rev.*, **98**, 307–314, doi:10.1175/1520-0493(1970)098<0307:ATSO>2.3.CO;2.

Grist, J. P., 2002: Easterly Waves over Africa. Part I: The Seasonal Cycle and Contrasts between Wet and Dry Years. *Mon. Weather Rev.*, **130**, 197–211, doi:10.1175/1520-0493(2002)130<0197:EWOAPI>2.0.CO;2.

Grist, J. P., and S. E. Nicholson, 2001: A Study of the Dynamic Factors Influencing the Rainfall Variability in the West African Sahel. *J. Climate*, **14**, 1337–1359, doi:10.1175/1520-0442(2001)014<1337:ASOTDF>2.0.CO;2.

Grogan, D. F. P., T. R. Nathan, and S.-H. Chen, 2016: Effects of Saharan Dust on the Linear Dynamics of African Easterly Waves. *J. Atmos. Sci.*, **73**, 891–911, doi:10.1175/JAS-D-15-0143.1.

Grogan, D. F. P., T. R. Nathan, and S.-H. Chen, 2017: Saharan Dust and the Nonlinear Evolution of the African Easterly Jet–African Easterly Wave System. *J. Atmos. Sci.*, **74**, 27–47, doi:10.1175/JAS-D-16-0118.1.

Hall, N. M. J., G. N. Kiladis, and C. D. Thorncroft, 2006: Three-Dimensional Structure and Dynamics of African Easterly Waves. Part II: Dynamical Modes. *J. Atmos. Sci.*, **63**, 2231–2245, doi:10.1175/JAS3742.1.

Hess, M., P. Koepke, and I. Schult, 1998: Optical Properties of Aerosols and Clouds: The Software Package OPAC. *Bull. Am. Meteorol. Soc.*, **79**, 831–844, doi:10.1175/1520-0477(1998)079<0831:OPOAAC>2.0.CO;2.

Hoskins, B., 2015: Potential vorticity and the PV perspective. *Adv. Atmos. Sci.*, **32**, 2–9, doi:10.1007/s00376-014-0007-8. https://doi.org/10.1007/s00376-014-0007-8.

Hsieh, J.-S., and K. H. Cook, 2007: A Study of the Energetics of African Easterly Waves Using a Regional Climate Model. *J. Atmos. Sci.*, **64**, 421–440, doi:10.1175/JAS3851.1.

Hsieh, J.-S., and K. H. Cook, 2008: On the Instability of the African Easterly Jet and the Generation of African Waves: Reversals of the Potential Vorticity Gradient. *J. Atmos. Sci.*, **65**, 2130–2151, doi:10.1175/2007JAS2552.1.

Iacono, M. J., J. S. Delamere, E. J. Mlawer, M. W. Shephard, S. A. Clough, and W. D. Collins, 2008: Radiative forcing by long-lived greenhouse gases: Calculations with the AER radiative transfer models. *J. Geophys. Res.*, **113**, D13103, doi:10.1029/2008JD009944.

Jones, C., N. M. Mahowald, and C. Luo, 2004: Observational evidence of African desert dust intensification of easterly waves. *Geophys. Res. Lett.*, **31**, L17208, doi:10.1029/2004GL020107.

Jury, M. R., and M. J. Santiago, 2010: Composite analysis of dust impacts on African easterly waves in the Moderate Resolution Imaging Spectrometer era. *J. Geophys. Res.*, **115**, D16213, doi:10.1029/2009JD013612.

Karyampudi, V. M., and T. N. Carlson, 1988: Analysis and Numerical Simulations of the Saharan Air Layer and Its Effect on Easterly Wave Disturbances. *J. Atmos. Sci.*, **45**, 3102–3136, doi:10.1175/1520-0469(1988)045<3102:AANSOT>2.0.CO;2.

Kiladis, G. N., C. D. Thorncroft, and N. M. J. Hall, 2006: Three-Dimensional Structure and Dynamics of African Easterly Waves. Part I: Observations. *J. Atmos. Sci.*, **63**, 2212–2230, doi:10.1175/JAS3741.1.

Knippertz, P., and M. C. Todd, 2010: The central west Saharan dust hot spot and its relation to African easterly waves and extratropical disturbances. *J. Geophys. Res.*, **115**, D12117, doi:10.1029/2009JD012819.

Knippertz, P., and M. C. Todd, 2012: Mineral dust aerosols over the Sahara: Meteorological controls on emission and transport and implications for modeling. *Rev. Geophys.*, **50**, RG1007, doi:10.1029/2011RG000362.

Kok, J. F., 2011: A scaling theory for the size distribution of emitted dust aerosols suggests climate models underestimate the size of the global dust cycle. *P. Natl. Acad. Sci. U.S.A.*, **108**, 18–20, doi:10.1073/pnas.1014798108/-/DCSupplemental.www.pnas.org/cgi/doi/10.1073/pnas.1014798108.

Landsea, C. W., 1993: A Climatology of Intense (or Major) Atlantic Hurricanes. *Mon. Weather Rev.*, **121**, 1703–1713, doi:10.1175/1520-0493(1993)121<1703:ACOIMA >2.0.CO;2.

Laurent, B., B. Marticorena, G. Bergametti, J. F. Léon, and N. M. Mahowald, 2008: Modeling mineral dust emissions from the Sahara desert using new surface properties and soil database. *J. Geophys. Res. Atmos.*, **113**, n/a-n/a, doi:10.1029/2007JD009484.

Leroux, S., and N. M. J. Hall, 2009: On the Relationship between African Easterly Waves and the African Easterly Jet. *J. Atmos. Sci.*, **66**, 2303–2316, doi:10.1175/2009JAS2988.1.

Ma, P.-L., K. Zhang, J. J. Shi, T. Matsui, and A. Arking, 2012: Direct Radiative Effect of Mineral Dust on the Development of African Easterly Waves in Late Summer, 2003–07. *J. Appl. Meteorol. Clim.*, **51**, 2090–2104, doi:10.1175/JAMC-D-11-0215.1.

Nathan, T. R., D. F. P. Grogan, and S.-H. Chen, 2017: Subcritical destabilization of African easterly waves by Saharan mineral dust. *J. Atmos. Sci.*, **74**, 1039–1055, doi:10.1175/JAS-D-16-0247.1.

Nicholson, S. E., and J. P. Grist, 2003: The Seasonal Evolution of the Atmospheric Circulation over West Africa and Equatorial Africa. *J. Climate*, **16**, 1013–1030, doi:10.1175/1520-0442(2003)016<1013:TSEOTA>2.0.CO;2.

Pedlosky, J., 1987: *Geophysical Fluid Dynamics*. Springer-Verlag, New York, pp. 710.

Pytharoulis, I., and C. D. Thorncroft, 1999: The Low-Level Structure of African Easterly Waves in 1995. *Mon. Weather Rev.*, **127**, 2266–2280, doi:10.1175/1520-0493(1999) 127<2266:TLLSOA>2.0.CO;2.

Reale, O., W. K. Lau, K.-M. Kim, and E. Brin, 2009: Atlantic Tropical Cyclogenetic Processes during SOP-3 NAMMA in the GEOS-5 Global Data Assimilation and Forecast System. *J. Atmos. Sci.*, **66**, 3563–3578, doi:10.1175/2009JAS3123.1.

Reale, O., K. M. Lau, and A. da Silva, 2011: Impact of Interactive Aerosol on the African Easterly Jet in the NASA GEOS-5 Global Forecasting System. *Weather Forecast.*, **26**, 504–519, doi:10.1175/WAF-D-10-05025.1.

Reed, R. J., D. C. Norquist, and E. E. Recker, 1977: The Structure and Properties of African Wave Disturbances as Observed During Phase III of GATE. *Mon. Weather Rev.*, **105**, 317–333, doi:10.1175/1520-0493(1977)105<0317:TSAPOA>2.0.CO;2.

Reed, R. J., E. Klinker, and A. Hollingsworth, 1988: The structure and characteristics of African easterly wave disturbances as determined from the ECMWF operational analysis/forecast system. *Meteorol. Atmos. Phys.*, **38**, 22–33, doi:10.1007/ BF01029944.

Rossby, C.-G., 1940: Planetary flow patterns in the atmosphere. *Q. J. Roy. Meteor. Soc.*, **66**, 68–87.

Tegen, I., and I. Fung, 1994: Modeling of mineral dust in the atmosphere: Sources, transport, and optical thickness. *J. Geophys. Res.*, **99**, 22897–22914, doi:10.1029/94JD01928.

Thorncroft, C. D., and M. Blackburn, 1999: Maintenance of the African easterly jet. *Q. J. Roy. Meteor. Soc.*, **125**, 763–786, doi:10.1002/qj.49712555502.

Thorncroft, C. D., N. M. J. Hall, and G. N. Kiladis, 2008: Three-Dimensional Structure and Dynamics of African Easterly Waves. Part III: Genesis. *J. Atmos. Sci.*, **65**, 3596–3607, doi:10.1175/2008JAS2575.1.

Tompkins, A. M., C. Cardinali, J.-J. Morcrette, and M. Rodwell, 2005: Influence of aerosol climatology on forecasts of the African Easterly Jet. *Geophys. Res. Lett.*, **32**, L10801, doi:10.1029/2004GL022189.

Wilcox, E. M., K. M. Lau, and K.-M. Kim, 2010: A northward shift of the North Atlantic Ocean Intertropical Convergence Zone in response to summertime Saharan dust outbreaks. *Geophys. Res. Lett.*, **37**, L04804, doi:10.1029/2009GL041774.

Zhu, A., V. Ramanathan, F. Li, and D. Kim, 2007: Dust plumes over the Pacific, Indian, and Atlantic oceans: Climatology and radiative impact. *J. Geophys. Res.*, **112**, D16208, doi:10.1029/2007JD008427.