# THE SENSITIVITY OF RAINFALL DISTRIBUTIONS TO TIME, SPACE, AND THE ENVIORMENT OVER KWAJALEIN ATOLL

An Undergraduate Research Scholars Thesis

by

LILY CAMPBELL

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# ABSTRACT

The Sensitivity of Rainfall Distributions to Time, Space, and the Environment over Kwajalein Atoll

Lily Campbell
Department of Atmospheric Sciences
Texas A&M University

Research Advisor: Dr. Courtney Schumacher
Department of Atmospheric Sciences
Texas A&M University

North of the equator, winds converge causing bands of heavy rain in a region called the Intertropical Convergence Zone (ITCZ). Due to the small-scale processes that are not fully represented by weather models, modeled rainfall and its characteristics are often not indicative of what is observed in the ITCZ. This study attempts to bridge that gap by using observations from a weather radar on Kwajalein Atoll, located within the central-western tropical Pacific, as well as reanalysis data over Kwajalein Atoll to investigate characteristics of ITCZ rainfall. Two wet seasons are analyzed to quantify rainfall variations in terms of different spatial scales, temporal averaging, and environmental conditions. Rain observed by the radar is first categorized as either convective (i.e., heavy and sporadic) or stratiform (i.e., light and widespread). Rain rates, conditional rain rates, and rain area are calculated for different time (10 minutes to 1 day) and spatial (2 km to 128 km) scales and then compared to specific humidity (moisture in the atmosphere), omega (vertical motion in the atmosphere), and sea surface temperature (SST) to determine if a relationship exists between the large-scale environment and the observed rainfall characteristics. The results obtained from this study hold the potential to quantify to what extent environmental factors may influence precipitation intensity and extremes at Kwajalein Atoll.

Significant results can lead to calibrating weather and climate models, which creates more accurate rainfall predictions through numerical weather prediction and analysis from radars.

# DEDICATION

This thesis is dedicated to everyone who has ever been told that they cannot do something. Do not ever let what someone else may think or say about you limit what your potential could be. Always aim for the moon for if you miss, at least you will end up amongst the stars.

## ACKNOWLEDGEMENTS

Firstly, I would like to thank Dr. Courtney Schumacher and the A-Team for their guidance and support throughout the course of this research and just in general. Thank you for the wonderful work environment and the endless conversations and the great memories we have made. I would also like to thank Dr. Don Conlee for linking me to Dr. Schumacher to begin with and giving me this great opportunity.

Thanks also go to my friends and colleagues for making my time at Texas A&M University a great experience. Thank you for the late night company, peer revisions, and just in general grounding throughout the past year.

I would also like to thank the University Honors program (and LAUNCH) for the three years I spent within their Living Learning Community and providing me with the guidance and opportunities to participate in the Undergraduate Research Scholars program and succeed in general as I have.

Finally, thanks to my family and everyone else who built me to be the person I am today. If it were not for them, who knows where I would have ended up.

# NOMENCLATURE

| | |
|---|---|
| ITCZ | Intertropical Convergence Zone |
| km | Kilometer |
| mb | Millibar |
| mm/hr | Millimeter per Hour |
| SST | Sea Surface Temperature |
| Z-R | Reflectivity and Rain Rate |

# CHAPTER I

# INTRODUCTION

One of the major research topics within the atmospheric sciences community is how weather models represent processes that occur at smaller scales than the spatial resolution of the model, known as parameterization. Incorrect parameterizations can lead to large errors in model output. Rainfall errors are often largest over the tropics amongst general circulation models since rainfall is very convective in the tropics and occurs on small (on the order of 10 km) spatial scales (Stephens et al. 2010) compared to the large (on the order of 100 km) spatial scales of the general circulation models. The manner in which convection is parameterized can cause wide variations in model rainfall (Wang and Seaman 1997). Model errors have been shown to be a factor in the estimation of rainfall in the ITCZ (Kooperman et al. 2016), which is a band of intense rainfall over the tropical oceans resulting from the convergence of the northeasterly and southeasterly trade winds.

Studies of the ITCZ have previously used observations to analyze precipitation extremes (Rossow et al. 2013); however, most of these observations were from satellites rather than ground-based systems such as weather radars. Satellite observations can be limited in spatial resolution and temporal sampling compared to ground systems due to the satellite's need to orbit the Earth at high altitudes. Recent analysis of precipitation datasets over the Pacific Basin has also shown trends of precipitation extremes in the Western Pacific Ocean decreasing in frequency but increasing in intensity (Kruk et al. 2015), which makes the location of this study, the Kwajalein Atoll (~9°N, 168°E) in the central-western Pacific ITCZ, relevant.

In order to understand why these changes are occurring, rain events should be characterized in a way to eliminate biases that may appear in the data due to different types of rain (convective or stratiform) being present. Another way of characterizing rain statistics is by sorting rain events by environmental factors since each factor has a different effect on precipitation processes. Recently, Ahmed and Schumacher (2015) showed that convective rain increased linearly with increasing moisture, whereas stratiform rain increased exponentially.

**Rain Variables**

Rainfall can be categorized into two major subtypes, stratiform or convective, depending on physical differences of the rainfall production and storm structure (Houze 1997). Convective precipitation is denoted by strong updrafts that cause coalescence and the formation of large raindrops that start to rime until they fall out of the updraft and onto the surface. On the other hand, stratiform rain is characterized by weak updrafts and small raindrops that grow by vapor diffusion. Thus, stratiform rain is generally characterized by low rain rates (less than a few mm/hr) and large spatial areas and is indicated on a radar image as large swaths of rain with lower values of reflectivity. Convective rain is generally characterized by high rain rates (greater than a few mm/hr) and small spatial areas, and is indicated on radar image by small areas of high reflectivity.

Rainfall measurements from a weather radar can be calculated as an area-averaged rain rate, which takes the rainfall calculated from an empirical reflectivity-rain rate (Z-R) relationship and divides it over the area of the whole radar domain. This makes comparing rain rates between differing areas simple. The two components that are used to calculate area-averaged rain rate can also be used to characterize rainfall. These two parameters are called conditional rain rate and rain area. Conditional rain rate is defined as the summation of rain divided by the area of rain pixels (i.e., it denotes how intense rainfall is only over pixels that are raining). Rain area fraction is defined as the area of raining pixels divided by the domain area.

**Environmental Variables**

Since Ahmed and Schumacher (2015) showed that convective and stratiform rain characteristics are related to column moisture, specific humidity was used as a proxy due to the high correlation between column moisture and specific humidity (Hollaway and Neelin 2009) to see if the results in Ahmed and Schumacher hold true for the Kwajalein Atoll. To expand on environmental impacts, omega and SST are also compared in this study. The omega at 500 mb is associated with mid-level lift in the atmosphere. The more lift present, the more likely convection could be occurring and thus heavier rain rates. Negative values of omega lead to upward motion and more convection, while positive values of omega lead to downward motion and inhibit convection. Increased SST impacts rainfall by presenting a temperature change between the ocean and overlying atmosphere, creating instability, which would lead to increased convection and rain chances.

**Objectives**

First and foremost, the goal of this project is to quantify the variability of rainfall distributions in the ITCZ over a wide range of time and space scales based on ground radar observations. Another aspect of this research is to determine if relationships between specific humidity and rainfall hold for the Kwajalein radar observations over these varied time and space scales. This project is also focused on investigating how precipitation distributions could be influenced by SST and omega values for the Kwajalein Atoll. The results obtained from this study can help impact the atmospheric sciences community in a myriad of ways, mainly to help improve the accuracy of weather models to help warn those that will be potentially be affected by extreme rainfall events.

# CHAPTER II

# DATA AND METHODS

## Radar Data

Rain rates were calculated from the base (i.e., the lowest elevation angle) reflectivity data gathered by the Kwajalein ground-based, S-band radar from July to September of 1999 and 2000. The radar produced scans every ten to twelve minutes of the surrounding land and water inside a 150 km radius from the radar. Due to beam blockage and island clutter in the northern portion of the radar domain, causing the data to be an inaccurate representation of rainfall (Houze et al. 2004), only a 128 km by 128 km square area south of the radar is used for this study as shown in Figure 1.

Figure 1 is also a prime example of what spatial averaging does to the observations. The less averaging and the higher the resolution, the better the details of the data, though once we are in a one-by-one pixel field like at 128 km, there is no detail present in the data. The wide range of values that make up the 2 km box have been averaged into a single data point that may not be very representative of the overall rain distribution.

The reflectivity data from the Kwajalein radar is processed using the empirical Z-R relationship, $Z=aR^{b}$, with $a$ having a value of 175 and $b$ having a value of 1.5, to determine rain rate data in mm/hr (Houze et al. 2004). A convective-stratiform algorithm was run on the reflectivity field to classify all rain as either convective or stratiform (Steiner et al. 1995), any rain that failed to classify as either (a very small amount) was disregarded for this paper. Houze et al. (2004) contains more in-depth details about the radar data processing done for this study. After rain rates were calculated, the data were averaged into different temporal scalings (10 minutes, 1 hour, 3 hour, 6 hour, 12 hour, 18 hour, and daily averages), different spatial scalings (2 km, 4 km, 8 km, 16 km, 32 km, 64 km and 128 km boxes), and different types of rainfall (total rain, stratiform rain, and convective rain). Thus far, rain rate has been inferred to be area-averaged rain rate. The rain rate classifications were then separated even further into rain area or conditional rain rates.

**Environmental Data**

Three environmental variables are being compared to the rainfall characteristics: SST, omega at 500 mb, and specific humidity integrated over the column (will be called specific humidity throughout the rest of this paper for brevity). Data for the environmental variables were averaged over the radar domain to attempt to remove interpolation errors since the resolution of the environmental datasets covered unequal portions of the radar domain. Since there is one value, this can be assumed to be true for the entire area, though small-scale features from the precipitation that would change the environmental variables at small scales and possibly effect rainfall cannot be inferred from the current datasets being used.

SST data comes from the Earth System Research Laboratory (ESRL) and is averaged daily over the complete 128 km box. Omega values are also averaged daily over the 128 km box but come from the ERA-Interim reanalysis. Specific humidity values are also obtained from ERA-Interim reanalysis and averaged over the 128 km box every six hours. The lowest temporal resolution used for SST and omega values versus for specific humidity is done to prevent interpolation assumptions in the data.

**Methods**

In order to visualize the difference between the area-averaged and conditional rain rates and rain area compared to rain type, temporal and spatial scaling, and environmental factors, IDL was used to process all the numeric data and create all images used for this project. Area-averaged rain rate distributions for all types of rain were plotted to make sure that the retrievals were physically reasonable. Following this, rain area and conditional rain rates were calculated and plotted against both each other and area-averaged rain rates for each time and space scale and type of precipitation. Percentile charts were created for all of the above based on time or spatial scale for total, convective, and stratiform rainfall.

This study will assume that the environmental variables do not change until the next reception of data. These environmental variables will be compared to rain area, conditional rain rate, and area-averaged rain rate for the time scales available for each variable for the entire 128 km region. Each variable will have different rain characteristics separated out by either the mean value or quarter percentiles to demonstrate the environmental variables effect on rainfall characteristics.

# CHAPTER III

# RESULTS

## Stratiform Rain and Extremes

Stratiform rain, while light and precipitating over large areas, varies for the different areas and time scales over which the data is analyzed. Figures 2-4 show that as the spatial averaging increases from 2 km to 128 km (colored lines in each plot), stratiform rain extremes decrease in magnitude, though as temporal averaging increases from 10 minutes (Figure 2) to 1 day (Figure 4), the difference in extremes decreases until spatial scale is not very indicative of the rainfall extremes.

The stratiform rain rates in Figures 2-4 are plotted on a logarithmic scale with different slopes below and above the 90$^{th}$ percentile values. As the time averaging increases from 10 minutes to 1 day, the smaller spatial rain extremes decrease towards the 128 km line, which hovers around 1 mm/hr at all time scales. The relative variability in rain rates is greatest near the 50$^{th}$ percentile and least near the 99$^{th}$ percentile, although the extreme values still encompass a wider range of rain rate magnitudes (e.g., 99$^{th}$ percentile values at 10 min range from 1-7 mm/hr versus 0.02-0.7 mm/hr for the 50$^{th}$ percentile values).

## Convective Rain and Extremes

Similar to that of stratiform rain, Figures 5-7 show that convective rain extremes are logarithmic in nature with differing slopes less than or greater than the 90$^{th}$ percentile value. Rain rates in general will be higher in convective precipitation (with extremes in the tens of mm/hr) than stratiform rain (with extremes in the single digits of mm/hr) based on the definition of each rain classification. As averaged time increases from 10 minutes (Figure 5) to 1 day (Figure 7), the smaller spatial scales start to approach 128 km like that of the stratiform rain percentiles. However, there are times when the 128 km percentiles are larger than the 64 or 32 km, particularly at lower percentile values where an outlier or much-heavier-than-average rain is occurring in only one of the smaller boxes but gets averaged in when the entire 128 km box rain rate is computed. Another likely scenario that could cause this discrepancy can be due to the low sample size of the 128 km box since there are only 184 total days that had rainfall, and thus only 184 data points for 128 km at 1 day unlike 64 which has four times as many data points. Unlike stratiform precipitation, the 2 km line does not completely get overridden by the other spatial scales at the largest time scales. This is due to convective storms being small-scale and having intense rain rates, which even when averaged over a long period of time do not completely filter out of the time-averaged data.

**Conditional Rain Rates and Rain Area**

Due to the different physical nature of convective and stratiform rainfall, each type will have a different range of conditional rain rates. Figure 8 shows that stratiform rain has small rain intensities due to the light total rainfall while convective rain has larger rain intensities due to larger total rainfall over the same amount of time. Since conditional rain rates are a ratio including area-average rain rates, the trends seen with the area-averaged rainfall carry over to the rain intensities. This means that there will be a decrease of conditional rain rates with an increase in temporal resolution, as expected since area-averaged rain rates decrease as well.

Figure 9 shows that rain area is also dependent on what type of rainfall is occurring. If stratiform rainfall is present, the amount of area covered by rain is typically high, with values ranging from 0.05 to 0.75 of the 128 km domain being covered by rainfall during the specific 10-minute period. If the rainfall is convective, the amount of area covered by rain is typically lower than 0.25. Because of this, total rain areas vary greatly from scan to scan depending on how much of the domain is covered by stratiform or convective rain.

When comparing rain area to conditional rain rates at 10 minutes and over the 128 km domain (Figure 10), the precipitation types naturally separate from each other, with the total rain observed somewhere in between since a grouping of radar pixels can be composed of both stratiform and convective rain. This occurs since stratiform rain has a low conditional rain rate or intensity but covers large areas of the domain, while convective rain has a high conditional rain rate intensity but covers small areas of the domain. However, there is a tendency for both rain types to have a larger conditional rain rates when covering more area of the 128 km domain.

**Rainfall Compared to Specific Humidity**

Figures 11-15 compare radar-observed precipitation characteristics to the column-integrated specific humidity. Results are only shown for 6-hourly and 128-km scales since the specific humidity data was only available once every six hours and over a large grid from the model reanalysis. Figures 11 and 12 show that lower area-averaged rain rates are associated with less than average values of specific humidity (dashed yellow line), which is about 47.5 g/kg, while larger area-averaged rain rates are associated with larger than average values of specific humidity (dotted blue line). This holds true regardless if the rain is convective (Figure 11) or stratiform (Figure 12). This trend is also seen in the conditional rain rates, with lower values having more contribution from less than average values of specific humidity, and larger values having more contribution from higher than average values of specific humidity (not shown). When comparing specific humidity to rain area (Figures 13-15), it can be seen that stratiform rain area is more sensitive to specific humidity than convective rain area, which supports the findings in Ahmed and Schumacher (2015).

**Rainfall Compared to SST**

Figures 16-21 composite the radar-observed area-averaged rain rates by daily SST. For brevity, only 2 km and 128 km images are shown. When separating area-averaged rainfall by the first quartile and last quartile of SST temperatures (28.09°C and 28.75°C respectively), the total area-averaged rainfall looks as expected with larger SSTs (red dotted lines) contributing to higher rain rates. This is true for both total and convective rainfall at both the 2 km and 128 km images, though for stratiform rainfall, lower SST values (green dashed lines) contribute to the larger rain rates. This is thought to be because at the largest values of stratiform rain rates, there would be more cloud cover and downdrafts near the surface, leading to cooling of SSTs.

**Rainfall Compared to Omega**

Figures 22-27 composite the radar-observed area-averaged rain rates by daily omega at 500 mb. For brevity, only 2 km and 32 km images are shown to best show the data. Omega has a consistent trend when compared to area-averaged rain rate and separated into either greater than or less than the mean amount of omega present (-0.069 kg*km/s). Recall that negative values of omega are indicative of upward motion, while positive values of omega are indicative of downward motion. Stronger rain rates have more values of omega that are less than average (green dashed lines), while weaker rain rates have omega values that are higher than average (red dotted lines). A less than average omega would be indicative of a stronger updraft and thus be more likely to be convective and have a stronger area-averaged rain rate, which is supported by the data. The values of omega that are higher than average are indicative of a weak updraft and thus more likely to be stratiform precipitation and have smaller values of area-averaged rain rate, which is also supported by the data, though if in the presence of a large storm system, like a MCS, this logic can break down due to large areal coverage of both convective and stratiform rainfall.

# CHAPTER IV

# CONCLUSIONS

Spatial and temporal resolution is important to consider in the process of handling weather data. Changing the spatial or temporal scale of a dataset has an impact on the results. As the spatial scale increases, area-averaged rain rates, rain area, and conditional rain rates decrease due to the addition of values with no rain except for the case of conditional rain rates where this is due to the increase of area. With an increase in temporal scale, rain area increases with time since there are more opportunities for some measurable rainfall to occur over the area and create a non-zero average as seen in Figure 1. These changing scales affect rain rate extremes, with the most extreme rain rates occurring at the smallest time (10 minutes) and space (2 km) scales. However, spatial scale becomes much less of a factor in extreme values as time averaging approaches 1 day.

The environmental variables of column-integrated specific humidity, omega at 500 mb, and SST impact rainfall characteristics differently. Less than average values of specific humidity lead to lower rain rates and rain intensities. Distributions of convective rain area and stratiform rain area compared to specific humidity support Ahmed and Schumacher (2015). SST analysis yields anticipated results with stratiform area-averaged rain rates having more contributions from below average SST values due to increased cloud cover and cooling near the surface, while convective and total area-average rain rates having more contributions from above average SST values due to increased convection. Omega values followed what would be expected based on the type of rain present; lower rain rates and stratiform rain were characterized by less negative values of omega due to a weaker updraft, while higher rain rates and convective rain were characterized by more negative values of omega due to a stronger updraft. The most intense rain rates had values that were less than average (indicating anomalous upward motion) for omega.

Future applications can start with expanding this methodology into other regions to see if these trends hold true for other parts of the tropics. A major component that could be added to this analysis is comparing the data collected and analyzed here with model rain rate distributions to see how well models are currently representing what is actually occurring in the atmosphere. This can be done with getting model data over Kwajalein for different time and spatial scales and attempt to reproduce what was done here and see if improvements or calibrations to models can be achieved.

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# APPENDIX

# SUPPLEMENTAL FIGURES

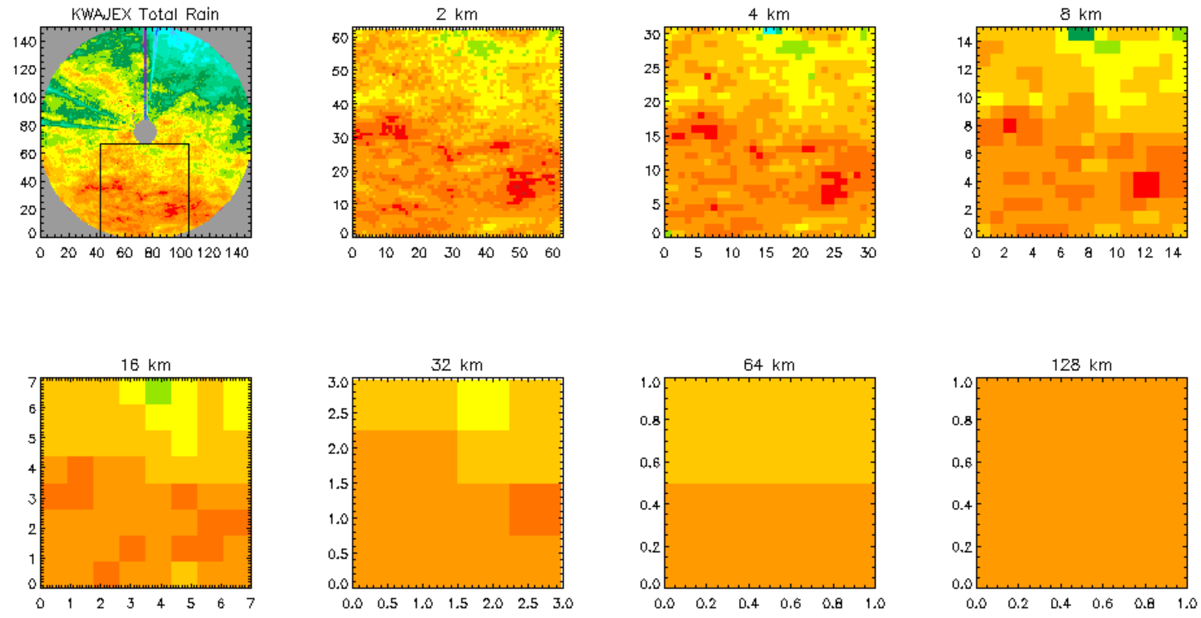


Figure 1: Radar domain visualization. This image shows where in the complete radar domain (the 128 by 128 km box) is, as well as how spatial scaling effects the data (axis are in number of boxes)

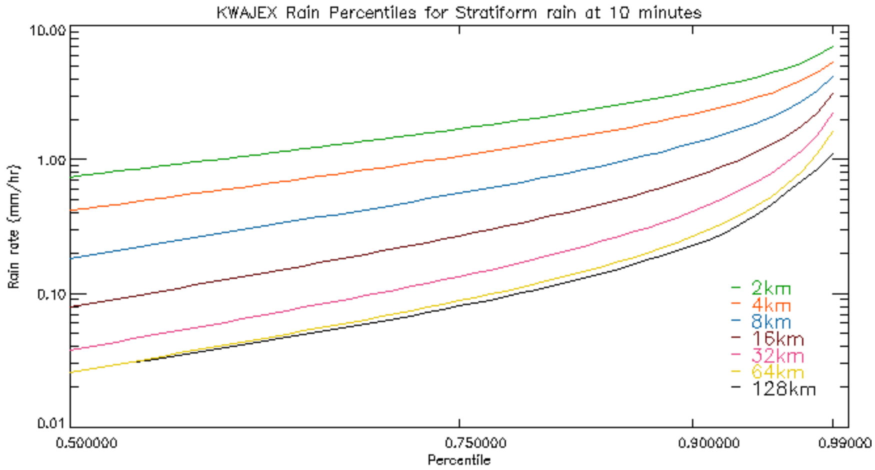


Figure 2: Stratiform area-averaged rain rate percentiles at 10 minutes

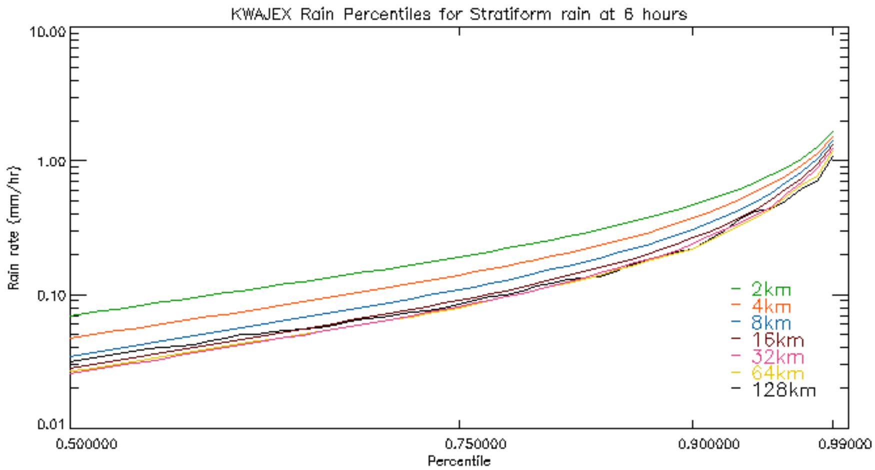


Figure 3: Stratiform area-averaged rain rate percentiles at 6 hours

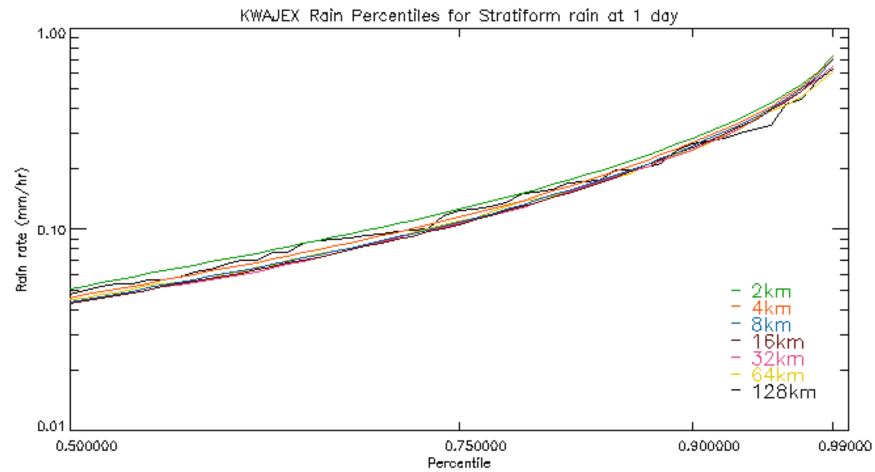


Figure 4: Stratiform area-averaged rain rate percentiles at 1 day

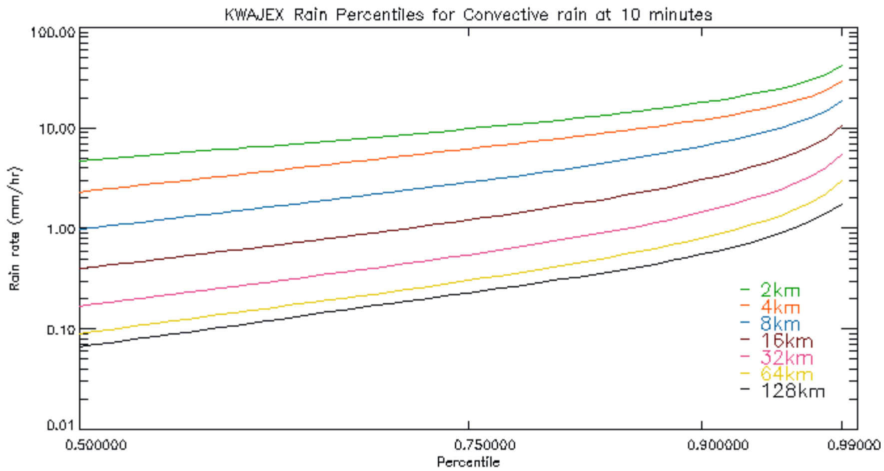


Figure 5: Convective area-averaged rain rate percentiles at 10 minutes

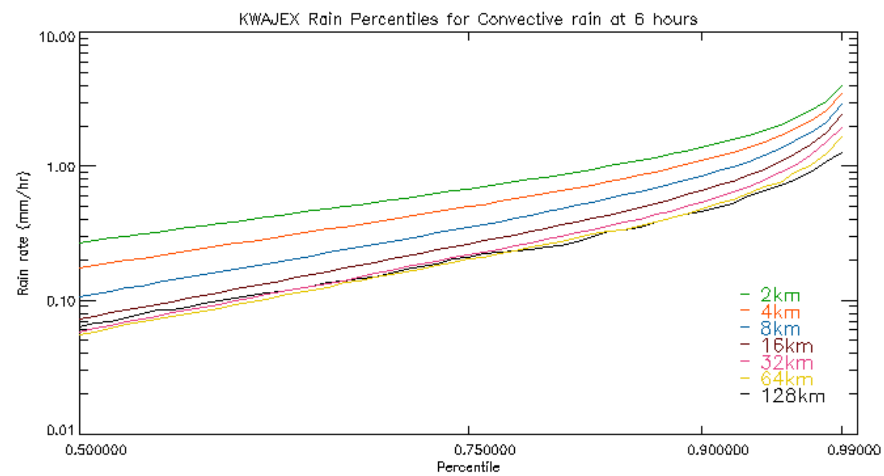


Figure 6: Convective area-averaged rain rate percentiles at 6 hours

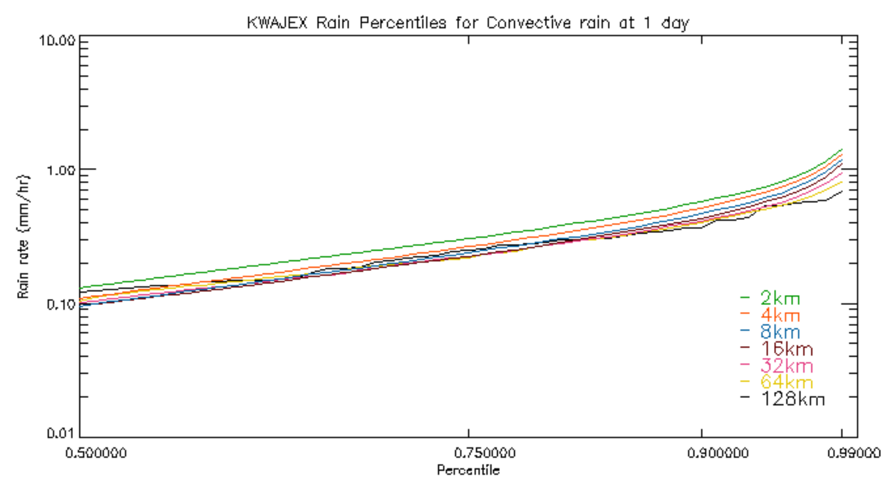


Figure 7: Convective area-averaged rain rate percentiles at 1 day

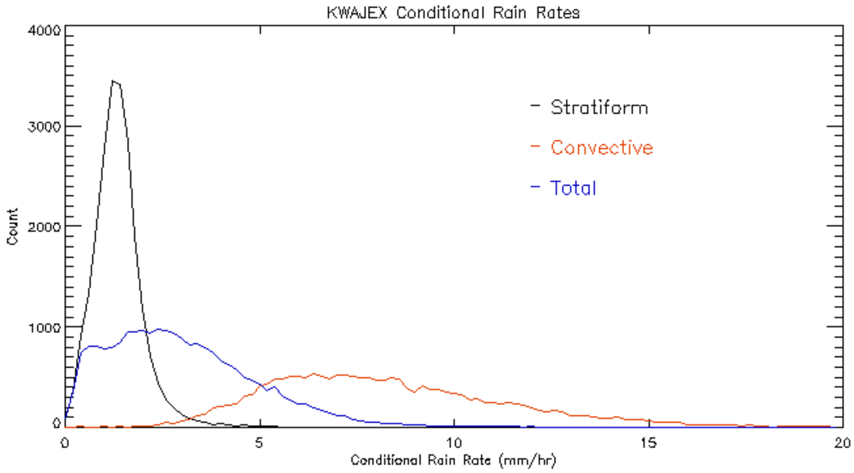


Figure 8: Conditional rain rate histogram: This shows conditional rain rates at 10-minute time scales at 128 km for convective, stratiform, and total rain events.

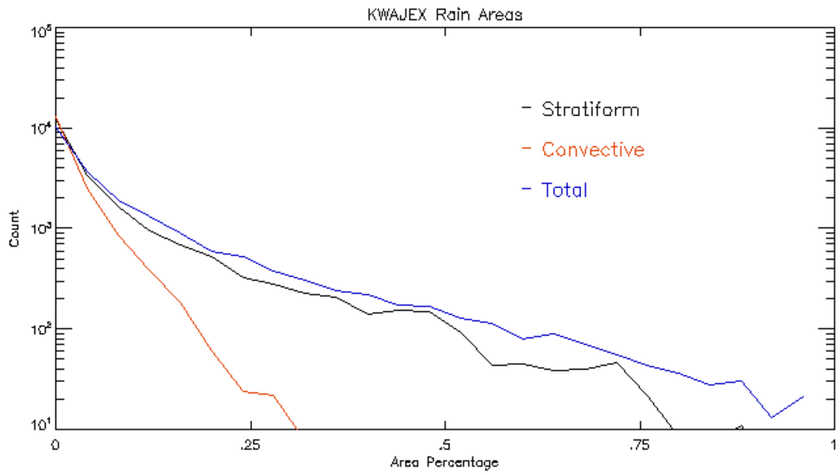


Figure 9: Rain area histogram: This shows rain area at 10-minute time scales over 128 km domain for convective, stratiform, and total rain events.

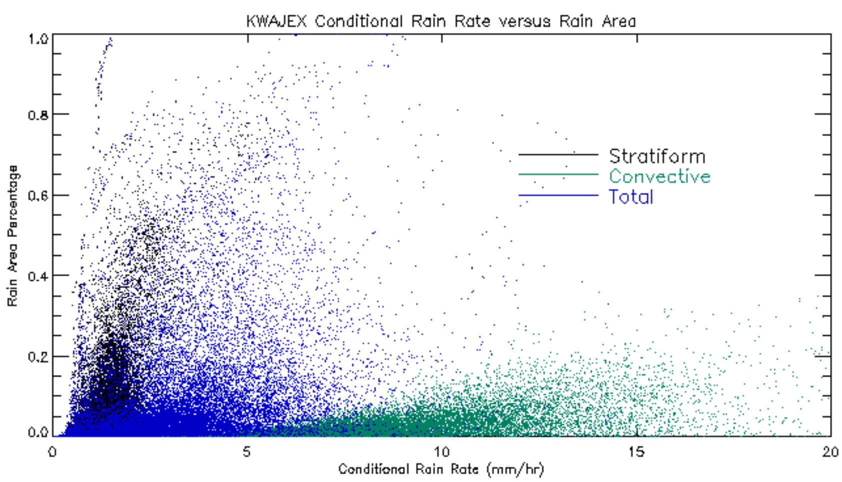


Figure 10: Rain area versus conditional rain rate: this image shows how comparing these rainfall characteristics naturally sorts out stratiform from convective rainfall.

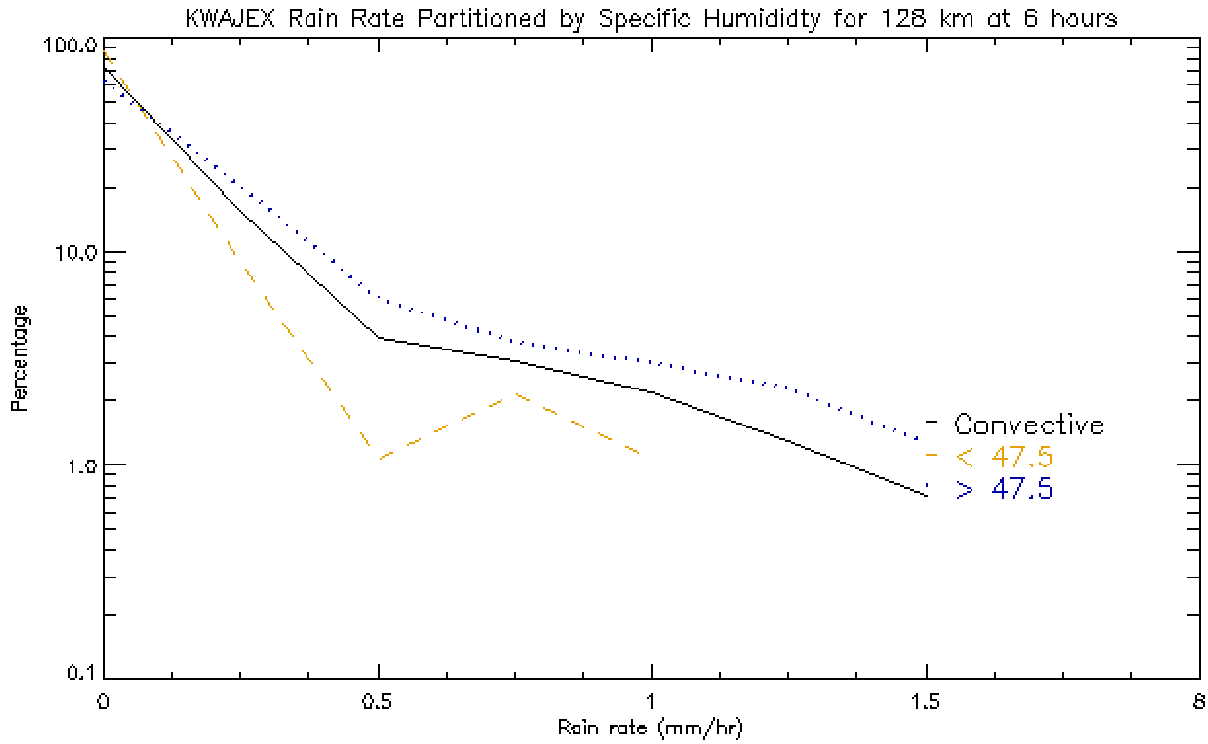


Figure 11: Convective area-averaged rain separated by specific humidity.

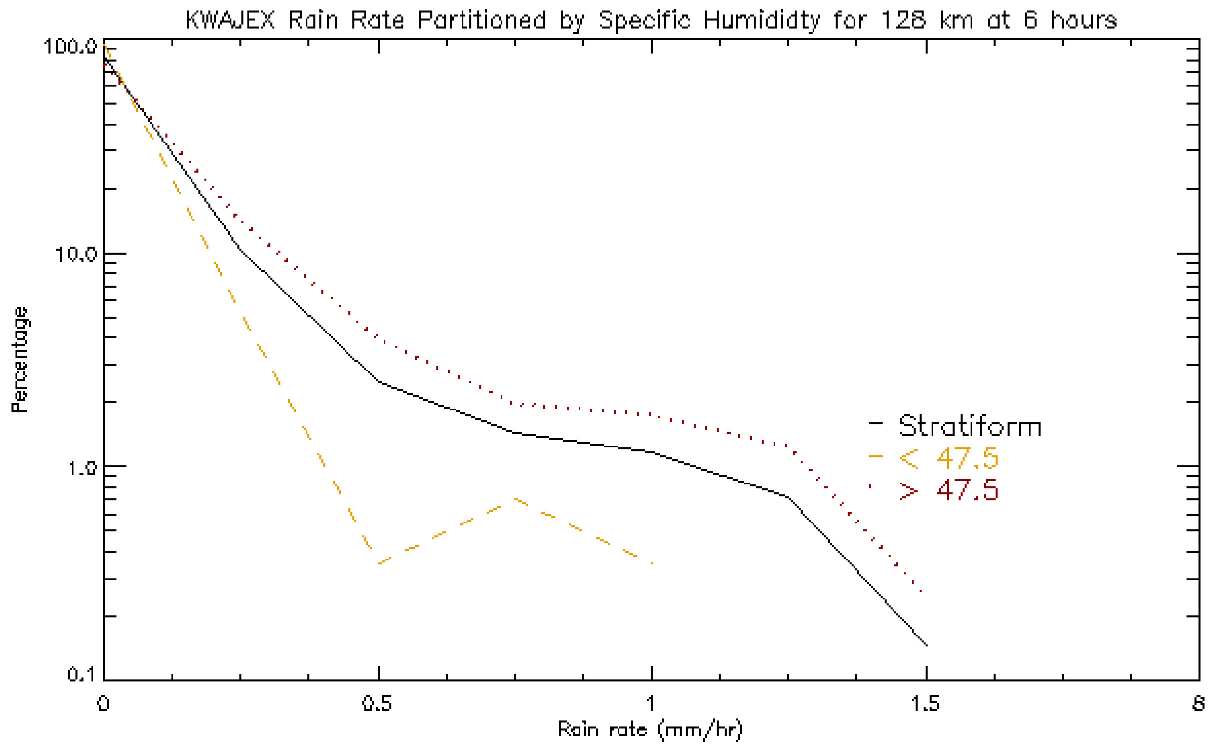


Figure 12: Stratiform area-averaged rain separated by specific humidity.

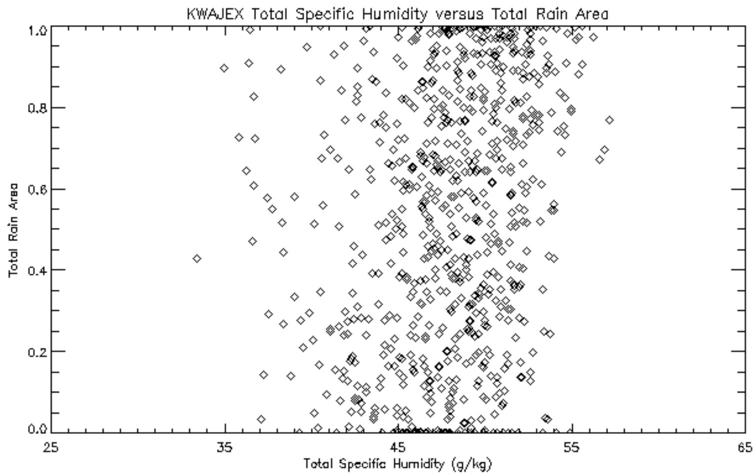


Figure 13: Total rain area separated by specific humidity

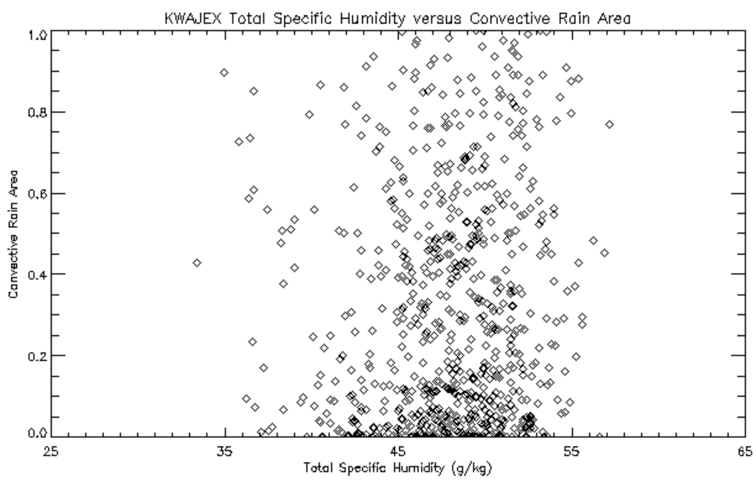


Figure 14: Convective rain area separated by specific humidity.

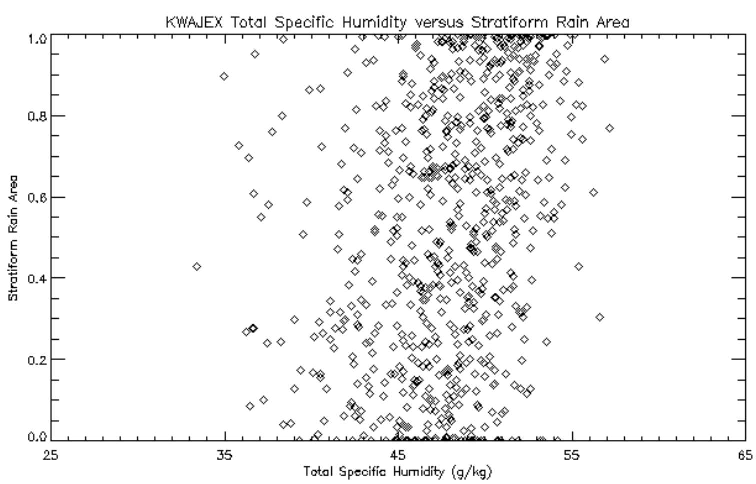


Figure 15: Stratiform rain area separated by specific humidity.

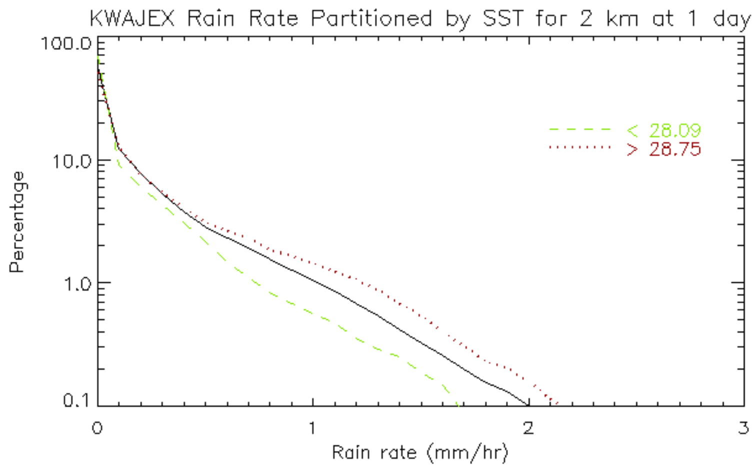


Figure 16: Total area-averaged rain rate separated by SST for 2 km at 1 day.

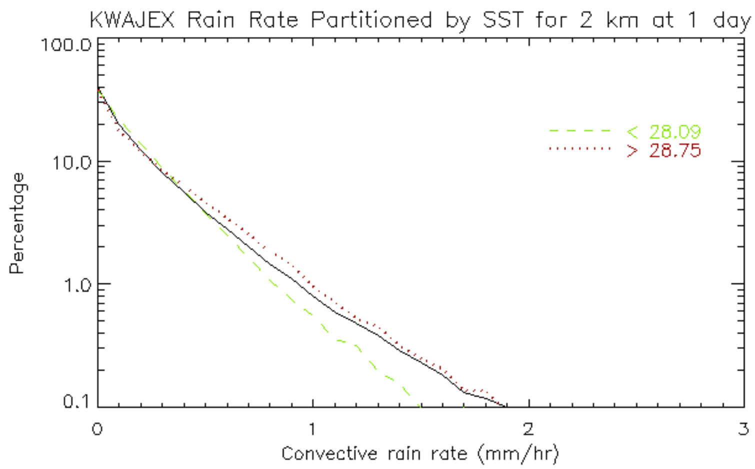


Figure 17: Convective rain rate separated by SST for 2 km at 1 day.

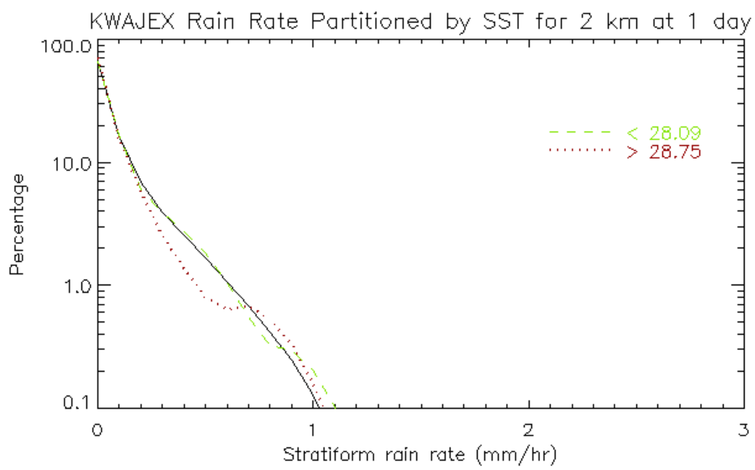


Figure 18: Stratiform area-averaged rain rate separated by SST for 2 km at 1 day.

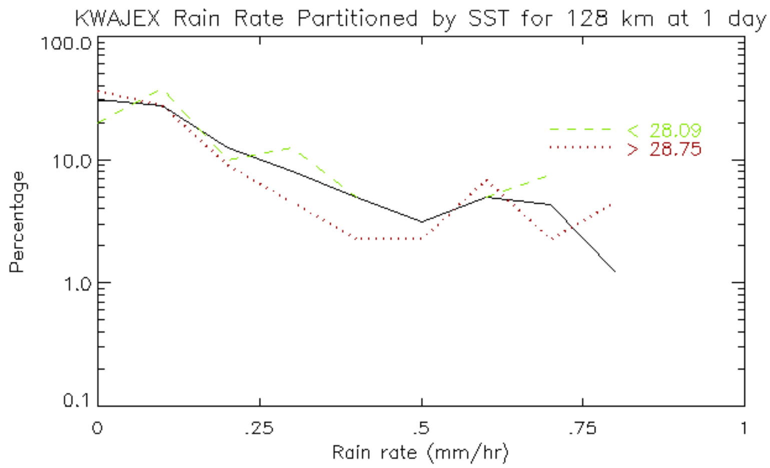


Figure 19: Total area-averaged rain rate separated by SST for 128 km at 1 day.

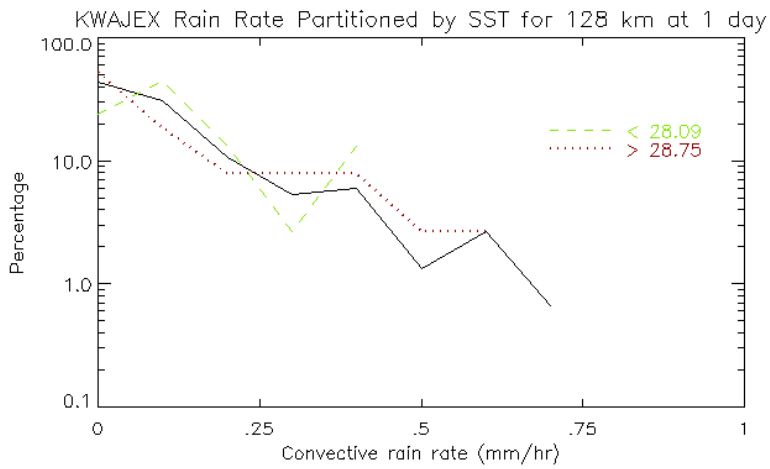


Figure 20: Convective area-averaged rain rate separated by SST for 128 km at 1 day.

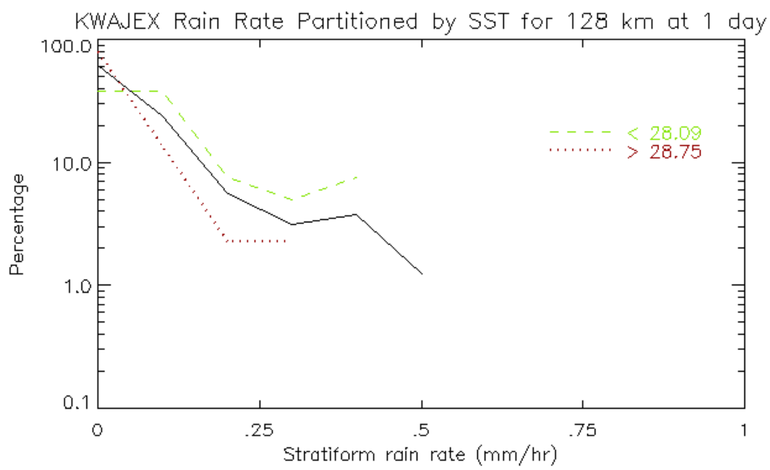


Figure 21: Stratiform area-averaged rain rate separated by SST for 128 km at 1 day.

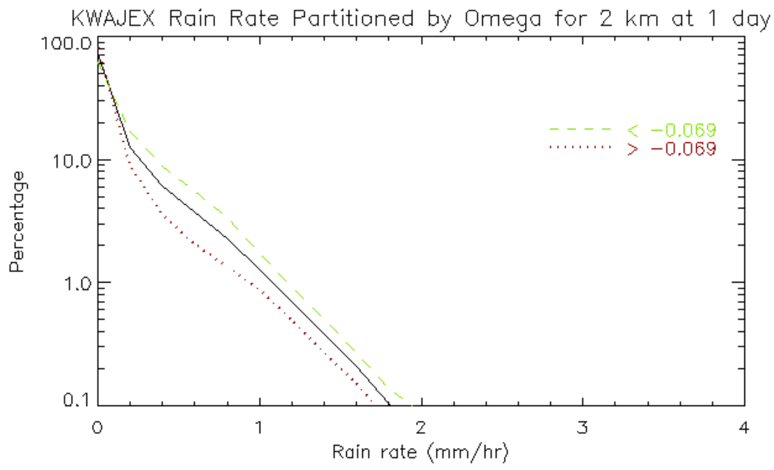


Figure 22: Total area-averaged rain rate separated by omega for 2 km at 1 day.

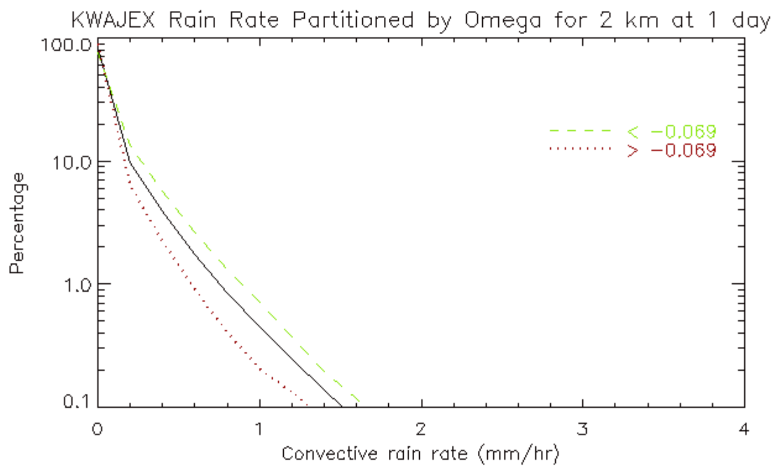


Figure 23: Convective area-averaged rain rate separated by omega for 2 km at 1 day.

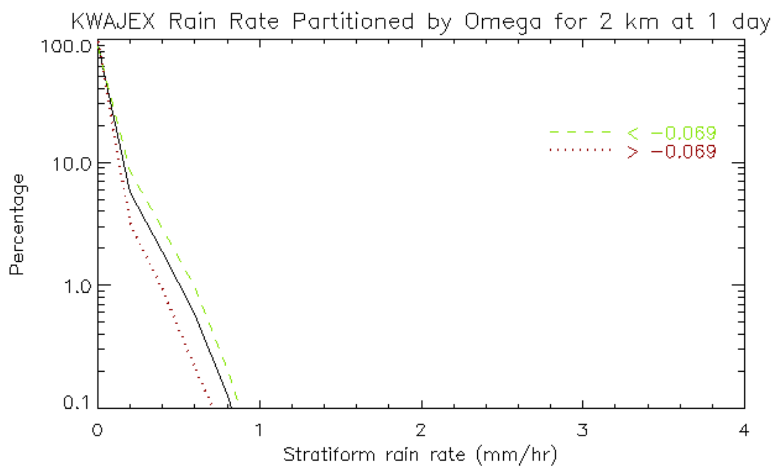


Figure 24: Stratiform area-averaged rain rate separated by omega for 2 km at 1 day.

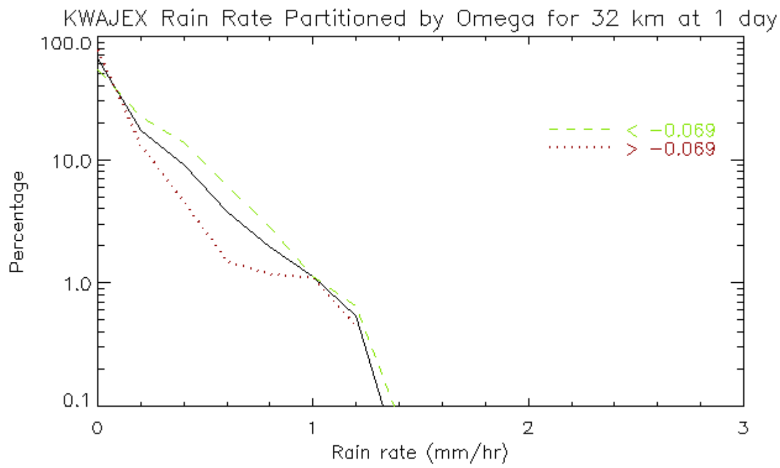


Figure 25: Total area-averaged rain rate separated by omega for 32 km at 1 day.

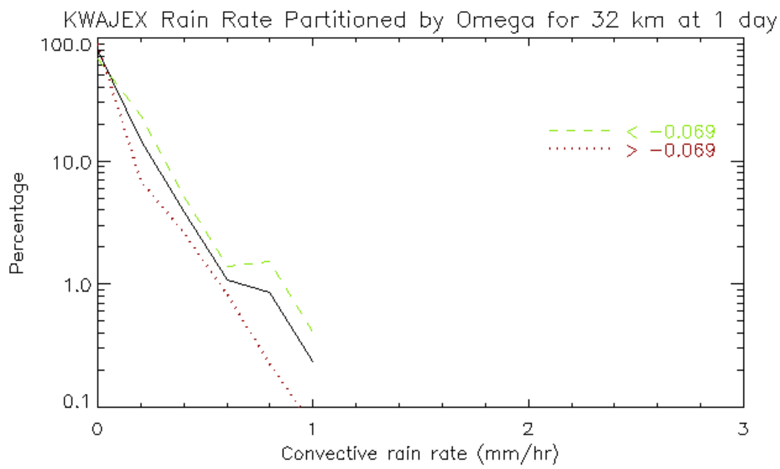


Figure 26: Convective area-averaged rain rate separated by omega for 32 km at 1 day.

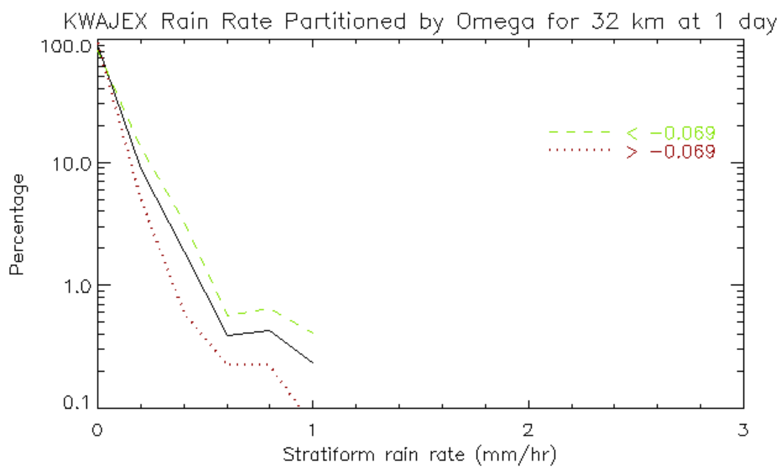


Figure 27: Stratiform area-averaged rain rate separated by omega for 32 km at 1 day.