Lightning/Precipitation Relationships on a Global Basis

by

Carlos Ramón Labrada

Massachusetts Institute of Technology

Submitted to the Department of Electrical Engineering and Computer Science in partial fulfillment of the requirements for the degree of

Master of Engineering in Electrical Engineering and Computer Science

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 1999

© Massachusetts Institute of Technology 1999. All rights reserved.

Author

Department of Electrical Engineering and Computer Science
May 21, 1999

Certified by

Earle Williams
Principal Research Scientist
Thesis Supervisor

Accepted by

Arthur C. Smith
Chairman, Department Committee on Graduate Students
Department of Electrical Engineering and Computer Science
Lightning/Precipitation Relationships on a Global Basis

by

Carlos Ramón Labrada

Submitted to the Department of Electrical Engineering and Computer Science
on May 21, 1999, in partial fulfillment of the requirements for the degree of
Master of Engineering in Electrical Engineering

Abstract

Rainfall and lightning are measured and compared on a global basis using data gathered
from the Tropical Rainfall Measuring Mission (TRMM) satellite, launched in November
1997. The satellite provides simultaneous lightning-precipitation measurements that allow
for comprehensive relationships to be created for future rainfall monitoring utilizing
unique electromagnetic methods.

Precipitation and lightning comparisons using TRMM data showed that there is no unique
relationship between lightning and near surface rainfall. No definite bimodality over land
was found that indicated distinct regimes; however, maps of the mass of precipitation per
flash showed a latitudinal dependence in both South America and Africa indicative of dif-
ferent regimes. Reflectivity-height distribution plots established reflectivity thresholds at 7
km and 10 km where lightning over land completely dominates lightning over ocean. For
reflectivity greater than 25 dBZ at 7 km altitude over land, there is 87% probability it will
produce lightning. Ocean, on the other hand, requires higher than 35 dBZ at 7 km to gen-
erate lightning with a probability of 77%.

Venn diagrams determined that lightning is not a good choice for measuring precipitation
on a global scale when less than 6% of all precipitating clouds exhibit lightning. For pre-
cipitating clouds over land, lightning appears in 15% of the clouds at 2 km altitude. Light-
ning may be better suited for measuring rainfall over land.

The mass of precipitation[kg] per lightning flash was found to be highly variable, with val-
ues ranging over four orders of magnitude. Correlation coefficients of scatter plots of mass
of precipitation versus lightning rate confirmed a non-unique relation between precipita-
tion and lightning for rain measured near the surface (2km, 4 km), with numbers close to
0. The correlation coefficients increased to 0.5 for altitudes 7 km and above.

The kg per flash values addressed the issue of an order of magnitude difference in light-
ning between continental and oceanic convection. This finding is consistent with the idea
of mid-level updrafts being larger in continental than oceanic convective clouds.

Thesis Supervisor: Earle Williams
Title: Principal Research Scientist
Acknowledgments

I wish to acknowledge several people that provided invaluable help during the course of the thesis project. First I will like to thank NASA Marshall Space Flight Center (MSFC) and Goddard Space Flight Center (GSFC) for providing TRMM data to make possible this study. I will also like to thank Dennis Boccippio at MSFC for his valuable assistance with the LIS/OTD software and detailed explanations of viewtime granules; Dr. Bob Meneghini for his support and cooperation in understanding the 2A25 dataset, as well as Dr. Iguchi for providing the convective cloud Z-R relations for the 1C21 dataset. Thanks to everyone at DAAC and Otto Thiele for assisting with my participation in the Brazil field experiment on January 1999; Everest Huang for supporting me with maintaining and setting up the computer’s hardware and software; Gwynn Fireman and everybody at the TSDIS helpdesk for answering and locating contacts for my questions and requests; David Fanning for his IDL tips and suggestions; Nadia Madden for being a friend, and providing a helping hand during my last few days in Brazil. Thanks to all the people I met during my stay in Ji-Parana, Rondonia.

I cannot forget my roommates and friends (Ivan, Antonio, Gregorio, Ramón, Nitza, Edixa, Paola, and Paula) for their 100% support during the final days in writing the thesis. Thank you guys for bringing food, smiles, and lending a hand during the sleepless nights. Special thanks to my friend Antonio Fuentes for his nitty MATLAB commands and programs to plot data, and of course getting the thesis printed and on the cover.

To the love of my heart, Yezabel, thank you for being there all the way. I love you. Thanks to my family for all their sacrifices during these 5 years I have been away from home. Thanks to my brother and sister (Luis and Beatriz) for their unconditional support during the rough days, thanks, I love you guys! Tío Juan, tía Lucy, y primos (Juan, Celia, y
Maritza) gracias por ser parte de mi familia y apoyar a mi madre durante estos últimos años. Mamá y Papá esto es para ustedes. Gracias por su amor. Los quiero con toda mi alma.

Last, but very important, thanks to Dr. Earle Williams for believing in me, for his guidance and continuous support throughout the entire year in MIT and in Brazil.
Contents

1 Introduction ................................................................. 13

2 Background Information .................................................. 17
  2.1 Background Studies .................................................... 17
  2.1.1 Lightning Formation ................................................. 17
  2.1.2 Rainfall Formation .................................................. 18
  2.1.3 Temperature .......................................................... 19
  2.1.4 Convective Regimes ................................................. 20

3 Space-Based Instrumentation ............................................ 25
  3.1 Precipitation Radar (PR) .............................................. 27
  3.1.1 PR Scan Geometry .................................................... 28
  3.2 Lightning Imaging Sensor (LIS) ...................................... 31
  3.2.1 LIS Geometry ........................................................ 31

4 Software Tools ................................................................ 33
  4.1 Computer Tools .......................................................... 33
  4.2 Data Processing ........................................................... 33
    4.2.1 PR Data ................................................................. 34
    4.2.2 LIS Data ............................................................... 38
  4.3 Calculations of Physical Quantities ................................... 39
    4.3.1 Lightning Rate ......................................................... 39
    4.3.2 Mass Flux ............................................................. 43
    4.3.3 Rainfall Fractional Area ............................................ 46

5 Data Analysis .................................................................. 47
  5.1 Global Observations ..................................................... 47
  5.2 Flash Rate versus Precipitation Fractional Area .................... 59
    5.2.1 Near Surface Region up to 0°C Isotherm ......................... 59
    5.2.2 Mixed Phase Region ............................................... 61
    5.2.3 Ice Region ............................................................. 63
  5.3 Lightning Rate versus Mass Flux ...................................... 65
    5.3.1 Near Surface Region up to 0°C Isotherm ......................... 65
    5.3.2 Mixed Phase Region ............................................... 71
    5.3.3 Ice Region ............................................................. 74
  5.4 Precipitation Mass Flux versus Precipitation Fractional Area .... 77
    5.4.1 Near Surface Region up to 0°C Isotherm ......................... 78
5.4.2 Mixed Phase Region ........................................ 80
5.4.3 Ice Region .................................................. 81
5.5 Reflectivity-Height Distribution Plots ...................... 82

6 Conclusions ............................................................. 89

7 References ............................................................. 93
List of Figures

1-1 Precipitation mass [kg] versus Total CG Flash counts .......................... 15
2-1 Global Map of Radar Reflectivity > 40dBZ at 7 km altitude ...................... 21
2-2 Prototypical Reflectivity Profiles ......................................................... 22
3-1 Schematic View of the Scan Geometry of TMI, PR, and VIRS ..................... 26
3-2 PR Radar Scan Geometry ................................................................. 29
3-3 Normal Sample Data Schematic ........................................................... 30
3-4 Scan Geometry of LIS imager ............................................................... 32

4-1 Height calculation of dBZ sample .......................................................... 36
4-2 PR SQUARE Schematic ................................................................. 37
4-3 Co-located LIS and PR Squares ......................................................... 39
4-4 PR Squares to Find the LIS Flashes .................................................... 40
4-5 1C21 vs. 2A25 Precipitation Mass Flux Comparison at 7 km .................. 44

5-1 TRMM Satellites Orbit 5 January 1, 1998 and PR Square Number 16 .......... 48
5-2 Maximum radar reflectivity (dBZ) ........................................................ 52
5-3 Mass Precipitation per flash [kg/flash] ............................................... 55
5-4 Venn Diagrams .................................................................................. 57
5-5 Flash Rate vs. Precipitation Fractional Area for 2 km ............................ 60
5-6 Flash Rate vs. Precipitation Fractional Area for 4 km ............................ 61
5-7 Flash Rate vs. Precipitation Fractional Area for 7 km ............................ 62
5-8 Flash Rate vs. Precipitation Fractional Area for 10 km ......................... 64
5-9 Precipitation Mass Flux vs. Flash Rate and Histograms (Land, Ocean) 2 km 68
5-10 Precipitation Mass Flux vs. Flash Rate and Histograms (Total, Combo) 2 km 69
5-11 Precipitation Mass Flux vs. Flash Rate and Histograms (Land, Ocean) 4 km 70
5-12 Precipitation Mass Flux vs. Flash Rate and Histograms (Total, Combo) 4 km 71
5-13 Precipitation Mass Flux vs. Flash Rate and Histograms (Land, Ocean) 7 km 73
5-14 Precipitation Mass Flux vs. Flash Rate and Histogram (Total, Combo) 7 km 74
5-15 Precipitation Mass Flux vs. Flash Rate and Histograms (Land, Ocean) 10 km 76
5-16 Precipitation Mass Flux vs. Flash Rate and Histograms (Total, Combo) 10 km 77
5-17 Precipitation Mass Flux vs. Precipitation Fractional Area for 2 km .......... 79
5-18 Precipitation Mass Flux vs. Precipitation Fractional Area for 4 km .......... 80
5-19 Precipitation Mass Flux versus Precipitation Fractional Area for 7 km .... 81
5-20 Precipitation Mass Flux versus Precipitation Fractional Area for 10 km .... 82
5-21 Reflectivity-Height Distribution Plot for All Cases ................................ 84
5-22 Reflectivity-Height Distribution Plot (Rain and Lightning Over Land) .... 85
5-23 Reflectivity-Height Distribution Plot (Rain and No Lightning Over Land) . 86
5-24 Reflectivity-Height Distribution Plot (Rain and Lightning Over Ocean) .... 87
5-25 Reflectivity-Height Distribution Plot (Rain and No Lightning Over Ocean) .. 88
### List of Tables

3-1 Major Parameters of TRMM PR ........................................... 27
4-1 Data Saved in .rc File for Rain Certain ............................ 34
4-2 Data Saved in .rc File for Rain Uncertain ....................... 35
4-3 Information Contained in .pr File ................................. 38
4-4 Coefficients for Z-R Relations ..................................... 45
5-1 Correlation Coefficients and Least Square Fit Line at 2 km Altitude ........ 66
5-2 Correlation Coefficients and Least Square Fit Line at 4 km Altitude ........ 66
5-3 Correlation Coefficients and Least Square Fit Line at 7 km Altitude ........ 72
5-4 Correlation Coefficients and Least Square Fit Line at 10 km Altitude ...... 75
Chapter 1

Introduction

This research is concerned with finding relationships between precipitation and lightning on a global scale in the tropics, using data gathered from the Tropical Rainfall Measuring Mission (TRMM) satellite. Global rainfall is of great meteorological importance, but it is difficult to measure. In these past years, climatological events such as El Niño have affected the planet. Satellite observations of events such as this have helped to understand and predict them more accurately. The precipitation-lightning dependence that this thesis seeks will improve modern methods for determining on ground accumulation of rainfall using lightning rate measurements which are easier to calculate.

This is the first time ever that an orbiting satellite carries precipitation radar instrumentation along with lightning imagers. Previous work investigated regimes of localized storms (Battan, 1965; Piegrass et al., 1982, Nielsen et al., 1990, Williams et al., 1992; Buechler et al. 1994, Zipser, 1994; Petersen and Rutledge, 1996) for specific geographical locations and meteorological regimes. Figure 1.1(a,b) shows lightning versus rainfall diagrams from Williams et al, 1992, and Petersen and Rutledge, 1996, respectively. The coefficients of precipitation mass [kg] per flash are different in both of them. Figure 1.1 confirms that precipitation mass and lightning flash count are proportional within specific convective regimes and geographical regions, with flash count per unit rainfall values varying between 2 to 3 orders of magnitude between break period and monsoonal convection.
Figure 1.1 (a) Total Precipitation [kg] versus Total Number of CG flashes plot with “x” for monsoonal convection and “o” for continental. High-cloud-base continental convection appears to have the highest flash yield per kilogram of rain and oceanic ITCZ convection has the lowest value. (From Williams et al., 1992)
(b) Normalized CG flash density (ordinate) vs. rain mass (abscissa). Sloping black lines are lines of constant rain-yield (kg/fl). The filled circles, squares, and open triangles are seasonal means for subareas of the "arid", "mid-continent", and "humid" climate regimes respectively (continental U.S.). Data points for the tropical continental "DWN", "Island", and oceanic "COARE" regimes are also indicated. Bold arrows indicate trends toward arid or oceanic regimes, and two bold lines are placed to separate arid and tropical/oceanic regimes. (From Petersen and Rutledge, 1996)

**Figure 1.1:** Precipitation mass [kg] versus Total CG Flash counts

The non-geostationary satellite is equipped with a 13.8 GHz radar for rainfall estimation (PR radar) and a Lightning Imaging Sensor (LIS) that allows for simultaneous measurement of lightning. However, the non-geostationarity of the satellite prevents the surveillance of a storm from beginning to end. If a storm is seen by the precipitation radar at onset, there will be a lag between the initial flashes and the falling precipitation. The
satellite data only allow for a quick 90 second 'snapshot' observation of a 4kmx4km area below and if the lag is large, the precipitation mass per flash rate will not provide good insight on these convective clouds. Nevertheless, the integration of large amounts of data over the whole globe will average out the plots of precipitation mass flux per flash rate.

Chapter 2 will give an overview of rainfall and lightning formation, as well as the role of temperature. It will also have a section devoted to explaining the different types of regimes available in tropical zones.

Chapter 3 will give a description of the satellite and its on board instruments. Sections in this chapter will be devoted to the Precipitation Radar (PR) which measures reflectivity and the Lightning Imaging Sensor (LIS) that detects lightning flashes.

Chapter 4 will discuss the software tools and programs used to process and analyze the TRMM data. Sections will be devoted to explaining the processing of raw PR and LIS data, as well as the calculation of specific quantities: Lightning Rate [flashes/minute], Precipitation Mass Flux [kg/sec], and Precipitation Fractional Area [%].

Chapter 5 will provide an analysis of the data. It will first provide a global analysis for the tropical zone with color coded maps and Venn diagrams. Then it will discuss each of the calculated variables discussed in Chapter 4 in the ice region (10 km), the mixed phased region (7 km), and the near surface region (2 km and 4 km). It will also provide distribution functions for land with rain and lightning, land with rain and no lightning, ocean with rain and lightning, and ocean with rain and no lightning, for the four selected heights.

Chapter 6 will conclude with a remark on the contribution of this work to the scientific community.
Chapter 2

Background Information

2.1 Background Studies

Lightning flashes are events that are easy and relatively inexpensive to measure compared to rainfall. If the lightning flashes produced by a storm were proportional to the accumulated rainfall, then the flash rate could be used as a means to measure that rainfall. It has been suggested that lightning is the result of the gravitational potential energy of falling ice particles. If these ice particles become the rainfall, then there should be a proportionality between rainfall and lightning (Williams, 1996). However, the proportionality between flash count and rainfall is dependent on geographical location and convective regime (Williams, 1996). This chapter will provide the necessary background on the formation of precipitation and lightning and how meteorological elements such as temperature and convective regime affect them.

2.1.1 Lightning Formation

Lightning activity is closely coupled to atmospheric instability, deep convective activity and the release and transport of heat. It has been observed that lightning initiates soon after the onset of strong convective activity. The theory is that strong vertical updrafts and the formation of ice particles in the upper regions of a thunderstorm are the important processes that lead to lightning formation. Due to the charge separation process, the top of the cloud is positively charged while the bottom part becomes negatively charged. These negatively charged particles will induce a local positive charge accumulation on the Earth
below. These large charge differences are said to be caused by repeated collisions of small ice pellets, called graupel, within the cloud. A bolt of lightning occurs when the local electric field becomes large enough, either between clouds or cloud and ground. This lightning will carry electrical energy from one region to the other, neutralizing the potential difference.

2.1.2 Rainfall Formation

The formation of precipitation is due to a physical mechanism in which air parcels become heated as the Sun’s rays warm the ground. These air parcels rise until they become neutrally buoyant. Because of atmospheric pressure they expand in volume and cool adiabatically (Lin, 1998). When the air parcels reach the lifting condensation level, vapor condenses and cloud droplets form.

Clouds that are not cold enough to be dominated by ice, also called warm clouds, rely on the collision and coalescence between cloud droplets. As cloud droplets grow within the cloud and fall toward Earth, they collide with smaller droplets and become larger. The descent and evaporation of raindrops below cloud base help drive downdrifts which promote the formation of new clouds and sustain existing clouds by causing the lifting of warm, moist air to the level of free convection (Lin, 1998).

The amount of precipitation received is affected by two important additional factors, wind and by topographical barriers. Wind affects the areal distribution of rain. Strong winds cause rain to be spread over a large area, while a slack wind minimizes the storm’s motion and therefore the rain becomes localized over a specific area. Geographical features such as mountains and landmasses, on the other hand, will experience decreased pre-
cipitation downwind. Leeward slopes and adjacent lowland are deficient in moisture, while windward mountain slopes will receive abundant precipitation (Lin, 1998).

2.1.3 Temperature

The Sun is the major player in the weather system on Earth. As Earth travels in an elliptical orbit around the Sun, the amount of solar energy received from the Sun changes depending on the distance between the two bodies. The change in Earth’s orientation affect the energy received in different regions at the same time. The Earth’s axis is tilted 23.5° with respect to the plane of its orbit around the Sun. As the Earth journeys around the Sun, the North Pole remains pointed in the same direction. This will cause the orientation of the Earth’s axis to the sun rays to keep changing. Therefore, regions located at different latitudes will receive varying amounts of solar energy, giving rise to seasons.

Temperature is controlled by the presence of clouds. Clouds are a barrier to solar radiation during the day, thus causing a drop in surface temperature. However, clouds also serve as barriers to infrared radiation and intercept much of the heat that will otherwise be lost from the surface at night. Clouds suppress wide fluctuations of temperature between day and night.

Temperature is affected by the type of surface. During the day, land tends to return the heat to the atmosphere, while the ocean stores it. An important unit of measure is the specific heat of a substance which gives the thermal units required to raise a unit mass of the substance to 1 degree Celsius. For example, a typical specific heat for land is 0.2 cal/g/deg, while the specific heat of water is 1.0 cal/g/deg. This means that it takes five times more heat energy to raise the temperature of water than that of land. Land will heat and cool faster than water. During the day, water is cooler than the land. At night this situation is
reversed, with land being cooler, and water warmer. If other meteorological factors were to be held constant, then these wide fluctuations of temperature (stored energy) in the atmosphere over the land will be the basis for the larger lightning activity over land than over water.

2.1.4 Convective Regimes

Rainfall and lightning relationships have been found to be specific to convective regimes and geographical location. In earlier studies, continents are found to have deep-cloud break-period convection with small storm fractional area of coverage, and high flash yield per kilogram of rain. Conversely, monsoonal convection is characterized by large storm fractional area of coverage, and low flash yield per kilogram of rain. The physical basis for these differences lies in the ice phase partitioning of storm condensate (Williams). Assuming that ice is causal to lightning, then the majority of rainfall in continental convection has experienced the solid phase of water earlier in its history at higher altitudes. For that reason, high flash rates are common in the break-period regime. On the other hand, Inter-Tropical Convergence Zone (ITCZ) oceanic convection in which only modest lifting of high mixing ratio boundary layer air is needed to initiate the coalescence process, only a small fraction of the rainfall ever appears in ice form.

Graupel formation in the mixed phase region aloft is also controlled by updraft speeds. Large updraft speeds are needed for liquid drops to populate the mixed phase region, which in turn lead to the separation of charges by ice particle collisions and gravitational motions. The more vigorous this charge separation process is, the larger the lightning activity. Large updraft speeds are caused by large CAPE (Convective Available Potential Energy), which is more prevalent over land than water (Williams et al., 1992). For this rea-
son, it has been common to refer to ‘break period’ convection as continental, and ‘monsoon’ convection as oceanic because of the prevalent nature of those regimes in those areas. However, recent observations carried out in the TRMM/LBA field program near Ji-Parana, Rondonia, Brazil proved that the monsoon regime was prevalent in January. The ITCZ over the South American Continent brought widespread cloudiness, infrequent lightning, and strong rainfall. This can be appreciated in the global map showing observations of TRMM radar reflectivity greater than 40 dBZ at 7km altitude for January 1998 in Figure 2.1.

![Global Map of Radar Reflectivity > 40dBZ at 7 km altitude](image)

**Figure 2.1: Global Map of Radar Reflectivity > 40dBZ at 7 km altitude**

Based on numerous ground based (Williams, 1996) radar observations, lightning activity is strongly correlated with the profiles of radar reflectivity. Prototypical reflectivity profiles can be used to categorize convective regimes. A set of six prototypical profiles are sketched in Figure 2.2.
Figure 2.2: Prototypical Reflectivity Profiles
(a) Stratiform (b) Warm Rain Cloud (c) Midlatitude Thunderstorm (d) Tropical Monsoon
(e) Tropical Continental (d) Midlatitude Supercell
Stratiform precipitation with radar bright band convection (Figure 2.2a), characterizes the dissipating stages of active convection, the trailing regions of squall lines, and the widespread convection of the ITCZ monsoon. These storms can generate sporadic lightning, or no lightning at all. The way to determine whether they produce lightning, is by looking at the amplitude of the reflectivity profile within the region where ice is prevalent above the of 0°C isotherm (~4 km).

Warm rain clouds (Figure 2.2b) have tops no higher than the 0°C isotherm (~4 km). Some evidence suggest that clouds with no ice particles do not have lightning, though this issue remains controversial (E. Williams, personal communication, 1999). Warm clouds just reach the mixed phase region and are not expected to produce lightning. The TRMM/LIS data may provide an additional test of the validity of whether warm clouds occasionally produce lightning.

Midlatitude or subtropical thunderstorm convection (Figure 2.2c) is limited in height because of the lower tropopause. However, the storms at higher latitudes may be able to produce stronger reflectivity profiles in the mixed phase region (4 km - 7 km). These storms usually produce lightning rates between 1-10 flashes per minute.

Tropical monsoon or oceanic clouds (Figure 2.2d) can reach the tropopause, but they develop with modest CAPE and small vertical draft speeds (10 - 15 m/s). The figure shows how the reflectivity declines sharply above the 0°C isotherm and rarely exceeds 30 dBZ in this region. Near the surface reflectivity may reach 40 dBZ values.

Tropical continental or break period convection (Figure 2.2e) is characterized by strong reflectivity profiles in the ice region, as well as strong lightning activity. The areal fraction of these storms, often are only a few percent. It is important to note, that fractional
area is not a robust indicator of regime by itself. The cloud tops, however, can reach up to 16 km -18 km in height, and occasionally overshoot the tropopause.

Supercell convection (Figure 2.2f) is a severe storm containing hail and tornadoes. They produce the most active lightning on the planet and exhibit the most dramatic Z max profiles above the ice region (Williams, 1996). Such storms are however not prevalent in the tropics.

The vertical resolution offered by the TRMM 13.8 GHz Precipitation Radar (PR) allows the possibility to define the above reflectivity profiles which can be related to observed lightning activity using the Lightning Imaging Sensor (LIS) on board the same satellite. This research will focus on two convective regimes, mainly monsoonal and break period. The following chapter will introduce the space-based observation instruments used to gather the lightning and precipitation data used for the study.
Chapter 3

Space-Based Instrumentation

The Tropical Rainfall Measuring Mission (TRMM) is a joint mission between the National Aeronautics and Space Administration (NASA) of the United States and the National Space Development Agency (NASDA) of Japan (Kummerow et al., 1998). The TRMM satellite, launched in November 1997, is the space-based observation system used to measure rainfall and energy exchange of tropical and subtropical regions of the world. The satellite is designed for a 350km circular orbit with a 35° inclination angle to the equator. It orbits the Earth 16 times in a day, with an orbital period equal to 90 minutes. Its low altitude allows the sensors to provide high resolution (4km) images with a total viewing area of nearly 215km. Five instruments on board the TRMM satellite simultaneously collect the data. These are the Precipitation Radar (PR), the TRMM Microwave Imager (TMI), the Visible Infrared Scanner (VIRS), the Clouds’ and Earth’s Radiant Energy System (CERES) and the Lightning Imaging Sensor ( LIS). Figure 3.1 shows a schematic view of the scan geometries of the three TRMM primary rainfall sensors: TMI, PR, and VIRS.
Figure 3.1: Schematic View of the Scan Geometry of TMI, PR, and VIRS Rainfall Sensors.

The PR radar obtains quantitative rainfall measurements over land and ocean, and provides the three-dimensional structure of rainfall. The TMI is a nine-channel microwave radiometer that gathers information on content, intensity, and distribution of precipitation. The VIRS is a five-channel imaging spectroradiometer that provides coverage on type, top temperature, and other aspects of a cloud. The CERES is an infrared sensor used to measure radiation emitted and reflected by Earth. Finally, LIS is responsible for recording lightning occurrences optically.

The focus of this thesis is to quantify the relationship between flash activity and rainfall. The datasets that will be used to make the analysis are collected by the LIS and PR radar. In order to understand the processing of the data, it is necessary to know the geome-
try of the instruments used to gather the information. The next sections will describe the specifics of the LIS and PR.

3.1 Precipitation Radar (PR)

The Precipitation Radar (PR) operates at 13.8 GHz with horizontal polarization and records energy reflected from atmospheric and surface targets. It obtains three dimensional information on rainfall over both land and ocean, including parameters such as radar reflectivity and storm cloud heights.

Observations made from above storms with this short-wavelength radar are less affected than ground-observations in liquid phase precipitation. Signal attenuation is substantially stronger in liquid than in ice. The portion of vertical reflectivity profiles at altitudes above the melting level are the most important and reliable, as this is the unattenuated end of the cloud system, as shown in all prototypical reflectivity profiles in Figure 2.2.

The major parameters of the TRMM PR are listed below in Table 3.1:

<table>
<thead>
<tr>
<th>Item</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>13.796, 13.802 GHz</td>
</tr>
<tr>
<td>Wavelength</td>
<td>2.2 cm</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>$\leq -0.7$ mm/hr (S/N pulse $\approx 0$ dB)</td>
</tr>
<tr>
<td>Swath Width</td>
<td>215 km</td>
</tr>
<tr>
<td>Observable Range</td>
<td>Surface to 15 km altitude</td>
</tr>
<tr>
<td>Horizontal Resolution</td>
<td>4.3 km (nadir)</td>
</tr>
<tr>
<td>Vertical Resolution</td>
<td>0.25 km (nadir)</td>
</tr>
</tbody>
</table>
Table 3.1: Major parameters of TRMM PR

<table>
<thead>
<tr>
<th>Item</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna:</td>
<td>128-element WG Planar array</td>
</tr>
<tr>
<td>Type</td>
<td>0.71° x 0.71°</td>
</tr>
<tr>
<td>Beam width</td>
<td>2.0 m x 2.0 m</td>
</tr>
<tr>
<td>Aperture</td>
<td>±17° (Cross track scan)</td>
</tr>
<tr>
<td>Scan Angle</td>
<td></td>
</tr>
<tr>
<td>Transmitter/Receiver:</td>
<td>SSGA &amp; LNA (128 channels)</td>
</tr>
<tr>
<td>Type</td>
<td>≥ 500W (at antenna input)</td>
</tr>
<tr>
<td>Peak power</td>
<td>1.6μs x 2 ch. (Transmitted pulse)</td>
</tr>
<tr>
<td>Pulse width</td>
<td>2776 Hz</td>
</tr>
<tr>
<td>PRF</td>
<td>70 dB</td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>93.2 kbps</td>
</tr>
</tbody>
</table>

3.1.1 PR Scan Geometry

The radar scans from right to left looking in the +x direction across the ground track of the satellite. Figure 3.2 shows this clearly. It scans every 0.6 seconds with a swath width of about 215 km. Each scan contains 49 ray samples over an angular sector of 34° across the swath. This means that the nadir ray is numbered 25, and 17° to the right (from the satellite’s perspective) are rays numbered 1 through 24, each separated by 0.7°, and 17° to the satellite’s left are numbered 26 through 49.
For a given ray, the satellite records samples at a fixed distance from the satellite every 125 m along the ray. The number of samples read, and the initial reading distance is different for each ray. The PR data contains variables that describe both the number of samples in the ray and the initial distance at which the ray began sampling data. The satellite saves the data in three samples. These are the normal sample data, the rain echo oversample data, and the surface oversample data. This study uses only the normal sample data which are saved in every other data point in the vertical. Thus the normal sample has a spacing of 250 m along the ray. The horizontal resolution of the radar is 4 km. For documenting single storms, the vertical resolution of 250 m is excellent, however the 4 km horizontal resolution is somewhat marginal, given the fact that the reflectivity cores in individual cumulonimbus clouds are less than 4 km in diameter. See Figure 3.3 for a schematic of the normal sample spacing along a ray.
Figure 3.3: Normal Sample Data Schematic

All data are saved in what are called bins. Bin number 1 is located roughly at 327 km from the satellite, and increments by one every 125 m down to the maximum bin 400 at 377 km from the satellite. The exact value for the starting bin distance, the distance from the bin from the satellite, is given as the variable, RayStart, in the data. Due to the noncircular orbit of the satellite, its distance from Earth is also given as a variable in SpaceCraftRange, in the data set. The number of normal samples in each ray differs from ray to ray. The nadir ray contains 140 normal sample bins, because this ray keeps extra data that is known as the “mirror”. This is extra data saved at the end of the ray and contains energy reflected not once from the target, but three times (ground to target to ground). Rays, other than nadir, sample “below” the surface in order to clearly identify the location of the Earth’s surface. Due to the curvature of the Earth, the bin number that identifies the Earth’s surface is different for each ray. Therefore, the number of normal sample bins is different for every ray. This information is saved in a variable called, RaySize, in the data. Whenever reflectivity data are not found because of a transmission, calibration, or other problem with the PR radar, the onboard processor records it as a special number -32700. Also,
because ray sizes differ, the elements after the end of each ray are filled with a MISSING value of -32767 as shown in Figure 3.3.

3.2 Lightning Imaging Sensor (LIS)

The Lightning Imaging Sensor (LIS) is an instrument designed to study mesoscale phenomena such as storm convection, dynamics, and microphysics. These studies will be related to global rates and amounts and distribution of convective precipitation, as well as to the release and transport of latent heat, which are influenced by global scale processes. LIS, alongside the PR, adds the ability to uniquely identify and quantify convective regions of storm systems by generating rain volume and lightning flash rate proportionalities. LIS’s lightning detection over oceans and tropical regions is essential in identifying meteorological regimes. That is the reason why having a lightning sensor and precipitation radar on the same satellite makes TRMM a breakthrough. Spaced-based observations by LIS will clearly delineate regions of deep convection hidden within stratiform cloud systems (Lin, 1998).

3.2.1 LIS Geometry

The LIS instrument has been on a 35° tropical orbit since November 1997. LIS is a staring scanner, comprised of a 128x128 charge coupled device (CCD) pixel array, with individual pixel resolution between 3-6 km across. In other words, LIS is able to detect lightning with a storm scale resolution of 3-6 km over a region of 550x550 km² (Boccippio, 1998). The LIS sensor does not rotate and the field of view (FOV) is sufficient to observe a point on the Earth's surface for 90 seconds. Each LIS square, or 550x550 km² area, is divided into 0.5° Earth locations called viewtime grids. These will in turn contain
the view time each of them was in the FOV of the LIS imager. Figure 3.4 depicts the scan geometry of the LIS imager.

![Diagram of LIS imager scan geometry](image)

**Figure 3.4: Scan Geometry of LIS imager**

The lightning sensor uses a wide-field-of-view expanded optic lens with a narrow-band filter in conjunction with a high speed charge-coupled device detection array. A real-time event processor (RTEP), inside the electronics unit, is used to determine when a lightning flash occurs, even in the presence of bright sunlit spots. Weak lightning signals that occur during the day are difficult to detect because of background illumination. The RTEP removes this background signals, thus enabling the system to detect weak lightning with a 90% detection efficiency.
Chapter 4

Software Tools

4.1 Computer Tools

The entire data processing was done on a Gateway 2000 300 MHz personal computer running on Linux OS. The total hard disk space available was 6 GBytes with 98 MB of SRAM. The software tool used for data analysis and manipulation was the Interactive Data Language (IDL) supported by Research Systems. It is an array oriented environment for the analysis and visualization of data. IDL allows for large datasets to be handled easily and rapidly, with built in procedures to map, plot, and contour the data. The least square line fits and correlation coefficients of the scatter plots were done using MATLAB.

4.2 Data Processing

Two data sets are used for this study that are collected by the Precipitation Radar and the Lightning Imaging Sensor on board the TRMM satellite: PR and LIS data.

The PR dataset is obtained from the Tropical Rainfall Measuring Mission Science Data and Information Systems (TSDIS) at the NASA Goddard Space Flight Center (GSFC). The data product is radar reflectivity and is called 1C21, or reflectivity. It contains information such as cloud height and the corresponding reflectivity profiles in dBZ over water and land. dBZ is $10 \log_{10}Z$, where $Z$ is the reflectivity factor. For dilutely distributed spherical scatters whose diameters are small compared to a radar wavelength, $Z$ is the summation of the sixth powers of equivalent sphere diameters per unit volume of the surveillance volume, in mm$^6$/m$^3$ (Lin, 1998). The 1C21 data are not corrected for microwave attenuation.

The LIS dataset is available at the Global Hydrology and Resource Center (GHRC) at the NASA Marshall Space Flight Center, which is part of the Global Hydrology and Cli-
mate Center. The instrument records the time of occurrence of a lightning event, measures the radiant energy, and estimates the location. LIS contributes significantly to several TRMM mission objectives by providing a global lightning and thunderstorm climatology.

The PR and LIS data files are distributed in Hierarchical Data Format (HDF). An HDF structure is a flexible, self-describing data format, which allows collections of different data (i.e. ‘type’: integer, floating point, etc. and ‘order’: point, vector, array), to be stored together in the same data file (Boccippio, 1998). HDF is a scientific data management tool that until quite recently required low-level programming to access the data. For this reason GHCC and TSDIS offer software packages that allow for easier HDF data access. TSDIS offers the TSDIS Science Algorithm Toolkit which is used to process HDF data (1C21 in this case) to ASCII format using C language. GHCC has a software package, LIS/OTD Software Suite, that allows for simple LIS data access by including a collection of high level programming libraries in C++ and IDL.

4.2.1 PR Data

One week of 1C21 data comes in compressed HDF format in 2GB tapes. The satellite orbital speed is about 6111 m/s, and one day of data contains approximately 16 complete orbits of the Earth. After the tape in fully decompressed and unnecessary data are filtered it takes up 600 MB of memory space. In order to read the tapes and convert them from HDF to ASCII format, the program PR_DATA.C, shown in Appendix A, was written.

PR_DATA.C generates two files. The names of the files have the following formats: <date>.rc and <date>.pr. The first file contains only rain certain data (.rc). Table 4.1 shows the data recorded when the ray is categorized as ‘ray certain’ and ‘rain uncertain’.

Table 4.1: Data Saved in .rc File for Rain Certain

<table>
<thead>
<tr>
<th>RAIN CERTAIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scan Number</td>
</tr>
<tr>
<td>Scan Quality</td>
</tr>
</tbody>
</table>
When the ray is categorized as 'rain certain', it records the scan number, scan quality, pr on/off flag, orbit number, land/ocean flag, scan time in UTC hours, 37 samples of dBZ data along the ray (from 1 km to 10 km in height seemed to be a trade-off between computer memory space and good convective clouds that reached the ice region) with a sample separation of 250 m, ray number, latitude, and longitude. However, when the ray is categorized as 'rain uncertain', it is common to see the next consecutive rays and scans to be 'rain uncertain' as well. Therefore, the first number recorded is -9999 to flag the line of data as 'uncertain'. It then records the start and end scan numbers that were continuously found to be 'rain uncertain'. It then saves the orbit number, and finally it records the number of continuous scans flagged as 'rain uncertain' (i.e. ['Rain Uncertain’ Start Scan Number] - ['Rain Uncertain’ End Scan Number] + 1).

In order to generate CAPPI (Constant Altitude Plan Position Indicator) plots, the altitude of the normal reflectivity samples (dBZ) from the Earth needs to be calculated and
recorded accordingly in the .rc file. Figure 4.1 shows the trigonometric procedure used to calculate the height of the dBZ normal sample.

![Diagram](image)

\[ a = \text{SpaceCraft Range} \]
\[ b = \text{dBZ Distance from Satellite} \]
\[ H = (a-b) \times \cos \theta \]

**Figure 4.1: Height calculation of dBZ sample**

As seen in figure 4.1, the height, \( H \), of a dBZ point, \( P \), is calculated by using three variables given in the 1C21 data. SpaceCraft Range is the distance between the spacecraft and the center of the beam’s footprint on the Earth ellipsoid. The dBZ distance from the satellite is calculated by using two facts. First, the distance of bin number 1 from the satellite is approximately 377 km (see Sec. 3.1.1), and the distance between bins is 125 m. Therefore, by knowing the bin number of the dBZ datum you are looking at, then the dBZ distance from the satellites is: \( D = (\text{Bin#} - 1) \times 125 \text{ m} + (\text{Bin#1 distance from satellite} = 377 \text{ km}) \). The last variable needed is the angle of elevation of the ray from Earth. 1C21 data has the variable scLocalZenith which is the angle, \( \theta \), in degrees between the zenith and the beam’s center line (the zenith at the intersection between the ray and the Earth’s ellipsoid is used). This zenith angle, \( \theta \), is shown in Figure 4.1. The pieces needed to write the equation for the height of a normal sample dBZ point are in place. This is shown in equation 4.1.

\[ H = (\text{SpaceCraftRange} - \text{dBZDistanceFromSatellite}) \times \cos \theta \]  

(4.1)
The second file generated by PR_DATA.C is called <date>.pr. This file contains the necessary data to generate what is called a PR SQUARE. A PR SQUARE is a collection of 49 continuous scans, where every scan contains 49 rays. Figure 4.2 shows a schematic of a PR SQUARE.

![PR SQUARE Schematic](image)

**Figure 4.2: PR SQUARE Schematic**

The satellite moves in the +x direction and scans from right to left in the +y direction. Each row in the PR SQUARE corresponds to a scan number starting from 1 to 49. Each scan contains 49 rays, from ray number 0 to 48. The nadir, or center square, corresponds to the combination of scan number 25 and ray number 24. The .pr file contains only the necessary data to generate these PR SQUARES. Table 4.2 shows the information saved only for scan numbers 1, 24, and 49 and ray numbers 0, 25, and 48, which give the corners locations of the PR square:
Table 4.3: Information Contained in .pr File

<table>
<thead>
<tr>
<th>INFORMATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scan Number</td>
</tr>
<tr>
<td>Ray Latitude</td>
</tr>
<tr>
<td>Ray Longitude</td>
</tr>
<tr>
<td>Ray Number</td>
</tr>
<tr>
<td>Orbit Number</td>
</tr>
</tbody>
</table>

4.2.2 LIS Data

One month of lightning data comes in 2 GB tapes in HDF tar and compressed format. The files have the following name: TRMM_LIS_SC.04.0_<YEAR>,<DAY>.hdf.tar.Z. An entire month worth of data could be kept on tar tape (i.e., tared) and compressed in 750 MB of memory space. In order to read the data, GHCC already has a LIS/OTD package with IDL procedures that allow for an entire orbit of flashes to be read. Due to the lack of space, the data are kept compressed and tared. When lightning information of a specific orbit needs to be read, the data for that day is untared and uncompressed and the IDL procedure: (read_orbit, <orbit file name>, orbit, /quiet, /no_areas, /no_groups, /no_events) is run in order to read the flash information. Each orbit number in a LIS file corresponds to the same orbit number in the PR 1C21 file. The LIS files contain valuable information for generating flash rate estimates such as flash count of an orbit, lat/lon location of every flash, and an effective observation time for each viewtime grid (i.e. 0.5 °cells, see Section 3.2.1) which accounts for partial observation of a LIS square.

Every scan of the LIS imager is co-located with the nadir point of the precipitation radar. Figure 4.3 shows a picture of the larger LIS square superimposed on the smaller PR square. The single 4kmx4km nadir pixel is marked with an ‘x’, exaggerated in size.
4.3 Calculations of Physical Quantities

In order to determine the accumulated rainfall using lightning rate estimates, as well as for comparisons of the monsoonal/break period regimes using rain and flash information, three important quantities are needed: lightning rate [flashes/min], mass flux [kg/sec], and fractional area [f]. Studies have shown that unstable thunderstorms have a small fractional area of coverage and a large flash count. Monsoonal convection, on the other hand, which often covers a large fractional area, shows a small flash rate (Williams et al., 1992; Rutledge et al., 1992). The following three subsections describe how variables are to be calculated using 1C21 and LIS data.

4.3.1 Lightning Rate

The flash rate needs to be compared to the mass flux and fractional area within a PR square to get valuable information in the possibility of distinguishing regimes. The LIS square is approximately three times larger than a PR square (see Figure 4.3), therefore not all the flashes within a LIS square are relevant for direct comparison. In order to get the correct flashes for the comparisons, each PR square was divided with four intersecting lines (see Figure 4.4). The flashes bounded by these lines were included in the count.
Figure 4.4: PR Squares to find the LIS flashes
Figure 4.4 shows the four lines that form the PR square and the selection mechanism of the flashes. Each line is created by using the latitude and longitude data of the corners of the square to define the boundary lines:

\[ y = mx + b, \text{ where } m = \text{slope and } b = \text{y-intercept.} \]  

(4.2)

The slope, \( m \), is found by using the slope equation:

\[ m = \frac{y_2 - y_1}{x_2 - x_1}, \text{ where longitude } \rightarrow x, \text{ and latitude } \rightarrow y \]  

(4.3)

The y-intercept is then found by using the lat/lon information of a corner of the PR square for which the line equation is being calculated, and use it as input to Equation 4.2, and solving for b. Line 1 uses the lat/lon data of the corner squares (Scan 1, Ray 0) and (Scan 1, Ray 48), line 2 uses (Scan 1, Ray 48) and (Scan 49, Ray 48), line 3 uses (Scan 49, Ray 48) and (Scan 49, Ray 0), and line 4 uses (Scan 49, Ray 0) and (Scan 1, Ray 0). Depending on the direction of the satellite, the PR squares and the lines formed will have different slopes. When the slope of the PR Square is positive (i.e. satellite is a positive slope), the flashes that are included are the ones above Line 1 and are also below Line 2, below Line 3, and above Line 4 as shown in Figure 4.4a. When the slope of the PR square in negative (see Figure 4.4b), the flashes must be below Line 1, below Line2, above Line 3, and above Line 4. In other words, the latitude and longitude information of the flashes that solve the following inequalities correctly are considered:
Positive PR square Slope
\[ y \rightarrow \text{flash latitude}; \ x \rightarrow \text{flash longitude} \]
Line1 and Line4: \( y \geq mx + b \)
Line2 and Line3: \( y \leq mx + b \)

Negative PR square Slope
\[ y \rightarrow \text{flash latitude}; \ x \rightarrow \text{flash longitude} \]
Line2 and Line4: \( y \geq mx + b \)
Line1 and Line3: \( y \leq mx + b \)

This way, only flashes found within the PR square are used to calculate the flash rate.

The equation to calculate the flash rate is:

\[
\text{Flash Rate} = \frac{\text{Total number of flashes in an area}}{\text{Total Viewtime for that area}}
\]

The one critical aspect in the computation of lightning rate using LIS data is the viewtime of the area for which the flash rate will be computed. Every time the sensor begins seeing a 0.5° x 0.5° gridded ground location, a new "viewtime granule" is opened; when the sensor stops seeing the location, the granule is closed. Each granule contains the start time, end time, total duration viewed, and an "effective duration", which is the total duration scaled to account for partial grid box viewing. The effective observation times are stored in the variable `orbit.point.viewtime[*].effective_obs` from the LIS/OTD IDL procedures. These are the times that account for partial grazing near the edges of the array, and are the ones to be used to calculate flash rate. The viewtimes also contain latitude and longitude information about the center of each 0.5° x 0.5° viewtime granule in the variable `orbit.point.viewtime[*].location[*]`, where location[0] is latitude and location[1] is longitude. By knowing the latitude and longitude of each viewtime granule, then the same process is used in selecting the viewtimes to be used in the calculation of flash rate. Only those viewtime granules inside the PR square are considered. Each viewtime granule sees a ground location for about 90 seconds. Therefore, to get a good estimate for the viewtime
of a PR square, those viewtime granules that are inside the PR square are added up and
divided by the number of view time granules inside the PR square as described by the fol-
lowing equation:

\[
\text{viewtime} = \frac{\sum \text{viewtimes}}{\text{number of viewtimes granules inside PR square}}
\] (4.7)

4.3.2 Mass Flux

Mass flux is the amount of rainfall per second falling through an arbitrary area. The
mass flux calculation is done for every PR square. In order to avoid the use of yet another
TRMM dataset, (specifically the dataset 2A25 which contains information on rain rate in
[mm/hr] for every scan), it was decided that 1C21 data gave the reflectivity information
necessary to generate rain rate [mm/hr] information and from this quantity a direct trans-
formation into mass flux for a PR square [kg/sec] was carried out.

The 2A25 data set contains a flag called 'Rain Certain' as in 1C21. It also contains a
variable called CorrectZFactor that corrects data for attenuation, clutter, and non-uniform
beam filling. This gives more of a spread of the data when compared to 1C21, as this cor-
rection is non-linear. The attenuation correction is more evident at lower altitudes owing to
the greater path length of precipitation. Hence, the approximations used in the thesis that
neglect attenuation are not as accurate as at higher levels. Figure 4.5 shows 2A25 vs. 1C21
precipitation mass flux for a height of 7 km for January 1st, 1998. Most of the data does
fall near the 45° line, and at high dBZ the data closes down on the line because of the
attenuation corrections done to produce 2A25. This comparison gives credibility to the
1C21 precipitation mass flux, especially at high altitudes (mixed phase and ice regions)
where less attenuation is present, but this also puts a word of caution on the low level
results, which have not been corrected for attenuation
Figure 4.5: 1C21 vs. 2A25 Precipitation Mass Flux Comparison at 7 km for January 1st, 1998

Since we are concerned only with PR squares that contain lightning, in the majority of cases at least some clouds within the PR square were convective. Therefore, by using Z-R relationships for convective clouds, 1C21 dBZ data could be used to infer the precipitation rate. Dr. Toshio Iguchi from the Communication Research Laboratory of the Kashima Space Research Center from Japan, provided the power law Z-R relationships, effectively:

$$ R = \alpha Z^\beta $$

(4.8)

In this case, $R$ is the rain rate, $\alpha$ and $\beta$ are empirical parameters that are a function of the height at which the cloud reflectivity information is taken, and radar reflectivity $Z$ is $(\text{dBZ}/10)^{10}$ in units of $\text{mm}^6/\text{m}^3$. Table 4.4 shows coefficients for Z-R relations for convective systems in the 2A25 dataset using temperature dependence:
Table 4.4: Coefficients for Z-R Relations

<table>
<thead>
<tr>
<th>Temperature</th>
<th>1/α</th>
<th>1/β</th>
</tr>
</thead>
<tbody>
<tr>
<td>rain 30°C</td>
<td>140.6</td>
<td>1.557</td>
</tr>
<tr>
<td>rain 20°C</td>
<td>145.6</td>
<td>1.537</td>
</tr>
<tr>
<td>rain 10°C</td>
<td>150.3</td>
<td>1.518</td>
</tr>
<tr>
<td>rain 0°C</td>
<td>154.7</td>
<td>1.498</td>
</tr>
</tbody>
</table>

For all heights with temperatures less than 0°C (4 km and higher), \( \alpha = \frac{1}{154.7} \) and \( \beta = \frac{1}{1.498} \). As for heights below 4 km the Z-R parameters become, \( \alpha = \frac{1}{145.6} \) and \( \beta = \frac{1}{1.537} \).

In order to generate the mass flux of a PR square, each dBZ value in the PR square is converted to Z using the relation:

\[
Z = \left( \frac{\text{dBZ}}{10} \right)^{10}
\]  

(4.9)

Then, the Z-R relationship is applied where \( \alpha \) and \( \beta \) are functions of height:

\[
R = \alpha Z^\beta
\]  

(4.10)

This R is in [mm/hr]. In order to get mass flux in [kg/sec] for a 4 km x 4 km dBZ pixel within the larger PR square, the relation is as follows:

\[
\text{Mass Flux for dBz cell [kg/sec]} = R[\text{mm/hr}] \times \frac{1 \text{ hour}}{3600 \text{ sec}} \times \frac{10^{-3} \text{ meters}}{1 \text{ mm}} \times \frac{10^3 \text{ kg}}{\text{m}^3} \times 16 \text{km}^2
\]

(4.11)

This process is repeated for all dBZ values inside the PR square. At the end, the mass flux for the entire PR square becomes:

\[
\text{Mass Flux for PR square [kg/sec]} = \sum_{i=0}^{\# \text{ dBZ Pixels in PR square}} \text{Mass Flux}_i
\]

(4.12)
4.3.3 Rainfall Fractional Area

Fractional area is the number of 4 km x 4 km pixels in the PR square that were flagged as 'rain certain' and contain a minimum reflectivity value of 17 dBZ. The calculation of rainfall fractional area is as simple as:

\[
\text{Rainfall Fractional Area} = \frac{\text{Number of 4km by 4km PR pixels with rain}}{\text{Total 4km x 4km pixels in PR square}} \quad (4.13)
\]

Equation 4.13 says that the fractional precipitating area of a PR square is the number of pixels in a PR square with rain divided by the total number of pixels in a PR square, which is usually 2041 (49 Rays x 49 Scans). However, the PR radar sometimes is turned off for maintenance or it has calibration problems. During this time, there will be no scan information. This study takes this down time into account when calculating the rainfall fractional area for the PR square. The rainfall fractional area for each PR square also contains an effective PR ON TIME variable, which is the percentage of scans that were available for the calculation of fractional area.
Chapter 5

Data Analysis

5.1 Global Observations

Accumulated global rainfall is of great meteorological importance, but it is difficult to measure owing to its extreme variability in space and time. This analysis is geared towards finding ways to measure the precipitation mass given the information about the lightning activity of the convective cloud, because lightning counts are easier and inexpensive to measure.

Precipitation and lightning data for January 1998 were selected to perform the analysis because field experiments were to be conducted in Brazil in the same month in 1999. The analysis tests included global observations of the behavior of the mass of precipitation per flash around the globe for selected heights of 2 km, 4 km, 7 km and 10 km. These heights were chosen because they incorporated all three regions (surface, mixed phase, and ice). One orbit consists of about 186 PR squares, with 15 or 16 orbits per day. Figure 5.1 shows orbit number 5 of the TRMM satellite for January 1, 1998 alongside the zoom in of PR square number 16 for a 7 km cappi located in eastern Brazil (this is shown with an arrow in Figure 5.1a. The red dots in Figure 5.1a represent areas where lightning flashes occur. The zoom in version of PR square 16 shows 3-4 convective cells producing high flash rate. This is the continental break-period regime, having small precipitation fractional area per convective cell system, and a high precipitation mass. This PR square contains:

- Fractional Area = .41
- Precipitation Mass Flux = 1.64 x 10^7 kg/sec
- Flash Rate = 2907 flashes/minute

The latter flash rate is among the largest values documented for January 1999.
(a) TRMM satellite orbit number 5 for January 1, 1998.

(b) Zoom in of PR square number 16.

Figure 5.1: TRMM Satellites Orbit 5 January 1, 1998 and PR Square Number 16
It has been suggested in Figure 5.2 of (Williams, 1996), that if ice particles become rainfall and the lightning is the result of gravitational potential energy of these particles, then some interdependence must exist. These ideas are trusted further with TRMM observations in Figure 5.2. Figures 5.2 (a-d) show the global maps of maximum radar reflectivity (dBZ) for every 1° by 1° latitude/longitude Earth location near the surface (2 km), in the liquid water region (4 km), in the mixed phase region (7 km), and in the ice region (10 km), respectively. Figure 5.2d includes the maximum flash rate [flashes/min] in every 1° by 1° latitude/longitude location for the entire month of January 1998.

It should be noted that high mountainous regions, like the Himalaya and the Andes, or even aircraft targets inject noise into the reflectivity data at low altitudes such as 2 and 4 km. Both Figures 5.2 (a,b), corresponding to 2 km and 4 km, show a distinct high reflectivity profile, shown in purple, along the western coast of South America where the Andes are located. The Himalayan mountains in Asia, add noise to the reflectivity data from 2 km up to 7 km as can be observed in purple on Figures 5.2 (a-c). This added noise will present itself later on during Precipitation Mass Flux versus Fractional Area plots in Chapter 6, as an offset band of values that are geophysically impossible as precipitation.

Maximum reflectivity figures (Figures 5.2 (a-d)) show that the highest reflectivity values, at all heights, are found over land. However, large reflectivity values along the equatorial belt in the ocean are due in part to the high meridional temperature gradient. On the other hand, the maps show ocean with typical ITCZ convection, where only a modest lifting of high mixing ratio boundary layer air is needed to initiate the coalescence process, and therefore only a small fraction of raindrops ever make it to the mixed phase region and appear in solid form. This is appreciated by looking at the decreasing number of maximum reflectivity values when going from the near surface (2 km) to the mixed phase (7 km) and to the ice region (10 km). At 7 km and 10 km (Figure 5.2 (c,d)) the highest con-
centration of maximum reflectivity points cluster on land regions, especially in South America and South Africa.

Figure 5.2c shows the concentration of peak flash rates [flashes/minute] occurring over land. This is consistent with the previous four plots of maximum reflectivity, where most clouds that reach the 10 km height are found over land (Figure 5.2d). This is consistent with the previous comment that either more supercooled raindrops or more graupel particles are carried by high updrafts speeds within the mixed phase region. As discussed in Chapter 2, deep oceanic or monsoonal convection is characterized by modest CAPE and vertical speeds. The radar reflectivity declines strongly above the 0° isotherm, and as shown in Figure 5.2c, at the 7 km height, the maximum reflectivity rarely exceed 30 dBZ. Land convection exhibits higher updraft speeds, and this is shown in the maximum lightning rate plot with points clustering on the continents. South America shows the highest local peak flash rate compared to Africa and the Maritime Continents, but this peak flash rate is not found in the near equatorial tropics. It should also be noted, that there are larger reflectivity values at 4 km than at 2 km (Figures 5.2(a and b)) due to the uncorrected attenuation of the 1C21 dataset, which is higher at lower altitudes.
Figure 5.2 (a) Maximum Radar Reflectivity at 2 km Altitude

Figure 5.2 (b) Maximum Radar Reflectivity at 4 km Altitude

Figure 5.2 (c) Maximum Radar Reflectivity at 7 km Altitude
Figure 5.2 (d) Maximum Radar Reflectivity at 10 km Altitude

Figure 5.2 (e) Maximum Flash Rate [flashes/min] for January 1998

**Figure 5.2:** Maximum radar reflectivity (dBZ) at (a) 2 km (b) 4 km (c) 7 km (d) 10 km (e) Maximum Flash Rate for January 1998

An important calculation is the mass of precipitation per flash. This variable [kg/flash] is useful for determining whether a region on Earth has a prevalent monsoonal regime (large accumulated rainfall and small number of flashes) or break period regime (small accumulated rainfall and high number of flash). Figure 5.3 shows the [kg/flash] figures for heights of 2 km, 4 km, 7 km, and 10 km respectively.
Figure 5.3 shows that the lowest kg/flash (red color) values are located in the South American extratropical baroclinic zone, in which high vertical updraft speeds are available to generate deep convective cells of storms. This type of storm generates a large number of flashes. They tend to cover small areas, but are deeply convective and can reach heights up to 17 km (See Figure 2.2e). Proper depiction of the vertical reflectivity profile in these convective cells with the PR radar does become a problem, as they are often less than 4 km in width, less than the PR horizontal resolution. Also, these storms are not only difficult to depict quantitatively, but they are only grazed by the radar for a period of at most 90 seconds. The zone of Ji-Parana, Brazil, where the recent radar experiments were held, appears in Figure 5.3 in the northwestern part of Brazil with kg/flash on the ‘blue’ end of the spectrum. This means that it had a monsoon-like kg/flash relation, meaning that there are more stratiform type clouds formed which give lower flash yield than deep convective clouds. The color difference between light blue and red, the extreme of the range of values, is two orders of magnitude difference. This is consistent with my personal experience in Ji-Parana during January 1999, one year later.

Figure 5.3 is the direct result of combining Figures 5.2 (a-d) with Figure 5.2e, after converting radar reflectivity to a precipitation mass flux, as explained in Chapter 4, Section 3.3, and comparing them on a PR square basis with the location and view time of the flashes.

The maps of mass precipitation per flash show regional differences that are indicative of different regimes. South America generates greater lightning per kg of precipitation (color concentrated at the red side of the color spectrum) than the central tropics. This is also apparent in South Africa. This will mean that there is a latitudinal dependence of regimes within individual land areas. The scatter plots of precipitation mass flux versus lightning rate in Chapter 5, Section 2, will not exploit this latitudinal dependence because
the plots take into consideration all land on Earth, rather than separate regions of land on Earth.

**Mass Precipitation Per Flash**

<table>
<thead>
<tr>
<th>3x10^4</th>
<th>10^5</th>
<th>3x10^5</th>
<th>10^6</th>
<th>3x10^6</th>
<th>10^7</th>
<th>&gt;10^8</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^4</td>
<td>3x10^4</td>
<td>10^5</td>
<td>3x10^5</td>
<td>10^6</td>
<td>3x10^6</td>
<td>10^7</td>
</tr>
</tbody>
</table>

Figure 5.3 (a) Mass of Precipitation (kg) per Flash at 2 km

Figure 5.3 (b) Mass of Precipitation (kg) per Flash at 4 km
Figure 5.3 (c) Mass of Precipitation (kg) per Flash at 7 km

**Mass Precipitation Per Flash**

<table>
<thead>
<tr>
<th>3x10^6</th>
<th>10^7</th>
<th>3x10^7</th>
<th>10^8</th>
<th>3x10^8</th>
<th>10^9</th>
<th>&gt;10^10</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^6</td>
<td>3x10^6</td>
<td>10^7</td>
<td>3x10^7</td>
<td>10^8</td>
<td>3x10^8</td>
<td>10^9</td>
</tr>
</tbody>
</table>

Figure 5.3 (d) Mass Precipitation (kg) per Flash at 10 km

**Figure 5.3:** Mass Precipitation per flash [kg/flash] at selected heights of (a) 4km (b) 7km (c) 10km
A useful construct for looking at the percentage of PR squares that contained rain and lightning is the Venn diagram. Figure 5.4 shows the Venn diagrams for the selected heights of 2 km, 4 km, 7 km, and 10 km.

Figure 5.4 (a) Venn Diagram at 2 km.

Figure 5.4 (b) Venn Diagram at 4 km Altitude
Figure 5.4 (c) Venn Diagram at 7 km Altitude

Figure 5.4 (d) Venn Diagram at 10 km Altitude

**Figure 5.4**: Venn Diagram categorizing all PR squares for January 1998 at selected heights of: (a) 2 km (b) 4 km (c) 7 km (d) 10 km

The Venn diagrams include the following information:
1. The outside circle represents the total number of PR squares analyzed for all orbits in January 1998.

2. A subset of this large circle includes PR squares with and without precipitation.

3. The subset of PR squares with precipitation is separated into two categories:
   - PR Squares with precipitation and lightning
   - PR Squares with precipitation and no lightning
   - PR Squares with no precipitation and no lightning

4. Each of these categories is subdivided into the different regions of Earth:
   - Land - PR squares that include only land
   - Ocean - PR squares that include only water
   - Combo - A PR squares that include water and land

5. The percentages that are not in parenthesis, correspond to the percentage that specific case represents of the entire system (system being the total number of PR squares analyzed)

6. The percentages that are in parenthesis, correspond to the percentage within the subset. For example, in Figure 5.4 (d), PR squares With Precipitation and No Lightning is 16% of the Total Number of PR squares, but 86% of the number of PR squares with Precipitation.

These Venn diagrams are a quick way to break down the problem. First, it can be observed that as the height increases, the number of PR squares that contain precipitation decreases.

The number of PR squares with precipitation and lightning, remains constant at 3% of the entire system, from 4 km to 10 km. However, the subset percentage (the percentage that it represents in comparison with PR squares flagged as containing rain) increases steadily from 8% at 4 km to 14% at 10 km as expected. When PR squares are flagged as containing precipitation at altitudes of 10 km, most of those correspond to deep convective clouds, which in turn have a higher probability of producing lightning.

The Venn diagrams indicate that of the PR squares flagged as having precipitation and lightning, on average 55% of these occur over land. This is twice the number of PR squares that contained precipitation and lightning over the ocean, which is usually a steady 25%. It is important to observe that about 10% - 15% (at 7 km and 10 km altitudes) of precipitating clouds will be accompanied by lightning. If such a low percentage of the rain
comes with lightning, then lightning is not a good indicator to measure rainfall globally. In cases where precipitation occurs over land, 15% (i.e. 1.6/(1.6 + 9.7)) of the time it comes with lightning at 2 km altitudes, steadily increasing to 27% (i.e. 1.7/(1.7 + 4.5)) at 10 km altitudes. Lighting over land may present a good choice for measuring precipitation.

5.2 Flash Rate versus Precipitation Fractional Area

Flash rate versus precipitation fractional area plots show lightning activity over different regions: land, ocean, and ‘combo’ (both land and ocean) covered by the PR squares. This section explores this relation for selected heights of 2 km, 4 km, 7 km, and 10 km over land, ocean, and ‘combo’. A ‘total’ plot appears containing all three regions (i.e. land, ocean, ‘combo’).

5.2.1 Near Surface Region up to 0°C Isotherm (2-4 km Altitudes)

Flash rate versus precipitation fractional area plots are shown in Figure 5.5 and Figure 5.6, respectively, for the near surface region (2 km) extending to the liquid phase region (4 km).

Both figures show similar scatter, with their upper envelopes following a 45° line. As the fractional area of a storm increases, there is an increase in flash rate for all cases.

The scatter of the plot does not allow for convective regimes to be determined. However, for regions above the line 10^2 flashes/min per fractional area, flashes over the ocean are rare compared to land. The highest flash rate values for ocean above this line were found to occur near coasts of highly active inland storms like Brazil and Africa.
Figure 5.5: Flash Rate [flashes/min] vs. Precipitation Fractional Area [f] for 2 km Altitude
Figure 5.6: Flash Rate [flashes/minute] vs. Precipitation Fractional Area [f] for 4 km Altitude

5.2.2 Mixed Phase Region (7 km Altitude)

In the mixed phase region, the flash rate over land increases proportional to the precipitation fractional area alongside a 45° line (Figure 5.7). The ocean plot; however, begins to scatter and flatten out with flash rate for lower precipitation fractional area numbers. These
are above the 45° line. Nevertheless, land shows an order of magnitude larger flash rate for \( f > 0.1 \). Convective storms with clouds reaching the mixed phase region and \( f < 0.1 \), have comparable flash rates over land and ocean.

**Figure 5.7:** Flash Rate [flashes/minute] vs. Precipitation Fractional Area \([f]\) for 7 km Altitude
5.2.3 Ice Region (10 km Altitude)

The relation for fractional area versus flash rate appears extremely scattered in Figure 5.8. The ice region is expected to have small convective cumulonimbus clouds with high flash rates in their cores and occurring predominantly over land. However, the scatter on the plots may tell a different story. The plots on land do show higher flash rate than on water, with the maximum fractional area observed over land close to $f = .30$. The fractional area of storms reaching this high have at most 30% coverage of a PR square (with area = 215 km x 215 km) over both land and water.
Figure 5.8: Flash Rate [flashes/minute] vs. Precipitation Fractional Area [f] for 10 km Altitude
5.3 Lightning Rate versus Mass Flux

Lightning rate versus precipitation mass flux plots are useful for determining regions where there is higher rainfall accumulation [kg] with little or no flash rate (monsoon), and regions where the accumulated rainfall [kg] is small but the flash rate activity is large (break period). These are essential for determining whether a relation between lightning and precipitation exists. The plots below were made using January 1998 data from the precipitation radar and lightning imaging sensor from the TRMM satellite. The slope of the diagonal red lines in the plots are represented in kg/flash (the amount of falling rain in kg per flash count within a PR square).

5.3.1 Near Surface Region up to 0°C Isotherm (2-4 km Altitudes)

Figures 5.9, 5.10, 5.11, and 5.12 show the precipitation mass flux versus flash rate scatter plots (top) and histograms of precipitation mass flux not accompanied by lightning (bottom) for all cases (i.e. land, ocean, ‘combo’, and total). The histograms are evaluated for the decade intervals: 1-2, 2-5, and 5-10.

The top plots show that there is an absence of bimodality in land and ocean that would distinguish between regimes. It is evident from the diagrams, that the spread of kg/flash covers 3 decades. With such non-uniqueness it is impossible to distinguish between monsoon and break period regimes by simply looking at the flash rate versus precipitation mass flux relation. Nevertheless, a line that minimizes the data in the logarithmic least square sense is drawn in blue. This line represents the best power law relationship between flash rate (F), and mass flux (M) of the form: \( F = bM^a \). The power law line fits’ slopes and y-intercepts (\( \log(F) = a\log(M) + \log(b) \)), are shown in Table 5.1 for the 2 km cappi, and Table 5.2 for the 4 km cappi. The correlation coefficients (R) for the scatter plots are also shown in the tables.
Table 5.1: Power Law Slope (A), Prefactor (b), and Correlation Coefficient (R) for Least Square Fit Line (2 km Altitude)

<table>
<thead>
<tr>
<th>Case</th>
<th>A</th>
<th>b</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTAL</td>
<td>0.2160</td>
<td>-0.9114</td>
<td>.0316</td>
</tr>
<tr>
<td>LAND</td>
<td>0.1317</td>
<td>-0.2010</td>
<td>.0075</td>
</tr>
<tr>
<td>OCEAN</td>
<td>0.3186</td>
<td>-1.4404</td>
<td>.0322</td>
</tr>
<tr>
<td>COMBO</td>
<td>0.2921</td>
<td>-1.8290</td>
<td>.1213</td>
</tr>
</tbody>
</table>

Table 5.2: Power Law Slope (A), Prefactor (b), and Correlation Coefficient (R) for Least Square Fit Line (4 km Altitude)

<table>
<thead>
<tr>
<th>Case</th>
<th>A</th>
<th>b</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTAL</td>
<td>0.3817</td>
<td>-1.9994</td>
<td>.0228</td>
</tr>
<tr>
<td>LAND</td>
<td>0.2639</td>
<td>-1.0954</td>
<td>.0044</td>
</tr>
<tr>
<td>OCEAN</td>
<td>0.3479</td>
<td>-1.9409</td>
<td>.2186</td>
</tr>
<tr>
<td>COMBO</td>
<td>0.5531</td>
<td>-3.1534</td>
<td>.2363</td>
</tr>
</tbody>
</table>

The least square fit lines of the precipitation mass flux versus lightning rate over ocean for near surface capps have a steeper slope than the data over land. However, the kg/flash values over ocean are at least an order of magnitude larger than in land. In both figures, the points over land concentrate between the $10^6$ kg/flash and $10^7$ kg/flash 45° lines, compared to a concentration of points between $10^7$ kg/flash and $10^8$ kg/flash 45° lines in the ocean plots.

The correlation coefficients show an extremely uncorrelated situation between mass of precipitation and lightning rate at near surface regions for all four cases, with values close to 0. This is of importance as it says that lightning rate cannot be used to predict precipitation at low altitudes.
It should be remembered that 1C21 data are not corrected for attenuation, especially at the low altitudes. Figure 4.5 showed that the attenuation correction increases the precipitation mass flux. The plots will shift to the right about a decade if corrected for attenuation, clutter, and non-uniform beam filling. This is clear from Figure 4.5 where the difference between the 1C21 mass flux and 2A25 mass flux (corrected for attenuation) is about a decade. At high reflectivity, the points line up above the 45° line, which means it will increase the 1C21 mass of precipitation if corrected for attenuation as the 2A25 dataset.

The histograms for the non lightning precipitation mass flux cases for each region (i.e. land, ocean, ‘combo’, ‘total’) show that there is a steady increase of discarded values from the mass flux versus flash rate plot, from $10^4$ kg/sec to a maximum between $10^6$ kg/sec and $10^7$ kg/sec. It is important to notice that the peak of the lower histograms is a decade less than the peak of the plots above. Although part of the peak values in the scatter plots sit on top of the right-end tail of the histogram, if 1C21 data were corrected for attenuation the difference between the peaks will increase as the scatter plots will shift right more than the histogram below. This is of great value as the larger mass flux values dictate lightning regimes. This could be of use when trying to measure mass flux with lightning counts.
Figure 5.9: Precipitation Mass Flux [kg/sec] vs. Flash Rate [flashes/minute] and Histograms of Precipitation Mass Flux not Accompanied by Lightning for 2 km Altitude (Land and Ocean) The histogram axis is common in top and bottom plots.
Figure 5.10: Precipitation Mass Flux [kg/sec] vs. Flash Rate [flashes/minute] and Histograms of Precipitation Mass Flux not Accompanied by Lightning for 2 km Altitude (Total and Combo) The histogram horizontal axis is common in top and bottom plots.
Figure 5.11: Precipitation Mass Flux [kg/sec] vs. Flash Rate [flashes/minute] and Histograms of Precipitation Mass Flux not Accompanied by Lightning for 4 km Altitude (Land and Ocean) The histogram horizontal axis is common in top and bottom plots.
5.3.2 Mixed Phase Region (7 km Altitude)

Figures 5.13 and 5.14 show the precipitation mass flux versus flash rate scatter plot (top) and the non-lightning precipitation mass flux histograms (bottom) for each case (i.e. land, ocean, 'combo', total). In the mixed phase region, the top kg/flash number over land is $10^5$ kg/flash, whereas over ocean it is $10^4$ kg/flash. Once again, there is an order of magnitude difference between land and ocean. The ocean plot spreads through the precipita-
tior mass flux values with a fairly constant flash rate. Meanwhile, the land plot increases steadily with a spread of 2 decades in kg/flash values compared to 3 decades in the near surface region at 2 km and 4 km.

At 7 km there is no bimodality over either the land and ocean, that could be used to distinguish between regimes. The log best fit lines are shown in ‘blue’ on the scatter plots. The slopes and y-intercepts for the log least square fit lines and correlation coefficients (R) appear in Table 5.3 for 7 km altitude.

Table 5.3: Power Law Slope (A), Prefactor (b), and Correlation Coefficient (R) for Least Square Fit Line (7 km Altitude)

<table>
<thead>
<tr>
<th>Case</th>
<th>A</th>
<th>b</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTAL</td>
<td>0.5232</td>
<td>-2.5004</td>
<td>.5068</td>
</tr>
<tr>
<td>LAND</td>
<td>0.8325</td>
<td>-4.2942</td>
<td>.5235</td>
</tr>
<tr>
<td>OCEAN</td>
<td>0.2168</td>
<td>-0.8497</td>
<td>.3921</td>
</tr>
<tr>
<td>COMBO</td>
<td>0.5309</td>
<td>-2.5720</td>
<td>.5456</td>
</tr>
</tbody>
</table>

The slope of the log best fit lines for 7 km are different over land and ocean from the near surface regions. After the melting level, the rate of change of mass of precipitation per lightning flash increases over land and decreases over the ocean. Again, the least squares fit line proves that after a cloud reaches above the mixed phase region (the cold part of the atmosphere) over land it increases its lightning activity for small changes in precipitation mass flux faster than clouds over ocean that reach the mixed phase.

The increase of the correlation coefficients (see Table 5.3) for the scatter plots in Figures 5.13 and 5.14, indicate that lightning is related to ice phase development in deep convection. This confirms an earlier claim in Chapter 2 Section 1, that if ice particles become rainfall, then a proportionality must exist between rainfall and lightning. At 7 km, a cloud is above the melting level and reaching the cold part of the atmosphere where ice particle
formation is more attainable. Hence, the larger correlation between precipitation mass flux and lightning rate.

The histograms of precipitation mass flux values unaccompanied by lightning show a peak of $10^5$ kg/sec, while the scatter plots' peaks appear at $10^6$ kg/sec. This is still consistent with near surface observations.

**Figure 5.13:** Precipitation Mass Flux [kg/sec] vs. Flash Rate [flashes/minute] and Histograms of Precipitation Mass Flux not Accompanied by Lightning for 7 km Altitude (Land and Ocean) The histogram horizontal axis is common in top and bottom plots.
**Figure 5.14:** Precipitation Mass Flux [kg/sec] vs. Flash Rate [flashes/minute] and Histograms of Precipitation Mass Flux not Accompanied by Lightning for 7 km Altitude (Total and Combo) The histogram horizontal axis is common in top and bottom plots.

### 5.3.3 Ice Region (10 km Altitude)

The ice region plots (Figures 5.15 and 5.16) do not offer new information on a bimodality between flash rate and precipitation mass flux over land and ocean. The spread of values of kg/flash over land continues to be 2 decades. Most of the flash rate values over ocean stay below 50 flashes/min. The maximum precipitation mass flux decreased to less than $10^6$ kg/sec over the ocean from the earlier $10^7$ kg/sec at 7 km. However, the maximum precipitation mass flux for land stayed at $10^7$ kg/sec as for 7 km.
The logarithmic least square fit lines' slopes and y-intercepts for the scatter plot at 10 km, and the correlation coefficients (R) are shown in Table 5.4. Similar to the log best fit slopes for 7 km cappi, the 10 km slope over the land is 3 times steeper than the ocean least squares fit line. At 10 km, lightning generation increases over land for small changes in mass flux.

Table 5.4: Power Law Slope (A), Prefactor (b), and Correlation Coefficients for Least Square Fit Line (10 km Altitude)

<table>
<thead>
<tr>
<th>Case</th>
<th>A</th>
<th>b</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTAL</td>
<td>0.5119</td>
<td>-2.0046</td>
<td>.5730</td>
</tr>
<tr>
<td>LAND</td>
<td>0.6694</td>
<td>-2.7749</td>
<td>.5508</td>
</tr>
<tr>
<td>OCEAN</td>
<td>0.2138</td>
<td>-0.7278</td>
<td>.5837</td>
</tr>
<tr>
<td>COMBO</td>
<td>0.4750</td>
<td>-1.8330</td>
<td>.6314</td>
</tr>
</tbody>
</table>

The correlation coefficients in Table 5.4, still present higher correlation factors from near surface altitudes. The correlation coefficients in Table 5.4 support the fact that lightning rate relates better to mass flux at higher altitudes.

The histograms for lightning-free precipitation mass flux show maxima that are dramatically smaller than the scatter plots' kg/sec peaks.
Figure 5.15: Precipitation Mass Flux [kg/sec] vs. Flash Rate [flashes/minute] and Histograms of Precipitation Mass Flux not Accompanied by Lightning for 10 km Altitude (Land and Ocean) The histogram horizontal axis is common for top and bottom plots.
5.4 Precipitation Mass Flux versus Precipitation Fractional Area

Plots of precipitation mass flux versus precipitation fractional area show that as the precipitation area increases, the mass flux increases accordingly. The plots also show that as the height of the cappi increases, both the precipitation fractional area and mass flux decrease.
5.4.1 Near Surface Region up to 0°C Isotherm (2-4 km)

At 2 km and 4 km heights, the plots (Figure 5.17 and 5.18) show an offset band of points that are geophysically impossible values for precipitation. After analyzing the PR squares corresponding to these values, it was concluded that they correspond to radar returns from tall mountains such as the Himalayas and Andes. These appear as large reflectivity values with small fractional area (only in land; not in ocean), and are shown as the purple areas in Figure 5.2a (2 km), Figure 5.2b (4 km). This feature will only be evident in these plots of precipitation mass flux versus precipitation fractional area. The validity of the earlier plots against flash rate (Sections 5.2, 5.3) depend on the fact that this offset band of noise at low altitudes, due to tall mountains, is not generating flashes. The plots from Sec. 5.2 and Sec. 5.3, include only convective clouds with lightning activity.
Figure 5.17: Precipitation Mass Flux [kg/sec] vs. Precipitation Fractional Area [f] for 2 km Altitude
Figure 5.18: Precipitation Mass Flux [kg/sec] vs. Precipitation Fractional Area [f]
for 4 km Altitude

5.4.2 Mixed Phase Region (7 km)
In the mixed phase region the plots (Figure 5.19) show points clustering near a 45° line. Anomalous values at 7 km are minimum, as the attenuation corrections are less than at near surface altitudes, and there are fewer 7 km high mountains. The precipitation mass flux points are concentrated above $10^5$ kg/sec for land, with very few points below. The ocean however, has a very distributed precipitation mass flux and precipitation fractional area covering the whole range of kg/sec values.
Figure 5.19: Precipitation Mass Flux [kg/sec] versus Precipitation Fractional Area [f] plots for 7 km Altitude

5.4.3 Ice Region (10 km)

At 10 km, the points on the precipitation mass flux versus precipitation fractional area plot (Figure 5.20) tighten up around a 45° line. The fractional area of precipitation at 10 km barely reaches 30% for any PR square.
Figure 5.20: Precipitation Mass Flux [kg/sec] versus Precipitation Fractional Area [f] plots for 10 km Altitude

5.5 Reflectivity-Height Distribution Plots

Reflectivity-height distribution plots are a useful tool for distinguishing factors that play a role in lightning development over both land and ocean. By plotting the number of 4km by 4km pixels reflectivity values over selected heights (2 km, 4 km, 7 km, and 10 km) and for different situations (precipitation with/without lightning over land, precipitation with/without lightning over ocean), it will zoom into the differences (height, reflectivity,
or regime) between ocean and land lightning development. These differences could be used as signatures for regime classification.

Figure 5.21 shows the total number of reflectivity pixels for the selected heights of 2 km, 4 km, 7 km, and 10 km. The x-axis is the reflectivity value, the y-axis is the height, and the value inside the box is the number of pixels with reflectivity shown on the x-axis at the height shown on the y-axis.

For reflectivity (dBZ) less than 25 dBZ, the liquid phase region (4 km) contains a count of reflectivity values similar to that in the near surface region (2 km). The 2 km cappi is the clear winner (for reflectivity greater than or equal to 25 dBZ) over the 4 km cappi by at least a factor of 2 in each case. On the other hand, the 7 km mixed phase region contains more dBZ counts for all cases than the ice region. This first plot integrates too many observations to be useful for meaningful conclusions on regime classification. The next four plots will explore the reflectivity-height distribution for land and ocean with and without lightning to improve on this situation.
Figure 5.21: Reflectivity-Height Distribution Plot for All Cases

Figure 5.22 shows the number of reflectivity pixels over land at four selected heights (2 km, 4 km, 7 km, 10 km) for PR squares containing lightning.

- 2 km: From 15 - 35 dBZ there is an increase in reflectivity counts. For reflectivity > 35 dBZ, the number of reflectivity counts decreases steadily.
- 4 km: Very few 15-20 dBZ counts. It jumps to a large reflectivity count at 20 dBZ, only to decrease steadily.
- 7 km: For lower reflectivity values (15-25 dBZ), 7 km contains higher reflectivity counts than the warm part of the atmosphere (2 km and 4 km). Highest reflectivity found at 7 km is 50 dBZ.
- 10 km: Contains more reflectivity counts between 15-25 dBZ. The maximum reflectivity at 10 km is 50 dBZ.
Figure 5.22: Reflectivity-Height Distribution Plot For Rain With Lightning Over Land

By comparing these values to Figure 5.23, where there is no lightning over land, it can be observed that above the melting level (4 km) the reflectivity counts over land with lightning are larger in all categories by more than a factor of 2. For the cases where there is no lightning over land, at 10 km reflectivity greater than 30 dBZ is scarce, whereas clouds generating lightning, easily reach the 45 dBZ mark. At 4 km, the no lightning over land case wins for the lowest reflectivity bins (15-25 dBZ). For reflectivity > 30 dBZ, the lightning over land is the clear winner. A similar case happens at 2 km, where the lightning over land reflectivity counts are larger only for the 35-40 dBZ bins. This creates a problem in using reflectivity values at heights below the melting level as unique signatures for
lightning activity. Clouds that reach 7 km or higher over land and have a reflectivity greater than 35 dBZ at one level, have more than 98% probability of making lightning.

![Reflectivity-Height Distribution Plot For Rain Without Lightning Over Land](image)

**Figure 5.23:** Reflectivity-Height Distribution Plot For Rain Without Lightning Over Land

The case for the ocean is similar to the land. Figures 5.24 and 5.25 show the reflectivity height distribution functions over ocean with and without lightning, respectively. These are the comparisons at each level:

- **2 km:** The no lightning case is the clear winner up to 45 dBZ. It is important to note that clouds generating lightning is a small subset (~ 0.8% see Figure 5.4) of all clouds in the ocean.
- **4 km:** The no lightning case contains higher reflectivity counts up to 45 dBZ. Higher reflectivity, is controlled by the lightning over land case.
- **7 km:** This is above the melting level, and the lightning case wins for all reflectivity bins greater than 35 dBZ by more than 75%.
- **10 km:** Few clouds with reflectivity greater than 25 dBZ over the ocean, in the no
lightning case, attain 10 km altitudes. The oceanic lightning case wins for reflectivities above 25 dBZ. At 30 dBZ and higher, the lightning case has more dBZ counts than the no lightning case by more than a factor of 5. At 10 km, 30 dBZ is a threshold for oceanic lightning development.

Figure 5.24: Reflectivity-Height Distribution Plot For Rain With Lightning Over Ocean
Figure 5.25: Reflectivity-Height Distribution Plot For Rain Without Lightning Over Ocean

From the above reflectivity height distribution functions the following can be deduced:

1. Land:
   - Lightning generation is controlled by the cold part of the cloud, above the 0° isotherm. For reflectivity greater than 25 dBZ at 7 km, there is more than 87% probability that it will generate lightning.

2. Ocean:
   - Lightning over the ocean is also controlled by the part of the radar-reflective cloud that reaches above the melting level. Above 7 km there must be reflectivity greater than 35 dBZ to have a probability of 77% of generating lightning. If it reaches the tropopause (10 km), it only needs reflectivity higher than 30 dBZ to create lightning with 85% probability.

These findings confirm that regime classification could be accomplished by having information on cloud tops, reflectivity profiles, and lightning activity.
Chapter 6

Conclusions

The study of the TRMM data confirms that there is no unique relation between lightning flash rate and precipitation rate. This non-uniqueness is attributable to the specific role for ice in lightning production and the frequently dominant role for the warm rain coalescence process in surface rainfall production. The contrast of lightning activity between land and ocean, and the faster decline of maximum radar reflectivity with height in ocean than in land shown in Chapter 5, Section 1, presents a division between oceanic and continental regimes. However, the precipitation mass flux versus flash rate scatter plots established that there is no bimodality over land that will enable a clear distinction between a monsoon and a break period regime. However, the maps of mass of precipitation per flash in Chapter 5, Section 1, showed that there is a latitudinal dependence within South America and Africa, where more lightning is generated per mass of precipitation outside the central tropics. Figure 5.3, clearly shows as much as two orders of magnitude difference in kg/flash between the central tropics and the extra tropics in South America and in Africa for near surface altitudes (2 km and 4 km). In the mixed phase and ice regions, this difference in kg/flash is still an order of magnitude with the red spectrum (fewer kg/flash) concentrating further South, and yellow/green (kg/flash values ten times greater) clustering in the central tropics.

Earlier studies of kg/flash values (Williams et al., 1992, Petersen and Rutledge, 1996) showed that precipitation mass flux and lightning counts are proportional within specific regimes. Their plots of kg/flash were created using data gathered over the same region and on specific storms for one day at a time. The TRMM data gathers values from all land/
ocean regimes and takes only 90 second snapshots of this data. The kg/flash relation in this thesis has more scatter because of the short window for sampling data. The kg/flash values obtained in this study, are an order of magnitude lower than in earlier studies, because the present study uses total lightning whereas only cloud-to-ground (CG) lightning was used earlier. Another factor that contributed for a lower kg/flash relation is the under-estimation of the precipitation mass flux number [kg] in this thesis, on account of attenuation in the 1C21 data.

Venn diagrams in Chapter 5, Section 1, showed that lightning is present in only a small percentage (5% - 15%) of precipitating clouds. This discourages the use of lightning as a tool for measuring mass of precipitation on a global scale. However if rain occurs over land (at 2 km), there is about a 15% chance that it will generate lightning. This number increases to 27% at 10 km altitude. Hence, for the land case lightning will be a notable variable for predicting precipitation.

The plots of mass of precipitation versus lightning rate provided best fit power law which became steeper (kg/flash) for clouds over land as they extended above the melting level (4 km) and entered the mixed phase region (7 km). Clouds over the ocean did not present such variability in kg/flash slope from the 4 km to the 7 km level, because very few oceanic clouds that reach high altitudes generate high flash rate.

The comparison between the scatter plots of mass of precipitation versus lightning rate and the histograms of mass of precipitation without lightning showed that the larger mass flux values are in regimes (PR squares) populated with lightning. The difference in peak values between the scatter plots and the diagrams exceeded one decade. This fact is good news for the purpose of measuring mass flux with lightning. It provides a marker for distinguishing high mass of precipitation at different altitudes.
Correlation coefficients confirmed a non-unique relation between precipitation and lightning at near surface levels with numbers close to zero. However, the correlation coefficient between precipitation and lightning exceeds 0.5 for clouds 7 km and above. This lends further support to the idea that ice plays a major role in the creation of lightning.

The reflectivity-height distribution functions in Chapter 5, Section 5, provide additional information for why lightning predominates over land. Land is observed to have a lower reflectivity threshold (25 dBZ above 7 km) for generating lightning compared to oceanic lightning activity (35 dBZ above 7 km).
References


[10] E.R.Williams et al., A radar and electrical study of tropical “hot towers”, *Journal of*

