USE OF THE ELECTROSTATIC CLASSIFICATION METHOD TO INVESTIGATE THE SIZE DISTRIBUTION OF AEROSOLS NEAR HURRICANE ERIKA

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Abstract. We present measurements of aerosols acquired with a differential mobility analyzer – condensation particle counter (DMA-CPC) system aboard a P-3 flight from Miami, FL to Bermuda during Hurricane Erika in 1997. We have analyzed particle number densities as a function of particle diameter, wind speed, and distance from the eye of the hurricane. Our results indicate that particles with diameters larger than .025 μm are scavenged efficiently within the hurricane, resulting in a mono modal distribution near the eye.

Introduction

Tropospheric aerosol global distributions and properties are poorly known due in part to their short lifetimes and reactivity. Airborne particle sampling offers the unique advantage of gaining in situ, highly resolved temporal and spatial aerosol distributions (Flagan et al., 1996; Daum and Springston, 1993). Russell et al. (1995) reported that observing the dynamics of atmospheric aerosols where nucleation is occurring requires near real-time measurement of the particle size distribution under study. In marine air, or over water surfaces, there are fewer small aerosols present, unless some perturbation, such as a tropical cyclone or hurricane, affects the distribution of these particles. Findings discussed in Russell et al. (1996) states that aerosols show low-concentration bimodal distributions in cleaner air masses and higher-concentration single-mode distributions in air masses with apparent recent continental influence. However, studies of aerosols depend heavily on interpretations of observations and measurements to provide guidelines for the development of models and for attaining an understanding of the workings of aerosol cycles (Prospero et al., 1983). A leading force in the hurricane research field is the Convection And Moisture Experiment (CAMEX), whose using remote sensing instrumentation to yield high spatial and temporal information of hurricane structure, dynamics, and motion. This paper describes the analysis of aerosol data acquired in the presence of a hurricane. An airborne, *in situ* system of an electrostatic classifier (EC), differential mobility analyzer (DMA), and condensation particle counter (CPC) was used to obtain concurrent measurements at high temporal and spatial resolutions in order to assess some of the *instantaneous* effects of hurricanes on tropospheric aerosols.

The primary objective of this work is to provide an assessment of the local (or regional) effect of hurricanes on the size and number distributions of tropospheric aerosols. A secondary objective is to demonstrate that the EC-CPC system used in this investigation is suitable for future in situ aircraft studies *in the vicinity of a hurricane*. Measurements of aerosol concentrations have been used to quantify the effects of wind speed and convective processes of Hurricane Erika on tropospheric aerosol distributions.

The upward and downward convection processes within the hurricane can cause a measurable and characteristic change in the aerosol distribution. The variation in particle distribution is also influenced by the rainband distribution of the hurricane via the scavenging of larger particles. These factors can effectively be determined through airborne, in situ particle measurements.

Aircraft Measurements

Hurricane Erika occurred from September 3rd to September 15th of 1997 in the Atlantic Ocean. The flight track of the P-3 aircraft is shown in Figure 1, extending from the base of Miami, Florida to Bermuda on September 10th, 1997.

During the day of the flight, the wind speed of Hurricane Erika (HE) peaked at 110 knots and was moving north-northeast of Bermuda. The force winds extended outwards up to 145 miles from the center and the tropical storm winds extended outward up to 290 miles. Aerosol measurements, with diameters from .01 to 1.0 μm, were obtained at altitudes up to 21,000 feet.

The instrumentation utilized for the measurements was an electrostatic classifier (EC), composed of a TSI model 3071 differential mobility analyzer (DMA), and a TSI model 3010 condensation particle counter (CPC). The Flagan and Russell research team used a similar mechanism during their

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study of mixing effects in accelerated DMA-CPC measurements (Russell et al., 1995). Atmospheric aerosols were collected by the common inlet system through one window of the P-3 aircraft *every one and a half minutes*. The sample inlet enabled collected particles to enter the classifier, and sequentially pass through the DMA, and into the CPC. The inlet system was positioned forward of the engines. Once the aerosol inlet tubing reached inside of the aircraft, a smaller tube of 1.5 inches was inserted in the center of the larger inlet (2.0 inches) in order to transfer the particles to the impactor.

Although, electrostatic classifiers are standard instrumentation for laboratory measurement of aerosols, several modifications to the commercial system were necessary in order to use the EC for research flights. In this study, the modifications made were the flow rates of the inner and outer cylinders of the DMA, the scanning electrode voltage used, and the resolution of the DMA. The aerosols pass into the EC system through an impactor, which discriminates aerosols above/below 1 μm or with a resolution of .01 to 1.0 μm. The nominal flow through the impactor is regulated at 0.3 L/min. After the impactor, aerosols enter a Kr-85 bipolar charger, set at 2 mC where high concentrations of both positive and negative ions are distributed to the aerosols. Once the particles reach an equilibrium charge distribution, they travel to the outer cylinder of the differential mobility analyzer (DMA). There are two concentric cylindrical electrodes within the DMA. A 3 L/min flow of sheath air through the inner cylinder of the DMA is maintained while a 0.3 L/min sample flow is maintained in the outer cylinder, without any mixing of the two streams; the sheath air and the sample aerosol flow. The electric field in the DMA is generated by the interaction of the negatively charged electric rod, scanned from 20 to 10,000 negative volts, centered in the inner cylinder of the DMA and the grounded outer cylinder of the DMA. Since the negatively charged rod is in the center, the positively charged particles are attracted through the particle-free sheath air and radially flowed to the rod. As the electrical mobility of the particle decreases, particles of a narrow, predictable mobility range are released through the center electrode and directed into the condensation particle counter (CPC). Therefore, the modifications were necessary in order to achieve the specified diameter band of particles due to the fact that the resolution of the released particles through the center electrode of the DMA is a factor of the flow rates and electric field produced within the EC. Further discussion of this mechanism can be found in Knutson and Whitby (1975).

The CPC measures the concentration of the aerosols coming from the DMA. In this study, it was configured to measure in the .01 to 1.0 μm diameter size range.

Results and Discussion

The aerosol number density and size distribution was analyzed continuously along the flight path. The data bank for this study includes over 200 locations representing the evolution of the aerosols over the course of the flight. Three example plots are shown in Figures 2-4.

The local maxima in the size distribution plots were. In the following discussion, a mode is defined as a local maxima in the particle size distribution of the atmospheric aerosol (Morawska, 1999). Quantitatively, this point should exceed its surrounding points by a concentration great enough to be characterized as a peak in the distribution. The aerosol plots displayed complex multimodal distributions everywhere, except within the hurricane.

The trend line plotted along the aerosol data is a moving average for every three readings. It is denoted in the legend as *3 per. Mov. Avg.*. Additionally, the points or peaks that were found to be significant have been marked and numbered accordingly, as demonstrated on each of the plots.

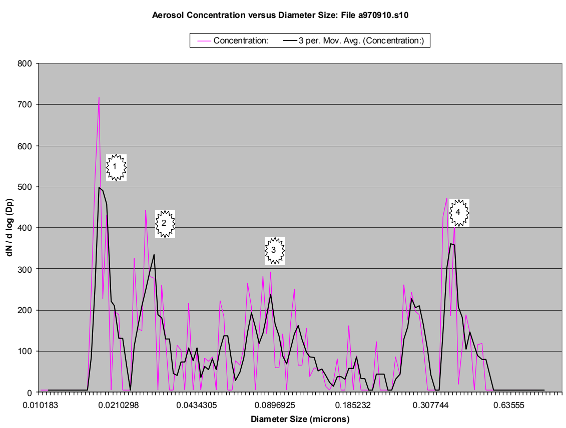

Figure 2. Aerosol Concentration versus Diameter Size (25.89N, -79.7 E, 2.75 km altitude)

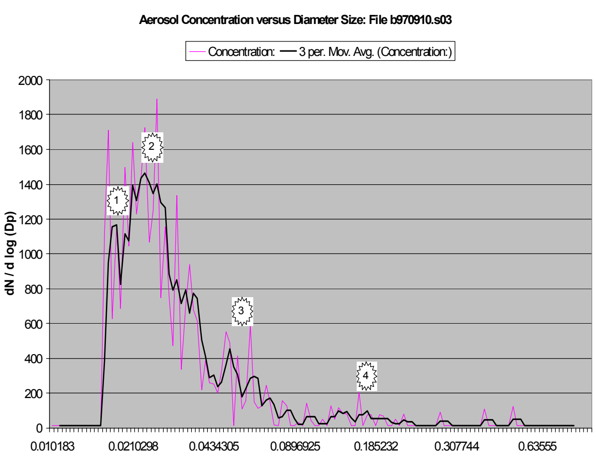

Figure 3. Aerosol Concentration versus Diameter Size (26.18N, -78.1 E, 4.80 km altitude)

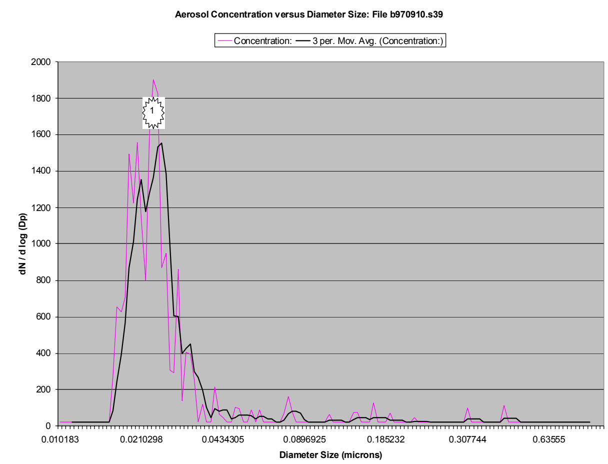

Figure 4. Aerosol Concentration versus Diameter Size (33.44N, -58.5 E, 6.32 km altitude)

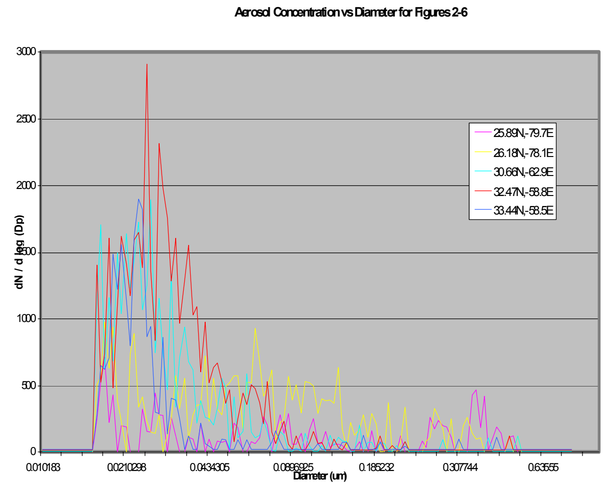

Figure 5. Aerosol Concentration versus Diameter for Figures 2 thru 4

Figure 2 represents a well-mixed distribution of particles that is primarily due to its proximity to Miami. The P-3 aircraft was flying at ground level, approximately 3 km, where all sizes of aerosols normally subsist at high concentrations. Florida is a landmass with a high ambient concentration of Aitken nuclei. Additionally, Florida is bordered by the Atlantic Ocean where Aitken nuclei are major precursors for marine air aerosols and water surfaces are a source of large aerosols due to the bursting of sea bubbles or wind-induced wave breaking [Hobbs and Wallace, 1977; Wexler, 1995]. The combination of these factors leads to the observed size distribution of aerosols. Figure 2 is multimodal with four maxima at .017 μm (715 m^{-3}), .027 (450 m^{-3}), .082 (275 m^{-3}), and .440 μm (475 m^{-3}). It is likely that numerous sources contributed to the distributions due to the mixture of particles (including traffic-, urban-, and vegetation burning-influenced aerosols).

Figure 3 is the first of two remote ocean points that have an identical longitude reading of -62.9 °E and an altitude of 6.3 km. A multimodal size distribution is observed for the aerosols in narrow size band from 0.01 - 0.16 μm. The peaks are .017 μm (1700 m^{-3}), .026 μm (1900 m^{-3}), .06 μm (600 m^{-3}), and .16 μm (200 m^{-3}). The sharp and distinct decrease in larger aerosols may be due to the updrafts of the hurricane, where horizontal wind speeds were measured at about 100 knots ($\cong$ 115 mph). Since the distance of the aircraft from HE is approximately 232 km at this time, the updrafts are reaching severe conditions and the wind speed is increasing. The effects of the hurricane are causing severe wind conditions and the size distribution displays an increase in particle concentrations at the .017 and .025 μm modes relative to the previous concentration shown in Figure 2.

The range of the aerosol size distribution shown in Figure 4 is very narrow (.017 - .080 μm) and the distribution has evolved from a complex multimodal distribution to a near-mono modal distribution. At this location, the aircraft was flying at 6.32 km in altitude. The size distribution shown in the figure, a point inside of HE, has collapsed to a near unimodal from the multimodal (four or more maxima) pattern of aerosols shown for the early points in the flight. This is an effect of the hurricane where size-dependent particle scavenging increases the number density of the .026 μm mode by more than 50% and slowly depletes particles larger than this mode. HE acts to collapse the ambient aerosol size distribution to sizes within the .015 to .04 μm diameter range. There is a distinct peak at .025 $\pm$ .002 μm with a number density at 1900 m^{-3} in figures 4. According to the time that this measurement was taken, the flight was approximately 11 km from the eye of the hurricane.

Although the aerosol distributions were analyzed as functions of both altitude and sea & land components, the influence of either were not gainfully apparent. Perhaps the sea & land comparisons of aerosol distributions were not effective because the majority of the flight occurred over water masses. However, the distributions over the Miami base revealed *more sources* of particle size distributions, but at much *lower concentrations* than found in the presence of the hurricane. The existence of the forcing winds from Hurricane Erika appeared to overwhelm most altitudinal factors of the aerosol distribution. Another reason that the altitude comparisons were *not* found to be significant was that over 80% of the flight occurred at altitudes around 20,000 feet without much variation. Yet, the altitude did seem to correlate with the concentration of particles in the initial flight period. As the altitude increased, so did the particle number density. This can be seen in Figure 6.

The results presented show that there was a ubiquitous size mode at ~ .025 μm. Aerosols small in diameter size, known as Aitken nuclei, dominated the distributions observed during this flight with number densities over 4000 m^{-3} (refer to Figure 6). Aitken nuclei characterize aerosols with diameters less than .2 µm. The concentration of large aerosols observed is likely a result of marine-influenced aerosols, where the typical accumulation mode ($0.1 < D_p < 0.6$ µm) results from the cycling of the particle through cloud formation and evaporation cycles producing larger than original cloud condensation nucleis (Wexler, 1995; Morawska, 1999). Convection and strong updrafts advect the larger particles and effectively collapse the size distribution from 0.017 – 0.65 µm down to 0.017 – 0.025 µm. During these updrafts, air is spiraled towards the eye of the hurricane and whirls upward. At the point where the winds of HE were maximized, larger aerosols ($D_p > .1$µm) are forced into rain bands where they are scavenged by raindrops.

Figures 6 and 7 provide a total view of the modality distribution, in number density, for each mode along the flight path. The most common modes were chosen and averaged, .023, .025, and .027 µm averaged to .025, to show the number distribution measured in the eye of Hurricane Erika (HE). The wind speeds are also included on the x-axis notation to see how they vary with increasing distance to/from HE.

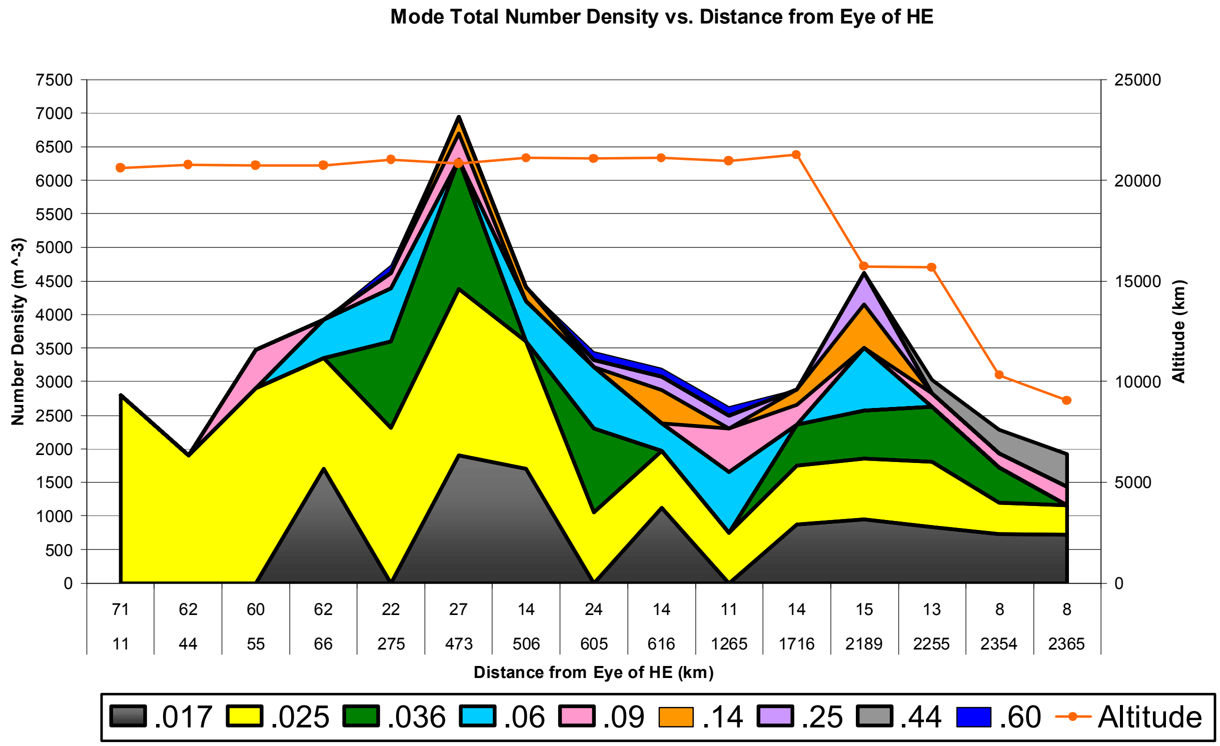

Figure 6. Total Modality Distribution vs. Distance from Eye of HE (.017, .025, .036, .06, .09, .14, .25, .44, .60µm). The top line of the x-axis is the wind speed (in knots) at the respective distance from HE.

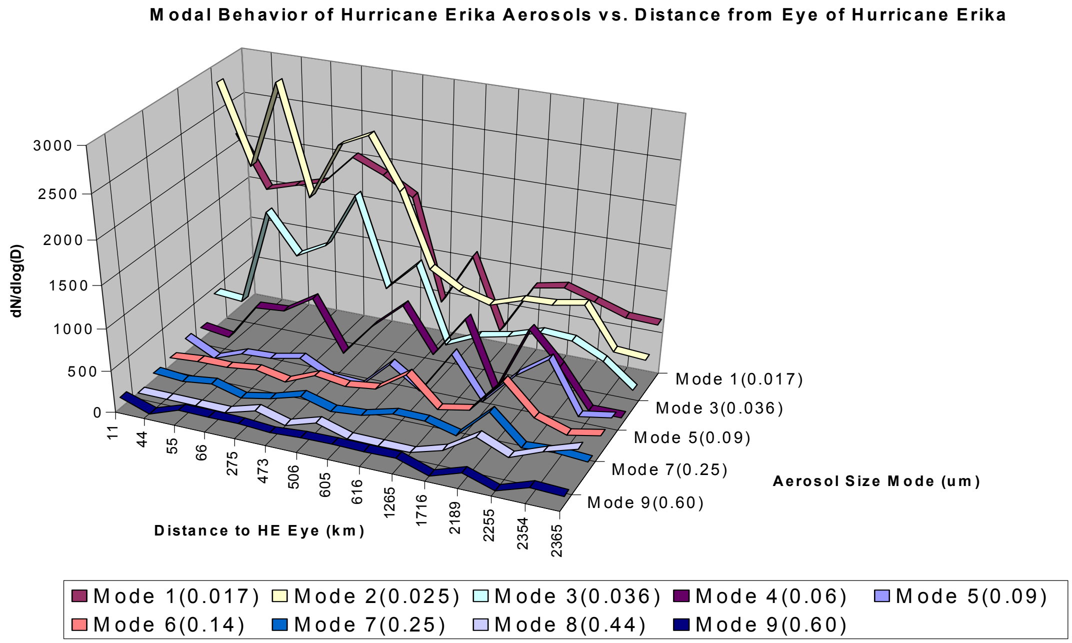

Figure 7. Modality Distribution vs. Distance from eye of HE (.017, .025, .036, .06, .09, .14, .25, .44, .60 μm)

Figure 6 shows the *total* number density of aerosols with varying distances from the eye of HE. It can be determined that the higher wind speeds, at 11, 44, and 55 km away from the eye of HE, patterns a decreasing number mode (number of particle *sizes* present) with increasing wind speeds. For instance, the distance from the eye of HE at which there is a unimodal distribution has a peak wind speed of 71 kts. The figure also displays two distinct peak locations with varying mode diameters at 2189 km and at 473 km. The 2189 km peak is measured at about 15,000 feet, over the islands of the Bahamas. Several size modes are present at this point indicating a multisource distribution. The second peak in the aerosol number density is in the remote ocean (Point 5) immediately after exiting the hurricane. This increase in total number density is indicative of rain droplet scattering of the larger size particles within the hurricane. In fact, at about 473 km, aerosols greater than .14 μm are virtually absent. At distances of 11 and 44 km, there is a single dominant mode at .025 μm. Figure 7 displays a 3-D overview of the modality distribution versus the distance from the eye of HE. The plotted modes are .017, .025, .060, .090, .14, .25, .44, and .60 μm. The figure clearly shows that the predominance in number distribution of the smaller aerosols, .017 and .025, that peaked in the vicinity of HE and first appeared off the coast of Miami and over the Bahamas. The larger aerosols had concentrations more dominant in distances farther from the eye of HE. Therefore, the mode analysis in Figure 7 clearly displays higher relative concentrations of particles for the smaller mode sizes reflecting size dependence to the updraft mechanism of HE. In other words, the larger the particle size, the faster their removal rate resulting in an aerosol size and number distribution that was skewed towards smaller-sized aerosols less than .1μm. This is compounded by the fact that larger size particles (greater than .01 μm in diameter) tend to be hygroscopic enabling them to serve as cloud condensation nuclei (CCN) and form raindrops through nucleation of cloud particles.

Figures 8 thru 10 are plots of the concentration of collected aerosols versus the wind speed measured during our time of flight. The concentration is measured in m^{-3}, wind speed in knots, and the time in hours. The figures show that the flight track intercepts HE from about 20.5 to 22.5 hours. The bin size is defined as the diameter *range* of particles measured. In this study, the bin size was randomly selected for a size distribution of small diameter ranges, such as .018-.023 in Figure 8, slightly larger diameter ranges (such as, .032-.042 in Figure 9), and truly large diameter ranges (such as, .442-.570 in Figure 10). The average concentration of aerosols measured outside of the hurricane area and within the hurricane area was analyzed. The majority of the flight was flown at altitudes above 20,000 feet. In Figure 8, the examination of bin sizes revealed an average difference of about two between the aerosol concentration measurements within (1162.94 m^{-3}) and without (526.96 m^{-3}) the hurricane vicinity. The larger of the two concentrations was favored within Hurricane Erika. Notice that the *range* of particles centers on the size of .025 μm.

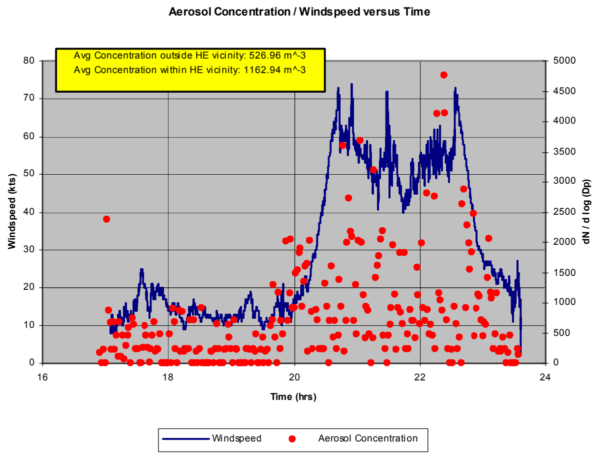

Figure 8. Aerosol Concentration/ HE Wind Speed vs. Time (bin size: .0181904-.0234465 µm)

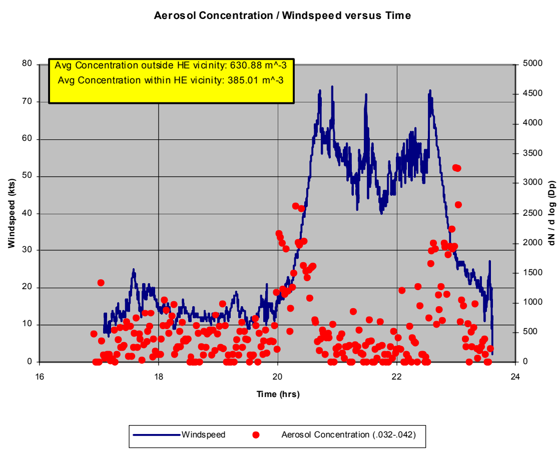

Figure 9. Aerosol Concentration/ HE Wind Speed vs. Time (bin size: .0324946-.0418839 µm)

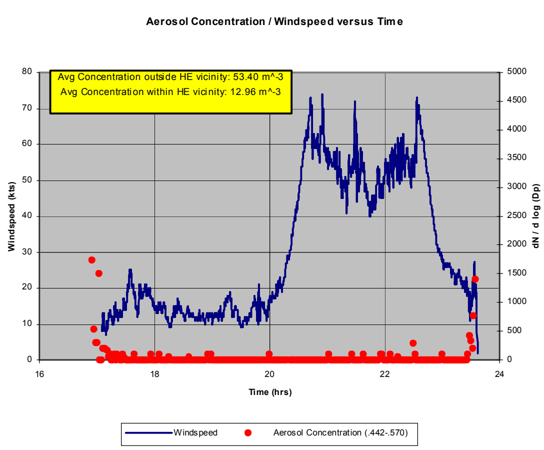

Figure 10. Aerosol Concentration/ HE Wind Speed vs. Time (bin size: .442252-.570040 µm)

Figure 9, .032 - .042 µm, is the first indicator of the hurricane effect that acts to scavenge particles larger than .025 µm. The concentration without the HE vicinity is 630.88 m^{-3}, while within the vicinity of HE is 385.01 m^{-3}. Figure 15 continues to display the effectiveness of the hurricane's scavenging ability on aerosol distributions. Following the path of bin sizes from small to large will show that there is a size-dependent process of particle advection by Hurricane Erika. As the range of particles increase, the presence of these aerosols *within* the vicinity of the hurricane, from 20.5 to 22.5 hours, decreases. This can also be determined by the average concentration measurements as noted on each plot.

Summary and Conclusions

Most points along the flight course were observed as a multimodal aerosol size distribution with size modes in the diameter range between .017 to .65 µm. The number distribution is dominated by Aitken nuclei. The narrow size distribution can be explained on the basis of a rather simple argument. Large aerosols have a rather short lifetime, on the order of a few days, and are not able to subsist at high altitudes when most of the flight was flown above 20, 000 feet (6 km). The number density of the larger aerosols, with diameters greater than .2µm, was highest at the beginning of the flight, near Miami and over the Bahamas at altitudes below 6 km, and at the end of the flight, after departing the vicinity of Hurricane Erika (HE). The total number density of small aerosols was greatest in the vicinity of HE. Thus, we report that the hurricane scattered virtually all particles larger than .025 µm, a ubiquitous mode throughout the flight, resulting in a very narrow size distribution within Hurricane Erika.

We also observed a consistent decrease in the total number density of small aerosols by an average factor of two *outside* of the rain bands. This may be due to the convective processes or precipitation within the hurricane. Unfortunately, we have not been able to access the precipitation data acquired during the flight. However, we can report with certainty that the total aerosol number densities, increased at closer distances to Hurricane Erika. Particularly, the small aerosols (< .025 µm) had their highest values at only 11 km away from the hurricane. Additionally, these particle concentrations generated a pattern with the wind speed of HE and distance to HE. The maximum horizontal winds revealed a greater advection of small particles as demonstrated in Figure 8, where the number density generally increased at wind speeds of 60 knots and greater. In contrast, the max winds showed a weaker advection of larger (> .025 µm) particles.

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Information was taken from the website, http://fermi.jhuapl.edu/hurr/97/erika.

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