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Abstract approved:

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Cynthia Twohy

Knowledge concerning trade wind cumulus, one of the most dominant cloud types on the planet, has become increasingly important when considering global issues such as climate change due to their potential influence on the Earth's energy budget. In this project, using data from the Rain in Cumulus over the Ocean (RICO) experiment, it was observed that the origin of the air mass in which these clouds form affects the type of particles found in the air, which subsequently has an effect on the drop concentration of those clouds. Higher particle concentrations follow from more polluted areas, and more particles often indicate an increased number of cloud droplets. Later analysis of data from RICO will examine the effects of the particle composition on these clouds.

Key Words: aerosol, cumulus, cloud condensation nuclei, air mass origin

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The Effects of Air Mass Origin on Cumulus Clouds in the Caribbean

by

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I understand that my project will become part of the permanent collection of Oregon State University, University Honors College. My signature below authorizes release of my project to any reader upon request.

Kimberly M. Johnson, Author

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INTRODUCTION

Aerosols are found everywhere in the atmosphere. They can form from dust clouds raised by wind, smoke from forest fires and other forms of burning, and from combustion in automobiles and industrial plants. An aerosol is defined as "a suspension of solid or liquid particles in a gas, usually air" (Reist 1993). Types of aerosol include dust, fumes, smoke, fog, and haze. Many of these aerosols fall into the category of cloud condensation nuclei, or CCN, which are particles that allow water to condense onto them and eventually become cloud droplets as more water vapor becomes liquid. Each cloud droplet in existence formed on a CCN. This is due to the fact that the values for relative humidity in the Earth's atmosphere are never high enough to allow water to condense onto itself; thus a medium, or surface, other than water is necessary for cloud droplet formation.

Learning about CCN is important due to the implications they hold over cloud properties and behavior. For example, small CCN in large numbers will produce more cloud droplets of smaller size in a given set of atmospheric conditions, while larger CCN in a lower quantity will produce fewer cloud droplets of larger size (Twomey 1974). This is important because the more numerous small droplets will reflect more light and appear more opaque than a cloud formed from the larger droplets. This affects the radiation budget of the atmosphere and could produce a cooling effect to partially counteract the warming effect of greenhouse gases. Also, the increase in the number of cloud drops reduces the amount of water available for droplet growth, potentially limiting the amount of precipitation the cloud can produce.

However, not any aerosol particle can serve as a nucleus for the formation of a cloud droplet. The chemical composition of the particle has a major impact on its effectiveness as a CCN. First of all, the particle must be hygroscopic - that is, it must attract water. If a chemical compound cannot mix well with water, then it will not readily serve as a CCN. Examples of good CCN are sulfates and sea salt, as both of these are hygroscopic, or absorb water. On the other hand, soot, minerals, and some organic carbon serve as poor CCN as they do not attract water easily. However, it is possible to see a hygrophilic compound mixed with a non-hygrophilic one, as sulfuric acid can be found on the surface of carbon. Due to the presence of sulfuric acid, it is possible for this hybrid particle to serve as a CCN, though it will not be as efficient for droplet formation as a pure sulfate particle.

The path air travels from one place to another can greatly affect the types of aerosol found within due to the geography it passes over. Air moving over North America will often contain pollutants such as nitrates, sulfates, and organic material, while air moving over northern Africa will likely contain fewer pollutants and more particles containing silicon and aluminum from the abundance of Saharan dust. Also, these origins, and the path traveled since then, may also change the number of particles per unit volume within the air, as regions with higher rates of emission will place more particles in a given volume, and the converse is true as well.

This particular project focuses on two aspects of a certain type of cloud: trade wind cumulus clouds. These aspects are the effect of air mass origin on the number of particles suspended in the air per unit volume, and subsequently the relationship between this number concentration and the number of cloud droplets actually formed. Data for the project comes from the Rain in Cumulus over the Ocean (RICO) experiment that took place during December 2004 through January 2005 (http://www.eol.ucar.edu /projects/rico/).

In order to collect data, a specialized National Science Foundation (NSF) research aircraft spent hours in the air flying through regions with clouds, making passes under, through, and above these clouded regions. Many parameters were measured in-flight, from location and altitude to temperature and pressure to the variables associated with this project, particle concentration and drop concentration. (The aircraft data files can be found here: http://www.eol.ucar.edu/raf/Catalog/taplog.lrt.135.html) Samples of the cloud droplets themselves were also collected in order to study the properties of the CCN themselves, especially their chemical composition.

Scientific Questions

There are two major scientific questions this research project seeks to address: How does air mass origin affect particle concentration? And is there a relationship between particle and drop concentration?

METHODS

Data Collection

For this project data from a number of instruments on board the C-130 aircraft used by the National Center for Atmospheric Research (NCAR) in the RICO project was analyzed. The data used were CONCF, CONCN, CONCP, GGALTC, GGLAT, and GGLON. All parameters were measured once every second.

CONCF is the parameter that denotes the cloud droplet concentration in number per cubic centimeter. This measurement occurs through the use of an instrument known as a forward scattering spectrometer probe, or FSSP. This instrument, developed by Particle Measurement Systems, Inc, is in a general class of instruments known as optical particle counters (OPCs). The method by which the FSSP measures particle size and number is by light scattering from a laser within the instrument, from which a detector interprets the scattered light and thus determines these parameters.

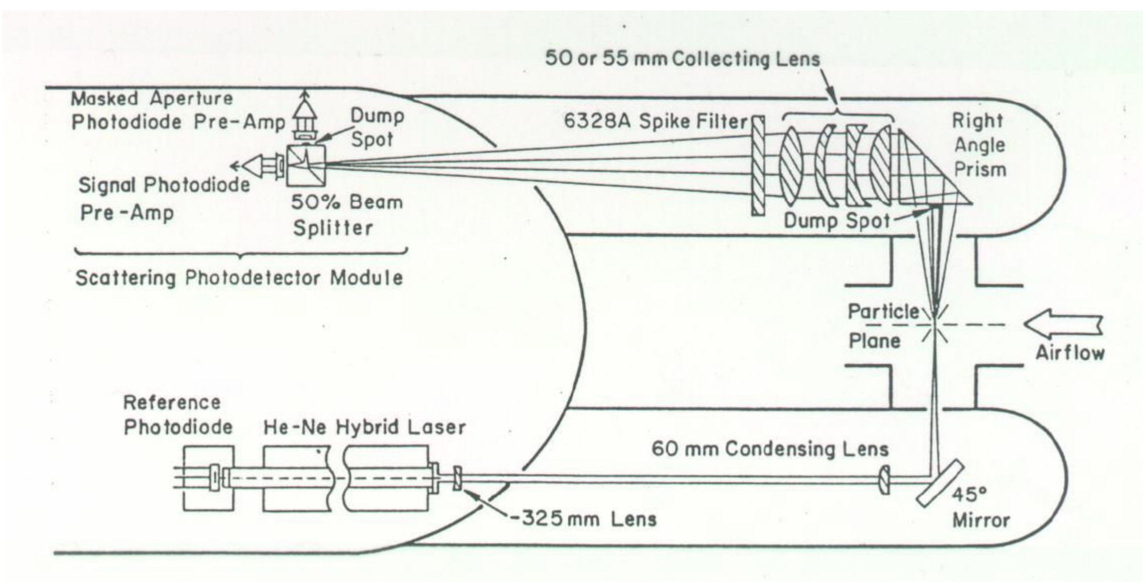

Figure 1. Diagram of FSSP instrument (Dye & Baumgardner, 1984).

Known issues arise from mixed phase clouds, or those clouds containing both ice and water droplets due to the large difference in their scattering properties, but due to the tropical location of the RICO experiment, as well as the low altitude of the clouds sampled, this issue did not pose a problem.

CONCN is the parameter that denotes the condensation nucleus (CN) concentration in number per cubic centimeter. This parameter is measured using a CN counting instrument made by TSI, Inc., and the value itself is a corrected value from the raw output given by the instrument. The other particle concentration parameter, CONCP, is measured by a passive cavity aerosol spectrometer probe (PCASP) instrument. CONCP denotes the ambient (cloudless air) aerosol particle concentration in number of particles per cubic centimeter. PCASP is also in the OPC category. CONCN counts the largest range of particle sizes, from 0.01μm to 3μm in diameter, while CONCP counts a subset of this range, ignoring the smallest particles and counting from 0.1μm to 3μm sized particles.

GGLAT, GGLON, and GGALTC are latitude, longitude, and altitude parameters respectively, measured using a Garmin Global Positioning System (GPS) onboard the aircraft. GGALTC is the value of GGALT corrected for any potential errors.

Data Analysis

The data were imported into a program called AEROS (http://www.eol.ucar.edu /raf/Software/) specifically designed by NCAR to interpret data stored in netCDF files, the format the data is written to from the instruments on the plane. These files are quite large, often on the order of 100 megabytes, and must be interpreted a certain way in order for the data to be usable and/or converted into other formats. For this project I used

AEROS to read netCDF files and import particular parameters' data sets into ASCII files that could be read by programs such as Microsoft Excel.

Within Excel, the imported data was cut into smaller segments corresponding to the in-cloud and below-cloud intervals of interest during the flight. Due to the extreme length of the aircraft flights and the number of areas of interest, time intervals corresponding to these criteria were logged during the course of each flight. Many of these intervals were measured over the course of the RICO experiment.

In order to determine which intervals would be examined in this project, two criteria had to be met. First of all, only intervals with no drop shattering were desired. This is important when looking at the instrument taking samples of the clouds, known as a counterflow virtual impactor (CVI) (Noone et al., 1988).

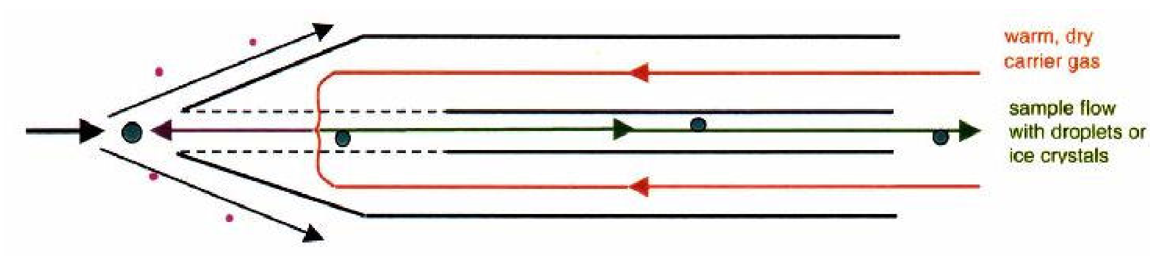

Figure 2. Diagram of CVI instrument (Twohy et al., 2003).

The CVI collects cloud samples of a certain size by accepting the incoming flow of air due to the movement of the aircraft through the cloud and removing the smallest particles by the presence of a "counterflow", often nitrogen gas. However, this does nothing to deter large droplets, such as those reaching drizzle size (greater than 50μm in diameter) which can hit the inside surfaces of the inlet and shatter, producing many tiny droplets that the instrument then interprets as individual cloud droplets, skewing the sample's count. By comparing the average value of the count from the CVI instrument to the count from the FSSP instrument (also counting cloud droplets), shattering events can be avoided when intervals with a CVI count value less than the FSSP count value is chosen. For example, the in-cloud interval from Flight 06, 183845-184410, passed under this criterion because the ratio of the two values was 0.2211. Conversely, interval 171530-173130 from the same flight had a ratio of 1.621, showing the CVI count value greater than the FSSP count value and thus failing under this criterion.

The other parameter used to choose intervals was the value found from the instrument measuring the presence of rain, the 2D-P probe. If no rain-sized droplets were detected, then the likelihood of shattering events would be close to zero and the interval would be viable for further data analysis. As long as the value from this instrument was zero, the interval passed. Using the same example interval from Flight 06, the value from the 2D-P probe was zero during the measurement, thus it also passed under this criterion.

In order to determine the location of each sample, as well as its altitude, the averages of GGLAT, GGLON, and GGALTC were found and used to pinpoint the approximate location of the interval in question.

The online model Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT, http://www.arl.noaa.gov/ready/hysplit4.html) was used to determine the approximate path of the air mass of the interval in question through 168 hours (one week) prior to the time of measurement. In order to use the model, the date, time, latitude, longitude, and altitude of the measurement were all necessary. This model, which uses the meteorological model's velocity vector fields to calculate the trajectory, outputs an image with the path over the course of given time outlined against a geographic map of the region.

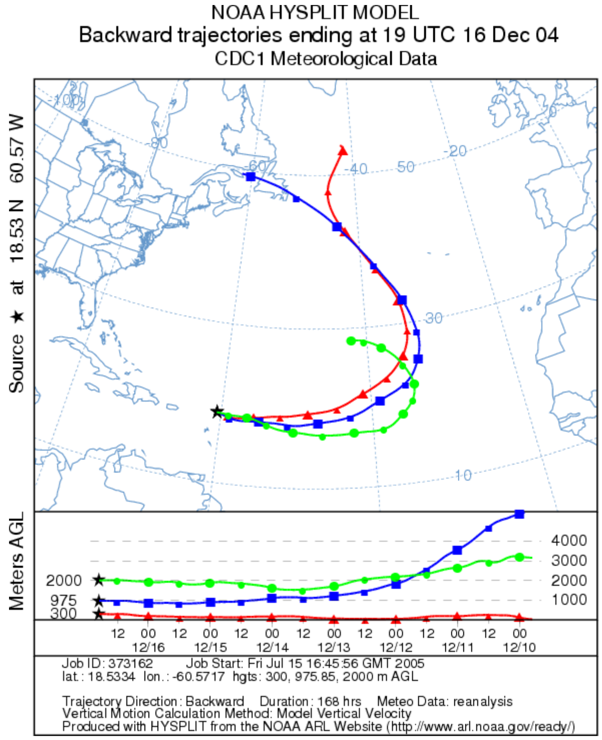

Figure 3. Example of trajectory plot generated from the HYSPLIT model, Flight 06, IC 183845-184410. Green line denotes path of air above measured air mass at 2000 meters. Blue line denotes path of measured air mass. Red line denotes path of air below measured air mass at 300 meters.

These maps were used to determine the approximate origin location of each in-cloud and below-cloud interval.

In order to avoid errors due to rain from the two particle-counting instruments, the data was plotted against the time for each data point in order to determine if any abnormal spikes due to rainfall were present. (In the event of precipitation, large anomalous numbers are recorded by the PCASP and TSI CN instruments due to breakup of large drops on inlet surfaces.) Any portion of the interval with such spikes was removed, and the remaining parts of the interval were averaged to determine the true average amount of particles per cubic centimeter over that time period.

For CONCF, the data was plotted against the time for each data point in order to determine where clouds had been measured.

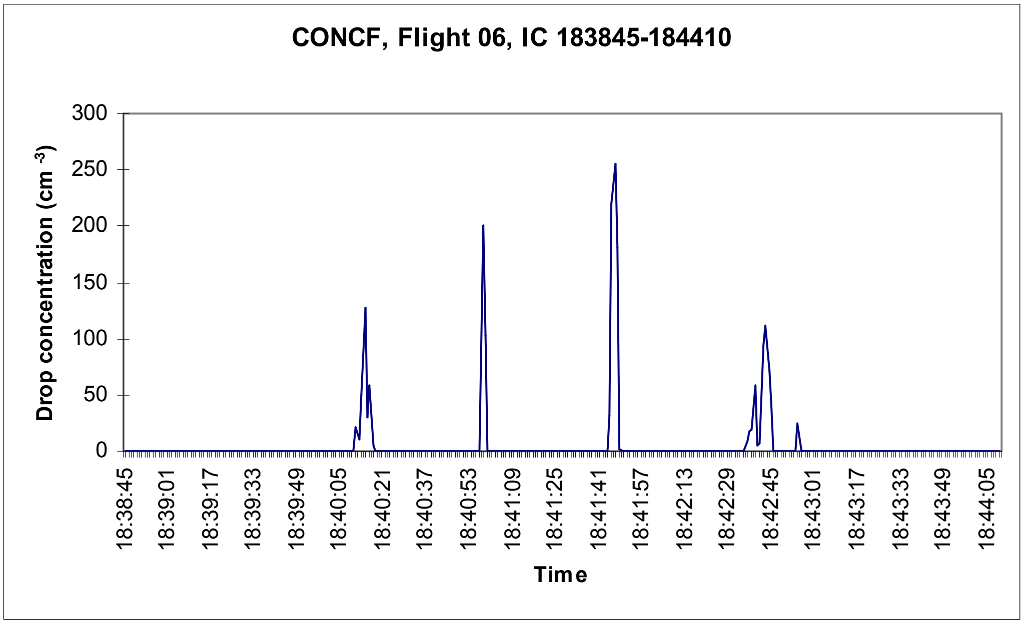

Figure 4. CONCF time series interval from Flight 06.

In the case of this parameter, the regions with large values were desired because they indicated where the clouds were located, as these cumulus clouds are often small and the aircraft cruising at speed did not spend much time within any one cloud. Cloud regions were determined as those brief intervals during which the drop concentration was at least $10/cm^3$. These values were then averaged to give an in-cloud CONCF value for the entire interval.

In order to determine the correspondence of below-cloud and in-cloud intervals within a particular flight, their latitude and longitude data was put into ArcMap in order to measure the approximate distances between these average location values. This information, along with the duration of the intervals themselves, was used to determine which below-cloud interval most closely corresponded to a particular in-cloud interval.

Once all this information was assembled, the averages for each parameter value were placed into Excel in order to create graphs from the data. Each in-cloud interval was placed alongside its corresponding below-cloud interval, complete with CONCF, CONCN, and CONCP averages. Separately, each below-cloud interval's average was placed in the category corresponding to its week-old origin location.

DATA AND RESULTS

The following tables and figures depict the results of extensive analysis performed upon trajectory (including latitude, longitude, and altitude), CONCN, CONCP, and CONCF data. The results from plotting the origin of below-cloud air masses against the air parcel's particle concentrations, denoted by CONCN and CONCP, are shown. Also included are plots of drop concentration, CONCF, versus particle concentration, CONCN and CONCP.

A subset of data from one flight (Flight 18) is also included to demonstrate correlation between CONCN and CONCP values during the course of an experimental flight on one particular day.

Origin Effects on Particle Concentration

Origin	*CONCF*	*CONCN*	*CONCP*
Africa	57.26	276.82	37.72
North America	62.60	364.04	32.06
Ocean - Africa	51.36	229.50	57.40
Ocean - N. America	73.48	262.58	35.92

Table 1. Average values for CONCF, CONCN, CONCP for four different origins.

In Table 1, the origins were defined as the beginning point of the 168-hour trajectory being situated over that landmass or ocean. With regards to the Ocean – Africa and Ocean – North America areas, the trajectory beginning was definitively over water, but quite close to the nearby continent, close enough that the continent likely had recent influence on the air mass just prior to 168 hours before measurement. Only one sample found its origin in the central Atlantic Ocean, and since no others could collaborate with it, the interval was left out of the data set.

The Africa average is computed from the average values of six intervals and the North America average is composed from five for all three parameters. Conversely, due to the limited number of passing intervals from these regions, the two ocean origins each have only two values composing their averages.

The following two figures show these values graphed as columns to explicitly show the difference in concentration between the source regions.

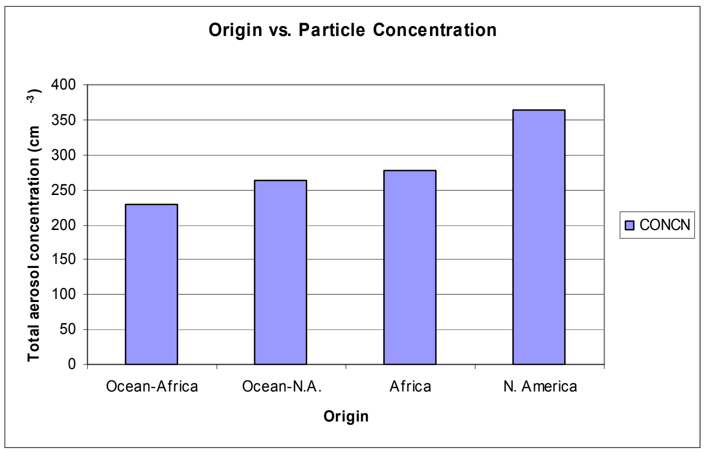

Figure 5. Air mass trajectory origin vs. average CONCN values from each interval with that origin.

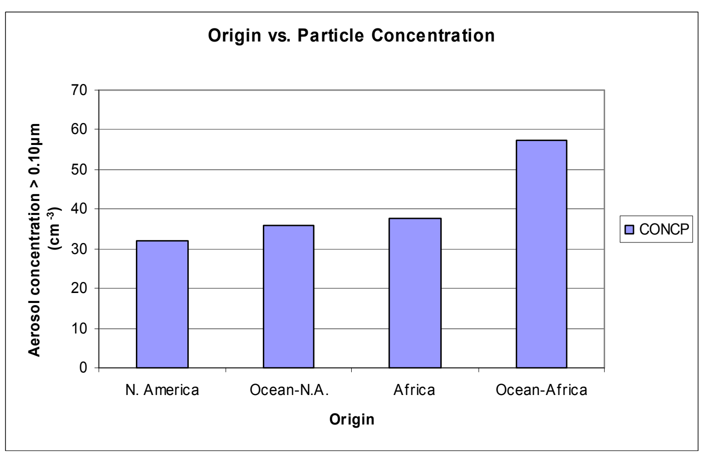

Figure 6. Air mass trajectory origin vs. average CONCP values from each interval with that origin.

From these graphs it is apparent that the highest concentration of particles covering the widest size range (beginning at 0.01μm in diameter) is found in air masses with North

American origin, while air from the ocean near Africa has the least. It is also apparent that the highest concentration of larger particles, those beginning at 0.1µm in diameter, comes from air originating over or near the African continent, while the air from North America has the least.

The large number of total particles from North America, and the small number of particles in the larger size range from the same region, shows that the type of particle coming from North America, in general, is small in diameter. The small number of total particles, with the large number of larger particles, shows that the type of particle coming from Africa and the ocean near Africa is large in diameter. From this data it appears that the air mass origin affects the size of particle present in that air.

Particle Effects on Drop Concentration

The following figures show the two different particle size concentrations compared with the drop concentration in corresponding intervals. The data points are color-coded by flight, with a legend included with the graphs. The error bars represent the 90th percentile for data parameters where a measurement was taken once per second.

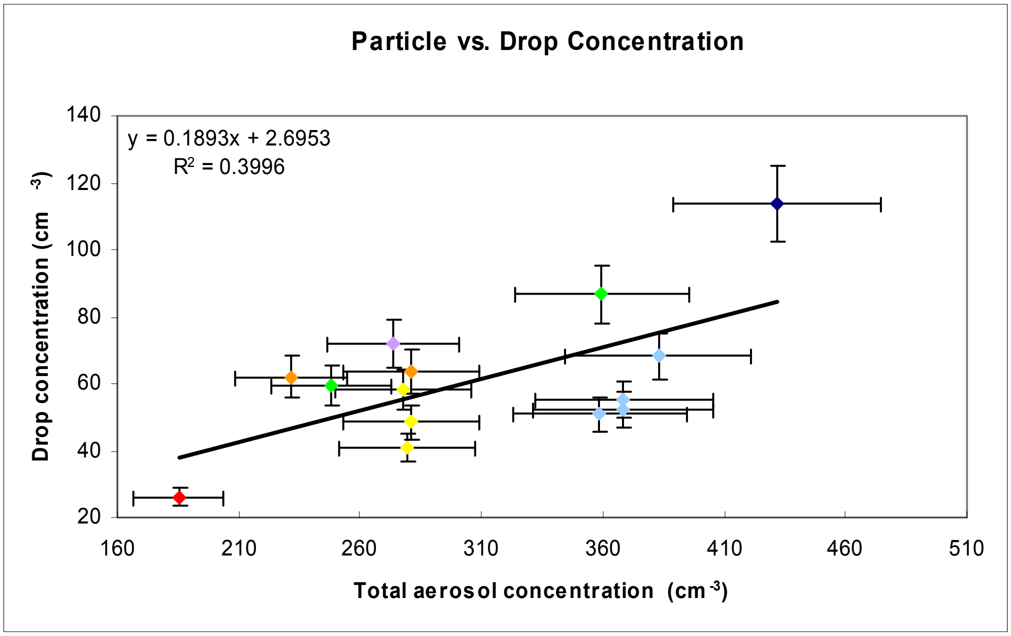

Figure 7. CONCN plotted against CONCF, with data color-coded by flight.

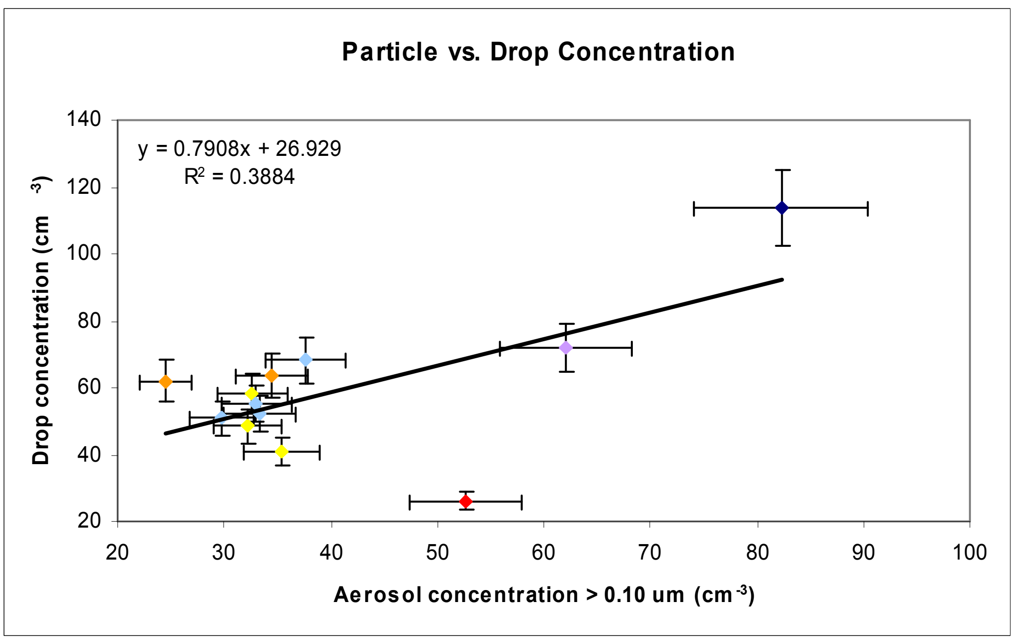

Figure 8. CONCP plotted against CONCF, with data color-coded by flight.

Legend

Flight 01: **dark blue**
Flight 04: **red**
Flight 06: **green**
Flight 11: **yellow**
Flight 12: **orange**
Flight 14: **violet**
Flight 18: **light blue**

In Figure 7, for CONCN, there is a clear spread of data on either side of the trendline, with two extreme points on either end. The coefficient of determination is close to 0.4, demonstrating a less-than-perfect correlation between the two variables. In Figure 8, for CONCP, there is a closer cluster of data, though two extreme points, from the same flights as in the previous graph, contribute to a similarly low R^2 value.

There are many factors involved in this. One, it is important to note the presence of outliers in both plots, particularly that involving the PCASP measurement. If one outlier is removed from this particular graph, the R^2 value nearly doubles:

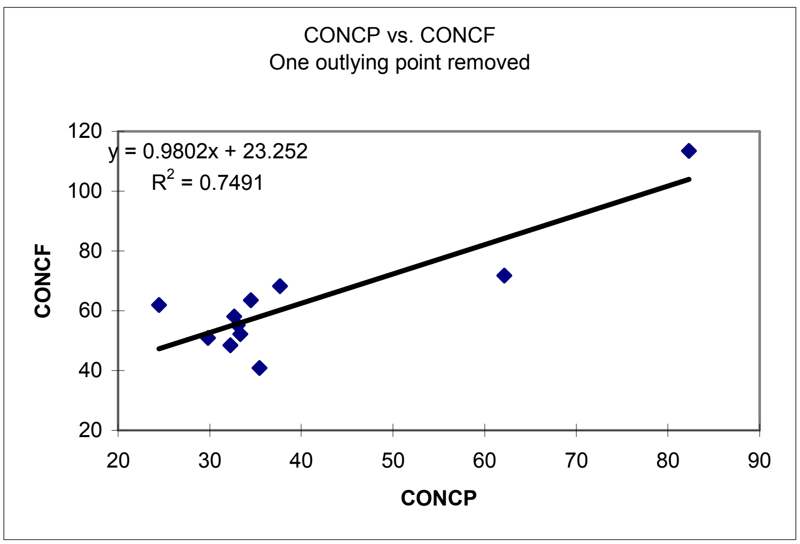

Figure 9. Larger particle concentration compared with drop concentration, one point removed.

The removed interval came from Flight 04, where both the in-cloud and below-cloud intervals found their origin off the coast of Africa. This result makes this particular interval a distinct point of interest for further study.

A t-test was also performed on both data sets in order to determine whether the null hypothesis, or the lack of relationship between particle and drop concentration, could be viable for them at a fixed probability of 0.05. "If the null hypothesis can be rejected, the relationship is statistically robust" (Twohy, 2005). For Figure 7, CONCN vs.

CONCF, the critical t value for 15 degrees of freedom was 2.13, and the observed t value was 12.83. Since t-observed is greater than t-critical, this rejects the null hypothesis for Figure 7's data set, indicating a statistical relationship between CONCN and CONCF. To reinforce this conclusion, the p-value for t-observed was very close to zero, which is much less than the fixed p-value of 0.05.

For Figure 8, CONCP vs. CONCF, the critical t value for 21 degrees of freedom was 2.08, and the absolute value of t-observed was 2.37. This goes beyond the t-critical value, so this rejects the null hypothesis for Figure 8's data set, indicating the presence of a statistical relationship. Again, this conclusion is reinforced by the p-value for t-observed being 0.0274, which is less than the fixed p-value of 0.05. Upon examination of the same data set with Flight 04's "outlying" point removed, the absolute value of t-observed increases to 2.90, further removing it from the t-critical value, and the p-value decreases to 0.00881, also further removed from the fixed p-value. This denotes the interval found during Flight 04 as a definite point of interest for further study.

Other factors playing a part in the variation of data within these graphs is the varying composition of the particles, a parameter left unexamined in this analysis. Different types of particles will be borne aloft depending on the source region, the path traveled by the air, the amount of time spent over certain types of terrain, whether or not precipitation occurred during its travel (this would remove particles from the air mass), and the altitude of the air as it affects the amount of particles reaching the parcel from the surface. Aerosol size and number are also affected by this. The composition, number, and size of the particles then influence the number of cloud droplets formed. Also, updraft velocity within the air mass remains unaccounted for, as increased velocities will increase the supersaturation levels within the air mass, leading to more particles becoming activated and serving as CCN.

However, there are multiple important notes to be made with this data. It appears that more fine particles can be found within air masses originating over North America, and more large particles within those coming from Africa. This can be understood when the particle composition is examined: more pollution-type particles, which tend to be smaller, come from the industrialized countries of North America, while dust and sea salt from Africa and the ocean nearby comprise larger particles (Wallace and Hobbs 2006).

Within a particular flight, however, the correspondences are much improved, being more than double those values found in the all-encompassing data set.

Interval	*CONCF*	*CONCN*	*CONCP*
124720-125723	50.85	358.57	29.80
124720-130330	52.15	368.49	33.32
125949-130651	55.14	368.67	33.05
133614-134525	68.25	383.03	37.69

Table 2. Average values for CONCF, CONCN, CONCP for four different passing intervals in Flight 18.

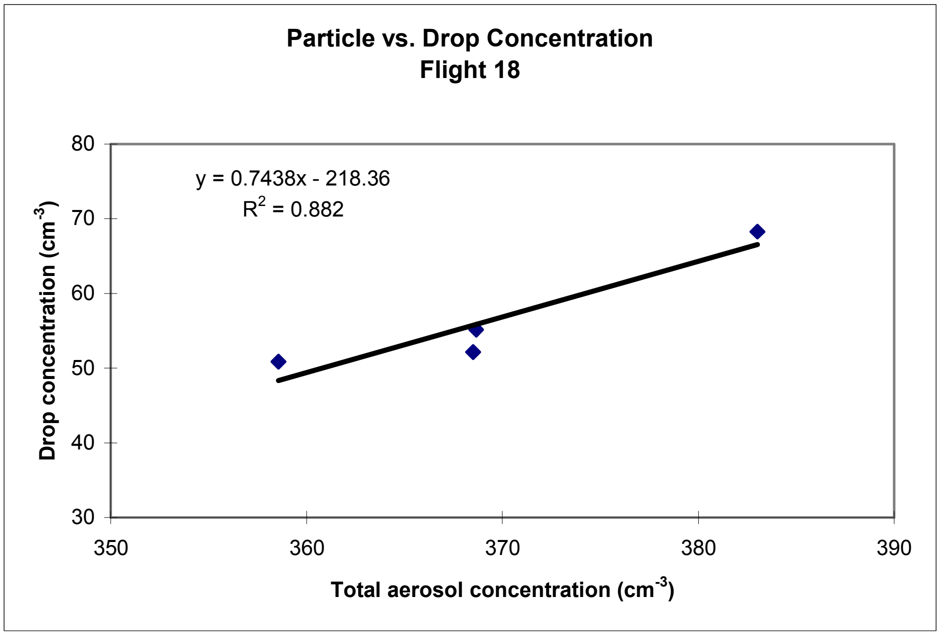

Figure 10. CONCF vs. CONCP from all passing intervals during Flight 18.

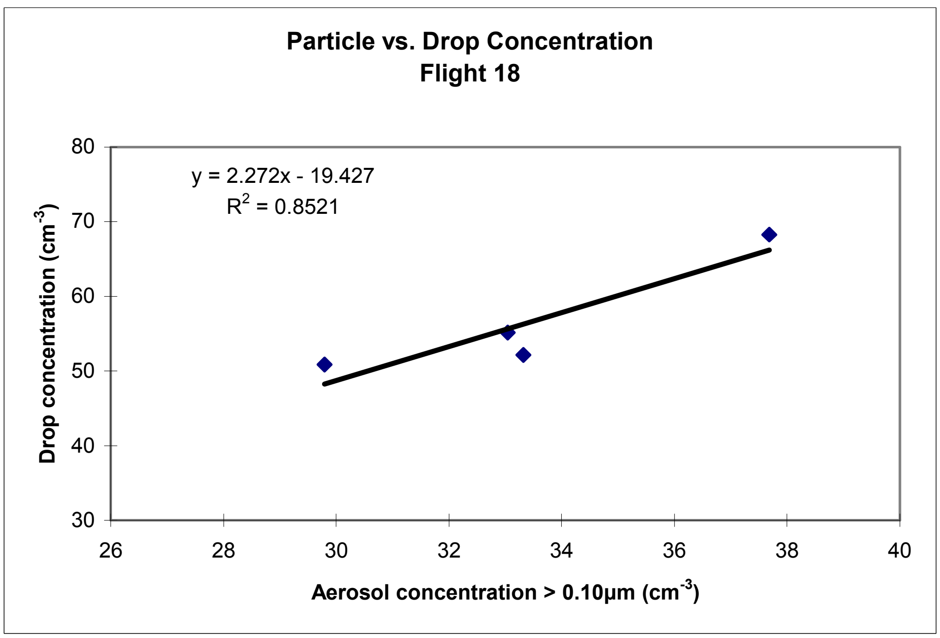

Figure 11. CONCF vs. CONCP from all passing intervals during Flight 18.

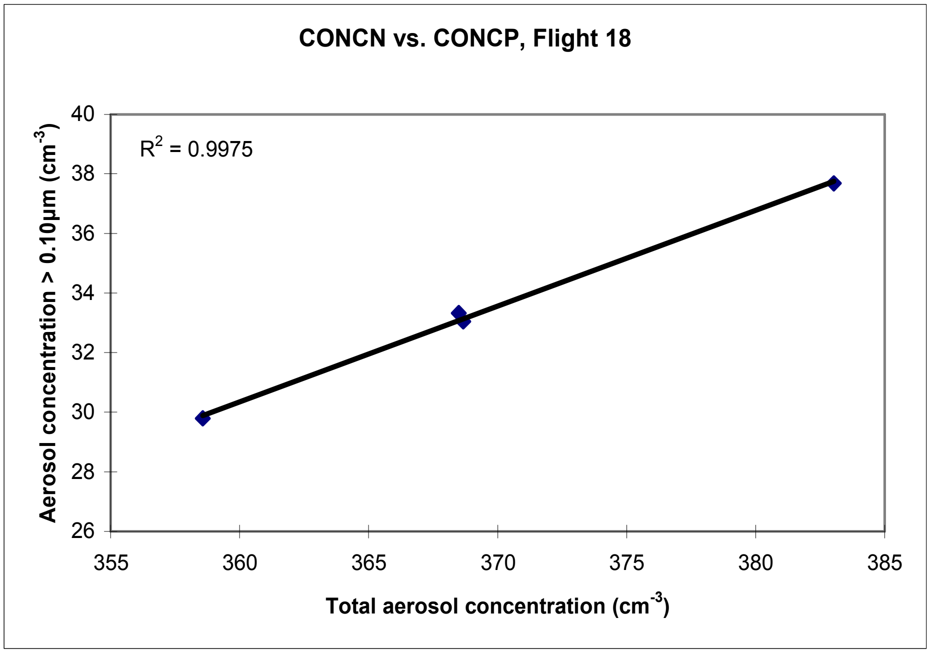

Figure 12. CONCN vs. CONCP from all passing intervals during Flight 18.

Factoring into this are the shorter lapses of time taking place between each interval measured as well as higher correlations between in-cloud and below-cloud data. Also, having four distinctly passing intervals within the course of one flight increased the number of data points for study. Finally, all the intervals found their origin over North America for both the in-cloud and below-cloud trajectories, a factor likely giving a heavy contribution to the higher correlation of these results. The following figure displays the paths for an in-cloud interval and its corresponding below-cloud data from this flight.

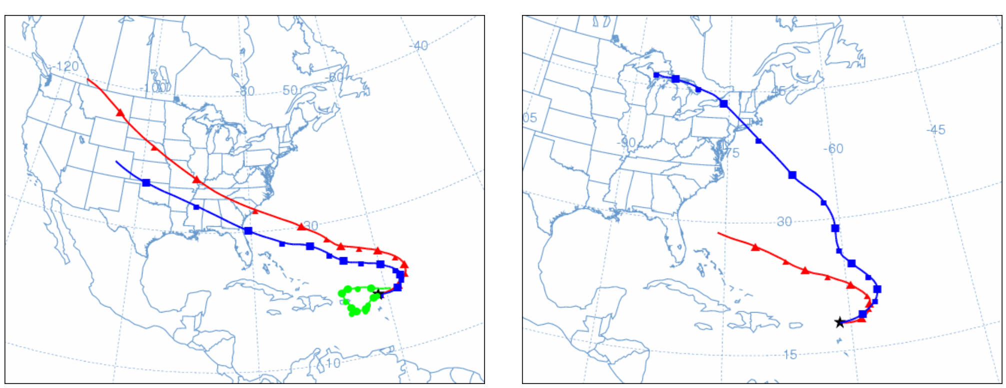

Figure 13. Trajectory from in-cloud (left) and below-cloud (right) intervals during Flight 18, both in blue, where the below-cloud interval corresponds to the in-cloud interval.

In order to decidedly determine what relationship, if any, exists between in-cloud drop concentration and ambient particle concentration, it is important to take the two measurements as close together as possible. In optimal conditions, one aircraft would fly through a cloud layer as another flew underneath it through clear air in a nearly identical flight path. However, this solution is highly untenable due to financial expense, aircraft availability, and many other factors. Also, the duration of each recording interval would be highly similar, varying on the order of seconds rather than minutes.

Another factor involved in this is the small number of data sets available for analysis. Looking at numbers on the order of fifteen intervals is much more likely to produce a skewed result than a similar examination of fifty intervals or more.

As observed earlier, one must also consider the effect of different days' results counted within the same analysis. With this in mind, it may be important to run measurements for more intervals during each flight in order to have an expanded data set.

CONCLUSIONS

Overall, from this data, more small particles come from North America and more large particles come from Africa and the ocean near Africa. This is likely due to the influence of sea salt, Saharan dust, and pollution.

There is some relationship between particle and drop concentrations when looking solely at the particle and drop count data sets. This becomes more readily apparent when comparing intervals within one particular flight, as all the intervals in Flight 18 had the same air mass origin and were close in time and duration. Varying composition of particles across flights, partially due to air mass origin, and changing air dynamics within air masses contribute to the variability in data between flights.

Also, there is enough variation within ambient particle concentration to produce a radiatively important drop concentration – that is, it is possible that an increase in drop concentration will produce an increase in the reflectivity of the clouds, thus raising the albedo and the amount of light reflected back to space (Charlson, 1987). As cloud droplets increase in number and decrease in size, their reflectivity increases as the scattering of light due to droplets becomes more pronounced.

To show this mathematically, the following equation is used:

$$L = \frac{4}{3}\pi r^3 \rho N$$

where L is the liquid water content (g m^{-3}), r is the droplet diameter, ρ is the density of water (g m^{-3}), and N is the number density of droplets (m^{-3}). Exploration of the effect of droplet number density on droplet radius can be done by employing a fixed L value. The following table gives the average radius as found by particular N values for a set L value of 0.20 g m^{-3}.

N (m^{-3})	r (μm)
32.06	11.42
35.92	10.99
37.72	10.82
57.40	9.405

Table 3. Radii values due to given droplet number density values for a fixed liquid water content. (N values taken from average CONCF found in four origin regions.)

It is readily apparent from Table 3 that, for a given amount of liquid water, as the number of droplets increases, the average radius of those droplets decreases. This increases the total droplet surface area, as there are many more droplets while their average radius has not decreased greatly. Since the total surface area has grown, the reflectivity, and thus the albedo, of the cloud increases.

This change in particle concentration may also affect the precipitation efficiency of the clouds, as more CCN produce more, smaller cloud drops that could decrease the amount of water available to grow drops sufficiently large enough to fall as rain.

Future Work

Future work on this project might include reexamination of previously deemed "iffy" intervals in order to ensure that no relevant data was lost. This could potentially include more data points for increased accuracy in the data analysis as it could improve statistics. Also, examination of above-cloud intervals could begin, comparing those results with the below-cloud data. It is possible that more passing data could be found by looking at this ambient air region, though this air would have less influence on cloud development compared to the air below the clouds that would rise and thus contribute more to the clouds' formation.

When examining the particle vs. drop concentration graphs, there appear to be "outliers" in the data sets. Further exploration of these intervals to determine why they stray from the trendline set by the data could produce interesting results. Such exploration might include examination of the cloud particles sampled during the interval and looking at other data gathered during this time. These particular intervals offer a good place to begin the analysis of particles by looking at their size, shape, and composition, as the eventual study of all intervals would provide a larger amount of data with which to examine the plots produced by the concentration data in this project. Other important pieces of data to examine would be the liquid water content and updraft velocities of the clouds sampled.

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