PNNL-30253

An Analysis of Shallow Orographic Cumulus Clouds Observed During the CACTI Field Campaign

A SULI Internship Final Report

August 2021

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I ABSTRACT

In 2018, the Atmospheric Radiation Measurement Aerial Facility (AAF) deployed its G-1 research aircraft to the Sierras de Córdoba mountain range in north-central Argentina to support the research of environmental factors on deep convective cycles as part of the Cloud, Aerosol, and Complex Terrain Interactions (CACTI) field campaign. The aircraft was fitted with a suite of instruments to holistically measure *in situ* the current state of the atmosphere. In this study, we organize the campaign's 22 flights by environmental conditions. Data from each flight was transected by the aircraft's position relative to cloud, allowing for in depth analysis of cloud processing on aerosol populations. My project was a case study of selected flights where warm, shallow orographic cumulus clouds were observed.

During my time at PNNL, I worked towards my goals for the internship, which were both professional and educational goals. I learned about some of the instruments AAF uses on their aircraft campaign and utilized data from those instruments to perform my analysis. I improved my skills in the programming language Python. I gained the confidence to analyze data critically

and independently, which has further encouraged and prepared me for graduate school level research. I also met many amazing scientists at PNNL.

II INTRODUCTION

Climate models are used to predict future climate and study processes that occur to better understand the climate system. Aerosols are solid or liquid particles suspended in the atmosphere. The biggest uncertainty in climate models are clouds and how aerosols can interact with and impact clouds[1]. The uncertainty from climate models is largely due to geographically limited datasets. Instrumentation is necessary to quantify the number of aerosols in the atmosphere. A large fraction of aircraft data is collected in the northern hemisphere. Most aircraft campaigns are away from severe storms due to dangerous atmospheric conditions or are over oceans that have horizontally uniform clouds.

Aerosols have a direct effect on the amount of radiation absorbed on Earth's surface and an effect on clouds[2,3]. A fraction of aerosols, called cloud condensation nuclei (CCN), are needed for water to condense on to form cloud droplets. The number of aerosols in clouds is one factor that determines how long a cloud's lifetime is and if a cloud will precipitate or not[4] .The more aerosols that are in a cloud, the smaller the droplets and smaller droplets are less likely to precipitate because they cannot get large enough to precipitate [2]. Climate models that model cloud and aerosol interactions have uncertainty regarding aerosol concentrations.

While we can observe aerosols from the surface, which is cheaper and easier to operate, it is important to consider where aerosols are vertically. Where the aerosols are vertically determines their atmospheric lifetime, which extends their spatial and temporal effect on the climate. Aerosols in the boundary layer, the layer in the atmosphere that is in contact with the surface, have a shorter lifetime, in the scale of hours, than in the free troposphere which is on a scale of days to weeks to months[5]. Aerosols in the boundary layer are the ones interacting with clouds. However, aerosols in the free troposphere can transport across the world and can get pulled into the boundary layer if there are strong vertical winds. Only in-*situ* measurements can give the true picture of where aerosols are vertically.

In 2018, the Department of Energy's Atmospheric Radiation Measurement (ARM) group conducted the Cloud, Aerosol, and Complex Terrain Interactions (CACTI) to study environmental factors on deep convective cycles in north-central Argentina. The campaign included the use of the ARM Mobile Facility (ARM) ground site as well as the use of the ARM Aerial Facility's (AAF) G-1 research aircraft. While the campaign was conducted for a total of 6 months, the aircraft flew for an intensive period of 6 weeks. The CACTI field experiment was held at a unique location that expanded the global availability of atmospheric data. My project focused on using data gathered by the G-1 to characterize the atmospheric environment, including aerosol, cloud, and meteorological properties. We hypothesized that we could create masks relative to the aircraft's position to the cloud to analyze environmental factors on clouds and aerosol processing. We also hypothesized that we would see atmospheric conditions that are similar to other geographic locations with the same measurements.

The location of the CACTI campaign is unique geographically for an aircraft campaign. North-central Argentina is the same latitude as Oklahoma, but at a higher elevation with a mountain. The Sierras de Cordoba mountain range provides an environment for orographic precipitation and synoptic scale meteorology. This area was a reliable steady source for data collection because clouds often form in a line over the ridge and in the summer, there are routinely deep convective events and super deep convective events that form. Smoke plumes from fires burning in the Amazon also influences the Sierras de Cordoba. The topography of the surrounding area is also unique. To the east of the Sierras de Cordoba, there is great plains and to the west the Sierras de Cordoba is surrounded by the Andes Mountains. The height of the Sierras de Cordoba mountain range is an average of 2000 meters, with a peak of 3000 meters.

III METHODS

The G-1 aircraft, pictured in Figure 1a, had over 50 instruments collecting data on these flights. The G1 measured atmospheric state, navigational and meteorological conditions, trace gas concentrations, aerosols, and hydrometeors. Important for characterizing aerosols and cloud droplets is to measure both their total concentration and size distribution from radii of a few nanometers to microns. One measurement to quantify cloud-aerosol interactions is the total concentration of potential CCN, performed by measuring the fraction of aerosol that can 'activate' to become a CCN at pre-set supersaturation values. For this analysis I focused on three primary aircraft measurements. The cloud condensation nuclei counter measured total CCN concentrations at supersaturation values of 0.2% and 0.5%. Finally, the multi element water counter system (WCM) measured the total amount of liquid water (cloud) in the atmosphere. The condensation particle counter (CPC) measured the total concentration of aerosols. Measurements from a CPC at the ground site were also analyzed.

Figure 1: Picture of the AAF G-1 research aircraft, courtesy of the U.S. Department of Energy Atmospheric Radiation Measurement (ARM) user facility (a) and (b) flight track from November 20th, 2018, from: http://catalog.eol.ucar.edu/maps/relampago.

Flights during the CACTI campaign had a routine flight track, shown in Figure 1b. For the CACTI campaign, the clouds forming along the ridge gave a unique environment to sample in a structured and organized manner. The aircraft flew relative to horizontal and vertical positions to the cloud. The consistent and structured flight paths allowed analysis that could focus on aerosol and cloud interactions as well as the transport of aerosols. The G-1 aircraft flew below the cloud base, beside the cloud line, and above the cloud. The aircraft sampled points that were to the left and to the right of the ridge. This flight track is unique because most aircraft campaigns have flight patterns that are irregular or focused on chasing a cloud or a plume.

For my project, we selected a subset of flights that had a shallow cumulus cloud line over the ridge as the main feature. The days selected were November 20th, 24th, 28th, and December 3rd, 2018. We chose flights that all took place in the late morning to allow for consistent analysis. For each flight, we transected the data by the aircraft's location to the cloud by creating masks to focus on each of the different locations and analyze each position independently. For this analysis, we were able to create masks for the datasets and analyze each property relative to horizontal and vertical positions to the cloud.

IV RESULTS

Figure 2 shows background surface aerosol concentrations during the intensive period of the campaign. Each shaded area represents the times where the G-1 was in-flight. The colors represent the conditions observed each day there was a flight. These conditions were determined from weather reports and analyzing the weather radar that was situated at the ground site. On days that have blue shading, the observed feature for the day was a shallow cumulus cloud line over the ridge. For flight times shaded in green, the G-1 flew before deep convection was observed that day. For flights shaded in yellow, the environment was free of clouds for a clear sample day. For days with pink shading, there was a cold front observed. Finally, for the flight time shaded in orange, a mesoscale, or large scale, convective event occurred that day. From the figure, we observed a diurnal flux of aerosol, indicating the growing of boundary layer and shrinking of the nocturnal boundary layer. Flights were often flown during the local peak of aerosol concentration. These conditions confirm our hypothesis that the Sierras de Cordoba would be a good place to routinely sample convection.

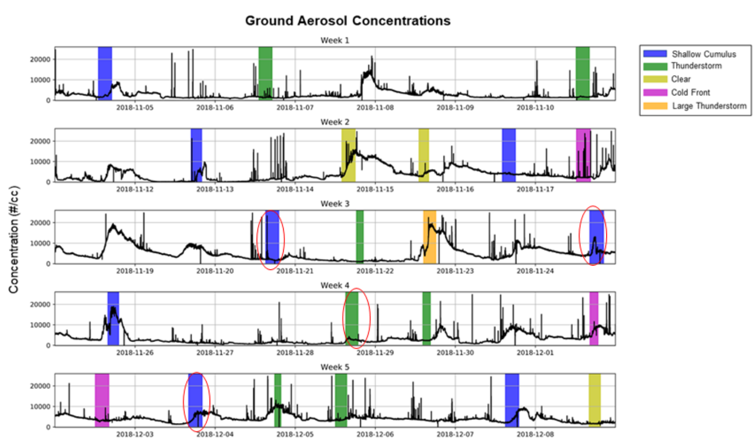


Figure 2: Time series of aerosol concentration (#/cc) at the AMF site. Each plot is a different 7 day stretch with times the aircraft flew shaded. The colors represents environmental conditions observed. Selected flights for analysis circled in red.

The aerosol concentrations are the highest at the surface since the primary source of aerosols is the surface over land. Figure 3 shows the vertical profile of aerosol concentrations for each selected flight. On the x-axis is the aerosol concentrations in units of per cubic centimeter. There is good agreement between the surface aerosol measurements and the lowest measurements taken from the G-1 which indicates good agreement between the two CPC instruments. Altitude is the y-axis in units of meters. Each line represents a different case, color coded by day. These measurements were from the CPC on the aircraft when flying through clear air. Periods when the aircraft were flying through cloud have been masked out to avoid contamination. Since the flights were in the late morning to early afternoon, we would expect the boundary layer to be well-mixed. However, the case of November 20th is the only day that has relatively consistent levels of aerosol concentrations with height. On November 24th, aerosol concentration increases with height until about 3000 meters, then there is a sharp inversion and the aerosol concentration decreases and increases in small amounts until the maximum height of flight. On November 28th, the aerosol concentration is increasing with height until an inversion at about 3500 meters. December 3rd had the largest variation in aerosol concentration with height. The concentration increases with height until just below 3500 meters, then decreases with height less gradually. This strong inversion indicates limited mixing between the boundary layer and free troposphere.

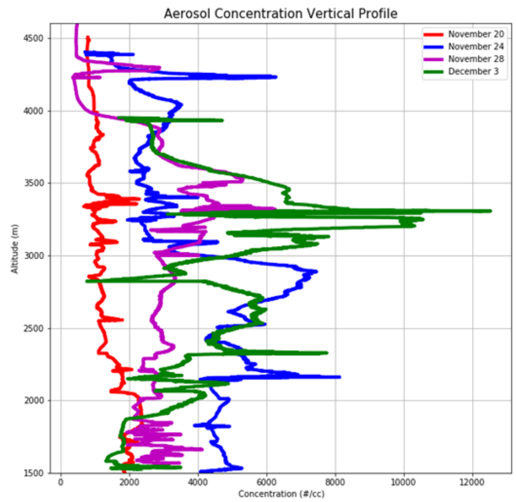


Figure 3: Aerosol concentration (#/cc) vertical profiles for cases on Nov. 20th (red), Nov. 24th (blue), Nov. 28th (pink), and Dec. 3rd (green). The x-axis is concentration and the y-axis is altitude (m).

For each flight, the cumulus cloud along the ridge was at similar heights, about 3000 to 3500 meters. The vertical profile of water content (Figure 4) is a good estimate for where the clouds on each day are. The x-axis represents the total water content in units of g/m^3, which is liquid only since no ice was observed on the selected days. The y-axis is altitude in meters. The color of each line represents each of the different days and is the same as in Figure 3. Although similar clouds were observed on each of the four flights, there was variety in the amount of water in each cloud and each atmospheric profile. We define a cloud as when the water content of the sampled air contains more than 0.1 g/m^3 of liquid water. For all four of the cases, the water content is greater than 0.1 g/m^3 between 3000 and 3500 meters. On November 20th, the water content meets that threshold up to 4000 meters. November 28th had the highest water content of the four cases. There appears to be another cloud layer above 4500 meters, so this indicates a multilayered dynamic cumulus cloud. After the flight on November 28th, a deep convection event was observed, so the higher water content could be indictive of the storm that occurred later in the day. On December 3rd, it was observed that the air was too dry for the cloud to deepen, so that explains why the water content only passes the cloud threshold for a thin layer.

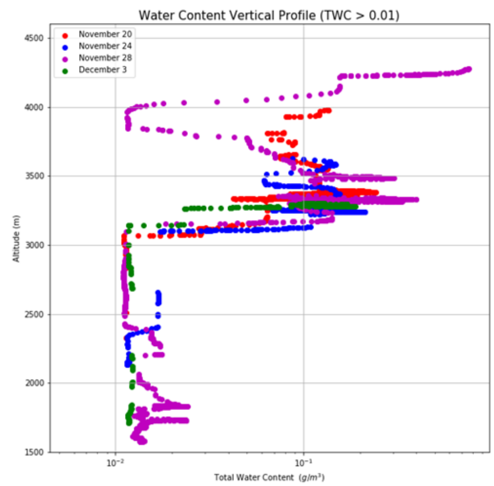
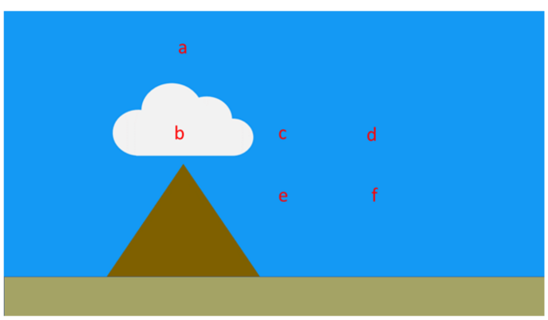


Figure 4: Scatter plot of total water content (g/m^3) versus height (m). The colors correspond to a different day.

We then used the masks for the flight's position relative to the cloud to analyze cloud processing, which is shown in Figure 5. Figure 5 shows a scatterplot of CCN as the y-axis plotted against aerosols, or condensation nuclei (CN) as the x-axis for each different mask. On the left is a diagram of each mask's location, corresponding to the labeled plots on the right. Figure 5a represents the mask above cloud. Figure 5b represents the mask when the aircraft flew in the cloud. Figures 5c and 5d represent the masks beside the cloud to the left and right, with 5c representing the mask within 10 kilometers horizontally from the cloud and Figure 5d representing the area beside the cloud but greater than 10 kilometers from the cloud. Figure 5d and 5e are at altitudes below the cloud on the left and the right side of the ridge. 5e is data collected within 1000 meters vertically below the cloud and Fig 5f is data collected below 1000 meters above the cloud. We separated the below and beside locations to see if aerosol near the cloud was different from regions sufficiently far enough away from cloud not to be affected. We also chose these bounds because we were limited by how close the aircraft flew to the clouds. We determined distance from the cloud by distance to the center of the cloud where the aircraft flew. For each figure, there is two points of the color representing the mean CCN and CN for each mask for the flight. There are two points because the CCN counter has two inlets that measures CCN from two different supersaturations, 0.5% and 0.2%. The higher supersaturation means that more water will want to condense, so there is more CCN. The 0.5% supersaturation point is denoted with a square and the 0.2% supersaturation point is denoted with a circle. The lines represent the standard deviations of the CN and CCN for each mask. The colors correspond to the same color scheme as previous figures in this paper.



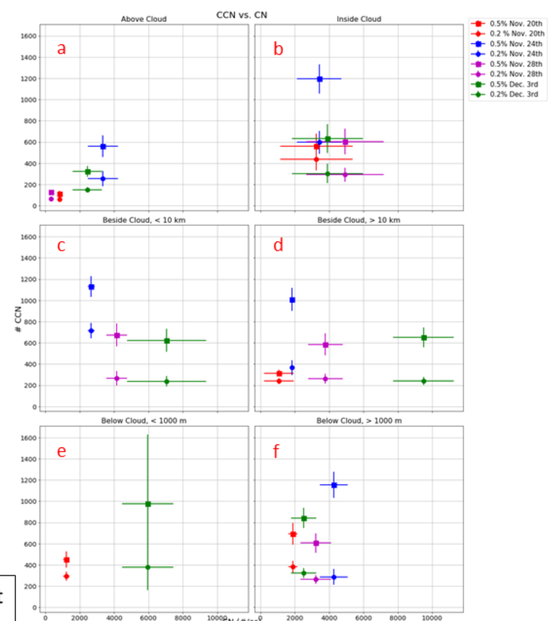


Figure 5: A scatterplot of the fraction of total CCN activation at 6 different positions, with the position marked on the diagram on the left.

The environmental factor of altitude is the primary factor in differences in the CCN/CN ratio, so we expect to see some decrease with CCN and CN concentrations with height. We would also expect to see the ratio between CCN and CN remain the same with height without cloud processing. We see this most clearly when comparing Figure 5b to Figure 5a. However, cloud processing is a secondary factor and is the factor we are most interested in, so the way we masked these data points is an attempt to distinguish between the two. For the below cloud cases where there were data collected withing 1000 meters of the cloud, there was not much difference between the ratio on December 3rd, but there is a big difference for November 20th. The case of November 24th has higher CCN counts than the other 3 cases for each position relative to the cloud. This could be due to the mesoscale deep convective event that occurred a little over 24 hours before the flight. November 24th and 28th have different beside the cloud positions for the point within 10 kilometers comparing the two beside the cloud plots. We wouldn't expect that change from profile/boundary layer conditions alone, so this is likely due to cloud or mountain effects. Another interesting result is how clustered the points are for inside the cloud. We would expect to see points more clustered near the surface, where we expect a constant biogenic source.

The results for the initial analysis of four cases were very promising. They showed that the way the aircraft flew consistently in relative positions to the cloud is a viable method for aircraft campaigns. Though my project was only the tip of the iceberg for the comprehensive CACTI dataset, it laid the groundwork for exploring the environmental conditions of the Sierras de Cordoba mountain range in north-central Argentina. Climate modelers can input these results into their models to more accurately depict aerosols in the southern hemisphere. Scientists can use these results to guide future in depth of processes in the Sierras de Cordoba.

For future work for this project, there is a lot to explore. We will explore all the other 22 cases to see if any patterns persist or change. A change in aerosol size distribution is another sign of cloud processing that will be analyzed going forward. We will also look at other datasets including satellite data to compare the datasets and analyze the aircraft data from different angles. We are also interested in analyzing size distributions

V ACKNOWLEDGEMENTS

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