The TRMM Precipitation Radar: Comparison to a Ground-Based Radar and Application to Convective-Stratiform Precipitation Mapping over the Tropics

by Courtney Schumacher

Chairperson of the Supervisory Committee:
Professor Robert A. Houze, Jr.
Department of Atmospheric Sciences

This thesis explores limitations in the sensitivity and sampling of the Tropical Rainfall Measuring Mission (TRMM) satellite-borne Precipitation Radar (PR). Instantaneous comparisons with the Kwajalein radar (KR) show that the PR misses < 3% of surface rainfall but almost 50% of surface rain area. In addition, the PR sees very little above the freezing level. At reflectivities > 17 dBZ, the PR and KR agree quite well.

The temporal sampling of the PR accurately captures the KR’s overall frequency distribution of reflectivity and its subdivision into convective and stratiform components. However, monthly rain amounts and diurnal and latitudinal variations of precipitation in the vicinity of Kwajalein are not well sampled.

PR convective-stratiform percentages of monthly rain agree within 10% of KR values. Using the full coverage of the PR, we find that tropic-wide monthly mean values of the convective fraction of rain amount hover ~50% and of rain area are ~15%, never exceeding 40%. The central oceans have high percentages of stratiform rain while the continents, Indonesia, and the Gulf of Mexico have high percentages of convective rain. The Indian Ocean and west Pacific warm pool are close to tropic-wide averages. The proportion of rain amount and rain area accounted for by convective rain increases with increasing SST. Regions with very high monthly rainfall have a larger stratiform component and occur at less than maximum SST.
TABLE OF CONTENTS

List of Figures ......................................................... ii
List of Tables .......................................................... v

Chapter 1: Introduction ........................................... 1

Chapter 2: The TRMM satellite and Kwajalein oceanic validation site ............... 9
  2.1 TRMM satellite overview ........................................ 9
  2.2 Precipitation radar on the TRMM satellite ...................... 11
  2.3 Kwajalein radar .................................................. 14
  2.4 Kwajalein rain gauge networks .................................. 17
  2.5 Calibration of the KR ............................................ 19
  2.6 Drop-size distribution .......................................... 22
  2.7 Kwajalein climatology .......................................... 26

Chapter 3: Validation of the TRMM PR measurements .................................. 30
  3.1 Reflectivity comparisons ....................................... 32
  3.2 Subdivision of rainfall into convective and stratiform categories .......... 40
  3.3 Rainrate ......................................................... 43

Chapter 4: Characterization of longer scale precipitation at Kwajalein ........... 47
  4.1 PR sampling of reflectivity distributions ...................... 47
  4.2 PR and TMI sampling of monthly precipitation .................. 52
  4.3 Relationship of monthly precipitation to SST ................... 42
  4.4 Diurnal variation of precipitation ................................ 63

Chapter 5: Convective-stratiform precipitation mapping over tropics ............ 65
  5.1 Monthly variation at Kwajalein ................................ 65
  5.2 Representativeness of Kwajalein .............................. 68
  5.3 Tropic-wide patterns .......................................... 74
  5.4 Relationship to SST ............................................. 81

Chapter 6: Conclusions and future research ........................................... 83

References ............................................................. 87

Appendix A: University of Washington Quality Control (UWQC) .................... 93
LIST OF FIGURES

Number | Page
-------|------
1.1     | 2
1.2     | 3
1.3     | 5
2.1     | 10
2.2     | 15
2.3     | 16
2.4     | 18
2.5     | 23
2.6     | 25
2.7     | 26
2.8     | 27
2.9     | 28
2.10    | 29
3.1     | 30
3.2     | 33
3.3     | 34
3.4     | 35
3.5     | 37
3.6     | 39
<table>
<thead>
<tr>
<th>Number</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.7</td>
<td>KR and PR convective-stratiform maps for the case in Fig. 3.2.</td>
<td>41</td>
</tr>
<tr>
<td>3.8</td>
<td>KR versus PR convective and stratiform areas ≥17 dBZ for the 50 overpass cases.</td>
<td>42</td>
</tr>
<tr>
<td>3.9</td>
<td>KR and PR rainrate maps for the case in Fig. 3.2.</td>
<td>43</td>
</tr>
<tr>
<td>3.10</td>
<td>Area-integrated precipitation rates for the KR and PR for the 50 overpass cases.</td>
<td>44</td>
</tr>
<tr>
<td>3.11</td>
<td>Histograms of KR and PR reflectivity and rain distributions accumulated at a height of 3 km for the 50 overpass cases.</td>
<td>46</td>
</tr>
<tr>
<td>4.1</td>
<td>Monthly frequency distributions of KR total echo area and total rain amount.</td>
<td>48</td>
</tr>
<tr>
<td>4.2</td>
<td>KR and PR reflectivity frequency distributions for August 98-May 99 and June 99-Aug 99.</td>
<td>49</td>
</tr>
<tr>
<td>4.3</td>
<td>Frequency distributions comparing KR distributions for August 1998-August 1999 and the KR overpass subset at near surface.</td>
<td>50</td>
</tr>
<tr>
<td>4.4</td>
<td>Time series of KR overpass rainrate frequency distributions being continually added in order to approach the August-November 1998 KR distribution.</td>
<td>51</td>
</tr>
<tr>
<td>4.5</td>
<td>Kwajalein validation site in relation to geometry of PR 0.5° and 5° monthly products.</td>
<td>52</td>
</tr>
<tr>
<td>4.6</td>
<td>Monthly gauge, KR, PR and TMI rain amounts for Kwajalein validation area and 5° x 5° grid containing Kwajalein validation site.</td>
<td>54</td>
</tr>
<tr>
<td>4.8</td>
<td>Kwajalein area gauge monthly accumulations versus latitude for September 1997, 1998, and 1999.</td>
<td>56</td>
</tr>
<tr>
<td>4.9</td>
<td>September SST climatology for Pacific basin and Kwajalein area.</td>
<td>57</td>
</tr>
<tr>
<td>4.10</td>
<td>SST in the vicinity of the Kwajalein validation site for September 1997, 1998, and 1999.</td>
<td>58</td>
</tr>
<tr>
<td>4.11</td>
<td>Average monthly SST and gauge accumulations and their correlations with latitude at Kwajalein.</td>
<td>60</td>
</tr>
<tr>
<td>4.12</td>
<td>18 years of Reynolds and Smith (1994) SST data in the vicinity of Kwajalein.</td>
<td>61</td>
</tr>
<tr>
<td>Number</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>---------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>4.13</td>
<td>Monthly values of rain accumulation and SST between 1998 and 1999 for Kwajalein gauges, PR, and TMI.</td>
<td>62</td>
</tr>
<tr>
<td>4.14</td>
<td>Two years of cloud-to-ground lightning strike data at Kwajalein.</td>
<td>63</td>
</tr>
<tr>
<td>4.15</td>
<td>Rain gauge and PR 3-h accumulations for August 1998-1999.</td>
<td>64</td>
</tr>
<tr>
<td>5.1</td>
<td>KR and PR monthly convective fraction of total precipitation and precipitation area.</td>
<td>66</td>
</tr>
<tr>
<td>5.2</td>
<td>KR 5-h and monthly convective fractions of total precipitation and precipitation area.</td>
<td>67</td>
</tr>
<tr>
<td>5.3</td>
<td>The stratiform area fraction of precipitation area and total precipitation versus size of precipitation area over the Pacific warm pool.</td>
<td>69</td>
</tr>
<tr>
<td>5.4</td>
<td>As in Fig. 5.4 but for KR 5-h samples from August 1998-1999.</td>
<td>70</td>
</tr>
<tr>
<td>5.5</td>
<td>PR 5º grid convective fractions of total precipitation and precipitation area for January and August 1998.</td>
<td>73</td>
</tr>
<tr>
<td>5.6</td>
<td>PR maps of monthly rain and convective fraction of total precipitation and precipitation area.</td>
<td>75</td>
</tr>
<tr>
<td>5.7</td>
<td>Grids with PR monthly accumulations &gt; 200 mm as a function of SST for August 1998. Convective fraction of total precipitation and precipitation area for above grids.</td>
<td>82</td>
</tr>
<tr>
<td>A.1</td>
<td>Anomalous propagation at Amarillo, TX on 25 May 1994.</td>
<td>96</td>
</tr>
<tr>
<td>Number</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>1.1</td>
<td>Stratiform fraction of total precipitation</td>
<td>7</td>
</tr>
<tr>
<td>2.1</td>
<td>TRMM satellite instrument specifications</td>
<td>9</td>
</tr>
<tr>
<td>2.2</td>
<td>Characteristics of the TRMM PR and Kwajalein radar</td>
<td>11</td>
</tr>
<tr>
<td>2.3</td>
<td>TRMM standard PR algorithms</td>
<td>14</td>
</tr>
<tr>
<td>2.4</td>
<td>The PR and Kwajalein gauges compared to the KR</td>
<td>20</td>
</tr>
<tr>
<td>3.1</td>
<td>50 PR overpasses with significant rain over Kwajalein Aug 98-99</td>
<td>31</td>
</tr>
<tr>
<td>3.2</td>
<td>KR rain area distributions</td>
<td>36</td>
</tr>
<tr>
<td>5.1</td>
<td>Tropical field projects</td>
<td>72</td>
</tr>
<tr>
<td>5.2</td>
<td>Tropical regions by relative proportion of convective precipitation</td>
<td>80</td>
</tr>
<tr>
<td>A.1</td>
<td>UWQC parameter list</td>
<td>97</td>
</tr>
</tbody>
</table>
ACKNOWLEDGEMENTS

Many thanks to many people. First and foremost to David Kalil whose love and patience kept everything in perspective. My family and Dave’s were always there to cheer me on, I only hope to make them proud. Much thanks for the support and friendship of my advisor, Bob Houze, and members of the Mesoscale Group, in particular Sandy Yuter and Stacy Brodzik. The Atmospheric Science graduate students, especially my classmates, provided essential friendship whether it manifested itself in study groups or coffee breaks. Seth Hartley and Dave Groves were my most steadfast allies in these activities. I’d also like to thank Chris Bretherton and Dennis Hartmann for being on my reading committee.
1. Introduction

The primary goal of the Tropical Rainfall Measuring Mission (TRMM) is to determine the four-dimensional distribution of precipitation in the tropics (Simpson et al. 1988). Two-thirds of the earth’s rainfall occurs in the tropics and tropical precipitation, as a measure of condensational latent heat release, effectively accounts for half of the atmosphere’s heat energy. The ability to quantify this energy should result in more accurate global circulation models (GCMs) and a better capability to forecast conditions that affect humans and economies.

The TRMM satellite, with an assortment of precipitation sensors, is ideally suited to TRMM’s primary goal in two notable ways. One is that surface observations over the tropics are rare and difficult to obtain, especially considering that 75% of the tropics is open ocean. Remote sensing is a logical solution to acquire rainfall data over the entire tropics. The other way is that the TRMM satellite contains the first quantitative precipitation radar placed in space. The Precipitation Radar (PR) observes the vertical structure of precipitation and thus estimates can be made concerning the vertical distribution of latent heat at fine spatial resolution which in turn can be related to large-scale dynamics. For instance, Hartmann et al. (1984) determined that a heating profile based on the ensemble heating of a mesoscale convective system versus a conventional heating profile was necessary to model a realistic large-scale tropical response (i.e., the Walker circulation).

The TRMM satellite is in a low-altitude, low-inclination orbit. The low-altitude is excellent for high spatial resolution but a drawback in terms of temporal sampling. The low-inclination (and precessing) orbit allows for diurnal sampling but, at best, its largest instrument swath observes a point only twice a day. Rain measurement is always a complicated task because of its innate spatial and temporal variability and when a quantity has a standard deviation comparable to its mean value (e.g., monthly rain accumulation), intermittent sampling is inadequate. Therefore, TRMM focuses on 5° x 5° monthly satellite
products to smear out sampling insufficiency. Studies by Laughlin (1981) and Kedem (1987) suggest that such products will suffer less than 10% sampling error.

TRMM includes a ground validation component, in part to validate the satellite instruments but also to document the climatological information lost by the satellite due to its infrequent sampling. The validation program has four primary sites and six secondary sites located in various parts of the tropics (Fig. 1.1). Kwajalein is one of the primary validation sites and is important because of its unique open ocean location. This study focuses on Kwajalein, particularly its centerpiece, an S-band radar, which allows definitive comparisons with the PR. The PR, as a new technology, must entertain intense scrutiny before acceptance of its measurements is warranted, especially since it operates at an attenuating frequency and its minimum sensitivity does not allow it to observe the whole precipitation field.

Figure 1.1 TRMM validation sites. Darwin, Kwajalein, Texas and Florida are the primary validation sites. One day of the TRMM satellite orbit is shown. The orbit extends from 35°N to 35°S.
An especially useful aspect of the PR is its ability to discern convective rain from stratiform. Convective and stratiform precipitation are characterized by distinctly different processes and have distinctly different latent heating profiles (Houze 1993, 1997, Fig 1.2).

Convective systems are generally identified with intermittently strong vertical velocities (> 1 m/s in magnitude), high rainfall rates (> 3 mm/h), and small (1-10’s of km), intense, horizontally inhomogeneous radar echo (Fig. 1.2b). The aforementioned strong updrafts are very effective in condensing water vapor and releasing latent heat. Therefore the heat-

**Figure 1.2** Characteristics of (a) stratiform precipitation and (b) convective precipitation. Shading shows higher intensities of radar echo, with hatching indicating the strongest echo. Adapted from Houze (1993). (c) Characteristic profiles of latent heating in convective and stratiform regions of tropical precipitation. Adapted from Houze (1997).
The vertical velocity profile associated with convection is very similar to the mean profile of vertical velocity in which updrafts dominate throughout the profile and maxima occur in the mid to upper-troposphere (Fig. 1.2c). Conversely, stratiform systems are characterized by small vertical velocities (< 1 m/s), low rainrates (< 5 mm/h), and widespread (10-100’s of km), horizontally homogeneous radar echo (Fig. 1.2a). The vertical velocity profile of stratiform regions is dominated by weak updrafts above the 0º C level and net downward motion (owing to melting and evaporation) below. Therefore, there is weak heating in the upper troposphere and weak to moderate cooling in the lower troposphere (Fig. 1.2c). At times, stratiform regions exhibit a feature linked to the melting of ice-particle aggregates at the 0ºC level which reveals itself as a brightband in radar observations. The existence of this feature is often used in radar convective-stratiform separations, along with the horizontal homogeneity or inhomogeneity of the radar echo.

Much work has been done to understand the growth mechanisms of and interactions between convective and stratiform regions. Houghton (1968) noted that collection is the dominant mechanism in strong convective updrafts. Large updrafts can hold aloft larger drops for longer periods, a prime environment for precipitation particles to rime and coalesce. In stratiform regions, the upper level updrafts are too weak to support precipitation particles and therefore the particles fall slowly, growing almost solely by vapor diffusion (Rutledge and Houze 1987). Houze (1993) points out that there exists a necessary relationship in precipitation formation between strong, isolated updrafts and gentle, widespread ascent. Deep convection provides ice particles large enough to descend and grow by vapor diffusion in the mesoscale updraft. If there were no influx of particles from the convective to the stratiform region, the mesoscale updraft would have to nucleate and grow the ice particles exclusively, however particles cannot nucleate and obtain precipitable size in the weak vertical velocities of a mesoscale updraft (Rutledge and Houze 1987). On the other hand, without a mesoscale updraft, the small particles expelled by convection at upper levels would fall too quickly to acquire much mass and rainfall amounts would be significantly diminished.
To illustrate the relative contributions of convective and stratiform processes for a single event, Churchill and Houze (1984) plotted the temporal variation of the convective and stratiform components of a tropical cloud cluster by area and areal precipitation rate over a 16 h period (Fig. 1.3). Convective rain production dominates for the first eight hours of the time series after which the stratiform area grows considerably and becomes the main rainfall producer. The statistics of the entire storm indicate that, while convective rainrates are much higher and dominate early on, stratiform processes still contribute significantly to storm total rainfall, most notably through greater areal coverage and longer lifetime.

**Figure 1.3** (a) Area covered by stratiform and convective precipitation at 3 km. (b) Area-integrated precipitation rate at 3 km. Adapted from Churchill and Houze (1984).
The PR convective-stratiform separation algorithm (Awaka et al. 1997) is based on Steiner et al.’s (1995) classification method for ground radars which has proven viable in many studies (DeMott and Rutledge 1998, Yuter and Houze 1998, etc.). Convective-stratiform separation techniques exist for satellite infrared (IR, Adler and Negri 1988, Goldenberg et al. 1990) and microwave (Anagnostou and Kummerow 1997) observations, however, there are drawbacks to both. IR observations suffer from the fact that an anvil is typically displaced downshear of the convective region after the initial growth of the cell. The anvil appears cold to the IR and may be classified erroneously as convective (Heymsfield and Fulton 1988). Microwave brightness temperatures avoid this displacement but a microwave radiometer’s field of view is generally much coarser than typical convective cells. Beam filling problems occur (McConnell and North 1987) and the small-scale variability of convective precipitation cannot be resolved. In addition, IR and microwave instruments only measure column amounts, they cannot observe the vertical structure of precipitation which is important in convective-stratiform separation. PR observations do not suffer from these factors and thus provide the best means with which to classify rain as convective or stratiform. A task undertaken by this study is to validate whether the PR convective-stratiform separation algorithm is robust from space.

It is also a focus of this work to document the variation of the relationship between convective and stratiform processes across the tropics. Previous studies have concentrated on single events or areas related to field studies. Gamache and Houze (1983), Houze and Rappaport (1984), and Leary (1984) examined various Global Atmospheric Research Program’s Atlantic Tropical Experiment (GATE) squall lines and cloud clusters off the coast of west Africa. Cheng and Houze (1979) compiled statistics over the entire GATE project. Chong and Hauser (1989) studied a continental west African squall line in the Convection Profonde Tropicale (COPT) 81 experiment while Churchill and Houze (1984) and Goldenberg et al. (1990) focused on a cloud cluster during the Winter Monsoon Experiment (WMONEX) in Borneo. Steiner et al. (1995) analyzed a month of radar data from Darwin,
Australian (another primary TRMM validation site) and Yuter and Houze (1998) examined 24 aircraft missions flown during the Tropical Ocean and Global Atmosphere Coupled Ocean-Atmosphere Response Experiment (TOGA COARE) in the western Pacific. A common measurement delineating convective and stratiform processes in these papers was the percent of total rain that was stratiform. Table 1.1 details their results. The variation in percentages (30-85%) leads to the conclusion that convective and stratiform processes and the relative importance of each varies across the tropics. There is as yet, no clear breakdown of the spatial and temporal variations of convective and stratiform precipitation across the tropics beyond these handful of field projects. Once patterns of variation are defined (as is possible with the TRMM PR), it will be feasible to address the environmental variables that contribute to the patterns, such as variations in sea surface temperatures (SST), wind shear and moisture profiles.

Table 1.1. Stratiform fraction of total precipitation.

<table>
<thead>
<tr>
<th>Location (Project)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leary (1984)</td>
<td>30</td>
</tr>
<tr>
<td>Cheng and Houze (1979)</td>
<td>40</td>
</tr>
<tr>
<td>Houze and Rappaport (1984)</td>
<td>42</td>
</tr>
<tr>
<td>Gamache and Houze (1983)</td>
<td>49</td>
</tr>
<tr>
<td>Chong and Hauser (1989)</td>
<td>35-45</td>
</tr>
<tr>
<td>Steiner et al. (1995)</td>
<td>41</td>
</tr>
<tr>
<td>Churchill and Houze (1984)</td>
<td>46</td>
</tr>
<tr>
<td>Goldenberg et al. (1990)</td>
<td>62</td>
</tr>
<tr>
<td>Yuter and Houze (1998)</td>
<td>50-85</td>
</tr>
</tbody>
</table>
The main objectives of this research are to: 1) compare the instantaneous fields measured by the Kwajalein radar (KR) and PR in order to validate the PR attenuation correction and quantify the loss of information resulting from the PR’s low sensitivity; 2) compare the temporal sampling of the PR to the full record of the Kwajalein validation site instrumentation in order to determine the usefulness of PR data for climatological purposes; and 3) utilize PR observations to examine the variation of convective and stratiform processes across the tropics.
Chapter 2: The TRMM satellite and Kwajalein oceanic validation site

2.1 TRMM satellite overview

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. The TRMM spacecraft was launched November 28, 1997, with an active Precipitation Radar (PR), a multi-channel passive TRMM Microwave Imager (TMI), a Visible Infrared Scanner (VIRS), a Clouds and Earth’s Radiant Energy System (CERES), and a Lightning Imaging Sensor (LIS, Kummerow et al. 1998, Table 2.1). The TRMM satellite is a low-altitude, low-inclination polar orbiter. It orbits 350 km above the earth’s surface which allows high horizontal resolution measurements. Its inclination is 35º, and thus it covers the tropics and subtropics from 35ºS to 35ºN. Its non-sunsynchronous orbit provides potential documentation of the diurnal cycle of rainfall. Fig. 2.1a is an illustration of the TRMM satellite and Fig. 2.1b is a schematic of the scanning geometry. The PR far exceeds the other instruments in size and mass. It also occupies the nadir position on the satellite.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PR</th>
<th>VIRS</th>
<th>TMI</th>
<th>CERES</th>
<th>LIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency/wavelength</td>
<td>13.8 GHz</td>
<td>0.6-12 µm</td>
<td>10.65-85.5 GHz</td>
<td>0.3-50 µm</td>
<td>0.7774 µm</td>
</tr>
<tr>
<td>Resolution (km)</td>
<td>4.3 (nadir)</td>
<td>2.1 (nadir)</td>
<td>5-63</td>
<td>10 whole globe</td>
<td>4 (nadir)</td>
</tr>
<tr>
<td>Swath width (km)</td>
<td>215</td>
<td>720</td>
<td>759</td>
<td></td>
<td>550</td>
</tr>
</tbody>
</table>

Table 2.1. TRMM satellite instrument specifications.
The PR, TMI, and VIRS are the three main sensors of precipitation on the TRMM satellite. The PR is an active microwave sensor that provides specific height information on a precipitating system while the TMI is a passive microwave sensor that measures the integrated absorption, emission and scattering along the sensor viewpath, it is essentially limited to column amounts. They are complementary in that the observations from the PR are used to tune the TMI retrieval assumptions for more accurate rain estimates over the TMI’s swath which is 3.5 times wider that of the PR. The VIRS provides the additional information of cloud-top temperatures and structure. The VIRS also acts as a link between the long time series of visible and IR observations available from geostationary platforms and the brief but more viable precipitation measurements of the TRMM microwave sensors.

Figure 2.1 (a) The TRMM satellite. (b) TRMM satellite scanning geometry. Adapted from Okamoto et al. (1998).
2.2 Precipitation radar on the TRMM satellite

The PR is crucial to the TRMM mission because of its ability to see the precipitation field with high resolution in both the horizontal and vertical. PR specifications can be found in Table 2.2. The PR scans ± 17º of vertical at intervals of 0.35º. This geometry provides data over a swath 215 km wide at the earth’s surface with a horizontal footprint of about 4 km and a vertical resolution of 250 m at nadir. The PR has a relatively low sensitivity, detecting echoes of only ~17 dBZ and higher. Occasionally, the PR captures meteorological phenomena at reflectivities less than 17 dBZ but the signal to noise ratio at those lower reflectivities is weak.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>PR</th>
<th>KR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency/wavelength</td>
<td>13.8 GHz/ 2.17 cm (Ku band)</td>
<td>2.8 GHz/ 10.71 cm (S band)</td>
</tr>
<tr>
<td>Beamwidth</td>
<td>0.71º</td>
<td>1.12º</td>
</tr>
<tr>
<td>Peak transmit power</td>
<td>500 W</td>
<td>500 kW (250 kW horizontal, 250 kW vertical)</td>
</tr>
<tr>
<td>Horizontal (h) and vertical (v) resolution</td>
<td>h=4.3 km (nadir) v=0.25 km (nadir)</td>
<td>h=0.25 km (gate spacing) v=varies (interpolated 1 km)</td>
</tr>
<tr>
<td>Horizontal range</td>
<td>215 km (swath width)</td>
<td>150 km (radius from radar)</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>1.6 µsec</td>
<td>0.72 µsec</td>
</tr>
<tr>
<td>Min. detectable signal</td>
<td>~17 dBZ</td>
<td>-108 dBm</td>
</tr>
<tr>
<td>Doppler</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>PRF</td>
<td>2776 Hz</td>
<td>396-960 Hz</td>
</tr>
<tr>
<td>Antenna height AMSL</td>
<td>350 km</td>
<td>24.8 m</td>
</tr>
<tr>
<td>Speed of one scan</td>
<td>34º in 0.6 s</td>
<td>360º in 18 s (max)</td>
</tr>
<tr>
<td>Scan range</td>
<td>±17º (cross-track)</td>
<td>-0.4 to 90.5º (elevation)</td>
</tr>
</tbody>
</table>
Operating at a frequency of 13.8 GHZ (2.17 cm wavelength), the PR is subject to strong attenuation. The PR must use a higher frequency than typically used by ground-based radars because its space-based platform necessitates the use of a much smaller antenna. The reflectivity profile in each beam is corrected for attenuation by a hybrid method based on the Hitschfeld-Bordan (1954) method and the surface reference technique (Iguchi and Meneghini 1994). Other factors considered when calculating an attenuation-corrected rain profile are surface clutter, non-uniform beam filling (NUBF), and the identification of the phase state (i.e., water, mixed or ice) and drop-size distribution of the precipitating particles (Iguchi et al. 1997).

The rain profiling algorithm first removes surface clutter with an automatic rejection technique. Surface clutter results from the fact that the PR’s beam reflects off the earth’s surface. Data less than 1 km in altitude (except near nadir) is normally removed so that the PR never measures rain directly at the surface. Next, a clear-air observation of the surface reflectivity is referenced to estimate the attenuation of the surface echo seen through rain, the path-integrated attenuation (PIA). This quantity is then used as a basis for correcting the observed reflectivity for attenuation as a function of range.

The Hitschfeld-Bordan method assumes a power-law relation of the form $k = \alpha Z^\beta$, where $k$ is the specific attenuation coefficient, $Z$ is the true reflectivity factor, $\alpha$ varies with range and rain type and $\beta$ may vary between angle bins but is constant in range, to correct the attenuation effect. However, the forward solution of the Hitschfeld-Bordan method is very sensitive to the estimate of PIA and tends to become unstable at high levels of attenuation. The surface reference method provides an independent measure of PIA at the furthest point of measurement and avoids instabilities at high levels of attenuation. However, the surface reference technique is unreliable at low levels of attenuation (i.e., when the apparent decrease in surface cross section is smaller than the variations of the true surface cross section). Thus, the surface reference technique works best in heavier rain, while in weaker rain it is necessary to use the Hitschfeld-Bordan method.
Once the attenuation correction is ascertained, the non-uniformity of the reflectivity field is calculated within the PR footprint (~4 km). The spatial variation of reflectivity within the PR footprint is assumed to be similar to the variations at larger scales in the vicinity of the footprint (i.e., the eight angle bins surrounding the bin in question). Attenuation is recalculated with the Hitschfeld-Bordan/surface reference hybrid method after these NUBF affects are taken into account. The final step towards an adjusted rain profile is to convert reflectivity to rainrate. An assumption is made regarding the drop-size distribution of the precipitation detected by the radar. Implicit in this assumption is the phase state of the precipitation. The PR rain profiling algorithm utilizes different Z-R relations as functions of phase state to convert reflectivity to rainrate depending on whether the column was classified as convective or stratiform. Z-R relations are based on Darwin, Australia, disdrometer measurements and are applied uniformly to each location in the tropics.

Despite efforts to create accurate rain profiles, errors still occur (Durden et al. 1998). However, Steiner and Houze (1998) showed that without a correction for attenuation, the PR data are probably only reliable at heights of ~5-7 km above MSL (i.e., at and just above the melting level). Thus, these corrections are essential to extend the usefulness of the PR observations.

TRMM has three levels of standard products (Table 2.3). Level 1 consists of the raw data. 1C21 contains reflectivities before any corrections. Level 2 products are Level 1 products taken through various algorithms to create more meaningful variables. 2A23 is the convective-stratiform classification and 2A25 is the rain profiling discussed previously. Level 3 refers to the monthly products compiled to 5° x 5° and 0.5° x 0.5° grids.

1. These products are publicly available through the Goddard Distributed Active Archive Center (DAAC) at http://lake.nascom.nasa.gov/data/dataset/TRMM/index.html/.
Kwajalein Atoll is part of the Marshall Islands which are on the eastern edge of the western Pacific warm pool. Kwajalein is the world’s largest atoll and houses a United States Army missile range, which provides the infrastructure for the validation site. Aeromet, an Army contractor, operates most of the validation site instruments. The Kwajalein radar (KR) is located at the southern tip of the Kwajalein Atoll on Kwajalein Island (8.72ºN, 167.73ºE) and the validation area is defined as the 150 km radius around the radar (Fig. 2.2). Because Kwajalein Atoll and neighboring atolls are thin strips of land surrounding large lagoons, the area covered by the KR is nearly 100% oceanic. Kwajalein is the only
permanent TRMM validation site where ground-based coverage is almost entirely over water. Since passive microwave rain algorithms operate much differently over ocean than over land, Kwajalein stands as a unique validation site for TRMM.

**Figure 2.2** Map of the Kwajalein area centered on the KR. The geography of the Kwajalein Atoll and neighboring atolls are indicated by dashed lines. The interior of each atoll is a giant lagoon; thus the area covered by the radar is almost all open ocean. Rain gauge locations are indicated by the key for each network.
The KR is a highly sensitive, three-dimensionally scanning S-band (i.e., non-attenuated), dual-polarization, Doppler weather radar with a beamwidth of 1.12° (Table 2.2), similar to the well-known WSR-88D (NEXRAD) radars used by the U.S. National Weather Service. However, since the KR is a TRMM facility, it was not constrained to the scan strategy of the NEXRAD radars, and it therefore has been possible to design scan strategies especially for TRMM purposes. The scan strategies have 17-22 elevation angles and were devised to maximize vertical resolution within the validation area to assess more precisely the high vertical-resolution echo of the PR. Current KR and NEXRAD scan strategies are shown in Fig. 2.3.

**Figure 2.3** Scan strategies for the Kwajalein and NEXRAD radars. Center of beam is plotted.
Radar data is quality controlled using an algorithm developed by the Mesoscale Group at the University of Washington that looks at textures of the base reflectivity field and continuity between lower level tilts to detect and remove clutter and other non-meteorological echo (Appendix A). Sea clutter and second-trip echoes are the prevalent non-meteorological returns at Kwajalein. The quality control generally removes the sea clutter but does not always eradicate second-trip echoes. Second-trip echo is typically weak but widespread and has the potential of skewing rain statistics, especially toward stratiform processes.

2.4 Kwajalein rain gauge networks

There are 17 rain gauges located within a 200 km radius of the Kwajalein radar (Fig. 2.2). The rain gauges are Qualimetrics tipping buckets equipped with Unidata Starloggers. Seven of the gauges are controlled by Aeromet: Carlos, Gagan, Illeginni, Kwajalein, Legan, Meck, and Roi-Namur. All of these are located on the Kwajalein Atoll. The other ten gauges are controlled by the Republic of the Marshall Islands (RMI) and are located on other atolls in addition to Kwajalein’s: Biggarenn, Lae, Lib1, Lib2, Loen, Majkin, Mejatio, Namu, Wotja, and Yabbernohr. The tipping buckets measure the number of tips per 15 seconds for the Aeromet network and per 10 seconds for the RMI network. Each tip registers 0.01 inches (0.25 mm) of rain.

The Mesoscale Group at the University of Washington processes the raw rain gauge data into minute, hour, day and month accumulations. All accumulations are in mm. If there were more than four tips in a 10 s period or five tips in a 15 s period (equal to rainrates > 300 mm/h) the data were usually removed. Months that are obviously missing data or seem to have large gaps compared to surrounding gauges are flagged as .nf (not full). In

1. Because of the low pulse-repetition frequency required for Doppler velocity measurements, long-range echoes from a previous pulse may be received along with the return of the subsequent pulse. Distant echoes can thus be plotted incorrectly close to the radar. These falsely plotted echoes are called second-trip echoes.
addition, the data are split into events. A new event is defined when there is a minimum of two tips with < 30 min between tips. A significant event is any event that lasts > 30 min, has an accumulation > 10 mm, and has an average rainrate > 1 mm/h. Gauge-averaged daily and monthly accumulations are also calculated. Some of the rain gauge locations are quite remote so regular equipment maintenance and data retrieval are not always possible. Consequently, there are significant data gaps for some of the gauges (Fig. 2.4).

![Figure 2.4 Inventory of rain gauge data from the Aeromet and RMI networks as of 4 February 2000. A filled circle represents a complete month of data, an open circle represents an incomplete month or problematic data and an X indicates no data.](image-url)
2.5 Calibration of the KR

The calibration of the KR, while generally stable, can shift as a result of repairs, upgrades, and other factors. Both the Kwajalein gauges and the PR provide independent, stable time series by which to track the calibration of the KR. There were two distinct calibration periods between August 1998 and August 1999 separated by major upgrades and repairs made to the KR during late-May to late-June 1999. The KR calibration was low compared to the PR and Kwajalein gauges for both periods but was significantly lower during the second period. An official calibration offset for the second period, which includes the Kwajalein Experiment (KWAJEX), is in the process of being defined. However, a preliminary calibration estimate brings the KR within 1-2 dB of its appropriate measurements for both periods, which is sufficient for the analyses of this thesis.

Two steps were involved in the preliminary KR calibration estimates. The first step compared areal coverage by PR and KR echo ≥ 17 dBZ for the 50 overpasses. The second step compared rain gauge and KR monthly rain accumulations. A total of 34 overpasses occurred during the first period (August 1998-May 1999); 16 overpasses occurred during the second period (June-August 1999).

PR and KR echo areas ≥ 17 dBZ at 1 km height intervals from 3-15 km were accumulated for the 50 overpass cases. Table 2.4 shows ratios of PR to KR total areas for each period at varying calibration offsets. ΣPR/ΣKR represents the ratio of total echo area ≥ 17 dBZ seen by the PR to that seen by the KR for the entire period. Median PR/KR represents the median of individual overpass PR/KR echo areas. ΣPR/ΣKR weights the larger rain overpasses more heavily while the median PR/KR weights each overpass equally. There tends to be a greater percent difference between the PR and KR for overpasses with less rain so the median PR/KR requires higher offsets to approach 1. The ratios indicate a KR offset between +2 and +3 dB for the first period and between +5 and +6 dB for the second period.
Kwajalein gauge accumulations were compared to the reflectivity values of the $2 \times 2$ km pixel above the gauge in the lowest tilt (usually 0.4º) of the KR. The complete KR data set was used instead of just the overpass subset. When there was rain at both the gauge and the radar pixel above the gauge, 10 min of gauge data centered on the radar observation time was summed and the radar rainrate was assumed to exist for 10 min. The 10 min gauge and radar amounts were then accumulated for monthly amounts of radar-estimated rainfall and gauge-estimated rainfall. The median ratio of gauge to KR monthly rain accumulations for both periods at varying calibration offsets is shown in Table 2.4. Various factors influence the derivation of surface rain from radar reflectivity; most importantly, the height of the radar beam above the surface (Joss and Waldvogel 1990). This factor typically leads to underestimation of surface rainfall by the radar and is not taken into account in the KR values. Therefore, gauge/KR should be > 1. Austin (1987) and Steiner et al. (1995) found gauge/KR values to be 1.1 and 1.3, respectively. However, these ratios are very dependent on the default $Z-R$ relation and the number of gauges and range of the

### Table 2.4. The PR and Kwajalein gauges compared to the KR.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.33</td>
<td>1.37</td>
<td>2.2</td>
<td>0</td>
<td>1.75</td>
<td>2.05</td>
<td>5.2</td>
</tr>
<tr>
<td>+1</td>
<td>1.18</td>
<td>1.24</td>
<td>1.8</td>
<td>+4</td>
<td>1.09</td>
<td>1.26</td>
<td>2.3</td>
</tr>
<tr>
<td>+2</td>
<td>1.05</td>
<td>1.12</td>
<td>1.5</td>
<td>+5</td>
<td>0.98</td>
<td>1.11</td>
<td>1.9</td>
</tr>
<tr>
<td>+3</td>
<td>0.94</td>
<td>0.99</td>
<td>1.2</td>
<td>+6</td>
<td>0.87</td>
<td>0.99</td>
<td>1.5</td>
</tr>
<tr>
<td>+4</td>
<td>0.84</td>
<td>0.89</td>
<td>1.0</td>
<td>+7</td>
<td>0.77</td>
<td>0.89</td>
<td>1.3</td>
</tr>
<tr>
<td>+8</td>
<td>0.70</td>
<td>0.79</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
gauges from the radar. Monthly gauge/KR values for well-calibrated months in the Kwajalein network using the climatological $Z-R$ relation (Sec. 2.6) tend to be between 1.5 and 2. The Kwajalein gauge data can be erratic and sparse so care should be taken when using the gauge/KR values quantitatively. The gauge/KR values suggest a KR offset of +1-2 dB for the first period and +5-6 dB for the second period.

Based on this analysis of both PR and Kwajalein gauge data, the preliminary KR calibration estimate is +2 dB before June 1999 and +6 dB after June 1999. To indicate the range of uncertainty in these adjustments, we present results for the corrections of +2 and +6 dB in the following sections and state how much the results would be affected if an additional +2 dB adjustment was made for each time period. The -2 dB reduction makes the offset 0 before and 4 after June 1999, which leads to Median PR/KR ratios of 1.37 and 1.26, respectively (Table 2.4). We suggest that this 30% difference is unacceptable. The + 2 dB increase makes the offset 4 before and 8 after June 1999, leading to Median gauge/KR ratios of ~1, which we suggest is too small, for reasons discussed above. Thus the calibration adjustments of $2 + 2$ dB and $6 + 2$ dB before and after June 1999 represent the range of optimal comparisons of the KR with both the PR and the raingauge networks.

It may seem odd to adjust the KR to agree with the PR, since the former is a ground-validation radar. However, this adjustment does not diminish the role of the KR. No ground radar in existence has absolute calibration of rain estimates. The usefulness to TRMM of ground-based radars such as the KR is in: 1) their high sensitivity and absence of attenuation, which allow accurate characterization of the frequency distribution of reflectivity as a function of altitude; and 2) their continuous sampling at a fixed location. These characteristics allow the KR to assess the echo missed by the PR because of sensitivity, attenuation, or sampling.
2.6 Drop-size distribution

Since measurement of precipitation is a main goal of TRMM, near surface reflectivity from the KR is converted to rainrate using a Z-R relationship. The Kwajalein climatological Z-R table was derived from one year of drop-size distribution measurements made on Majuro Atoll from March 1959-April 1960 (Mueller and Sims 1967). Majuro is 427 km southeast of Kwajalein Island and can be considered to be in a similar climatic regime. Measurements were made with a drop camera at one minute intervals during rain events (a total of 2660 minute measurements were made during the year). The Kwajalein Z-R relationship has a minimum rainrate of 0.05 mm/h at 8 dBZ while the maximum rainrate is set to 170 mm/h at 54 dBZ and above (Fig. 2.5). The exponential fit to the Mueller and Sims (1967) data is $Z = 293R^{1.26}$ and is very similar to Hudlow’s (1979) GATE Z-R relation of $Z = 280R^{1.25}$ (S. Yuter and W. Parker, personal communication, 2000). Joss-Waldvogel disdrometer measurements taken at Kwajalein during the summer of 1999, derive a similar Z-R relation (S. Yuter and W. Parker, in progress). No differentiation is made between convective and stratiform Z-R relations at this time due to the active debate on whether it is physically meaningful or misleading (c.f., Tokay and Short 1996 and Yuter and Houze 1997).

Near surface rainfall rate estimates from the TRMM satellite (TRMM Product Standard Number, TPSN, 2A25) are calculated using separate convective and stratiform Z-R relationships. The Version 4 convective and stratiform Z-R relations for the water phase are $Z = 146R^{1.54}$ and $292R^{1.53}$, respectively (T. Iguchi, personal communication, 1998; Fig. 2.5). The KR and PR Z-R relations are somewhat similar, but the Kwajalein Z-R ascribes lower rainrates when $Z < 25$ dBZ and higher rainrates when $Z > 35$ dBZ compared to the PR.
There are many factors that affect the relation between measured radar reflectivity and surface precipitation. First and foremost is that the radar’s lowest beam increases in height above the surface the farther it gets from the radar due to its angle and to the earth’s curvature (Joss and Waldvogel 1990). Thus, variations in drop-size distribution, enhancement by hail, diminution by downdraft, low level growth in fog or stratus and low level evaporation in dry air can act within the distance between the lowest radar beam and surface to change the amount of precipitation measured (Austin 1987).

Figure 2.5 Z-R relations used for the KR and PR. The single relation of the Kwajalein validation site is based on the climatological drop-size distribution from the Marshall Islands, whereas the two relations for the PR (Version 4) are based on disdrometer measurements from Darwin, Australia.
In principal, comparison of radar reflectivity over a network of rain gauges at the surface can help define the bias created by the factors mentioned above (Joss and Waldvogel 1990, Smith 1990, Steiner et al. 1995). However, there are temporal and spatial drawbacks to comparing rain gauge data and radar reflectivity. A rain gauge network consists of nearly continuous measurements of discrete, practically infinitesimal points, while a ground radar covers a much larger area but has a typical resolution of 2 km x 2 km and only samples roughly every 10 minutes. However, these drawbacks are accepted due to the greater uncertainty of deriving surface precipitation from radar reflectivities without any form of Z-R adjustment.

One method of gauge-radar adjustment is to calculate the monthly amount of rain at each gauge and at the radar pixel above each gauge (using a standard Z-R relation to convert reflectivity into rainrate). Then the average ratio of gauge to radar monthly accumulations is used to adjust the Z-R relation assuming the gauges to be ground truth (Steiner et al. 1995). However, this method is often not viable at Kwajalein because there are too many gaps in the rain gauge and radar data for a sufficient number of full data months. A slight variation allows the use of more data and thus a more robust adjustment. When there is rain at both the gauge and radar pixel above the gauge, the gauge data 10 min centered on the time of the radar’s lowest sweep is summed and the radar rainrate is assumed to exist for 10 minutes. These values are then summed for the monthly amounts of radar estimated rainfall and gauge estimated rainfall. A common gauge to radar ratio is 1.5 to 2, suggesting that the factors discussed previously that affect the relation between measured radar reflectivity and surface precipitation are significant at Kwajalein.

Although most of the Kwajalein validation site is oceanic, the infrastructure on the handful of islands controlled by the Kwajalein Missile Range can at times cause severe surface clutter at specific points in range of the radar. Some radar pixels above the gauges within 50 km of the radar are affected by clutter due to their proximity to the radar and the presence of tall towers on the gauge island (Fig. 2.6). The Kwajalein and Carlos gauges are
within 15 km of the radar and are in perpetual clutter. This negates their usefulness for
gauge-radar adjustments. Meck, Legan and Illeginni are affected by clutter to varying
degrees but some useful data can be extracted from these sites for gauge-radar adjustment
by either using higher radar elevation angles or by using only the pixels around the island
and not the pixel over the island itself. Lae and Wotja are located over 150 km from the
radar so are not viable for radar-gauge adjustment. These factors greatly limit the usefulness of the Kwajalein rain gauges.

Figure 2.6 KR surface clutter. The edge of the 0.4° beam is always intercepted by the
infrastructure at Carlos and intermittently by the infrastructure at Meck, Legan, and
Illeginni depending on the index of refraction.
2.7 Kwajalein climatology

For eight months of the year (May-December), Kwajalein receives over 200 mm of rain per month. Fig. 2.7 illustrates that the average gauge monthly accumulation has been generally lower than Kwajalein Island’s climatological norm since the TRMM launch. Especially disconcerting was the drought that occurred at Kwajalein January through June, just after the TRMM launch in November 1997. Average rain gauge monthly accumulations were less than 40 mm for that period with only one exception. June averaged 100 mm, which was still well below the climatological value of 245 mm.

![Figure 2.7](image-url)

**Figure 2.7** Kwajalein area average gauge monthly accumulations (bars) compared to Kwajalein Island’s gauge climatology. The number of gauges used for each monthly average are indicated before the month. TRMM launch was in late November 1997, soon after Kwajalein had a serious drought.
Tipping-bucket rain gauge data at Kwajalein Island for March 1997-March 1999 were separated into individual events, defined as having a minimum of two tips and no more than 30 min between tips. There were 719 events over two years. Cumulative frequency plots of rain event accumulations and durations for this period indicate that rain events at Kwajalein are generally short-lived and intense with only a small percentage lasting for longer periods and accumulating large amounts of rain. The cumulative frequency plot of event total rainfall amounts shows a sharp slope for the lightest 75% of the events with total rainfall < 5 mm (Fig. 2.8a). For the most significant 25% of events the curve begins to approach an asymptote and very few events achieve accumulations of 25 mm (1 inch). The maximum event accumulation was 68 mm. Similarly, in the cumulative frequency plot of rain event durations, there is a sharp slope for the shortest 75% of events, those < 30 min. The slope then decreases indicating that few events are much longer than three hours (Fig. 2.8b). The maximum event duration was 11 h. These calculations are consistent with radar data for the same two-year period in which echoes were generally isolated, convective, and short-lived. Long-lasting systems that possess large stratiform areas occur relatively infrequently.

**Figure 2.8** (a) Cumulative frequency plot for rain event accumulations using Kwajalein Island rain gauge from March 1997-March 1999. Vertical lines mark 5 and 25 mm. (b) Cumulative frequency plot for rain event durations. Vertical lines mark 30 and 180 min.
Average monthly sea surface temperatures (SST) for the Kwajalein validation area range between 27 and 30°C (Fig. 2.9). Lower SST occur during months of low rain (January-April). Kwajalein lies on the northern edge of the inter-tropical convergence zone’s northern migration (July-November, Fig. 2.9a). Kwajalein also lies on the eastern edge of the west Pacific warm pool (May-December, Fig. 2.9b).

**Figure 2.9** (a) Time series of climatological SST at 165°E based on Reynolds and Smith (1994). The solid line indicates the position of the KR. (b) As above but for 8°N.

1. Reynolds and Smith (1994) SST climatology data were provided by the IRI/LDEO Climate Data Library at http://ingrid.ldgo.columbia.edu/SOURCES/.IGOSS/.ncm/.
Relative humidity at Kwajalein generally remains above 80% with a stronger peak during April-June and a weaker peak from September to November (Fig. 2.10). Scalar wind speeds range between 4 and 8 m/s with stronger winds occurring during January-April (when monthly SST and rain accumulations are lowest). The climatological zonal wind component at Kwajalein is always westerly while the meridional wind component is generally northerly except for a brief switch to southerlies in September.

![Figure 2.10](image)

**Figure 2.10** Time series of COADS climatological values at 165ºE for relative humidity, scalar wind speed, zonal wind, and meridional wind.

---

1. COADS climatological data were provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado at http://www.cdc.noaa.gov/.
3. Validation of the TRMM PR measurements

A dearth of events limited validation of the TRMM PR at Kwajalein during the first months of the mission. The 215 km swath of the PR overlaps the 150 km radius area around the KR 15-20 times each month. Only half of these swaths cover more than 50% of the ground validation area and of these only a few actually occur when significant rain is present. For example, Fig. 3.1 shows overpasses in September 1998, climatologically a rainy month. Ground radar echo is overlaid in black. In addition, a drought during January-June 1998 exacerbated the limited opportunity for PR/KR comparisons (see Sec. 2.7, Fig 2.7). As a result, events for comparison effectively began in the second half of 1998.

Figure 3.1 PR swaths over Kwajalein for September 1998. Circle radius is 150 km, centered on the KR. KR echo is outlined in black. Date, time, orbit number, and distance of subsatellite point from the KR is indicated for each overpass.
Fifty events between August 1998 and August 1999 had reasonable PR/KR overlap and precipitation (Table 3.1). This chapter presents statistical analyses of all 50 cases along with a brief case study of orbit 5712 (passing over Kwajalein on 25 November 1998). We compare PR and KR reflectivities, convective-stratiform separations and rainmaps of instantaneous events. Sampling issues will be addressed in Chapter 4.

Table 3.1. 50 PR overpasses with significant rain over Kwajalein August 98-August 99.

<table>
<thead>
<tr>
<th>Date</th>
<th>Orbit</th>
<th>Dist</th>
<th>Date</th>
<th>Orbit</th>
<th>Dist</th>
</tr>
</thead>
<tbody>
<tr>
<td>98-08-09</td>
<td>00:49 UTC</td>
<td>4008</td>
<td>101</td>
<td>99-02-09</td>
<td>11:20 UTC</td>
</tr>
<tr>
<td>98-08-15</td>
<td>21:10 UTC</td>
<td>4116</td>
<td>26</td>
<td>99-02-27</td>
<td>15:34 UTC</td>
</tr>
<tr>
<td>98-08-20</td>
<td>05:20 UTC</td>
<td>4184</td>
<td>83</td>
<td>99-03-01</td>
<td>14:45 UTC</td>
</tr>
<tr>
<td>98-08-24</td>
<td>16:50 UTC</td>
<td>4255</td>
<td>156</td>
<td>99-03-03</td>
<td>23:41 UTC</td>
</tr>
<tr>
<td>98-08-31</td>
<td>13:10 UTC</td>
<td>4363</td>
<td>75</td>
<td>99-03-06</td>
<td>11:51 UTC</td>
</tr>
<tr>
<td>98-09-04</td>
<td>21:20 UTC</td>
<td>4431</td>
<td>130</td>
<td>99-04-22</td>
<td>11:44 UTC</td>
</tr>
<tr>
<td>98-09-07</td>
<td>09:30 UTC</td>
<td>4471</td>
<td>3</td>
<td>99-05-03</td>
<td>16:13 UTC</td>
</tr>
<tr>
<td>98-09-11</td>
<td>17:40 UTC</td>
<td>4539</td>
<td>57</td>
<td>99-05-10</td>
<td>12:36 UTC</td>
</tr>
<tr>
<td>98-09-18</td>
<td>13:57 UTC</td>
<td>4647</td>
<td>21</td>
<td>99-05-21</td>
<td>20:23 UTC</td>
</tr>
<tr>
<td>98-09-21</td>
<td>02:11 UTC</td>
<td>4687</td>
<td>143</td>
<td>99-06-22</td>
<td>04:15 UTC</td>
</tr>
<tr>
<td>98-09-23</td>
<td>01:30 UTC</td>
<td>4718</td>
<td>53</td>
<td>99-06-26</td>
<td>12:22 UTC</td>
</tr>
<tr>
<td>98-10-08</td>
<td>17:18 UTC</td>
<td>4965</td>
<td>100</td>
<td>99-07-03</td>
<td>08:45 UTC</td>
</tr>
<tr>
<td>98-10-29</td>
<td>06:28 UTC</td>
<td>5289</td>
<td>122</td>
<td>99-07-07</td>
<td>20:10 UTC</td>
</tr>
<tr>
<td>98-11-02</td>
<td>14:36 UTC</td>
<td>5357</td>
<td>71</td>
<td>99-07-12</td>
<td>04:18 UTC</td>
</tr>
<tr>
<td>98-11-07</td>
<td>02:02 UTC</td>
<td>5428</td>
<td>3</td>
<td>99-07-16</td>
<td>15:44 UTC</td>
</tr>
<tr>
<td>98-11-18</td>
<td>06:32 UTC</td>
<td>5604</td>
<td>22</td>
<td>99-07-20</td>
<td>23:51 UTC</td>
</tr>
<tr>
<td>98-11-20</td>
<td>05:43 UTC</td>
<td>5635</td>
<td>176</td>
<td>99-07-25</td>
<td>21:02 UTC</td>
</tr>
<tr>
<td>98-11-25</td>
<td>02:51 UTC</td>
<td>5712</td>
<td>97</td>
<td>99-07-28</td>
<td>09:16 UTC</td>
</tr>
<tr>
<td>98-11-29</td>
<td>14:19 UTC</td>
<td>5783</td>
<td>32</td>
<td>99-08-03</td>
<td>16:34 UTC</td>
</tr>
<tr>
<td>98-12-05</td>
<td>21:38 UTC</td>
<td>5882</td>
<td>213</td>
<td>99-08-10</td>
<td>12:56 UTC</td>
</tr>
<tr>
<td>98-12-10</td>
<td>18:49 UTC</td>
<td>5959</td>
<td>49</td>
<td>99-08-17</td>
<td>09:18 UTC</td>
</tr>
<tr>
<td>98-12-12</td>
<td>18:01 UTC</td>
<td>5990</td>
<td>149</td>
<td>99-08-19</td>
<td>08:30 UTC</td>
</tr>
<tr>
<td>98-12-17</td>
<td>15:12 UTC</td>
<td>6067</td>
<td>113</td>
<td>99-08-23</td>
<td>19:55 UTC</td>
</tr>
<tr>
<td>98-12-22</td>
<td>02:38 UTC</td>
<td>6138</td>
<td>38</td>
<td>99-08-28</td>
<td>17:06 UTC</td>
</tr>
<tr>
<td>99-01-22</td>
<td>10:30 UTC</td>
<td>6632</td>
<td>59</td>
<td>99-08-30</td>
<td>16:17 UTC</td>
</tr>
</tbody>
</table>
3.1 Reflectivity comparisons

Quantitative comparison of the PR and KR is complicated by their significantly different wavelengths, sensitivities, scan strategies and scattering volumes. Attenuation at the PR’s operating frequency (13.8 GHz) occurs most severely at lower altitudes where rain is heaviest. The PR observes downward from the storm top so that upper levels are not affected by the attenuation that occurs closer to the surface. The S-band KR does not suffer from attenuation, but its lowest beam starts at the surface and attains a height of 2 km 150 km from the radar (Fig. 2.3). Therefore, both the PR and KR have difficulty making true measurements of near-surface reflectivity.

The PR’s minimum sensitivity is 17 dBZ whereas the KR can see < 0 dBZ. This difference in sensitivity allows quantification of how much rain and rain area the PR misses owing to its 17 dBZ threshold. Both radars have 250 m gate spacing. This high resolution along the beam results in the PR having excellent vertical resolution because it is quasi-downward looking, and in the KR having excellent horizontal resolution because it looks out quasi-horizontally. Both radars experience beam spreading which affects spatial resolution. The PR’s beam spreads to a ~4 km footprint by the time it reaches the surface while the KR beam spreads to ~3 km at a distance of 150 km from the radar. In order to perform meaningful statistics, the PR and KR data need to be interpolated to comparable but still meaningful scales (i.e., it would not be appropriate to interpolate the KR data to match the 250 m vertical resolution of the PR or to interpolate the PR to horizontal scales less than its 4 km footprint). Using NCAR SPRINT software (a bilinear interpolation scheme based on Mohr and Vaughn 1979), the KR volumes were mapped to grids of 4 km horizontal resolution and 1 km vertical resolution. The PR data were kept to their original footprint size and averaged every kilometer in the vertical. In principal, one should disregard any data > 100 km from the KR because of beam spreading. For this study, this limitation was relaxed in order to have a larger sample size with which to compare the PR and KR. Preliminary tests showed that results were not dramatically different when KR data were included out to a 150 km range.
We begin by mapping data from the orbit 5712 event to see qualitatively what each instrument observes. At 0251 UTC 25 November 1998, the TRMM satellite passed within 97 km of the KR. The KR 3 km horizontal cross-section shows a pattern of relatively small convective cells, some with reflectivity up to 40 dBZ, interconnected in places by lighter precipitation (Fig. 3.2a). The PR 3 km horizontal cross section interpolated onto a 4 km × 4 km Cartesian grid (2A25, Fig. 3.2b) is generally consistent with the KR cross section in location and intensity of echo. The PR echo < 17 dBZ (represented by darker blue and purple) is unconnected and random, indicating noise. The KR has a realistic contiguous low reflectivity structure. Vertical cross sections constructed at PR ray 28 (Fig. 3.3a and b) show the convective cells had similar basic structure and heights; the 25 dBZ contour is consistently ~5 km for both radars. The PR had a more well-defined bright band in the middle cell (Fig. 3.3b) because of its greater vertical resolution. In each cross section, the anvil of the cell farthest east is very similar in structure and intensity. Fig. 3.3c is the difference between the attenuation-corrected and uncorrected PR cross sections. The magnitude of the difference at each level is between 0 and 4 dB. Strong convective cells demand the most correction while weaker stratiform areas have need of only small corrections. In addition, the bright band requires some correction.

**Figure 3.2** Convective precipitation case observed on 0251 UTC 25 November 1998. Three km horizontal cross sections of the (a) KR and (b) PR reflectivity data. The line indicates PR ray 28. The missing beam directly north of the KR occurs in the raw data.
Figure 3.3 Vertical cross sections of the case in Fig. 3.2 at PR ray 28 using (a) interpolated KR reflectivity data, (b) attenuation-corrected PR reflectivity data, and (c) the difference between attenuation-corrected and uncorrected PR reflectivity fields.
Histograms of the accumulated echo area versus reflectivity at six different heights for all 50 overpass cases indicate the vertical variation of the PR and KR data at heights up to 8 km (Fig. 3.4). Weak reflectivities not considered “rain certain” by 2A25 were removed from the PR histogram counts.

**Figure 3.4** Histograms of KR and PR reflectivity distributions accumulated at six different heights for the 50 overpass cases. Vertical line marks 17 dBZ to indicate the limit of the PR sensitivity. Counts are total number of 4 x 4 km pixels.
The PR does not sense the peaks of the true distributions, which are seen by the KR to be centered at 15-20 dBZ below the 0°C level (~5 km), decreasing to 8 dBZ by 8 km. The KR detects less echo above the 17 dBZ threshold than the PR at 3, 4, 7 and 8 km. Different wavelengths, sensitivities, scan strategies, and scattering volumes all potentially play a role in offsetting the amount of echo observed by each radar.

The distributions agree best at 5 and 6 km which is consistent with Steiner and Houze’s (1998) conclusion that PR data will be most reliable from 5-7 km because it highly attenuates below the 0°C level (~5 km) and there is little to no reflectivity data ≥ 17 dBZ observed at heights above 7 km. The amount of echo area 0-16 dBZ compared to the total echo area ≥ 0 dBZ (indicating the percent of echo area missed by the PR) is listed in Table 3.2 for each height in Fig. 3.4. Below 5 km, the PR detects about half of the echo area. Once above 5 km, the PR misses the majority of the reflectivity field. In order to explore the sensitivity of the analysis to the KR calibration, Table 3.2 also includes the percentages assuming an additional +2 dB calibration offset to the KR. A +2 dB offset only marginally affects the results. Table 3.2 highlights that the low sensitivity of the PR prevents it from detecting widespread, lower-reflectivity precipitation at lower levels and most of the ice region aloft.

<table>
<thead>
<tr>
<th>height (km)</th>
<th>% area 0-16 dBZ</th>
<th>% area +2dB/-2dB</th>
<th>height (km)</th>
<th>% area 0-16 dBZ</th>
<th>% area +2dB/-2dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>51</td>
<td>47/57</td>
<td>6</td>
<td>72</td>
<td>64/79</td>
</tr>
<tr>
<td>4</td>
<td>51</td>
<td>47/57</td>
<td>7</td>
<td>87</td>
<td>80/92</td>
</tr>
<tr>
<td>5</td>
<td>57</td>
<td>52/64</td>
<td>8</td>
<td>94</td>
<td>89/97</td>
</tr>
</tbody>
</table>

Table 3.2. KR rain area distributions.
The role of the attenuation correction is explored in Fig. 3.5 which plots histograms of PR corrected (2A25) and uncorrected (1C21) 4 km x 4 km pixel count versus reflectivity at six heights for the 50 overpasses. As to be expected, the largest differences between PR distributions occurs at lower levels (2-3 km) where precipitation is heaviest. The 2 km panel shows the most clear correction, with uncorrected data at 20-35 dBZ being shifted to corrected values of 35-45 dBZ. The peak of the uncorrected values $< 20$ dBZ is noise. The corrected curves indicate only “rain certain” pixels.

Figure 3.5 As in Fig. 3.4 but for PR attenuation-corrected (2A25) and uncorrected (1C21) reflectivity data at heights of 2-7 km.
A different perspective of frequency distributions that includes all the vertical information in the data is possible using Contoured Frequency by Altitude Diagrams (CFAD), a statistical graphing technique outlined in Yuter and Houze (1995). The PR and KR CFADs for a highly stratiform case (20 August 1998, orbit 4184) and more convective case (18 September 1998, orbit 4647) also show agreement within the range of the PR’s sensitivity (Fig. 3.6a-b, d-e). The full KR CFADs indicate how much can be seen with the KR that cannot be seen with the PR (Fig. 3.6c, f). The stratiform CFADs from August (Fig. 3.6a-c) show a tendency for maximum reflectivity just below the 0°C level (nominally placed at 5 km) with a narrow distribution marked by packed contours just above the level of maximum reflectivity. There is a hint of the ice region in panels (a) and (b), but there is not enough data (> 20% of the largest level in the volume) at levels above 6.5 km in altitude to construct significant contours. The convective CFADs from September (Fig. 3.6d-f) exhibit a broad distribution marked by loose contours, and again the ice mode is suggested in panels (d) and (e) up to heights of 8.5 and 7.5 km, respectively.

Much microphysical information can be inferred from CFADs. Contours in the stratiform KR CFAD (Fig. 3.6c) show a narrow distribution of reflectivity at any given height above the freezing level. The mode of this narrow distribution increasing downward is consistent with ice particles drifting down, growing at higher levels by vapor deposition and then by aggregation closer to the 0°C level, thus producing higher reflectivities. The KR convective CFAD (Fig. 3.6f) has a broad distribution (loose contours) aloft. Higher reflectivities in this broad distribution aloft indicate a predominance of graupel, consistent with convective drafts favoring growth of particles by riming. The convective case has a mode with a more vertical slope in the ice region than the stratiform case which suggests aggregation wasn’t an important process. Despite the loss of information from its low sensitivity, the PR data still manages to look different in the convective and stratiform CFADs (Fig. 3.6a and d), indicating that part of the microphysical distinction between the two types of precipitation can be captured by the PR. The next step is to separate the convective and stratiform components of each event.
Figure 3.6 PR and KR CFADs for a (a-c) highly stratiform case that occurred on 20 Aug 98 (orbit 4184) and (d-f) highly convective case that occurred on 18 Sep 98 (orbit 4647). The first two CFADs for each case have cutoffs at 17 dBZ whereas the third CFAD indicates the full range of KR measurements and microphysical information.
3.2 Subdivision of rainfall into convective and stratiform categories

The PR and KR algorithms used to divide radar echo patterns into convective and stratiform components are based on the horizontal variability of reflectivity (Steiner et al. 1995, Awaka et al. 1997). In the Steiner et al. (1995) method, any grid point with a reflectivity $\geq 40$ dBZ is automatically considered convective—very rarely is radar echo of this intensity found in stratiform rain. Next, the algorithm examines the peakedness of each grid point. If the reflectivity at a grid point not already identified as convective exceeds a prescribed value typifying the surrounding grid points, it is considered convective (e.g., a point with a reflectivity value of 30 dBZ that is, on average, 10 dB greater than the surrounding grid points might be labeled convective whereas if it was only 3 dB greater it would be labeled stratiform). The higher the grid value, the smaller the surrounding grid reflectivity difference need be for it to be considered convective. Once a point is classified convective, a convective radius is assigned to it so that neighboring pixels become part of the convective entity centered on this point. All other points not defined as convective by any of the criteria above are labeled stratiform.

The PR algorithm contains an additional condition based on the vertical structure of the radar echo. The high vertical resolution (250 m at nadir) and nearly vertical beam of the PR allow it to detect a bright band a higher percentage of the time than a ground radar; therefore the PR algorithm uses the presence of the bright band as a primary indicator of stratiform precipitation. However, detection of the brightband by the PR is angle dependent with a detection efficiency of 80% near nadir ($\pm 7^\circ$) decreasing to 20% at the scan edge ($\pm 17^\circ$). The bright band enters the KR convective-stratiform separation only indirectly. The KR algorithm is tuned specifically for Kwajalein and the presence of the bright band helps calibrate the horizontal structure analysis.
It should be noted that an intermediary category exists when convective cells age and are turning stratiform. However, Mapes and Houze (1993) and Yuter and Houze (1995) found this category to be more statistically and dynamically stratiform in its divergence profiles and bulk microphysical characteristics. Thus, intermediary echo is most safely categorized as stratiform in terms of large-scale latent heating profiles.

The KR and PR convective-stratiform maps for orbit 5712 are shown in Fig. 3.7. The larger convective areas match well for the KR and PR maps. However, the KR map identifies more isolated convective elements than the PR. This incongruity is either because of the different algorithms or because the KR has higher horizontal resolution than the PR with which to create more accurate $4 \text{ km} \times 4 \text{ km}$ grid values, thus bypassing some of the effects of non-uniform beam filling. An additional difference between the maps is that the PR algorithm has an undecided category, which upon inspection appears to be either stratiform echo or noise.

![Convective-stratiform maps for the case in Fig. 3.2 for (a) KR and (b) PR. The KR convective-stratiform separation utilizes only two categorizations: one for convective, one for stratiform, whereas the PR algorithm has a third undecided category.](image)

**Figure 3.7** Convective-stratiform maps for the case in Fig. 3.2 for (a) KR and (b) PR. The KR convective-stratiform separation utilizes only two categorizations: one for convective, one for stratiform, whereas the PR algorithm has a third undecided category.
The convective and stratiform rain areas ≥ 17 dBZ for the 50 overpasses (Fig. 3.8) show that the KR and PR convective-stratiform classifications match well. The ratio of the sum of the individual overpass values (KR/PR) for convective rain area is 1.13 and for stratiform rain area is 0.90; correlations are 0.84 and 0.98 respectively. The KR/PR values and correlations near one indicate fairly consistent areal convective-stratiform classification between the two radars. An additional KR calibration offset of +2 dB (-2 dB) increases (decreases) the KR convective area by 25% and the KR stratiform area by 10%. Therefore, convective rather than stratiform rain areas ≥ 17 dBZ are more sensitive to calibration offsets.

**Figure 3.8** KR versus PR. (a) Convective and (b) stratiform areas ≥ 17 dBZ for all 50 overpasses. KR/PR is the average ratio between individual overpass KR and PR areas. Areas are 10³ km².
3.3 Rainrate

Near surface reflectivity from the KR is converted to rainrate using a single climatological $Z-R$ relation, while the near surface rainfall rate estimates from the PR (2A25) are calculated using separate convective and stratiform $Z-R$ relations (see Section 2.6, Fig. 2.5). Fig. 3.9 illustrates the KR and PR 3 km rainmaps for orbit 5712 using each radar’s respective $Z-R$ relations, the maps are qualitatively very similar. The KR has sharper rainrate peaks and a larger area of small rainrates.

![Rainrate maps for the case in Fig. 3.2 for (a) KR and (b) PR. Each instruments respective $Z-R$ relation was used.](image)

Area-integrated precipitation rates (kg/h) at 3 km height for the PR and KR were calculated for the 50 overpasses using, first, the Kwajalein climatological $Z-R$ relation and, then, the respective $Z-R$ relations of each instrument (Fig. 3.10). The KR/PR value for the total precipitation field $\geq 17$ dBZ using the Kwajalein $Z-R$ relation was 0.99 with a correlation of 0.96, indicating that the KR and PR rain amounts match almost exactly with little variation (Fig. 3.10a). The convective component of the KR/PR value was 1.05 (Fig. 3.10b).
3.10b), whereas the stratiform component was 0.92 (Fig. 3.10c). Thus the KR and PR convective and stratiform rain amounts both agree within 10%. An additional KR calibration offset of +2 dB (-2 dB) leads to an increase (decrease) of ~60% in KR convective rain amount and ~35% in KR stratiform rain amount. Rain amount is more sensitive to calibration offsets than rain area.

Calculations applying the PR $Z$-$R$ relation to the PR data gave similar results to using only the Kwajalein $Z$-$R$ relation (Fig. 3.10). The two PR $Z$-$R$ relations ascribe 7% less rain to PR total rain amounts (2% less to convective events and 13% less to stratiform events) than the single Kwajalein $Z$-$R$ relation.

**Figure 3.10** Area-integrated precipitation rate ($10^{10}$ kg/h) for the KR and PR. KR/PR values represent the average ratio between individual overpass KR and PR area-integrated precipitation rates.

Fig. 3.11 is meant to synthesize Chapter 3; it represents KR and PR echo area and rain amount histograms at 3 km height accumulated for all 50 overpasses, the long dashes depict the PR’s 17 dBZ sensitivity. Panel (a) shows total KR and PR echo area as already seen in Fig. 3.4a and panel (b) displays the echo area distribution converted to rain amount.
using only Kwajalein’s climatological Z-R relation. Reflectivities < 8 dBZ are not considered measurable by the Kwajalein Z-R relation. The relatively small differences between the KR and PR’s Z-R relations and resulting rainmaps are discussed in Secs. 2.6 and 3.3. Above the 17 dBZ threshold, the KR and PR have fairly similar distributions, although the KR area is less when reflectivities are between 20 and 38 dBZ. Note that this comparison does not hold at other heights (Fig. 3.4). The difference in area covered translates to the rain amount distribution with the PR showing greater accumulations between 0.4 and 15 mm/h. The left side of the 17 dBZ threshold illustrates the cessation of PR measurements and the extent of rain area and amount the PR misses as a result. The KR is capable of measuring these lower reflectivities and shows large rain area coverage but very little rain accumulation below the 17 dBZ threshold—51% of rain area and 3% of rain amount is < 17 dBZ at 3 km. These percentages are excellent validation for PR rain amounts but leaves much to be desired concerning PR rain patterns.

The total echo area and rain amount histograms were separated into convective and stratiform components (Fig. 3.11c-f). Immediately obvious is the small amount of area covered by convective echoes with the majority of echo area accounted for by stratiform precipitation (Fig. 3.11c,e). More specifically, 20% of rain echo area ≥ 17 dBZ is convective for both the KR and PR, while the other 80% is stratiform. There is a more equitable distribution between convective and stratiform processes for rain amount (Fig. 3.11d,f). The convective amounts sharply peak between 35 and 40 dBZ (8-21 mm/h) while the stratiform amounts have a more gentle peak ~30 dBZ (3 mm/h). Convective percentage of rain amount ≥ 17 dBZ is 48% for the two radars, while the other 52% is stratiform. Including reflectivities ≥ 0 dBZ, convective and stratiform percentages of rain area not sensed by the PR are 23 and 55%, respectively. Only 0.5% of convective rain and 5.5% of stratiform rain occurs below 17 dBZ. Thus PR convective-stratiform rain-amount statistics based on PR data are accurate, but rain area statistics are not, especially for stratiform areas.
Figure 3.11 Histograms of KR and PR reflectivity and rain distributions accumulated at a height of 3 km for the 50 overpass cases. Vertical line marks 17 dBZ to indicate the limit of the PR sensitivity. (a) Total echo area, (b) total rain amount, (c) convective area, (d) convective rain, (e) stratiform area, and (f) stratiform rain.
4. Characterization of longer scale precipitation at Kwajalein

Whereas Chapter 3 focused on instantaneous comparisons between the KR and PR, Chapter 4 addresses temporal sampling of the TRMM satellite. Longer time-scale measures of precipitation, such as seasonal frequency distributions, monthly rainmaps and diurnal accumulations, will be the vehicles of comparison.

4.1 PR sampling of reflectivity distributions

The composites of all 50 overpass cases use events throughout a year so any seasonal differences in distributions would be obscured. Fig. 4.1 plots normalized monthly frequency distributions of total echo area and rain amount using the entire KR data set. To simplify processing, the lowest tilt in the KR scan strategy (usually 0.4°) was used in the following analyses as opposed to a constant height cross-section (thus we avoid interpolating the full set of 17-22 elevation angles obtained at each observation time). Very little difference is evident in the monthly area distributions from August 1998 to May 1999 (Fig. 4.1a). Then a shift occurs for the months June through August 1999. This shift could either be a function of seasonal or annual variation in distributions or be related to the major upgrades and repairs to the KR that occurred during late-May to late-June 1999. The calibration has already been taken into account. Interestingly, the shift is not evident in the rain amount distributions which have very little variation month to month, except for January 1999 which was a period of low rainfall (Fig. 4.1b).

As an independent check of the distribution shift, KR and PR data was combined before and after June 1999 (Fig. 4.2). Panel (a) shows two distinct area distributions for the KR, with higher reflectivities emphasized in the second period. Panel (b) shows some change in PR area distributions between the two periods, with higher reflectivities more prevalent in the second period. However, a shift in the peak is hard to discern because the real peak occurs at or below the PR’s sensitivity. A concern is the quantification of rain area and
amount that the PR misses as a result of its low sensitivity. In the first period, the KR observes that 52% of rain area and 2.2% of rain amount is < 17 dBZ while in the second period the percentages are 31% and 1.5%, respectively. A longer time series is necessary before definitive description of seasonal to annual variation in the radar data is possible.

Figure 4.1 Monthly frequency distributions of KR (a) total echo area and (b) total rain amount.
Setting aside possible seasonal variations in reflectivity distributions, we next extracted the KR data delineated by the 50 overpass swaths of the PR and compared them to the complete KR distributions from August 1998-August 1999 (Fig. 4.3). Both frequency distributions of KR echo area versus near surface reflectivity show a distribution with a peak of reflectivity between 10 and 15 dBZ (Fig. 4.3a). The distributions, converted to rainfall using Kwajalein’s climatological Z-R relation, show that most of the near-surface precipitation occurs when reflectivities are > 17 dBZ (Fig. 4.3d). Whereas 46% of KR near-surface echo area ≥ 0 dBZ is not seen by the PR because of its sensitivity; only 2.3% of near-surface rainfall is missed (similar to the percentages at 3 km height of 51 and 3%). These numbers are the same for both the overpass subset and the entire KR period. An additional KR calibration offset of +2 dB (-2 dB) changes these percentages to 40 (53) and 1.5% (3.4%) respectively; therefore the percentages are robust to moderate calibration offsets.

**Figure 4.2** KR and PR reflectivity frequency distributions for the time periods of August 1998-May 1999 and June 1999-August 1999.
The echo area overpass subset (Fig. 4.3a) undersamples reflectivities greater than 25 dBZ compared to the entire KR period. The undersampling of higher reflectivities places more emphasis on lower reflectivities which shifts the rain amount distributions such that the overpass peak of rainfall occurs at a lower reflectivity (Fig. 4.3d). Panels (b, c, e, f) illustrate the contribution by the convective and stratiform components to the sampling discrepancies highlighted by (a) and (b). It appears the undersampling of higher reflectivities and thus the shift in distribution by the overpass subset is equally distributed between the convective and stratiform distributions. Otherwise, the convective and stratiform overpass distributions match the total KR distributions nicely.

**Figure 4.3** Frequency distributions comparing KR distributions for August 1998-August 1999 and the KR overpass subset at near surface. Vertical dashed line indicates the PR 17 dBZ threshold.
Sample size is important if PR data are used at shorter time scales. Up to this point we have been working with 50 overpasses from 13 months of data. Sample sizes less than 50 might not necessarily approach climatological distributions. During the rainy (dry) season, one can expect 5-7 (2-3) reasonable PR overpasses per month in terms of overlap and rain amount. Fig. 4.4 plays out a time series for the first 20 overpasses (August-November 1999). The solid line indicates the KR rain amount distribution for the entire four month period while the dashed line shows the successive accumulation of KR overpass data. The exercise is to determine how quickly the overpass subset can approach the climatological distribution, if at all. Consider every five overpasses a month. The first month is rocky as the distribution tries to approach some sort of equilibrium. The second month substantially stabilizes the distribution. Finer alterations occur during the third and fourth months, however higher reflectivities remain undersampled. Apparently ~10 overpasses (or approximately 2 months) are desirable for longer term statistics.

Figure 4.4 Time series of KR overpass rainrate frequency distributions (dashed) being continually added in order to approach the Aug-Nov 1998 KR distribution (solid).
4.2 PR and TMI sampling of monthly precipitation

TPSN 3A25 bins monthly data from 2A23 and 2A25 into 5º and 0.5º grids. The Kwajalein validation site is located in the upper half of the 5º grid covering 5ºN to 10ºN and 165ºE to 170ºE (Fig. 4.5). A set of 25 0.5º grids overlaps most of the Kwajalein validation area. The 5º grid size allows more monthly samples than the 0.5º grids, but there is a trade-off in lower spatial resolution. The validation area covers only a fourth of the larger grid, therefore quantitative comparisons are done between the 25 smaller grids and the Kwajalein instrumentation. However, the applicability of the larger grids will be touched upon.

![Diagram showing Kwajalein validation site in relation to PR 0.5º and 5º monthly products.]

**Figure 4.5** Kwajalein validation site in relation to geometry of PR 0.5º and 5º monthly products.

PR monthly rain amounts are calculated as follows:

\[
3A25 \text{ monthly rain accumulation} = \text{avg rainrate} \times \text{probability of rain} \times \# \text{ hours in month}
\]

where \(\text{probability of rain} = \# \text{ pixels with rain} / \# \text{ total pixels in swath}\)
TPSN 3A26 provides a different method of estimating space-time rain statistics using only the middle of the measured probability distribution function and assuming a log-normal form for the tails where noise and attenuation cause uncertainties. This method is still being tested and thus the 3A25 product is recommended for current research purposes.

Fig. 4.6a compares the 1998-99 monthly rain accumulations of the Kwajalein gauges, near-surface KR, and near-surface PR over the validation area. The gauges provide a complete time series whereas the KR has intermittent monthly accumulations. The gauges and KR agree well in trends but the gauge accumulations are generally 40% larger. This difference in magnitude partly has to do with the factors discussed in Secs. 2.3 and 2.4, i.e., gauges are point-source, isolated instruments on the ground whereas radars measure much larger areas sometimes a kilometer or more above the surface. In addition, the gauges represent only a small fraction of the area covered by the radar. We do not expect the gauges to accurately capture the monthly rain accumulation for the entire validation area.

The PR accumulations approximate the KR’s during the rainy season of 1998 but are generally less during the rainy season of 1999. The differences are most likely a matter of satellite sampling. Rain events at Kwajalein tend to be intense and short-lived so that events are easily missed by the relatively narrow PR swath. However, these short-lived events occur often so that the PR has the potential to capture accurate rain amounts in a probabilistic sense.

The TRMM Microwave Imager (TMI) is not a focus of this study but it is nevertheless interesting to compare it to the PR for monthly accumulations. The TMI swath is 3.5 times wider than the PR’s, thus its sampling is considerably better. Fig. 4.6b plots the 1998-99 monthly accumulations for the TMI¹ and PR over the 5° grid encompassing Kwajalein. The PR follows the trend of the TMI monthly accumulations but with lower magnitudes. It is not certain whether this offset is due to sampling, the TMI retrieval or the PR drop-size distribution assumptions, most likely it is a combination of all of these factors.

---

1. TPSN 3B31, “Rainfall Combined”, was used for the TMI monthly rain accumulations. High quality retrievals are calculated using coincident PR data to adjust the input hydrometeor profiles. The resulting correction is applied to the entire TMI swath.
The difficulty of the PR in capturing accurate monthly rain amounts throws into doubt the ability of the PR to capture monthly rain patterns. KR rainmaps for September 1998 and 1999 were accumulated from 6-10 min volumes of KR data (Fig. 4.7). PR and TMI subsets of the KR rainmaps illustrate the spatial rainfall patterns sampled by each instrument. The PR and TMI overpass rainrates were assumed to last one hour and then were added together. The lack of PR coverage during a one month period is striking. Referring back to Fig. 3.1, it is obvious that just a handful of events determine the monthly PR coverage. The TMI monthly rainmaps have significantly better coverage but the rainfall patterns still lack the cohesion of the full KR month.

Figure 4.6 (a) Gauge, KR and PR monthly rain amounts for the Kwajalein validation area and (b) TMI and PR monthly rain amounts for the 5º grid containing Kwajalein.
Figure 4.7 September 1998 (a) KR monthly rainfall map, (b) cumulative KR rainfall for PR overpasses, and (c) cumulative KR rainfall for TMI overpasses. Instantaneous KR rainrates (mm/h) were added together for the month assuming an hour duration for each rainrate. (d-f) As above, except for September 1999.
The September 1998 KR rainmap indicates a strong latitudinal precipitation gradient spanning the 300 km diameter region covered by the KR. Accumulations range from 250-300 mm in the southwest to 50-150 mm in the northeast. There was a concern that second-trip echoes could artificially produce such a strong gradient but gauge accumulations for this month independently corroborate the radar-observed spatial gradient (Fig. 4.8b). The sampling by the PR and TMI was insufficient to detect the north-south gradient. The September 1999 KR rainmap portrays a more homogeneous field with only the far northeast corner having lower accumulations than the rest of the validation area. The gauge accumulations mirror the lack of latitudinal gradient (Fig. 4.8c). The PR and TMI subsets seem to match the spatial pattern of the September 1999 KR rainmap better simply because no obvious pattern exists.

![Figure 4.8](image)

**Figure 4.8** Kwajalein area gauge monthly accumulations as a function of latitude for (a) September 1997, (b) September 1998, and (c) September 1999. The dashed vertical line represents the average monthly accumulation.
4.3 Relationship of monthly precipitation to SST

A physical explanation for the latitudinal precipitation gradient may be sea surface temperatures (SST). SST data for the Kwajalein area was obtained from the Reynolds and Smith (1994) optimum interpolation SST analyses. Kwajalein is on the eastern edge of the warm pool with an average September SST of 29.3°C (Fig. 4.9a). There tends to be a north-south SST gradient across the region covered by the KR in September, with an average 0.25°C higher SST to the south (Fig. 4.9b). A tongue of 29.4°C water extends out over the validation area centered on 7ºN.

![Figure 4.9](image-url) September SST climatology based on Reynolds and Smith (1994). (a) Across the Pacific basin. The solid contour represents 28.5°C. K indicates Kwajalein and the dashed box indicates the area plotted in (b). (b) In the vicinity of the Kwajalein validation site. The circle represents the 150 km radius around the KR. SST contours are in ºC.
Variability in the SST pattern around Kwajalein is evident in the past three Septembers (Fig. 4.10). September 1997 was dramatically different than climatology–SST actually decreased 0.4°C to the south. September 1997 was part of a strong El Niño, which could account for the anomaly. The gauges for this month showed very little latitudinal organization, e.g., the correlation between accumulations and latitude was 0.07. If anything, the gauge accumulations tended to increase with latitude (Fig. 4.8a). The September 1998 SST field had a sharper, warmer tongue to the south, centered on 5ºN. This is the closest of the three years to climatology. The gauges showed a significant latitudinal gradient this month (correlation = -0.96). In September 1999, the warm tongue is displaced even further south, centered on 3ºN. It is roughly of climatological magnitude, 29.4°C. The gauge accumulations show no relationship to latitude in September 1999 (correlation = 0.19).

Figure 4.10 SST in the vicinity of the Kwajalein validation site based on Reynolds and Smith (1994). (a) September 1997, (b) September 1998, and (c) September 1999. The circle represents the 150 km radius around the KR. SST are in °C.
These observations question the role of SST in precipitation patterns and amounts. The average SST for the validation area during these three Septembers ranged only from 28.6 to 29.2°C and the mean gauge accumulation ranged only from 220 to 232 mm (denoted by the dashed lines on Fig. 4.8). Thus, monthly averages of SST and rain accumulation indicate a stable and homogeneous physical system whereas analysis of the spatial patterns indicate the opposite. Rain patterns at Kwajalein depend not only on mean SST but also on SST gradients. The shifting nature of the warm tongue in Fig. 4.10 may indicate a variation in the location of the inter-tropical convergence zone (ITCZ) which appears to affect rainfall distribution across the validation area.

Fig. 4.11 illuminates somewhat the relationships between SST and rainfall in the validation area. Monthly rain accumulation and SST track very closely (Fig. 4.11a). Both show a seasonal cycle with the highest accumulations and SST occurring in June-December and the lowest in January-May. Note the drought of early 1998 occurred in conjunction with climatologically low SST (< 27.5°C). SST only went below 27.5°C three other times in the past 18 years (1983, 1992 and 1993), all of which were El Niño events (Fig. 4.12).

Fig. 4.11b plots the time series of correlations of SST (along 3-12°N, 167.5°E) and gauge accumulations with latitude. When correlations are near zero, there is no obvious latitudinal gradient for either variable. Correlations near +1 suggest a strong latitudinal gradient with higher values to the north, correlations near -1 indicate a strong gradient with higher values to the south. An SST gradient does not coincide with a precipitation gradient. For over 80% of the months, SST has correlations near -1 (warmer values to the south) with occasional spikes of positive correlation (warmer values to the north). 40% of the time rain accumulations have correlations close to -1 but are uncorrelated the rest of the time (no latitudinal explanation).
The different physical responses between SST and precipitation with latitude are more clear when both panels of Fig. 4.11 are compared. SST is at its lowest in January, as is precipitation. As SST increases, deeper convection is triggered and more precipitation is produced. In September, SST begins to track downward (possibly being limited by deep convection) toward typical January values. Near zero to positive SST latitudinal gradients tend to occur just after monthly rain amounts are highest (September to November). The sharpness of the SST gradient suggests a quick response where SST becomes more homo-

Figure 4.11 (a) Average monthly SST and gauge accumulations for the Kwajalein validation site. (b) Monthly SST and gauge accumulations correlated with latitude. There was insufficient gauge data for spatial correlations in the first half of 1998 as a result of the drought.
geneous with deep convection, at times even reversing its latitudinal gradient. SST then rapidly returns to a climatological gradient with warmer SST to the south as rainfall decreases. The time series of the precipitation latitudinal gradient is more variable with very little seasonal trend (perhaps because of the variability of precipitation itself or the sparseness of the gauges). Rarely does it rain more in the north of the validation area so that gauge correlations with latitude are almost always negative. SST and its latitudinal gradient from 1982-1999 indicate that a SST gradient response occurs almost every year but the strong events are intermittent (Fig. 4.12). There is no corresponding long term rainfall information.

![Figure 4.12](image-url) Eighteen years of Reynolds and Smith (1994) SST data in the vicinity of Kwajalein. Monthly SST is indicated by the solid line. SST correlated with latitude is represented by the dashed line.
It has often been observed that large-scale organization of tropical convection starts at SST of \(~27^\circ\) and then increases up to SST of \(29.5^\circ C\) (Graham and Barnett 1987, Waliser and Graham 1993, Zhang 1993, Fu et al. 1994). At Kwajalein, we also observe this trend. Fig. 4.13 compares two years (1998-1999) of monthly SST and rain accumulations for the gauges over the validation area and the PR and TMI over the 5\(^\circ\) grid encompassing Kwajalein. SST ranged between \(27^\circ\) and \(29.5^\circ C\) at Kwajalein during this two year period with rain accumulations (by all three sensors) increasing linearly with SST. Each graph shows a similar correlation (0.79-0.85) indicating that SST can explain > 60\% of monthly rain accumulations. However, each graph has a different slope relating rain amount and SST signifying that the relationship between convection and SST is very dependent on the area of interest and the method used to measure convection.

**Figure 4.13** Monthly values of rain accumulation and SST between 1998 and 1999 for (a) Kwajalein gauges, (b) PR in 5\(^\circ\) grid containing the Kwajalein validation site, and (c) as in (b) but for the TMI. The sloped lines represent a linear best fit.
4.4 Diurnal variation of precipitation

Albright et al. (1985) noted a weak semi-diurnal cycle in IR satellite imagery in Kwajalein’s area of the tropics. Bedrick and Burgett (1998) found a strong morning peak and weaker evening peak in two years of cloud-to-ground lightning strike data from four low gain lightning direction finders located around Kwajalein Atoll (Fig. 4.14). However, studies of the TOGA COARE region to the west indicate a stronger diurnal cycle than semi-diurnal (Chen and Houze 1997, Sui et al. 1997).

Daily cumulative rain amounts in 3-h periods were calculated for each gauge in the Kwajalein validation network for the period August 1998-August 1999 in order to identify any diurnal variability of precipitation within the Kwajalein region. Data from three gauges, ranging in latitude from 9.4°N to 7.8°N, are shown in Fig. 4.15 (Note: none of the gauges had a complete record during the period of accumulation). The barplots indicate a weak early morning peak and an even weaker early afternoon peak for accumulations at each
gauge. Lines representing the beginning time of the more intense precipitation events (> 10 mm accumulation) show a double peak at Roi and Loen, there is no signal at Kwajalein (although longer periods of data do show the double peak at Kwajalein).

PR diurnal sampling by the 50 significant overpasses between August 1998 and August 1999 shows no resemblance to the weak semi-diurnal signal seen in the gauge data (Fig. 4.15). The bias from undersampled diurnal variability, especially of small-scale phenomena, is most serious in polar-orbiting measurements from a single platform (Salby and Callaghan 1997). The precessing orbit of the TRMM satellite allows for diurnal sampling, but it might take more years than the expected life span of the satellite to detect the weak semi-diurnal signal suggested by the rain gauges.

**Figure 4.15** (a)-(c) Rain gauge 3-h accumulations for August 1998-August 1999 at three gauges within the Kwajalein validation area. The bars indicate rainfall accumulation. The lines show the begin times of events that accumulated > 10 mm. (d) PR accumulations from the 50 overpass cases binned into 3 h increments.
5. Convective-stratiform precipitation mapping over tropics

Chapter 1 discussed the importance of classifying precipitation as convective or stratiform. This chapter uses KR observations to test the validity of PR monthly convective-stratiform precipitation statistics at Kwajalein and discusses the similarity of Kwajalein observations to other parts of the tropics. We then use PR data to examine the variations of convective-stratiform precipitation contributions across the tropics and briefly explore the variations in relation to SST.

5.1 Monthly variation at Kwajalein

The comparison of overpass versus true reflectivity distributions in Sec. 4.1 (Fig. 4.3) suggests that the PR can capture longer time-scale convective-stratiform statistics, especially distributions of convective and stratiform rain amounts on which the PR’s low sensitivity does not have a significant impact. However, we are interested in monthly convective-stratiform statistics and Fig. 4.3 incorporated 50 overpasses from over a year while a typical month has only 5-7 PR overpasses with good swath coverage and precipitation amounts. Before extending PR convective-stratiform analysis to the rest of the tropics, we examine the feasibility of PR monthly convective-stratiform statistics at Kwajalein.

Fig. 5.1 is a two-year time series that compares the KR and PR convective percentages of total monthly rain amount and area. Stratiform percentages would be the same curves mirrored across the 50% line. The KR percentages use all reflectivity data ≥ 0 dBZ in order to show the convective fractions unaffected by PR sensitivity issues, while the PR percentages are limited to observations ≥ 17 dBZ. The time series show some month to month variation in relative contributions of convective precipitation but within a limited dynamic range. There is much less monthly variation in convective fraction of rain than in monthly rain amounts. The KR distributions indicate that convective precipitation accounts for on
average 63% of the total precipitation (Fig. 5.1a) but only 13% of the total area (Fig. 5.1b). The PR has average values (excluding the drought months of January-March 1998 because of insufficient sampling) of 55 and 23%, respectively; within 10% of the KR values. A correction factor of 0.7 can be applied to the PR convective area percentages to account for the roughly 50% of stratiform area missed by the PR as a result of its low sensitivity. The correction factor decreases the PR convective fraction of rain area to 16%, bringing it much closer to the KR value of 13%. Small adjustments could be made to the PR rain amount distributions because of the PR 17 dBZ threshold and different Z-R relations, but the effect would be minor. PR convective fractions of rain area remain slightly low compared to the KR fractions but, overall, PR monthly convective-stratiform proportions are robust at Kwajalein.

**Figure 5.1** KR and PR monthly (a) convective fraction of total precipitation and (b) convective fraction of precipitation area. Gaps are from months with too little data. The stratiform fractions would be the same curves mirrored across the 50% line.
A bound on the variability of monthly convective-stratiform statistics at Kwajalein can be found by subsetting KR monthly amounts into shorter time scales. The points in Fig. 5.2 are the KR monthly values from Fig. 5.1 and tend to cluster around 15% for convective fraction of precipitation area and 65% for convective fraction of total precipitation. The points outside of the cluster are from the drought period in the beginning of 1998. The contour is composed from over 1900 5 h samples (~30 accumulated 10 min volumes) from August 1998-November 1999. Five h was a convenient sample size to compute and manages to give the physical extremes of convective-stratiform percentages although 15-20 independent samples would better mimic the PR monthly climatology. The amount of area covered by convective precipitation, as indicated by the 5 h contour, ranges from 0 to 40%. The amount of rain that is convective runs the gamut from 10-80% with a larger concentration > 50%.

**Figure 5.2** KR 5 h and monthly convective fractions of total precipitation and precipitation area. Each of the 1900+ 5 h samples from August 1998-November 1999 were accumulated from ~30 10 min radar volumes.
5.2 Representativeness of Kwajalein

Although Kwajalein is an excellent tropical oceanic validation site, it is not necessarily representative of other tropical locations. When we compare the percent of stratiform rain amount at Kwajalein (~35%) to the other values found in Table 1.1, we see that Kwajalein is close to but lower than the percentages found at other tropical locations. The higher percentage of convective rain at Kwajalein agrees with the analysis of the rain gauge events, which showed that long-lasting systems with large stratiform areas occur infrequently. Kwajalein lies on the fringes of the intertropical convergence zone and on the edge of the Pacific warm pool, in an environment evidently less supportive of mesoscale organization than the regions in Table 1.1.

As a site comparison, two plots from Yuter and Houze’s (1998) TOGA COARE study were compared to similar plots for the 1900+ KR 5 h samples from August 1998-November 1999 (Figs. 5.4, 5.5). The first panel of each figure plots stratiform fraction of precipitation area versus the percentage of the study area covered by precipitation. The TOGA COARE and KR plots are similar in that stratiform fraction of precipitation is almost always > 50% and that precipitation areas > 20% have at least 75% stratiform coverage. However, the KR scatter plot shows area covered by precipitation rarely exceeding 50% whereas many points (from a much smaller sample) in TOGA COARE exceed 50%. This is in part because the aircraft sought out large precipitation areas but also probably reflects the more frequent occurrence of larger mesoscale convective systems over the warm pool.
Figure 5.3 Analysis of airborne radar data taken over the west Pacific warm pool shows the stratiform area fraction of (a) precipitation area and (b) total precipitation versus size of precipitation area at a spatial resolution of ~200 km. Points coded by active/suppressed/unclassified phase of the intraseasonal oscillation. Adapted from Yuter and Houze (1998).
Figure 5.4 As in Fig. 5.3 but for KR 5 h samples from August 1998-August 1999. Each of the 1900+ 5 h samples were accumulated from ~30 10 min radar volumes. Points are not coded by the phase of the intraseasonal oscillation.
For the lower panels of Figs. 5.3 and 5.4, the rain amounts at Kwajalein were calculated directly from the reflectivity fields using Kwajalein’s climatological Z-R relation whereas Yuter and Houze converted the stratiform fraction of precipitation area into stratiform fraction of total precipitation using an areal average conditional rain-rate ratio. The resulting average stratiform fraction of total precipitation from Yuter and Houze (1998) of ~85% is an upper bound since the aircraft sought out large precipitation areas, which inevitably contained large proportions of stratiform precipitation. Whereas the majority of points from the TOGA COARE study fall above 75%, most of the rain at Kwajalein is 75% or less stratiform. If the aircraft sampled at random, one would expect more TOGA COARE points to fall below 75% stratiform fraction of total precipitation which would be more akin to Kwajalein’s distribution. Still, the difference between the TOGA COARE and KR plots on the amount of rain that is stratiform is distinct. In a year of sampling, stratiform rain at Kwajalein never accounted for more than ~75% of the total precipitation when the area covered by rain was > 50%. The aircraft in TOGA COARE, however, sampled this combination repeatedly. Environmental factors controlling mesoscale organization of precipitation systems evidently favor the production of stratiform rain in the larger systems over the warm pool.

Another factor leading to the observed differences in fractional stratiform amounts between Kwajalein and the warm pool (and the other studies listed in Table 1.1) is the use of different convective-stratiform separation algorithms and different radars. The PR has the advantage of applying the same algorithm to data from the same instrument across the entire tropics—a unique aspect of the space radar. And while PR convective-stratiform classifications compare well to the ground-radar classifications at Kwajalein, PR convective-stratiform statistics still need to be validated for other tropical locations. The TRMM validation sites in Fig. 1.1 and tropical field projects in Table 5.1 all have radar data to extend the work of PR convective-stratiform validation, whether it be through data reanalysis or literature review.
Table 5.1 Tropical field projects.

<table>
<thead>
<tr>
<th>Project</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMONEX</td>
<td>15</td>
<td>90</td>
<td>May-Aug 79</td>
</tr>
<tr>
<td>BOMEX</td>
<td>13</td>
<td>-59.6</td>
<td>Jun-Jul 69</td>
</tr>
<tr>
<td>COPT-81</td>
<td>9</td>
<td>-5</td>
<td>May-Jun 81</td>
</tr>
<tr>
<td>GATE</td>
<td>9</td>
<td>-22</td>
<td>Jun-Sep 74</td>
</tr>
<tr>
<td>KWAJEX</td>
<td>8.7</td>
<td>167.7</td>
<td>Jul-Sep 99</td>
</tr>
<tr>
<td>TEPPS</td>
<td>7.8</td>
<td>-125</td>
<td>Aug-Sep 97</td>
</tr>
<tr>
<td>JASMINE</td>
<td>5</td>
<td>89</td>
<td>Apr-Jun 99</td>
</tr>
<tr>
<td>WMONEX</td>
<td>3</td>
<td>112</td>
<td>Dec 78-Mar 79</td>
</tr>
<tr>
<td>CEPEX</td>
<td>-2</td>
<td>175</td>
<td>Mar-Apr 93</td>
</tr>
<tr>
<td>TOGA COARE</td>
<td>-4</td>
<td>155</td>
<td>Nov 92-Feb 93</td>
</tr>
<tr>
<td>TRMM-LBA</td>
<td>-11</td>
<td>-62</td>
<td>Nov 98-Feb 99</td>
</tr>
<tr>
<td>EMEX</td>
<td>-12</td>
<td>40</td>
<td>Jan-Feb 87</td>
</tr>
<tr>
<td>MCTEX</td>
<td>-12</td>
<td>130.5</td>
<td>Nov-Dec 95</td>
</tr>
</tbody>
</table>

Fig. 5.5 uses PR 5º convective fractions over the entire tropics (40ºN to 40ºS) for January and August 1998. January 1998 was part of a strong El Niño, August 1998 is more representative of other months. Symbols differentiate points > 100, 200, and 300 mm accumulation. The KR (Fig. 5.2) and PR (Fig. 5.5) plots are very similar. The amount of rain area that is convective rarely exceeds 50% and monthly values cluster between 10 and 25% (7 and 18% after adjustment for the low PR sensitivity assuming the 0.7 correction factor holds for the rest of the tropics). The amount of precipitation that is convective ranges from 15-90% with a tendency for more points to be > 50%. Therefore, the observation that, at Kwajalein, convective precipitation contributes more to rainfall amounts and stratiform precipitation dominates the area covered by rain holds for the rest of the tropics.
Figure 5.5 PR 5° grid convective fractions of total precipitation and precipitation area for the entire tropics (40°N-40°S). (a) January 1998 and (b) August 1998. Points are coded by accumulations > 100, 200, and 300 mm. Ovals indicate the outer limits of grids with > 300 mm accumulations.
However, there are many points along the scatter diagram that represent regimes unique from Kwajalein. Kwajalein had > 100 mm accumulation in August 1998 and its PR values of 18% convective rain area and 45% convective rain amount fell within the high density of points that month. Thus, Kwajalein is similar in terms of convective-stratiform precipitation contributions to some other locations in the tropics but certainly not to the entire tropics.

January 1998 was included in order to indicate the degree of month to month variation in convective-stratiform precipitation percentages. The outer limits for points > 100 mm are similar to August 1998 but the center distribution of points > 300 mm is more elongated, indicating a much wider range of convective-stratiform contributions at high rain amounts.

Fig. 5.5 can be used to identify different convective-stratiform regimes in the tropics. Regions with points falling at the upper right of the convective fraction distribution are highly convective and at the lower left, highly stratiform. These outer regions tend to have lower rainfall. Areas with higher rainfall occur in the middle of the distribution, suggesting that a limited combination of convective and stratiform processes produces significant monthly accumulations. Future work should analyze these plots according to climatic region—such as the ITCZ, monsoon areas, the continents, etc.

5.3 Tropic-wide patterns

In order to discern the spatial variability of convective and stratiform contributions across the tropics, PR 5º maps of monthly rain, convective fraction of total precipitation, and convective fraction of precipitation area are shown for two years of January and August data (Fig. 5.6). To insure sufficient sampling by the PR, grids with monthly rain < 100 mm were not included. Letters show locations of the field projects in Table 5.1.
Figure 5.6 PR maps based on 5º grid values of monthly rain, convective fraction of total precipitation, and convective fraction of precipitation area. (a) January 1998, (b) January 1999, (c) August 1998, and (d) August 1999. Grids with accumulations < 100 mm were not included. Letters show locations of field projects listed in Table 5.1.
Figure 5.6 Continued.
Figure 5.6 Continued.
Figure 5.6 Continued.
In January 1998, three areas had monthly rain > 300 mm–Zambia (30ºE, 15ºS), a large swath in the western-central Pacific from 0-10ºS, and Uruguay (55ºW, 30ºS). Areas with a high percentage of rain that was convective (> 80%) occurred over Zaire (20ºE, 5ºS), Indonesia (115ºE, 5ºS), the Gulf of Mexico (90ºW, 25ºN), and Argentina/southern Brazil (55ºW, 30ºS). Areas with a low percentage of rain that was convective (< 40%) were over southern Japan (130ºE, 30ºN) and the central-eastern Pacific from 0-15ºS. The amount of area covered by convective precipitation generally coincides with the amount of rain that is convective but is on a different dynamic scale (i.e., 30-40% would be considered high; < 10% would be considered low).

The very high rain amounts over the central Pacific Ocean had very low percentages of convective precipitation and area, whereas the continental precipitation maximums coincided with or were nearby regions of large convective proportions. High rain amounts juxtaposed with low contributions from convective precipitation indicate greater mesoscale organization over the central Pacific.

The January 1999 pattern of precipitation in the Pacific was very different from the January 1998 (El Niño) pattern. Most of the high rain areas shifted to the west and south. The eastern Pacific had no areas above 100 mm accumulation. The percent of rain that was convective was generally greater at all locations in January 1999, except in Indonesia which received significantly more rain in 1999. The percent of rain area accounted for by convective precipitation also decreased in January 1999 over Indonesia. In general, the two January patterns suggest that the more it rains, the greater the stratiform proportion, which is consistent with greater mesoscale organization.

August saw a shift in precipitation to the Northern Hemisphere. August 1998 and 1999 were considerably more similar than were January 1998 and 1999. Regions of precipitation > 300 mm were over Nigeria (5ºE, 15ºN), Bay of Bengal (90ºE, 20ºN), Indonesia (120ºE, 0º), the far western Pacific (135ºE, 10ºN), the far eastern Pacific (100ºW, 10ºN),
and Panama/Columbia/Venezuela (60ºW, 5ºN). These areas of high monthly accumulation tended to have near average convective fractions (60% of total precipitation, 15% of precipitation area). The ITCZ regions of the central-eastern Pacific and eastern Atlantic Oceans had lower than average convective percentages whereas the rain maxima associated with land in Africa, Indonesia, and Central/South America had higher than average convective fractions.

Regions that differentiate themselves in terms of convective and stratiform contributions during January and August are listed in Table 5.2. The stratiform component of precipitation is larger over the eastern oceans while the convective component is greater over the continents. Precipitation over the Indian Ocean and west Pacific warm pool has tropic-average convective-stratiform percentages. Validation sites and field projects related to the regions of interest are listed in Table 5.2. These sites and projects have data and literature dedicated to the interpretation of factors that may affect the relative importance of convective and stratiform processes including SST, moisture availability and wind profiles.

Table 5.2. Tropical regions by relative proportion of convective precipitation.

<table>
<thead>
<tr>
<th>Region</th>
<th>Related field projects and validation sites</th>
<th>Convective proportion</th>
</tr>
</thead>
<tbody>
<tr>
<td>eastern-central Pacific Ocean</td>
<td>TEPPS</td>
<td>very low</td>
</tr>
<tr>
<td>eastern Atlantic Ocean</td>
<td>GATE Japan validation site</td>
<td>low</td>
</tr>
<tr>
<td>southern Japan</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Indian Ocean</td>
<td>JASMINE, CEPEX, EMEX, KWAJEX, TOGA COARE, Darwin and Kwajalein validation sites</td>
<td>average</td>
</tr>
<tr>
<td>western Pacific Ocean</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Indonesia</td>
<td>MONEX</td>
<td>high</td>
</tr>
<tr>
<td>Africa Central/South America</td>
<td>COPT-81, TRMM-LBA, Florida and Texas validation sites</td>
<td>very high</td>
</tr>
</tbody>
</table>
5.4 Relationship to SST

This section is a very brief foray into the relationships between SST and convective fraction of total precipitation and precipitation area. PR precipitation and Reynolds and Smith (1994) SST monthly values over 5º grids ranging from 40ºN to 40ºS were compared for August 1998 (Fig. 5.7). The first panel shows the frequency of occurrence of precipitation amounts > 200 mm as a function of SST. The PR precipitation amounts > 200 mm occur nearly exclusively at SST of 28-30ºC with a peak at 28.5ºC. The second and third panels depict SST versus convective fractions of total precipitation and precipitation area, respectively. The convective component of the amount of rain and the total area covered by rain tends to increase with increasing SST, especially when accumulations are between 200-300 mm. Thus, SST > 28ºC seems to favor convective precipitation in moderate rain regimes. However, regions with accumulations > 300 mm have SST between only 28.5 and 29.5ºC and do not have much of a trend to increase with increasing SST. Regions with such heavy rainfall normally have more highly organized precipitation systems. As systems organize on the mesoscale, large areas of cloud and precipitation develop and a large cold pool forms in the boundary layer. The widespread precipitation areas are largely stratiform, and the convective fraction of the total rain decreases. The widespread cloud cover, rain, and cold pool in turn all lower the temperature of the underlying ocean. Evidently, these processes keep heavy rain regimes within a small range of SST and within limited convective-stratiform rain percentages.

The use of smaller grids, shorter times, and more defined geographical regions could possibly illuminate tighter relationships between SST and convective-stratiform contributions to precipitation. That will be left for future work, along with the investigation of the role of moisture availability and wind shear/advection speeds in convective-stratiform precipitation patterns.
Figure 5.7 (a) Number of 5° grids with PR monthly accumulations > 200 mm as a function of SST for August 1998. Oceanic grids from 40°N-40°S were used. (b) Convective fraction of total precipitation of grids from (a). Grids with accumulations > 300 mm are indicated by diamonds. (c) As in (b) but for convective fraction of precipitation area.
6. Conclusion and future research

Before TRMM, surface rainfall measurements over the tropics had uncertainties on the order of 50% and the vertical distribution of precipitation across the tropics was unknown outside of a few field experiments. The TRMM satellite (most importantly the PR) removes many of the unknowns and uncertainties in tropic-wide precipitation measurement and therefore paves the way for much better quantification of the four-dimensional distribution of latent heating throughout the tropics.

Because of the limitations imposed by sensitivity and attenuation, the TRMM validation program has emphasized comparison of PR data with data from highly sensitive three-dimensionally scanning, non-attenuated radars such as the S-band KR. The KR and the attenuation-corrected PR reflectivity data agree well within the range of sensitivity of the PR, i.e., for reflectivity values exceeding the PR threshold of 17 dBZ. The convective-stratiform and rainfall-rate fields which are based on reflectivity also compare well within the range of the sensitivity of the PR. Differences between the PR and KR convective-stratiform separation algorithms and $Z$-$R$ relations do not strongly affect these results. The comparisons indicate that the attenuation correction generally works well.

The main distinction between the KR and PR and their ability to capture the instantaneous precipitation field lies in the sensitivity of the PR which effectively limits it to detecting surface rainrates $\geq 0.5\text{ mm/h}$. The low PR sensitivity biases PR measurements toward convective precipitation. The PR highly undersamples stratiform rain regions and echo associated with ice hydrometeors aloft (anvils). Comparisons with the KR show that the PR misses almost 50% of near-surface stratiform rain area but less than 3% of near-surface stratiform rainfall. Aloft, the PR cannot sense 85% of the ice region. The probability distribution of KR reflectivity provides a basis for correcting the undersampling of weaker echoes by the PR from ice particles and stratiform rain.
The same low orbit that gives the PR high spatial resolution (~4 km footprint at nadir) limits the PR’s 215 km swath to pass over a point only 8-10 times per month. According to Seed and Austin (1990) and Steiner et al. (1995), one would need to sample 8-10 times per day to estimate monthly rainfall with 10% accuracy. Therefore, the applicability of monthly PR rain accumulations is questionable. Comparisons of the KR and PR showed that PR estimates of monthly rain amounts at Kwajalein could approach the KR estimates but were sometimes lower (up to a factor of two). A weak semidiurnal signal, evident in three-hour gauge accumulations over a year period, was not captured by the PR. At times, a strong monthly latitudinal precipitation gradient occurred over the 300 km diameter region centered on the KR (possibly caused by variations in SST patterns) which the PR did not detect. However, other PR statistics that are not as variable as rainfall accumulation have the potential to be useful, e.g., the temporal sampling of the PR accurately captures the KR’s overall frequency distribution of reflectivity and its subdivision into convective and stratiform components.

The classification of precipitation as convective or stratiform is especially pertinent to determining latent heating profiles. At Kwajalein, the KR observes that convective precipitation normally accounts for 65% of monthly rainfall but only 15% of total rain area with very little seasonal variation; PR percentages are within 10% of the KR monthly values. Kwajalein’s convective-stratiform percentages are similar to past field projects but Kwajalein has a smaller proportion of precipitation that is stratiform, especially compared to ITCZ regions in the eastern oceans and the Pacific warm pool. The environment at Kwajalein apparently does not support mesoscale organization and hence stratiform precipitation areas as readily as the ITCZ and warm pool regions. It should be noted that while Kwajalein is an excellent oceanic validation site, it is not representative of the entirety of the tropical oceans.

The tropic-wide coverage of the PR allows precise regional intercomparisons of convective-stratiform contributions to precipitation. The PR observes that on average, the amount
of rain that is convective hovers around or just above 50% while the amount of area covered by convective precipitation is typically 15%. However, proportions of convection and stratiform precipitation have significant geographical variability. Analysis of January and August maps show the stratiform extreme to be the ITCZ region of the eastern-central Pacific Ocean; the ITCZ region of the eastern Atlantic also has high percentages of stratiform precipitation. The convective extremes are the continental regions associated with rain maxima over Africa and Central/South America (including the Gulf of Mexico); Indonesia also tends to have relatively more convective precipitation. The Indian and western Pacific Oceans are close to tropic-wide averages in their convective-stratiform precipitation proportions. Highly stratiform regions that produce a large amount of rain suggest a high degree of mesoscale organization and most often occur over open ocean.

SST is one of the environmental factors that affect convective and stratiform rain amounts and areal coverage. As SST increases from 28 to 30°C, the proportion of rain and rain area accounted for by convective precipitation also increases. However, regions with the highest monthly rainfall do not follow this pattern, evidently owing to their higher level of mesoscale organization and thus higher proportion of stratiform rainfall. These regions have a limited SST range (28.5-29.5°C) and a limited range of percent rain that is stratiform (45-60%), probably resulting from the feedbacks between SST and the organized, widespread systems that produce the large quantities of rain.

Other environmental factors that can affect convective-stratiform precipitation contributions include wind and moisture profiles. Wind shear, advection speeds, and moisture availability all dictate the relationship between nimbostratus cloud and the deep convection that seeds it to create stratiform precipitation. Future work on what controls convective-stratiform rain proportions will focus on the varying environmental factors at the regions defined in Table 5.2. Both the data and existing literature from the accompanying field projects will be key in this endeavor. As the TRMM satellite observes ever more events, longer-term variations in convective-stratiform precipitation patterns can be stud-
ied, especially in relation to the Madden-Julian (Madden and Julian 1971) and EL Niño-Southern Oscillations. Of additional interest is the importance of the portion of stratiform rain that does not contribute much to total rain but does contribute significantly to total rain area, especially the radiative affects.
References


Appendix A: University of Washington Quality Control (UWQC)

The University of Washington quality control (UWQC) algorithm was created to automatically remove non-precipitation echo from NEXRAD Level II radar data. The algorithm removes clear air return, echo from insects and most ground clutter and anomalous propagation (AP). Strong ground clutter, AP, and second-trip echo that exist in the second tilt are only partially removed in the general application of the quality control. The UWQC algorithm expects an input reflectivity field (DZ or ZT) and outputs the original field and a corrected reflectivity field (CZ). Additional fields in the UF volume such as radial velocity are copied from the input volume into the output volume unchanged.

The first step in the algorithm examines the texture of the reflectivity field. The volume is processed starting from the highest angle tilt and ending with the lowest tilt. For each tilt, the UWQC algorithm looks at the 9 x 9 pixel grid around every range gate. If any pixel in the neighborhood (excluding the center pixel) is greater than or equal to a specified reflectivity threshold, the center pixel is kept. Otherwise, the pixel is set to a BAD value flag. The reflectivity threshold used is a function of height. This part of the algorithm removes areas of low reflectivity non-precipitation echo (such as insects) and isolated high reflectivity ground clutter and AP while preserving the low reflectivity storm edges.

Nine x nine was chosen as the optimal grid size after comparing grids ranging from 5 x 5 to 21 x 21 at various reflectivity thresholds. In general, the smaller grids take out too much of the storm edges, while the larger grids take longer to run through the quality control and leave in too many unwanted low reflectivity pixels.

The set of reflectivity thresholds used in the texture processing were originally determined by observing the reflectivity of large swarms of insects in Wichita, Kansas during the summer. The highest reflectivity insect values were found closer to the surface, while lower reflectivity values occurred higher up. Physically this makes sense because there are more
insects closer to the surface and their density decreases with altitude. Consequently, the corresponding reflectivity thresholds also decrease with altitude. By similar reasoning, ground clutter and other abnormal phenomena are seen mainly in the lowest tilts and thus a higher reflectivity threshold is necessary for removal of near surface non-precipitation echo. Three reflectivity thresholds are determined for each of three height regions. We found that the empirically derived altitudes from Wichita have rough physical equivalents in which the top of the high reflectivity insect layer (1.75 km) corresponds to the top of the boundary layer and the altitude at which insects cease to appear on the radar (4.5 km) corresponds to the 0°C level. There is a one km buffer after the “high reflectivity insect layer” or boundary layer in order to take into account that insect densities gradually decrease from the top of the boundary layer to near the freezing level. The texture algorithm is not applied to data at altitudes higher than the 0°C level except that all the data in the lowest tilt is always examined whether it is above 0°C or not. Modifications still need to be made when the freezing level is less than one kilometer.

The lowest sweep is treated differently from the sweeps above in that additional checks are performed. Before processing the lowest sweep, the output of the texture algorithm on the second tilt is dilated in order to create a binary version of the second tilt’s reflectivity field with smoothed and thicken edges. The dilation works as follows: if there is real echo within the 3 x 3 grid surrounding a pixel the center pixel is turned on in the dilated field, even if it had no echo or was set to a BAD value in the texture processing. For each pixel in the lowest tilt, the dilated pixel above is examined. If the dilated second tilt pixel above the first tilt pixel is set to a BAD value flag then the first tilt pixel is also set to a BAD value flag. If the pixel above is not a BAD value then the texture algorithm as stated above is applied to the 9 x 9 grid surrounding the first tilt pixel. The dilated pixel-above test removes random high reflectivity insect values and much of the AP in the lowest tilt. Without dilation, the pixel-above test would take out too much real echo when echo tilts in the vertical (i.e., from wind shear).
The third part of the algorithm attempts to remove any remaining AP by examining an areal average difference in reflectivity with height. This part of the algorithm is applied after the texture test has been applied to the entire volume (and before the dielectric adjustment which is discussed in the next paragraph). The 3 x 3 pixel averages of the second tilt and lowest tilt are computed. If the difference between the average reflectivity at a point in the lowest sweep and the point directly above in the next to lowest sweep is more than a specified threshold (normally between 25 and 35 dBZ), then both points are set to a BAD value. This method eats away the middle of strong AP in multiple tilts but often leaves the edges of strong AP region intact. An example of UWQC results on AP with imbedded real echo is shown in Fig. A.1.

The last part of the algorithm is optional. In the summer of 1994, the KICT radar dielectric was not changed from the winter ice value to the summer water value. Therefore, all of KICT’s UF reflectivity volumes from that time period need to be adjusted -6.7 dBZ. The dielectric adjustment was applied to the UWQC and tested on KICT hourly data for July 1994. Examination of the resulting volumes showed that it performed very well.

Parameter values need to be adjusted according to climatology and season. Radar volumes were tested from various locations and seasons. The same parameters performed well for locations with similar climatologies (Table A.1). To test interseasonal change in parameters, Wichita radar volumes from the spring and summer of 1994 were compared and it was found that adjusting the parameters that correspond to the height of the boundary layer and 0°C level worked well.
Figure A.1 Anomalous propagation at Amarillo, TX on 25 May 1994 at 0029 UTC. The 0.5 and 1.5° tilts are shown before and after the application of the UW quality control.
Table A.1. UWQC parameter list.

<table>
<thead>
<tr>
<th>Radar</th>
<th>Location</th>
<th>Season</th>
<th>BL</th>
<th>FL</th>
<th>UL</th>
<th>ML</th>
<th>LL</th>
<th>diff</th>
</tr>
</thead>
<tbody>
<tr>
<td>KICT</td>
<td>Wichita, KS</td>
<td>April*</td>
<td>1.0</td>
<td>3.5</td>
<td>18</td>
<td>15</td>
<td>8</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td></td>
<td>May-Aug</td>
<td>1.8</td>
<td>4.5</td>
<td>25</td>
<td>20</td>
<td>12</td>
<td>35</td>
</tr>
<tr>
<td>KWAJ</td>
<td>Kwajalein</td>
<td>Jul-Aug</td>
<td>0.9</td>
<td>4.9</td>
<td>18</td>
<td>12</td>
<td>10</td>
<td>35</td>
</tr>
<tr>
<td>KMLB</td>
<td>Melbourne, FL</td>
<td>Aug</td>
<td>1.5</td>
<td>4.0</td>
<td>22</td>
<td>15</td>
<td>12</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sep</td>
<td>2.0</td>
<td>4.5</td>
<td>25</td>
<td>18</td>
<td>15</td>
<td>25</td>
</tr>
</tbody>
</table>

BL-boundary layer  
FL-freezing level  
UL-upper level hit dBz  
ML-mid level hit dBz  
LL-lower level hit dBz  
diff-dBZ difference between lowest and next lowest tilt for AP

*before dielectric adjustment